THE DEVELOPMENT OF A NOVEL
SUSPENSION ARM WITH 2-DIMENSIONAL
ACTUATION, FOR USE IN ADVANCED HARD
DISK DRIVES

By

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"The development of a novel suspension arm with 2-dimensional actuation, for use in advanced hard disk drives."

As magnetic computer disks are developed to ever-greater data storage densities, the accuracy required for head positioning is moving beyond the accuracy provided by present technology using single-stage voice-coil motors in hard disk drives. This thesis details work to develop a novel active suspension arm with 2-dimensional actuation for use in advanced hard disk drives. The arm developed is capable of high-bandwidth data tracking as well as precision head flying height control motion. High-bandwidth data tracking is facilitated by the use of piezoelectric stack actuator, positioned closer to the head.

The suspension arm is also capable of motion in the orthogonal axis. This motion represents active flying height control to maintain the correct altitude during drive operation. To characterise the suspension arm's structural dynamics, a high-resolution measurement system based on the optical beam deflection technique has been developed. This has enabled the accurate measurement of minute end-deflections of the suspension arm in 2-dimensions, to sub-nanometre resolution above noise. The design process of the suspension arm has led into the development of novel piezoelectric-actuated arms. In the work involving lead zirconate titanate (PZT) thick films as actuators, work in this thesis shows that reinforcing the films with fibre improves the overall actuation characteristics of the thick films. This discovery benefits applications such as structural health monitoring.

The final suspension arm design has been adopted because it is simple in design, easier to integrate within current hard disk drive environment and easier to fabricate in mass. Closed-loop control algorithms based on proportional, integral and derivative (PID) controller techniques have been developed and implemented to demonstrate high bandwidths that have been achieved. The suspension arm developed presents an important solution in head-positioning technology in that it offers much higher bandwidths for data tracking and flying height control; both very essential in achieving even higher data storage densities on magnetic disks at much reduced head flying heights, compared to those in existing hard disk drives.
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Chibesa Chilumbu.
Author's Declaration

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Chapter 1

Introduction

1.1 Advances in Hard Disk Drive Industry

Since its advent in 1955, the magnetic recording industry has constantly and dramatically increased the performance and capacity of hard disk drives to meet the computer industry's insatiable demand for more and better storage. Applications like multimedia, Internet based applications such as e-business, real-time digital video and audio, and graphical user interfaces, along with ever-increasing program sizes, are driving the need for ever-greater storage capacity. This has resulted in the data-storage recording densities of magnetic hard disk drives (HDDs) doubling every 18 months in recent years. Five years ago, a storage capacity of 2 GB (gigabytes) was considered to be enormous. Today (2002), commercially available hard disk drives have in excess of 40 GB of storage capacity. Over the past two years, the data-storage density growth rate accelerated rapidly. In February of 1999, Seagate set a new data-storage density mark of 16.3 GB/in² (2.53 GB/cm²) [1]. Within this same development, a flying height of 15 nm (0.6 μm) was achieved and a new benchmark for track density, 43,000 tpi (tracks per inch), was established. Within the same year, IBM demonstrated an even higher data-storage density of 35.3 GB/in² (5.49 GB/cm²) [2]; with the aid of the giant magneto resistive (GMR) read head. These aggressive and enormous strides towards increasing storage capacities and densities indicate that if this trend of growth
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continues, we should expect data-storage densities of commercial hard disk drives to be well in excess of 40 GB/in$^2$ by the year 2004, as predicted in Figures 1.1(a) and 1.1(b). The corresponding head flying height is expected to be lower than 10 nm (0.4 μm). In order to achieve such high data-storage densities, very narrow data tracks are required.

![Data Storage Density Diagram](image)

**Fig. 1.1(a)** Diagram showing the magnetic head evolution and advances in data storage densities in hard disk drives [3].

Sustaining this growth rate to satisfy the ever growing needs for more and faster storage requires progressive advances in all technologies used to make computer hard disk drives. Along with these is the need to improve the accuracy required for head positioning, currently provided by a single-stage voice-coil motor (VCM). In order to increase storage densities on magnetic disks of the same diameter, the data tracks will have to become smaller and smaller. This will mean that positioning the magnetic
read-write head right on top of a narrow data track with the necessary high accuracy and precision, using a conventional VCM will become increasingly more difficult. In striving to achieve high data storage densities, improved reliability and increased data access times in hard disk drives, the following technologies (presented in the next section) are some of the few that are constantly being investigated and improved, and are detailed in the following section.

![Diagram showing how track widths have reduced with bit lengths in recent years](image-url)

**Fig. 1.1(b)** Diagram showing how track widths have reduced with bit lengths in recent years [3].
1.1.1 Load-Unload Technology

To achieve ever-increasing storage densities, the head-to-disk spacing must decrease correspondingly. This can be achieved only with a virtually perfectly smooth disk. Today's disk drives operate with a head-disk spacing of less than 50 nm. Previously, most hard disk drives operated a CSS (contact stop-start) mode, in which the head could slide, in contact, over the disk surface during starting and stopping of the disks, that is when the disks are rotating at less than full speed. In order to prevent the read-write heads from sticking to the disks, the disks were textured (roughened). However, it is becoming difficult to texture disks for extremely high storage densities and hence, IBM have developed a mechanism which allows the read-write head to rest on a ramp when it is not reading or writing data on the disk [4]. This process is referred to as the load-unload mechanism. Dynamic load/unload has been widely used in portable and removable drives, and recently, the disk drive industry has started to apply it in desktop and server drives [5]. The load-unload drive has three main advantages over a CSS drive. Firstly it enables increased storage densities as ultra-smooth disks are used; it is possible to have very low head-to-disk spacing and enables a close disk-to-disk spacing. In addition, it provides improved shock resistance for greater disk durability and reliability by preventing head-to-disk interaction and start-up wear. Lastly, there is reduced power consumption for cost savings by introducing a new idle mode in which heads are unloaded while the disks continue to spin [6].
1.1.2 Glass Substrate Disk

The use of glass substrate disks in hard disk drives, as demonstrated in the IBM Ultrastar 18LZX and 36ZX, can potentially provide much higher reliability than traditional disks (nickel phosphorous-plated aluminium/magnesium substrate disks) over both short and long term [7]. The better surface finish and increased hardness of glass results in a more rugged disk with far superior performance and reliability. When using glass substrate disks, there is a considerable improvement in the uniformity of the magnetic film surface to increase disk reliability and data integrity and, there is a significant reduction in overall surface defects, reducing read-write errors. There is also a greater fly-height margin to minimise head-to-disk contact, thereby improving the accuracy of the drive operation. Lower flying heights, which are necessary to achieve increased storage densities, can be implemented reliably in a highly error-tolerant design. At very high rotation speeds of disk drives, air friction may cause unpredictable slight movements of the disks outer edge, increasing the potential for track misregistration (TMR) problems, and these can delay the arrival of the head at the desired disk track. The high stiffness of the glass helps reduce these disk dynamics, increasing the ability of the disk to withstand shock and damage [7].

1.1.3 Servo Writing Technology

Another area of technology that is advancing, together with the continually increasing storage capacities in hard disk drives, is that of servowriting. To read and write data, the disk drive head must remain accurately centred on a selected track. At today’s high
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track densities, this must be achieved to within a tolerance of one-millionth of an inch [8]. To achieve this level of precision, the head must read position information along the track that is already written permanently onto the disk. The position information is used by a precision electronics control system that servos the recording head onto the track. Servowriting is the process, by which this position information is written onto the disks, a process performed only once, during the manufacture. The machines that write servo patterns are called servo writers. These instruments are required to be of very high precision. Traditional servowriting has been performed in clean room environments with external sensors invading the head disk assembly to provide the precise angular and radial position information to write the servo patterns. At today's increased track densities, servowriting must be so precise, as to avoid the mechanical vibration of the file, relative to the external sensors, thereby limiting the accuracy or increasing the complexity of setting the patterns.

In response to this need for increased precision, new manufacturing technology for servowriting, called no-clock-head (NCH) servowriters, has been developed using IBM servowrite self-timing technology [8]. NCH servowriters replaces the clock heads used in traditional servowriting with an electronic non-invasive process to create the nanosecond-level time alignment of servo patterns between adjacent tracks. A digital signal processor executing mathematical algorithms is used for this task. The hard disk drive generates its own timing information while the drive is being servo written, using only the product data head. The patterns are self-propagated and aligned by a digital signal processor, increasing time alignment. There are three main benefits of this new method. Firstly, improved performance because the NCH process eliminates mechanical vibrations associated with external clocking while improving
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servo pattern time alignment significantly, resulting in fewer servo errors, and improving the disk drive performance. The improved time alignment enables a reduction in the size of the sector fields, thereby increasing data capacity. Secondly, improved reliability as the NCH servowriter eliminates external invasive clock heads, which may damage the drive during manufacture. And lastly, improved quality because the NCH servowriter includes in-process algorithms to detect and correct servowriter errors as they occur.

1.1.4 Aims of this Research

As well as improving the accuracy and precision with which data can be accessed and written to disk, a need has been identified by the computer industry to be able to control the head flying height, maintaining or adjusting it to a desired height above a rotating magnetic disk [43]. Maintaining the correct flying height is becoming increasingly more important as flying heights are reduced even further, in order to realise greater data-storage densities in magnetic disks. Current technology uses a sprung stainless steel cantilever, to which the head and gimbal assembly is attached at the end. As stated previously, a voice coil motor is used to position the head in the $x$-$y$ plane for track selection, whereas the flying height ($z$-axis) is determined from the compliance of the arm, aerodynamic characteristics of the air-bearing slider and the speed of rotation of the disk.

To achieve both these goals, the ultimate aim of the research described in this thesis is the investigation, design, fabrication and characterisation of a novel ‘active suspension arm’, preferably using hybrid piezoelectric composite materials. The suspension arm
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is intended to give precision control over the positioning of a read-write head to sub-nanometre accuracy in advanced HDDs. It is intended that the active arm be capable of motion in two orthogonal axes. The first plane of motion is intended to provide high-bandwidth data tracking and, the other, precision head flying height control. Both planes of motion are required to give positioning control of the suspension arm to sub-nanometre accuracy. The research is expected to go further and demonstrate a robust servo system to control the positioning of the arm in 2-dimensions. As the transient dynamic characteristics of the arm will be different for each dimension of motion, two independent controllers will be developed and implemented to show much improved closed-loop bandwidths of the suspension arm.

1.1.5 Layout of the Thesis

Chapter Two, *Hard Disk Drive Actuator Mechanisms*, introduces the concept of dual-stage actuation mechanisms in advanced HDD and why this is the solution to achieve high-bandwidth data tracking to realise even higher data storage densities in HDDs. A brief review of actuator theory in HDDs is also presented.

Chapter Three, *Development of Measurement Channel*, presents the experimental arrangement adopted in this project for measuring displacements of small mechanical structures. Comparisons between different methods to measure cantilever end-deflections are made, in order to choose one to use in this work. A detailed experimental arrangement, based on the Optical Beam Deflection technique (OBD), is also developed for monitoring actuator displacement.
Chapter Four, *OBD Optimisation*, presents work carried out to optimise the OBD technique. A novel analytical model is presented, representing the end-displacement of a bimorph element. The displacement is analysed to distinguish between curvature and horizontal displacement of a bending structure. The relationship between the end-displacement of the laser beam on the photodiode during OBD operation and the bimorph end-displacement is also investigated in order to characterise the OBD technique. A new model, which accurately takes into account the curvature, and the displacement of the bimorph is proposed and compared to an existing approximate model. To optimise the measurement technique even further, the relationship between the photodiode gap and the laser beam radius for an elliptical beam of Gaussian power distribution is investigated and the results compared to those obtained through modelling.

Chapter Five, *OBD Characterisation*, presents the characterisation of the OBD technique. The limiting sensitivity and resolution of the OBD measurement channel developed is quantified. The sensitivities of various photodiodes are also compared in order to find one that would be adopted in all future experiments. A detailed analysis of noise affecting the OBD measurement channel is also investigated.

Chapter Six, *Suspension Arm Design*, investigates the design, fabrication and characterisation of the active suspension arms developed. The requirements of the suspension arm for use in HDDs are outlined, taking into account factors such as bandwidth, actuator stiffness, magnitude of end-deflections and ease of fabrication and integration into a commercial HDD environment, as well as costs of integration and implementation in a commercial fabrication process.
Chapter Seven, *Suspension Arm Controller Design*, presents the detailed design and implementation of the servo controllers based on PID compensators. The controllers are independent of each other. Through modelling and simulations, the controllers are designed, tested for stability and implemented.

Chapter Eight, *Thesis Conclusions*, summarises and concludes the research work done in this project. The contributions to knowledge made as a result of this work are presented, and recommendations for further work are given.
1.2 Physics of Magnetic Recording

1.2.1 Basic Principle

The magnetic recording process converts an electric current signal into an equivalent magnetisation in the coating of a magnetic disk. This is done using a record (or write) head that transforms the electrical signal into a magnetic field through which the coating passes. Magnetic recording is based on the interaction between a magnetic storage medium and a magnetic head (transducer), in relative motion with respect to one another. During the recording (or writing) process, the magnetic head magnetises the magnetic storage medium traversing through the head gap as shown in Figure 1.2. On readback, the head provides an induced voltage reflecting the rate of change of magnetisation recorded along this magnetic path.

Fig. 1.2 Diagram showing magnetic recording principle
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The storage layer must be capable of retaining a sequence of permanent magnetic states, which are directly related to the applied magnetising field. The path generated along the recording surface by the magnetic head is called a track, and is parallel to the direction of relative motion. The output signal from an inductive head is proportional to the rate of change of flux linking the magnetic head, and hence to the track width [9].

Magnetic recording is dependent on the phenomena of magnetic hysteresis, which is exhibited by most magnetic materials [10]. The hysteresis behaviour for a ring core is represented in Figure 1.3, where $M$ is the magnetisation induced in the material in the presence of a field of intensity $H$. Important attributes of hysteresis behaviour are the remanent magnetisation $M_r$ (the magnetisation that remains after saturation when $H$ is reduced to zero) and the coercivity $-H_C$ (the field required to reduce magnetisation to zero). The diagram shows an example for a hard magnetic material (typical for magnetic medium) in which the material holds its magnetisation after it has been moved away from the magnetic field. An $M$-$H$ loop for a soft magnetic material used for the head core is shown in figure 1.4. In read, write and erase heads, the ring core has a narrow air gap, which results in the formation of north (N) and south (S) free poles on the two gap surfaces, drastically reducing $M_r$ to $M'_r$. $M'_r$ is a very small value, typically, and if not reduced would cause serious noise and distortion problems in recording.
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Fig. 1.3 Magnetisation curve and hysteresis loop for a hard magnetic material

Fig. 1.4 Magnetisation curve and hysteresis loop for a soft magnetic material with an air gap (broken lines are for material without air gap)
Demagnetising the recorder head periodically is recommended in order remove remanence. The coercivity of a soft magnetic material is very low and its permeability is very high. Note that only a small field is required to saturate the ring core without an air gap. This shows the materials ability to produce a large flux density for small fields - this is extremely desirable in magnetic heads.

In the sections that follow, the two main types of magnetic recording, longitudinal and perpendicular, are discussed briefly, and some comparisons are made. The aim is to appreciate and understand the principles of magnetic recording further.

1.2.2 Longitudinal Recording

In longitudinal (or horizontal) recording, as shown if Figure 1.5, the principle direction of magnetisation is in the plane of the surface and parallel to the direction of surface motion [9]. This method has been used traditionally, and it still dominates all major analogue and digital applications. Longitudinal recording enables a minimum magnetic coupling zone along a track between the head and the surface, hence achieving a high resolution. A ring head with a narrow gap oriented normal to the direction of relative motion best meets this criterion. However, in longitudinal recording the north or south poles of neighbouring cells are adjacent to each other when a transition is made from one magnetic orientation to another. This has the effect of the cells demagnetising each other, weakening them and making them less stable compared to those in perpendicular recording.
1.2.3 Perpendicular Recording

In perpendicular, or vertical recording, as shown in Figure 1.6, the principle orientation of the magnetisation is normal to the plane of the surface [9]. Single-pole heads for recording and a ring head for reading are generally used in perpendicular recording. However, both the recording and reading processes have been achieved with the same single-pole head (auxiliary pole driven type) [11]. Perpendicular recording has the advantage, over longitudinal recording, of reduced self-demagnetisation because the opposing poles of adjacent cells lying next to each other enable the emanating magnetic fields to reinforce each other. This makes the cells stable. Consequently, for a digital signal, sharp magnetisation transitions are possible, even at high recording densities, without being affected by demagnetisation. Hence smaller cells are possible. It is believed that the theoretical minimum bit length is as
small as the dimension of a magnetic domain [11]. There is no limitation due to
demagnetisation imposed on the recording density for perpendicular recording. Hence
higher storage densities can be achieved as opposed to longitudinal recording where
the circular magnetisation mode in high bit densities is a limiting factor.

![Perpendicular recording using single-pole read head, shield and inductive
write head](image)

**Fig. 1.6** Perpendicular recording using single-pole read head, shield and inductive
write head

The main disadvantage of perpendicular recording is that the reproduced signal during
readout is reduced considerably because of flux lines of adjacent cell link to each
other. Hence, shields on each side of the single pole read head are used sometimes to
prevent flux lines from adjacent tracks from interfering with the read head during the
readout process.
1.3 Rigid Disk Drives: Overview

In a rigid disk drive, disks rotate at a constant angular speed, with concentric data tracks recorded on their surfaces. An actuator moves the heads, positioning each one above a desired data track. Typically one or two heads are moving over each disk surface. While all the heads are actuated together, only one head is selected at a time to read or write. The actuator generally uses a stepper motor or a voice coil motor (VCM). The diameters of the disks range from 95 to 355 mm. A close-up of an IBM 3370 thin-film head slider is shown in Figure 1.7 – refer to [10] for a more detailed account of slider-head configurations.

Fig. 1.7 Schematic of the self-acting IBM 3370-type head slider on a recording disk [10]
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A schematic of the 3370-type suspension-head slider assembly is shown in Figure 1.8. The suspension that supports the slider consists of thin leaf springs. They are referred to as the load beam and flexure. The slider is attached to the flexure. The suspension supports the slider over the disk surface in an attitude that, in part, determines its flying characteristics. The suspension design allows the head to move freely around the load point and permits freedom of motions about the pitch-and-roll axes provided by the flexure, whereas all other motions are constrained. Suspension supplies a vertical spring force of about 0.15 N (15 g) in high-capacity drives and about 0.095 N (9.5 g) in low-capacity drives, which is balanced by the hydrodynamic air film when the disk is spinning [10]. Please note in this case that a physical contact exists during starts and stops.

![Schematic of the IBM 3370-type suspension-head slider assembly](image)

**Fig. 1.8** Schematic of the IBM 3370-type suspension-head slider assembly [10]
1.3.1 Magnetic Recording Heads

There are two main types of magnetic recording heads, the inductive type and the magneto-resistive type. Figure 1.1 shows the evolution in magnetic head technology from the thin film inductive head of the early 80's to the advanced GMR (giant magneto-resistive) predicted to be achieved by the year 2005. Some of these head technologies are described briefly below.

1.3.1.1 Inductive Recording Heads

Inductive read/write heads consist of a ring of high-permeability magnetic material with an electrical winding and a gap in the magnetic material at or near the surface of the storage medium, as shown in Figure 1.9. Writing is accomplished by passing a current through the coil. When writing, the coil carries a peak current, which is typically of magnitude 10 to 20 mA [12]. The flux is confined to the magnetic core, except in the region of the small nonmagnetic gap. The fringe field in the vicinity of the gap, when sufficiently strong, magnetises the medium, moving past the write head.

![Diagram showing ideal inductive head for read/write process](image-url)  
**Fig. 1.9** Diagram showing ideal inductive head for read/write process
The magnetic medium consists of high-coercivity magnetic material that retains its magnetisation after it has passed through the field from the write head gap. The medium passes over the read head, which, like the write head, is a ring core with an air gap. Each particle in the medium is a miniature magnet, and its flux lines will add to those of the other particles to provide an external medium flux, proportional in magnitude to the medium magnetisation. The flux lines in the medium permeate the core and induce a voltage in the head winding. This voltage can thus be amplified to reproduce the original signal. When an inductive head is used for magnetic recording, a single head can be used for both read and write processes [10].

1.3.1.2 Magneto-Resistive type Read Heads

In magneto-resistive (MR) type read heads, a strip of ferromagnetic alloy (nickel-iron film) is mounted vertically. The variation of the magnetic-field component in the magnetic medium, perpendicular to the plane of the medium, $H$, causes a variation in the electrical resistance of the MR stripe [10], as shown in Figure 1.10.

![Fig. 1.10 Principle operation of a MR type read head](image-url)
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Shielding layers are usually used to protect the MR sensor element from adjacent magnetic fields. MR type heads are attractive because they can be miniaturised without reducing sensitivity to an unacceptably low value. This is important in systems where more than one track has to be read out simultaneously. One disadvantage of this type head is that both the read and record (write) processes cannot be combined in one head [10].

To realise even higher storage densities, giant magneto-resistive heads (GMR) have been developed. Whereas in MR sensors, a single film changes resistance in response to a change in magnetic field on the disk, in GMR sensors, two films, separated by a very thin electrically conducting layer, perform this function. GMR sensors exploit the quantum nature of electrons and this is explained in detail in [13]. GMR sensors are very much smaller in size than the MR sensors. They can also operate at significantly higher storage densities because their percent change in resistance is greater, making them more sensitive to magnetic fields [14].

1.3.2 Encoding Binary Information

Computer data is stored in digital form. In this form, data can be processed, transmitted and stored with minimum error, using error-correction codes. Magnetic flux reversals on a storage medium, in either one direction or the opposite, lend themselves readily to the representation of bits. The direction of magnetisation of the medium depends on the direction of current flow in the coil. Thus a pattern of reversals in the direction of current flow in the coil will result in a pattern of reversals in the magnetisation of the medium. Reading is accomplished by sensing
magnetisation reversals in the medium by the voltage induced in the winding of the read head [10]. Some of methods used in the encoding process of binary information are; non-return to zero inverted (NRZI), non-return to zero (NRZ) and run-length-limited codes (RLL). NRZI is the most common [10] and is shown in Figure 1.11. The bit 1 (one) is represented by a change in the recorded magnetisation direction and the bit 0 (zero) by the absence of change in magnetisation in the medium. This is known as pulse-duration encoding. Thus, with NRZI, on read back, a signal in the coil represents 1 and no signal represents 0. NRZ is based on pulse-position encoding, a process where 1s and 0s are encoded into regions of opposite magnetisation direction. 

RLL codes with \((d, k)\) constraints are useful for self-clocking and for packing data at a higher density on the disk [15]. The \((d, k)\) constraints apply to the message bits, which are encoded on the disks as if they were NRZ. The \(d\) and \(k\) constraints specify that there be at least \(d\) and not more than \(k\) 0s between adjacent 1s in the message bit stream. The \(k\) constraint allows for self-clocking, whereas the \(d\) can be used to increase the minimum distance between the 1s. For more details on binary encoding of data, please refer to [15].

Fig. 1.11 (a) Scheme in a NRZI code, (b) Current Waveform
1.3.3 Head-Positioning Servomechanism

The ever-increasing data storage capacities of HDDs and the need for faster data rates have increased the demands for higher performance from head-positioning mechanisms in today's HDDs. At high track densities, the read-write head must be positioned more accurately to achieve reliable operation, even though the recorded reference signals are becoming weaker and noisier. The head-positioning servomechanism in a disk file, as shown Figure 1.12 [16], provides a means for locating a set of read-write heads in fixed radial locations over the disk surface and allowing the repositioning of these heads from one radial location to another.

![Diagram showing head-positioning servomechanism. Cross-section of disk stack, spindle, head-arm assembly, and VCM are shown with storage controller and servomechanism control](image)

Fig. 1.12 Diagram showing head-positioning servomechanism. Cross-section of disk stack, spindle, head-arm assembly, and VCM are shown with storage controller and servomechanism control.

The servo system has two main functions. Firstly, it determines the position of the actuator and secondly, it compares the measured position to the desired position command input and determines how to best reduce the position error signal to as close
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to zero as is practical. The position information usually consists of two parts: coarse position information in the form of a cylinder number (known as the “track ID”) and fine position information relative to each track used to centre the read-write head over a track. The goal while reading and writing data is to keep the heads following the same radial path throughout the lifetime of the disk file. However, this is not practical because of effects such as disk vibration, spindle vibration, spindle bearing runout and imperfections in the position measurement reference. All these factors require a significant control action and motion to reduce head-position error to near zero.

In high performance disk files, the actuator position is measured with respect to a disk surface with embedded position information. There are two such implementations. First, the dedicated-servo technique uses one head, the servo head, to provide only position information to the system. In this method, the servo disk surface is servo-written with position information at the time of manufacture. Dedicated servo systems reserve an entire data surface for the position information. They have the advantage that servo patterns are continuous around an entire revolution of the disk. Therefore, they allow an analogue, continuous-time, servo system that avoids the sample rate and bandwidth limitation of a digitally sampled system. A major disadvantage of the dedicated approach is that it uses an entire disk surface just for servo data. Also, the mechanical offsets between the heads on the dedicated and data surfaces will change with time and temperature, and this will cause positioning inaccuracies.

In the second implementation, called the embedded servo, position information is interleaved with user data. Servo burst information, together with other information, is placed between sectors of user data on each disk surface. The same head is used to
read both servo and user information. The embedded approach, being a digitally sampled system, is used mostly in digital signal processing [17]. The vast majority of HDDs today have embedded servo systems.

### 1.3.3.1 Position Error Channel

The position error signal (PES) is defined as the output of the position channel. This signal is proportional to the relative difference of the positions of the centre of the servo head and the nearest track centre. The PES is periodic and contains the motion of the actuator itself and the motion of the disk surface. A simple mathematical description of the PES is given by [15]:

\[
PES = k_s x_e = k_s \left\{ \text{MOD}\left((r-x) + c, w\right) - \frac{w}{2} \right\}
\]  

(1.1)

Where \( w \) = track width, \( r \) = track centre position reference and, \( c \) = any constant such that \( \{r(t) - x(t) + c\} > 0 \), for all \( r, x \).

A recorded servo wedge has a digital portion that contains, among other data, the track ID, which is usually written in gray code. During the seeking operation, when the head reads across two tracks during the rotation of the servo wedge, the track ID can be resolved within \( \pm 1 \) track of the actual track. Seek velocities follow profiles based on the number of tracks to be traversed. The required travel distance is calculated by subtracting the desired track ID from the current track ID, hence, accurate feedback on the current location is important. Track following then uses fine position information to resolve the position within a few percentage points of track centre [17].
Servo demodulators then decode this fine position information, encoded in each servo frame by measuring the relative amplitudes of the servo bursts and providing this information to the analogue-to-digital converter (ADC). Two basic types of demodulation are usually used: peak detection and area detection. Both these methods are sensitive to the amplitude of the readout signal from the servo head. Area detection is less sensitive to disk surface defects and noise and thus more commonly used. The area demodulator detects sinusoidal burst data by using full-wave rectification to produce a set of positive “lobes”. By using area integration, each burst’s area is summed and applied to the ADC. Once the servo burst information is captured, it is measured, digitised and then converted into a PES by a process known as “normalisation”. This process limits the signal response such that the PES ranges from $-1$ to $+1$. Because many parameters affect a wide range of the readout signal amplitude, an automatic gain control (AGC) technique is employed to avoid unwanted variations in the position-error signal gain [15].

Fig. 1.13 Diagram showing an embedded servo wedge, which includes a digital field that contains the encoded track ID. A group of position bursts are offset from each other so that the track position can be decoded to drive the actuator servo loop.
Fig. 1.14 (a) Ideal triangular output waveform, the zero crossings represent track centres; (b) Actual PES showing rounding of peaks; (c) PES ramps derived from ideal and rounded PES waveforms. PES has a slope with a constant sign; (d) Cylinder pulses indicate servo head is at half-track point.
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The output signals of a typical position error channel are shown in Figures 1.14(a) to 1.14(d) [15]. Figure 1.14(a) shows the PES as a function of the actuator position. All PES channels suffer degradation in performance under non-ideal conditions. Shown in Figure 1.14(b) is a common defect of most PES channels, non-linear output/input relationship. This non-linearity results when a servo head is narrower than the design value. Converting the signals shown in Figure 1.14(a) or (b) into PES (ramps) yields the signals shown in Figure 1.14(c). To keep track of the absolute position of the actuator, cylinder pulses are generated as shown in Figure 1.14(d). These indicate that a track boundary was traversed.

The effect of servo surface irregularities or defects on the PES and hence on servo system performance can be severe. The most significant effects are large track misregistration contributions, excess noise leading to unreliable operation, and non-optimal seek performance. In order to improve linearity, and reduce sensitivity to disk surface effects, most position channels employ a quadrature technique, and some use a servo head twice as wide as the desired data-track spacing. The purpose of a quadrature system is that two position error signals, called normal and quadrature are demodulated. The signals are derived from two sets of patterns, which, when demodulated, produce position error signals that are in space (x direction) quadrature to each another. Having two signals allows the use of only the most linear part of each. Figure 1.15 shows the basic outputs of a quadrature position channel as a function of motion x [15].
Fig. 1.15 Normal and quadrature position channel outputs. Note that ramps developed from normal and quadrature outputs are linear even when some rounding is present.

1.3.4 Design of the Controller

The controller is responsible for seeking the actuator and regulating it to a desired track location. Seeking operation may involve large motions of the actuator, which require moving the head from one track (or cylinder) to another desired track in the shortest possible time. Track-following operation must ensure that the head is kept on track even in the presence of actuator disturbances such as external vibrations, noise in the position measurement system and disk spindle bearing run-out and imbalance [16]. To accomplish these tasks, closed-loop position control systems are employed to centre the data head over the target track on the magnetic disk. By using position information on the disk containing the actual position of the read-write head, the actuator control system compares that information to the desired position. A
compensating current is then generated in the VCM that drives the actuator, resulting in a force that acts to move the head to the desired position.

1.4 Summary

In this Chapter the advances in the magnetic storage industry have been discussed, taking note of the rapid increase in the storage capacity of magnetic hard disks. As the track widths on the disks become narrower, and data is packed ever-so-closely on the magnetic disks, the need for more accurate head positioning, currently provided by a single-stage actuator, operated by a voice-coil motor, is required. The use of a novel 'active suspension arm' - in a dual-actuation configuration - is proposed to give precision control over the positioning of a flying head to sub-nanometre accuracy. The novel suspension arm is required to provide motion in two orthogonal planes. The first corresponds to high-bandwidth data tracking of the arm (while maintaining the use of the voice-coil motor to provide coarse actuation). In this Chapter, another need to maintain the correct head flying height during drive operation has been identified. This is very important because in order to achieve higher data storage densities on magnetic disks, the flying height must fall tremendously. It is for this reason that the novel suspension arm is required to be able to correct and maintain the flying height of the head during operation. While enormous strides are being made in data storage density capacities on magnetic disks, other areas associated with hard disk drives have to develop as fast to accommodate these advances.
Chapter 2

Hard Disk Drive Actuator Mechanisms

2.1 Introduction

In Chapter One, the rapid advancements in recent years in the magnetic storage industry have been explained. This advancement was shown to be due to the insatiable demand for more and more storage to accommodate ever-growing applications such as Internet, digital photography, computer games, digital audio and video. The storage capacities and data storage densities on magnetic disks are thus increasing at an accelerated rate to meet some of these demands. Data is recorded at ever-narrower tracks, which must be followed with extreme precision. Current high-end HDDs have data storage densities of around 10 Gb/in$^2$, and the data track density is fast approaching the 25,000 tracks per inch mark, resulting in very narrow data tracks of less than 1 μm in width. This will allow servo-tracking accuracy of 100 nm at bandwidths of 2 kHz or greater [18]. It is predicted that the industry would have to deliver at least 100,000 tracks per inch by the year 2005. This will correspond to a track pitch of 250 nm and a servo resolution of 25 nm [109]. Current commercial head-positioning technology uses a single-stage voice-coil motor (VCM) providing a servo bandwidth of around 500-600 Hz, and does not have adequate bandwidth to provide the necessary tracking accuracy. To achieve such high levels of track following, the use of a second micro-actuator located nearer the read-write elements to
provide rapid, fine-motion, position correction of the recording head has been suggested by the hard disk drive industry [43]. The micro-actuator provides high-bandwidth fine head positioning, while retaining the use of the VCM for low-bandwidth coarse positioning. A two-stage (or dual-stage) actuation mechanism is thus realised for high-bandwidth high-accuracy head positioning.

A conventional VCM is affected by structural mechanical resonances, which occur in the suspension, actuator, disk and housing. These resonances may lead to track misregistration (TMR) and therefore limit the servo bandwidth. TMR is defined as the offset between the actual head position and the track centre. Other factors, which may lead to TMR, are the hysteresis effect of the actuator’s pivot bearing, and poor velocity estimations during the head settle mode. All these factors limit the performance of the VCM during head positioning process and hence the need for a high-bandwidth micro-actuator to be used in a dual-actuation mechanism [19].

2.2 Dual-Stage Actuation

As early as 1991, the need for dual-stage actuation for high-bandwidth track following in HDDs was realised [20]. Most research into dual-stage actuators has involved the use of the micro-actuator for data tracking only [20][21][22][23]. Three distinct types of dual-stage actuation implementations have been proposed to date by research workers [18]. The first, as shown in Figure 2.1(a), makes use of an actuated suspension, an approach where conventional assembly and machining techniques are used to integrate an electromagnetic or piezoelectric actuator into a conventional steel suspension [24] [25]. The main disadvantage of this method is that the actuator is
located far from the read-write elements, resulting in a limited bandwidth due to suspension vibration.

Fig. 2.1(a) Schematic showing actuator elements incorporated into body of suspension arm.

The second type, as shown in Figure 2.1(b), may be classified as an actuated head, a method where the actuator is located on the slider and the read/write elements are placed on top of the actuator [26][27]. This design requires the minimum actuation force and also has the potential of providing the highest bandwidth due to the actuator being placed so close to the read-write elements.
However, its critical limitation is that the actuator fabrication process must be compatible with the head/slider fabrication process, since the actuator and heads are manufactured as a single unit. Therefore, integrating this arrangement into a current commercial HDD assembly for mass production does not seem to be economically feasible. In the third method, as shown in Figure 2.1(c), which is a compromise between the first two, the actuator is placed between the slider and the gimbal of a conventional suspension [19][28]. Although this design provides a higher bandwidth than the first method, it still requires relatively complex fabrication and actuator deposition processes, which result in higher fabrication costs.
Fig. 2.1(c) Schematic showing micro-actuator placed in between slider and gimbal.

A dual-stage actuator mechanism, implemented with an appropriate servo controller, is a possible key to achieving high track densities in HDDs, since structural resonant frequencies in current VCM's put a severe limit on the bandwidth of the servo controller. However, one major concern in dual-stage systems is the complexity of the servo controller due to its Multiple-Input-Multiple-Output (MIMO) configuration. This complexity contributes to the degradation of the servo performance owing to the delay time, as well as increasing the cost of the HDD [29].
2.3 Actuators in current HDDs: Overview

Voice coil motors (VCMs) drive most modern linear and rotary actuators in conjunction with servo systems, which sense position information from the disks. The forces developed by the motors are adequate to achieve desired access times for current commercial HDDs. Most linear actuators are of moving coil type: A coil of wire is rigidly attached to the structure to be moved and suspended in a magnetic field created by permanent magnets. A current (prime mover) passed through the coil generates a force, which tends to accelerate the coil radially inward or outward, depending on the direction of the current [16].

The force on a coil with $N_1$ turns in a permanent magnetic field is given by [15]

$$ F = B_g l_{\text{coil}} N_1 i = k_f i $$  \hspace{1cm} (2-1)

Where $B_g$ = air gap flux density, $l_{\text{coil}}$ = coil length, $i$ = coil current and $k_f$ = force factor.

In a rotary actuator, two permanent magnets are magnetised in opposition, which results in a "push-pull" force on the two sides of the coil, thereby doubling the resulting force.

The rotary actuator has found wide use in small-integrated high-performance disk drives because of its small size. In a rotary actuator, the heads are mounted on the end of arms, which pivot about an axis parallel to the disk spindle. A current produces
torque in much the same manner as the VCM, but the coil is an armature of a rotary motor, similar to that of a torque motor. Rotary actuators with dynamic balance are less susceptible, than linear actuators, to shock and vibration that cause the heads to be forced off track. With linear actuators, radial forces can result in radial motion of the heads, particularly if the frequency of excitation is outside the bandwidth of the servo system. Torque for a rotary actuator with bearing-to-centre-of-force distance $r$ is given by \[ \text{Torque} = B_g l_{	ext{coil}} r = k_i i \] (2-2)

Where $B_g =$ gap flux density, $l_{	ext{coil}} =$ length of coil wire in the gap flux, $i =$ coil current and $k_i =$ torque constant.

Rotary actuators are simple, inexpensive, and provide compact packing opportunities. They are, however, considered to be inferior because of two main reasons. Firstly, the head gap does not remain parallel to a disk radius as a function of the angle of rotation (track location) – this is often referred to as head skew. Secondly, the unwanted dynamics of a rotary actuator are usually lower in frequency thereby limiting the control system bandwidth compared to that obtained with a linear actuator [16].
2.4 Summary

This chapter has presented the need for high-bandwidth data tracking motion as data storage densities in HDDs increase to levels beyond that which can be handled by current single-stage motion suspension arm, provided by a voice-coil motor. It has been discussed that the use of a second micro-actuator in a piggyback or dual-stage mechanism would increase the data tracking bandwidth of the suspension arm. Structural resonance effects within the suspension arm do not affect the bandwidth of the micro-actuator. The three major types of dual-stage actuators have been presented, outlining their advantages and disadvantages. A brief review of HDD actuator types (rotary and linear) has also been presented in this Chapter.
Chapter 3

Development of Measurement Channel

3.1 Introduction

The development of high-bandwidth secondary actuator arms for use in a dual-stage actuation mechanism involving data tracking and precision flying height control in advanced hard disk drives is of primary importance in the work presented in this thesis. Developing a system to measure the end-deflections of these fabricated arms is a vital part of fully characterising their dynamic behaviour. This Chapter outlines the various methods that can be used to measure cantilever end-deflections. Comparisons between these methods are made with a view to adopting a method to use in this project.

3.2 Displacement Detection Techniques

The accurate measurement of the end-deflections of miniature mechanical cantilevers is of great importance in areas of research such as in scanning probe microscopy, atomic force microscopy [30-34] and magnetic force microscopy [35-37]. Several detection methods have been used to measure the end-deflection of the cantilever, such as Optical Beam Deflection (OBD), capacitive, optical interferometry, strain gauges and piezoelectric. Which technique to adopt for cantilever deflection measurements depends largely on the resolution, sensitivity of the technique and accuracy required in the measured quantity. However, simplicity, stability and cost also influence the choice of the
Chapter Three Development of Measurement Channel

The methods mentioned above are now discussed and compared in order to adopt one for use in this project.

3.2.1 Strain Gauges

In 1843, the English physicist Sir Charles Wheatstone (1802-1875) built a bridge circuit for the measurement of electrical resistances. In this bridge circuit, known today as the Wheatstone bridge, an unknown resistor is compared with a known accurate resistor [38]. Based on this principle a device called a strain gauge has been developed for the measurement of a wide range of physical parameters. Tanimoto et al. [39] used strain gauges as micro force sensors installed on the tips of catheters – catheters are medical tools used by medical doctors in endovascular surgeries and sometimes, in neurosurgical operations – to measure the contact force between the catheter and blood vessels. Having this force information during operations enables doctors to experience reduced fatigue levels, and hence ensure more effective surgical operations. Desouza et al. [40] used piezo-resistive strain gauges in a high-density tactile imager suitable for reading embossed characters on credit cards. The sensor has flexible silicon shanks onto which the strain gauges are incorporated to give a high-sensitivity analogue readout as the tips of the shanks deflect over characters on the scanned card surface. Karasaridis et al. [41] instrumented a road bridge in Nova Scotia, Canada, with strain gauges to monitor the occurrence and location of structural damage in the bridge.

Electrical-resistance strain gauges are based on the principle that the resistance $R$ of a conductor changes as a function of normal strain $\varepsilon$. A function of this relationship is the strain sensitivity, $S_R$, a function of the dimensional changes that take place when the
conductor is stretched or compressed elastically, plus any change in the basic resistivity of
the material with strain. The strain sensitivity is given mathematically as [42]

\[ S_A = \frac{\Delta R}{R \cdot \varepsilon} \]  

(3-1)

Where \( \varepsilon = \Delta L/L \), \( R \) = initial resistance (\( \Omega \)), \( \Delta R \) = change in resistance (\( \Omega \)), \( L \) = initial length (m), \( \Delta L \) = change in length (m).

Strain gauges are very thin devices and can be attached using adhesive to a variety of
materials in order to measure applied strain. The most commonly used material for strain
gauges is a copper-nickel alloy called Constantan, which has a strain sensitivity of 2.1.
Other alloys used for strain gauge application are modified Karma, Nichrome V, and
Isoelastic, which have sensitivities of 2.0, 2.2, and 3.6, respectively [42]. Constantan has
the advantage of having strain sensitivity \( S_A \) that is linear over a wide range of strain and
does not change significantly as the material goes plastic. Constantan also has excellent
thermal stability. The metallurgical properties of Constantan, and modified Karma, are
such that they can be processed to minimise the error induced due to the mismatch in
thermal expansion coefficients of the gauge and the structure to which it is adhered over a
wide range of temperature.

Semiconductor gauges are also available and can reach sensitivities as high 175.
However, care must be exercised with respect to the poor thermal stability of these
piezoresistive gauges. Most gauges have a nominal resistance of 120-ohm or 350-ohm.
Considering a 120-ohm Constantan gauge, to obtain a measurement of strain within an
accuracy of ±5 μ, it would be necessary to measure a change in resistance within ± 1.2 m-ohm. In order to measure these changes in resistance accurately, a Wheatstone bridge is used.

Metallic alloy electrical-resistance strain gauges come in two basic types, bonded -wire (Figure 3.1a) and bonded-foil (Figure 3.1b).

Fig. 3.1 Strain gauge configuration (a) bonded-wire and (b) bonded-foil

Bonded-foil gauges are by far the more prevalent. They are constructed with many loops to make them compact over a shorter active length. For normal applications, bonded-foil gauges are either mounted on a very thin polyimide carrier (backing) or are encapsulated between two thin films of polyimide. The most widely used adhesive for bonding a strain gauge to a test structure is the pressure-curing methyl-2-cyanoacrylate cement [42]. Other adhesives include epoxy, polyester, and ceramic cements.
In both wire or foil gauges many configurations and sizes exist. Typically, in wire form, gauge lengths range from 0.16 to 20 cm whereas foil gauge lengths range from 0.02 to 10 cm. Strain gauges come in many forms for transducer applications. The fundamental configurations are shown in considerable detail in [42]. The resolution, i.e. the ability of the gauge to detect small changes in strain, could be considered as being infinite. However, instrumentation noise will limit the strain gauge resolution. Bakush [45] quotes a strain resolution of 0.01 μ (one part in ten million) as achievable. Strain gauges are extremely sensitive to temperature fluctuations and therefore must be operated in a bridge circuit with reliable temperature compensation, using another strain gauge. For instance, consider a cantilever beam with a force $F$ applied to the free end with identical strain gauges one directly below the other, as shown in Figure 3.2 [42]. The top gauge is attached to the $R_1$ position of the bridge and the bottom gauge to the $R_2$ (or $R_4$) position. Since the gauges are on adjacent arms of the bridge, temperature compensation is achieved. $R_1$ is the active gauge, whereas the $R_2$ gauge is called the inactive compensating, or dummy gauge, and is placed at 90 degrees angle to $R_1$.

![Fig. 3.2 Strain gauge attachment for transducer application](image-url)
Strain gauges are also generally limited to extensions of about 0.3% of their length and can behave in a non-linear manner (having a typical linearity of about 1%). Strong magnetic fields have also been known to introduce errors into strain gauge measurements. But these can be overcome by paying particular attention to the gauge wiring and shielding [37]. Attaching the strain gauge to the structure under test can be a problem. Extreme care must be taken to ensure good bonding with, and electrical insulation from, the structure. To ensure good bonding, the adhesive material should have sufficient elasticity under strain without losing its adhesive properties and should also be resistant to temperature, humidity and other environmental conditions [45].

3.2.2 Optical Interferometry

Optical interferometry can be used to obtain an absolute measure of minute displacements of cantilevers. As well as being capable of measuring static deflections of the cantilever, the optical interferometer method can also measure cantilever vibration amplitudes at high frequencies with minimum disturbance to the cantilever. Because of its high resolution and accuracy, optical interferometry methods have been used in many varied applications, from atomic force microscopy (small scale) to the calibration of 50 m tapes for surveying at the national physics laboratory (large scale). Liu et al. [43] reviewed and analysed some existing interferometry methods (intensity and polarisation interferometry) currently used in hard disk drives for measuring the flying height of a magnetic head. They then proposed another method, a dual-beam normal incidence polarisation method, which has the improved feature of being able to measure much smaller flying heights down to near contact recording. Oda et al. [44] proposed an optical interferometry
method, using photo-refractive two-wave mixing, for the detection of small amplitude vibration.

As far back as 1991, Putman et al. [48] explored the sensitivity of an ideal Michelson interferometer used in atomic force microscopy. In its basic set-up, as shown in Figure 3.3 [48], an incident laser beam passes through a beam splitter. One part of the laser beam reflects onto a mirror as a reference beam and is then incident onto a photodetector. The other is focused onto the back of a cantilever and then reflected back along the same incident path to the beam splitter (and is now referred to as the signal beam) and then reflected onto the same photodetector. The interaction between the reference and signal beams at the photodetector produces a pattern of interference fringes, which can then used to determine the position of the cantilever tip and the end deflection of the cantilever can then be calculated.

---

**Fig. 3.3** Set-up of a Michelson interferometer
Fundamentally, the wavelength of light and the Poisson distribution of the photon-emission rate of the light source determine the minimum displacement that can be measured with an interferometer. Optical interferometry provides excellent long-range accuracy and high resolution. This resolution is independent of the range. However, thermal instabilities are a problem, due to the different optical components and paths used.

Three interferometry methods are now reviewed in the section that follows below. These are the homodyne, heterodyne and polarisation interferometric methods.

3.2.2.1 Homodyne Detection Method

The homodyne detection method is a form of the optical interferometry method [46][47]. The basic form of the homodyne detection system is shown in Figure 3.4. A polarised laser beam passes through a beam splitter and is focused, via an objective lens, onto a cantilever (which has a reflective coating attached to it) whose displacements are to be measured. The laser beam is reflected back along the same optical path, combining and interfering with the incident laser beam and is then deflected onto the photodetectors. This generates photocurrents used to monitor the displacement of the tip of the cantilever [45]. In a differential homodyne detection system, the laser beam is partially deflected by the beam splitter BS1 onto photodetector PD1. This serves as a reference signal. The rest of the laser beam passes through the beam splitter, optical flat and is reflected back by the cantilever. It is then reflected by BS2 onto the second photodetector PD2. This is the signal beam.
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Fig. 3.4 Diagram of the differential homodyne system showing beam splitters BS1 and BS2, and photodetector PD1 and PD2.

The difference between the photodetector currents gives a signal that is proportional to the cantilever end-deflection. Although using this differential arrangement reduces laser noise, the differential homodyne detection system has a drawback in that the output signal depends on the optical path length, which is susceptible to drift due to thermal or mechanical instabilities.

3.2.2.2 Heterodyne Detection Method

The heterodyne system [49][50][51] is shown in Figure 3.5. The laser beam is split into two components by a beam splitter BS1. The first passes through an acoustic-optic modulator (AO) that shifts the frequency of the beam, another beam splitter BS2, a quarter-wave plate, and finally, an objective lens that focuses the laser beam onto the cantilever. This beam, serving as the signal beam, is reflected back along the lens, the quarter-wave plate and is then deflected by the beam splitter BS2 through an analyser.
(polariser) onto a photodetector. The other laser beam component is reflected through the mirror arrangements M1 and M2, and serves as the reference signal. It then passes through the beam splitter BS2, the analyser and is then incident onto the photodetector. The reference signal then interferes with the signal beam to produce a current that consists of a spectrum of frequencies. The photocurrent is fed into a single side-band receiver driving a phase-sensitive detector that produces the signal used to display the force acting on the tip. The major advantage of the heterodyne detection system is that it is independent of noise introduced into the system due to optical path length drifts. The drawback of the system is that it cannot operate in the direct-current (d.c.) mode [45].

![Diagram of the heterodyne system showing an acoustic-optic modulator AO, beam splitters BS1 and BS2, and mirrors M1 and M2.](image)

**Fig. 3.5** Diagram of the heterodyne system showing an acoustic-optic modulator AO, beam splitters BS1 and BS2, and mirrors M1 and M2.

### 3.2.2.3 Polarisation Detection Method

The polarisation detection system [52][53] shown in Figure 3.6 differs from other optical detection systems in that the amplitude of vibration of the cantilever is first converted into
a polarisation modulation that is subsequently converted into amplitude modulation. Two polarising prisms, rotated 45° relative to each other, are responsible for the conversion from polarisation to amplitude modulation [54]. The laser beam first passes through a Babinet Soleil compensator, which introduces an adjustable phase shift between the two orthogonally-polarisation components of the beam; this phase shift is adjusted to give maximum output sensitivity. The beam then passes through a beam splitter, a microscope objective and a calcite prism. The calcite prism separates the laser beam into two; a reference beam that is focused onto the base of the cantilever, and a signal beam that is focused onto the flexible part of the cantilever close to the force-sensing tip. As the cantilever is deflected, the phase shift between the reference and signal beams is modulated [55].

The two reflected beams from the cantilever are recombined by the calcite prism and are deflected by the beam splitter onto the Wollaston prism. The Wollaston prism separates the two polarisation components of the beam and directs them onto the photodetectors. The movements of the cantilever cause a rotation of the polarisation of the signal beam. Because the beams recombine and then split again into two, a difference in power between the two components exists, due to the rotation in polarisation of the signal beam.

Because the polarisation detection system uses differential amplifiers, laser noise should be eliminated. The thermal drift of this detection system can be minimised by making the optical pathlength difference between the reference and signal beams small [54]. However, many optical components are needed, making the system expensive, bulky and difficult to set up.
3.2.3 The Optical Beam Deflection Technique

The Optical Beam Deflection (OBD) technique has been investigated and used widely in research [56][57] for the measurement of displacements of miniature mechanical structures. In 1991, Putman et al. [48] made a theoretical comparison between interferometry and the OBD technique for the measurement of cantilever displacement in atomic force microscopy. Using shot noise analysis; they showed that under optimal conditions the OBD technique is theoretically as sensitive as the interferometer. In 1995, Cunningham et al. [58] used the technique in active vibration control and actuation of a small cantilever for applications in scanning probe instruments. They managed to remove unwanted vibrations in a cantilever operated using a single active piezoelectric element and were still able to deflect the cantilever statically or dynamically as required.
In its simplest form, as shown in Figure 3.7, the OBD technique uses a collimated laser beam focused onto a structure under test, which has a mirror attached to it to reflect the laser beam onto a position sensitive split photodetector. This generates photocurrents, which are then fed into differential amplifier. When the beam is initially placed in the middle of the photodetector, so that each quadrant of the detector receives equal amounts of light, a small movement of the structure deflects the laser beam causing one part of the photodetector to receive more light than the other. The difference in intensity between the two halves of the detector gives a measure of the deflection and angular tilt of the mirror.

![Diagram](image)

**Fig. 3.7** Diagram showing basic principle of the OBD technique

The photodetectors available commercially at present are sensitive enough to measure extremely small displacements of the laser beam. The OBD technique itself is highly
sensitive and can detect sub-Ångstrom end deflection of small mechanical structures [59]. Deflections of 0.1 Å have been reported as being detected [55].

In summary, the OBD technique is experimentally simple as it contains very few components. It is therefore cheaper to implement than optical interferometric methods. As well as being non-intrusive, the technique permits a high degree of spatial resolution along the structure [56]. However, the technique suffers from thermal and mechanical drift and is affected by laser noise. The use of a differential detector arrangement does however cancel out most of the common-mode laser noise (principally laser pointing instability). However, the main disadvantage of the OBD technique is that it requires calibration, meaning that the method only gives a relative measure of displacement of the cantilever. It is also difficult to differentiate between displacement and curvature of the cantilever, but this point will be made clearer later in this thesis.

3.2.4 Capacitive Detection Method

Capacitance sensors have found wide use in measurement systems [60-62]. The sensors can be used to measure various physical quantities such as displacement, force, pressure, strain, stress, angle, torque and density. In 1987, Dean et al. used an improved capacitance technique to measure the moisture content in samples of soil [63]. Wongkomet at the University of California, Berkeley, has worked on capacitive position sensing for microsensors and microactuators. While investigating the fundamental issues and limits in the design of capacitance position sensing circuits, he also implemented position-sensing circuits in different surface-micromachined applications such as accelerometers and microactuators [64].
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The principle of the capacitive sensor is straightforward. In a capacitance detection system, such as that shown in Figure 3.8 [55], the deflections of the cantilever are monitored by the changes in capacitance between the cantilever and a reference plate. A high-Q-tuned electronic circuit is necessary to be able measure small changes in capacitance. By operating on the slope of the resonance curve, small resonance frequency changes caused by changes in the capacitance translate into voltage changes that are used to map the dynamic tip displacement of the sample.

![Diagram showing basic capacitance displacement detection technique.](image)

In comparison with strain gauges, capacitor sensor systems are much more sensitive and less temperature dependent. In addition, problems of bonding contact are non-existent and much smaller displacements can be measured, sometimes much less than a nanometre (0.01 nm) [45]. They also do not suffer as much from thermal instabilities. However, capacitor sensors are sensitive to humidity and stray capacitance problems. Careful shielding and earthing is needed to overcome this.
3.2.5 Piezoelectric Detection Method

Piezoelectric materials can also be used to measure displacements of small mechanical structures. Their use as actuators is well documented [65][66][67]. In principle, the application of an electric field to such materials results in a change in dimension of the material. The reverse effect is true as well. Applying a stress to the material results in a generation of electric polarisation. Therefore, when a piezoelectric actuator is attached to the structure, any small movements of the structure will cause a change in the dimensions of the piezoelectric material resulting in the generation of a voltage at the electrodes attached to the piezoelectric material. This output voltage is directly proportional to the displacement of the structure over a fairly wide range of displacements. By calibration, the displacement of the structure can be calculated.

Piezoelectric materials are relatively inexpensive and can operate over a wide range of frequencies. They are also lightweight, usually stiff, and available in different sizes, including bulk, thick and thin films. Compared with the frequencies of the structural vibrations, piezoelectric actuators usually have very high resonant frequencies. Therefore the actuator's dynamic response can be ignored in the system model. As well as only requiring fairly simple processing electronics, they generally have a high output meaning that a small amount of stress applied to the material results in a fairly large voltage output. However, this output tends to be non-linear at high levels of stress. As well as showing considerable hysteresis, piezoelectric materials are mechanically unstable over long periods of time and their parameters are sensitive to temperature, pressure, humidity and ageing. They also become inactive when the material is depolarised by any improper
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treatment, e.g. high temperature above the critical temperature value, very high reverse voltages.

3.3 Summary of Displacement Detection Methods

The methods used to measure displacements of small mechanical structures are presented and compared. The main advantages and disadvantages of the different methods for measuring the displacement of small structures are summarised in Table 3.1.

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain gauge</td>
<td>Can measure displacements in more than one axis. Requires minimum signal processing. Fairly economical and small size.</td>
<td>Requires matching of gauges to minimise temperature effects/drift. Good bonding to structure needed. Requires amplifier for bridge</td>
</tr>
<tr>
<td>Optical Interferometry</td>
<td>High long-range accuracy, high-resolution. Resolution independent of range.</td>
<td>Thermal instabilities due to variety of optical components and paths used. Expensive.</td>
</tr>
<tr>
<td>Optical Beam Deflection</td>
<td>Extremely sensitive, relatively inexpensive, experimentally simple, large magnification and is differential.</td>
<td>Suffers from thermal and mechanical drift and affected by laser noise. Requires calibration.</td>
</tr>
<tr>
<td>Capacitive detection</td>
<td>Easy mechanical design, allowing choice of electrode materials to give high stability and low thermal coefficients. High resolution possible. Small size. Large range.</td>
<td>Stray capacitance, shielding being required. Accuracy affected by dielectric changes between electrodes. Non-linear law.</td>
</tr>
</tbody>
</table>

Table 3.1 Advantages and disadvantages of different types of transducers (adapted from [45]).
After a careful and thorough consideration of the different methods available to measure displacements of small mechanical structures, the OBD method was selected. This technique is experimentally simple compared to the other methods and capable of high-resolution measurements of structure end-displacements. As well as being relatively inexpensive, this technique has been used extensively in research.

3.4 The OBD Experimental Arrangement

This section discusses in detail the whole experimental arrangement for the Optical Beam Deflection (OBD) system used. The experimental arrangement comprises the optical measurement system with its associated signal processing. The optical measurement system section describes the optical test bed and considers the parameters that limit its performance. The signal processing section looks at the associated electronic circuitry and explains how it has optimised for this application.

3.4.1 Optical Measurement System

The experimental rig comprises a laser diode, a quadrant photodetector and a mechanical structure, which allows the structure under investigation to be mounted and positioned in $x$, $y$ and $z$-axes. Each of these is rigidly mounted on to a standard v-carrier, and clamped to an optical breadboard that is supported on top of a 0.9m x 1.2m optical table. The optical table is suspended on active air bearings for passive vibration isolation. This optical measurement system is shown schematically in Figure 3.9, (see Appendix A for pictures of the experimental arrangement).
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The piezoelectric bimorph element (mounted as a cantilever) is excited sinusoidally by the function generator, which causes the end of the cantilever to be displaced synchronously with the excitation frequency. This causes the laser beam to be periodically reflected from the small mirror, mounted at the end of the cantilever, to shift accordingly on the photodetector. The laser beam falling on the photodiode causes currents to be generated in the photodiode, with the associated photocurrents being converted to voltages using current-to-voltage converters – for details, see section 3.4.6.

![Diagram showing schematic layout of the OBD measurement system](image)

**Fig. 3.9** Diagram showing schematic layout of the OBD measurement system

The voltages are then amplified differentially and, if required, filtered to remove unwanted signal components using a low-pass filter. The output voltage signal can be observed on an oscilloscope, or detected more accurately using a lock-in amplifier.
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The novel active suspension arm being developed in this research work is required to be able to realise motion in two orthogonal axes. The first corresponding to motion required for high-bandwidth track following, and the other, for precision head flying height control. The optical measurement system developed must thus be able to detect, and measure accurately, each of these motions, independently or simultaneously, as required. Therefore, the design process of the optical measurement system has incorporated this requirement. To test this feature, and in place of an active suspension, to produce very small, controlled deflections in 2-dimensions, 2 bimorph elements are glued together, one on top of the other (as shown in Figure 3.10), such that when excited, they produce motion in orthogonal axes, simulating the motions of the suspension arm being developed. Each element is excited at different frequencies and amplitudes. The output signal due to each deflection can be seen simultaneously on the digital oscilloscope. In theory, to prove that the motions are independent of each other, the excitation of only one bimorph element results in there only being one signal output on the oscilloscope. In practice, however, because the bimorph elements are mechanically coupled to each other, motion of one bimorph induces minute vibrations in the other, setting it into resonance. These can be suppressed using closed-loop control as discussed in Chapter 6.
3.4.2 The Laser Diode

The laser diode used has a wavelength of 670 nm and an output power of 3 mW [68]. It is held such that its direction can be adjusted in x, y, z axes as well as angle \( \theta \). In addition, the height of the laser diode from its fixed position can be varied. This laser module can be run from an unregulated supply within the range of -8 to -12 V. By operating at a reduced voltage, less heat will be dissipated within the device and hence the expected life will increase. Since the laser diode here is operated at room temperature, no heat sink is necessary. The general characteristics of this laser module are shown in the table below.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal wavelength</td>
<td>670</td>
<td>nm</td>
</tr>
<tr>
<td>Maximum output power</td>
<td>3</td>
<td>mW</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>-8 to -12</td>
<td>V</td>
</tr>
<tr>
<td>Pointing stability</td>
<td>&lt;0.05</td>
<td>mRad</td>
</tr>
<tr>
<td>Minimum focus (lens extended)</td>
<td>25</td>
<td>mm</td>
</tr>
<tr>
<td>Spot size at minimum focus</td>
<td>100</td>
<td>μm</td>
</tr>
</tbody>
</table>

Table 3.2 General characteristics of the modulated laser diode module βeta TX series manufactured by Vector Technology.

### 3.4.3 The Bimorph Element

For initial experimental purposes, before the ‘active arm’ is fabricated, the mechanical structure used for test purposes is a piezoelectric bimorph element (RS components). The bimorph element (dimensions 15 x 1.5 x 0.6 mm and weighing about 110 mg) is held upright and has a mirror (approximate dimensions 2.0 x 2.0 mm, 0.5 mm thick and weighing about 25 mg) glued on top of it using Araldite adhesive. The mirror, which is plated with two layers- the top being 40 nm of gold and the bottom being 40 nm of nickel iron, must be as light as possible to reduce damping effects, as this would lower the resonant frequency of the bimorph-mirror arrangement. The lower part of the bimorph is held in a specially designed clamp between two sheets of Teflon, which rigidly clamps about a third of it leaving the other two thirds free to deflect when excited, as shown in Figure 3.11.
This bimorph element is a versatile low power electromechanical transducer capable of converting mechanical or acoustic energy to electrical energy and vice-versa. In this project, it is being used to convert an electrical signal (a.c. voltage) to a mechanical signal (displacement). The element is constructed by bonding two pieces of PZT-5J [69] (PZT stands for lead zirconate titanate) together and connected electrically in series (Figure 3.12) as opposed to a parallel connection (Figure 3.13). When the element is bent, the minute movement causes one layer to be under tension while the other is under compression. This sort of displacement of the bimorph element will be further investigated later in the report.
The bimorph elements shown above each consist of two plates bonded together such that applying a voltage to its electrodes causes the plates to deform in opposite directions. This opposition causes the bimorph element to bend. Conversely, mechanical bending of the element, which induces strain, causes it to develop a voltage between the electrodes.
The bimorphs can be operated in either series or parallel. The series bimorph develops twice the voltage as the parallel, making a better arrangement for use as a sensor. The parallel bimorph produces twice the displacement on application of a voltage thus making it a better choice for use as an actuator [69]. The table below summarises the relationships between displacement and applied voltage for a bimorph when used as a sensor and as an actuator for both series and parallel connections.

<table>
<thead>
<tr>
<th>Bimorph connection</th>
<th>Displacement (static)</th>
<th>Voltage (static)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series</td>
<td>$\Delta x = \frac{3 \cdot d_{31} \cdot V \cdot r^2}{2 \cdot t^2}$</td>
<td>$V = \frac{3 \cdot g_{31} \cdot F \cdot r}{2 \cdot w \cdot t}$</td>
</tr>
<tr>
<td>Parallel</td>
<td>$\Delta x = \frac{3 \cdot d_{31} \cdot V \cdot r^2}{t^2}$</td>
<td>$V = \frac{3 \cdot g_{31} \cdot F \cdot r}{4 \cdot w \cdot t}$</td>
</tr>
</tbody>
</table>

Table 3.3 Relationship between displacement and applied voltage for bimorph element for both series and parallel connections [69].

In Table 3.3, $V$ is the applied voltage across the bimorph electrodes in volts, $r$, $w$ and $t$ are the length, width and thickness of the bimorph in metres, $F$ is the applied force in Newton’s and $\Delta x$ is the bimorph displacement in metres. $d_{31}$ is the piezoelectric charge (or strain) constant in metres/volt and $g_{31}$ is the voltage constant in volt-metre/Newton.

Some technical information on the bimorph element [70] is now given in Table 3.4
Table 3.4 Technical specification of the bimorph element from RS: stock no. 285-784

The parameters and notation used in table 3.4 are explained fully in section 3.4.3.1. When used as a cantilever, i.e. clamped 5mm from the lead end, leaving 10mm free, a displacement of 10μm peak-to-peak results in the generation of a peak-to-peak voltage of 4V [70].

3.4.3.1 Piezoelectric Characteristics, Symbols and Notation

Superscript and subscript notations are used to describe the characteristics of a piezoelectric device. The superscripts describe the external factors, e.g. physical mounting, electrical conditions, etc., that affect the piezoelectric property. The subscripts describe the relationship of the property to the poling axes [71]. The characteristics of piezoelectric properties depend on their orientation to the poling axis. This orientation determines the direction of the action or response associated with the property.
Fig. 3.14 Labelling of reference axes and planes for piezo-ceramics.

The convention is to define the poling direction as the 3-axis, as illustrated in Figure 3.1.4. The shear planes are indicated by the subscripts 4, 5 and 6 and are perpendicular to directions 1, 2 and 3 respectively. The first subscript position identifies the direction of the action; the second identifies the direction of the response. For example, with reference to the piezoelectric constant $d_{31}$, the first subscript refers to the direction of the field and the second refers to the direction of the strain. For the converse piezoelectric voltage coefficient $g_{31}$, the first refers to the stress and the second to the voltage.

The piezoelectric charge coefficient $d_{31}$ is defined as the ratio of the electric charge generated per unit area to an applied force and is expressed in coulomb/Newton (C/N) [71]:

$$d_{31}$$
\[ d_{31} = \frac{\text{Strain developed}}{\text{Applied field}} \quad (\text{Vm}^{-1}) \quad (3-1) \]

or

\[ d_{31} = \frac{\text{Short circuit charge density}}{\text{Applied stress}} \quad (\text{CN}^{-1}) \quad (3-2) \]

The piezoelectric charge constant \( d_{31} \) is calculated from the equation [71]:

\[ d_{31} = k_{31} \sqrt{\varepsilon_0 \cdot K_3^T \cdot s_{11}^E} \quad (\text{C/N}) \quad (3-3) \]

Where \( \varepsilon_0 \) is the permittivity of free space \((8.854 \times 10^{-12} \text{ F/m})\), \( K_3^T \) is the relative dielectric constant, \( k_{31} \) is the electromechanical coupling coefficient and \( s_{11}^E \) is the compliance \((\text{m}^2/\text{N})\).

The relative dielectric constant \( K_3^T \) in equation (3-3) is defined as the ratio of the permittivity of the material to that of free space. This is generally measured well below the mechanical resonance of the material [71].

\[ K_3^T = \frac{\varepsilon_{33}^T}{\varepsilon_0} \quad (3-4) \]
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Where $\varepsilon_{33}^T$ is the permittivity of the material. The superscript $T$ in $K_3^T$ indicates that all stresses on the material are constant - for example: zero external forces. The 3 indicate that the electrodes are perpendicular to axis 3.

The electromechanical coupling factor $k_{31}$ is defined as the ratio of the mechanical energy accumulated in response to an electrical input or vice versa. The piezoelectric coupling coefficient can be expressed as follows [71]:

$$k_{31} = \frac{\text{Mechanical energy stored}}{\sqrt{\text{Electrical energy applied}}} \quad (3-5)$$

$$k_{31} = \frac{\text{Electrical energy stored}}{\sqrt{\text{Mechanical energy applied}}} \quad (3-6)$$

The compliance $s_{11}^E$ is defined as the ratio of the strain to the stress in a material. This is the inverse of the Young’s modulus $Y$ that describes the mechanical stiffness properties and is expressed as the ratio of stress to strain. In a piezoelectric material, mechanical stress produces an electrical response that opposes the resultant strain. The value of the Young’s modulus depends on the direction of stress and strain and the electrical conditions [71]. Thus,

$$s_{11}^E = \frac{1}{Y} = \frac{\text{strain}}{\text{stress}} \quad (\text{m}^2/\text{N}) \quad (3-7)$$
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The superscript $E$ in $s_{11}^E$ indicates that the compliance is measured with electrodes connected together. Both $1s$ indicate that the stress or strain is in direction $1$.

The piezoelectric voltage coefficient $g_{31}$ is the ratio of the electric field produced to the mechanical stress applied and is expressed as volt-metre/Newton (V·m/N) [71]. Thus,

\[
g_{31} = \frac{\text{Strain developed}}{\text{Applied charge density}} \quad (C^1\cdot m^{-2}) \quad (3-8)
\]

or

\[
g_{31} = \frac{\text{Field developed}}{\text{Applied mechanical stress}} \quad (V\cdot m/N) \quad (3-9)
\]

The piezoelectric voltage constant $g_{31}$ is calculated from the equation below [69]:

\[
g_{31} = \frac{d_{31}}{e_0 \cdot K_3} \quad (V\cdot m/N) \quad (3-10)
\]

3.4.4 The Photodetector

The photodetector used to detect the laser being reflected by the mirror on the bimorph element is a Hamamatsu S5980 4-element (quadrant) surface mount photodiode [72]. It has a dead gap of 50 μm, a photosensitivity of 0.50A/W to light of a wavelength of 670nm and dimensions of 5 mm x 5 mm. To provide shielding from electromagnetic interference, this diode is placed in a screened aluminium diecast box, together with the current to voltage converters and differential amplifiers. This photodetector is used initially for the experiments purposed. Other photodetectors are investigated in Chapter
Four to find out which one gives optimum performance when used in the OBD measurement system.

3.4.5 Signal Processing

In this section the signal processing, which includes the electronic circuits used for current-to-voltage conversion and differential amplification, is designed. The design process is based on calculations and analysis using the specifications of the Hamamatsu S5980.

3.4.5.1 Signal Processing of Output from Photodiode

When the laser beam falls on the split photodetector, a current is generated in whichever quadrant(s) the laser beam illuminates. The magnitude of this current is proportional to the amount of light falling on the photodiode. If the laser beam is positioned in the centre of the photodiode, each quadrant will receive the same amount of light and hence, will generate identical magnitudes of current. Any minute deflection of the laser beam will cause uneven intensity distribution of the laser beam on the photodiode and hence will result in the generation of unequal magnitudes of current in the individual quadrant elements. The differences in the current between the photodiode elements may be sensed differentially using operational amplifiers. The measurement system is required to have the capability of detecting deflections of small mechanical structures in two orthogonal axes. Hence the signal processing from the photodiode must be designed such that laser beam deflections, in orthogonal axes, can be detected accurately. The notation adopted in this thesis for the laser beam motion on the photodiode, corresponding to motion of the cantilever in orthogonal axes, is up and down and right and left. The section below
describes the electronic implementation design necessary in order to distinguish the sensing of deflection by the photodetector along each axis.

The laser beam that is incident onto the photodiode active surface is converted into current by the photodiode. Because the photodiode is split into four quadrants, current is generated in each individual quadrant, provided that the laser beam is incident on the quadrant. The magnitude of this current is directly proportional to the amount (or area) of laser beam incident onto the quadrant element. For design purposes, let the current generated in the upper left quadrant be called \( U_L \). Correspondingly let \( D_L, U_R, D_R \) represent the currents generated in the lower left, upper right and lower right quadrants respectively, as shown in Figure 3.15.

![Diagram showing photodetector with laser beam positioned centrally.](image)

**Fig. 3.15** Diagram showing photodetector with laser beam positioned centrally.
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For the up and down motion \((U/D)\) of the laser beam, as shown in Figure 3.16, a measure of the laser beam deflection is directly proportional to the difference between the sum upper currents and the sum of the lower currents of the photodiode. This is shown mathematically as:

\[
U/D = (U_L + U_R) - (D_L + D_R)
\]  
(3-11)

This is now re-arranged in the form below:

\[
U/D = (U_L - D_R) + (U_R - D_L)
\]  
(3-12)

Fig. 3.16 Diagram showing up and down motion analysis of laser beam.
For left and right (L/R) motion of the laser beam, as shown in Figure 3.17, a measure of the laser beam deflection may be described as:

\[ \frac{L}{R} = (U_L + D_L) - (U_R + D_R) \]  

(3-13)

This is now re-arranged to a form similar to equation (3-12):

\[ \frac{L}{R} = (U_L - D_R) - (U_R - D_L) \]  

(3-14)

Fig. 3.17 Diagram showing left and right motion analysis of laser beam.
It can be seen that in both cases that if the signals are written as \((U_L - D_R)\) and \((U_R - D_L)\), then their sum or difference senses the two orthogonal axes of motion. By using operational amplifiers for differential and summing purposes, the processes above have been implemented as shown below in Figure 3.18.

![Block diagram showing electronic implementation of 2-dimensional measurement system of laser beam.](image)

From Figure 3.18, a detailed electronic circuit was implemented. The values of the components at each stage are carefully chosen to meet the bandwidth requirements of the system - this is explained in section 3.4.5.3. The electronic circuit that is responsible for sensing the up and down motion of the cantilever beam is shown in Figure 3.19, and that responsible for sensing the left and right motion is shown in Figure 3.20. The two circuits

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are designed on separate printed circuit boards (PCBs). They are however linked together, as the output of one PCB forms the input of the other and vice versa, as shown in the diagrams.

Fig. 3.19 Detailed electronic implementation of up and down motion sensing.

Fig. 3.20 Detailed electronic implementation of left and right motion sensing.
3.4.5.2 Photodiode Operation Modes

During the signal processing stage, it is very important to obtain as large an output signal as possible, in order to maximise signal-to-noise ratios. Therefore, the design process must incorporate methods that would introduce the least noise, while enabling as high an operational bandwidth as possible, even at low light levels. It must also ensure that the measurement system remains stable during external variations such as temperature and pressure. The photodiode can be operated in an arrangement such that noise and bandwidth parameters can be controlled through the design process. A photodiode can be operated in three main modes. These are the photovoltaic, photoconductive and photoamperic modes. Each one of these modes is described briefly below.

3.4.5.2.1 Photovoltaic

In this mode no external bias voltage is applied across the photodiode. The result is that there is no dark current generated and hence the noise is low. This mode of operation is slower than the other two, but it allows increased sensitivity to low light-levels [74]. The photovoltaic mode is used in low noise, low frequency applications.

3.4.5.2.2 Photoconductive

In this mode a reverse bias voltage is applied resulting in a wider depletion region, lower junction capacitance, lower series resistance, shorter rise time, and linear response in photocurrent over a wide range of light intensities [39]. This mode is thus ideal to obtain the fastest response (with rise times ranging from hundreds of pico seconds to tens of nanoseconds depending on operating conditions [45]) and greatest bandwidth (from DC...
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to over 1GHz [45]) [74]. However, this mode of operation introduces shot noise due to
the dark current generated. This method is used mostly in very high-frequency
applications, such as the detection of high-speed light pulses.

3.4.5.2.3 Photoamperic

In this mode the photodiode is connected to a low value of load resistance resulting in a
negligible value of dynamic resistance. The output current is therefore linearly related to
the light level incident on the photodiode. The usual method of providing a low resistance
with subsequent amplification is to connect the photodiode to the virtual earth of an
operational amplifier [73]. When operated in this mode, the photodiode can be connected
in a circuit as shown in Figure 3.21 to convert its output current into a voltage.
Applications include operations where high temperature stability is required and, where
low light levels may need to be detected.
3.4.5.3 Design of the Current-to-Voltage Converter

The general arrangement of the current-to-voltage converter using a photodiode operating in the photoamperic mode is shown in Figure 3.21.

The component values chosen in the circuit are based on using a Hamamatsu S5890 photodiode, which has a photosensitivity of about 0.50 A/W to light of 670 nm. The operational amplifier used is the OPA 2111 KP, and the reasons for choosing this opamp are given later in this Chapter.

At the current-to-voltage conversion stage, a value for the feedback resistor is chosen so that during operation, saturation is avoided. The maximum power output of the laser $P_{\text{max}} = 3$ mW. Keeping the laser beam right in the middle of the photodetector, the
maximum 3 mW may be equally divided between all four quadrants of the photodiode. This is 0.75 mW per quadrant of the photodiode. This results in a current of \( I_p = 0.375 \) mA being generated in each photodiode quadrant. For this current, the feedback resistor for each of the current-to-voltage stages is calculated using Ohm's law, as shown below:

\[
R_f = \frac{V_{\text{out(max)}}}{I_p}
\]  

(3-15)

In choosing the feedback resistor, the calculations are based on \( V_{\text{out(max)}} \) as the maximum possible output voltage before saturating the opamps. The feedback resistor \( R_f \) is calculated as:

\[
R_f = \frac{11 \text{V}}{0.375 \text{mA}} = 29.33 \text{ k}\Omega
\]  

(3-16)

For practical purposes, i.e. high stability and availability, a value of 27 k\( \Omega \) (metal film type \( \pm 1\% \)) was chosen for this circuit. A feedback resistor of this value gives a peak-to-peak voltage output \( V_{\text{out}} \) at the current-to-voltage conversion stage of 10.125 V, which is lower than the typical maximum output voltage \( V_{\text{out(max)}} \) of the OPA 2111 KP. This output avoids saturation of the opamps.

In advanced hard disk drives, the bandwidth \( B \) required for servo positioning on a magnetic hard disk rotating at about 10,000 revolutions per minute should be about 10 kHz [75]. Using this bandwidth \( (B = 10 \text{ kHz}) \), the value of the capacitor \( C_1 \) in parallel with the feedback resistor \( R_f \) (27 k\( \Omega \)) for this required bandwidth is calculated as:
\[ C_i = \frac{1}{2 \cdot \pi \cdot R_t \cdot B} = 589 \text{pF} \quad (3-17) \]

Again for practical purposes and availability we choose a capacitor value of 560 pF (ceramic type ± 2%). This gives a bandwidth \( B_p \) as shown below:

\[ B_p = \frac{1}{2 \cdot \pi \cdot 27k \Omega \cdot 560 \text{pF}} \approx 10.53 \text{kHz} \quad (3-18) \]

An ISIS (LISA) simulated frequency response graph for the current-to-voltage conversion stage using values of feedback resistor and capacitors as shown in Figures 3.19 and 3.20.

Fig. 3.22 Frequency response graph of the current-to-voltage conversion stage.
From the frequency response graph above, it can be seen that the current-to-voltage conversion stage gives a high signal magnitude of about 55 dB. This is good because it is desirable to have as high a signal as possible at this stage in the measurement channel to get a high signal-to-noise ratio (SNR). At the 3dB point, the bandwidth of the system occurs at around 10.5 kHz. Beyond this point, the signal attenuates drastically. At the output of the current-to-voltage conversion stages, the total noise voltages add up to about 309 $\mu$V, giving a SNR of 91 dB. This figure is based on calculations made in Chapter 5, but are presented here to give an indication of the levels of the SNR achievable at this stage of the measurement channel. A more detailed analysis of noise in the optical beam detection channel is presented in Chapter 5 of this thesis.

### 3.4.5.4 The Operational Amplifier OPA 2111KP

The opamp used is the OPA 2111KP, which is a high precision monolithic dielectrically isolated FET (Difet) operational amplifier [76]. Outstanding performance characteristics allow its use in the most critical instrumentation applications. Noise, bias current, voltage offset, drift, open-loop gain, common-mode rejection, and power supply rejection are superior to BIFET amplifiers. Some features of the OPA 2111KP are listed below:

- **Low noise**: $8nV/\sqrt{Hz}$ max. at 10 kHz
- **Low bias current**: 4pA max.
- **Low offset voltage**: 500 $\mu$V max.
- **Low drift**: 2.8 $\mu$V/°C
- **High open loop gain**: 114dB min
- **High common-mode rejection**: 96dB min
3.5 Summary

In this Chapter, the experimental rig has been developed, for high-resolution end-deflection measurements of small mechanical structures. This measurement technique is based on the OBD technique, which has also been presented in this Chapter. The two main components of the rig, the optical measurement system and the electronic signal processing have each been described. Regarding the optical measurement system, the function and specification of each component used on the experimental rig has been given. The three major components of the measurement channel (laser diode, the small mechanical structure under test (bimorph element in this section) and the photodiode), are rigidly mounted onto a triangular optical bench. The optical bench, in turn, is bolted to a heavy base supported on air bags on top of an optical table, which is suspended on active air bearings to minimise external vibrations to the experimental rig. Electronic circuits have been developed, for signal processing and low-pass filtering, to monitor the motion of the laser beam in two orthogonal axes. The photodiode operation modes are briefly investigated from which the photoamperic mode is chosen in which to operate the photodiode for the current-to-voltage conversion stage. The systematic design of the current-to-voltage stage is also given, giving reasons for the choice of the values of the components used.
4.1 Introduction

Most methods used to measure displacements of miniature structures are affected by external conditions (such as temperature and vibration) that may lead to inaccuracies or errors in measurements taken. Some of these limiting conditions have been outlined in Chapter 3 of this thesis. It is, therefore, important to optimise the measurement technique so as to maximise the signal-to-noise ratio (SNR) at the output of the measurement system. The aim in this Chapter is to explore ways in which the optical beam deflection (OBD) technique can be optimised for measuring cantilever end-displacements. As well as understanding the laser beam optics better, this chapter investigates the relationship between the laser beam spot size, and the metallurgical separation (referred to as the ‘gap’ in this thesis) between the individual elements of the photodiode. The aim is to investigate whether sensitivity of the OBD technique can be optimised, and how this may be achieved.

4.2 Model of Laser Beam Dynamics on Photodiode

The voltage output from the differential amplifiers shown in Chapter Three is directly proportional to the amount by which the laser beam shifts on the photodiode. A
quantitative measure of this laser beam shift on the photodiode is important for the development of a complete model of the OBD system to aid the optimisation of the measurement technique. However, making a direct measurement of this laser beam shift is not practical due to the complexity of the process. Thus by creating an accurate model, the laser beam shift can be calculated based on the knowledge of how the bimorph beam bends when under strain, and how this affects the dynamics of the laser beam on the photodiode.

In 1991, Putman et al. [48] while investigating the sensitivity of an ideal optical beam deflection system calculated a value of the shift of the laser beam, \( S_r \), on the photodetector as:

\[
S_r = \frac{2 \cdot \Delta x \cdot L}{r}
\]  

(4-1)

Where \( \Delta x \) is the bimorph end-deflection (m), \( L \) is the focal length (or the optical lever arm) (m) and \( r \) is the length of the bimorph (m).

Putman’s model assumes that the cantilever does not experience any curvature when under strain, but in reality, it does experience some curvature. A more accurate model that incorporates the curvature of the cantilever is thus needed to simulate the OBD system to optimise its performance.

Jenkins et al. [77] studied the free vibrations of systems such as simple cantilevers to determine their eigenvalues (frequencies) and eigenfunctions (modal shapes). Using the
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OBD technique, the cantilever modal shapes were measured non-invasively at each modal frequency. In the first mode of vibration, the results obtained show that the cantilever initially experiences some curvature for nearly a quarter of its total length and then the rest of it is virtually straight, as shown in Figure 4.1.

![Diagram of cantilever bending showing curvature near the clamped end.](image)

Based on these findings, the cantilever beam is modelled to two extremes. The first one assumes that the bimorph element bends in such a way that it appears to be an arc of a large circle. This model is referred to as the bimorph circular bending model, and takes into account that the bimorph element experiences some curvature when under strain. The second model assumes that the bimorph simply bends at the root and does not experience any curvature. This model is referred to as the bimorph straight deflection model. It is believed that actual bimorph bending lies somewhere between these two extremes, thus the necessity to study them as limiting cases. The models proposed in this Chapter are compared to each other, as well as to that proposed by Putman.
4.2.1 Analysis of Bimorph Circular Bending Model

This section investigates the bimorph circular bending model. When a direct current voltage is applied to the electrodes of the bimorph, it experiences an end-deflection directly proportional to this applied voltage. Using co-ordinate geometry, the shift of the laser beam on the photodiode can be calculated based on how the cantilever bends. A diagram of this model is shown in Figures 4.2(a) and 4.2(b).

**Convention used:**

+ve y-axis
+ve x-axis

![Diagram showing bimorph circular bending](image)

**Fig. 4.2(a) Diagram showing bimorph circular bending**

Figure 4.2(a) is enlarged to show clearly, how and where the laser beam hits the mirror, before and after the application of an electric field, to show the laser beam and bimorph angular transformations that occur.
The initial co-ordinates $A (0,0)$ represent the centre of the mirror at the end of the bimorph before it bends, assuming the laser beam initially hits the mirror at its centre - but this need not be the case as the analysis can be applied to any position on the mirror. When the bimorph bends due to an applied voltage, the above initial position ($A$) moves to a new position ($A'$). The position $A$ experiences a shift in the x-axis, $\Delta x$, and another in the y-axis, $\Delta y$.

The co-ordinates of the new position $A'$ are calculated from Figures 4.2(a) and 4.2(b) as:
\[ A' = (\Delta x, \Delta y,) = \left( \frac{r}{\phi} \cdot \cos(\phi) - \frac{r}{\phi}, \frac{r}{\phi} \cdot \sin(\phi) - r \right) \]  

(4-2)

From the diagrams, it can be seen that the horizontal displacement \( \Delta x \) of the bimorph, as shown in Figure 4.2(a), is related to the curvature of the bimorph and its other parameters. The horizontal displacement of the bimorph \( \Delta x \) is related to the angle \( \phi \) and the length of the bimorph \( r \). This relationship is calculated using Figure 4.2(b) as a reference:

\[ \tan(b) = \frac{\Delta x}{h} \]  

(4-3)

Where: \( h = \frac{r}{\phi} \cdot \sin(\phi) \)

As \( b \to 0 \), \( \tan(b) \equiv b \) and \( \phi \) becomes so small such that \( \sin(\phi) \equiv \phi \). Hence,

\[ b \equiv \frac{\Delta x}{r} \]  

(4-4)

Also as \( b \to 0 \), \( k \equiv r \) and hence, \( \sin(\phi) \equiv \frac{\Delta x}{r} \)  

(4-5)

And as \( \phi \to 0 \), \( \sin(\phi) \equiv \phi \) and therefore, \( \phi \equiv \frac{\Delta x}{r} \)  

(4-6)

In this model of bimorph end-deflection, there are two components that add to the final shift of the laser beam on the photodiode. The first is due to the **angular deflection**, which gives rise to a shift \( S_{A1} \) on the photodiode. The other is due to the **positional displacements** (\( \Delta x \) and \( \Delta y \)), which give rise to laser beam shift \( S_{D1} \) on the photodiode. The sum of these two shifts results in the overall shift that the laser beam experiences on the photodiode.
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The step-to-step method using co-ordinate geometry to calculate the shift of the laser beam on the photodiode is shown in Appendix B. Referring to Figure 4.2(a), the total shift $S_{T1}$ of the laser beam on the detector is the distance between the points $P_2(x_2,y_2)$ and $P_3(x_3,y_3)$ and is equal to the sum of the angular shift $S_{A1}$ and the displacement (due to shifts $\Delta x$ and $\Delta y$) $S_{D1}$.

$$S_{T1} = S_{A1} + S_{D1}$$  \hspace{1cm} (4-7)

$$S_{T1} = \sqrt{(y_3 - y_2)^2 + (x_3 - x_2)^2}$$  \hspace{1cm} (4-8)

Where:

$$x_2 = L \cdot \sin \alpha,$$  \hspace{1cm} (4-9)

$$y_2 = L \cdot \cos \alpha,$$  \hspace{1cm} (4-10)

$$x_3 = \frac{\cot(a + 2 \cdot \phi) \cdot \sin(a) + \cos(a) \cdot (r \cdot \phi \cdot \cos(\phi) - (2 \cdot \cos(\phi) - 1) \cdot r \cdot \sin(\phi))}{\phi \cdot \cos(a + \phi) \cdot (\cot(a + 2 \cdot \phi) + \tan(a))} + \frac{L}{\cos(a)}$$  \hspace{1cm} (4-11)

$$y_3 = \frac{L}{\cos(a)} - \frac{\cot(a + 2 \cdot \phi) \cdot \sin(a) + \cos(a) \cdot (r \cdot \phi \cdot \cos(\phi) - (2 \cdot \cos(\phi) - 1) \cdot r \cdot \sin(\phi))}{\phi \cdot \cos(a + \phi) \cdot (\cot(a + 2 \cdot \phi) + \tan(a))} + \frac{L}{\cos(a)}$$  \hspace{1cm} (4-12)

By plotting graphs using Mathcad, it is possible to observe how the above shifts vary individually with the bimorph end-deflection $\Delta x$ in the range 0 to 25nm, a bimorph length
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$r$ of $10\, \text{mm}$, a laser incident angle $\alpha$ of $60^\circ$ and a distance $L$ of $100\, \text{mm}$ between the bimorph mirror and the photodiode.

![Graph of angular deflection against bimorph end-deflection](image)

**Fig. 4.3** Graph of angular deflection against bimorph end-deflection

![Graph of positional shift of laser beam against bimorph end-deflection](image)

**Fig. 4.4** Graph of positional shift of laser beam against bimorph end-deflection $\Delta x$. 
Fig. 4.5 Graph of the total laser beam shift $S_{T1}$ against bimorph end-deflection.

A comparison between the angular laser beam shift $S_{A1}$ and the positional shift (due to $\Delta x$ and $\Delta y$) $S_{D1}$ is now made, by plotting a graph of the ratio of $S_{A1}$ to $S_{D1}$ over a range of bimorph end-deflections 0 to 25nm.

Fig. 4.6 Graph of the ratio of $S_{A1}$ to $S_{D1}$ against bimorph end-deflection.
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As seen in Figure 4.3, the end-deflection of the bimorph $\Delta x$ is directly proportional to the angular shift $S_{A1}$ of the laser beam on the photodiode. In Figure 4.4, it can be seen that as the bimorph end-deflections increase, the positional laser beam shift $S_{D1}$ also increases. However, this rate of increase is not uniform but appears to be of a quadratic nature such that increases bimorph end-deflection result in larger increases in the shift $S_{D1}$ on the photodiode. The gradient of the slope becomes steeper and steeper with increasing bimorph end-deflection. In Figure 4.5, it can be seen that the total shift $S_{T1}$ of the laser beam on the photodiode is linearly related to the end-deflection of the bimorph, even for large deflections. Increases in the end-deflection result in a uniform increase in the total shift $S_{T1}$ of the laser beam. The angular shifts $S_{A1}$ are so much bigger than the positional laser beam shifts $S_{D1}$, as seen in Figure 4.6. In fact, by comparing the values of the angular shifts to those of the total shift $S_{T1}$, it can be seen that they appear to be identical for the same magnitudes of bimorph end-deflection. The fact is that they are very nearly the same because the values of the $S_{A1}$ are so much larger than those of $S_{D1}$ over the whole range of bimorph end-deflections investigated in this work, and this leads to the deduction that the shift $S_{D1}$ has no significant effect on the total shift of the laser beam on the photodiode. Hence, the total shift of the laser beam on the photodiode is largely determined by the amount of angular deflection $S_{A1}$ of the laser beam.

4.2.2 Analysis of Bimorph Straight Deflection Model

Using the same analysis as that adopted in section 4.2.1, the shift of the laser beam on the photodiode is investigated, assuming that the bimorph bends at its root but does not experience any curvature along its length. A diagram of this model is shown in Figures 4.7(a) and 4.7(b). Assuming that the initial co-ordinates $A$ are (0,0), when a voltage is
applied across the electrodes of the bimorph, the initial position moves to a new position $A'$ with co-ordinates shown below:

$$A' = (r \cdot \sin \beta, r \cdot \cos \beta - r)$$  \hspace{1cm} (4-13)

The horizontal displacement, $\Delta x$, of the bimorph as shown in Figure 4.7(a) is related to the angle, $\beta$, between the bimorphs' positions before and after bending. The angle $\beta$ is calculated as:

$$\beta = \sin^{-1} \left( \frac{\Delta x}{r} \right) \equiv \frac{\Delta x}{r} \quad \text{(As $\Delta x \to 0$ for fixed $r$)}$$  \hspace{1cm} (4-14)

**Convention used**

[Diagram of the bimorph deflection with labels and angles]

Fig. 4.7(a) Deflection of bimorph assuming bimorph straight deflection model.
Fig. 4.7(b) Close-up of bimorph deflection assuming straight deflection model.

Figure 4.7(a) is enlarged to give Figure 4.7(b) showing clearly how the laser beam is reflected from the mirror on the bimorph, and also how the bimorph end-deflection is related to other parameters shown in the diagrams above. The step-to-step method, using coordinate geometry, taken to calculate the shift of the laser beam on the photodiode is also given in Appendix B. Referring to Figure 4.7(a), the total shift $S_{T2}$ of the laser beam on the detector is the distance between the points $P_2 (x_2,y_2)$ and $P_3 (x_3,y_3)$ and is equal to the sum of the angular shift $S_{A2}$ and the positional shift $S_{D2}$ of the laser beam (due to shifts $\Delta x$ and $\Delta y$).

$$S_{T2} = S_{A2} + S_{D2}$$  \hspace{1cm} (4-15)

$$S_{T2} = \sqrt{(y_2 - y_3)^2 + (x_2 - x_3)^2}$$  \hspace{1cm} (4-16)
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Where:

\[ x_2 = L \cdot \sin \alpha, \]  \tag{4-17} \\
\[ y_2 = L \cdot \cos \alpha, \]  \tag{4-18} \\
\[ x_5 = \frac{r \cdot \cot (\alpha + 2 \cdot \beta) \cdot \cos (\beta) - r \cdot \cot (\alpha + 2 \cdot \beta)}{\cos (\beta) \cdot (\cot (\alpha) - \tan (\beta))} + \frac{r \cdot \cos (\alpha) \cdot \cos (\beta) - r \cdot \cos (\alpha)}{\cos (\alpha + \beta)} + \frac{L}{\cos (\alpha) + (\cot (\alpha + 2 \cdot \beta) + \tan (\alpha))}, \]  \tag{4-19} \\
\[ y_5 = \frac{L}{\cos (\alpha)} - \tan (\alpha) \cdot (x_5) \]  \tag{4-20}

By plotting graphs using Mathcad, it is possible to observe how the above shifts of the laser beam vary individually with the bimorph end-deflection \( \Delta x \) in the range 0 to 25nm, using a bimorph length \( r \) of 10mm, a laser beam incident angle \( \alpha \) of 60° and a distance \( L \) of 100mm between the bimorph mirror and the photodiode.

![Graph of angular deflection against bimorph end-deflection](image)

**Fig. 4.8** Graph of angular deflection against bimorph end-deflection
Fig. 4.9 Graph of positional shift against bimorph end-deflection.

Fig. 4.10 Graph of the total laser beam shift $S_{T2}$ against bimorph end-deflection.
A comparison between the angular laser beam shift $S_{A2}$ and the positional shift (due to $\Delta x$ and $\Delta y$) $S_{D2}$ is made, by plotting a graph of the ratio of $S_{A2}$ to $S_{D2}$ over a range of bimorph end-deflections 0 to 10nm.

The explanation of Figures 4.8 to 4.11 is the same as that given for Figures 4.3 to 4.6, which assumes a bimorph circular bending model. The important points to note are that the shift $S_{A2}$ of the laser beam on the photodiode due to angular deflection is so much bigger than the positional shift $S_{D2}$. It is this shift, which has significance on the total shift $S_{T2}$ of the laser beam on the photodiode.
4.2.3 Comparisons between the Bimorph Bending Models

The three bimorph models are compared in this section to see how the shift of the laser beam on the photodiode varies as the end-deflection of the bimorph in the range 0.01nm to 25nm, assuming a bimorph length $r$ of 10mm, a distance $L$ between bimorph and mirror of 100mm and a laser incident angle $\alpha$ of 60°. It is important to point out that the incident angle of the laser beam does not affect the shift of the laser beam that much.

![Graph of laser beam shifts against bimorph end-deflection for the three models](image)

**Fig. 4.12** Graph of laser beam shifts against bimorph end-deflection for the three models

From the above graph, it can be seen that there is a close correlation between the three bimorph bending models that they appear to be superimposed over one another in the range of displacements shown. The bimorph straight-deflection model is probably a more accurate model of the way the bimorph bends than the other two models. This is because most of the length of the bimorph remains straight when it bends and only about a quarter of it...
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experiences some curvature [77]. However, the error between the bimorph straight-deflection method and the other two models is very small, for small bimorph displacements.

To give an indication of how small the magnitudes shown in Figure 4.13, a bimorph end deflection of about 0.12nm results in a shift of the laser beam on the photodiode of around 1nm. To appreciate that even though the errors between these models are very small, they are finite, the table below is presented.

<table>
<thead>
<tr>
<th>End-deflection Δx (nm)</th>
<th>Shift $S_{T1}$ (nm)</th>
<th>Shift $S_{T2}$ (nm)</th>
<th>Shift $S_{T3}$ (nm)</th>
</tr>
</thead>
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<td>0.199999998139</td>
<td>0.20000000000</td>
</tr>
<tr>
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<td>2.00000000000</td>
</tr>
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<td>199.999991362</td>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>25.0</td>
<td>500.000072168</td>
<td>499.999945890</td>
<td>500.0000000000</td>
</tr>
</tbody>
</table>

Table 4.1 Bimorph end-deflections with corresponding values of laser beam shifts for model presented.
4.3 Laser Beam Profile with Gaussian characteristics

This section introduces optics of Gaussian beams. The laser beam characteristics are investigated in detail to enable the development of an accurate model of the laser beam that is being used in this project so as to optimise the OBD technique. The laser beam is modelled as both a circle and as an ellipse of Gaussian power distribution.

4.3.1 Optics of Gaussian Beams

A coherent, monochromatic beam whose complex amplitude distribution in a cross-sectional plane is described by a Gaussian function is known as a Gaussian beam [79]. When propagating in free space (or any other isotropic, homogeneous medium), a Gaussian beam's cross-sectional profile remains Gaussian at all times. In addition, a Gaussian beam remains Gaussian on passage through a lens. It is also true to say that a laser oscillating in the TEM 00 mode emits a beam with Gaussian intensity distribution [80]. Higher order modes exhibit Gaussian intensity distributions, multiplied by certain polynomials (Hermite polynomials). Thus, beams emitted by any laser are called Gaussian beams. For a circular Gaussian beam, the power is concentrated within a small cylinder surrounding the beam axis. The intensity distribution in any transverse plane is a circularly symmetric (in practice, laser diodes emit asymmetrical beams that are elliptical) Gaussian function centred about the beam axis. When viewed by the eye, this pattern appears to be a circle of light whose edges are not sharp but instead, the light intensity drops off gradually [81]. For a circular Gaussian beam, the irradiance is defined as power per unit area and is given [79]:

\[ I(r) = \frac{P}{2\pi r^2} \]
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\[ I(r,z) = I_0 \cdot \frac{w_0^2}{w^2(z)} \cdot \exp\left(\frac{-2 \cdot r^2}{w^2(z)}\right) \]  (4-21)

Where:

- \( I_r \) is a function of the axial and radial distances \( z \) and \( r = \sqrt{x^2 + y^2} \) (A/W)
- \( w_0 \) is the beam waist (m)
- \( w(z) \) is the spot radius as a function of \( z \) (m)
- \( I_0 \) is the peak value of irradiance. (A/W)

It can also be seen that the field varies as \( \exp(-r^2/w_0^2) \) at the plane \( z=0 \) [82]. At an arbitrary plane located at point \( z \), the total power transported by the beam is found by integrating over an entire cross section as follows:

\[ P = \int_0^\infty \int_0^{2 \pi} I(r,z) \cdot r \cdot dr \cdot d\phi \]  (4-22)

\[ \Rightarrow P = \frac{w_0^2}{w(z)^2} \cdot 2\pi \cdot I_0 \cdot \int_0^\infty \exp\left(\frac{-2 \cdot r^2}{w^2(z)}\right) \cdot r \cdot dr = \pi \cdot w_0^2 \cdot \frac{I_0}{2} \]  (4-23)

Thus, in terms of the total optical power \( P \), \( I_0 = \frac{2 \cdot P}{\pi \cdot w_0^2} \) and the irradiance may be written as:

\[ I(r,z) = \frac{2 \cdot P}{\pi \cdot w^2(z)} \cdot \exp\left(\frac{-2 \cdot r^2}{w^2(z)}\right) \]  (4-24)

100
\( w(z) \) is the beam radius, or the spot size, of the beam at \( z \). At \( r = w(z) \), the irradiance drops by the factor \( 1/e^2 \) of its peak on-axis value. \( w(z) \) has a minimum value \( w_0 \) at the point \( z = 0 \), which is known as the beam waist. The spot size \( w(z) \) does depend on the beam waist \( w_0 \) as \[ 82 \]:

\[
w^2(z) = w_0^2 \cdot \left[ 1 + \left( \frac{\lambda \cdot z}{\pi \cdot w_0^2} \right)^2 \right] \tag{4-25}
\]

Where \( \lambda \) is the wavelength of the laser (in metres). For large distances \( z \) from the beam waist the approximation below can be made:

\[
w(z) \approx \frac{\lambda}{\pi \cdot w_0} \cdot z \tag{4-26}
\]

4.3.2 Model of Laser Beam with Gaussian Power Distribution

For a Gaussian beam, the output voltage \( V_{out} \) from the differential amplifier can be calculated in terms of its power as:

\[
V_{out} = \frac{R_f \cdot R_2}{R_1} \cdot s_p \cdot \Delta P \tag{4-27}
\]

Where \( \Delta P \) is the difference in power between the two halves of the photodetector. The assumption is made that the laser beam incident on the photodiode is positioned in the centre of the photodiode and moves symmetrically along the \( x \)-axis. The analysis is the same for movement in the \( y \)-axis and the results obtained are identical if equal laser beam shifts on the photodiode are experienced.
4.3.2.1 Model of a Circular Beam of Gaussian Power Distribution

In this section, the laser beam is modelled as a circle of Gaussian power distribution. If the laser beam shifts to the right by a small displacement \( d \), the power of the beam on the right half of the detector is given by:

\[
P_1 = \frac{2 \cdot P}{\pi \cdot w^2} \int_{-\infty}^{\infty} \int_{g/2+d}^{\infty} e^{-\frac{2 \cdot ((x-d)^2 + y^2)}{w^2}} dy \, dx
\]

The power of the laser beam on the left half of the detector is given by:

\[
P_2 = \frac{2 \cdot P}{\pi \cdot w^2} \int_{-\infty}^{\infty} \int_{g/2-d}^{\infty} e^{-\frac{2 \cdot ((x-d)^2 + y^2)}{w^2}} dy \, dx
\]

The difference in power \( \Delta P = (P_1 - P_2) \) between the two halves evaluates as:

\[
P_1 - P_2 = \frac{P}{2} \left( \text{erf} \left( \frac{g}{w \cdot \sqrt{2}} \right) + \text{erf} \left( \frac{-g + 4 \cdot d}{w \cdot \sqrt{2}} \right) \right)
\]
4.3.2.1.1 Optimisation of Output Voltage

The sensitivity, $S$, is given as:

$$ S = \frac{d(V_{out})}{dt} $$

(4-31)

$$ S = \frac{2 \cdot \sqrt{2} \cdot P \cdot C}{w \cdot \sqrt{\pi}} \cdot \exp \left[ \frac{-(g + 4 \cdot d)^2}{2 \cdot w^2} \right] $$

(4-32)

Where $C = \frac{R_f \cdot R_2}{R_1} \cdot s_p$

(4-33)

To find out what the relationship between $g$ and $w$ is, that yield the maximum sensitivity, the sensitivity, $S$, is differentiated with respect to $w$ and equated to zero, as $d \to 0$:

$$ \frac{dS}{dw} = \lim_{d \to 0} \frac{d}{dw} \left[ \frac{2 \cdot \sqrt{2} \cdot P \cdot C}{w \cdot \sqrt{\pi}} \cdot \exp \left[ \frac{-(g + 4 \cdot d)^2}{2 \cdot w^2} \right] \right] $$

(4-34)

$$ \frac{dS}{dw} = \left[ \frac{2 \cdot \sqrt{2} \cdot P \cdot C \cdot (w^2 + g^2)}{w^4 \cdot \sqrt{\pi}} \cdot \exp \left[ \frac{-g^2}{2 \cdot w^2} \right] \right] = 0 $$

(4-35)

The solutions to the above are $w = \pm g$

(4-36)

Therefore, to get maximum sensitivity for Gaussian circular laser beams, the spot radius, $w$, must be equal to the size of the photodiode gap ($g$). The sensitivity plotted against the laser beam radius, for different values of photodiode gap is shown in Figure 4.13 (Refer
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to Appendix C: Task3.m and Graph3C.m for Matlab code), for \( d = 18.3 \text{ nm} \), \( R_f = 30 \text{ k}\Omega \), \( R_s = 4k7 \text{ } \Omega \), \( R_i = 1 \text{ k}\Omega \), \( P = 2.6 \text{ mW} \) (allowing for power loss after reflection from mirror).

Assumption is made that the photodiode photosensitivity (0.5A/W) remains constant for all values of \( g \). Note that \( g \) is in micrometers.

\[ E > C \]

\[ g = 10 \mu m \]

\[ g = 50 \]

\[ g = 100 \]

\[ g = 200 \]

\[ 0 \quad 100 \quad 200 \quad 300 \quad 400 \quad 500 \quad 600 \quad 700 \quad 800 \]

\[ 0 \quad 2000 \quad 4000 \quad 6000 \quad 8000 \quad 10000 \quad 12000 \quad 14000 \quad 16000 \quad 18000 \]

**Fig. 4.13** Graph of sensitivity against spot radius for a Gaussian circular beam

From the figure above, it can be seen that there is a value for which the sensitivity is maximum and this value occurs when the value of the laser beam spot radius, \( w \), is equal to the value of the photodiode gap, \( g \). The lower the value of \( g \), the higher the sensitivity for a fixed value of spot radius. To achieve the highest sensitivity possible at this value of \( g \), the spot radius \( w \) should be equal to \( g \). Hence both the gap of the photodiode \( g \) and the spot radius \( w \) should be kept as small as possible. As the gap of the photodiode is
increased, the spot radius should also be increased (to maintain the ratio of \( w \) to \( g \)) to get maximum sensitivity at that value of the photodiode gap. However, this results in an overall decrease in sensitivity. The rule in getting a maximum sensitivity is to first choose a photodiode to use, and then focus the laser beam radius down to the same value of magnitude to that of the photodiode gap. In the work being done in this project, the laser beam cannot be focused right down to the order of size of the gap of the photodiode. So to get very high sensitivities, it is necessary to use photodiodes with as small a gap as possible, and with as high a photosensitivity as possible.

4.3.2.2 Model of an Elliptical Beam of Gaussian Power Distribution

The laser diode that has been used in experiments for this project emits an elliptical Gaussian beam. It is therefore important to model the laser beam as an ellipse and compare the results with those obtained through experiments. This would enable us to model the whole measurement and instrumentation channel even more accurately.

The modelling analysis is similar to that done for a circular laser beam of Gaussian power distribution. The irradiance is given as:

\[
Ir = Io \cdot \left( \frac{w_x}{w(x)} \cdot \frac{w_y}{w(y)} \cdot \exp\left( -\frac{2 \cdot x^2}{w(x)^2} \right) \cdot \exp\left( -\frac{2 \cdot y^2}{w(y)^2} \right) \right)
\]

Where \( Io \) is the peak value of irradiance (Wm\(^{-2}\)), \( w(x) \) is the major axis spot radius (m), \( w_x \) is the major axis beam waist (m), \( w(y) \) is the minor axis spot radius (m), \( w_y \) is the minor axis beam waist (m).
In terms of the total optical power $P$ the peak irradiance $I_0$ can be written as:

$$I_0 = \frac{2 \cdot P}{\pi \cdot w_x \cdot w_y}$$  \hspace{1cm} (4-38)

Replacing (4-68) into (4-67) the irradiance $I_r$ is thus written as:

$$I_r = \frac{1}{\pi} \left( \frac{2 \cdot P}{w_x(z) \cdot w_y(z)} \cdot \exp \left( \frac{-2 \cdot x^2}{w_x(z)^2} \right) \cdot \exp \left( \frac{-2 \cdot y^2}{w_y(z)^2} \right) \right)$$  \hspace{1cm} (4-39)

If the laser beam shifts to the right by a small displacement $d$ in the direction of $w_x(z)$, the power of the beam on the right half of the detector is given by:

$$P_1 = \frac{2 \cdot P}{\pi \cdot w_x(z) \cdot w_y(z)} \int_0^{\infty} \int_{d/2}^{\infty} \exp \left( -\frac{2 \cdot (x-d)^2}{w_x(z)^2} \right) \cdot \exp \left( -\frac{2 \cdot y^2}{w_y(z)^2} \right) \, dx \, dy$$  \hspace{1cm} (4-40)

The power of the laser beam on the left half of the detector is given by:

$$P_2 = \frac{2 \cdot P}{\pi \cdot w_x(z) \cdot w_y(z)} \int_0^{\infty} \int_{-\infty}^{d/2} \exp \left( -\frac{2 \cdot (x-d)^2}{w_x(z)^2} \right) \cdot \exp \left( -\frac{2 \cdot y^2}{w_y(z)^2} \right) \, dx \, dy$$  \hspace{1cm} (4-41)

The difference in power $\Delta P (P_1 - P_2)$ between the two halves evaluates as:
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\[ P_1 - P_2 = \frac{-P}{2} \left( \text{erf} \left( \frac{g}{\omega x(z) \cdot \sqrt{2}} \right) + \text{erf} \left( \frac{-g + 4 \cdot d}{\omega x(z) \cdot \sqrt{2}} \right) \right) \] (4-42)

4.3.2.2.1 Optimisation of Output Voltage

The sensitivity, \( S \), is given as:

\[ S = \frac{d(V_{\text{out}})}{d \omega} \] (4-43)

\[ S = \frac{2 \cdot \sqrt{2} \cdot P \cdot C}{\omega x(z) \cdot \sqrt{\pi}} \cdot \exp \left[ \frac{-(g + 4 \cdot d)^2}{2 \cdot \omega x(z)^2} \right] \] (4-44)

Where \( C = \frac{R_2}{R_1} \cdot s_p \) (4-45)

To find out the relationship between \( g \) and \( \omega x(z) \) that yield the maximum sensitivity, the sensitivity, \( S \), is differentiated with respect to \( \omega x(z) \) as \( d \to 0 \), and equated to zero to solve for \( \omega x(z) \) in terms of \( g \):

\[ \frac{dS}{d(\omega x(z))} = \lim_{d \to 0} \frac{d}{d(\omega x(z))} \left[ \frac{2 \cdot \sqrt{2} \cdot P \cdot C}{(\omega x(z)) \cdot \sqrt{\pi}} \cdot \exp \left[ \frac{-(g + 4 \cdot d)^2}{2 \cdot \omega x(z)^2} \right] \right] \] (4-46)
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\[
\frac{dS}{d(wx(z))} = \left[ \frac{2 \cdot \sqrt{2} \cdot P \cdot C \cdot \left( -w^2 + g^2 \right)}{(wx(z))^4 \cdot \sqrt{\pi}} \cdot \exp \left[ \frac{-g^2}{2 \cdot (wx(z))^2} \right] \right] = 0
\]  \hspace{1cm} (4-47)

The above gives the solution shown below:

\[
wx(z) = \pm g
\]  \hspace{1cm} (4-48)

For practical purposes, only the positive solution is of significance. From the solution derived, it can be deduced that for Gaussian elliptical beams, to get maximum sensitivity, the spot radius must be equal to (in magnitude) to the gap of the photodiode. The analysis for the Gaussian elliptical beam deflected along the minor axis \(wy(z)\) also gives the solution shown below:

\[
wy(z) = \pm g
\]  \hspace{1cm} (4-49)

A graph of sensitivity, \(S\), against spot radius, \(wx(z)\), is shown in Figure 4.14, assuming \(g=30 \mu m, d=18.3 \text{ nm (corresponding to an applied peak voltage \(V\) of 5 mV), } R_f=30 \text{ k}\Omega, \ R_s=4.7 \text{ k}\Omega, \ R_i=1 \text{ k}\Omega, \ P=2.6 \text{ mW (allowing for power loss after reflection from the mirror) and a photodiode photosensitivity of 0.5 A/W. The laser beam is maintained right in the centre of the photodiode and then displaced in the direction of the positive major axis } wx(z).
The output voltage is then divided by the shift, \( d \), worked out (18.3 nm in this case) to give a value of the sensitivity. The same results are expected if the laser beam is displaced in the negative major axis, or either direction of the minor axis assuming the same laser beam shift on the photodiode is experienced and the laser beam maintains symmetry on the photodiode at all times.

![Graph of sensitivity against spot radius in the major axis](image)

**Fig. 4.14** Graph of sensitivity against spot radius in the major axis
From the figure above, it can be seen that the peak occurs at a point where the spot size is equal in magnitude to the gap $g$ of the photodiode ($30 \, \mu m$). Hence, to get maximum sensitivity when using an elliptical laser beam of Gaussian power distribution, the spot radius $w_x(z)$ must be equal to the photodiode gap $g$ ($30 \, \mu m$).

This relationship will be compared to experimental results later in this chapter to see how accurate the model is. It was shown earlier in the previous section that to get even higher sensitivity, both the gap of the photodiode and the spot radius of the laser beam must be kept small. It has also been found that higher sensitivities are even possible when both the photodiode gap $g$ and the spot radius in all cases for the various beam types are kept as small as possible. With the exception of the ratios for elliptical beams with Gaussian power distribution, the solutions presented in the table above are based on calculations worked out experimental work has to be done though to ascertain these findings.
4.4 Summary

In this chapter, the way the bimorph element bends when a voltage is applied across it has been investigated. This bending of the bimorph element causes the laser beam incident on the bimorph element to shift in position on the photodetector. Two bimorph-bending models are presented, together with their resulting laser beam shift on the photodetector. The first model, circular bending, assumes that the bimorph element bends in such a way that it is an arc of a very large circle, experiencing uniform curvature along its entire length. The other model, straight-deflection, assumes that the bimorph simply bend at its root and does not experience any curvature along its length at all. These two models have been compared to an existing model, which does not take the incident angle of the laser beam into consideration.

The total shift of the laser beam for the three models, under the same conditions, have been compared and found to be very close. However, the differences in the shift between these models increase as the bimorph end-deflections increase. The distinction between the laser beam shift on the photodiode due to angular tilt of the mirror, and due to horizontal and vertical movements of the tip of the bimorph element has been made.

In order to model the measurement and instrumentation channel, laser beam optics have also been investigated in this Chapter. The laser beam has been modelled as a circle and as an ellipse of Gaussian power distribution in order to optimise the detection technique by maximising the output voltage at the differential amplifier stage.
achieved. By investigating in detail the relationship between the dead space (or the gap $g$) between individual quadrant active elements of the photodiode and the laser beam spot radius, optimum ratios of the gap to the spot radius have been found to give us the highest sensitivity giving us the highest output voltage. The table below summarises the findings.

<table>
<thead>
<tr>
<th>Beam type</th>
<th>Gaussian power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>$\frac{w(z)}{g} = 1$</td>
</tr>
<tr>
<td>Elliptical (major axis)</td>
<td>$\frac{w_x(z)}{g} = 1$</td>
</tr>
<tr>
<td>Elliptical (minor axis)</td>
<td>$\frac{w_y(z)}{g} = 1$</td>
</tr>
</tbody>
</table>

*Table 4.2 Summary of optimum ratios of spot radius to photodiode gap $g$. 
Chapter 5

OBD Characterisation

5.1 Experimental Results

Experiments have been carried to find out the smallest deflection of the bimorph measurable with the electronics developed in Chapter 3 to determine the limiting sensitivity of the OBD measurement instrumentation channel. The aim is to be able to detect as small a deflection as possible above noise. The importance of such fine movements of the bimorph will be discussed later in this thesis. Further experiments have done to compare the sensitivities of different quadrant photodetectors with a view to choosing a standard one for use in future experiments. In addition, the experiments would test the theory that the smaller the gap between the individual quadrants of the photodiode the higher the sensitivity of the overall system and the higher the output voltage obtained for the same laser beam dimensions. During all the experiments in this section, the laser diode was kept running all the time when taking a set of readings to ensure consistency in the measurements obtained.

5.1.1 Limiting Sensitivity of Bimorph Deflection

The minimum detectable deflection of the bimorph possible in the experimental set-up was investigated. The bimorph element of total length 15 mm (with 10 mm of free length) was clamped firmly in an upright position and was driven at 192 Hz (1/6th of its
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resonance frequency) along its major axis radius (horizontally). The voltage applied (V_{app}) across its electrodes was stepped down in halves from about 40 mV r.m.s., and the resulting output voltage (V_{out}) read using a DSP lock-in amplifier (EG&G 7260) - with the amplifier set to a time constant of about 5 seconds before taking readings. With the laser beam major axis diameter being of dimension 1.105 mm, and the distance between the bimorph mirror and the photodiode about 100 mm, readings were taken until they are no longer distinguishable from noise. In this experiment, the photodiode used was the Hamamatsu S4349, which has an element gap of 0.1 mm and a photosensitivity of 0.42 A/W. The results are shown in the figure below.

![Graph of output voltage against applied drive voltage.](image-url)
Fig. 5.2 Graph of output voltage against applied drive voltage showing limiting sensitivity.

For the bimorph used, $d_{31} = -220 \times 10^{-12}$ Vm/N, and using the equation given in Table 3.3 for the parallel bimorph connection (assuming that this equation holds at these very small values of drive voltages), the bimorph end-deflection $\Delta x$ at the minimum possible applied voltage of 0.156 mV r.m.s (acceptable reading above noise) is calculated:

$$\frac{\Delta x}{\sqrt{2}} = \frac{3}{2} \cdot d_{31} \cdot 0.156 \text{mV} \cdot \frac{(10 \text{mm})^2}{(0.6 \text{mm})^2}$$

$$\Delta x = 20.2232 \cdot 10^{-12} \text{m} \approx 20 \text{ pm}$$
Therefore, a bimorph end-to-end displacement of about 40 picometres (pm) can be measured well above noise. This is much better than the target of 1 nanometre aimed for at the start of the project. Noise levels have also been calculated and they have amplitude of about 0.080 mV r.m.s, corresponding to a bimorph end-to-end deflection of about 20.8 picometres (about $\frac{1}{5}$\textsuperscript{th} of an Angstrom). The experiment above was repeated with a different photodiode (the Telefunken S239P) to see if the limiting sensitivity is affected. The photodiode has gap of 0.01 mm and a photosensitivity of 0.35 A/W. The laser beam diameter in the major axis is 1.184 mm. All other conditions were kept constant. The results are shown in the figure below:

![Graph](image.png)

**Fig. 5.3** Graph of output voltage against applied drive voltage.
Fig. 5.4 Graph of output voltage against applied drive voltage showing limiting sensitivity.

From the graphs above, it can be seen that the limiting sensitivity is the same as that obtained when using the S4349 photodiode. The end-deflection, Δx, is also 20 pm at the minimum possible applied voltage of 0.156 mV r.m.s. The noise floor in the measurement channel, corresponding to a bimorph end-deflection of 10.4 pm (using a lock-in amplifier to take readings), is the same for both photodiodes tested.

5.1.2 Determination of Laser Beam Radius

Several methods to determine the beam radius w(z) exist. One method involves using a pinhole to probe the irradiance distribution of the beam [78], but such a method is very time consuming. Other methods, based on knife-edges, thin wires, or narrow slits, have been devised and are more convenient [78]. These methods may be automated and can
be used to measure the beam radius quickly. However, such methods are predicated on the assumption that the beam has a Gaussian distribution. The result would be erroneous if the beam is not Gaussian. These methods, however, assume a circular Gaussian beam. The laser beam from the laser diode in use in the experiments in this project is of Gaussian elliptical form and its beam dimensions are measured differently.

The laser beam spot is elliptical with its major axis along the horizontal axis. The spot radius was measured by scanning the spot over the photodiode horizontally and the output voltage of the differential amplifier noted. The method is simple and quick. The spot was first positioned exactly in the centre of the photodiode. In this position, we expect zero voltage output from the differential amplifier. This is because the sum of the currents in the right half of the photodiode is equal to the sum of the currents in the left half of the photodiode.

![Experimental arrangement for laser spot measurement](image)

**Fig. 5.5** Experimental arrangement for laser spot measurement

The laser beam was then scanned horizontally across the photodiode as shown in the diagram below. This was done by keeping the position of the laser beam fixed, and then
moving the photodiode slowly horizontally in steps of about 25 micrometers to get the
positions shown below:

![Fig. 5.6 Movement of laser spot on photodiode.]

The pattern in output voltage is shown in the figure below:

![Fig. 5.7 Output voltage against position of laser spot on photodiode]

The laser spot was moved from left to right slowly in micrometers and as soon as part of
it intercepted the gap of the photodiode, the output voltage started to drop off. The drop
in voltage was small at first but suddenly increased. This refers to position 1 above. The
reading on the micrometer screw gauge, which controls the movement of the photodiode
scanning the laser spot, was denoted \( d_1 \). The laser spot was moved along the photodiode
and a point was reached where the output voltage reached zero. This refers to the
position 2 in the diagram where the laser beam was positioned exactly in the middle of
the photodiode. As spot was moved further on along the diode to the right, the voltage
started to increase until a point where it just stopped increasing and stayed constant. The reading on the micrometer gauge was taken and denoted $d_2$. This was repeated for 3 more values of $d_1$ and $d_2$ and an average value of each reading worked out.

With reference to the Figure above, the laser beam spot radius $w(z)$ can thus be estimated as follows as shown below:

$$w(z) = \frac{d}{3.2} = \frac{d}{6}$$  \hspace{1cm} (5-3)

Where $d = |d_2 - d_1|$

This method of estimating the spot size is very quick and accurate, as long as the spot size is bigger than the gap of the photodiode across which it is being scanned and as long as the photodiode output is linear.
5.1.3 Relationship between Laser Spot Size and Photodiode gap

In this section, the relationship between the spot size of the laser beam and the gap separating the elements on the photodiode is investigated. The laser beam spot is a Gaussian ellipse. The mathematics to model the spot as Gaussian ellipse were thoroughly investigated and presented early on in this Chapter. The modelled results are tested, by comparing them to those obtained through experiment in this section. As it is not possible to focus the laser spot to the size of the photodiode gap for the work being done in this project, the gap is widened artificially by sticking a black light-absorbing tape vertically in the middle of the photodiode if the spot is being scanned horizontally and vice-versa. The width of the gap $g$ is 600 $\mu$m, and the spot size was varied by adjusting the lens in the laser diode. Interest here is to see how the sensitivity varies as the spot size is changed. The sensitivity, $S$, is worked out on the basis of keeping the shift of the laser beam on the photodiode constant as well as keeping the distance between the laser diode and the photodiode constant. This is done because it would not be easy to measure the actual shift of the laser spot on the photodiode practically. In doing this, effectively, as the laser spot size is varied, the sensitivity also changes and this can be seen by a change in the output voltage, which is directly proportional to the sensitivity. Therefore, the shift of the laser beam spot on the photodiode can be normalised and called an arbitrary 1. The bimorph was excited at a frequency of 192 Hz (1/6th resonant frequency) and driven at a peak-to-peak voltage of 1 V. The spot size was measured as described in section 5.5.2, and the output voltage at each spot size noted. The results are shown in Figure 5.9. The photodiode used is the Hamamatsu S4349. [Applied drive voltage $V=1$ V peak-to-peak, bimorph excited at 1.15 kHz]
(natural frequency), \( d = 650 \text{ nm}, \ s_p = 0.42 \text{ A/W}, \ g = 600 \ \mu\text{m} \) (widened artificially by uniform black strip), \( R_f = 30 \text{ k}\Omega, \ R_L = 4 \text{k}\Omega, \ R_i = 1 \text{k}\Omega, \ P = 2.6 \text{ mW}. \]

Figure 5.9 shows that there is a value of the laser spot size, which gives a maximum value of sensitivity. In this experiment, that value occurs at somewhere around beam diameter \( 2w(z) \) of 1100 \( \mu\text{m} \) (a beam radius \( w(z) \) of 550 \( \mu\text{m} \)). However, the artificial gap \( g \) of the photodiode is 600 \( \mu\text{m} \). This gives a relationship between the gap of the photodiode and the laser beam radius as shown below:

\[
\frac{w(z)}{g} = \frac{550}{600} \approx 0.917 \text{ (To 3 dec. places)} \quad \text{(5-4)}
\]
This experimental result shows that the beam radius \( w(z) \) should be approximately equal to the gap of the photodiode to get maximum sensitivity. This is similar to the theoretical relationship obtained through modelling for the Gaussian elliptical beam.

### 5.1.4. Investigation of Sensitivities of different Photodiodes

In this section, different photodiodes are investigated to see which one gives the highest sensitivity. Some of the electrical and optical characteristics of the photodiodes being investigated are shown in Table 5.1. All the photodetectors have spectral responses wide enough to cover the wavelength of the laser diode being used (\( \lambda = 670 \text{ nm} \)). Each of the values in the table is per quadrant only and is assumed at temperature of 25°C. This literature is obtained from the technical data sheets of the devices [83][84].

<table>
<thead>
<tr>
<th>Model</th>
<th>S4349</th>
<th>S6242</th>
<th>S5980</th>
<th>S239P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manufacturer</strong></td>
<td>Hamamatsu</td>
<td>Hamamatsu</td>
<td>Hamamatsu</td>
<td>Telefunken</td>
</tr>
<tr>
<td><strong>Photosensitivity</strong>(Aw(^{-1}) at 670nm)</td>
<td>0.42</td>
<td>0.43</td>
<td>0.48</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Gap between Quadrants</strong>(mm)</td>
<td>0.1</td>
<td>0.015</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Dark current</strong>(nA)</td>
<td>0.01</td>
<td>0.1</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Element size</strong>(mm)</td>
<td>(3X3)/4 ch.</td>
<td>(1.5X2)/4 ch.</td>
<td>(5X5)/4 ch.</td>
<td>(3X3)/4 ch.</td>
</tr>
</tbody>
</table>

Table 5.1 Electrical and optical characteristics of photodiodes being investigated
The graphs of sensitivity against laser beam spot size for the photodiodes being investigated are presented below.

Fig. 5.10 Graph of sensitivity against spot size for S4349

Fig. 5.11 Graph of sensitivity against spot size for S6242
Fig. 5.12 Graph of sensitivity against spot size for S5980

Fig. 5.13 Graph of sensitivity against spot size for S239P
From the graphs above, comparisons and conclusions can now be drawn. The S6242 photodiode has the highest sensitivity, where as the S4349 gives the lowest. The S239P photodiode gives a slightly higher sensitivity than the S5980. In order to achieve a high sensitivity, the photodiode must have a very small gap between its elements and, must have a very high photosensitivity to light of 670 nm wavelength. A small photodiode active area is also desirable to allow a higher signal-to-noise ratio. In order to minimise dark current noise and shot noise, as low a dark current as possible is necessary.

With reference to Table 5.2, the S6242 photodiode has a very small gap and a reasonably high photosensitivity. It also has a small dark current and the smallest photodiode active area. This is why it gives the highest sensitivity, making it the ideal choice for the photodiode to use in all experiments undertaken in this project. The S4349 photodiode has a very big gap in comparison to the S6242, a lower photosensitivity and a much larger photodiode active area. Even though it has a lower dark current, its sensitivity is much lower. The S5980 photodiode has a very high photosensitivity (in comparison to the S6242) and a bigger gap between its elements. Even though it has a low dark current value, it has a much bigger photodiode active area, making it more prone to noise. Therefore, it is less sensitive. The S239P has a very low photosensitivity, a very high value for the dark current, and a big photodiode active area. Even though it has the smallest gap between its elements, its sensitivity is much lower than that of the S6242.
5.2 Noise Analysis in the OBD Measurement Channel

The OBD measurement channel consists of a laser diode, a mechanical test structure (bimorph element in this Chapter) and a photodetector (which is connected to current-to-voltage converters, differential amplifiers and further signal processing). Each of these components introduces noise into the measurement channel. In this section, the various types of noise affecting the OBD measurement channel are investigated, and ways of minimising them discussed.

5.2.1 Thermal Noise

At a finite temperature, all particles, charged or uncharged, move in random directions. The random thermal motion of charge carriers is the most fundamental noise-generating mechanism in resistive components, as long as the temperature is above 0K. This thermal noise, also known as Johnson-Nyquist noise, or simply Johnson noise, is the minimum noise generated by a resistor [78]. Depending on the resistor’s material and construction, additional noise may be generated by other physical processes. The frequency spectrum of thermal noise is flat for practically all frequencies of interest. The thermal noise current $i_T$ and voltage $e_T$, respectively, are given as [85]:

\[ i_T = \sqrt{\frac{4 \cdot k \cdot T \cdot B}{R}} \]  
\[ e_T = \sqrt{4 \cdot k \cdot T \cdot B \cdot R} \]

Where $k$ is the Boltzmann constant ($1.38 \times 10^{-23}$ J/K)
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\[ T \text{ is the absolute temperature (} ^\circ \text{K)} \]
\[ B \text{ is the bandwidth (Hz)} \]
\[ R \text{ is the current-to-voltage feedback resistance (} \Omega \text{).} \]

To minimise thermal noise, it is important to use as large a feedback resistor \( R \) as possible (consistent with bandwidth requirements), which improves the signal-to-noise by \( \sqrt{R} \).

The thermal noise currents \( i_{T1}, i_{T2}, i_{T3}, i_{T4} \) at each of the four current-to-voltage conversion stages (given in Chapter three of this thesis) are equal, and \( i_{T1} \) is calculated (neglecting the thermal noise currents due to the photodiode series resistance and junction impedances) as:

\[
i_{T1} = \sqrt{\frac{4 \cdot 1.38 \times 10^{-23} \text{J/K} \cdot 293 \text{K} \cdot 10 \text{kHz}}{27 \Omega}} = 77.4 \text{pA} \tag{5-7}
\]

The thermal noise voltages are also equal, and hence \( e_{T1} \) is calculated as:

\[
e_{T1} = 77.4 \text{pA} \cdot 27 \Omega = 2.09 \mu \text{V} \tag{5-8}
\]

The thermal noise voltages, being equal, cancel out at the output of each of the two differential amplifiers that follow.
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5.2.2 Shot Noise

The direct detection of optical signals usually entails their conversion into electrical signals by a photodetector. Photo-detection is a quantum process whereby incident photons cause the release of electrons, which then go on to produce an electric current. These photons do not arrive at well-defined instants of time; rather, their arrival times are random. The random arrival of photons at the detector creates fluctuations in the resulting photocurrent known as shot noise [79]. The basic property of coherent light is that the number of photons arriving during any time interval, say \([t, t + \tau]\), is independent of that arriving during any other (non-overlapping) interval. If the interval is sufficiently short, then there is either one photon arriving in that interval, or non-at all. Assuming that the incident beam is monochromatic with frequency \(\nu\), and that its power at time \(t\) is \(P_0(t)\), the probability of a single photon arriving during the short interval \(\Delta t\) is:

\[
p(n = 1, [t, t + \Delta t]) = \frac{P_0(t) \cdot \Delta t}{\hbar \nu} \tag{5-9}
\]

Where \(\hbar \nu\) is the energy of individual photons of frequency \(\nu\). Not every photon of course creates one photoelectron. The quantum efficiency \(\eta\) of a photodetector is defined as the probability of a free electron beam generated by an incident photon. Thus the chance that one photoelectron is released during the short interval \(\Delta t\), is given

\[
p(n = 1, [t, t + \Delta t]) = (\eta / \hbar \nu) \cdot P_0(t) \cdot \Delta t \tag{5-10}
\]

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The shot noise $i_{SL}$ from each quadrant of the photodiode at each current-to-voltage conversion stage, due to photocurrent generated as result of light incident on a photodiode, is given as [86]:

$$i_{SL} = \sqrt{2 \cdot q \cdot I_L \cdot B} = 1.10 \text{nA} \quad (5-11)$$

The shot noise voltage $e_{SL}$ is calculated as:

$$e_{SL} = 1.10 \text{nA} \cdot 27 \text{k}\Omega = 29.7 \mu \text{V} \quad (5-12)$$

Where $q$ is the electronic charge ($1.6 \times 10^{-19}$C), 27 k$\Omega$ is the value of the current-to-voltage feedback resistor, $I_L$ is the average photocurrent due to incident light (0.375 mA per quadrant of the photodiode) and $B$ is the noise bandwidth (10 kHz).

The dark current noise of photodiodes is closely related to the photo shot noise above. The similarity arises from the fact that dark-current electrons, which are thermally generated, are produced randomly and independently of each other. In an ideal diode, there is no current when the diode is reverse biased. In a real p.n. diode, however, the reverse current is not zero. This is due to the leakage current in the reverse bias junction.

The reverse current is commonly referred to as the dark current. If the photodiode is kept at a constant temperature, then the rate of generation of the dark-current electrons is constant. The shot noise $i_{SD}$ per quadrant of the photodiode, due to the generation of dark current $I_B$ in a photodiode, is given as [86]:

$$i_{SD} = \sqrt{2 \cdot q \cdot I_B \cdot B}$$
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\[
i_{SD} = \sqrt{2 \cdot q \cdot I_D \cdot B} = 0.98 \text{pA} \tag{5-13}
\]

Where:

\(I_D\) is the average dark current (0.3 nA per quadrant for the Hamamatsu S5980 photodiode). Because \(I_L\) is much greater than \(I_D\), the shot noise current due to photocurrent dominates and hence, the shot noise current due to the dark current can be neglected.

Therefore, the shot noise voltage at the output of the current-to-voltage conversion stage is 29.7 \(\mu\text{V}\). For a perfectly balanced system, and when the laser beam is stationary and positioned exactly in the centre of the photodiode so that all the photocurrents from the individual quadrants of the photodiode are equal, then the shot noise current at the output of the differential amplifier will be zero.

5.2.3 Laser intensity noise

The dominant source of noise in laser diodes is spontaneous emission. The laser diode, which behaves like a thermal source, is actually an amplifier for this noise. Apart from the spontaneous emission, we have to take into account the mode-partition noise, mode-0 hoping noise, and \(1/f\) noise. The theory of these contributions is lengthy and will not be dealt with in this thesis [87]. The intensity noise present in laser diodes is often normalised to the average intensity. Practically, we can use the specifications accompanying a laser diode that give the Relative Intensity Noise (RIN) measured in a given bandwidth around a centre frequency [87]. The laser-intensity-related RIN present in the laser light is given as [87]:

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\[ \text{RIN}_{\text{int}} = \left( \frac{\langle \Delta P^2 \rangle}{\langle P \rangle^2} \right) \]  
(5-14)

Where:

\[ \langle \Delta P^2 \rangle \] is the power spectral density of the laser intensity noise (W^2/Hz)

\[ \langle P \rangle \] is the average power of the laser (W)

A typical value for the laser-intensity-related RIN is [87]:

\[ \text{RIN}_{\text{int}} = 10^{-13} \cdot B \]  
(5-15)

Where \( B \) is the system bandwidth (Hz). This shows a flat noise spectrum for frequencies up to approximately 100 MHz. The noise current \( i_L \) and voltage \( e_L \) are given, respectively, by [87]:

\[ i_L = s_p \cdot P \cdot \sqrt{\text{RIN}_{\text{int}}} \]  
(5-16)

\[ e_L = s_p \cdot P \cdot R \cdot \sqrt{\text{RIN}_{\text{int}}} \]  
(5-17)

Where \( P \) is the average laser power incident on the photodiode (3 mW), \( s_p \) is the photosensitivity of the photodiode (0.48 A/W for the Hamamatsu S5980 photodiode to a light of wavelength 670 nm, refer to table 5.2). \( R \) is the current-to-voltage feedback resistor (27 k\( \Omega \)), \( \text{RIN}_{\text{int}} = 10^{-13} \cdot B \) and \( B = 10 \text{ kHz} \).
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The photocurrent noise (A) in each quadrant of the photodetector, due to the influence of laser intensity noise on the OBD technique, is given as:

\[ i_{L1} = \frac{P}{4} \cdot s_p \cdot \left(1 + \frac{d}{b}\right) \cdot \sqrt{\text{RIN}_{\text{int}}} = 11.38438\,\text{nA} \quad (5-18) \]

\[ i_{L2} = \frac{P}{4} \cdot s_p \cdot \left(1 - \frac{d}{b}\right) \cdot \sqrt{\text{RIN}_{\text{int}}} = 11.38362\,\text{nA} \quad (5-19) \]

\[ i_{L3} = \frac{P}{4} \cdot s_p \cdot \left(1 + \frac{d}{b}\right) \cdot \sqrt{\text{RIN}_{\text{int}}} = 11.38438\,\text{nA} \quad (5-20) \]

\[ i_{L4} = \frac{P}{4} \cdot s_p \cdot \left(1 - \frac{d}{b}\right) \cdot \sqrt{\text{RIN}_{\text{int}}} = 11.38362\,\text{nA} \quad (5-21) \]

Where \( i_{L1}, i_{L2}, i_{L3} \) and \( i_{L4} \) are the photocurrent noises generated from the upper right, lower left, upper left and lower right quadrants of the photodiode (refer to Figure 3.15).

The noise voltages at the output of the current-to-voltage stage are 307.38 \( \mu \text{V} \) (due currents \( i_{L1} \) and \( i_{L3} \)) and 307.36 \( \mu \text{V} \) (due to currents \( i_{L2} \) and \( i_{L4} \)). The noise currents \( i_{L1} \) and \( i_{L2} \) are fed into one differential amplifier. The low-frequency noise at the output of the differential amplifier is obtained by subtracting equation (5-19) from equation (5-18), yielding:

\[ i_{L3} = \frac{P}{2} \cdot s_p \cdot \frac{d}{b} \cdot \sqrt{\text{RIN}_{\text{int}}} = 0.76\,\text{pA} \quad (5-22) \]

\[ e_{L4} = \frac{P}{2} \cdot s_p \cdot \frac{d}{b} \cdot R \cdot \sqrt{\text{RIN}_{\text{int}}} = 3.57\,\text{nV} \quad (5-23) \]
The noise currents $i_{L3}$ and $i_{L4}$ are fed into another differential amplifier, yielding low-frequency noise current and voltage, respectively, at the output of the differential amplifier as shown below:

\[ i_{L2} = \frac{P}{2} \cdot s_p \cdot \frac{d}{b} \cdot \sqrt{\text{RIN}_{\text{int}}} = 0.76\text{pA} \quad (5-24) \]

\[ e_{L2} = \frac{P}{2} \cdot s_p \cdot \frac{d}{b} \cdot R \cdot \sqrt{\text{RIN}_{\text{int}}} = 3.57\text{nV} \quad (5-25) \]

Where $b$ is the major axis radius of the laser beam (550 $\mu$m), $d$ is the shift of the laser beam on the photodiode (18.3 nm) along the major axis and $R$ is the feedback resistor (4.7 kΩ). Since $b$ is much greater than $d$, the low-frequency components of the noise at the output of the differential amplifier are reduced considerably at this first stage of differential amplification. At the next stage, the low-frequency components of the laser intensity noise cancel out at the differential amplifiers to yield zero laser intensity noise current at the output of the left/right movement of the laser beam. The output at the up/down movement of the laser beam (summing amplifier) doubles and is multiplied by the feedback gain of 4.7 to yield a laser intensity noise current of 7.14 pA and voltage of 33.6 nV.
5.3 Summary

In this Chapter, the limiting sensitivity of the OBD technique developed in this project has been investigated by measuring the minimum detectable bimorph deflection above noise. The noise floor has also been measured in the system using a lock-in amplifier. The method used to measure the radius of the laser beam has been given and the relationship between the laser beam radius of the Gaussian elliptical beam and the gap of the photodiode has been investigated experimentally and, a comparison made to the results obtained through modelling. The sensitivities of different photodiodes have also been investigated experimentally, noting the factors, which are desirable in a good photodiode.

A noise analysis of the measurement channel has also been made. The various sources of noise in the OBD technique developed in this research have been reviewed and calculated at each stage of the measurement channel. At the current-to-voltage conversion stage following each photodiode element, the laser intensity noise voltage is the highest (307.4 μV). The other noise voltages are much less in comparison. The maximum signal voltage possible $V_{\text{out(max)}}$ at the current-to-voltage conversion stage has been worked out in Chapter 3 as 10.125 V. The sum of all the noises at this stage $\sum e_{\text{Total}}$ is given as:

$$\sum e_{\text{Total}} = \sqrt{e_{\text{T1}}^2 + e_{\text{SL}}^2 + e_{\text{L}}^2} = \sqrt{2.09 \mu V^2 + 29.7 \mu V^2 + 307.4 \mu V^2} \approx 308 \mu V$$

(5-26)
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The signal-to-noise ratio SNR at each current-to-voltage stage is thus:

\[
\text{SNR} = \frac{V_{\text{out(max)}}}{\sum e_{\text{Total}}} = \frac{10.125 \text{V}}{308 \text{mV}} = 32873.4
\]

\[(SNR)_{\text{dB}} = 90.34 \text{dB} \quad (5-27)\]

At the first stage of differential amplification, the laser intensity noise reduces tremendously, and the thermal and shot noises, if equal, simply cancel out. If they are not equal, the amounts due to them are very small at the output of the differential amplifier stages.
6.1 Introduction

In Chapter One of this thesis, the reasons for needing a high-bandwidth load suspension arm in advanced hard disk drives have been explained. The aim of the work presented in this Chapter is to show progress towards the fabrication of a stiff, light weight active composite ‘smart’ arm, fabricated from glass or carbon fibre-reinforced composites, which would be used in a dual-actuation mechanism in advanced computer hard disk drives. This would enable both positioning control of the head flying height (z-axis) above the disk and high resolution tracking (y-axis), capable of sub-nanometre positioning in both axes. The suspension arm is required to provide high-bandwidth track following in one axis as well as precision head flying height control in the other axis. To facilitate such high-bandwidth motion of the load suspension arm, an advanced and well-established actuation mechanism is required. In Chapter Three of this thesis, different sensor and actuator methods were presented and compared, and piezoelectric actuators were found to be the ideal choice of actuators for use in this project. The use of piezoelectric materials as smart structures has recently received considerable attention. Because of their lightweight, fast response, low cost, high stiffness and availability in different sizes; piezoelectric materials are widely used as sensors and actuators in applications such as active vibration control [88], noise reduction [89], shape control [90], and damage assessment [91]. However, another need has also been identified to be able to control the head flying height. The
micro-actuator, in conjunction with appropriate positioning control methods, will be able to control the suspension arm such that the flying height can be adjusted to maintain the head at the correct height above the rotating magnetic disk. Maintaining the correct flying height is becoming increasingly more important as flying heights are reduced even further to realise greater areal storage densities in magnetic disks. In order to improve hard disk performance, in terms of reliable data transfer, it is a fundamental requirement that the read/write head is maintained at a constant height above the rotating disk. Research has shown that disk flexure can severely affect data transfer under adverse conditions [117] [118], but it should be possible to circumvent this limitation by developing appropriate sensor-actuator systems. A number of possible configurations have been investigated, based upon optical sensing and piezoelectric micro-actuators. The wide bandwidth of piezoelectric actuators has already been shown to enable resonant vibrations to be damped whilst simultaneously allowing the flying height to be controlled. The work in this research has identified three possible routes to develop actuators that would enable precision active flying height control to be achieved as well as providing high-bandwidth data tracking. These three piezoelectric actuator types are:

- Bonded piezoelectric actuators (thick films)
- Composite piezoelectric arms
- Embedded piezoelectric actuators
6.2 Piezoelectric Fibre-Reinforced Thick Films

Piezoelectric bulk ceramic elements such as lead zirconate titanate (PZT) can be attached close to the root of the load beam suspension arm to either position the arm up or down or to suppress induced motion within the arm at resonant frequencies [88]. When operated in this way, the actuator should be unobtrusive, but its thickness comparable to that of the cantilever. The two main reasons for this are; to optimise the cantilever actuation [92] and, to prevent the actuator from affecting the dynamic characteristics of the cantilever. This technique has been used previously for micro-positioning and active vibration control [93].

Another route involving bonded actuators is the use of composite piezoelectric materials. It is possible to make a piezoelectric thick film by combining piezoelectric powder and epoxy resin [94] in the right proportions. This offers a quick and much cheaper alternative to using bulk ceramics.

Recent advances in the design and manufacturing of aerospace and automotive systems have extended the use of piezoelectric fibre-reinforced composite materials, owing to their high stiffness-to-weight and strength-to-weight ratios. As a result, research concerning the use of piezoelectric fibre-reinforced composite structures, both for continuous and distributed structures, has been on the increase. Chandrashekhara et al. [95] presented a mathematical model to demonstrate the dynamic response of piezocomposite beams. The independent behaviour of the sensor and actuator were investigated and numerical results presented to demonstrate the ability of the closed loop system to control actively the vibration of laminated beams. Han et al. [96] used a linear
quadratic Gaussian control algorithm to reduce the vibrational levels of lightweight composite structures with surface-bonded piezoelectric sensors and actuators. Jianguo et al. [97] investigated theoretically and experimentally the stress transfers that occur between a piezoceramic actuating laminate and a glass fibre/epoxy substrate. Doyle et al. [98] monitored advanced fibre-reinforced composites, using optical fibre sensors, to detect impact damage and stiffness reduction in the composite due to fatigue damage. Wenger et al. [99] demonstrated that in-situ piezoelectrets embedded in glass/epoxy laminates are suitable for acoustic emission sensors. The sections that follow investigate the effects of using fibre-reinforced PZT thick films on the actuation capabilities of the PZT films.

6.2.1 Glass Fibre-Reinforced PZT Thick Films

The aim of the work in this section is to investigate the effect of varying the glass fibre volume fraction in the PZT thick films on the actuation capabilities of the films. This would give indication of the amount of fibre to be added to PZT films when being used applications such as structural health monitoring (e.g. bridges and buildings), or any other application requiring micro-actuation and sensing.

6.2.1.1 Specimen Fabrication

To produce the piezoelectric thick films, the piezoelectric material (PZT-5H powder from Morgan Matroc Limited [100]) was combined in an epoxy resin (Araldite CY1300/HY1300). The volume fraction of the PZT powder was optimally between 50% and 60% [101][102]. The resulting paste was divided into six equal parts (specimens S₁ to S₆) prior to producing the final compositions. Five of these portions
had small amounts of 1 mm long strands of glass fibre added to them. The diameter of an individual strand of fibre is between 7 and 10 μm. The sixth composition was a pure PZT/epoxy mixture, with no glass fibre added to it. The fibres were mixed thoroughly within the film to ensure a 2-dimensional random glass fibre distribution in the PZT thick film. A suitable mask enabled a 5.0 (±1%) x 3.0 (±3%) x 0.39 (±10%) mm film of each composition to be deposited directly, near the root, onto rigidly clamped stainless steel cantilever substrates, as shown in Figure 6.1. The percentage compositions by volume of the glass fibre in the films are shown in Table 1. The dimensions of the stainless steel cantilever were 10 (free length) x 3.0 x 0.2 mm.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Fibre content in thick film (volume %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>0</td>
</tr>
<tr>
<td>S₂</td>
<td>4.2</td>
</tr>
<tr>
<td>S₃</td>
<td>8.4</td>
</tr>
<tr>
<td>S₄</td>
<td>16.8</td>
</tr>
<tr>
<td>S₅</td>
<td>25.2</td>
</tr>
<tr>
<td>S₆</td>
<td>33.6</td>
</tr>
</tbody>
</table>

Table 6.1 Composition by volume of glass fibre content in PZT thick films
The films were cured at room temperature for 72 hours. The stainless steel formed the lower electrode for the thick film, whereas conducting silver paint was used for the upper electrode. A mirror glued at the end of the stainless steel acted as a reflector for the optical beam deflection (OBD) technique used to measure beam deflections. The PZT thick films were then poled at 30 kV/cm for 50 minutes at 70°C. The poling voltage was below that which causes dielectric breakdown for each film. The actuation capabilities of the thick films were then characterised using the OBD technique.

![Diagram of Cantilever with PZT thick film](image)

**Fig. 6.1** Cantilever with PZT thick film deposited near the root

### 6.2.1.2 Experimental Results

The experimental arrangement used in this work is shown schematically in Figure 6.2. A positioning signal applied to the piezoelectric thick film forces the cantilever into periodic motion at the drive frequency by inducing in it a strain that is dependent on the magnitude of the applied voltage. To monitor the positional movements of the cantilevers, the optical beam deflection technique is used [103]:

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A constant drive voltage of 20 V peak-to-peak was applied to each film. The detector response was measured using a DSP lock-in amplifier (EG&G 7260) and the respective cantilever end-deflection $\Delta x$ (on and off-resonance) determined. The results are presented in Table 6.2.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\Delta x$ (nm) Resonant operation</th>
<th>$\Delta x$ (nm) Linear operation</th>
<th>Resonant frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>22.9</td>
<td>1.62</td>
<td>1.425</td>
</tr>
<tr>
<td>$S_2$</td>
<td>25.0</td>
<td>3.60</td>
<td>1.432</td>
</tr>
<tr>
<td>$S_3$</td>
<td>28.0</td>
<td>3.93</td>
<td>1.482</td>
</tr>
<tr>
<td>$S_4$</td>
<td>37.0</td>
<td>5.00</td>
<td>1.401</td>
</tr>
<tr>
<td>$S_5$</td>
<td>4.30</td>
<td>0.90</td>
<td>1.469</td>
</tr>
<tr>
<td>$S_6$</td>
<td>1.10</td>
<td>0.20</td>
<td>1.480</td>
</tr>
</tbody>
</table>

Table 6.2 Cantilever end-deflections on and off-resonance
It can be seen in Table 6.2 that as the glass fibre content in the PZT thick films is increased, the actuation capabilities of the films, on and off-resonance, also increases. However, increasing the fibre content further does not continue to increase the degree of actuation. Figure 6.3 shows that actuation capability is optimised, in this case when the volume percentage of glass fibres is around 16%.

![Graph showing cantilever end actuation as a function of glass-fibre content, for resonant and linear operation.](image)

Fig. 6.3 Cantilever end actuation as a function of glass-fibre content, for resonant and linear operation

6.2.1.3 Discussion and Conclusions

The higher end-deflections of the cantilevers, on and off-resonance, with increasing glass fibre content in the film are due to the increased stiffness of the composite PZT films. The stiffness of the composite PZT thick film is calculated as in [104] for fibres distributed randomly in a 2-dimensional matrix within the composite PZT thick film.
An increase in stiffness (or Young’s modulus $E_{\text{II}}$) of the thick film improves the electro-mechanical coupling between the composite PZT thick film and the stainless steel cantilever. A consequence of this is an improvement in the actuation capabilities of the composite PZT films, and hence, higher cantilever end-deflections are possible. However, a certain point is reached where the addition of more glass fibre results in a reduction in the actuation capabilities of the composite PZT thick film. Beyond this point, referred to as the ‘optimal actuation point’ in this thesis, the cantilever end-deflections are reduced, even though actuation stability improves. This is thought to be due to inadequate 3-dimension PZT grain connectivity with the thick film. The reason for this is that the volume percentage of piezoelectric material within the film has reduced. Table 6.3 shows the Young’s modulus of the composite PZT thick films with their corresponding cantilever actuation off-resonance (20 V peak-to-peak applied voltage at 300 Hz, and an average of six readings were taken).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Glass-fibre Volume %</th>
<th>Young’s modulus $E_{\text{II}}$ (GPa)</th>
<th>Cantilever Actuation (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>0</td>
<td>4.20</td>
<td>1.62</td>
</tr>
<tr>
<td>$S_2$</td>
<td>4.2</td>
<td>5.50</td>
<td>3.60</td>
</tr>
<tr>
<td>$S_3$</td>
<td>8.4</td>
<td>6.80</td>
<td>3.93</td>
</tr>
<tr>
<td>$S_4$</td>
<td>16.8</td>
<td>9.00</td>
<td>5.00</td>
</tr>
<tr>
<td>$S_5$</td>
<td>25.2</td>
<td>12.0</td>
<td>0.90</td>
</tr>
<tr>
<td>$S_6$</td>
<td>33.6</td>
<td>4.0</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 6.3 Effect of increasing stiffness of PZT thick film
In conclusion, the work presented in this section shows that reinforcing composite PZT thick films with glass fibre improves the actuation capabilities of these composite thick films up to a certain point (‘optimal actuation point’). Beyond this point, the actuation reduces steadily. These findings show that glass fibre reinforced composite PZT thick films would make good sensors in applications such as structural health monitoring when the right amount of fibre is reinforced within the PZT thick film.

6.2.2 Carbon Fibre-Reinforced Thick Films

The aim of the work in this section is to compare the actuation capabilities of carbon fibre reinforced films to glass fibre reinforced PZT thick films. This extends the work presented in the previous section to investigate if the carbon fibre reinforced PZT thick films would offer improved actuation capabilities.

6.2.2.1 Sample Fabrication

The produce the piezoelectric thick films, the piezoelectric material (PZT-5H powder from Morgan Matroc Limited [100]) was combined in an epoxy resin (Araldite CY1300/HY1300). The volume fraction of the PZT powder was in excess of 50% [101][102]. The resulting paste was divided into three equal parts prior to producing the final compositions. The first and second parts had small amounts of 1 mm long strands of carbon fibre and glass fibre added to them respectively. The diameters of the fibres were between 7 and 10 μm. The third composition was a pure PZT/epoxy mixture. The fibres were mixed thoroughly to ensure their uniform distribution. A suitable mask enabled a 5.0 x 3.5 x 0.32 mm film of each composition to be deposited directly, near the root, onto rigidly-clamped stainless steel cantilever substrates, as
shown in Figure 6.4. The percentage composition by volume of the carbon fibre and glass fibre in the films was 1 and 25 respectively. During this work, it was discovered that adding greater amounts of carbon fibre prevented the PZT thick film from being poled successfully as the carbon fibre creates a conducting path within the PZT matrix. The dimensions of the stainless steel cantilever were 16.5 (free length) x 3.5 x 0.2 mm. The samples were cured and poled in the same way as for glass fibre reinforced PZT thick films. The actuation capabilities of the thick films were then characterised using the OBD technique.

Fig. 6.4 Cantilever construction showing the PZT thick film deposited near the root, and, the mirror for optical reflection.

6.2.2.2 Experimental Results

The experimental arrangement used in this work is identical to that shown in Figure 6.2. A constant drive voltage of 7 V (r.m.s.) was applied to each cantilever and the excitation frequency varied from 400 to 800 Hz. For these cantilevers the response to the drive voltage is constant at lower frequencies, reaching a maximum at the first resonant frequency before rolling off again [103]. The fundamental frequencies of vibration of the cantilevers were 600, 615 and 612 Hz for the carbon fibre-reinforced, glass fibre-reinforced and normal PZT thick films respectively. The results are shown in Figure 6.5.
It can be seen that the cantilever with the carbon fibre-reinforced PZT film produced the highest resonant peak (end-deflection), slightly higher than the cantilever with the glass fibre-reinforced PZT film. The cantilever with the PZT thick film without any reinforcement produced a much lower resonant peak than the other two films. In addition, the resonant curves of the cantilevers with fibre-reinforced films are much sharper than those without any fibre-reinforcement, with mechanical quality factors \( Q \) being 150, 100 and 20 for the PZT/carbon, PZT/glass and PZT alone respectively. However, off-resonance, the cantilever with the PZT film without any fibre-reinforcements appears to experience marginally higher end-deflections than the PZT fibre-reinforced films.

Fig. 6.5 Frequency response curves for different piezoelectric-epoxy film compositions: PZT/carbon fibre, PZT/glass fibre and PZT alone.
6.2.2.3 Discussion and Conclusions

The higher end-deflections of the cantilevers with the fibre-reinforced PZT films indicate greater actuation capabilities possible with these films at resonance. It is believed that the reason for this is, due to the increased stiffness of the PZT-composite films, the carbon and glass fibre enable better coupling between the PZT thick film and the stainless steel cantilever substrate, causing greater actuation when the PZT films are under stress. The sharper resonant curves indicate that the cantilevers with the fibre-reinforced PZT films have a much higher Q-factor than those without any fibre-reinforcements, which is also a consequence of greater structural stiffness. The higher Q-factor is very valuable in making these structures more sensitive in electronic measurement applications and more stable in resonant applications. In conclusion, the work presented in this section shows that fibre-reinforced PZT thick films have better actuation capabilities at resonance and, they exhibit higher Q-factor values. This makes them better as actuators for certain control applications.

6.2.3 Glass/Carbon Fibre-Reinforced PZT Thick Films

The aim of the work in this section is to investigate the actuation capabilities of combined carbon and glass fibre reinforced PZT thick films. This extends the work presented in the previous section to investigate if the fibre combinations mixed in the right proportions would enhance actuation capabilities of PZT thick films.
6.2.3.1 Sample Fabrication

The method used to fabricate the specimens is similar to those used in sections 6.2.2.1.1 and 6.2.2.1.1. To produce the piezoelectric thick films, the piezoelectric material (PZT-5H powder from Morgan Matroc Limited [100]) was combined in an epoxy resin (Araldite CY1300/HY1300). The volume fraction of the PZT powder was in excess of 50% [101][102]. The resulting paste was divided into three equal parts prior to producing the final compositions. The following thick film combinations were then made:

- PZT/Glass/carbon combination
- PZT/Glass
- PZT alone

The fibre strands are aligned in such a way that they formed a 2-dimensional uniform fibre distribution within the PZT thick film along the cantilever length, as shown in Figure 6.6.

![Fibre distribution within PZT thick film](image)

Fig. 6.6 Fibre distribution within PZT thick film
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A suitable mask enabled a 5.0 x 3.5 x 0.52 mm film of each composition to be deposited directly, near the root, onto rigidly-clamped stainless steel cantilever substrates, as shown in Figure 6.7.

![Diagram of cantilever construction](image)

**Fig. 6.7** Cantilever construction showing the PZT thick film deposited near the root, and, the mirror for optical reflection.

The percentage composition by volume of the carbon fibre and glass fibre in the films is shown in Table 6.4, where $V_G$, $V_C$ and $V_P$ are the percentage volume fractions of glass, carbon and PZT/epoxy compositions respectively in the thick film.

<table>
<thead>
<tr>
<th>Thick Film</th>
<th>$V_T$</th>
<th>$V_G$</th>
<th>$V_C$</th>
<th>$V_P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT/carbon/glass</td>
<td>100</td>
<td>3.73</td>
<td>11.0</td>
<td>85.3</td>
</tr>
<tr>
<td>PZT/glass</td>
<td>100</td>
<td>4.2</td>
<td>0</td>
<td>95.8</td>
</tr>
<tr>
<td>PZT</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 6.4** Volume composition of fibres in the PZT thick films

The samples were cured and poled in the same way as for glass fibre reinforced PZT thick films. The actuation capabilities of the thick films were then characterised using the OBD technique.
6.2.3.2 Experimental Results

The experimental arrangement and methodology used in this work is identical to that shown in Figure 6.2. A constant drive voltage of 7 V (r.m.s.) was applied to each cantilever and the excitation frequency varied from 500 to 1400 Hz. For each frequency of interest, the output voltage readings were measured using a DSP lock-in amplifier (EG&G 7260) and the end deflection determined. The fundamental frequencies of vibration of the cantilevers were 925, 906 and 820 Hz for the PZT/carbon/glass, PZT/glass, and PZT alone thick films respectively. The results are shown in Figure 6.8.

![Graph showing frequency response curves for different piezoelectric-epoxy film compositions: PZT/carbon/glass fibre, PZT/glass fibre and PZT alone.]

**Fig. 6.8** Frequency response curves for different piezoelectric-epoxy film compositions: PZT/carbon/glass fibre, PZT/glass fibre and PZT alone.
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The cantilever with the PZT film alone produced the highest resonant peak (end-deflection) - on and off-resonance, slightly higher than the cantilever with the PZT/carbon/glass fibre-reinforced PZT film. The resonant frequencies of the cantilevers with fibre-reinforced films are higher than that without any fibre-reinforcement.

6.2.3.3 Discussion and Conclusions

The cantilever comprising PZT film alone is seen to exhibit higher end-deflections than other thick films, which have fibre reinforcements. This is because the film without fibre reinforcements has a higher $d_{31}$ coefficient than the others, as seen in Table 6.5.

<table>
<thead>
<tr>
<th>Thick film</th>
<th>Resonant Frequency (Hz)</th>
<th>Young's Modulus (GPa)</th>
<th>$d_{31}$ (pm/V)</th>
<th>Quality factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT/carbon/glass</td>
<td>925</td>
<td>24</td>
<td>0.102</td>
<td>85</td>
</tr>
<tr>
<td>PZT/glass</td>
<td>906</td>
<td>6.4</td>
<td>0.096</td>
<td>78</td>
</tr>
<tr>
<td>PZT</td>
<td>820</td>
<td>4.2</td>
<td>0.900</td>
<td>62</td>
</tr>
</tbody>
</table>

Table 6.5 PZT thick film transient and mechanical characteristics

However, the fibre-reinforced films exhibit higher mechanical quality factors (Q) because they have higher Young's modulus. The PZT/carbon/glass thick film was most stable, being least susceptible to mechanical drift. The PZT alone film was least stable, suffering heavily from drift. The proposed dual-actuator has a requirement for both on
and off-resonance operation, for active vibration control of the smart arm and head micro positioning. The fibre-reinforced thick films have demonstrated increased stability and sensitivity during operation. And this desirable feature is enhanced when glass and carbon fibres are combined in the PZT thick film to produce a stiff and stable film, exhibiting properties, which are needed for the desired dual-actuator to be used in advanced hard disk drives.

5.3 Composite Piezoelectric Arms

The novel suspension arm being investigated in this thesis is required to be lightweight, but stiff. One route investigated in an attempt to realise these mechanical qualities was to fabricate the whole load suspension arm from carbon and glass fibre, with PZT material impregnated within the fibre matrix, ensuring uniform PZT distributed within the composite framework to make it active for actuation purposes. Such a structure being used, instead of stainless steel load beam, would enable faster disk access times resulting from the reduced moment of inertia. The composite arm would control the head flying height and the current aluminium base frame would have a piezoelectric-stack embedded within its frame to produce high-bandwidth motion for data tracking in the other orthogonal of motion. This mechanism would realise dual-stage actuation of the suspension arm, meeting the requirements as outlined in Chapter One of this thesis.

6.3.1 Sample Fabrication

The methods used to fabricate both the carbon and glass fibre composite arms are the same. About 0.5 ml of HY1300 hardener and 1.5 ml of CY1300 resin were mixed thoroughly together in an ultrasonic bath for about 5 minutes. A volume fraction of
PZT-5H powder of about 60% was then added to it and mixed thoroughly together in the ultrasonic bath for a further 5 minutes. The resulting epoxy mixture was then put in a vacuum oven for about 10 minutes to remove any air bubbles, and then carefully coated onto both sides of a piece of 5 x 5 mm 5h-satin glass fibre weave. The fibre now forms the substrate with PZT epoxy coating on either side of it. The specimen was then wrapped into a heat resistant non-stick film and rigidly clapped between two clean hot plates. The specimen was then cured at 100°C for about 4 hours. The resulting substrate was left to cool for about an hour, and miniature mechanical structures were cut from it. The approximate dimensions of the structures were about 40 x 5 x 2 mm. These structures (both carbon and glass) were then coated with silver conducting paint to form electrodes and about a third of each specimen glued rigidly onto plates as shown in the Figures 6.9 and 6.10.

**Fig. 6.9** Picture of PZT glass composite fibre arm
The PZT glass composite fibre was then poled at about 5 kV/cm (just below its electrical breakdown voltage) for about 50 minutes. The PZT carbon composite fibre was poled at a much lower voltage for the same amount of time (about 5 V) because at any higher voltages, the carbon simply forms a conducting path within the specimen and internal voltage breakdown occurs.

6.3.2 Experimental Results

The experimental arrangement and methodology used in this work is identical to that shown in Figure 6.2, based on the OBD technique. However, none of the fibre composite arms exhibited any actuation activity when an electric field was applied across its electrodes, at varying magnitudes of voltage and frequency.
6.3.3 Discussion and Conclusions

The composite arms were scanned using electron micrograph technique to see the PZT grain distribution and connectivity within their structure matrix. The results of the scans are shown below.

![Cross-section electron micrograph scan of PZT glass fibre composite arm](image)

**Fig. 6.11** Cross-section electron micrograph scan of PZT glass fibre composite arm
It can be seen that the PZT grains within the glass and carbon composite fibre are not adequately connected throughout the structure. The PZT grains within the 3-dimensional composite fibre structure of both the glass and carbon fibre does not satisfy the required connectivity, i.e. physical contact in 3-dimensional between active grains. The poling of the film (to make it active) is thus hindered because of the dielectric mismatch between the epoxy resin and the piezoelectric grains. However, better techniques of fabrication may be needed to ensure that this 3-dimensional PZT connectivity is achieved, but the costs, complexity and time associated with such improved methods may not be commercially viable.
In addition, the current composite fibre arrangement does not make it possible to enable the bending of the structure, as it does not have a substrate to actuate. To realise some appreciable level of actuation activity, it is suggested that two such composite structures are connected in a bimorph arrangement (parallel or series connection) such that compression in the dimensions of one of the composite structure results in an expansion of the dimensions of the other composite structure. However, the actuation capabilities of the resulting bimorph structures is still expected to be low because of the inadequate PZT grain connectivity within the composite fibre structure. The carbon fibre composite structure is definitely not feasible in any form of arrangement because of its electrical conducting properties, which hinders the poling process.

Current hard disk drive technology uses a sprung stainless steel cantilever, to which the head and gimbal assembly is attached at the end. As stated in Chapter Two of this thesis, a voice coil motor is used to position the head in the x-y plane for track selection, whereas the flying height (z-axis) is determined from the compliance of the arm, aerodynamic characteristics of the air-bearing slider and the speed of rotation of the disk.

The conclusion of the work in this section is that the fabrication of such a composite arm is time consuming and requires several stages of intricate work, and hence may not be attractive for commercial adoption in current disk drive mass-producing factories.
6.4 Embedded Piezoelectric Arms

The use of PZT thick films and PZT fibre composite suspension arms does not provide adequate actuation to meet the requirements of a high-bandwidth suspension arm. One alternative to the techniques described so far is to consider the use of bulk PZT stack (or multi-layer) actuators. These have the advantage that they can induce much larger motion in a structure compared to the methods used in the previous sections. Through careful design and with the use of multi-layer bulk PZT actuators, the suspension arm is able to realise motion in two orthogonal axes. One corresponds to motion required to provide fine data tracking and the other, precision flying height control. In current commercial HDDs, the net loading force is approximately 35mN during normal operation [10]. An adjustment of ±10mN of this loading force would result in a change in the flying height of about ±20%, giving sufficient tolerance for active flying height control.

6.4.1 Suspension Arm Design

The simplest method to realise such an arm is to embed piezoelectric stacks into the head suspension system. While retaining the current stainless steel load beam suspension, the piezo-stacks are embedded at the end of the aluminium frame arm. One PZT actuator stack is embedded such that when actuated, it produces an x-y plane motion of the arm (for fine data tracking). The other stack is embedded such that it produces a z-axis motion of the load beam suspension (for flying height adjustments). Since both piezoelectric stacks are embedded at the end of the aluminium frame (and this is near the root of the load beam suspension arm), resonance effects within the
aluminium arm do not affect the performance of the piezoelectric stacks. In addition, the location of the piezoelectric stacks ensures that increased servo bandwidth can be realised.

A prototype of the suspension arm described above has been built as shown in Figure 6.13. It comprises a duralumin frame (aluminium and copper alloy) within which piezoelectric actuator stacks (type 711/2/05051, Morgan-Matroc, UK) are embedded. One actuator maintains the desired flying height of the head above a rotating disk whereas the other ensures high-bandwidth precision and accurate track following. The prototype suspension arm incorporates a stainless steel loading beam (glued rigidly to the duralumin frame) – similar to that in current commercial hard disk drives – but instead of the slider-head arrangement attached at its end, it has a small mirror attached to facilitate the characterisation of the arm when using the optical beam deflection technique.

The detailed design diagram of the suspension arm is shown in Appendix F. The design of the arm is aimed for easy integration into current commercial HDD technology. The actuator stack to control data tracking is positioned to give the tracking motion high-bandwidth. The stack controlling the flying height is positioned nearer the root of the stainless steel load arm to maximise the bending moment of the arm, while giving precision flying height motion. The design idea of the suspension arm (for the tracking stage) is adopted from that proposed by Gou et al. [119]. In this arrangement, a series of pre-loaded piezoelectric stack elements are mounted in a cross-shaped rotational spring frame at the top-end of the suspension arm. Using finite element analysis, they demonstrated the resonant frequency of the suspension arm to
be around 10.9 kHz. The design used in this work has two adjacent slots holding pre-loaded piezoelectric stack elements, as shown in Appendix F. The slot for the piezoelectric stack responsible for data tracking is constructed such that maximum end-deflection of the suspension arm is achieved while still providing high-bandwidth rapid motion. The slot for the piezoelectric stack responsible for flying height control is designed such that maximum force is realised to enable precision rapid movement of the head during active flying height control. The bandwidth of the flying height control plane is limited by the dynamics of the stainless load beam.

Fig. 6.13 Prototype suspension arm incorporating multi-layer bulk PZT actuators
6.4.2 Suspension Arm Characterisation

The suspension arm is tested dynamically by investigating the amount of end-deflection possible at voltages comparable to those used in a hard disk drive environment. Also, resonance modes of the arm are investigated in order to help develop a suitable closed-loop servo controller.

The arm is set into resonance by applying bursts of band-limited white noise to the piezoelectric stack and the resonant modes sensed optically. It is important to remember that due to the complex nature of the arm, resonance effects in one plane of motion does induce resonance effects in other plane of motion (used for track following). The results are shown in Figures 2 and 3. It can be seen that the lowest resonant frequency of the tracking stage occurs at 1.7 kHz though because of its complex mechanical structure, there are other resonance peaks at higher frequencies. A similar comment applies to the height control stage though as expected with the more compliant structure in this axis, the fundamental resonance peak is lower at 140 Hz.
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Active Suspension Arm Design

Fig. 6.14 Frequency response of suspension arm (data tracking motion)

Fig. 6.15 Frequency response of suspension arm (flying height control motion)
6.5 Summary

This Chapter has investigated the fabrication of a stiff, lightweight active composite 'smart' arm, fabricated from glass or carbon fibre-reinforced composites, which would be used in a dual-actuation mechanism in advanced computer hard disk drives. The first investigation was the use of PZT thick films deposited on the stainless steel load beam (to provide precision flying height control), while retaining the aluminium frame (which may have an embedded PZT stack actuator) to give high-bandwidth data tracking motion. It was found that such films gave much better actuation when reinforced with glass and/or carbon fibre uniformly dispersed within its 3-dimensional matrix. The reinforced films are much stiffer and hence produce stable actuation (due to improved mechanical quality factors). However, the levels of actuation (a few nanometers off-resonance and a few hundred nanometers on-resonance) are not adequate to meet the specification of the intended suspension arm, and the manufacturing process is rather slow and may prove commercially unattractive. One suggestion to improve the actuation capabilities of these thick films is to use active PZT fibre reinforcements, instead of glass or carbon fibre. This type of fibre reinforcement would form 'an actively reinforced thick film', which should offer improved activity and improved rigidity. This may form future work in applications such as structural health monitoring where sensing levels in the nanometer region are more than adequate.

The second investigation was the use of composite PZT arms, where the whole load suspension arm is made from carbon and/or glass fibre, with PZT material impregnated within the fibre matrix ensuring uniform PZT distributed within the
composite framework to make it active for actuation purposes. Such a structure being used, instead of stainless steel load beam, would enable faster disk access times resulting from the reduced moment of inertia. The composite arm would control the head flying height and the current aluminium base frame would have a piezoelectric-stack embedded within its frame to produce high-bandwidth motion for data tracking in the other orthogonal of motion. This mechanism would realise dual-stage actuation of the suspension arm, meeting the requirements as outlined in Chapter One of this thesis. These arms have been fabricated and tested for actuation capabilities, but none have been found. This is partly because of the inadequate distribution of the PZT grains within the composite arm. To improve actuation properties of the composites, a bimorph arrangement is suggested. In this configuration, the compression in the dimensions of one arm would result in the expansion of the dimensions of the other composite arm. Even so, actuation capabilities of such an arrangement are expected to be low, due to the poor distribution of the PZT grains within the composite arm. Much improved fabrication techniques may address this problem, but at much higher costs and time. The integration of these arms into commercial HDDs may also not be commercially feasible in the near future.

The third investigation was the use of embedded PZT stacks, where a duralumin frame has PZT stacks embedded within its framework to realise dual-actuation of the arm. Such an arrangement produces much-improved actuation in both planes of motion, as well as much higher resonant frequencies. This arrangement seems the way forward for the development of suspension arm in the next generation HDDs. The design of the arm is aimed for easy integration into current commercial HDD technology. The actuator stack to control data tracking is positioned to give the tracking motion high-
bandwidth. The stack controlling the flying height is positioned nearer the root of the stainless steel load beam to maximise the bending moment of the arm, while giving precision flying height motion. The slot for the piezoelectric stack responsible for data tracking is constructed such that maximum end-deflection of the suspension arm is achieved while still providing high-bandwidth rapid motion. The slot for the piezoelectric stack responsible for flying height control is designed such that maximum force is realised to enable precision rapid movement of the head during active flying height control.
Chapter 7

Suspension Arm Controller Design

7.1 Introduction

The design and development of a sufficiently fast, stable and robust closed-loop servo control mechanism in hard disk drives (HDDs) is essential in ensuring an improvement in the overall performance and reliability of HDDs in the development of next generation hard disk drives with very high data storage densities. That is the reason why the successful design and implementation of servo controllers capable of this task has received a lot of attention in recent years. As early as 1988, Hanselmann et al. [105] developed a fast fine-positioning controller for a rotary actuator type magnetic storage disk drive using the linear quadratic gaussian (LQG) methodology, implemented on a digital signal processor. This technique solved some of the problems associated with structural resonances of the actuator. Since then, other methods have been investigated and some of them implemented successfully. Some of the common control methods that have been used to control HDDs in recent years have included proportional, integral and derivative controller (PID) [20] and optimal control methods such as $H_2/H_\infty$ [106], $H_\infty$ [107], linear quadratic gaussian (LQG) [108] and LQG/LTR (LTR stands for loop transfer recovery) [109]. Others include mode switching control (MSC) [110], adaptive control [111] and fuzzy logic [112].
In Chapter Six of this thesis, a prototype active suspension arm for use in advanced HDDs capable of 2-dimensional motion, one dimension used for high-bandwidth data tracking and the other for precision flying height control, has been developed and characterised. The suspension arm has two embedded piezoelectric stacks to actuate it, each enabling motion in orthogonal axes to the other, when an electric field is applied across them. The suspension arm has been thoroughly tested and fully characterised to understand its static and dynamic characteristics. In this Chapter, these characteristics are utilised to develop an advanced closed-loop servo algorithm for positioning the suspension arm in 2-dimensions. Because the two orthogonal axes of motion of the suspension arm have different dynamic characteristics, the closed-loop servomechanism for each axis is developed independently of the other. This is particularly important, as both motions of the arm may occur simultaneously and may thus need to be controlled at the same time. This may happen because the suspension arm is a complex structure, and motion in one axis may induce unwanted resonances in the other. These resonances must be suppressed effectively and quickly to avoid any track misregistration (TMR) that may limit the overall performance of the servo controller.

The controllers developed in this project are based on proportional, integral and derivative (PID) controllers. PID is a commonly used technique in classical control. It is simple to design, and analogue implementation is quick. It is also well established [20]. In designing controllers, simply minimising a term proportional to the error is usually not sufficient. This is why the integral and differential of the error term are included to form what is usually known as the ‘three-term controller’. The integral of the error term reduces the steady-state error to zero because it represents the accumulated error. The differential of
the error term is included to improve stability and plant dynamics further. This term represents the error rate [113].

7.2 Suspension Arm Dynamic Characteristics

In order to develop compensation algorithms to provide precision micro-positioning signals to the suspension arm, it is important to know the transfer functions that govern the arm. These are derived from the transient dynamic characteristics of the arm, which can be observed when the suspension arm is subjected to a very low-frequency square wave. The transfer functions of the data-tracking stage and the flying height control stage are different from each other and will be derived separately. In addition, it is important to investigate and understand the suspension arm resonance modes in order to know which ones need suppressing by the controller.

7.2.1 Dynamic Response Analysis: Data Tracking Stage

A square wave of peak-to-peak amplitude of 5 V and frequency of 0.2 Hz is applied to the tracking stage of the suspension arm and the resulting waveform observed on a Tektronix TDS 220 digital oscilloscope as shown below. From Figure 7.1, we can measure the average time constant $\tau = 20\text{ms}$ (time taken for the waveform to decay to $\frac{1}{e}$th of its initial amplitude value). In addition, the settling time $T_s = 60\text{ms}$ (time taken for the waveform to decay to $\pm 5\%$ its final value — this is called the 5 % criterion, as opposed to the 2 % criterion), the resonant frequency $F_r (1.72\text{kHz})$ and the time to the first peak $T_p = 291\ \mu\text{s}$. The damped angular frequency of oscillation $\omega_d(\text{rad/s})$ is given by [113]
Chapter 7

Suspension Arm Controller Design

\[
\omega_d = \frac{\pi}{T_p} = \omega_n \cdot \sqrt{1 - \zeta^2} \approx 10807 \text{ rad}\cdot\text{s}^{-1} \tag{7.1}
\]

\[
\omega_n \cdot \zeta = \frac{1}{\tau} = \frac{1}{20\text{ms}} = 50 \text{ s}^{-1} \tag{7.2}
\]

Where \( \omega_n \) is the natural angular frequency of the arm (\text{rad}\cdot\text{s}^{-1}) and \( \zeta \) is the damping factor.

![Waveform showing transient decay characteristics of suspension arm.](image)

Solving the simultaneous equations (7.1) and (7.2), we get the values of \( \omega_n \) and \( \zeta \) as shown below:

\[
\omega_n \approx 10807 \text{ rad}\cdot\text{s}^{-1} \quad \text{and} \quad \zeta \approx 4.63 \times 10^{-3}
\]

The very low value of \( \zeta \) shows that this system is very under-damped. The transfer function, \( G_T(s) \), of the data tracking stage of the suspension arm is assumed to be a second order system. The normalised transfer function of a second order system is given as [113]:

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Replacing values of $\omega_n$ and $\zeta$ into equation (7.3):

$$G_T(s) = \frac{116.77 \cdot 10^6}{s^2 + 100s + 116.77 \cdot 10^6}$$ (7.4)

The complete transfer function of the plant $G_{PT}(s)$ must be developed. This incorporates not only the transfer function of the data tracking stage of the suspension arm but also includes the gain of the optical beam deflection sensor (OBD). The schematic of the complete plant is shown in Figure 7.2 below.

**Fig. 7.2** Schematic diagram of plant incorporating suspension arm transfer function and OBD sensor gain.
To determine the value of the OBD sensor gain $k_r$, a range of peak-to-peak quasi-static voltages at a constant frequency of 300Hz is applied to the data tracking stage of the suspension arm. The resulting displacement of the suspension arm due to each applied voltage is directly proportional to the output voltage obtained using the OBD technique and measured on the digital oscilloscope.

![Graph of applied voltage against output voltage](image)

**Fig 7.3** Graph of applied voltage against output voltage to determine the value of the OBD sensor gain.

**Note:** In this Chapter, all references to settling time are based on the 5% criterion.

The average value of $k_r$ is obtained by finding the average value of the ratio of the output voltage to the applied drive voltage shown in Figure 7.3. Hence, $k_r$ is calculated to be:

$$k_r = 0.3324 \pm 17\%$$
We note here the hysteresis effect of the piezo-stack actuator shown by the difference in the displacement paths taken when increasing the applied voltage from 0 to 70 V (line with square points) to that taken when decreasing the applied voltage from 70 to 0 V (line with diamond point).

The complete transfer function of the plant \( G_{PT}(s) \) is hence given as:

\[
G_{PT}(s) = \frac{116.77 \times 10^6 \cdot k_T}{s^2 + 100s + 116.77 \times 10^6} 
\]

(7.4)

\[
G_{PT}(s) = \frac{116.77 \times 10^6 \cdot 0.3324}{s^2 + 100s + 116.77 \times 10^6} 
\]

(7.5)

### 7.2.2 Dynamic Response Analysis: Flying Height Control Stage

A square wave of peak-to-peak amplitude of 5 V and frequency of 0.2 Hz is applied to the flying height control stage of the suspension arm and the resulting waveform observed on a Tektronix TDS 220 digital oscilloscope as shown in Figure 7.4. From Figure 7.4, we can deduce or calculate the average time constant \( \tau = 1.113 \) s, the settling time \( T_s = 5 \) s, the resonant frequency \( F_r \) (140 Hz) and the time to the first peak \( T_p = 3.571 \) ms.

The damped angular frequency of oscillation \( \omega_d \) (rad/s) is given by [113]

\[
\omega_d = \frac{\pi}{T_p} = \omega_n \cdot \sqrt{1 - \zeta^2} \approx 879.7 \text{ rad}\cdot\text{s}^{-1} 
\]

(7.6)
\[
\omega_n \cdot \zeta = \frac{1}{\tau} = \frac{1}{1.113s} = 0.8982 \text{ s}^{-1}
\]  

(7.7)

Where \( \omega_n \) is the natural angular frequency of the arm (rad·s\(^{-1}\)) and \( \zeta \) is the damping factor.

Solving the simultaneous equation (7.6) and (7.7) we get the values of \( \omega_n \) and \( \zeta \) as shown below:

\[\omega_n \approx 879.6 \text{ rad·s}^{-1} \quad \text{and} \quad \zeta \approx 1.02 \times 10^{-3}\]

Fig. 7.4 Waveform showing transient decay characteristics of suspension arm.

The low value of \( \zeta \) shows that this system is very under-damped. The normalised transfer function, \( G_{FH}(s) \), of the flying height control stage of the suspension arm is also approximated to be a second order system (as shown in equation 7.3) and is given as:
The complete transfer function of the plant $G_{PFH}(s)$ must be developed. This incorporates the transfer function of the flying height control stage of the suspension arm and the gain of the OBD sensor. The schematic of the complete plant is shown in Figure 7.5 below.

\[ G_{FH}(s) = \frac{0.774 \cdot 10^6}{s^2 + 1.7964s + 0.774 \cdot 10^6} \quad (7.8) \]

Fig. 7.5 Schematic diagram of plant incorporating suspension arm transfer function and OBD sensor.

To determine the value of the OBD sensor gain $k_{FH}$, a range of peak-to-peak quasi-static voltages at a constant frequency of 300 Hz is applied to the flying height control stage of the suspension arm. The resulting displacement of the suspension arm, due to each applied voltage, is directly proportional to the output voltage obtained using the OBD technique and measured on the digital oscilloscope.

The average value of $k_{FH}$ is obtained by finding the average value of the ratio of the output voltage to the applied drive voltage shown in Figure 7.6. Hence, $k_{FH}$ is calculated to be:
Chapter 7  Suspension Arm Controller Design

\[ k_{FH} = 0.4265 \pm 10\% \]

The hysteresis effect of the piezo-stack actuator can also be seen in Figure 7.6. This is can be observed by the difference in the displacement paths taken when increasing the applied voltage from 0 to 60 V (line with square points) to that taken when decreasing the applied voltage from 60 to 0 V (line with diamond point).

![Graph](image)

**Fig 7.6** Graph of applied voltage against output voltage to determine the value of the OBD sensor gain.

The complete transfer function of the plant \( G_{PFH}(s) \) is hence given as:

\[
G_{PFH}(s) = \frac{0.774 \cdot 10^6 \cdot 0.4265}{s^2 + 1.7964s + 0.774 \cdot 10^6}
\] (7.9)
7.3 PID Controller Analytical Design

To design the PID controllers in this work, frequency-response methods have been used. Other methods that can be used include the Ziegler-Nichols method [114] and several other self-tuning techniques [115]. The frequency-response method is based on the Nyquist criterion and is useful in giving information such as steady-state response (low-frequency response), stability margins and system bandwidth. A basic example of a closed-loop control system is shown in Figure 7.7. It is assumed that the system in the figure has been converted to the equivalent unity feedback model, with the system characteristic equation [113]:

\[ 1 + G_C(s)G_P(s) = 0 \]  

(7.10)

![Fig. 7.7 Basic diagram showing closed-loop control system](image)

The transfer functions of the plant \( G_P(s) \) have already been developed in this Chapter for data tracking and flying height control stages. We now wish to design the compensator...
transfer functions $G_c(s)$ such that the closed-loop transfer function exhibits good transient response characteristics and steady state accuracy. Other desirable features of the closed-loop system are high and practical system bandwidth, relative stability and a good degree of disturbance rejection [113]. In analysis and design, we are always ultimately concerned with the closed-loop transfer function. However, some of the analysis and design procedure in this work requires that we work with the open-loop function.

The compensator $G_c(s)$ in Figure 7.7 is the PID controller. This controller is second order, with a phase-lag controller followed by a phase-lead controller. The lag-lead controller offers much more flexibility than does either the phase-lag or the phase-lead controller separately [113]. The equation for the controller is given by:

$$m(t) = K_p \cdot e(t) + K_I \cdot \int_0^t e(t) \cdot dt + K_D \cdot \frac{de(t)}{dt}$$  \hspace{1cm} (7.11)

The transfer function is given by:

$$G_c(s) = K_p + \frac{K_I}{s} + K_D \cdot s$$  \hspace{1cm} (7.12)

Three parameters of the controller are to be determined by the design process: the proportional gain $K_p$, the integral gain $K_I$, and the derivative gain $K_D$. A block diagram of a PID controller is shown in Figure 7.8.
The integral term in the PID controller is phase-lag, contributing a low-frequency effect. The derivative term on other hand contributes a high-frequency effect, it being phase-lead.

\[ \phi_m = 180^\circ + \gamma \]  \hspace{1cm} (7.13)
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The gain margin $G_m$ of a system is the reciprocal of the magnitude $|G(j\omega)|$ at the frequency at which the phase angle is $-180^\circ$. Defining the phase crossover frequency $\omega_{cg}$ to be the frequency at which the phase angle of the open-loop transfer function equals $-180^\circ$ gives the gain margin $G_m$ as [114]:

$$G_m = \frac{1}{|G(j\omega_{cg})|} \quad (7.14)$$

An analytical method to determine the PID controller parameters based on the frequency-response method is given in [113]. We assume that the controller has a transfer function $G_c(s)$ as in equation (7.12) and that of the plant is $G_p(s)$. A phase margin to be achieved, $\phi_m$, is specified and the frequency $\omega_1$ at which this occurs is calculated from a specified settling time $T_s$. For this to happen, it is assumed that the compensated Nyquist diagram is to pass through the point $\alpha$, for the frequency $\omega_1$, were $\alpha = 1 \angle(-180^0 + \phi_m)$.

$$G_c(j\omega_1) \cdot G_p(j\omega_1) \cdot H(j\omega_1) = 1 \angle(-180^0 + \phi_m) \quad (7.15)$$

If the angle of $G_c(j\omega_1)$ is denoted by $\theta$, then from (7.15),

$$\theta = \arg G_c(j\omega_1) = -180^0 + \phi_m - \arg G_p(j\omega_1) \cdot H(j\omega_1) \quad (7.16)$$

From (7.15) and (7.16),
\[ K_p + j \left( K_d \cdot \omega_i - \frac{K_i}{\omega_i} \right) = |G_c(j\omega_i)| \cdot (\cos \theta + j \sin \theta) \]  \hspace{1cm} (7.17)

Where, from (7.15),

\[ |G_c(j\omega_i)| = \frac{1}{|G_p(j\omega_i) \cdot H(j\omega_i)|} \]  \hspace{1cm} (7.17)

The frequency \( \omega_1 \) at which the phase margin occurs is calculated from a specified settling time \( T_s \) as shown below [113]:

\[ \omega_1 = \frac{8}{T_s \cdot \tan \phi_m} \]  \hspace{1cm} (7.19)

The gain \( K_i \) may be chosen to satisfy low-frequency specifications, since at low frequencies, the PID compensator is dominated by the integral term. Equating real part to real part in equation (7.17) gives:

\[ K_p = \frac{\cos \theta}{|G_p(j\omega_1) \cdot H(j\omega_1)|} \]  \hspace{1cm} (7.20)

Then equating imaginary part to imaginary part gives:

\[ K_d \cdot \omega_1 - \frac{K_i}{\omega_1} = \frac{\sin \theta}{|G_p(j\omega_1) \cdot H(j\omega_1)|} \]  \hspace{1cm} (7.21)

With \( \omega_1 \), the gain \( K_p \) is calculated from (7.20). \( K_i \) is then determined from steady-state specifications and \( K_D \) can be calculated from (7.21). The phase angle of the compensator at \( \omega_1 \), \( \theta \), can be either positive or negative. The magnitude of the compensator transfer
function, \(|G_c(j\omega)|\), can be either greater than unity or less than unity. The only requirement on the choice of \(\omega_1\) is that the magnitude of \(\theta\) in (7.16) be less than 90\(^\circ\). The equation for \(K_D\) is thus given as [113]:

\[
K_D = \frac{\sin \theta}{\omega_1 \cdot |G_p(j\omega_1) \cdot H(j\omega_1)|}
\]

(7.22)

Matlab software routines (in Appendix C - all Matlab software routines referred to in this Chapter are found in this Appendix), based on the frequency-response method shown above, have been developed to calculate the PID parameter values \(K_p\) and \(K_D\) for a chosen value of \(K_i\). Note that \(K_i\) may be chosen to satisfy low-frequency specifications and for each value \(K_i\), we also calculate the phase (\(\phi_m\)) and gain (\(G_m\)) margins of the open-loop transfer function, the response of the system to a step input observing the percentage overshoot (\(M_p\)) and the settling time (\(T_s\)). The desired characteristics of the system response for both stages of motion are as follows: \(30^0 \leq \phi_m \leq 60^0\), \(G_m \geq 7\ dB\), \(M_p < 30\ %\). This would ensure system stability and a good transient response. The settling time of the data tracking stage is desired to be of the order of a few milliseconds and that of the flying height control stage, of about ten milliseconds.

### 7.3.1 Controller Design for Data Tracking Stage

The PID controller parameters for the data tracking stage are calculated following the steps outlined in section 7.3. A Matlab software routine, program1, has been developed for this task. To design the controller with characteristics similar to the ones listed in section 7.3, the table shown below is erected and the optimum value of \(K_i\) desirable for
PID controller design is investigated. The system is designed to achieve a phase margin $\phi_m$ of about 50$^\circ$ occurring at a frequency $\omega_1$ of 13.43 k rad\cdot s$^{-1}$.

<table>
<thead>
<tr>
<th>$K_i$</th>
<th>$K_p$</th>
<th>$K_D \times 10^5$</th>
<th>$M_p$ (%)</th>
<th>$T_S$ (ms)</th>
<th>$\phi_m$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1.5578</td>
<td>135</td>
<td>-46</td>
<td>40</td>
<td>51.3</td>
</tr>
<tr>
<td>1000</td>
<td>1.5578</td>
<td>138</td>
<td>-42</td>
<td>50</td>
<td>51.4</td>
</tr>
<tr>
<td>5000</td>
<td>1.5578</td>
<td>160</td>
<td>-31</td>
<td>3.5</td>
<td>52.0</td>
</tr>
<tr>
<td>10000</td>
<td>1.5578</td>
<td>188</td>
<td>-16</td>
<td>1.8</td>
<td>52.8</td>
</tr>
<tr>
<td>15000</td>
<td>1.5578</td>
<td>216</td>
<td>-1</td>
<td>1.7</td>
<td>53.7</td>
</tr>
<tr>
<td>20000</td>
<td>1.5578</td>
<td>243</td>
<td>11</td>
<td>1.7</td>
<td>54.6</td>
</tr>
<tr>
<td>25000</td>
<td>1.5578</td>
<td>272</td>
<td>22</td>
<td>1.6</td>
<td>55.9</td>
</tr>
<tr>
<td>30000</td>
<td>1.5578</td>
<td>299</td>
<td>32</td>
<td>1.9</td>
<td>56.9</td>
</tr>
<tr>
<td>35000</td>
<td>1.5578</td>
<td>327</td>
<td>39</td>
<td>2.5</td>
<td>58.3</td>
</tr>
</tbody>
</table>

Table 7.1 Design parameter investigation for PID controller design: Data tracking stage

Note: The system model is assumed second order, and therefore, cannot be unstable in theory, and hence the gain margin will always be infinity.

From the table, it appears that the optimum value of $K_i$ is 25000. For this value we obtain a quick settling time $T_S$ of 1.6 ms, a reasonable overshoot $M_p$ of about 22 % and the transient response to step input is good, settling quickly in a few cycles. $K_i$ is 20000 gives good values of $T_S$ (1.7 ms) and $M_p$ (11 %), but transient response is not as good. To obtain the percentage overshoot ($M_p$) and the settling time ($T_S$), the entire closed-loop
system is simulated in Matlab/Simulink and the block diagram for this arrangement is shown in Figure 7.9.

Fig. 7.9 Block diagram of closed-loop arrangement for the data tracking stage

The transient response of the system to a unit step input at $K_f$ is 25000 is shown in Figure 7.10.
We must now calculate the system bandwidth $B_T$ and investigate the stability of the closed-loop system further using the Nyquist stability criterion. To do this, we must calculate the transfer function $G_{CT}(s)$ of the PID controller for the data tracking stage, open-loop $OLTTF_T(s)$ and closed-loop $CLTF_T(s)$ transfer functions of the whole system and then analyse frequency-response plots (bode plots) of the closed-loop system. Using the PID optimum gain parameters as shown Table 7.1, the transfer function of the PID controller $G_{CT}(s)$ is hence given as:

$$G_{CT}(s) = \frac{272 \cdot 10^{-6}}{s} \left( s^2 + 5.727 \cdot 10^3 \cdot s + 9.191 \cdot 10^7 \right)$$  \hspace{1cm} (7.23)
The open-loop transfer function $\text{OLTFT}(s)$ of the system is calculated as:

$$\text{OLTFT}(s) = \frac{1}{s} \cdot \frac{(1.05575 \cdot 10^4 \cdot s^2 + 6.04650 \cdot 10^7 \cdot s + 9.70359 \cdot 10^{11})}{(s^3 + 10658 \cdot s^2 + 1.77235 \cdot 10^8 \cdot s + 9.70359 \cdot 10^{11})}$$

(7.24)

To show the location of the zeros and poles, the $\text{OLTFT}(s)$ is written as:

$$\text{OLTFT}(s) = \frac{1}{s} \cdot \frac{(s + 2864 - 9149j)(s + 2864 + 9149j)}{(s + 50 - 10806j)(s + 50 + 10806j)}$$

(7.25)

The closed-loop transfer function $\text{CLTF}(s)$ of the system is calculated as:

$$\text{CLTF}(s) = \frac{(1.05575 \cdot 10^4 \cdot s^2 + 6.04650 \cdot 10^7 \cdot s + 9.70359 \cdot 10^{11})}{(s^3 + 10658 \cdot s^2 + 1.77235 \cdot 10^8 \cdot s + 9.70359 \cdot 10^{11})}$$

(7.26)

To show the location of the zeros and poles, the $\text{CLTF}(s)$ is written as:

$$\text{CLTF}(s) = \frac{(s + 2864 - 9149j)(s + 2864 + 9149j)}{(s - 2097 + 12072j)(s - 2097 - 12072j)(s + 6464)}$$

(7.27)

Using the open-loop transfer function, a Matlab software routine (program3) has been developed to calculate the system phase margin ($\phi_m = 55.9^\circ$), gain margin ($G_m = \infty$), gain crossover frequency ($\omega_g = 14.52$ krad·s$^{-1}$) and phase crossover frequency ($\omega_{\phi} = \text{NaN}$) for $K_i = 25000$. 

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To calculate the closed-loop system bandwidth ($B_T$) for the data tracking stage, a Matlab software routine (program4) is developed to draw the plots as shown in Figure 7.11. The bandwidth ($B_T$) in this work is defined as the frequency (in Hz) at which the magnitude of the closed-loop transfer function falls by 3 dB. The angular frequency $\omega_T$ (in rad·s$^{-1}$) in Figure 7.11 is related to the system bandwidth by:

$$B_T = \frac{\omega_T}{2 \cdot \pi}$$

(7.28)

The point at which the $-3$ dB line crosses the curve of the magnitude of the closed-loop transfer function occurs at $\omega_T = 91.7$ krad·s$^{-1}$. This corresponds to a closed-loop system...
bandwidth \((B_r)\) of 14.6 kHz respectively. The plots can be explained with reference to the root-locus plot of the closed-loop transfer function as shown in Figure 7.12. The plot is enabled by a Matlab software routine, program5.

![Root-locus plot of system showing location of poles and zeros.](image)

**Fig. 7.12** Root-locus plot of system showing location of poles and zeros.

To investigate the stability of the control algorithm designed for the data tracking stage, we draw a Nyquist plot (refer to program6 of Matlab software code) and analyse its path. The plot is shown in Figure 7.13.
Figure 7.13 is plotted for the positive range of frequency $\omega$ (in rad-s$^{-1}$) of $0.1 \leq \omega \leq 10^3$. We note that the Nyquist path, while moving in the clockwise direction in the $s$ plane does not encircle the $-1 + j0$ point. This implies that the system is stable, as there are no poles of the open-loop transfer function of the system in the right-half $s$ plane [114].

### 7.3.2 Controller Design for Flying Height Control Stage

The controller design process is identical to that given in the previous section. A Matlab software routine, program7, has been developed to calculate the PID controller parameters. A table is erected as shown below to investigate which value of $K_i$ gives optimum parameters desirable for PID controller design for the flying height control stage.
The system is designed to achieve a phase margin $\phi_m$ of about $50^\circ$ occurring at a frequency $\omega_1$ of 1.342 krad·s$^{-1}$.

<table>
<thead>
<tr>
<th>$K_I$</th>
<th>$K_P$</th>
<th>$K_D$ ($\times 10^{-3}$)</th>
<th>$M_p$ (%)</th>
<th>$T_s$ (ms)</th>
<th>$\phi_m$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>2.2542</td>
<td>2.269</td>
<td>-16</td>
<td>30</td>
<td>50.0</td>
</tr>
<tr>
<td>1000</td>
<td>2.2542</td>
<td>2.546</td>
<td>-2</td>
<td>13</td>
<td>50.0</td>
</tr>
<tr>
<td>1200</td>
<td>2.2542</td>
<td>2.657</td>
<td>5</td>
<td>9.0</td>
<td>50.0</td>
</tr>
<tr>
<td>1400</td>
<td>2.2542</td>
<td>2.768</td>
<td>10</td>
<td>9.0</td>
<td>50.0</td>
</tr>
<tr>
<td>1500</td>
<td>2.2542</td>
<td>2.834</td>
<td>11</td>
<td>9.0</td>
<td>50.0</td>
</tr>
<tr>
<td>1600</td>
<td>2.2542</td>
<td>2.879</td>
<td>14</td>
<td>11</td>
<td>50.0</td>
</tr>
<tr>
<td>1800</td>
<td>2.2542</td>
<td>2.990</td>
<td>18</td>
<td>12</td>
<td>50.0</td>
</tr>
<tr>
<td>2000</td>
<td>2.2542</td>
<td>3.101</td>
<td>22</td>
<td>11</td>
<td>50.0</td>
</tr>
<tr>
<td>2500</td>
<td>2.2542</td>
<td>3.378</td>
<td>32</td>
<td>15</td>
<td>50.0</td>
</tr>
</tbody>
</table>

Table 7.2 Design parameter investigation for PID controller design: Flying height control

From the table, it appears that the optimum value of $K_I$ is 1800. For this value we obtain a quick settling time $T_s$ of 12 ms, a good overshoot $M_p$ of about 18 % and the transient response to step input is good, settling quickly in two cycles. At $K_I = 1500$ and $K_I = 1600$, we obtain quicker settling times and smaller overshoots. However, the transient response is not as good. To obtain the percentage overshoot ($M_p$) and the settling time ($T_s$), the entire closed-loop system is simulated in Matlab/Simulink and the block diagram for this arrangement is shown in Figure 7.14. Also note that for all values if $K_I$ in the table, the phase and gain margins are within the design specifications.
Fig. 7.14 Block diagram of closed-loop arrangement for the flying height control stage

The transient response of the system to a unit step input at $K_I$ is 1800 is shown in Figure 7.15.

Fig. 7.15 Transient response of closed-loop system to unit step input
We must now calculate the closed-loop system bandwidth $B_{FH}$ of the flying height control stage and investigate further the system stability using the Nyquist stability criterion. To do this, we must again calculate the transfer function $G_{CFH}(s)$ of the PID controller for the flying height control stage, open-loop $OLT_{FH}(s)$ and closed-loop $CL_{FH}(s)$ transfer functions of the whole system and then finally analyse frequency-response plots (bode plots) of the closed-loop system. Using the PID optimum gain parameters as shown Table 7.2, the transfer function of the PID controller $G_{CFH}(s)$ is given as:

$$G_{CFH}(s) = \frac{299 \cdot 10^{-3}}{s} \cdot \left( s^2 + 754 \cdot s + 6.02 \cdot 10^3 \right)$$  \hspace{1cm} (7.29)

The open-loop transfer function $OLT_{FH}(s)$ of the system is calculated as:

$$OLT_{FH} = \frac{1}{s} \cdot \frac{(769.26 \cdot s^2 + 5.79955 \cdot 10^5 \cdot s + 4.6310 \cdot 10^8)}{(s^2 + 1.7964 \cdot 10^3 \cdot s + 0.774 \cdot 10^6)}$$  \hspace{1cm} (7.30)

To show the location of the zeros and poles, the $OLT_{FH}(s)$ is written as:

$$OLT_{FH} = \frac{1}{s} \cdot \frac{(s + 377 - 678j)(s + 377 + 678j)}{(s + 0.90 - 880j)(s + 0.90 + 880j)}$$  \hspace{1cm} (7.31)

The closed-loop transfer function $CL_{FH}(s)$ of the system is calculated as:

$$CL_{FH} = \frac{(770 \cdot s^2 + 5.79955 \cdot 10^5 \cdot s + 4.63100 \cdot 10^8)}{(s^3 + 771 \cdot s^2 + 1.35396 \cdot 10^6 \cdot s + 4.63100 \cdot 10^8)}$$  \hspace{1cm} (7.32)
To show the location of the zeros and poles, the $CLTF_{FH}(s)$ is written as:

$$CLTF_r = \frac{(s + 377 - 678j)(s + 377 + 678j)}{(s + 193 + 1081j)(s + 193 - 1081j)(s + 384)} \tag{7.33}$$

Using the open-loop transfer function, a Matlab software routine (program7) has been developed to calculate the system phase margin ($\phi_m = 50^\circ$), gain margin ($G_m = \infty$), gain crossover frequency ($\omega_{cp} = 1.343$ krad·s$^{-1}$) and phase crossover frequency ($\omega_{cp} = \text{NaN}$) for $K_f = 1800$.

Fig. 7.16 Bode plot of closed-loop transfer function for flying height control stage
To calculate the closed-loop system bandwidth ($B_{FH}$) for the flying height control stage, another software routine (program8) has been developed, resulting in the plots as shown in Figure 7.16.

The point at which the -3 dB line crosses the curve of the magnitude of the closed-loop transfer function occurs at $\omega_{FH} = 30.2$ krad-s$^{-1}$. This corresponds to a closed-loop system bandwidth ($B_{FH}$) of 4.81 kHz respectively. The plots can be explained with reference to the root-locus plot of the closed-loop transfer function as shown in Figure 7.17. The plot is enabled by a Matlab software routine, program8.

Fig. 7.17 Root-locus plot of system showing location of poles and zeros
To investigate the stability of the control algorithm designed for the flying height stage, we draw a Nyquist plot (refer to program9 of Matlab software code) and analyse its path. The plot is shown in Figure 7.18.

![Fig. 7.18 Nyquist plot of open-loop transfer function of flying height control stage](image)

The Figure 7.18 is plotted for the positive range of frequency $\omega$ (in rad-s$^{-1}$) of $0.1 \leq \omega \leq 10^3$. We note that the Nyquist path, while moving in the clockwise direction in the $s$ plane does not encircle of the $-1 + j0$ point. This implies that the system is stable, as there are no poles of the open-loop transfer function of the system in the right-half $s$ plane.
7.4 Practical Implementation of PID Controllers

The practical implementation of the PID controllers for both stages of motion is implemented according to the circuit shown below:

Fig. 7.19 Circuit used to implement PID-controllers for both planes of motion [113]

The circuit shown above has been used to implements the practical PID compensators for both the flying height control stages and data tracking stages. The circuit introduces an additional pole to the PID compensator, in order to limit the high-frequency gain. The PID compensator has the transfer function as shown below [113]:

\[
\frac{V_o(s)}{V_i(s)} = \left( K_p + \frac{K_i}{s} + K_d s \right) \frac{1}{(rs + 1)}
\]  

(7.34)

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Where:

\[ K_p = \frac{C_f \cdot R_f + C_1 \cdot R_1}{C_f \cdot (R_1 + R_2)} \]  
(7.35)

\[ K_i = \frac{1}{C_f \cdot (R_1 + R_2)} \]  
(7.36)

\[ K_d = \frac{C_1 \cdot R_1 \cdot R_f}{(R_1 + R_2)} \]  
(7.37)

\[ \tau = \frac{C_1 \cdot R_1 \cdot R_2}{(R_1 + R_2)} \]  
(7.38)

The PID compensator component values for the data tracking motion stage and flying height control stage are as shown in the table below:

<table>
<thead>
<tr>
<th>Component</th>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( R_3 )</th>
<th>( R_4 )</th>
<th>( R_f )</th>
<th>( C_1 )</th>
<th>( C_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Tracking</td>
<td>90 k( \Omega )</td>
<td>10 k( \Omega )</td>
<td>10 k( \Omega )</td>
<td>10 k( \Omega )</td>
<td>200 k( \Omega )</td>
<td>2 nF</td>
<td>0.4 nF</td>
</tr>
<tr>
<td>Flying Height</td>
<td>10 k( \Omega )</td>
<td>10 k( \Omega )</td>
<td>10 k( \Omega )</td>
<td>10 k( \Omega )</td>
<td>100 k( \Omega )</td>
<td>120 nF</td>
<td>10 nF</td>
</tr>
</tbody>
</table>

Table 7.3 Component values for PID controller circuits
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PID controller: Flying height control stage

Differential amplifier

PID controller: Data tracking stage

Fig. 7.20 Picture of PID-controller analogue circuit implementation
7.4.1 Transient Response: Data Tracking Motion

A square wave of peak-to-peak amplitude of 10 V and frequency of 0.2 Hz is applied to the open-loop and closed-loop data tracking stage of the suspension arm and the resulting waveforms observed on a Tektronix TDS 220 digital oscilloscope as shown in Figure 7.21 and Figure 7.22.

The open-loop transient response yields a settling time $T_s = 1.2$ s, and a large overshoot $M_p$ of about 160 %. The closed-loop transient characteristics are better, giving settling time $T_s = 0.6$ s (half the open-loop settling time), and a much smaller overshoot $M_p$ of about 27 %.
7.4.2 Transient Response: Flying Height Control Stage

A square wave of peak-to-peak amplitude of 10 V and frequency of 0.2 Hz is applied to the open-loop and closed-loop flying height control stage of the suspension arm and the resulting waveforms observed on a Tektronix TDS 220 digital oscilloscope as shown in Figure 7.23 and Figure 7.24.
Fig. 7.23 Open-loop transient response: Flying height control

Fig. 7.24 Closed-loop transient response: Flying height control
The open-loop transient response yields a settling time $T_s$ of nearly 1 s, and a very large overshoot $M_P$ of greater than 200%. The closed-loop transient characteristics are better; giving settling time, $T_s$ of about 0.5 s (half the open-loop settling time), and a much smaller overshoot $M_P$ of about 22%.

7.5 Summary

This Chapter has presented the development of robust and stable controllers, for both stages of motion of the suspension arm, based on PID control techniques. These controllers have been designed through Matlab simulations to aid the practical realisation and implementation, which has resulted in much improved transient characteristics for both stages of motion. The discrepancies between the simulated transient responses and the practical responses may be due to some level of imperfection in the modelling of the plant transfer function. This is because the system is assumed to be a second order system (this is only an approximation), hence level of error is expected. However, the PID practical implementation does improve the transient responses of both stages of motion. Because the two orthogonal axes of motion of the suspension arm have different dynamic characteristics, the closed-loop servomechanism for each axis is developed independently of the other. This is particularly important, as both motions of the arm may occur simultaneously and may thus need to be controlled at the same time. This may happen because the suspension arm is a complex structure, and motion in one axis may induce unwanted resonances in the other. These resonances must be suppressed effectively and quickly to avoid any track misregistration (TMR) that may limit the overall performance of the servo controller.
For the data tracking motion servo loop, a closed-loop bandwidth of nearly 15 kHz has been achieved, compared to less than 1 kHz in current commercial HDDs. The closed-loop bandwidth achieved for flying height control is nearly 5 kHz. Both the closed-loop control implementations are stable.
Chapter 8

Conclusions

8.1 Summary of Research

Substantial progress has been made towards meeting the goals set at the start of this project. A novel active suspension arm capable of 2-dimensional motion (in a dual actuation mechanism) has been developed for use in advanced hard disk drives. The aim of this project was to develop and demonstrate a high-bandwidth, high-resolution suspension arm that can give motion in two orthogonal planes. One plane of motion represents data tracking sweep, whereas the other plane represents active flying height control in advanced HDDs.

8.2 Development of High-Resolution Measurement Channel

The suspension arm has been characterised using the OBD technique, which is an optical measurement channel also developed in this research to measure minute end-deflections of the suspension arm in 2-dimensions with sub-nanometre accuracy and precision above noise. The OBD technique has been optimised, to increase its measurement sensitivity, thus increasing the signal-to-noise ratios of the output voltage. This investigation has resulted in choosing the correct photodiode to use for the elliptical Gaussian laser beam that has been used in this project. This OBD optimisation has been achieved by thoroughly understanding the way cantilever beams bend when subjected to electric field
8.3 Development of Novel Active Suspension Arm

The development of a novel active suspension arm for use in advanced hard disk drives has been achieved. Different suspension arm designs have been investigated and developed to see if they meet the requirements set for the novel active suspension arm. Three different types of actuation mechanisms have been investigated.

The first investigation was the use of PZT thick films deposited on the stainless steel load beam (to provide precision flying height control), while retaining the aluminium frame (which may have an embedded PZT stack actuator) to give high-bandwidth data tracking motion. It was found that such films give much better actuation when reinforced with glass and/or carbon fibre uniformly dispersed within its 3-dimensional matrix. The reinforced films are much stiffer and hence produce stable actuation (due to improved mechanical quality factors). However, the levels of actuation (a few nanometers off-resonance and a few hundred nanometers on-resonance) are not adequate to meet the specification of the intended suspension arm, and the manufacture process is rather slow and may prove commercially unattractive. One suggestion to improve the actuation capabilities of these thick films is to use active PZT fibre reinforcements, instead of glass or carbon fibre. This type of fibre reinforcement would form 'an actively reinforced thick film', which should offer improved activity and improved rigidity. This may form future work in applications such as structural health monitoring where sensing levels in the nanometer region are more than adequate.
The second investigation was the use of composite PZT arms, where the whole load suspension arm is made from carbon and/or glass fibre, with PZT material impregnated within the fibre matrix ensuring uniform PZT distributed within the composite framework to make it active for actuation purposes. Such a structure being used, instead of stainless steel load beam, would enable faster disk access times resulting from the reduced moment of inertia. The composite arm would control the head flying height and the current aluminium base frame would have a piezoelectric-stack embedded within its frame to produce high-bandwidth motion for data tracking in the other orthogonal plane of motion. This mechanism would realise dual-stage actuation of the suspension arm, meeting the requirements as outlined in Chapter One of this thesis. These arms have been fabricated and tested for actuation capabilities, but none have been found. This is partly because of the inadequate distribution of the PZT grains within the composite arm. To improve actuation properties of the composites, a bimorph arrangement is suggested. In this configuration, the compression in the dimensions of one arm would result in the expansion of the dimensions of the other composite arm. Even so, actuation capabilities of such an arrangement are expected to be low, due to the poor distribution of the PZT grains within the composite arm. Much improved fabrication techniques may address this problem, but at much higher costs and time. The integration of these arms into commercial HDDs may also not be commercially feasible in the near future.

The third investigation was the use of embedded PZT stacks (multi-layer actuators), where a duralumin frame has PZT stacks embedded within its framework to realise dual-actuation of the arm. The design of the arm is aimed for easy integration into current commercial HDD technology. The PZT actuator stack to control data tracking is positioned to give
high-bandwidth data tracking motion. The stack controlling the flying height is positioned nearer the root of the stainless steel load beam to maximise the bending moment of the arm, while maintaining precision head flying height motion.

Such an arrangement produces much-improved actuation in both planes of motion, as well as much higher resonant frequencies. This arrangement seems the way forward for the development of suspension arm in the next generation HDDs, both in practical terms for easier integration within current HDD environment and economically more feasible.

8.4 Development of Suspension Arm Controller

The development of a sufficiently fast, stable and robust closed-loop servo control mechanism in hard disk drives (HDDs) is essential in ensuring an improvement in the overall performance and reliability of HDDs in the development of next generation hard disk drives with very high data storage densities.

In this thesis, a prototype active suspension arm for use in advanced HDDs capable of 2-dimensional motion has been developed and characterised. The prototype suspension arm has two embedded piezoelectric stacks to actuate it, each enabling motion in orthogonal axes to the other, when an electric field is applied across them. This demonstrates dual-actuation mechanism. The suspension arm has been thoroughly tested and fully characterised to understand its static and dynamic characteristics. These characteristics have been utilised to develop an advanced closed-loop servo algorithm for positioning the suspension arm in 2-dimensions. Because the two orthogonal axes of motion of the
suspension arm have different dynamic characteristics, the closed-loop servomechanism for each axis is developed independently of the other. This is particularly important, as both motions of the arm may occur simultaneously and may thus need to be controlled at the same time. This may happen because the suspension arm is a complex structure, and motion in one axis may induce unwanted resonances in the other. These resonances must be suppressed effectively and quickly to avoid any track misregistration (TMR) that may limit the overall performance of the servo controller.

To address these issues, fast, robust and stable controllers based on PID control techniques, for both stages of motion of the suspension arm, have been developed. These controllers have been designed through Matlab simulations to aid the practical realisation and implementation. Implementing the PID closed-loop control has resulted in much improved transient responses for both stages of motion. The discrepancies between the simulated transient responses and the practical responses may be due to some level of imperfection in the modelling of the plant transfer function. This is because the system is assumed to be a second order system (this is only an approximation), hence level of error is expected. For the data tracking motion servo loop, a closed-loop bandwidth of nearly 15 kHz has been achieved, compared to less than 1 kHz in current commercial HDDs. The closed-loop bandwidth achieved for flying height control is nearly 5 kHz. Both the closed-loop control implementations are stable.
8.5 Contributions to Knowledge

The contributions to knowledge as a direct result of the work presented in this thesis are quantified in the following aspects:

- Development of a novel active suspension arm, capable of motion in two dimensions. The first plane of motion of the suspension arm simulates high-bandwidth data tracking, whereas the other plane represents flying height control. The work to actively control the read-write flying height in HDDs is particularly novel, as the existing methods do not have active feedback to correct the position of the head.

- Different actuator configurations have been discovered. Although the initial aim was to fabricate the whole (or part) of the suspension arm from hybrid composite materials (light-weight, rigid and perhaps inherently piezoelectric active), work presented in this thesis shows why they may not be suitable for integration into a current commercial HDD environment. The main reasons being inadequate actuation capabilities of these films, problems due to drift and impractical to integrate within a commercial drive. The novelty in this work has been the development of fibre-reinforced (glass and/or carbon fibre) PZT thick films for sensing purposes. Reinforced PZT thick have demonstrated much improved stability and linearity, better actuation capabilities both on- and off-resonance, much higher rigidity resulting in higher film resonant frequencies meaning higher mechanical quality factors. These qualities would be much desired in applications such as structural health monitoring.
8.6 Future Work

The aim of this project was to develop and demonstrate a high-bandwidth, high-resolution suspension arm that gives motion in two orthogonal planes. One plane of motion represents data tracking sweep, where as the other plane represents active flying height control in advanced HDDs. It was initially intended that the suspension arm be fabricated using hybrid active fibre composite material. The work presented in this thesis has, however, shown that suspension arms fabricated in this manner do not offer adequate actuation capabilities. The solution provided in this work is a very good alternative because it is easier to fabricate and integrate the prototype suspension arm into current manufacturing set-ups. It is however recommended that the work on reinforced PZT thick films is continued. The reinforcement of the thick films with glass and/or carbon has shown improved qualities, such as better actuation, but it is thought that perhaps reinforcing the PZT thick films with PZT fibre (instead of glass and/or carbon fibre) would improve the actuation capabilities. This would result in PZT thick films being reinforced with piezoelectric active material in the form of PZT fibre of similar dimensions to the glass and carbon fibre. These active reinforced thick films would offer superior actuation capabilities to conventional thick films, which do not have any form of reinforcement.

The PID compensation for both planes of motion has been implemented using analogue electronics. In future work, it is highly recommended that digital PID compensators be implemented using a digital signal processor, such as the TMS320C5x [116]. Digital controllers, unlike analogue ones, are not affected by component ageing and temperature
drift, and they provide stable performance. When the design is done in the z-domain, the behaviour digital controllers can be more precisely controlled. They can also be used to implement more sophisticated techniques from modern control theory, such as state controllers, optimal control, and adaptive control. Digital controllers are programmable, thus making them easy to upgrade and maintaining design investment.

The suspension arm has been fabricated, tested and characterised. It is, however, recommended that the suspension arm be integrated within a HDD environment, and further tests carried out to assess its performance and characterise it even further. This would enable further integration studies. One of these would be developing more robust and reliable closed-loop algorithms to improve head-positioning mechanism. It would be desirable to also test dynamic flying height control. This would also help further research into active vibration control in advanced HDDs, for applications where maintaining the correct head flying height is of critical importance.
Appendix A

Fig. A1. Close-up picture showing arrangement of laser diode, suspension arm and photodiode all clamped firmly on the rail.
Fig. A2. Picture of triangular optical bench bolted to a heavy base supported on airbags on top of an optical table.
Appendix B

B1. Analysis of bimorph deflection assuming circular bending of the bimorph

Let the initial co-ordinates $A$ be $(0,0)$, representing the centre of the mirror at the end of the bimorph before it bends, assuming the laser beam initially hits the mirror at its centre - but this need not be the case as the analysis can be applied to any position on the mirror. When the bimorph bends due to an applied voltage, the above initial position $A$ moves to a new position $A'$. The position $A$ experiences a shift in the x-axis $\Delta x$ and another in the y-axis $\Delta y$.

The co-ordinates of the new position $A'$ have been calculated from Figures 4.2(a) and 4.2(b) as:

$$A' = (\Delta x, \Delta y, \phi) = \left(\frac{r}{\phi} \cdot \cos(\phi) - \frac{r}{\phi}, \frac{r}{\phi} \cdot \sin(\phi) - r\right) \quad (B-1)$$

From the diagrams we can see how the horizontal displacement $\Delta x$ of the bimorph as shown in Figure 4.2 (a) is related to the curvature of the bimorph and its other parameters. We see that the horizontal displacement of the bimorph $\Delta x$ is related to the angle $\phi$ and the length of the bimorph $r$. This relationship is calculated using Figure 4.2 (b) as a reference:

$$\tan(b) = \frac{\Delta x}{h} \quad \text{Where: } h = \frac{r}{\phi} \cdot \sin(\phi) \quad (B-2)$$

As $b \to 0$, $\tan(b) \equiv b$ and $\phi$ becomes so small such that $\sin(\phi) \equiv \phi$

Hence $b \equiv \frac{\Delta x}{r} \quad (B-3)$

Also as $b \to 0$, $k \equiv r$ and hence $\sin(\phi) \equiv \frac{\Delta x}{r} \quad (B-4)$

And $\phi \to 0$, $\sin(\phi) \equiv \phi$ and therefore $\phi \equiv \frac{\Delta x}{r} \quad (B-5)$
Appendix B  

Bimorph end-deflection modelling

We now work out, step by step using coordinate geometry, the shift of the laser beam on the photodiode when the bimorph element experiences a displacement $\Delta x$ from its initial position $A$ to $A'$. Refer to Figures 4.2(a) and 4.2(b) in Chapter 4.

- Equation of line $L_1$ along mirror after bimorph bending

The line $L_1$ passes through the new co-ordinates $A'$ (which is the new centre position of the mirror on the bimorph). From the diagram, we can see that the gradient of this line $L_1$ is $-\tan \phi$.

The equation of any straight line with co-ordinates $(x_1, y_1)$ is given:

$$y - y_1 = m(x - x_1)$$

where $m$ is the gradient of the line.

Therefore:

$$y - \frac{r}{\phi} \cdot \sin(\phi) + r \cdot \tan(\phi) \cdot \left(x - \frac{r}{\phi} \cdot \cos(\phi) + \frac{r}{\phi}\right)$$

$$= y \left(\frac{2 \cdot r \cdot \sin(\phi)}{\phi} - \frac{r \cdot \tan(\phi)}{\phi} - x \cdot \tan(\phi) - 1\right)$$

$$= \left(\frac{2 \cdot r \cdot \sin(\phi)}{\phi} - \frac{r \cdot \tan(\phi)}{\phi} - x \cdot \tan(\phi) - 1\right)$$

(B-6)

- Equation of line $L_2$ along incident laser beam

From the Figure 4.2 (a), we see that the incident angle of the laser beam is $\alpha$. Therefore, the gradient of the line $L_2$ along the incident laser beam is $-\cot \alpha$. We also know that the incident laser beam passes through the point $A$ with co-ordinates $(0,0)$.

$\therefore$ Equation of line along incident beam is:

$$y = -x \cdot \cot \alpha$$

(B-7)
Appendix B  Bimorph end-deflection modelling

- Point of interception $P_1$ of laser beam with mirror after bending of bimorph

\[
\alpha \cdot \cot(\alpha) = \left( \frac{2 \cdot \cos(\phi) \cdot \sin(\phi)}{\phi} - \frac{r \cdot \tan(\phi)}{\phi} - x \cdot \tan(\phi) - r \right)
\]

Making $x$ the subject of the formula:

\[
x = r \cdot \sin(\alpha) \cdot \frac{(\sin(\phi) + \phi \cdot \cos(\phi) - 2 \cdot \sin(\phi) \cdot \cos(\phi))}{\phi \cdot \cos(\alpha + \phi)}
\]

Now replacing $x$ into equation (B-7) we get:

\[
y = \cos(\alpha) \cdot r \cdot \frac{(2 \cdot \sin(\phi) \cdot \cos(\phi) - \sin(\phi)) - \cos(\phi) \cdot \phi}{\phi \cdot \cos(\alpha + \phi)}
\]

The laser beam hence hits the mirror on the bimorph at a point $P_1$ on the mirror with co-ordinates:

\[
[r \cdot \sin(\alpha) \cdot \frac{(\sin(\phi - 2 \cdot \cos(\phi) \cdot \sin(\phi) + \phi \cdot \cos(\phi))}{\phi \cdot \cos(\alpha + \phi)}], \; \; \; \; r \cdot \cos(\alpha) \cdot \frac{2 \cdot \cos(\phi) \cdot \sin(\phi) - \sin(\phi) - \phi \cdot \cos(\phi)}{\phi \cdot \cos(\alpha + \phi)}
\]

- Equation of line $L_3$ along reflected laser beam before bending of bimorph

We know that the laser beam passes through the point $A$ with co-ordinates $(0,0)$ and on reflection, the reflected angle is simply $-\alpha$. Hence, the gradient of the line $L_3$ is $\cot \alpha$.

\[ \therefore \text{Equation of line along reflected beam is: } y = x \cdot \cot \alpha \]

- Point of interception $P_2$ of line $L_3$ with photodiode
Appendix B  
Bimorph end-deflection modelling

If the photodiode is placed at a distance \( L \) from the mirror on the bimorph, the reflected laser beam will intercept it at a point lying on the line \( x = L \cdot \sin \alpha \).

Replacing this value of \( x \) into equation (B-12), we get:

\[
y_2 = L \cdot \cos \alpha
\]

The laser beam intercepts the photodetector at a point \( P_2 \) with co-ordinates \((x_2, y_2) = (L \cdot \sin \alpha, L \cdot \cos \alpha)\) (B-13)

- **Equation of line \( L_4 \) along photodetector**

To get the most concentrated area of the laser beam as possible on the detector, the photodetector is placed perpendicular to the reflected laser beam. Least area of the laser beam gives highest sensitivity possible of the deflection detection technique, as is shown in the next chapter. We now find the equation of the line \( L_4 \) along the detector plane.

We know that \( L_4 \) passes through \((L \cdot \sin \alpha, L \cdot \cos \alpha)\) and is perpendicular to \( L_3 \). Therefore, gradient of \( L_4 \) is \(-\tan \alpha\). And the equation of the line \( L_4 \) is:

\[
y = ( - \tan(\alpha) \cdot (x - L \cdot \sin(\alpha)) ) + L \cdot \cos(\alpha)
\]

\[
\Rightarrow y = \frac{L - x \cdot \sin(\alpha)}{\cos(\alpha)}
\]

(B-14)

- **Equation of line \( L_6 \) along reflected laser beam without angular deflection**

The gradient of the line \( L_6 \) is the same as that of \( L_3 \), \( \cot \alpha \), and passes through the point \( P_1 \) on the mirror. Therefore, its equation is calculated as:

\[
y_1 = \cot(\alpha) \cdot \frac{-(x \cdot \phi \cdot \cos(\alpha + \phi) + 2 \cdot r \cdot \sin(\alpha) \cdot \sin(\phi) + 2 \cdot r \cdot \phi \cdot \sin(\alpha) \cdot \cos(\phi) - 4 \cdot r \cdot \sin(\alpha) \cdot \sin(\phi) \cdot \cos(\phi))}{\phi \cdot \cos(\alpha + \phi)}
\]

(B-15)
Appendix B  
Bimorph end-deflection modelling

• Point of interception \( P_4 \) of laser beam along \( L_6 \) with plane of photodetector

\[
L - x \sin(\alpha) = \cot(\alpha) \left( -x \phi \cos(\alpha + \phi) + 2r \sin(\alpha) \sin(\phi) + 2r \phi \sin(\alpha) \cos(\phi) - 4r \sin(\alpha) \sin(\phi) \cos(\phi) \right) \frac{\phi}{\cos(\alpha + \phi)}
\]

We now calculate the co-ordinates of point \( P_4 (x_4, y_4) \).

Making \( x \) the subject of the formula in equation (B-16), we get the \( x_4 \):

\[
x_4 = \frac{L}{\cot(\alpha) + \tan(\alpha)} \left[ 2r \cot(\alpha) \sin(\alpha) \left( \phi \cos(\phi) + \sin(\phi) \left( 1 - 2 \cos(\phi) \right) \right) \right] \frac{\phi \cos(\alpha + \phi)}{\cos(\alpha)}
\]

Replacing \( x_4 \) into equation (B-15), we get the value of \( y_4 \) shown below:

\[
y_4 = \frac{L}{\cos(\alpha)} - \frac{\tan(\alpha)}{(\cot(\alpha) + \tan(\alpha))} \left[ 2r \cot(\alpha) \sin(\alpha) \left( \phi \cos(\phi) + 2 \cos(\alpha) \sin(\phi) \sin(\phi) \right) \right] \frac{\phi \cos(\alpha + \phi)}{\cos(\alpha)}
\]

• Equation of line \( L_5 \) along reflected laser beam after bimorph deflection

Gradient of \( L_5 \) is \( \cot(\alpha + 2\phi) \) and this line passes through point \( P_1 \).

\[ \therefore \text{Equation of } L_5 \text{ is:} \]

\[ y = \cot(\alpha + 2\phi) \left[ x - r \sin(\alpha) \left( \frac{\sin(\phi) + \phi \cos(\phi) - 2 \sin(\phi) \cos(\phi)}{\phi \cos(\alpha + \phi)} \right) \right] + \cos(\alpha) \cdot r \cdot \frac{(2 \sin(\phi) \cos(\phi) - \sin(\phi)) - \cos(\phi) \cdot \phi}{\phi \cos(\alpha + \phi)} \]

This is further simplified to:

\[ y = x \cot(\alpha + 2\phi) - \frac{(\cos(\phi) \cdot \phi + \sin(\phi) - 2 \sin(\phi) \cos(\phi)) \cdot (r \cos(\alpha + 2\phi) - r \cos(\alpha) \cdot \sin(\alpha + 2\phi))}{\sin(\alpha + 2\phi) \cdot \phi \cos(\alpha + \phi)} \]
Appendix B  
Bimorph end-deflection modelling

- Point of interception $P_3$ of reflected laser beam with plane of photodetector

$$x = \frac{\cot(\alpha + 2\phi) - \left(\frac{\cos(\phi) + \sin(\phi) - 2\sin(\phi)\cos(\phi)}{\sin(\alpha + 2\phi) \phi \cos(\alpha + \phi)}\right) (r \cos(\alpha + 2\phi) \sin(\alpha) + r \cos(\alpha) \sin(\alpha + 2\phi))}{\sin(\alpha + 2\phi) \phi \cos(\alpha + \phi)} = \frac{L - xsin(\alpha)}{\cos(\alpha)}$$

(B-21)

Making $x$ the subject of the formula:

$$x_3 = \frac{(\cot(\alpha + 2\phi) \sin(\alpha) + \cos(\alpha))(r \phi \cos(\phi) - (2 \cos(\phi) - 1) r \sin(\phi)) + \frac{L - xsin(\alpha)}{\cos(\alpha)}}{(\cot(\alpha + 2\phi) + tan(\alpha))}$$

(B-22)

Replacing $x_3$ into equation (B-20), we get the value of $y_3$ below:

$$y_3 = \frac{\tan(\alpha) \left(\frac{\cos(\alpha + 2\phi) \sin(\alpha) + \cos(\alpha))(r \phi \cos(\phi) - (2 \cos(\phi) - 1) r \sin(\phi)) + \frac{L - xsin(\alpha)}{\cos(\alpha)}}{(\cot(\alpha + 2\phi) + tan(\alpha))}}{\cos(\alpha)}$$

(B-23)

We now have two points $P_2$ and $P_3$ on the photodetector where the laser beam intercepts before and after the bending of the bimorph. We also have another point $P_4$ on the photodetector which we shall use to investigate the effects of the angular deflection (corresponding to the distance between $P_4$ and $P_3$) and the displacements due to shifts $\Delta x$ and $\Delta y$ (corresponding to the distance between $P_2$ and $P_4$) have on the overall shift (distance between $P_2$ and $P_3$) of the laser beam on the photodetector.

- Shifts of the laser beam on the photodetector

The angular shift $S_{A1}$ is the distance between $P_4(x_1, y_1)$ and $P_3(x_3, y_3)$ and is given as:
Appendix B  
Bimorph end-deflection modelling

\[ S_{A1} = \sqrt{(y_1 - y_2)^2 + (x_1 - x_2)^2} \]  
(B-24)

The displacement \( S_{D1} \) due to shifts \( \Delta x \) and \( \Delta y \) is the distance between \( P_2 \) \((x_2, y_2)\) and \( P_4 \) \((x_1, y_1)\) and is given as:

\[ S_{D1} = \sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2} \]  
(B-25)

The total shift \( S_{T1} \) of the laser beam on the detector is the distance between the points \( P_2 \) \((x_2, y_2)\) and \( P_3 \) \((x_3, y_3)\) and is equal to the sum of the angular shift \( S_{A1} \) and the displacement (due to shifts \( \Delta x \) and \( \Delta y \)) \( S_{D1} \).

\[ S_{T1} = S_{A1} + S_{D1} \]  
(B-26)

\[ S_{T1} = \sqrt{(y_2 - y_3)^2 + (x_2 - x_3)^2} \]  
(B-27)

B2. Analysis of bimorph deflection assuming straight-deflection of the bimorph

Using the same analysis and steps as in the previous section, we calculate the shift of the laser beam on the photodiode assuming that the bimorph bends at its root but does not experience any curvature along its length. In this thesis, we will refer to this type of bending as straight-deflection. Let initial co-ordinates \( A \) be \((0,0)\). When a voltage is applied across the electrodes of the bimorph, the above initial position moves to a new position \( A' \) with co-ordinates:

\[ A' = (r \sin \beta, r \cos \beta - r) \]  
(B-28)
Appendix B  

Bimorph end-deflection modelling

From the diagrams below we see how the horizontal displacement $\Delta x$ of the bimorph as shown in Figure 3.2(a) is related to the angle $\beta$ between the bimorphs' positions before and after bending. The angle $\beta$ is calculated as:

$$\beta = \sin^{-1}\left(\frac{\Delta x}{r}\right) \equiv \frac{\Delta x}{r} \quad \text{(as } \Delta x \to 0 \text{ for fixed } r)$$  \hspace{1cm} (B-29)

The straight-deflection model is now shown in Figure 4.7(a) and Figure 4.7(b).

We now work out, step by step using co-ordinate geometry, the shift of the laser beam on the photodiode when the bimorph element experiences a displacement $\Delta x$ from its initial position $A$ to $A'$ assuming a straight-deflection model.

- **Equation of line $L_1$ along mirror after bimorph bending**

The line $L_1$ passes through the new co-ordinates $A'$ (which are the new centre position of the mirror on the bimorph).

From the diagram, we can see that the gradient of this line $L_1$ is $-\tan \beta$.

Therefore, equation of $L_1$ is given as:

$$y - r \cdot \cos(\beta) = r \cdot \tan(\beta) \cdot (x - r \cdot \sin(\beta))$$

$$\Rightarrow y = \frac{r}{\cos(\beta)} - \frac{x \cdot \sin(\beta)}{\cos(\beta)} - r$$ \hspace{1cm} (B-30)

- **Equation of line $L_2$ along incident laser beam**
Appendix B  

Bimorph end-deflection modelling

From the Figure 4.2 (a) we see that the incident angle of the laser beam is \( \alpha \). Therefore, the gradient of the line \( L_2 \) along the incident laser beam is \(-\cot \alpha\). We also know that the incident laser beam passes through the point A with co-ordinates (0,0).

\[
\therefore \text{ Equation of line along incident beam is: } y = -x \cdot \cot \alpha \tag{B-31}
\]

Point of interception \( P_1 \) of laser beam with mirror after bending of bimorph

\[
-x \cdot \cot(\alpha) = \frac{r}{\cos(\beta)} - \frac{x \cdot \sin(\beta)}{\cos(\beta)} - r \tag{B-32}
\]

Making \( x \) the subject of the formula:

\[
x = \frac{r \cdot \cos(\beta) - r}{\cos(\beta) \cdot (\cot(\alpha) - \tan(\beta))} \tag{B-33}
\]

Now replacing \( x \) into equation (6) we get:

\[
y = -\cos(\alpha) \cdot r \cdot \frac{\cos(\beta) - 1}{\cos(\alpha + \beta)} \tag{B-34}
\]

The laser beam hence hits the mirror on the bimorph at a point \( P_1 \) on the mirror with co-ordinates:

\[
\left[ \frac{r \cdot \cos \beta - r}{\cos \beta \cdot (\cot \alpha - \tan \beta)}, \ -r \cdot \cos \alpha \cdot \frac{\cos \beta - 1}{\cos(\alpha + \beta)} \right] \tag{B-35}
\]

Equation of line \( L_2 \) along reflected laser beam before bending of bimorph
Appendix B  Bimorph end-deflection modelling

We know that the laser beam passes through the point A with co-ordinates (0,0) and on reflection, the reflected angle is simply $-\alpha$. Hence, the gradient of the line $L_3$ is $\cot \alpha$.

\[ \therefore \text{ Equation of line along reflected beam is: } y = x \cdot \cot \alpha \]  \hspace{1cm} (B-36)

* Point of interception $P_1$ of line $L_3$ with photodiode

If the photodiode is placed at a distance $L$ from the mirror on the bimorph, the reflected laser beam will intercept it at a point lying on the line $x = L \cdot \sin \alpha$.

Replacing this value of $x$ into equation (B-36), we get: $y_2 = L \cdot \cos \alpha$

The laser beam intercepts the photodetector at a point $P_2$ with co-ordinates $(x_2, y_2) = (L \cdot \sin \alpha, L \cdot \cos \alpha)$  \hspace{1cm} (B-37)

* Equation of line $L_4$ along photodetector

To get as least an area of the laser beam as possible on the detector, the photodetector is placed perpendicular to the reflected laser beam. We now find the equation of the line $L_4$ along the detector plane.

We know that $L_4$ passes through $(L \cdot \sin \alpha, L \cdot \cos \alpha)$ and is perpendicular to $L_3$. Therefore, gradient of $L_4$ is $-\tan \alpha$. In addition, the equation of the line $L_4$ is:

\[ y = ((-\tan \alpha) \cdot (x - L \cdot \sin \alpha)) + L \cdot \cos \alpha \]  \hspace{1cm} (B-38)

* Equation of line $L_4$ along reflected laser beam without angular deflection

The gradient of the line $L_4$ is the same as that of $L_3$, $\cot \alpha$, and passes through the point $P_1$ on the mirror. Therefore, its equation is calculated as:
Appendix B  

Bimorph end-deflection modelling

\[ y = \cot(\alpha) \left[ x - \frac{r \cdot \cos(\beta) - r}{\cos(\beta) \cdot (\cot(\alpha) - \tan(\beta))} \right] - \cos(\alpha) \cdot r \cdot \frac{\cos(\beta) - 1}{\cos(\alpha + \beta)} \]  

(B-39)

- Point of interception \( P_4 \) of laser beam along \( L_4 \) with plane of photodetector

\[ \frac{L - x \sin(\alpha)}{\cos(\alpha)} = \cot(\alpha) \cdot \left[ x - \frac{r \cdot \cos(\beta) - r}{\cos(\beta) \cdot (\cot(\alpha) - \tan(\beta))} \right] - \cos(\alpha) \cdot r \cdot \frac{\cos(\beta) - 1}{\cos(\alpha + \beta)} \]  

(B-40)

We now calculate the co-ordinates of point \( P_4 \) \( (x_4, y_4) \).

Making \( x \) the subject of the formula in equation (B-40), we get \( x_4 \):

\[ x_4 = \frac{1}{(\cot(\alpha) + \tan(\alpha))} \left[ \frac{r \cdot \cot(\alpha) \cdot (\cos(\beta) - 1)}{\cos(\beta) \cdot (\cot(\alpha) - \tan(\beta))} + \frac{r \cdot \cos(\alpha) \cdot (\cos(\beta) - 1)}{\cos(\alpha + \beta)} + \frac{L}{\cos(\alpha)} \right] \]  

(B-41)

Replacing \( x_4 \) into equation(B-39), we get the value of \( y_4 \) shown below:

\[ y_4 = \frac{L}{\cos(\alpha)} - \frac{\tan(\alpha)}{(\cot(\alpha) + \tan(\alpha))} \left[ \frac{r \cdot \cot(\alpha) \cdot (\cos(\beta) - 1)}{\cos(\beta) \cdot (\cot(\alpha) - \tan(\beta))} + \frac{r \cdot \cos(\alpha) \cdot (\cos(\beta) - 1)}{\cos(\alpha + \beta)} + \frac{L}{\cos(\alpha)} \right] \]  

(B-42)

- Equation of line \( L_5 \) along reflected laser beam after bimorph deflection

Gradient of \( L_5 \) is \( \cot(\alpha + 2\beta) \) and this line passes through point \( P_4 \).

\[ y = \cot(\alpha + 2\beta) \left[ x - \frac{r \cdot \cos(\beta) - r}{\cos(\beta) \cdot (\cot(\alpha) - \tan(\beta))} \right] - \cos(\alpha) \cdot r \cdot \frac{\cos(\beta) - 1}{\cos(\alpha + \beta)} \]  

(B-43)

- Point of interception \( P_3 \) of reflected laser beam with plane of photodetector
Appendix B

Bimorph end-deflection modelling

\[ \frac{L}{\cos(\alpha)} - \frac{x \cdot \sin(\alpha)}{\cos(\alpha)} = \cot(\alpha + 2\beta) \left[ x - \frac{r \cdot \cos(\beta) - r}{\cos(\beta) \cdot (\cot(\alpha) - \tan(\beta))} \right] - \cos(\alpha) \cdot \frac{r \cdot (\cos(\beta) - 1)}{\cos(\alpha + \beta)} \]  

(B-44)

Making \( x \) the subject of the formula, we get \( x_5 \):

\[ x_5 = \frac{r \cdot \cot(\alpha + 2\beta) \cdot \cos(\beta) - r \cdot \cos(\alpha) - r \cdot \cos(\alpha) \cdot \cos(\beta) - r \cdot \cos(\alpha)}{\cos(\alpha) \cdot (\cot(\alpha) - \tan(\beta))} + \frac{L}{\cos(\alpha + \beta)} + \frac{L}{\cos(\alpha + 2\beta) + \tan(\alpha)} \]

(B-45)

Replacing \( x_5 \) into equation (B-33), we get the below value of \( y_5 \):

\[ y_5 = \frac{-L}{\cos(\alpha)} - \tan(\alpha) \cdot \left[ \frac{r \cdot \cot(\alpha + 2\beta) \cdot \cos(\beta) - r \cdot \cos(\alpha) - r \cdot \cos(\alpha) \cdot \cos(\beta) - r \cdot \cos(\alpha)}{\cos(\alpha) \cdot (\cot(\alpha) - \tan(\beta))} + \frac{L}{\cos(\alpha + \beta)} + \frac{L}{\cos(\alpha + 2\beta) + \tan(\alpha)} \]  

(B-46)

We now have two points \( P_2 \) and \( P_3 \) on the photodetector where the laser beam intercepts before and after the bending of the bimorph. We also have another point \( P_4 \) on the photodetector which we shall use to investigate the effects of the angular deflection (corresponding to the distance between \( P_4 \) and \( P_3 \)) and the displacements due to shifts \( \Delta x \) and \( \Delta y \) (corresponding to the distance between \( P_2 \) and \( P_4 \)) have on the overall shift (distance between \( P_2 \) and \( P_3 \)) of the laser beam on the photodetector.

- Shifts of the laser beam on the photodetector

The angular shift \( S_{A2} \) is the distance between \( P_4 (x_4,y_4) \) and \( P_3 (x_3,y_3) \) and is given as:

\[ S_{A2} = \sqrt{(y_4 - y_3)^2 + (x_4 - x_3)^2} \]  

(B-47)

The displacement \( S_{D2} \) due to shifts \( \Delta x \) and \( \Delta y \) is the distance between \( P_2 (x_2,y_2) \) and \( P_4 (x_4,y_4) \) and is given as:

\[ S_{D2} = \sqrt{(y_2 - y_4)^2 + (x_2 - x_4)^2} \]  

(B-48)
Appendix B  Bimorph end-deflection modelling

The total shift $S_{T2}$ of the laser beam on the detector is the distance between the points $P_2 (x_2,y_2)$ and $P_1 (x_3,y_3)$ and is equal to the sum of the angular shift $S_{A2}$ and the displacement (due to shifts $\Delta x$ and $\Delta y$) $S_{D2}$.

\[ S_{T2} = S_{A2} + S_{D2} \]  \hspace{1cm} (B-49)

\[ S_{T2} = \sqrt{(y_2 - y_3)^2 + (x_2 - x_3)^2} \]  \hspace{1cm} (B-50)
Matlab Code for the Measurement Instrumentation Channel

% UNIVERSITY OF PLYMOUTH
% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
%
% Name: Chibesa Chilumbu
% Date: 13/07/97
% Supervisor: Professor W.W. Clegg
%
% Measurement Instrumentation Channel For Optical Detection System
%
% Task One: Program saved as Task 1
%
% Aims of the Program:
%
% 1. To Calculate a displacement for the PZT bimorph when given certain parameters
% 2. To analyse how this displacement varies with these input parameters
%
% clc
% disp('Welcome to Task One Of The Measurement Instrumentation Channel')
% disp('')
% disp('1. Retrieve saved bimorph details and Analyse it')
% disp('2. Enter New bimorph details')
%
% ans=input('Enter Digit Now... ');
% if ans==1
% graph1
% else
% if ans==2
% clc
% V = input('Enter peak voltage applied across bimorph In volts ') ;
% t = input('Enter thickness in meters ');
% r = input('Enter Initial length in meters ');
% disp('')
% disp('')
% disp('')
% d31=220e-12;
% dx=(3.*d31.*V.*r.^2)/(2.*(t.^2)); % Calculates the displacement of the bimorph
% ('Peak Voltage /V Length of bimorph /m Resulting displacement /m')
% disp(sprintf('%2.2e %2.2e %2.2e :V r dx))
% save disp1.mat V r t % Saves parameters to disk for Task2
% save disp2.mat dx d31
% disp('')
% disp('')
% disp('')
% disp('')
% disp('')
% disp('Please Make a Choice ')
% disp('')
% disp('')
% disp('1. Investigate Graphical Relationships between Parameters')
% disp('2. Move on to Task Two of The Measurement Instrumentation Channel')
% disp('3. Exit Program')
% disp('')
% an=input('Enter Your Choice.... ');
Appendix C

Matlab Code

```matlab
disp('')
disp('')
if an==1
    graph1
else
    if an==2
        Task2
    else
        if an==3
            disp('')
            disp('Your Parameters have been saved')
            disp('')
            disp('Program is now aborted')
            end
        end
    end
end
end

% UNIVERSITY OF PLYMOUTH
% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% Name: Chibesa Chilumbu
% Date: 14/07/97
% Supervisor; Professor W.W. Clegg
% Measurement Instrumentation Channel For Optical Detection System
% Graph One: {Program saved as Graph 1}
% Aims of the Program:
% 1. To Investigate The Graphical Relationship of input Parameters for the PZT-5H bimorph
% clc
% disp('Welcome to Graph One of The Measurement Instrumentation Channel')
% disp('')
% disp('')
% load disp1 % Loads parameters from Task One
% load disp2
% disp('')
% disp('1. See how displacement of bimorph varies with applied voltage, at constant bimorph thickness and length')
% disp('2. See how displacement of bimorph varies with its length, at constant bimorph thickness and applied voltage')
% disp('3. See how displacement of bimorph varies with its thickness, at constant bimorph length and applied voltage')
% disp('4. Change Parameter values in Task One')
% disp('5. Move on to Task Two of Instrumentation Channel')
% disp('6. Exit Program')
% disp('')
% disp('')
% an=input('Enter Your Choice Please... ');
% disp('')
% disp('')
% if an==1
%    clc
%    dx=zeros(0,0); % Sets initial displacement to zero
%    V=zeros(0,0); % Sets initial applied voltage to Zero
%    disp('')
%    disp('')
%    disp('Enter range of voltages to be investigated')
```
Appendix C

Matlab Code

```matlab
disp('')
a=input('Lower Voltage in volts= ');
b=input('Upper Voltage in volts= ');
disp('')
disp('Enter the number of points to be plotted')
disp('')
n=input('Number of steps= ');
V=linspace(a,b,n);
dx=(3.*dx1.*V.*(r.^2))/(2.*(t.^2)); % Calculates the displacement of the bimorph
plot(V,dx,Y)
grid
title('Graph of bimorph displacement against applied voltage')
xlabel('Voltage applied across bimorph in volts')
ylabel('Resulting displacement of bimorph in meters')
else
    if a==2
        clc
dx=zeros(0,0); % Sets initial displacement to zero
r=zeros(0,0); % Sets initial length to Zero
disp('')
disp('')
disp('Enter range of lengths to be investigated')
disp('')
a=input('Lower Length in meters= ');
b=input('Upper Length in meters= ');
disp('')
disp('Enter the number of points to be plotted')
disp('')
n=input('Number of steps= ');
r=linspace(a,b,n);
dx=(3.*dx1.*r.*(r.^2))/(2.*(l.^2)); % Calculates the displacement of the bimorph
plot(r,dx,'g')
grid
title('Graph of bimorph displacement against length of bimorph')
xlabel('Length of bimorph in metres')
ylabel('Resulting displacement of bimorph in meters')
else
    if a==3
        clc
dx=zeros(0,0); % Sets initial displacement to zero
l=zeros(0,0); % Sets initial thickness to Zero
disp('')
disp('')
disp('Enter range of thicknesses to be investigated')
disp('')
a=input('Lower Thickness in metres= ');
b=input('Upper Thickness in metres= ');
disp('')
disp('Enter the number of points to be plotted')
disp('')
n=input('Number of steps= ');
l=linspace(a,b,n);
dx=(3.*dx1.*r.*(r.^2))/(2.*(l.^2)); % Calculates the displacement of the bimorph
plot(t,dx,'r')
grid
title('Graph of bimorph displacement against thickness of bimorph')
xlabel('Thickness of bimorph in metres')
ylabel('Resulting displacement of bimorph in meters')
end
end
```
Appendix C

Matlab Code

```matlab
if an==4
    Task1
else
    if an==5
        Task2
    else
        if an==6
            disp('')
            disp('Thankyou for using the Measurement Instrumentation Channel')
            disp('')
            disp('Program is now aborted')
            end
        end
    end
end

% UNIVERSITY OF PLYMOUTH
% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% Name: Chibesa Chilumbu
% Date: 15/07/97
% Supervisor: Professor W.W. Clegg

% Measurement Instrumentation Channel For Optical Detection System
% Task Two: Task2
% Aims of the Program:
% 1. To find out the distance by which the laser beam shifts on the photo detector as the bimorph vibrates
% 2. To analyse how this shift is affected by other input parameters

clear
% disp('')
% disp('Welcome to Task Two Of The Measurement Instrumentation Channel')
% disp('')
% disp('')
% disp('Enter distance between bimorph and photo detector in meters ');
% disp('')
% disp('')
% disp('Enter angle of incidence of laser beam in degrees ');
% disp('')
% if A<0
%     disp('Incident angle must be between 0 and 90 degrees exclusive')
% elseif A>90
%     disp('Incident angle must be between 0 and 90 degrees exclusive')
% else
%     save disp3.mat L A % Saves parameters to disk
% clear
% disp('Please Enter Your Choice Now....')
% disp('')
% disp('')
% disp('1. Go back to Task One')
% disp('2. Shift on photo detector_Trigonometric approximation method')
% disp('3. Shift on photo detector_Assuming circular bimorph bend method')
% disp('4. Shift on photo detector_Assuming non-bending of bimorph method')
% disp('5. Move on to Task Three of Measurement Instrumentation Channel')
% disp('6. Exit Program')
```
Appendix C

Matlab Code

```matlab
% disp('')
disp('')
an=input('Please Enter Your Choice... ');
    if an==1
        Task1
    else
        if an==2
            Task2a
        else
            if an==3
                Task2b
            else
                if an==4
                    Task2c
                else
                    if an==5
                        Task3
                    else
                        if an==6
                            disp('')
                            disp('Your Parameters have been saved')
                            disp('')
                            disp('Program is now aborted')
                            end
                        end
                    end
                end
            end
        end
    end
end

% UNIVERSITY OF PLYMOUTH
% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% Name: Chibesa Chilumbu
% Date: 16/07/97
% Supervisor: Professor W.W. Clegg
% Measurement Instrumentation Channel For Optical Detection System
% Task Two_A: (Program saved as Task2a)
% Aims of the Program:
% 1. To Calculate the laser beam shift on the photo detector using the trigonometric approximation method
% 2. Calculate the shift on the photo detector
% 3. Observe graphical relationships between shift on detector and other parameters
% 4. Move on to Task Three of Measurement Instrumentation Channel
% 5. Exit Program
% cle
% disp('')
disp('Welcome to Task Two_A Of The Measurement Instrumentation Channel')
disp('')
disp('')
disp('1. Go back to Task Two')
disp('2. Calculate The Shift on photo detector')
disp('3. Observe graphical relationships between shift on detector and other parameters')
disp('4. Move on to Task Three of Measurement Instrumentation Channel')
disp('5. Exit Program')
% disp('')
disp('')
an=input('Please Enter Your Choice... ');```

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Appendix C

Matlab Code

if an==1
clc
Task1
else
if an==3
clc
graph2
else
if an==4
clc
Task3
else
if an==2
clc
load disp1
load disp2
load disp3

disp('')

sdt=(2.*L.*dx)./r; % Shift on detector by trigonometry
disp('')
disp('')
disp('

('Bimorph displacement/m     Distance of bimorph from detector/m     Shift on Photo detector/m')


save disp4.mat sdt % Saves parameters to disk

disp('')
disp('')
else
if an==5
clc
disp('')
disp('Your Parameters have been saved')
disp('')
disp('')
disp('Program is now aborted')
end
end
end

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% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% Name: Chibesa Chilumbu
% Date: 16/07/97
% Supervisor: Professor W.W. Clegg

% Measurement Instrumentation Channel For Optical Detection System

% Task Two_B: {Program saved as Task2b}
% Aims of the Program:
% I. To Calculate the laser beam shift on the photo detector using the circular bimorph bend method

clc
disp('')
disp('Welcome to Task Two_B Of The Measurement Instrumentation Channel')
disp('')
disp('')
Appendix C Matlab Code

disp(')
disp('1. Go back to Task Two')
disp('2. Calculate The Shift on photo detector')
disp('3. Observe graphical relationships between shift on detector and other parameters')
disp('4. Move on to Task Three of Measurement Instrumentation Channel')
disp('5. Exit Program')

if an==1
    Task1
else
    if an==2
        clc
        load disp1
        load disp2
        load disp3
        D=dx./r;
        disp(')
    end
    if an==3
        clc
        graph2
    else
        if an==4
            clc
            task3
        else
            if an==5
                clc
                disp(')
                disp('Your Parameters have been saved')
                disp(')
                disp('Program is now aborted')
            end
        end
    end
end

sdb=sqrt((x2-xl).^2+(y2-yl).^2); % Shift on detector due to bending
disp(')
disp(')

('Bimorph displacement/m Distance of bimorph from detector/m Shift on Photo detector/m')
disp('-----------------------------------------------

disp(sprintf('%2.2e %2.2e %2.9e',dx,L,sdb))

save disp5.mat x1 sdb % Saves parameters to disk
save disp6.mat ul vl w1
save disp7.mat x2 y1 y2
disp(')
else
else
if an==3
    clc
    graph2
else
    if an==4
        clc
        task3
else
    if an==5
        clc
        disp(')
        disp('Your Parameters have been saved')
        disp(')
        disp('Program is now aborted')
    end
end
end
end

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% Measurement Instrumentation Channel For Optical Detection System
% Task Two_C: (Program saved as Task2c)
% Aims of the Program:
% 1. To Calculate the laser beam shift on the photo detector using the bimorph non bend method

%%
clear

disp('Welcome to Task Two_C Of The Measurement Instrumentation Channel')
disp('')
disp('')
disp('1. Go back to Task Two')
disp('2. Calculate The Shift on photo detector )
disp('3. Observe graphical relationships between shift on detector and other parameters')
disp('4. Move on to Task Three of Measurement Instrumentation Channel')
disp('5. Exit Program')
%
disp('')
disp('')

an=input('Please Enter Your Choice... ');

if an==1
    disp('Task1')
else
    if an==2
        clear
doisp1
        load disp2
        load disp3
        B=asin(dx/r);
        disp('')
        u2=(r-r.*cos(B).*sin(B).*tan(B))./(tan(A.*pi/180).*tan(B)-1).*(cot(A)+tan(A.*pi/180+2.*B)));
        v2=(tan(A.*pi/180+2.*B)+tan(A.*pi/180));
        w2=(L.*cos(A.*pi/180).*cot(A.*pi/180)+L.*sin(A.*pi/180))/(cot(A.*pi/180)+tan(A.*pi/180+2.*B));
        x3=L.*cos(A.*pi/180);
        y3=-L.*sin(A.*pi/180));
        x4=u2.*v2+w2;
        y4=(u2.*v2+w2).*cos(A.*pi/180)+L.*cos(A.*pi/180)+L.*sin(A.*pi/180);
        disp('')
        sdn=sqrt((x3-x4).^2+(y3-y4).^2); % Shift on detector due to non_bending
        disp('')
    end
end

disp('Bimorph displacement/m  Distance of bimorph from detector/m  Shift on Photo detector/m')
disp('')

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Appendix C

Matlab Code

```matlab
disp(sprintf('%2.2e %2.2e %2.9e', dx, x, y))

save disp8.mat sdn x4 % Saves parameters to disk
save disp9.mat u2 v2 w2
save disp10.mat x3 y4 y3

else
    if an==3
        graph2
    else
        if an==4
            Task3
        else
            if an==5
                clc
                disp('Your Parameters have been saved')
                disp('Program is now aborted')
            end
        end
    end
end

% UNIVERSITY OF PLYMOUTH
% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% Name: Chibesa Chilumbu
% Date: 17/07/97
% Supervisor: Professor W.W. Clegg

% Measurement Instrumentation Channel For Optical Detection System
% Graph Two: (Program saved as Graph2)
% Aims of the Program:
% 1. To Investigate The Graphical Relationship between shift on photo detector and input Parameters for the PZT-5H bimorph
% clc
% disp('Welcome to Graph Two of The Measurement Instrumentation Channel')
% disp('1. Go back To Task Two of The Instrumentation Channel')
% disp('2. See how shift on photo detector varies as the displacement of the bimorph')
% disp('3. See how shift on photo detector varies as the length of the bimorph')
% disp('4. See how shift on photo detector varies as the distance between the bimorph and the detector')
% disp('5. See how shift on detector varies as the incident angle of the laser beam')
% disp('6. See error deviations between different models over a range of bimorph displacements')
% disp('7. Go on to Task Three of the Measurement Instrumentation Channel')
% disp('8. Exit Program')
% disp('Enter Your Choice Please... ');
% an=input('Enter Your Choice Please... ');
% disp('')
% disp('')
% disp('')
% disp('')
% if an==1
    Task2
```
else
    if an==2
        load disp1
        load disp2
        load disp3
        load disp4
        clc
        dx=zeros(0,0);  % Sets initial displacement to zero
        sdt=zeros(0,0);  % Sets initial shift on detector to Zero
        disp('Enter range of displacements to be investigated')
        disp('Enter the number of points to be plotted')
        a=input('Lower displacement in metres = ');  
        b=input('Upper displacement in metres = ');  
        disp('')
        n=input('Number of steps = ');  
        dx=linspace(a,b,n);
        sdt=(2.*L.*dx)./r;  % Shift on detector by trigonometry
        plot(dx,sdt,'r')
        grid
        title('Graph of Shift on detector against bimorph displacement')
        xlabel('Displacement of bimorph in metres')
        ylabel('Resulting shift on photo detector in metres')
    else
        if an==3
            load disp1
            load disp2
            load disp3
            load disp4
            clc
            r=zeros(0,0);  % Sets initial bimorph length to zero
            sdt=zeros(0,0);  % Sets initial shift on detector to Zero
            disp('Enter range of bimorph lengths to be investigated')
            disp('Enter the number of points to be plotted')
            a=input('Lower Length in metres = ');  
            b=input('Upper Length in metres = ');  
            disp('')
            n=input('Number of steps = ');  
            r=linspace(a,b,n);
            sdt=(2.*L.*dx)./r;  % Shift on detector by trigonometry
            plot(r,sdt,'g')
            grid
            title('Graph of Shift on detector against length of bimorph')
            xlabel('Length of bimorph in metres')
            ylabel('Resulting shift on photo detector in metres')
        else
            if an==4
                load disp1
                load disp2
                load disp3
                load disp4
                clc
                L=zeros(0,0);  % Sets initial distance to zero
Appendix C

Matlab Code

sdt=zeros(0,0); % Sets initial shift on detector to Zero
disp('')
disp('')
disp('Enter range of distances between bimorph and photo detector')
disp('')
a=input('Lower distance in metres= ');
b=input('Upper distance in metres=');
disp('')
disp('Enter the number of points to be plotted')
disp('')
n=input('Number of steps= ');

L=linspace(a,b,n);
sdi^2.*L.*dx)yr; % Shift on detector by trigonometry
plot(L,sdt,'b')
grid
title('Graph of Shift on detector against distance between bimorph and detector')
xlabel('distance between bimorph and photo detector in metres')
ylabel('Resulting shift on photo detector in metres')

else
  if an==5
    clc
    load disp1
    load disp2
    load disp3
    A=zeros(0,0); % Sets initial incidence angle to zero
    sdn=zeros(0,0); % Sets initial shift on detector to Zero
    disp('')
    disp('')
    disp('Enter range of incident angles to be investigated')
    disp('')
a=input('Lower Incident Angle in degrees= ');
b=input('Upper Incident Angle in degrees= ');
disp('')
disp('Enter the number of points to be plotted')
disp('')
n=input('Number of steps= ');

    A=linspace(a,b,n);
    B=asin(dx/a);
    disp('')
    disp('')
    u2=(r*cos(B)+r*sin(B).*tan(B))./(tan(A.*pi/180).*tan(B)-1).*tan(A.*pi/180+2.*B));
    v2=(tan(A.*pi/180+2.*B)+tan(A.*pi/180));
    w2=-(L.*cos(A.*pi/180)+L.*sin(A.*pi/180))./(cos(A.*pi/180)+tan(A.*pi/180+2.*B));
    x3=L.*cos(A.*pi/180);
    y3=-1.*(L.*sin(A.*pi/180));
    x4=u2.*v2+w2;
    y4=((u2.*v2+w2).*cos(A.*pi/180)-L.*cos(A.*pi/180).*cos(A.*pi/180)-L.*sin(A.*pi/180);
    disp('')
    sdn=sqrt((x3-x4).^2+(y3-y4).^2); % Shift on detector due to non_bending
    disp('')
    plot(A,sdn,'g')
    grid
    title('Graph of Shift on detector against Incident angle')
xlabel('Incident angle in degrees')
ylabel('Resulting shift on photo detector in metres')
else

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Matlab Code

if an==6
    Graph2a
else
    if an==7
        Task3
else
    if an==8
        clc
disp('')
disp('Thankyou for using the Measurement Instrumentation Channel')
disp('')
disp('')
disp('Program is now aborted')
    end
end
end
end

% UNIVERSITY OF PLYMOUTH
% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% %
% % Name: Chibesa Chilumbu
% % Date: 17/07/97
% % Supervisor: Professor W.W. Clegg

% Measurement Instrumentation Channel For Optical Detection System
% % Graph Two_A: (Program saved as Graph2a)
% %
% % Aims of the Program:
% %
% % 1. To Investigate Error deviations between the models used in Task Two
% %
% clc
% %
% disp('')
disp('Welcome to Graph Two_A of The Measurement Instrumentation Channel')
disp('')
disp('')
%
disp('1. Go back To Task Graph2 of The Instrumentation Channel')
disp('2. Error deviation between bimorph bending and approx. trig. methods')
disp('3. Error deviation between bimorph non bending and approx. trig. methods')
disp('4. Error deviation between bimorph bending and bimorph non bending methods')
disp('5. Go on to Task Three of the Measurement Instrumentation Channel')
disp('6. Exit Program')
%
disp('')
disp('')
an=input('Enter Your Choice Please... ');%
disp('')
disp('')
%
if an==1
    Graph2
else
    if an==2
        clc
        load disp1
        load disp2
        load disp3
        load disp4
        load disp5
        load disp6

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Appendix C

Matlab Code

```matlab
load disp7
clc
dx=zeros(0,0); % Sets initial displacement to zero
dsd=zeros(0,0); % Sets initial shift on detector to zero
dsb=zeros(0,0);
disp('')
disp('')
disp('Enter range of displacements to be investigated')
disp('')
a=input('Lower displacement in metres= ');
b=input('Upper displacement in metres= ');
disp('')
disp('Enter the number of points to be plotted')
n=input('Number of steps= ');

dx=linspace(a,b,n);
sdr=(2.*L.*dx)/r; % Shift on detector by trigonometry
D=dx/r;
disp('')

ul=(r*D.*cos(D)-r)/(D.*(tan(A.*pi/180)-tan(D)));
v1=(tan(A.*pi/180)+tan(A.*pi/180))/((A.*pi/180)+tan(A.*pi/180)+tan(A.*pi/180+2.*D));
w1=(L.*cos(A.*pi/180).*cos(A.*pi/180)+L.*sin(A.*pi/180))./(cos(A.*pi/180)+tan(A.*pi/180)+tan(A.*pi/180+2.*D));

x1=L.*cos(A.*pi/180);
y1=L.*sin(A.*pi/180);
x2=x1.*v1+w1;
y2=((x1.*v1+w1).*cos(A.*pi/180)-L.*cos(A.*pi/180)-L.*sin(A.*pi/180));
disp('')
sdb=sqrt((x2-xl).^2+(y2-yl).^2); % Shift on detector due to bending

semilogx(dx,(sdb-sd1),'r')
grid
title('Graph of Error deviation between bimorph bending and Approx. trig. methods')
xlabel('displacement of bimorph in metres')
ylabel('Error in shift between the two models in metres')
else
if an==3
load disp1
load disp2
load disp3
load disp4
load disp8
load disp9
load disp10

clc
dx=zeros(0,0); % Sets initial bimorph displacement to zero
dsd=zeros(0,0); % Sets initial shift on detector to Zero
dsb=zeros(0,0);
disp('')
disp('')
disp('Enter range of bimorph displacements to be investigated')
disp('')
a=input('Lower displacement in metres= ');
b=input('Upper displacement in metres= ');
disp('')
disp('Enter the number of points to be plotted')
n=input('Number of steps= ');

dx=linspace(a,b,n);
```

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Appendix C

Matlab Code

\[ sdt = \frac{2 \cdot L \cdot dx}{r}; \quad \text{% Shift on detector by trigonometry} \]
\[ \text{disp('')} \]
\[ B = \arcsin(dx/r); \quad \text{disp('')} \]
\[ \text{disp('')} \]
\[ u2 = (r - r \cdot \cos(B) + r \cdot \sin(B) \cdot \tan(B))/((\tan(A \cdot \pi/180) \cdot \tan(B) - 1) \cdot (\cot(A) + \tan(A \cdot \pi/180 + 2 \cdot B)); \]
\[ \text{disp('')} \]
\[ v2 = (\tan(A \cdot \pi/180 + 2 \cdot B) + \tan(A \cdot \pi/180)); \]
\[ \text{disp('')} \]
\[ w2 = (L \cdot \cos(A \cdot \pi/180) \cdot \cot(A \cdot \pi/180) + L \cdot \sin(A \cdot \pi/180))/((\cot(A \cdot \pi/180) + \tan(A \cdot \pi/180) + \tan(A \cdot \pi/180 + 2 \cdot B)); \]
\[ \text{disp('')} \]
\[ x3 = L \cdot \cos(A \cdot \pi/180); \quad y3 = -1 \cdot (L \cdot \sin(A \cdot \pi/180)); \]
\[ x4 = u2 \cdot v2 + w2; \quad y4 = ((u2 \cdot v2 + w2) \cdot \cot(A \cdot \pi/180) - L \cdot \cos(A \cdot \pi/180) - L \cdot \sin(A \cdot \pi/180); \]
\[ \text{disp('')} \]
\[ \text{sdn} = \sqrt{(x3 - x4)^2 + (y3 - y4)^2}; \quad \text{% Shift on detector due to non_bending} \]
\[ \text{disp('')} \]
\[ \text{semilogx(dx, (sdn - sdt), 'v')}; \]
\[ \text{grid} \]
\[ \text{title ('Graph of Error deviation between bimorph non bending and Approx. trig. methods');} \]
\[ \text{xlabel ('displacement of bimorph in metres');} \]
\[ \text{ylabel ('Error in shift between the two models in metres');} \]
\[ \text{clc} \]
\[ \text{load displ} \]
\[ \text{load disp2} \]
\[ \text{load disp3} \]
\[ \text{load disp5} \]
\[ \text{load disp6} \]
\[ \text{load disp7} \]
\[ \text{load disp8} \]
\[ \text{load disp9} \]
\[ \text{load displ0} \]
\[ \text{dx = zeros(0,0);} \quad \text{% Sets initial displacement to zero} \]
\[ \text{sdn = zeros(0,0);} \quad \text{% Sets initial shift on detector to Zero} \]
\[ \text{disp ('')} \]
\[ \text{disp('Enter range of bimorph displacements to be investigated');} \]
\[ \text{disp('')} \]
\[ a = \text{input('Lower bimorph displacement in metres = ')}; \]
\[ b = \text{input('Upper bimorph displacement in metres = ')}; \]
\[ \text{disp('')} \]
\[ \text{disp('Enter the number of points to be plotted');} \]
\[ \text{disp('')} \]
\[ n = \text{input('Number of steps = ')}; \]
\[ \text{dx = linspace(a,b,n);} \]
\[ D = dx/r; \]
\[ \text{disp('')} \]
\[ u1 = (r \cdot \cos(D) - r \cdot \tan(A \cdot \pi/180) \cdot \cot(D)); \]
\[ \text{disp('')} \]
\[ v1 = (\tan(A \cdot \pi/180 + 2 \cdot D) + \tan(A \cdot \pi/180))/((\cot(A \cdot \pi/180) + \tan(A \cdot \pi/180 + 2 \cdot D)); \]
\[ \text{disp('')} \]
\[ w1 = (L \cdot \cos(A \cdot \pi/180) \cdot \cot(A \cdot \pi/180) + L \cdot \sin(A \cdot \pi/180))/((\cot(A \cdot \pi/180) + \tan(A \cdot \pi/180 + 2 \cdot D)); \]
\[ \text{disp('')} \]
\[ x1 = L \cdot \cos(A \cdot \pi/180); \quad y1 = -L \cdot \sin(A \cdot \pi/180); \]
\[ x2 = u1 \cdot \sin(A \cdot \pi/180); \]
\[ y2 = ((u1 \cdot \sin(A \cdot \pi/180)) - L \cdot \cos(A \cdot \pi/180) - L \cdot \sin(A \cdot \pi/180); \]
\[ \text{disp('')} \]

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% UNIVERSITTY OF PLYMOUTH
% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% Name: Chibesa Chilumbu
% Date: 22/07/97
% Supervisor: Professor W.W. Clegg

\% Measurement Instrumentation Channel For Optical Detection System
\% Task Three: (Program saved as Task3)
\% Aims of the Program:
\% 1. To Calculate the output voltage after current to voltage conversion
\% 2. To analyse how to get a maximum output voltage by changing certain parameters

sdb=sqrt((x2-x1)^2+(y2-y1)^2); \% Shift on detector due to bending

elseif

sdn=sqrt((x3-x4)^2+(y3-y4)^2); \% Shift on detector due to non_bending

elseif

end

clc

end
Appendix C

Matlab Code

disp('')
disp('Welcome to Task Three Of The Measurement Instrumentation Channel')
disp('')
disp('')
disp('')

% PL = input('Enter Power of Laser that hits the photo detector in Watts '); disp('')
sp = input('Enter sensitivity of photo diode at in Amps per Watts '); disp('')
RF = input('Enter value of Current to Voltage feedback resistor in ohms '); disp('')
R1 = input('Enter value of Differential Amplifier input resistor in ohms '); disp('')
R2 = input('Enter value of Differential Amplifier feedback resistor in ohms '); disp('')
g = input('Enter dead space of photo detector in metres '); disp('')
save disp1.mat PL sp RF % Saves parameters to disk
save disp2.mat R1 R2
clc
disp('Please Enter Your Choice Now... ')
disp('')
disp('')
disp('1. Go back to Task Two')
disp('2. Calculate Voltage output with a uniform power distribution')
disp('3. Calculate Voltage output with a Gaussian power distribution')
disp('4. To see how Sensitivity varies as spot size of beam')
disp('5. Exit Program')
%
disp('')
disp('')
an=input('Please Enter Your Choice... ');

if an==1
  Task2
else
  if an==2
    Task3a
  else
    if an==3
      Task3b
    else
      if an==4
        Task3c
      else
        if an==5
          cle
disp('Your Parameters have been saved')
disp('')
disp('Program is now aborted')
        end
      end
    end
  end
end
%%
%% Task Three_A: (Program saved as Task3a)
%%
%% Aims of the Program:
%%
%% 1. To Calculate the output voltage for a uniform power distribution
%%
%%
%% clc
disp('')
disp('Welcome to Task Three_A Of The Measurement Instrumentation Channel')
disp('')
disp('')
disp('Please Choose from below..')
disp('')
disp('1. Go back to Task Three')
disp('2. Calculate Voltage output of circular beam of uniform power')
disp('3. Calculate Voltage output of elliptical beam of uniform power')
disp('4. Exit Program')
% disp('')
disp('')
an=input('Please Enter Your Choice... '):

if an==1
    disp('')
    Task3
else
    if an==2
        clear
clc
load disp5
load disp11
load disp12
disp('')
b = input('Enter beam radius in metres ');
disp('')
A1_A2 = (sqrt(4*b'^2-(2*sdb+g)'^2))*(g+2*sdb)/(2*b))+(2*sdb*g)/(2*b)'
Vout1 = ((Rf/R2)/R1)*((pi*b'^2))'*sp*(A1_A2);
('Power of Laser/W Irradiance/W/m Voltage output/V)'
disp('')
disp(sprintf('%2.2e %2.2e %2.2e',PL,P17(pi*b'^2),Vout1))
save disp13.mat Vout1
else
    if an==3
        clear
clc
load disp5
load disp11
load disp12
disp('')
a = input('Enter y-axis value of ellipse in metres ');
disp('')
disp('')
b = input('Enter x-axis value of ellipse in metres ');
disp('')
A1_A2=2*a*((1/(8*a^2))+(b^2*g(1-2*a)*sqrt(a+2-g^2)))*d*b*a^2...
% *(asin((1/(2*a)))*sqrt(a+2-g^2))+(4*g*a^2)*d*b*...
% *(asin((1/(2*a)))'*sqrt(a+2-g^2))+(4*g*a^2)*d*b*...
% *(asin((1/(2*a)))'*sqrt(a+2-g^2))+(4*g*a^2)*d*b*...
% *(asin((1/(2*a)))'*sqrt(a+2-g^2))+(4*g*a^2)*d*b*...
% *(asin((1/(2*a)))'*sqrt(a+2-g^2))+(4*g*a^2)*d*b*...

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Appendix C

Matlab Code

```matlab
% % a'^2*(asin((1/(2*a))*sqrt(4*a'^2-g^2)))+(4*a'^2*g/sdb))...
% -(1/(2*b)^2)*(-2*2*b*(g^2))/(g^2*sdb)+sqrt(4*2*b^2-g^2...% +4*b^2*sin((g^2*sdb)/(2*b))));
Vout2 = ((-Rf/R2)/(PL/(pi*b*o)))*sp*(A1/A2);

('Power of Laser/W Irradiance/W/m/m Voltage output/V')
disp('------------------------------------------------------------')
disp(sprintf('%2.2e %2.2e %2.2e',PL/(pi*b*o),Vout2))
save disp14.mat Vout2
else
if an==4
    disp('Your Parameters have been saved')
disp('Program is now aborted')
end
end

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% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% Name: Chibesa Chilumbu
% Date: 29/09/97
% Supervisor: Professor W.W. Clegg

% Measurement Instrumentation Channel For Optical Detection System
% Task Three_B: {Program saved as Task3b}
% Aims of the Program:
% I. To Calculate the output voltage for a Gaussian power distribution
% clc
disp('Please Choose from below...')
disp('1. Go back to Task Three')
disp('2. Calculate Voltage output of circular beam of Gaussian power distribution')
disp('3. Calculate Voltage output of elliptical beam of Gaussian power distribution')
disp('4. Exit Program')
if an==1
    Task3
else

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```
Appendix C

Matlab Code

if an==2
    clear
    clc
    load disp5
    load disp11
    load disp12
    disp('')
    w = input('Enter spot size of Gaussian beam in metres ');
    disp('')
    P1_P2 = (-PL/4)*((1+erf(g/w)*sqrt(2)))*((erf((2*sdb-g)/(w*sqrt(2))))+erf(2*sdb+g)/(w*sqrt(2))))
    disp('')
    Vout3 = ((R1*R2)/R1)*sp*(P1_P2);

('Power of Laser/W  Voltage output/V')
        disp('')
        disp(sprintf('%.2e %.2e %.2e %.2e %.2e', PL, PU(pi*b*a), Vout2))
        save disp14.mat Vout2
    else
        if an==3
            clear
            clc
            load disp5
            load disp11
            load disp12
            disp('')
            a = input('Enter y-axis value of ellipse in metres ');
            disp('')
            disp('')
            b = input('Enter x-axis value of ellipse in metres ');
            disp('')
            disp('')
            \% A1_A2=2*a*((1/(8*a^2))*b^2*b*(1-2*a)*sqrt(4*a^2-g^2))-4*b*a^2...
            \% -((1/(2*a))^(-2)*b^2*b*(1-2*a)*sqrt(4*a^2-g^2))+(4*b^2*a^2*sdb)... % +4*b^2*asin((g/(2*a))*sqrt(4*a^2-g^2))+(4*b^2*a^2*sdb)... % -((1/(2*a))^(-2)*b^2*b*(1-2*a)*sqrt(4*a^2-g^2))+(4*b^2*a^2*sdb)... % +4*b^2*asin((g/(2*a))*sqrt(4*a^2-g^2))+(4*b^2*a^2*sdb)... % +4*b^2*asin((g+(2*a^2))/(2*b)));
            disp('')
            Vout2 = ((-Rf*R2)/R1)*PL/(pi*b*a)*sp*(A1_A2);

('Power of Laser/W  Irradiance/W/m/m  Voltage output/V')
        disp('')
        disp(sprintf('%.2e %.2e %.2e %.2e %.2e', PL, PU(pi*b*a), Vout2))
        save disp14.mat Vout2
    else
        if an==4
            clear
            disp('')
            disp('Your Parameters have been saved')
            disp('')
            disp('')
            disp('Program is now aborted')
            end
            end
            end
            end
            end
            end
            % UNIVERSITY OF PLYMOUTH

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Appendix C

Matlab Code

% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% 
% Name: Chibesa Chilumbu
% Date: 08/10/97
% Supervisor: Professor W.W. Clegg

% Measurement Instrumentation Channel For Optical Detection System
% 
% Aims of the Program:
% 
% I. To Investigate How The Sensitivity varies as the beam radius of a uniform circular beam
% 
clc

disp('Welcome to Graph Three_A of The Measurement Instrumentation Channel')

% Enter range of beam radii to be investigated

a=input('Lower radius in metres= ');

h=input('Upper radius in metres= ');

% Enter the number of points to be plotted

n=input('Number of steps= ');

b=linspace(a,h,n);

S=((Rf*R2)./RI).^2.*pl./(pi.*b.^2)).*sp.*(sqrt(4.*b.^2+4.*g.*sdb-4.*sdb.^2-g.^2));

plot(b,S/n)

grid
title('Graph of Sensitivity against spot radius')
gtext('g=30')

xlabel('radius of beam in metres')
ylabel('Sensitivity in Volts/metre')

end

% UNIVERSITY OF PLYMOUTH
% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% 
% Name: Chibesa Chilumbu
% Date: 17/04/98
% Supervisor: Professor W.W. Clegg

% Measurement Instrumentation Channel For Optical Detection System
% 
% Aims of the Program:
% 
% I. To Investigate How The Sensitivity varies as the beam radius of a uniform elliptical beam
% 
clc
Appendix C

Matlab Code

```matlab
% disp('')
disp('Welcome to Graph Three_B of The Measurement Instrumentation Channel')
disp('')
disp('')

% disp('')
clc
load disp5
load disp11
load disp12
load disp15

b=zeros(0,0); % Sets initial displacement to zero
S=zeros(0,0); % Sets initial shift on detector to Zero
disp('')
disp('')
disp('Enter range of beam radii to be investigated')
disp('')

c=a=input('Lower radius in metres= ');
h=input('Upper radius in metres= ');
disp('')
disp('Enter the number of points to be plotted')
disp('')
n=input('Number of steps= ');

d=linspace(a,h,n);

S = ((1/(2*pi))*((R*R1)/((pi)*b.*2))).*exp(-((sqrt(4*b.*2+4*g.*sdb-4*sdb.*2-g.*2)+sqrt(4*b.*2-4*g.*sdb-4*sdb.*2-g.*2))/2));
ploa(b,S,')
grid
title('Graph of Sensitivity against spot radius')
gtext('g=30')
xlabel('radius of beam in metres')
ylabel('Sensitivity in Volts/metre')
end
end
```

% UNIVERSITY OF PLYMOUTH
% School of Electronic, Communication And Electrical Engineering
% Centre for Research in Information Storage Technology
% 
% Name: Chibesa Chilumbu
% Date: 29/09/97
% Supervisor: Professor W.W. Clegg

% Measurement Instrumentation Channel For Optical Detection System
% 
% Graph Three_C: [Program saved as Graph3c]
% 
% Aims of the Program:
%
% 1. To Investigate How The Sensitivity varies as the spot size for a circular Gaussian beam
%
clc
% disp('')
disp('Welcome to Graph Three_C of The Measurement Instrumentation Channel')
disp('')
disp('')
disp('')
clc
load disp5
load disp11
load disp12
load disp15

w=zeros(0,0); % Sets initial displacement to zero
S=zeros(0,0); % Sets initial shift on detector to Zero

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Matlab Code

disp('Enter range of beam radii to be investigated')
disp('')
a=input('Lower radius in metres= ');
b=input('Upper radius in metres= ');
disp('')
disp('Enter the number of points to be plotted')

disp('')
n=input('Number of steps= ');

wx=linspace(a,b,n);
wy=60e-6;

S = ((R1*R2*PL*sp*2*sqrt(2))./(R1.*w.*sqrt(pi))).*(exp(-(4.*sdb-g).^2))./(2.*w.^2);

plot(wx,S,w)
grid
title('Graph of Sensitivity against spot size')
xlabel('Spot radius of laser beam in metres')
ylabel('Sensitivity in volts per metre')
Appendix C

Matlab Code

```matlab
%gtext('g=IOO')
xlabel('Spot size of beam in metres')
ylabel('Sensitivity in volts per metre')
end

%Name: Program 1
%Closed loop response for PID and Plant
%a=5.892e-4; %b=1.437709e-4; 
a=175e-6; %b=42.86e-6; 
c=116.7766; 
d=100; 
Kp=17.5; 
K=0.23; %Gain is between 0.2 and 0.3
num=[0 a*b*c*Kp*Kp*Kp*Kp*Kp*Kp];
den=[a d+a*b*c*Kp a*c-a*c*Kp c*Kp*Kp]; 
%dt=0.000001:0.005; 
step(num,den)
grid

% % %Bode plot analysis of system OLTF(Flying Height control)

%Closed loop response for PID and Plant: Flying Height Control
%KI=2500; %Integral gain
KD=3.378e-3; %Derivative gain
KP=2.2542; %Proportional constant
K=0.4265; %OBD sensor gain is between 0.42 and 0.43
c=0.7746; %wn^2

d=1.7964; %2*wn*p

%Open-loop transfer function
num=[0 KD*Kp*Kp*Kp*Kp*Kp];
den=[1 d c 0]; 

%w=1e4:1e4:1e5;
w=logspace(-2.5,100000);
[mag,pha,w] = bode(num,den,w);
magdB=20*log10(mag);

%Phase and gain margins
[Gm, Pm, Wcg, Wcp] = margin(magdB, pha, w)
bode(num,den)
grid

% % %Bode plot analysis to find Bandwidth
%(Flying Height control)

%Closed loop response for PID and Plant: Flying Height Control

%KI=1500; %Integral gain
KD=2.834e-3; %Derivative gain
KP=2.2542; %Proportional constant
K=0.4265; %OBD sensor gain is between 0.42 and 0.43
c=0.7746; %wn^2

d=1.7964; %2*wn*p

%Closed loop transfer function
num=[0 KD*Kp*Kp*Kp*Kp*Kp];
den=[1 d c*KD c*Kp c*Kp*Kp*Kp]; 

%w=logspace(-2.5,100000);
%[mag,pha,w] = bode(num,den,w);
%magdB=20*log10(mag);

%Phase and gain margins
[Gm, Pm, Wcg, Wcp] = margin(magdB, pha, w)
bode(num,den,w)
grid

% % %Bode plot analysis to find Bandwidth
%(Flying Height control)
```

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Appendix C

Matlab Code

% PID compensator alone with Plant

% \(a = 290.5 \times 10^{-6};\)
% \(b = 72.674 \times 10^{-6};\)
% \(c = 2 \times 10^{-3};\)
% \(d = 0.62 \times 10^{-3};\)
% \(e = 0.774 \times 10^{6};\)
% \(K_p = 10;\)
% \(k = 0.38;\)

\[
\text{num} = [0, K_p \times k \times k \times k \times k \times k];
\]
\[
\text{den} = [a \times d \times c \times 0];
\]
\[
\text{w} = \left[ \begin{array}{c}
1 \\
1.e4 \\
1.e5 \\
\end{array} \right];
\]
\[
[\text{mag}, \text{pha}, \text{w}] = \text{bode(num, den});
\]
\[
[\text{Wcg}, \text{Wcp}] = \text{margin(mag, pha, w)};
\]
\[
\text{bode(num, den)}
\]
\[
\text{subplot(2)};
\]
\[
\text{grid}
\]

%% Bode plot analysis of CLTF to find Bandwidth
%% of data tracking system

% \(k_l = 25000;\)
% \(K_D = 2.7117 \times 10^{-6};\)
% \(K_P = 1.5578;\)
% \(k = 0.3324;\)
% \(a = 116.77 \times 10^{-6};\)
% \(d = 100;\)

% Closed loop transfer function
\[
\text{num} = [0, K_D \times k \times k \times k \times k \times k];
\]
\[
\text{den} = [1 + c \times k \times K_D \times c \times k \times k \times k \times k];
\]
\[
\text{w} = \text{logspace(-2, 5.100000)};
\]
\[
[\text{mag}, \text{pha}, \text{w}] = \text{bode(num, den, w)};
\]
\[
\text{magdB} = 20 \times \log_{10} \text{mag};
\]
\[
[\text{Gm}, \text{Pm}, \text{Wcg}, \text{Wcp}] = \text{margin(magdB, pha, w)};
\]
\[
\text{bode(num, den, w)}
\]
\[
\text{subplot(2)};
\]
\[
\text{grid}
\]

%% Bode plot analysis of CLTF to find Bandwidth
%% of system

% \(K_I = 25000;\)
% \(K_D = 2.7117 \times 10^{-6};\)
% \(K_P = 1.5578;\)
% \(k = 0.3324;\)
% \(a = 116.77 \times 10^{-6};\)
% \(d = 100;\)

% Closed loop transfer function
\[
\text{num} = [0, K_D \times k \times k \times k \times k \times k];
\]
\[
\text{den} = [1 + c \times k \times K_D \times c \times k \times k \times k \times k];
\]
\[
\text{w} = \text{logspace(-2, 5.100000)};
\]
\[
[\text{mag}, \text{pha}, \text{w}] = \text{bode(num, den, w)};
\]
\[
\text{magdB} = 20 \times \log_{10} \text{mag};
\]
\[
[\text{Gm}, \text{Pm}, \text{Wcg}, \text{Wcp}] = \text{margin(magdB, pha, w)};
\]
\[
\text{bode(num, den, w)}
\]
\[
\text{subplot(2)};
\]
\[
\text{grid}
\]
Appendix C

Matlab Code

grid

% Nyquist stability criterion OLTF for PID/Plant (Flying Height)
% KI=1250; % Integral gain
% KD=1.9947e-3; % Derivative gain
% Kp=0.7228; % Proportional constant
% k=0.4265; % OBD sensor gain is between 0.42 and 0.43
% a=Kp/KI; % Integral time
% b=KD/Kp; % Derivative time
% c=0.774e6; % wn^2
% d=1.796e4; % 2*wn*p

% Open loop transfer function for Nyquist stability criterion
num=[0 KD*k*c Kp*k*c*KI];
den=[1 d c 0];

% w=0.1:1:100000;
[re,im,w]=nyquist(num,den,w);
plot(re,im)
v=[-20 45 -60 51]; axis(v)
grid
title('Nyquist Plot')

% Nyquist stability criterion OLTF for PID and Plant
KI=25000; % Integral gain
KD=2.7117e-4; % Derivative gain
KP=1.5578; % Proportional constant
k=0.3324; % OBD sensor gain is between 0.33 and 0.34
% c=116.77e6; % wn^2
% d=100;

% Open loop transfer function for Nyquist stability criterion
num=[0 KD*k*c Kp*k*c*KI];
den=[1 d c 0];

% w=0.1:1:100000;
[re,im,w]=nyquist(num,den,w);
plot(re,im)
v=[-20 45 -60 51]; axis(v)
grid
title('Nyquist Plot')

% Compensator parameters for tracking stage
% KI=[0.005 0.05 0.5];
% phim=50;
% w1=13.426e3;
Gpnum=[0 0 16.77e6*0.23]; Gpden=(1 100 16.77e61-

% for k=1:3
Gp1=conv(Gpden,Gpnum)+conv(Gpnum,Gp1);
theta=pi+phim/57.296-angle(Gp1);
Kp=cos(theta)/Gp1mag;
KD=sin(theta)/(w1*Gp1mag+Kp)/(w1^2);

% Gcnum=[0 KD KP K1];
Gcden=[1 100 116.77e6];
q=conv(Gpden,Gcden)+conv(Gpnum,Gcnum);
r=roots(q)
disp('press any key to continue...'), pause
end

% Compensator parameters for tracking stage
% KI=500;
% phim=50;
% w1=13.426e3;
Gpnum=[0 0 116.77e6*0.23]; Gpden=[1 100 116.77e6];
% for k=1:3
Appendix C

Matlab Code

Gpjw1=polyval(Gpnum,J*w1)/polyval(Gpden,J*w1);
Gpjw1mag=abs(Gpjw1);
theta=pi+phim/57.296-angle(Gpjw1);
KP=cos(theta)/Gpjw1mag;
KD=sin(theta)/(w1*Gpjw1mag)+KI/w1^2;

KP,KI,KD

% Gpnum=[KD KP KI(k)];
% Gpden=[0 1 0];
% q=conv(Gpden,Gpden)+conv(Gpnum,Gpnum);
% r=roots(q)
% disp('press any key to continue...'),pause
%end

%Root-locus plot CLTF for PID and Plant (Flying Height)

% KI=1250; %Integral gain
KD=1.9447e-3; %Derivative gain
KP=0.72284; %Proportional constant
k=0.4265; %OBD sensor gain is between 0.42 and 0.43
c=0.77466; %wn^2
d=1.7964; %2*wn*p

%Open loop transfer function

num=[0 KD*K c*K*K*K*K*K];
den=[1 d 0];
%disp(0.000001:0.005)
rlcous(num,den)
grid

%Root-locus plot showing CLTF path for PID and Plant

KI=2500; % Integral gain
KD=2.7174e-4; %Derivative gain
KP=1.5578; %Proportional constant
k=0.3324; % OBD sensor gain is between 0.33 and 0.34
c=116.776; %wn^2
d=100;
%Open loop transfer function

num=[0 KD*K c*K*K*K*K*K];
den=[1 d 0];
%disp(0.000001:0.005)
rlcous(num,den)
grid

%Closed loop response for PID and Plant: Flying Height Control

% KI=2000; %Integral gain
KD=3.1009e-3; %Derivative gain
KP=2.2542; %Proportional constant
k=0.4265; %OBD sensor gain is between 0.42 and 0.43
a=KP/KI; %Integral time
b=KD/KP; %Derivative time
c=116.776; %wn^2
d=1.7964; %2*wn*p

%Closed-loop transfer function

num=[a*b*c*K p k*K p a*c c*K p];
den=[a a*d a*b*c*K*K p a*c a*c*K p c*K*K];
%disp(0.000001:0.005)
step(num,den)
grid

%PID compensator alone with Plant, Tracking

%a=290.5e-6;
%b=72.674e-6;
c=116.776;
d=100;
Appendix C

Matlab Code

Kp=17.5;
k=0.23;

num=[0 Kp*a*b k*Kp*a*c k*Kp*c];
den=[a a*d a*c 0];
%s=s-1e4:1e4:1e5;
[mag,pha,w]=bode(num,den);
[bode(num,den)]

% Name: Program 4
% Closed-loop response for PID and Plant: Flying Height Control
% %
% KI=2000; %Integral gain
KD=3.1009e-3; %Derivative gain
Kp=2.2542; %Proportional constant
k=0.4265; %OBD sensor gain is between 0.42 and 0.43
a=Kp/KI; %Integral time
b=KD/Kp; %Derivative time
c=0.774e6; %wn^2
d=1.7964; %2*wn*p
%
% Closed-loop transfer function
num=[0 a*b*c*Kp k*Kp*a*c k*Kp*c];
den=[a a*d a*h*Kp k*Kp a*c+c*Kp a*d+a*b+c*Kp c*Kp];
%s=0.0.0.0.0.0.0.0.0.0.0.0.
step(num,den)
grid

%
Appendix D  PCB Layouts for the Electronic circuits

Fig. D1 (a) Bottom layer for the differential circuit

Fig. D1 (b) Component side for the differential circuit

Fig. D2 (a) Bottom layer for the summing circuit

Fig. D2 (b) Component side for the summing circuit
APPENDIX E  
PCB connections and external wiring

Fig. E1 PCB connections and wiring for summing circuit

Input from diff
- J3

DR (orange)
- J2

UL (light green)
- J1

Output to diff
- J4

Signal output (brown wire)
- J3

+15 V (red wire)
- J6

-15 V (blue wire)
- J7

Ground (black wire)
- Shielding (black wire)

Fig. E2 PCB connections and wiring for differential circuit

Input from sum
- J3

UR (light brown)
- J2

DL (dark green)
- J1

Output to sum
- J4

Signal output (pink wire)
- J3

+15 V (red wire)
- J6

-15 V (blue wire)
- J7

Ground (black wire)
- Shielding (black wire)

The output signals J4s are connected to a 2-wire insulated cable via a 4-pin socket. The pink wire from the differential circuit is connected to the white wire in the cable and the brown wire from the summing circuit is connected to the black wire in the cable. The output ground from both PCBs is connected to the insulation wire screen and this forms a common ground for both output signals. The power rail wires are connected to an external cable via a 3-pin socket. Each colour wire is connected to another of the same colour in the cable.
Proposed Suspension arm to give control over data tracking and head flying height

Fig. F1 Detailed drawing of novel suspension arm, capable of 2-dimensional motion.
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Multi-layer bulk PZT actuators for flying height control in ruggedised hard disk drives

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Abstract — When a hard disk drive is operated under hostile conditions fluctuations of the head flying height affect data-transfer, eventually leading to complete data-transfer failure. A test facility has been developed to enable data-transfer and their associated failure mechanisms to be characterised. In order to circumvent this problem and to obtain greater control of the head flying height a novel suspension arm has been developed which incorporates multi-layer bulk PZT actuators. This will enable real-time active adjustment of the head flying height with high precision and accuracy, while the disk drive is in operation. The arm developed is tested dynamically and characterised, and specialised closed-loop control algorithms developed to position and control the head above the disk surface.

INTRODUCTION

Hard disk drives are an economical form of mass storage, widely used as secondary memory in virtually all computer systems. Conventional hard drives are very reliable under normal operating conditions, but they can suffer from mechanically induced failure when operated in hostile conditions. Environments such as military and aerospace are synonymous with large shocks and vibrations. Ocean going craft can also encounter difficulties with hard drives as the engine and waves transmit vibrations through the hull. Dennis [1] evaluated many proposed solutions, though mainly large vibration isolation cages and mountings that damped the vibrations. However, additional isolation mountings are not the ideal solution. The extra space and weight needed precludes this method from many key areas: adding both weight and bulk to a drive is hardly an improvement. Passive dampers, which are only effective over a limited bandwidth, are all that are used in current ‘ruggedised’ laptops.

The data-storage recording densities of magnetic hard disk drives (HDDs) have doubled every 18 months in recent years. IBM recently demonstrated a storage density of 35.3 GB/in$^3$ [2]. In order to realise high track and storage densities of 40 GB/in$^3$ or more, flying height will be reduced to around 5-10 nm. One approach that has been considered to achieve such low flying heights is the use of an extremely smooth disk surface to enhance the slider flying stability and reduce thermal noise created by friction. This approach may, however, require zone texturing, when the conventional contact-start-stop (CSS) is used, to avoid serious head-disk damage [3]. Although a load/unload process has been proposed to address this problem [4], the challenge is to be able to maintain the correct flying height in conditions of shock and vibration while the drive is in operation. This is especially useful in portable hard disk drives or dedicated drives being used in critical applications for military and medical purposes, or fieldwork such as mineral exploration, sporting activities or even space navigation.

In this paper, a novel feature that incorporates actively controlling the correct flying height while the HDD is in operation is presented. Through careful design and with the use of multi-layer bulk PZT actuators, the suspension arm is able to realise motion in two orthogonal axes. One corresponds to motion required to provide fine data tracking and the other, precision flying height control. In current commercial HDDs, the net loading force is approximately 35mN during normal operation [5]. An adjustment of ±10mN of this loading force would result in a change in the flying height of about ±20%, giving sufficient tolerance for active flying height control.

DISK DRIVE FUNDAMENTALS

It is important to understand precisely what is happening within the drive, and which systems areas are failing under conditions of vibration. There are two major mechanical components that, when excited at resonance, can result in data-transfer failure. Firstly, there is the suspension arm that pre-tensions the head against the disc. This is designed to control the flying height of the head during normal operating conditions. If the flying height of the head is such that it is outside of its normal operating range, then the signal degrades, and ultimately can lead to data-transfer failure. In severe cases, the head will crash down onto the disk and cause irrecoverable damage. Secondly, there is the hard disk itself. The disk can be driven such that it flutters up and down, causing tracking (or mis-registration) problems [6]. The problem can be compounded by the fact that if the suspension arm is resonating, and therefore the head, the disk can be driven into oscillation due to the head pushing onto the disc and vice-versa [7, 8].

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SUSPENSION ARM CHARACTERIZATION

Fig. 3: Proposed suspension arm concept.

When the optical beam detection technique is used, the probe beam is reflected by the suspension arm's deflection and is detected by a laser sensor. The reflected beam is then used to calculate the suspension arm's deflection and to control the position of the probe head. The probe head is then used to control the position of the probe head. The probe head is then used to control the position of the probe head.

DVA LOSS PREVENTION

DVA is a transfer function that describes the transfer function from the input to the output of a system. In the case of a suspension arm, the DVA is used to prevent loss of damping and to ensure that the suspension arm remains stable.

Fig. 1: Displacement of the suspension arm.

A set of experiments were conducted to measure the

Fig. 2: Frequency response of the suspension arm.

The results of these experiments are shown in Figure 2. The results show that the suspension arm is effective in preventing loss of damping.

DVA DRIVE CHARACTERIZATION

The results of these experiments are shown in Figure 2. The results show that the suspension arm is effective in preventing loss of damping.

A set of experiments were conducted to measure the

Fig. 1: Displacement of the suspension arm.

The results of these experiments are shown in Figure 2. The results show that the suspension arm is effective in preventing loss of damping.
resonance effects in the orthogonal plane, and vice-versa. The results are shown in Figure 4 and it can be seen that the fundamental resonance is at 140 Hz, although because of its complex mechanical structure there are other resonances at higher frequencies. It is important to remember that due to the complex nature of the arm, resonance in one stage of motion does induce resonances in other stage of motion (used for track following).

Where $K_i$ is the integral gain, $K_d$ is the derivative gain and $K_p$ is the proportional gain term. All these three parameters of the controller must be determined. The transfer function $G_{CFH}(s)$ of the PID controller developed for the flying height control stage is:

$$G_{CFH}(s) = \frac{299 \cdot 10^{-3}}{s^2 + 754 \cdot s + 6.02 \cdot 10^{-5}}$$

(4)

The closed-loop transfer function $CLTF_{FH}(s)$ of the system for the flying height control motion, also showing the location of the poles and zeros, is calculated as:

$$CLTF_{FH} = \frac{(s + 377 - 678j)(s + 377 + 678j)}{(s + 193 + 1081j)(s + 193 - 1081j)(s + 384)}$$

(5)

The closed-loop system bandwidth of the flying height control motion stage is calculated from its Bode plot. The system bandwidth realised is about 4.8 kHz. The flying height control stage is closed with a gain crossover frequency of 1.34 kHz and phase and gain margins of 50° and infinity respectively. This implies that the control system is very stable.

Figure 5 shows the experimental open loop response and the theoretical closed loop response for flying height control respectively. This shows that a considerable improvement is possible with closed loop operation. The settling time is reduced from around 1.5 s to 10 ms. Control system refinement may yield improvements over this.
Fig. 5 Simulated closed response for flying height control, with inset showing the open loop response to a step input.

In an actual hard disk drive, position sensing would be achieved via the read/write head for flying height and from the tracking servo for track positioning. If data is read back from the disk, then according to the Wallace spacing loss equation [12], the amplitude of the read-back signal will be modulated by the spacing variations between the head and the disk due to the surface irregularities of the disk. The read-back signal from the magnetic head reflects the surface topography of the disk, and will ultimately provide a feedback signal for the control system.

CONCLUSIONS AND DISCUSSION

A test facility has been developed for the characterisation of hard disk drive performance under hostile operating conditions. The electrodynamic vibration system is enables failure mechanisms to be characterised in terms of vibration frequency and acceleration. Analysis of the data-transfer frequency response, and the CD-ROM optics and piezoelectric sensor systems, indicate that disk-flutter is a major factor in data-transfer error. Finite element analysis of a rotating drive, carried out in our laboratory, suggest that the use of a disk , laminated with a viscoelastic layer, will assist by passively damping the disk. However, this does not alleviate the requirement for active control of the suspension arm. The combined active-passive system should offer improved response times.

A novel suspension arm has been developed, with actuation enabled by the use of embedded multi-layer bulk PZT actuators. When this suspension arm is fully integrated into the HDD environment, it will enable real-time flying height adjustments to be made. This will improve data-transfer and also avoid, or reduce, head stiction and wear. Closed-loop positioning algorithms have been developed to enable the high-frequency positioning process of the arm to be achieved. After implementation of the control system in hardware the experimental closed loop performance will be confirmed. This work will be presented for future publication. Further work is also being undertaken to show that enough force is generated by the piezoelectric actuator to actively control the flying height of the head amidst the air bearing above the rotating magnetic disk.

REFERENCES

A Novel Suspension Arm with 2-dimensional actuation, for Flying Height Control and High-Bandwidth Track following in Advanced Hard Disk Drives

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Abstract

A novel suspension arm with 2-dimensional actuation has been developed. While retaining present technology to give coarse positioning of the head, the arm while making use of embedded piezoelectric materials is intended to provide high-bandwidth data tracking when fully integrated in a hard disk drive environment. This is known as dual-stage actuation. The suspension arm also has the added feature of adjusting the flying height of the head with great precision and accuracy. The arm developed is tested dynamically and characterised. Specialised closed-loop control algorithms are developed to position and control each dimension of motion independently.

1. Introduction

The data-storage recording densities of magnetic hard disk drives (HDDs) have doubled every 18 months in recent years. During 1999 data-storage density has increased from Seagate's mark of 16.3 GB/in² [1] to IBM's state-of-the-art drive with a storage density of 35.3 GB/in² [2]. These giant strides and rapid advances in data-storage densities are so enormous that other technologies associated with hard disk drives are under pressure to advance at similar rates in order to cope. The current prediction is that if this growth trend continues, it is expected that data-storage densities of commercial hard disk drives will be well in excess of the 40 GB/in² by the year 2002. The flying height of the head will correspondingly be reduced to accommodate the corresponding increase in track density.

In response to this requirement, Seagate revealed a high-speed, two-stage head-positioning system, enabling recordings of 36 GB on a single, two-sided disk [3]. Current technology uses a conventional voice-coil motor (VCM), but these have insufficient bandwidth to position a magnetic head right on top of such narrow data tracks, with the required accuracy and precision. Focus has now turned to the use of a two-stage actuation mechanism to address this problem. A VCM is retained to provide low-bandwidth coarse movement of the suspension arm, and a piezoelectric micro-actuator is incorporated into the suspension arm to provide high-bandwidth fine track positioning of the head. Most research into dual-stage actuators has involved the use of a micro-actuator for data tracking only [4-6]. In hard disk drives there is a need to be able to control the head flying height. However, with reduced flying heights there will also be a generic requirement for flying height control. The suspension is designed to maintain the head at a certain flying height. Variations in flying height can lead to data-transfer errors. In conditions of shock or vibration, there is a high probability of the head crashing, leading to head wear or even failure. In current commercial HDDs, the net loading force is approximately 35mN during normal operation [7]. An adjustment of ±10mN of this loading force would result in a change in the flying height of about ±20%, giving sufficient tolerance for active flying height control.

The piezoelectric micro-actuator that has been used by us for this purpose has produced such forces. In conjunction with appropriate positioning closed-loop control algorithms, the flying height can be adjusted to maintain the head at the correct height above the rotating magnetic disk. This paper shows the presents the findings of this work.

2. Suspension arm design

A prototype of the suspension arm described above has been built as shown in Figure 1. It comprises a duralumin frame within which piezoelectric actuator stacks are embedded. One actuator maintains the desired flying height of the head above a rotating disk whereas the other ensures high-bandwidth precision and accurate track following. The prototype suspension arm incorporates a stainless steel loading beam — similar to that in current commercial HDDs — but instead of the slider-head arrangement attached at its end, it has a small mirror attached to facilitate the characterisation of the arm when using the optical beam deflection technique [8-9].
3. Resonance modes

The suspension arm is set into resonance by applying bursts of band-limited white noise to the piezoelectric stacks and the resonant modes are sensed optically, for both data tracking and flying height control. However, actuation in one plane can induce resonance effects in the orthogonal plane, and vice-versa. The results are shown in Figures 2 and 3. It can be seen that the lowest resonant frequency of the tracking stage occurs at 1.7 kHz though because of its complex mechanical structure, there are other resonances at higher frequencies. A similar comment applies to the height control stage though as expected with the more compliant structure in this axis, the fundamental resonance is lower at 140 Hz.

4. Suspension arm controller design

Proportional integral and derivative (PID) controllers have been implemented to control and position the suspension arm with adequate bandwidth and stability. The controllers responsible for the orthogonal axes of motion are developed independent of each other. They are, however, both developed using frequency-response methods given in [10].

The transfer functions of both stages of motion, data tracking stage and flying height control stage, are both approximated to be of second order and are of the form:

$$G(s) = \frac{\omega_n^2}{s^2 + 2\rho\omega_ns + \omega_n^2}$$  \hspace{1cm} (1)

Where $\omega_n$ is the natural frequency of the individual stage of motion of the suspension arm and $\rho$ is the damping factor. Both these parameters are calculated from the values of the time constant ($\tau$) and the resonant frequency ($f_r$) of each individual stage of the suspension arm.

The transfer function of the plant $G_{PF}(s)$ for the data tracking motion stage includes the transfer function of the suspension arm (track motion) $G_T(s)$ plus the gain parameter of the OBD sensor $k_T$. This is shown in Figure 4.
Hence the transfer function of the plant \( G_{PT}(s) \) is given as:

\[
G_{PT}(s) = G_T(s) \cdot k_T = \frac{116.77 \cdot 10^{-6} \cdot 0.3324}{s^2 + 100s + 116.77 \cdot 10^{-6}}
\]

Where \( \omega_n^2 = 116.77 \cdot 10^{-6}, 2 \rho \omega_n = 100 \) and \( k_T = 0.3324 \).

The transfer function of the plant \( G_{PFH}(s) \) for the flying height control motion stage includes the transfer function of the suspension arm (flying height motion) \( G_{FH}(s) \) plus the gain parameter of the OBD sensor \( k_{FH} \). This is shown in Figure 5.

Hence the transfer function of the plant \( G_{PFH}(s) \) is given as:

\[
G_{PFH}(s) = G_{FH}(s) \cdot k_{FH} = \frac{0.774 \cdot 10^{-6} \cdot 0.4265}{s^2 + 1.7964 \cdot 10^{-6} + 0.774 \cdot 10^{-6}}
\]

The above response is obtained for optimum values of the PID parameters \( K_I = 2500, K_D = 272 \cdot 10^{-6} \) and \( K_P = 1.5578 \). The these values, we obtain a quick settling response.

The PID compensator is developed for each stage of motion is of second order and has a transfer function of the form:

\[
G_C(s) = K_p + \frac{K_I}{s} + K_D s
\]

Where \( K_I \) is the integral gain, \( K_D \) is the derivative gain and \( K_P \) is the proportional gain term. All these three parameters of the controller must be determined.

The complete diagram showing the closed-loop system for the tracking motion stage is shown in Figure 6.
time $T_S$ of 1.6 ms, a reasonable overshoot $M_P$ of about 22 
and the transient response to step input is good, settling 
quickly in a few cycles.

The complete diagram showing the closed-loop system 
for the tracking motion stage is shown in Figure 8.

![Block diagram of closed-loop arrangement for the flying height control stage](image)

Fig. 8 Block diagram of closed-loop arrangement for the flying height control stage

The transient response of the above system to a unit step 
input is shown in Figure 9.

![Transient response to step input](image)

The above response is obtained for optimum values of 
the PID parameters $K_T=1800$, $K_D=2.99 \cdot 10^3$ and 
$K_P=2.2542$. For these values, we obtain a quick settling 
time $T_S$ of 12 ms, a reasonable overshoot $M_P$ of about 18 
and the transient response to step input is good, settling 
quickly in two cycles.

The transfer function $G_C(s)$ of the PID controller 
developed for the tracking motion stage is:

$$G_C(s) = \frac{272 \cdot 10^{-6}}{s} \left(s^2 + 5.727 \cdot 10^3 \cdot s + 9.191 \cdot 10^7\right)$$  \hspace{1cm} (1)

The closed-loop transfer function $CLTF_T(s)$ of the system 
for the data tracking motion, showing the poles and zeros, 
is calculated as:

$$CLTF_T = \frac{(s + 2864 - 9149j)(s + 2864 + 9149j)}{(s - 2097 + 12072j)(s - 2097 - 12072j)(s + 6464)}$$  \hspace{1cm} (2)

The closed-loop system bandwidth of the tracking motion 
stage is calculated from the bode plot shown in Figure 10. 
The system bandwidth realised is 14.6 kHz. Bode plots 
show that the PID servo system’s control loop for the 
tracking stage can be closed with a 14.3 kHz gain 
crossover frequency and phase and gain margins of 55.9° 
and infinity respectively.

The transfer function $G_{CFH}(s)$ of the PID controller 
developed for the flying height control stage is:

$$G_{CFH}(s) = \frac{299 \cdot 10^{-3}}{s} \left(s^2 + 754 \cdot s + 6.02 \cdot 10^5\right)$$  \hspace{1cm} (3)

The closed-loop transfer function $CLTF_{FH}(s)$ of the system 
for the flying height control motion, also showing the 
location of the poles and zeros, is calculated as:

$$CLTF_T = \frac{(s + 377 - 678j)(s + 377 + 678j)}{(s + 193 + 1081j)(s + 193 - 1081j)(s + 384)}$$  \hspace{1cm} (4)

![Bode plot](image)
The closed-loop system bandwidth of the flying height control motion stage is calculated from the bode plot shown in Figure 5. The system bandwidth realised is about 4.81 kHz. The flying height control stage is closed with a gain crossover frequency of 1.34 kHz and phase and gain margins of 50° and infinity respectively.

5. Conclusions

A novel suspension arm, with 2-dimensional actuation capabilities has been developed. Actuation is enabled by the use of embedded piezoelectric stack actuators. One dimension of actuation is responsible for data tracking and the orthogonal axis for precision flying height control. When this suspension arm is fully integrated into the HDD environment, it will provide fine high-bandwidth head positioning and make sensitive flying height adjustments, while retaining the conventional VCM for coarse positioning. This demonstrates dual-actuation mechanism. Closed-loop control algorithms have been developed to enable the high-frequency positioning process of the arm to be achieved. Further is being done to show that enough force is generated by the piezoelectric actuator to actively control the flying height of the head amidst the air bearing above the rotating magnetic disk. The suspension arm developed is of commercial interest and will be used in future advanced HDDs to realise the ever-so-high storage densities and bring an added dimension of flying height control to advanced HDDs. This is particularly important as the disk drive technology moves towards contact recording.

6. References

Introduction

Hard disk drives are an economical form of mass storage, widely used as secondary memory in virtually all computer systems. Conventional hard drives are very reliable under normal operating conditions, but they can suffer from mechanically induced failure when operated in hostile conditions. In areas where vibrations exist hard disk drives can, and do fail, and no longer read or write data. At best the data transfer rate becomes vastly inferior.

Environments such as military and aerospace are synonymous with large shocks and vibrations. Ocean going craft can also encounter difficulties with hard drives as the engine and waves transmit vibrations through the hull. Dennis [1] evaluated many proposed solutions, though mainly large vibration isolation cages and mountings that damped the vibrations. However, additional isolation mountings are not the ideal solution. The extra space and weight needed precludes this method from many key areas: adding both weight and bulk to a drive is hardly an improvement. Passive dampers, which are only effective over a limited bandwidth, are all that are used in current ‘ruggedised’ laptops.

Disk drive fundamentals

It is important to understand precisely what is happening within the drive, and which systems areas are failing under conditions of vibration. When mechanical components are vibrated they bend and distort, however, if they are being vibrated at the right frequency they will go into resonance, creating comparatively large motions.

There are two major mechanical components that, when excited at resonance, can result in data transfer failure. Firstly, there is the suspension arm that pre-tensions the head against the disc. This is designed to control the flying height of the head during normal operating conditions. If the flying height of the head is such that it is outside of its normal operating range, then the signal degrades, and ultimately can lead to data transfer failure. In severe cases, the head will crash down onto the disk and cause irrecoverable damage. Secondly, there is the hard disk itself. The disk can be driven such that it flutters up and down, causing tracking (or mis-registration) problems [2]. The problem can be compounded by the fact that if the suspension arm is resonating, and therefore the head, the disk can be driven into oscillation due to the head pushing onto the disc and vice-versa [3,4].

Experimental

A test rig has been constructed to allow the hard drive to be vibrated at accelerations of up to 50g. The hard drive is rigidly clamped to a plate that is vibrated by an electro-dynamic
shaker, driven by computer controlled frequency sweeps. Mounted to the plate is a piezoelectric accelerometer that is used to monitor the vibrations that the drive experiences.

The first set of experiments were done to assess the data transfer performance of the drive whilst undergoing induced external vibration. Certain trends have been observed for all the drives tested. Consistent transfer data failure has been observed between 400Hz and 600Hz, as shown in Figure 1.

The next tests were designed to measure the movement of the suspension arm using a piezoelectric strain sensor. The strain, assumed to be proportional to suspension end displacement, was measured as a function of excitation frequency, as shown in Figure 2.

**Data Loss Prevention**

Ultimately, to prevent performance degradation, an actively controlled suspension arm will be fitted to a hard drive. The suspension arm will be built such that actuators will be able to control the head in two orthogonal planes. This will allow freedom to change the flying height and enable sensitive tracking adjustments. With an appropriate control system this will allow the head to carefully follow the disk surface and make sensitive tracking corrections.

**Suspension Arm Design**

A prototype of the suspension arm described above has been built. It comprises a duralumin frame within which piezoelectric stacks are embedded. One stack maintains the desired flying height of the head, whereas the other ensures precise and accurate track following. Careful design of the arm, as shown in Figure 3, allows both these processes to be achieved. This forms a dual-stage actuation mechanism [5-7] which will allow fine, high-bandwidth data tracking and precision flying height control when incorporated into a hard disk drive environment.

By investigating the dynamic characteristics of the arm, an appropriate feedback control algorithm (controller) can be implemented. The controller must be robust: resonant modes of the suspension arm must be actively controlled to enable a quasi-static positioning signal to be applied to the piezoelectric actuator. The resonant modes of the suspension arm are sensed optically, for both data tracking and flying height control. The results are shown in Figure 5. These resonant modes have been suppressed by using specially designed modified proportional integral and derivative (PID) controllers. The results of this compensation is much reduced overshoot and faster settling times for the tracking and flying height control.
closed-loop phase margins for the tracking motion and flying height control are 52° and 54° respectively, ensuring system stability.

Conclusions

Data loss was found to be significant at frequencies between 450 and 700Hz. This problem, further compounded by suspension-disk interactions at resonance, is the subject of further research. Optical measurements, supported by strain and acoustic measurements, will be taken with the drive in operation. This will further the understanding of the head-disk interface behaviour and enable us to differentiate between changes in flying height and off-track radial displacement.

Dual-stage actuation for simultaneous high-bandwidth data tracking and flying height control has been demonstrated. This has been achieved by using a specially designed suspension arm embedded piezoelectric stacks to give movement in orthogonal axes. In addition, system stability has been achieved, even in the presence of vibrations and shock, by using robust modified-PID controllers.

References

Research articles
Sensors for dynamic characterisation of magnetic storage systems

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Keywords
Inspection, Magnetic, Distance measurement

Abstract
The areal (surface area density of bits) storage density of magnetic hard disks is continually increasing, with typical available commercial storage densities being around 10Gb/s/in². It is predicted that densities in excess of 40Gb/s/in² will be possible before the year 2003. A number of key issues arise from this development, such as the need to determine and control accurately the dynamic flying height (z-axis) of the read-write head, which is affected by the apparent distortion of the disk surface due to rotation-induced disk resonance. As a result of the increasing storage density the positional control of the head in the plane of the disk (x-y plane) also becomes more critical. This paper deals generally, but with a particular emphasis on optical and piezoelectric sensors used in our laboratory for characterisation of storage media and systems.

Introduction
There is a vast array of sensors available to us at present. Sensors are selected according to the particular measurand and in many cases, the particular application, e.g. interfacing to a control system. Sensors are generally required to work in parallel with signal conditioning electronics, and may then be either used as a stand-alone measurement system or incorporated into a control system for real-time sensory feedback.

Depending on the measurand there is a vast array of sensors that can be used for surface and textural characterisation. One of the standard methods for investigating the surface profile is to use a profilometer[1]. A profilometer utilises a stylus much in the same way as a record player follows the variations along the track of a record, the main difference being that the profilometer uses optical sensing to determine the attitude of the stylus. In a record player the stylus generates a signal by electromagnetic induction (moving coil or moving magnet). The potential disadvantage of the stylus-based systems is modification of the surface, due to contact being made by the stylus.

However, the use of optical based profilometry is able to circumvent this, and a number of systems have been developed so far. Abou-Zeid and Wiese developed a compact interference profilometer that uses a wavelength-tunable diode laser as an optical stylus, with a measurement uncertainty of around 10nm[2]. A number of profilometry systems based on interferometry have also been reported[3,4]. Cuthbert and Huynh[5] have designed an optical system for fast non-contact measurement of surface texture, based on the optical Fourier transform pattern of the surface, which is correlated with the surface roughness obtained using a stylus based instrument.

Moving into the new millennium we are faced with the increasing demands of hard disk drive technology. Data storage density continues to increase, necessitating that the head flies even closer to the disk surface: state-of-the-art flying heights currently being around 15nm. This is coupled with the increasing demand for faster track access, which means that the disk drive is required to operate at increasingly higher speed. This represents a challenge for PCs operating in the office environment, but presents more...
serious difficulties for computers working in conditions where they are subjected to shock and vibration. This is of particular interest to military and aerospace applications; and to a lesser extent will also affect users of laptop computers.

This paper looks at a variety of sensor systems used in the CRIST research laboratory for the characterisation of magnetic media and data storage systems, namely: scanning laser microscopy, magnetic force microscopy, dual beam polarisation interferometry, CD-ROM optics and thick film piezoelectric sensors. Finally, there is a brief look at a complete sensor-control-actuator system, which includes optical beam deflection for displacement (or topography) sensing, which is currently being investigated for the improved operation of hard disk drives.

A. Dynamic scanning laser microscopy

Scanning laser microscopes are extremely useful tools for high-resolution point-by-point imaging of sample surfaces. The most common configuration employs a stationary laser beam, which can have either continuous or modulated (intensity or polarisation) output. The laser is brought to a focus using a microscope objective to yield a diffraction-limited spot, which is typically around 1μm on the sample surface. The sample can then be micro-positioned, with a motorised x-y stage, with respect to the sample and the reflected light collected by one or more detectors. An alternative configuration employs a pair of scan mirrors to move the spot on the sample surface. This set-up is significantly more complex as it requires auto focusing to maintain the same size spot at all points of the scan, and there is a trade-off between scan area and resolution. For example a 5mm × 5mm area can be scanned with a resolution of around 30μm[6]. However, the two systems are often combined: scan mirrors (high speed scanning) and x-y stage (large area scan). The use of different detectors and polarisation sensitive/insensitive optics enables different information to be acquired.

In our laboratory a scanning laser microscope has been designed and built to observe the dynamic behaviour of domain switching during the thermo-magnetic write process and the subsequent magnetisation state (domain orientation) in thin-films and devices[7-9]. It can also be used to write to magneto-optic disk material thermomagnetically prior to imaging. Images are derived from the longitudinal and polar magneto-optic Kerr effects, which are wavelength dependent.

The microscope system has been made modular, which enables the imaging system to be flexible and allows further functionality to be added as required. An overview of the system is shown in Figure 1. The scanning laser microscope is constructed around the basic frame of a Leitz Metallplan optical microscope, mounted on optical breadboard along with other optical and mechanical components, as shown in Plate 1.

The various modes of operation of the SLM are as follows:

- **XY table scanning mode.** In the XY scan mode a sample is raster scanned beneath the laser spot via a Burleigh XY Worm Table, with a resolution of 4nm. The
magnetic or intensity (pseudo-topographic) information is then extracted by sampling all the photodetector outputs using the computer I/O board, then applying the required algorithm to the data. Plate 2 shows bubble memory magnetic domain patterns using the polar Kerr effect (scan area $32 \mu m \times 40 \mu m$). The reflected light intensity is a function of the sample magnetisation (domain orientation), and LabView enables the reflected intensity to be represented by a grey scale image. The change in intensity represented here is typically less than 1 per cent.

- **Galvano meter scanning mode.** In the galvanometer scan mode the sample is held stationary whilst the laser spot is raster scanned over it via the scanning mirrors. The galvanometer position is controlled using the computer I/O board voltage outputs. Again the computer processes magnetic or topographic information after it is sampled to create an image. Plate 3 shows a pseudo-topographic (reflected intensity) image of an integrated circuit layout (galvanometer scan area $100 \mu m^2$).

- **Dye pulse laser.** A further imaging mode of the SLM utilises a dye pulse laser. This requires the software to trigger a waveform generator, and at a set time period later trigger the laser. Finally, at some point in time after this, data are acquired from the photo-detectors. Each of these time periods must be accurately related to the others. The magnetic image is retrieved from the quadrant photodetectors as for other modes of operation.

- **CCD camera image acquisition.** Another mode of image acquisition uses a super-cooled CCD camera, triggered after a pulse of light has illuminated a sample. The camera is supplied with a set of functions in the form of a Windows dynamic link library (DLL), also known as an application program interface (API). These functions cover all that is required to operate the camera.

**B. Magnetic force microscopy**

The magnetic force microscope (MFM) is based on the atomic force microscope (AFM)[10]. In the AFM a small probe, a silicon cantilever with an atomically sharp tip, is brought into contact with a sample surface, and raster scanned across it. The resultant deflection of the tip is recorded and used to create an image of the surface topography. In magnetic force imaging the tip is coated in a ferromagnetic material, and moved away from the surface several tens of nanometres. It is then raster scanned, and the interaction between the magnetic field of the sample and the tip recorded to create an image of the magnetic forces.

The development of our MFM, shown in Plate 3, is based on a versatile, modular form.
A variety of scanning modes exist for the MFM. The "static" scan, as described above, is the simplest; however, this requires samples with relatively powerful magnetic fields. Resonant scanning is a standard mode of operation, where the cantilever is resonated, and the effects of the sample's fields on that resonance are monitored in different ways to create an image. In recent years LiftMode™ has being recognised as a very useful mode of operation[12]. In this case the topography of the sample is mapped out with an initial scan, from which the data are used to control the height of the MFM probe, in resonant mode, to do a second magnetic scan. This results in removal of topographic effects from the resulting magnetic image.

The design and function of the probe used to interact with the stray fields from a magnetic sample are a major MFM research subject. The standard ferromagnetic design has several inherent problems. The tip magnetisation can suffer from hysteresis over time, together with wear and damage during its useful life. The magnetic properties of different samples, i.e. if the sample is magnetically "hard" or "soft", mean that a range of different designs and coatings need to be employed. Therefore, an instrument must be reconfigured each time a new type of sample is imaged. Furthermore, these imperfections may have serious consequences in the acquisition of useful, quantifiable data.

We are currently investigating a new type of MFM probe that uses an electromagnetically induced field as a replacement for the standard probe's stray field. Although electromagnetic MFM probes have been described before, this design is unique[13]. The field is induced around a micro-fabricated aperture using a controlled current. The aperture would be situated near the end of a standard cantilever that has been coated in a conductive material, e.g. gold. This design has the advantage that the specimen interaction is variable, giving controllable field intensity, and as such the results would be repeatable. The new probe has been theoretically simulated to create images of magnetic domain patterns, and it is anticipated that work on the fabrication of these new and innovative probes will begin soon. The practical issues of using the probe in our MFM instrument are also undergoing analysis.
C. Dual beam polarisation interferometry

Optical interferometry is a well established technique for precise and non-contact measurement. Various types of interferometry, such as heterodyne interferometry[14], sinusoidal phase modulating interferometry[15], and phase-shifting interferometry[16], have been developed to make high resolution measurement of small displacements. However, apart from the complexity of the system construction, these existing methods are generally feasible only for low-speed measurement applications. When a high-speed measurement is needed, it is difficult to find a suitable technique if the measurement accuracy requirement is high. The speed limitation in these displacement measurement interferometers is mainly due to the use of slow modulation or scanning techniques. In the CRIST laboratory, a dual beam polarisation interferometer has been constructed, which can be used for high-speed measurement of dynamic morphology/topography, and in our case for the complex measurement dynamic disk head flying height[17,18].

The polarisation interferometer configuration utilises two orthogonally-polarized light beams to remove the directional ambiguity of the displacement, and is shown schematically in Figure 2. The main part of the interferometer utilises a polarising beam splitter PBS1, two quarter-wave plates QW1 and QW2, two mirrors M1 and M2, and a non-polarising beam splitter NPBS1 as both a beam splitter and phase shifter.

Employing a polarising beam splitter PBS1 makes the best use of the laser beam and prevents the returning beam from feeding back into the laser diode. The mirror M2 is driven by a piezoelectric translator (PZT1), which can be used to perform system calibration. Mirror M3 is used as a reference plane when single point displacement is measured. When the system is used to measure the relative displacement of two adjacent points, such as the vertical movement of the hard-disk read/write head relative to the disk surface, M3 is removed and the reference beam is extracted by NPBS1 to the second measurement point. Mirror M2 can also be micro-positioned manually to adjust the spacing of the two measurement points. A 670nm wavelength laser diode is used as the light source. The laser beam passes through the polariser and enters the polarising beam splitter PBS1. Then the s-polarised component is coupled out and reflected by mirror M1 and focused on the measurement point on the sample. The p-polarised component passes through and is focused on to the reference mirror or another measurement point. The returning beam enters the interferometric receiver, which is used to measure the intensity and phase difference between the two polarised beams. The interferometric receiver consists of a non-polarising beam splitter NPBS2, two polarising beam splitters PBS2 and PBS3, a quarter-wave plate QW3 and four photo-detectors. The detected voltage signals are amplified and equalised, then sampled in by the computer through a 12-bit A/D converter board. The sampling rate of the A/D converter will determine the measurement speed of the system. The A/D converter board with a sampling rate of 20MS/s is commercially available at present. The computer, through a 12-bit D/A converter board and a high voltage (150V) amplifier also controls the piezoelectric translators.

We take the electric field of the two orthogonally polarised beams to be of the standard form:

\[ E_p = A_p \exp(i(\omega t)) \]  
\[ E_i = A_i \exp(i(\omega t + \phi)) \]

where \( \omega \) is the angular frequency of the radiation, \( A_p \) and \( A_i \) are the amplitudes of \( E_p \) and \( E_i \) respectively, and

\[ \phi = 4\pi(d + \Delta d)/\lambda. \]
In equation (3), \( \lambda \) is the wavelength of the laser beam, \( d \) is the static optical path difference between the two polarised beams and \( \Delta d \) is the displacement to be measured. The wave intensity being received by each of the four photo-detectors (\( P_{PD1} \) to \( P_{PD4} \)) is proportional to the square of the electric field, and by simple signal conditioning and processing quadrature signals \( P_{PD1} - P_{PD2} / 2 / b_1 \) and \( P_{PD1} - P_{PD3} / 2 / b_4 \) are obtained. The computer samples these signals with two channels of the A/D converter board. The displacement \( \Delta d \) is then determined by phase evaluation and unwrapping[19].

To test the ability and effectiveness of this interferometer, several experiments have been conducted. A 12-bit D/A converter, with a 0-10V voltage output, drives another piezoelectric translator, PZT2, to move the sample. One of the measurement results is shown in Figure 3, in which PZT2 moves the sample in a saw-wave form with amplitude of about 8.5nm.

The dual beam polarisation laser interferometer can be used for accurate high-speed measurement of small displacements, vibration, and disk flying height. Theoretically, a 12-bit A/D converter can provide a measurement resolution higher than \( \lambda / 4,096 \). However, because of the system noise, especially the electrical noise, the system in its present configuration has a general measurement resolution of about 0.5nm. The dual beam polarisation interferometer in its first version has been demonstrated to work effectively in our application. However, there are a number of issues to be addressed in order to realise its true potential. The interferometer will be developed from its present state to include a frequency stable He-Ne laser and the interferometer itself will be made to be compact and from thermally stable materials (invar as opposed to aluminium). These improvements will significantly improve the signal-to-noise ratio available, enabling more precise measurements of small displacements to be made. Choosing a higher sampling rate A/D board can also increase the system's measurement bandwidth.

### D. CD-ROM optics

The interaction between the read-write head and the disc surface causes the flying height of the head above the surface to change, and so the dynamic morphology of the rotating disk(s) is extremely important. As the head moves outside its operating margin data-transfer becomes a problem, eventually leading to data-transfer error, as shown in Figure 4. As the disk (aluminium-magnesium, coated with a thin magnetic layer and thin lubrication layer) rotates at speeds of up to 10,000rpm the disk flexes radially and circumferentially and the CD-ROM optics will be utilised to measure these rotation-induced effects.

A CD-ROM drive utilises a laser with photodiodes to read data from the disk. The photo detector comprises four sensors and when the disk is perfectly focused the laser spot reflected off the disk will be centrally placed on the four sensors. The spot will then move either left or right to cover one pair of spots depending on the distance of the disk.

Figure 4 Effect of vibration on disk drive operations: 3.5" hard disk
The CD head is mounted to a micrometer controlled sliding table and aligned so as to reflect off of a typical hard disk drive disk. In normal operation two of the segments are summed and the difference from the other two segments is compared, to yield a signal four times greater than that observed from just the one segment.

Using an oscilloscope to monitor the signal on one of the photodiodes it was recorded that a peak voltage of 30mV was measured when the lens was 2.80mm away from the disks' surface. The response from the detectors is linear with distance, with a change of ±0.2mm yielding a change in output of ±20mV, a response therefore of 0.1mV/µm. After signal conditioning, the response becomes 0.4mV/µm. Work in this area is part of ongoing research.

E. Piezoelectric sensors

An alternative means of characterising hard disk flutter is to use a thick film piezoelectric sensor, in this case polyvinylidene di-fluoride (PVdF). The sensor, in the form of a 110µm sheet, was used as a cantilever. When a piezoelectric material is deformed the potential difference across its electrodes is proportional to the average induced strain. The fixed end of the sensor was bonded to the drive's chassis such that the cantilever is pre-tensioned against the disk. Any movement of the disk would therefore bend the cantilever from its static position. Because the cantilever is pre-tensioned, when the disk is static there is always a DC voltage. If the disk causes the cantilever to move from its static position there will be a change in the strain and the output voltage will increase as the strain increases and vice-versa.

The end of the cantilever rests on the edge of the disk to sense maximum displacement. Figure 5 shows the results obtained using this sensor arrangement, for a 3.5" hard disk drive rotating at 4,500rpm. The first peak (at 75Hz) corresponds to disk rotation (disk clamping and spindle bearing), the second peak at around 500Hz corresponds to disk flutter, as predicted by finite element analysis, and the peaks at higher frequencies are attributed to disk-suspension arm interaction.

It is appropriate now to look at the control system that is being developed for active control of the read-write head for both track following and flying height[20]. Current hard disk drives utilise a voice coil motor for positioning the head with respect to the data tracks, and design the head suspension system such that air flow, due to the rapidly rotating disk, "lifts" the head to the desired height above the disk surface. The system developed in the CRIST laboratory will still use the voice coil motor for coarse track following, but fine positioning and flying height control will be affected using piezoelectric stack actuators, as shown in Plate 6. Stack actuators offer advantages of useful actuation at low voltage (<3V) and wide bandwidth operation.

The attitude of the head is monitored using optical beam deflection (OBD), whereby a laser beam is deflected by a small mirror above "the head" on to a position sensing quadrant photodetector, capable of simultaneously measuring displacements in the horizontal and vertical planes. The output of the detector, which is linear for small displacements, and has spatial resolution comparable with interferometers (i.e. sub nm), is applied to the DSP implemented proportional integral and derivative (PID) controller for real time active control of the head suspension system. The suspension arm is set into resonance by applying bursts of band-limited white noise to the piezoelectric stacks and the resonant modes are sensed.
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Plate 6 Suspension arm incorporating stack actuators for simultaneous head positioning and flying height control

optically, for both data tracking and flying height control. However, actuation in one plane can induce resonance effects in the orthogonal plane, and vice versa.

Modified PID controllers have been implemented to control and position the suspension arm with adequate bandwidth and stability. Bode plots show that the PID servo system's control loop for the tracking stage can be closed with a 25.6kHz gain cross-over frequency and phase and gain margins of 54° and infinity respectively. The flying height control stage is closed with a gain cross-over frequency of 2.33kHz and phase and gain margins of 51° and infinity respectively. Figure 6 shows the experimental open loop response and the theoretical closed loop response for track following, with the response for the flying height control similar to that for track following.

In an actual hard disk drive, position sensing would be achieved via the read/write head for flying height and from the tracking servo for track positioning. If data are read back from the disk, then according to the Wallace spacing loss equation[21], the amplitude of the read-back signal will be modulated by the spacing variations between the head and the disk due to the surface irregularities of the disk. The read-back signal from the magnetic head reflects the surface topography of the disk, and will provide a feedback signal for the control system.

Conclusion

In the CRIST laboratory a number of sensor systems have been developed for the characterisation of magnetic media and data storage systems. An SLM, with dynamic read-write capability, and an MFM have principally been developed for the characterisation of magnetic and magneto-optical thin films. By utilising the intensity imaging mode, the SLM is able to characterise the surface reflectivity with a spatial resolution of around 1μm. The MFM operates with the probe at constant height and so a prerequisite is that the surface topography is known. This is determined from a pre-imaging scan in AFM mode, whereby the probe tip is brought into contact with a sample surface, and raster scanned across it. The resultant deflection of the tip is recorded and used to create an image of the surface topography. The dual beam interferometer, for measuring head flying height, is so far able to measure dynamic surface topography of a rotating hard disk, with sub-nanometre resolution. Current instrument development is focused towards the simultaneous measurement of the head position, to realise the determination of its actual height above the disk surface in real time.

In parallel with this is work on the dynamic characterisation of disk drives for ruggedised operations, such as in seismic data logging. Two experimental systems have been
developed for this based on CD-ROM optics and thick film piezoelectric sensors to measure the topography of the rotating disk drive under hostile operating conditions. Measurements of data-transfer to and from the disk will be used to further the understanding of data-transfer failure mechanisms under hostile operating conditions.

Operation of hard disk drives relies on the head-to-disk flying height being maintained at a constant height. A sensor-controller-actuator system has been developed to enable both the flying height and the track position to be maintained. Optical sensing is used at present to determine the attitude of the head and the response used to drive two independent actuators via a DSP implemented PID controller. Future developments of this system will include the replacement of the optical sensor by a direct measurement of the head's position from the actual head readout signal itself. This will form the basis of a realisable system that will be developed commercially in partnership with our collaborators, the Data Storage Institute, Singapore.

References


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Actuators for Tomorrow's Ruggedised Hard Disk Drives

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Abstract

The areal storage density of magnetic hard disks is continually increasing. Typical available commercial storage densities at present are 3 Gbits/in² and it is predicted that densities in excess of 40 Gbits/in² will be possible before the year 2003. Along with this development is the requirement for the accuracy of head positioning to move beyond that provided by present technology, both in terms of x-y positioning for track/sector location and z-axis positioning for flying height control. The demands on head positioning control are even more demanding when the hard disk drive is operated under hostile conditions of shock and vibration. This paper considers the problem of read-write error associated with hard disk drives operating under adverse conditions and looks at how current actuator technology may be used to circumvent the problem.

Introduction

As we move towards the new millennium we are faced with the increasing demands of hard disk drive technology. Data storage density continues to increase, which means that the head must fly even closer to the disk surface: state of the art flying heights are currently around 15 nm. This is coupled with the increasing demand for faster track access, which means that the disk drive is required to operate at increasingly higher speed. This represents a challenge for PCs operating in the office environment, but presents even more serious difficulties for computers working in conditions where they are subjected to shock and vibration. This is of particular interest to military and aerospace applications: and to a lesser extent will also affect users of laptop computers.

The use of piezoelectric materials has received considerable attention because of their light weight, fast response, low cost, high stiffness and availability in different sizes. Piezoelectric materials are widely used as sensors and actuators in applications such as: active vibration control [11], noise reduction [21], shape control [31] and damage assessment [41]. Piezoelectric materials, such as lead zirconate titanate (PZT), are commonly available as bulk ceramics and in thick and thin film form. Recent advances in the design and manufacturing of aerospace and automotive systems have extended the use of piezoelectric fibre-reinforced composite materials, owing to their high stiffness-to-weight and strength-to-weight ratios. As a result, research efforts concerning the use of piezoelectric fibre-reinforced composite structures, both for continuous and distributed structures, have been on the increase. Chandrashekhara and Donthireddy [51] presented a mathematical model to demonstrate the dynamic response of piezo-composite beams. The independent behaviour of the sensor and actuator was investigated and numerical results were presented to demonstrate the ability of the closed loop system to actively control the vibration of laminated beams. The aim of the work presented in this paper is to show progress in this regard earlier in this paper. The aim of the paper is to show progress towards the fabrication of a stiff, light weight active composite 'smart' arm, fabricated from glass or carbon fibre-reinforced composites, which would enable both positioning control of the head flying height (z-axis) above the disk and high resolution tracking (y-axis), capable of sub-nanometre positioning.

Figure 1
Schematic experimental arrangement for evaluating readwrite data transfer as a function of frequency and acceleration
BARD DISK DRIVE CHARACTERISATION

A number of issues are being addressed in this work to characterise disk drive performance under conditions of shock and vibration:

- Read-write data transfer.
- Dynamic characterisation of the head.
- Dynamic characterisation of the disk.

A vibration test rig has been constructed to determine the conditions under which a given disk drive (hard or floppy) fails. The test system consists of an electrodynamic shaker driven via a power oscillator controlled by a PC-operated function generator. The software used is able to generate sinusoidal frequency sweeps or random frequency/amplitude tests. The disk drive under investigation is rigidly clamped to the top plate of the electrodynamic shaker and the disk is vibrated whilst data is being either read from or written to the disk. Data written to the disk can be either a 1 or 0, or a random mixture of both. The arrangement used is shown schematically in Figure 1. The data generated is interpreted to generate a plot of the Working Area and Failure Area as a function of frequency and acceleration.

Figures 2 and 3 show typical results for a 1 GB hard disk and a 3½" floppy disk drive. These figures show the regions of correct operation and failure. It should be noted that all regions above the line correspond to failure, whereas at any point below the line read-write operation is possible, but performance degrades as the boundary is approached.

Looking at Figures 2 and 3 it can be seen that floppy disk drives are considerably worse at transferring data under conditions of vibration at 500 Hz or less compared to hard disk drives, and the situation reverses at higher frequencies. For hard disk drives we observe that the device is particularly susceptible to failure in the frequency region 400 Hz to 800 Hz, and this has been true for all hard disk drives tested in our laboratory.

HEAD-DISK INTERFACE CHARACTERISATION

In order to improve the data transfer of hard disk drives under adverse conditions, it is necessary to determine how the relative motion of the head and disk correlates with the conditions under which failure occurs. This work falls into a number of areas:

- Finite element analysis of the dynamic morphology of rotating disks.
- Disk vibration measurements using accelerometers.
- Experimental measurement of disk vibration characteristics.
- Head flying height measurements.

The modelling of the hard disk has been carried out using finite element analysis. The disk is modelled to determine the modal frequencies of vibration. This shows that the resonant frequencies are 470 Hz and 800 Hz. To check...
Experimentally, initial work has been undertaken using a miniature accelerometer attached to the perimeter of a hard disk. The displacement of the disk was recorded over a large frequency range, after an initial excitation. This shows that the fundamental frequency was 564 Hz and that the resonant frequency was 488 Hz. Higher modes, with correspondingly reduced amplitudes, at 800 Hz and 960 Hz, are also observed. These results are in agreement with McAllister [6] and Edwards [7]. Figures 4 and 5 show the natural and resonant response of a typical hard disk drive respectively.

ACTUATORS

The areal recording densities of magnetic hard disk drives (HDDs) have doubled every 18 months in recent years. Seagate recently set a new areal density benchmark of 16.5 GB/in² [8]. Within this same development, a flying height of 15 nm has been set and a new benchmark for track density (43 000 tpi) has been established. The current prediction is that if this trend of growth continues, we should expect areal densities of hard drives to be around 40 GB/in² by the year 2002, and the head flying height to be around 10 nm. In order to achieve such high areal densities, very narrow data tracks will be required. With current technology, which uses a conventional voice-coil motor, it will become increasingly more difficult to position a magnetic head on top of a narrow data track with the high accuracy and precision required. This has been attributed partly to the interaction of the actuator's pivot bearing and the actuator's structural resonant modes, which limit the track-following servo's low-frequency error rejection attenuation and bandwidth [9]. One method that could circumvent this is the use of a dual-stage actuation mechanism. This involves the use of a fine high-bandwidth microactuator for very fine data tracking and head flying height control. Most research into dual-stage actuators has involved the use of the microactuator for data tracking only [9-12].

However, another need has also been identified to be able to control the head flying height. The microactuator, in conjunction with appropriate positioning control algorithms, will be able to control the suspension arm in such a way that the flying height can be adjusted to maintain the head at the correct height above the rotating magnetic disk. Maintaining the correct flying height is becoming increasingly more important as flying heights are reduced even further to realise greater areal storage densities in magnetic disks. In this laboratory, three possible routes have been identified to develop actuators that would enable active flying height control to be achieved as well as providing fine data tracking.

- Bonded piezoelectric actuators
- Embedded piezoelectric actuators
- Composite piezoelectric arms.

**BONDED PIEZOELECTRIC ACTUATORS**

Piezoelectric bulk ceramic elements such as lead zirconate titanate (PZT) can be attached close to the root of the load beam suspension arm to either position the arm up or down or to suppress induced motion within the arm at resonant frequencies [13]. When operated in this way, the actuator thickness should be as small as possible, but of comparable thickness to that of the cantilever. The two main reasons for this are: to optimise the cantilever actuation [14] and, to prevent the actuator from affecting the dynamic characteristics of the cantilever. This technique has been used previously for micro-positioning and active vibration control [15].

Another route involving bonded actuators is the use of composite piezoelectric materials. It is possible to make a piezoelectric thick film by combining piezoelectric powder and epoxy resin [16]. However, films produced using this method have a much lower piezoelectric activity compared to bulk ceramics and, because of the flexibility of the film, this activity cannot be coupled adequately to the underlying structure. In order to circumvent this problem, composite films have been reinforced using glass fibre and/or carbon fibre [17]. These films offer much improved rigidity, compared to standard composites, resulting in increased effective bending moments of the arm. Current work is being extended to improve the films by reinforcing the composite using PZT fibres. This will form what we will call an actively reinforced composite, which should offer improved actuation and rigidity.

**EMBEDDED PIEZOELECTRIC ACTUATORS**

The simplest method is to embed piezoelectric stacks into the head suspension system. While retaining the current stainless steel load beam suspension, the piezo-stacks are embedded at the end of the aluminium frame arm. One stack is embedded such that when actuated, it produces motion of the arm in the x-y plane (for fine data tracking). The other stack is embedded such that it produces motion in the z-axis. Since both piezoelectric stacks are embedded at the end of the aluminium frame, resonance effects within the aluminium arm do not affect the performance of the piezoelectric stacks. In addition, the location of the piezoelectric stacks ensures that increased servo bandwidth can be realised. This work is also currently in progress, and is of great commercial interest.

**ACTIVE COMPOSITE**

Current technology uses a sprung stainless steel cantilever, to which the head and gimbal assembly is attached at the end. As stated previously, a voice coil motor is used to position the head in the x-y plane for track selection, whereas the flying height (z-axis) is determined from the compliance of the arm. Aerodynamic characteristics
of the air-bearing slider and the speed of rotation of the disk. The whole load suspension arm is fabricated from carbon and glass fibre, with PZT distributed within the composite framework to make it active. The composite arm would control the head flying height and the current aluminium frame would have a piezo-stack embedded within its frame to produce fine motion for data tracking, hence realising the dual-stage 2-dimensional actuation. However, the fabrication of such a composite arm is time-consuming and requires several stages of intricate work, and hence may be unattractive for commercial adoption in current disk drive mass-producing factories. A prototype of such a composite arm is shown in Figure 7.

CONCLUSION
A measurement system has been developed to determine the success rates of data transfer to and from the hard disk under conditions of vibration (and shock). In parallel with work, the dynamic morphology of hard disks has been investigated experimentally using accelerometers and modelled using finite element analysis. The results obtained have, not surprisingly, shown that data transfer is strongly affected by the dynamic behaviour of the disk itself.

In order to improve hard disk performance, in terms of reliable data transfer, it is a fundamental requirement that the read/write head is maintained at a constant height above the rotating disk. Our research has shown that disk flexure can severely affect data transfer under adverse conditions, but it should be possible to circumvent this limitation by developing appropriate sensor-actuator systems. A number of possible configurations have been investigated, based upon optical sensing and piezoelectric micro-actuators. The wide bandwidth of piezoelectric actuators has already been shown to enable resonant vibrations to be damped whilst simultaneously allowing the flying height to be controlled. Future work will continue the research and development into sensor-actuator systems in parallel with the characterisation and modelling of hard disk drives. In particular, we are interested in modelling laminate disks incorporating passive damping. These may give a significant improvement in ruggedised systems, even without active control of the head-suspension system.

REFERENCES
ABOUT THE AUTHORS

David F.L. Jenkins holds the degrees of B.Sc. (Physics), M.Sc. (Lasers and their Applications) and Ph.D. (Photothermal Deflection Spectroscopy). After completing his Ph.D. research at Royal Military College of Science he became a post-doctoral Research Fellow at Coventry University in 1990, working on Magneto-Photo-Acoustic Spectroscopy. Between 1995 and 1997 he worked in the Information Storage Group, Division of Electrical Engineering at University of Manchester, researching into active vibration control of micro-mechanical structures. In 1997 he moved to University of Plymouth to take up the position of Lecturer in the Centre for Research in Information Storage Technology where he has continued his research into micro-actuators and micro-sensors.

Warwick Clegg studied Physics at the University of Liverpool in the mid-1960s and then went on to gain Masters and Doctoral Degrees at the University of Manchester for work on magnetic data stores. He has recently moved to the University of Plymouth where his current research includes instrumentation for optical and magnetic recording and micro-imaging using scanning laser and scanning probe techniques.

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Investigation of actuation capabilities of glass fibre reinforced composite PZT thick films

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Abstract. This paper investigates the use of glass fibre reinforcement to improve the actuation capabilities of lead zirconate titanate (PZT) thick films for micro-actuation applications. One of the potential applications of such thick film reinforcement is in structural health monitoring. The effect of increasing the volume fraction of the glass fibre in the PZT film on the actuation capabilities of the films is investigated – the fibre is randomly dispersed in a 2-dimensional array in the thick film.

I. Introduction

The use of piezoelectric materials as smart structures has continued to receive considerable attention. Because of their light weight, fast response, low cost, high stiffness and availability in different sizes; piezoelectric materials are widely used as sensors and actuators in applications such as active vibration control [1], noise reduction [2], shape control [3] and damage assessment [4]. Recent advances in the design and manufacturing of aerospace and automotive systems have extended the use of piezoelectric fibre-reinforced composite materials, owing to their high stiffness-to-weight and strength-to-weight ratios. As a result, research concerning the use of piezoelectric fibre-reinforced composite structures, both for continuous and distributed structures, has been on the increase. Chandrashekhara et al. [5] presented a mathematical model to demonstrate the dynamic response of piezo-composite beams. The independent behaviour of the sensor and actuator were investigated and numerical results were presented to demonstrate the ability of the closed loop system to control actively the vibration of laminated beams. Han et al. [6] used a linear quadratic Gaussian control algorithm to reduce the vibrational levels of lightweight composite structures with surface-bonded piezoelectric sensors and actuators. Jianguo et al. [7] investigated theoretically and experimentally the stress transfers that occur between a piezoceramic actuating laminate and a glass fibre/epoxy substrate. Doyle et al. [8] monitored advanced fibre-reinforced composites, using optical fibre sensors, to detect impact damage and stiffness reduction in the composite due to fatigue damage. Wenger et al. [9] demonstrated that in-situ piezoelectrets embedded in glass/epoxy laminates are suitable for acoustic emission sensors.

The authors of this paper have demonstrated in previous work [15] that reinforcing PZT thick films with fibre improves the actuation capabilities of the thick films. The aim of the work presented in this paper is to investigate the effect of varying the glass fibre volume fraction in the PZT thick films on the actuation capabilities of the films. This would give indication of the amount of fibre to be added to PZT films when being used in structural health monitoring applications or any other application requiring micro-actuation.
2. Specimen Fabrication

To produce the piezoelectric thick films, the piezoelectric material (PZT-5H powder from Morgan Matroc Limited [10]) was combined in an epoxy resin (Araldite CY1300/HY1300). The volume fraction of the PZT powder was between 50% and 60% [11][12]. The resulting paste was divided into five equal parts (specimens \( S_1 \) to \( S_6 \)) prior to producing the final compositions. Five of these portions had small amounts of 1mm long strands of glass fibre added to them. The diameter of an individual strand of fibre is between 7 and 10 \( \mu \)m. The sixth composition was a pure PZT/epoxy mixture. The fibres were mixed thoroughly within the film to ensure a 2-dimensional random glass fibre distribution in the PZT thick film. A suitable mask enabled a 5.0 (±1%) x 3.0 (±3%) x 0.39 (±10%) mm film of each composition to be deposited directly, near the root, onto rigidly-clamped stainless steel cantilever substrates, as shown in Fig. 1. The percentage compositions by volume of the glass fibre in the films are shown in Table 1. The dimensions of the stainless steel cantilever were 10 (free length) x 3.0 x 0.2 mm.

Table 1 Composition of glass fibre content in PZT thick films

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Fibre content in thick film (volume %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1 )</td>
<td>0</td>
</tr>
<tr>
<td>( S_2 )</td>
<td>4.2</td>
</tr>
<tr>
<td>( S_3 )</td>
<td>8.4</td>
</tr>
<tr>
<td>( S_4 )</td>
<td>16.8</td>
</tr>
<tr>
<td>( S_5 )</td>
<td>25.2</td>
</tr>
<tr>
<td>( S_6 )</td>
<td>33.6</td>
</tr>
</tbody>
</table>

The films were cured at room temperature for 72 hours. The stainless steel formed the lower electrode for the thick film, whereas conducting silver paint was used for upper electrode. A mirror glued at the end of the stainless steel acts as a reflector for the optical beam deflection (OBD) technique used to measure beam deflections. The PZT thick films were then poled at 30 kV/cm for 50 minutes at 70°C. The poling voltage was below that which causes dielectric breakdown for each film. The actuation capabilities of the thick films were then characterised using the OBD technique.
3. Experimental Results
The experimental arrangement used in this work is shown schematically in Fig. 2. A positioning signal applied to the piezoelectric thick film forces the cantilever into periodic motion at the drive frequency by inducing in it a strain that is dependent on the magnitude of the applied voltage. To monitor the positional movements of the cantilevers, the optical beam deflection technique is used [13]:

![Schematic of the experimental arrangement](image)

Fig. 2 Schematic of the experimental arrangement.

A constant drive voltage of 20 V peak-to-peak was applied to each film. The output voltage readings were measured using a DSP lock-in amplifier (EG&G 7260) and the respective cantilever end-deflection $\Delta x$ (on and off-resonance) determined. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\Delta x$ (nm)</th>
<th>$\Delta x$ (nm)</th>
<th>Resonant frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen</td>
<td>Resonant operation</td>
<td>Linear operation</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>22.9</td>
<td>1.62</td>
<td>1.425</td>
</tr>
<tr>
<td>S2</td>
<td>25.0</td>
<td>3.60</td>
<td>1.432</td>
</tr>
<tr>
<td>S3</td>
<td>28.0</td>
<td>3.93</td>
<td>1.482</td>
</tr>
<tr>
<td>S4</td>
<td>37.0</td>
<td>5.00</td>
<td>1.401</td>
</tr>
<tr>
<td>S5</td>
<td>4.30</td>
<td>0.90</td>
<td>1.469</td>
</tr>
<tr>
<td>S6</td>
<td>1.10</td>
<td>0.20</td>
<td>1.480</td>
</tr>
</tbody>
</table>

It can be seen in Table 2 that as the glass fibre content in the PZT thick films is increased, the actuation capabilities of the films, on and off-resonance, also increases. However, increasing the fibre content further does not continue to increase the degree of actuation. Figure 3 shows that actuation capability is optimised, in this case when the volume percentage of glass fibres is around 16%.
4. Discussion and Conclusions
The higher end-deflections of the cantilevers, on and off-resonance, with increasing glass fibre content in the film are due to the increased stiffness of the composite PZT films. The stiffness of the composite PZT thick film is calculated as in [16] for fibres distributed randomly in a 2-dimensional matrix within the composite PZT thick film. An increase in stiffness (or Young's modulus $E_{II}$) of the thick film improves the electro-mechanical coupling between the composite PZT thick film and the stainless steel cantilever. A consequence of this is an improvement in the actuation capabilities of the composite PZT films, and hence, higher cantilever's end-deflections are possible. However, a certain point is reached where the addition of more glass fibre results in a reduction in the actuation capabilities of the composite PZT thick film. Beyond this point, the 'optimal actuation point', cantilever end-deflections are reduced, even though actuation stability improves. This is thought to be due to the reduced volume percentage of piezoelectric material within the film, which also gives rise to poling inefficiency. This is due to the dielectric mismatch between the PZT grains and glass-fibre reinforced epoxy resin. Table 3 shows the Young's modulus of the composite PZT thick films with their corresponding cantilever actuation off-resonance (20 V peak-to-peak applied voltage at 300 Hz).

Table 3 Effect of increasing stiffness of PZT thick film

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Glass-fibre Volume %</th>
<th>Young's modulus $E_{II}$ (GPa)</th>
<th>Cantilever Actuation (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>0</td>
<td>4.20</td>
<td>1.62</td>
</tr>
<tr>
<td>$S_2$</td>
<td>4.2</td>
<td>5.50</td>
<td>3.60</td>
</tr>
<tr>
<td>$S_3$</td>
<td>8.4</td>
<td>6.80</td>
<td>3.93</td>
</tr>
<tr>
<td>$S_4$</td>
<td>16.8</td>
<td>9.00</td>
<td>5.00</td>
</tr>
<tr>
<td>$S_5$</td>
<td>25.2</td>
<td>12.0</td>
<td>0.90</td>
</tr>
<tr>
<td>$S_6$</td>
<td>33.6</td>
<td>4.0</td>
<td>0.20</td>
</tr>
</tbody>
</table>
In conclusion, the work presented in this paper shows that reinforcing composite PZT thick films with glass fibre improves the actuation capabilities of these composite thick films up to a certain point, where actuation is optimised. Beyond this point, the actuation reduces. These findings show that glass fibre reinforced composite PZT thick films would make good actuators for applications such as structural health monitoring.

Acknowledgements
The authors would like to thank the University of Plymouth for financial support.

References
An Investigation into the Use of Glass and Carbon Fibre Reinforced Piezoelectric Composites as Micro-Actuators

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It is predicted that areal storage densities of magnetic hard disk in excess of 40 Gbit/in² will be possible by the year 2005. Along with this development is the requirement for the accuracy of head positioning to move beyond that provided by present technology. To attain such accuracy, attention has turned to exploring the use of smart composite materials to develop an ‘active arm’ capable of sub-nanometre positioning to be used in advanced disk drives. In moving towards the fabrication of such an arm, fibre-reinforced lead zirconate titanate (PZT) structures of differing composition were fabricated and their micro-actuation capabilities characterised. This paper presents some initial findings and discusses the results.

Keywords: PZT fibre-reinforced composites; micro-actuators

INTRODUCTION

The use of piezoelectric materials as smart structures has recently received considerable attention. Because of their light weight, fast response, low cost, high stiffness and availability in different sizes, piezoelectric materials are widely used as sensors and actuators in applications such as active vibration control, noise reduction, shape control and damage assessment.
Recent advances in the design and manufacturing of aerospace and automotive systems have extended the use of piezoelectric fibre-reinforced composite materials, owing to their high stiffness-to-weight and strength-to-weight ratios. As a result, research concerning the use of piezoelectric fibre-reinforced composite structures, both for continuous and distributed structures, has been on the increase. Chandrashekhara et al.\cite{Chandrashekhara} presented a mathematical model to demonstrate the dynamic response of piezo-composite beams. The independent behaviour of the sensor and actuator were investigated and numerical results were presented to demonstrate the ability of the closed loop system to control actively the vibration of laminated beams. Han et al.\cite{Han} used a linear quadratic Gaussian control algorithm to reduce the vibrational levels of lightweight composite structures with surface-bonded piezoelectric sensors and actuators. Jianguo et al.\cite{Jianguo} investigated theoretically and experimentally the stress transfers that occur between a piezoceramic actuating laminate and a glass fibre/epoxy substrate. Doyle et al.\cite{Doyle} monitored advanced fibre-reinforced composites, using optical fibre sensors, to detect impact damage and stiffness reduction in the composite due to fatigue damage. Wenger et al.\cite{Wenger} demonstrated that in-situ piezoelectrets embedded in glass/epoxy laminates are suitable for acoustic emission sensors.

The aim of the work presented in this paper is to show progress towards the fabrication of a stiff, light weight active composite 'smart' arm, fabricated from glass or carbon fibre-reinforced composites, which would be used in a dual-actuation mechanism in advanced computer hard disk drives. This would enable both positioning control of the head flying height (z-axis) above the disk and high resolution tracking (y-axis), capable of sub-nanometre positioning in both axes.
To produce the piezoelectric thick films, the piezoelectric material (PZT-5H powder from Morgan Matroc Ltd.) was combined in an epoxy resin (Araldite CY1300/HY1300). The volume fraction of the PZT powder was in excess of 50%. The resulting paste was divided into three equal parts prior to producing the final compositions. The first and second parts had small amounts of 1 mm long strands of carbon fibre and glass fibre added to them respectively. The diameters of the fibres were between 7 and 10 μm. The third composition was a pure PZT/epoxy mixture. The fibres were mixed thoroughly to ensure their uniform distribution. A suitable mask enabled a 5.0 x 3.5 x 0.32 mm film of each composition to be deposited directly, near the root, onto rigidly-clamped stainless steel cantilever substrates, as shown in Fig. 1. The percentage composition by volume of the carbon fibre and glass fibre in the films was 1 and 25 respectively. We have found that greater amounts of carbon fibre prevent the PZT thick film from being poled successfully as the carbon fibre creates a conducting path within the PZT matrix. The dimensions of the stainless steel cantilever were 16.5 (free length) x 3.5 x 0.2 mm. The samples were cured at room temperature for 24 hours. The stainless steel formed the lower electrode for the thick film, whereas conducting silver paint was used for upper electrode. A mirror glued at the end of the stainless steel acts as a reflector for the optical beam deflection (OBD) technique used to measure beam deflections. The films were then poled at 18.75 kV/cm for 50 minutes at 70°C. The poling voltage was below that which causes dielectric breakdown for each film.
The actuation capabilities of the thick films were then characterised using the OBD technique.

The experimental arrangement used in this work is shown schematically in Fig. 2. A positioning signal applied to the piezoelectric thick film forces the cantilever into periodic motion at the drive frequency by inducing in it a strain that is dependent on the magnitude and frequency of the applied voltage. To monitor the positional movements of the cantilevers, the optical beam deflection technique is used. Light from a laser diode of wavelength 670nm is focused onto the mirror at the end of the cantilever and the reflected light collected by a position sensing photodetector. The output signal at the differential amplifiers is, for small displacements as in this case, directly proportional to the cantilever end-deflection. The optical beam deflection technique was calibrated using a bimorph element of known characteristics.\(^{13}\)

FIGURE 1 Cantilever construction showing the PZT thick film deposited near the root, and, the mirror for optical reflection.
A constant drive voltage of 7 V (r.m.s.) was applied to each cantilever and the excitation frequency varied from 400 to 800 Hz. For these cantilevers the response to the drive voltage is constant at lower frequencies, reaching a maximum at the first resonant frequency before rolling off again\textsuperscript{114}. For each frequency of interest, the output voltage readings were measured using a DSP lock-in amplifier (EG&G 7260) and the end deflection determined from our calibration. The fundamental frequencies of vibration of the cantilevers were 600, 615 and 612 Hz for the carbon fibre-reinforced, glass fibre-reinforced and normal PZT thick films respectively. The results are shown in Fig. 3.

It can be seen that the cantilever with the carbon fibre-reinforced PZT film produced the highest resonant peak (end-deflection), slightly higher than the cantilever with the glass fibre-reinforced PZT film. The cantilever...
with the PZT thick film without any reinforcement produced a much lower resonant peak than the other two films.

In addition, the resonant curves of the cantilevers with fibre-reinforced films are much sharper than those without any fibre-reinforcement, with mechanical quality factors (Q) being 150, 100 and 20 for the PZT/carbon, PZT/glass and PZT alone respectively. However, off-resonance, the cantilever with the PZT film without any fibre-reinforcements appears to experience marginally higher end-deflections than the PZT fibre-reinforced films.

FIGURE 3 Frequency response curves for different piezoelectric-epoxy film compositions: PZT/carbon fibre, PZT/glass fibre and PZT alone.
DISCUSSION AND CONCLUSIONS

The higher end-deflections of the cantilevers with the fibre-reinforced PZT films indicate greater actuation capabilities possible with these films at resonance. It is believed that the reason for this is, due to the increased stiffness of the PZT-composite films, the carbon and glass fibre enable better coupling between the PZT thick film and the stainless steel cantilever substrate, causing greater actuation when the PZT films are under stress. The sharper resonant curves indicate that the cantilevers with the fibre-reinforced PZT films have a much higher Q-factor than those without any fibre-reinforcements, which is also a consequence of greater structural stiffness. The higher Q-factor is very valuable in making these structures more sensitive in electronic measurement applications and more stable in resonant applications. Other compositions of these PZT-composite structures are now under investigation in an effort to combine improved performance both on- and off-resonance.

In conclusion, the work presented in this paper shows that fibre-reinforced PZT thick films have better actuation capabilities at resonance and, they exhibit higher Q-factor values. This makes them better as sensors and actuators for certain control applications.

Acknowledgements

The help of the British Council (Singapore) in facilitating this joint project is gratefully acknowledged. The ISAT group of the Institution of Physics is also thanked by one of us (C.C.) for travel support.

References

P1.22

Resolution issues in magneto-optic confocal imaging laser microscopy

Jutler, C D Wright

Further, University of Manchester

Spectral resolution in magneto-optic confocal scanning microscopes has been shown to be dependent not only on confocal pinhole size, but also on the MO detection scheme adopted. Indeed, the conventional differential pinhole scheme has been shown theoretically to offer no spectral resolution, even when used with the smallest of pinholes. Experimental measurements using a range of pinhole sizes from 10 to 100 microns seem to verify this conclusion.

P1.23

Techniques for reducing thermal intersymbol interference in optical recording

Wright, C D

Preston, University of Manchester

A fibre-based method for solving the heat conduction problem in a range of optical storage formats (magneto-optical DVD) has been used to investigate all possible schemes for reducing the level of thermal intersymbol interference and the practical potential of density in high speed optical recording.

P1.7

Optical scanning interferometry

College, Blackett Laboratory, London

To go beyond effective one electron calculations which are the parameter choice in Monte Carlo calculations. Variational MC and to a lesser extent local density functional MC calculations are only as good as the trial function used. As the MC algorithm is used for gaining insight into correlation effects, an important aspect of wavefunction is the so called Jastrow term which models the electron-electron interaction. Currently many systems use a homogeneous Jastrow term even when the inhomogeneous systems. The aim of our work is to go back to the origins of this widely used correlation term to the current Random Phase Approximation by Bohm. In order to improve the Jastrow term or at least understand better why a homogeneous correlation would work so well.

12.8

Magnesium study of critical behaviour in a dimensional hydrogen

van der Werf, D P, Rice-Evans, P C

Ludlow, University of London

not submitted.

17

Method for the accurate measurement of an electron current generated by surface waves

Jansen, A, Hartland

Physical Laboratory

There has been considerable interest in the laser community in developing a quantum standard to compare with the existing quantum standards and resistance. Such a measurement is equivalent to the metrological triangle between frequency, and current.

Uelligmly for a worthwhile metrological experiment it will be necessary to measure the current with a relative uncertainty of smaller than 1 part in 10^14. Single electron device currents available so far are typically smaller than 1 nA, i.e. an accurate measurement of current of smaller than 10^-16 will be necessary.

At NPL we are adopting a cryogenic current comparator (CCC) which should enable us to resolve the metrological triangle with an accuracy of 1 part in 10^14. The first results of this work will be presented.

OG.LP2.21

Investigation into the use of PZT fibre reinforced as micro-actuators: glass/carbon fibre combinations

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It is predicted that areal storage densities of magnetic hard disk in excess of 40 Gbits/in^2 will be possible by the year 2005. Along with this development is the requirement for the accuracy of head positioning to move beyond that provided by present technology. To achieve this, attention has turned to exploring the use of smart composite materials to develop an active arm capable of sub-nanometre positioning to be used in advanced disk drives. In recent years, the use of piezoelectric materials as sensors and actuators has received considerable attention in applications such as vibration control[1], shape control[2] and damage assessment[3]. Recent advances in the design and manufacture of aerospace and automotive systems have extended the use of piezoelectric fibre-reinforced composite materials, owing to their high stiffness-to-weight and strength-to-weight ratios. As a result, research concerning the use of piezoelectric fibre-reinforced composite structures, both for continuous and distributed structures, has been on the increase.

This paper presents some initial findings and discusses the results of moving towards the fabrication of such an arm by mixing lead zirconate titanate (PZT) powder with varying proportions of glass and carbon fibre combinations in an epoxy binder and depositing directly onto stainless steel substrates to form fibre-reinforced PZT composite thick films. The films were cured at room temperature, polished at an elevated temperature and their micro-actuation capabilities characterised.


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Paraconductivity and Excess Hall-Effect in Epitaxial YBa2Cu3Ox Thin Films

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Epitaxial c-axis oriented thin films of superconducting YBa2Cu3Ox were grown on LaAlO3 (100), MgO (100) and SrTiO3 (100) substrates by in-situ r.f. magnetron sputter deposition, using stoichiometric YBCO targets. The DC resistivity and the Hall effect were measured as a function of temperature and analysed in terms of excess conductivity theories for the direct and indirect fluctuation contributions in a two-dimensional layered superconductors (1-2). Above Tc, the resistivity was nearly proportional to T and the cotangent of the Hall angle proportional to T squared. Deviations from this behaviour in the vicinity of

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OPTIMISATION OF THE OPTICAL BEAM DEFLECTION TECHNIQUE FOR HIGH RESOLUTION DISPLACEMENT MEASUREMENTS OF MICRO-MECHANICAL STRUCTURES

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The accurate measurement of the end-deflections of miniature mechanical cantilevers is of great importance in some areas of research such as in scanning probe microscopy. Several methods exist to measure the end-deflection of the cantilever, such as Optical Beam Deflection detection (OBD) [1], capacitive detection [2], interferometry [3], strain gauges [4] and piezoelectric [5]. Which technique to adopt for cantilever deflection measurements depends largely on the resolution, sensitivity of the technique and accuracy thus obtained in the measured quantity. However, the cost of the whole experimental arrangement, its simplicity and the inability to suffer from thermal or mechanical drift does influence the choice of the technique. Because of its simplicity, and being relatively inexpensive compared to the other detection methods, the OBD technique has been adopted. It is an extremely sensitive technique which enables high resolution measurements of the cantilever end-deflections to be made.

The OBD technique has been investigated and used widely in research. In 1995, Cunningham et al. [6] used the technique in active vibration control and actuation of small cantilevers for applications in scanning probe instruments. In 1991, Putman et al. [7] made a theoretical comparison between interferometric and the OBD technique for the measurement of cantilever end-deflections in atomic force microscopy. They showed that under optimal conditions the OBD technique is just as sensitive as the interferometer.

The principle of the OBD technique is simple. A collimated laser beam is focused onto a mirror attached at the free end of the cantilever to reflect the laser beam onto a position sensitive quadrant photodetector. The photocurrents generated are converted into voltages and then amplified differentially. When the beam is placed in the middle of the photodetector, so that each quadrant of the detector receives equal amounts of light, a small movement of the structure deflects the laser beam causing one part of the photodetector to receive more light than the other. The difference in intensity between the two halves of the detector gives a measure of the end-deflection of the cantilever [8]. In applications where very small displacements (sub-nanometre levels) of the cantilever need to be measured, the OBD technique must be very sensitive. This paper investigates how the sensitivity of this measurement technique can be optimised for this purpose. The laser beam emitted by the laser diode is elliptical with a Gaussian intensity distribution [9]. To optimise the measurement technique the relationship between the radius of the laser beam and the gap of the photodiode is investigated to obtain the maximum possible voltage for a given displacement of the laser beam on the quadrant photodetector. We define the sensitivity $S$ as the rate at which the voltage at the output of the differential amplifiers changes as a function of the displacement of the laser beam spot on the photodetector. Assuming that the laser beam is shifted by a displacement $d$ along its major axis, $x$, and that the laser beam is initially positioned symmetrically in the middle of the photodiode, the sensitivity of an elliptical laser beam of Gaussian power distribution is given as [8]

$$S = \frac{2 \cdot \sqrt{2} \cdot P \cdot R_f \cdot R_1 \cdot s}{\omega_s(z) \cdot R_s} \cdot \exp \left[ -\frac{(g - 4 \cdot d)^2}{2 \cdot \omega_s(z)^2} \right].$$
Where \( \omega_n(z) \) is the beam radius along the major axis (m) in the plane of the photodetector, \( g \) is the separation between individual elements of the photodiode (m), \( d \) is the shift of the laser beam along its major radius (m), \( P \) is the power of the laser beam (W), \( s_p \) is the photodiode photosensitivity (AV), \( R_f \) is the current-to-voltage feedback resistor (\( \Omega \)), \( R_1 \) is the differential amplifier input resistance (\( \Omega \)) and \( R_2 \) is the differential amplifier feedback resistance (\( \Omega \)).

To test the validity of this model, the relationship between the laser beam spot size and the gap of the photodiode was investigated experimentally. The experimental arrangement is shown in Figure 1.

![Diagram](image)

Fig. 1 Schematic diagram showing experimental set-up of equipment

The spot size was varied (and measured as described in [8]) by adjusting the lens in the laser diode. It was not possible to focus the laser spot radius to the size of the photodiode gap without using any additional optics, and so the gap was widened artificially by placing black light-absorbing tape (width of 600\( \mu \)m) vertically in the middle of the photodiode. The laser beam is deflected by the bimorph which vibrates at constant amplitude. The shift of the laser beam \( d \) on the diode is kept constant by keeping the distance between the laser diode and the photodiode constant. This is done because it would not be easy to measure practically the actual shift of the laser spot on the photodiode. In doing this, effectively, as the laser spot size is varied, the sensitivity also changes and this can be seen by a change in the output voltage, which is directly proportional to the sensitivity. For each spot size, the output voltage readings are measured using a DSP lock-in amplifier (EG&G 7260). Figure 2 shows that maximum sensitivity for the measurement technique occurs when the size of the photodiode gap is equal to the radius of the laser beam.
In conclusion, the OBD technique has been described and a model presented to optimise the technique by investigating the relationship between the photodiode gap and the laser beam radius. Experimental results show good correlation with the model presented and, further show that to achieve maximum sensitivity in the OBD technique, the photodiode gap should be equal in size to the laser beam radius. However, at the optimum point, laser beam pointing instability affects the readings taken for very small cantilever end-deflections. Laser beam radii smaller than the photodiode gap reduce the sensitivity of the measurement technique drastically. For laser beam radii larger than the photodiode gap, system stability improves without significant decrease in sensitivity, and this is the preferred method of operation.

References: