DYNAMIC ANALYSIS OF WINCHESTER DRIVE READ/WRITE HEAD DESIGNS USING THE LASER REFLECTOMETER

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CHAPTER I

INTRODUCTION

Overview

In 1957, the first movable-head disk drive was produced by IBM. This particular drive had an areal density of 2 thousand bytes per square inch. Currently, hard disk drives are being produced with an areal density of 12 million bytes per square inch [1]. This dramatic increase in areal density can be attributed, at least partially, to the reduction in head to disk spacing from 800 microinches, in 1957, to around 11 microinches currently. The decrease in head to disk spacing, or flying height, was made possible by a thorough understanding of the read/write head's dynamics, knowledge of air bearing properties, and the development of extremely smooth, planar recording surfaces.

Figure 1 illustrates a typical hard drive read/write head assembly. The ceramic head, which is the device responsible for reading and writing information to and from the disk, is supported by the gimbal and load arm. Generally, the assembly "flies" above a rotating surface of iron oxide particulate. The assembly is designed specifically to afford the ceramic head, or slider, the degrees of freedom necessary to follow any asperities which arise in the disk. The air bearing is a thin film of air between the media and the slider, which

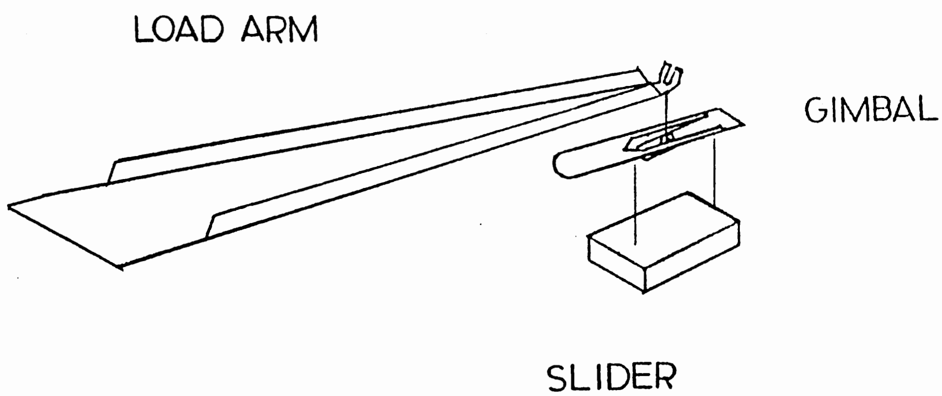

Figure 1. Typical Winchester Read/Write Head Assembly

is formed when the drive approaches operating speed. The air bearing allows the slider to fly very closely to the media without ever allowing contact between the two. If the slider ever comes in contact with the disk, or media, what is known as a "head crash" occurs. A head crash is unacceptable for normal operation of a hard disk drive because of the possibility of damaging the slider, the media, or information stored on the media. However, the slider must always maintain its standard flying height to avoid problems such as signal loss or unacceptable bit shift. Signal loss occurs when the distance between the slider and the media is too large to read or write, and bit shift is the variation between where the data is and where the data should be. On top of all of these problems, conventional present day Winchester drives operate at about 3600 rpm. Under these circumstances, one can see the complexity and importance of uncovering and understanding the slider's rotations and translations, and the significance of understanding the air bearing's effect on the slider.

Literature Survey

Studies on Hard Disk Drive Slider/Media Interfaces

An extensive amount of research has been performed concerning the properties of an air bearing, and the dynamics of a slider flying above a rotating media.

Yamada and Bogy [2] explored the characteristics of the air bearing on a Winchester drive using laser doppler vibrometry (LDV). LDV takes advantage of the doppler shift in frequency of a coherent light source, which occurs when the light is reflected off an object moving in the same direction as the light source. The shift in the frequency of light is proportional to the velocity of the object in question. Once the velocity is obtained, it can be integrated to find the displacement of the object; however, the absolute displacement can not be found because of the unknown constant that appears while integrating. The laser doppler vibrometer was accompanied in this research by an experimental setup which allowed the authors to vary the head to disk spacing, and thus permitted the air bearing to be examined at different flying heights. The paper states that when the slider is located at a point where the media velocity was 850 in./s., the air bearing seemed to be fully formed when the flying height was reduced to 157 microinches. In the study, the slider exhibited both low and high frequency motion. The low frequency motion was believed to be the slider following the contour of the media, which in this case had a peak-to-peak displacement of 985 to 1970 microinches, whereas the high frequency motion was believed to be "most likely related to the surface roughness of the disk and its vibration." The authors of the paper also mention that there were signs of the trailing edge of the slider flying lower than the leading edge (see Figure 2), and indications of the inner trailing edge flying lower than the outer trailing edge.

Bouchard et al. [3] conducted research using LDV to study three different Winchester drives. The first disk drive mentioned in the paper was a 5 1/4 inch drive, with a media velocity of 945 in./s. at the track where the head was positioned. The slider followed the disk runout (disk contour) very closely and exhibited no vibration above

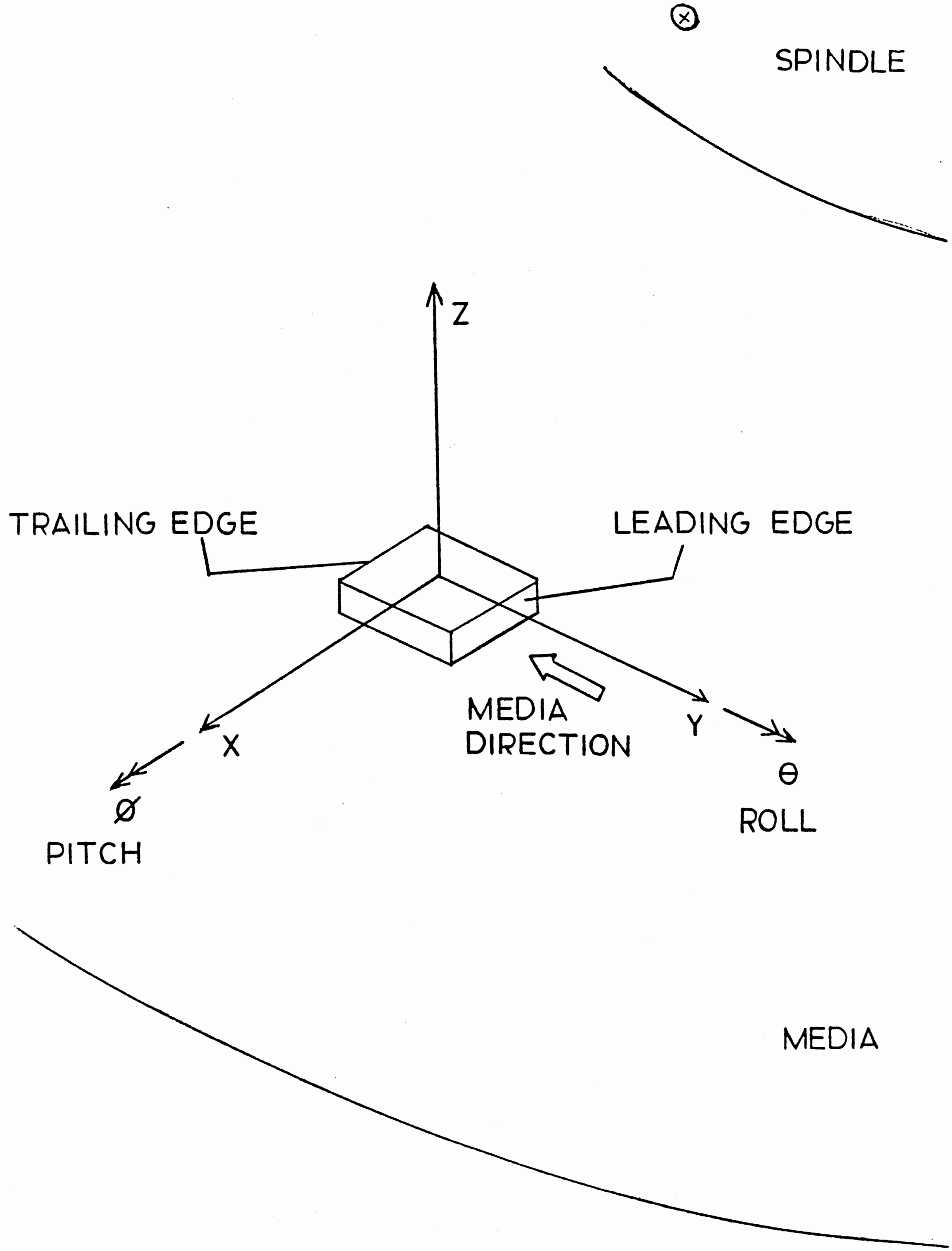

Figure 2. Definition of the Degrees of Freedom Associated with the Slider's Movements

1.5 kHz. The two remaining disk drives examined were both 8-inch drives, with inside and outside diameter velocities of 900 in./s. and 1300 in./s. respectively. For the first drive, the authors presented data which indicated the slider rotated about its trailing edge at a frequency of 6 kHz, with the amplitude of vibration decreasing from inner diameter to outer diameter. The amplitude of this vibration was on the order of 6 microinches at the leading edge, while the trailing edge was essentially unaffected. The authors also pointed out that the characteristic of the slider to fly in a leading edge up attitude did not appear to be dependent totally on the media velocity because it was noted on both the inside and outside diameters of the media. The second 8-inch drive was analyzed by taking data on an intermediate track (middle of the disk), and on the outside diameter of the disk. Two main frequencies appeared in the velocity spectrums, 7.5 kHz, and 9.5 kHz. The 7.5 kHz component seemed to be associated with the pitching of the slider, while the 9.5 kHz component appeared to be associated with the rolling of the slider (see Figure 2). The peak-to-peak displacement of the slider while pitching was noted to be as much as 4 microinches at the leading edge, and 2 microinches at the trailing edge. Although the actual read/write element is located at the rear of the slider, where the least activity occurs, the vibrations on both 8-inch disk drives were still considered significant in view of the fact that the steady state flying height of the slider was 12 microinches. The data pertaining to the second 8-inch disk drive also tends to suggest the point of rotation is not always located on the trailing edge of the slider. None of the higher frequency vibrations on either 8 inch drive were attributed to the runout of the disk, because neither media's frequency spectrum had any components above 2 kHz.

Bogy and Talke [4] used LDV to observe the out of plane motion of the disk media and two different sliders, the IBM 3340 and 3370. The in plane movement of these sliders was also investigated by utilizing laser doppler anemometry (LDA). A laser doppler anemometer splits a coherent light source, and upshifts the frequency of one of two beams by approximately 40 MHz. Next, the two beams are focused on an object which is moving in a direction perpendicular to the beams of light. The two beams of light combine on the surface of the object where they create interference fringes. When part of the object's surface crosses the fringe pattern with a given velocity, it scatters the light at a frequency proportional to its velocity normal to the fringe lines. Once again, the velocity can be integrated to obtain the displacement of the object; however, the absolute displacement is still unobtainable. With a media velocity of 750 in./s. beneath the slider, the authors collected data which indicated the disk runout had a peak-to-peak displacement of about 780 microinches. The 5 1/4-inch disk drive did not demonstrate any components of vibration above 1.5 kHz, while operating under normal conditions. To excite higher modes of vibration, the authors made a small defect in the disk on a specific track. When the slider passed over the defect a low pressure region was created, and thus the slider was excited. Both the sliders examined flew with a positive average pitch angle (leading edge up), so it was expected that the stiffness of the air bearing at the trailing edge of the slider would have a higher resonance frequency than the stiffness of the air bearing at the leading edge of the slider.

The results of the experiment seemed to confirm these beliefs. On both sliders, the resonant frequency for the trailing edge was considerably higher than that of the leading edge. The authors also conducted a study on the effects of applying different torques to the clamping bolts that attach the disk media to the spindle, and it was concluded that "higher torques produce more runout."

Miu et al. [5] used LDV to examine a purposely flawed 5 1/4-inch Winchester drive slider (similar to [4]) at a location where the media velocity was 750 in./s. The frequency spectrum obtained from the slider showed "a clear separation between low frequency components associated with the disk runout and higher frequency terms related to transient response." As in [4], the slider was thought to be flying with the leading edge up, and the trailing edge down. To verify this flying attitude, the slider was monitored flying over the induced defect. The resonant frequency of the air bearing under the trailing edge of the slider was found to be 11 kHz, which was higher than the 8 kHz resonant frequency that corresponded to the air bearing under the leading edge of the slider.

Tanaka et al. [6] not only studied read/write head dynamics through experimentation, but also approached their research through analytical methods. The experimental aspect of this paper was conducted using laser doppler interferometry (LDI). Laser doppler interferometry utilizes the property of coherent light to create interference fringes. The flying height at a particular point on the slider can be calculated if the wavelength of the light and the number of fringes between the media and the specific point on the slider are known. One problem that should be mentioned about LDI is the fact that a glass disk has to be used to allow the laser to pass through the disk surface. Thus, theoretically, all of the data that was taken does not recreate what actually occurs when the slider is flying above the standard aluminum oxide coated disk. The analytical section of the paper consisted of the authors solving the governing differential equations for slider motion which are called the "Reynolds Equation" and the dynamic motion equations. Because the governing differential equations do not simulate the asperities on the media either, exceptional agreement was achieved between the experimental and analytical results for media velocities above 600 in./s, and any difference between them above this lower limit can be considered negligible. The outer diameter of a 5 1/4-inch Winchester drive rotating at 3600 rpm had a media velocity of 945 in./s. The experimental and analytical results showed a flying height of 11 microinches for the trailing edge of the slider at this speed. The media velocity at the inner diameter for the same disk drive was 610 in./s. At this location, the flying height for the trailing edge of the slider was found to be 8.3 microinches. The authors also collected data that indicated the ratio of the flying height of the leading edge over the flying height of the trailing edge, while operating normally, was approximately 2.5. This suggests that the average pitch angle increased as the media velocity increased. Some work was also done on the transient response of the slider and it was determined that when the load arm was struck, the slider's flying height would fluctuate no more than five percent.

Mizoshita et al. [7] used LDI and a random noise generator to find the frequency response of a Winchester drive read/write head assembly. This experimental frequency response was compared to an analytical frequency response generated by a finite element analysis. The read/write head assembly was modelled using standard elements; however, to model the air bearing some simplifications had to be made. The air bearing was simplified by the system shown in Figure 3. The stiffnesses for the springs were approximated by solving the linearized modified Reynolds equation. The results from the analytical model agreed very well with the measured frequency response of the system.

Miller and Good [8] examined the stick-slip properties of floppy disk drive read/write heads. The device used in the research was designated by the authors as the laser reflectometer (LR). According to the authors, the LR had the capability of measuring vertical translation simultaneously with pitch and roll angles of either the slider or the media. The LR operated by splitting a laser beam, and focusing both beams on the same location of the object whose movements are unknown. The reflected beams each are positioned on a location sensitive lateral effect photodiode. The dynamics of the object can be determined through separately derived formulas for vertical translation, pitch, and roll, if the vertical and horizontal distances travelled by the laser beams relative to the lateral effect photodiodes are known. The system detected the slider's angular and vertical displacements and the frequencies associated with these displacements quite well. The displacements and rotations of a slider upon a floppy disk are approximately two orders of magnitude higher than that of a slider flying above a Winchester disk.

It is unclear if the LR is adequate to perform studies involving

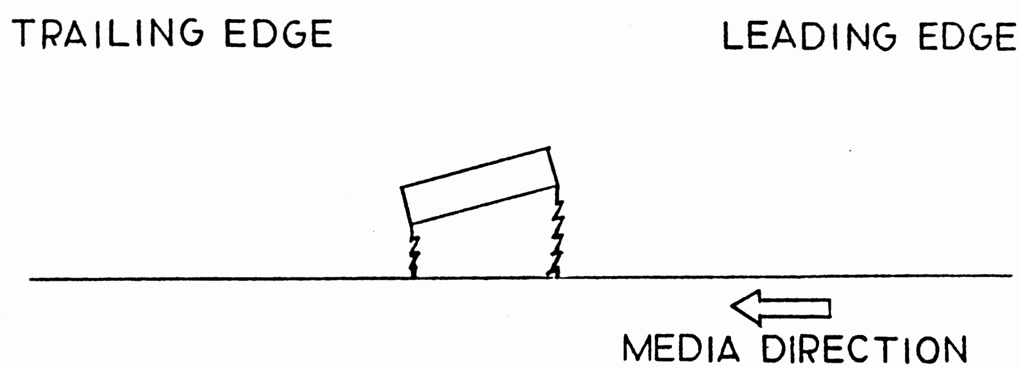

Figure 3. Finite Element Simplification of an Air Bearing

the dynamics of a Winchester drive slider, and herein lies a major objective of this research. If the experimental technique is proven viable, it will provide a simple, low cost alternative for evaluating various head/disk designs.

Selection of Experimental Apparatus

There are many different systems currently available that are capable of measuring the dynamics of an operating slider and media. Because the out of plane movements are of primary concern to this study, and LDA is not capable of making these measurements, it was not considered. Capacitance techniques were not considered either because this method of measuring slider motion requires that the slider be physically altered. This could drastically effect the movements of a hard disk drive slider in view of its small size. LDV and LDI were both viable choices but because cost made these systems impractical, they were ruled out. Thus, the LR was chosen because it was readily available, and theoretically could provide the measurements required.

Statement of Problem

The present study will examine how effectively laser reflectometry can determine the dynamics of a Winchester drive slider. If it is established that the LR does measure adequately the movements of a slider, a comparison will be made between two production read/write head assemblies to determine which assembly allows the slider to comply the closest with the media.

Approach to the Problem

This analysis will begin by recording the movements of one of the two production read/write head assemblies using laser reflectometry. If the results of the experimentation are consistent and comparable to the results found in the literature search for a similar slider, under like conditions, the system will be considered functional, and data will be collected for each of the read/write head assemblies in question. To resolve which of the read/write head assemblies is better, a series of comparisons will be made in the time and frequency domains, and the assembly that exhibits the most redeeming properties will be selected. The particular points of comparison will be: with what amplitude each slider vibrates around its steady state position, what is the average position of each slider during normal operation, the frequencies at which the sliders operate during normal operation, and a study of how well the slider's experimental frequency spectrum matches the media's frequency spectrum. A finite element analysis will also be made to distinguish between the read/write head assemblies resonant frequencies and those frequencies of the media.

Organization

Chapter II will discuss the theory and the system setup of the measurement system. Chapter III will describe the calibration, equipment used, and the procedures used during experimentation. Chapter IV will delineate the results of the study. And finally, Chapter V will assess the results presented in Chapter IV.

CHAPTER II

LASER REFLECTOMETER THEORY

An optical lever technique designated to be the laser reflectometer [8] was used in this analysis to record the movements of a Winchester drive's slider and media.

The degrees of freedom of significance for the slider, as depicted in Figure 2, are the rotations around the x and y axes, which will be referred to as pitch and roll, respectively, and the translation along the z axis which will be referred to as vertical translation. The remaining degrees of freedom are not mentioned because it is assumed that the load arm and gimbal effectively restrain these translations and rotations to very small negligible values.

As mentioned previously, the laser reflectometer, which is schematically represented in Figure 4, measures the movements of an object by means of analyzing the movements of laser beams that reflect off the object. The laser beam's change in position is determined by lateral effect photodiodes, which will be referred to as optical detectors. Because neither of the sliders examined in this study were reflective, it was necessary to mount a small mirror on each of them to reflect the incoming laser beams. The mirror was small (1.5mm x 1.5mm x 0.1mm) as compared to the slider (4mm x 3mm x 0.85mm), and it was assumed that the added mass (approximately 0.6mg) would not significantly influence the activity of the slider, which has a mass

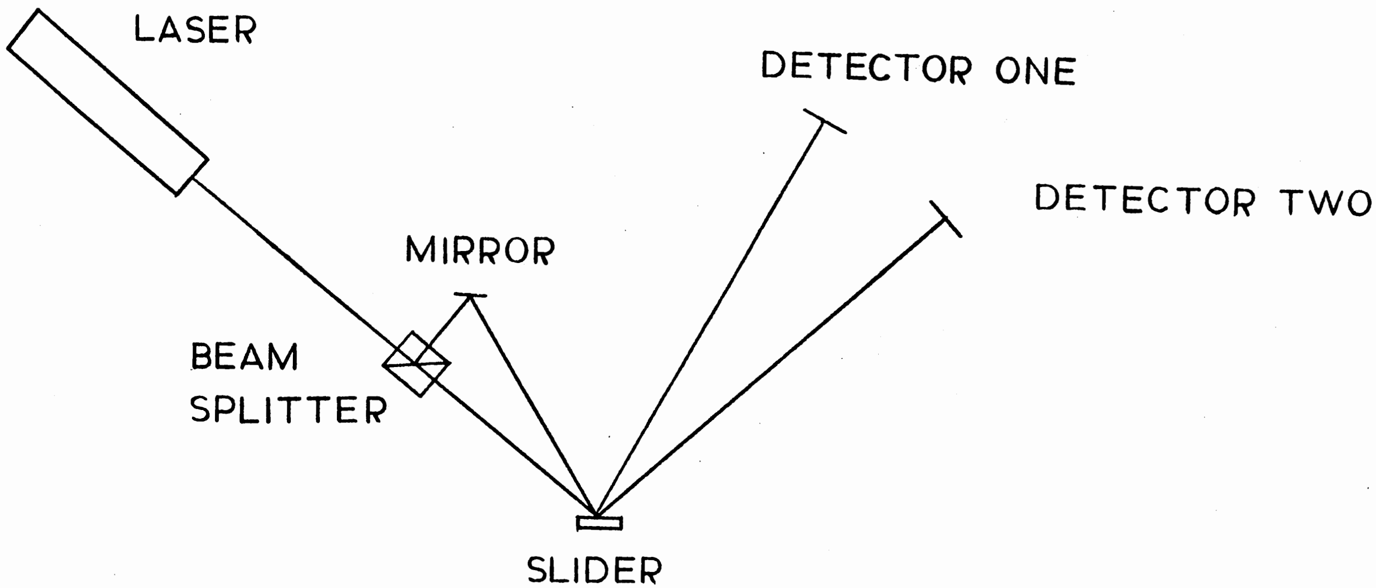

Figure 4. Schematic Representation of a Laser Reflectometer

of 44mg. Fortunately, the media surface was reflective, so no adjustments had to be made to record its movements.

Advantages and Disadvantages of the Laser Reflectometer

An important advantage of the LR was its ability to simultaneously determine the vertical translation, pitch, and roll of an object whose movements were unknown. In relation to other measurement systems, the LR can perform these tasks at a low cost. As previously stated, the LR required that a mirror be adhered to the sliders being examined. In the past, the objects being examined were relatively sizable so the mass of the mirror could be neglected. As a result, the LR was considered an unobtrusive system. In this case, the mass of the mirror was still considered negligible, because its mass was less than 2% of the mass of the slider; however, the effect of the mirror on the mass moments of inertia of the slider was a little more appreciable. On the first slider examined in this study, the mirror was placed at a location where the mirror's mass moment of inertia with respect to the y axis (see Figure 2) was nearly 5% of the slider's mass moment of inertia with respect to the same axis. If laser reflectometry is to be used to measure the dynamics of objects with smaller mass properties than those of the slider, alternate methods of making the objects reflective should be considered. One possibility is making the object reflective by means of thin reflective coatings instead of using mirrors. Some attempts were made at coating the sliders in this study with a reflective material, but this did not prove effective because the coatings were not of sufficient quality to produce acceptable beam reflections. Another problem that relates to the measurement system used in this study, was the inability of the lateral effect photodiode amplifiers to detect vibrations above 5 kHz. It is possible to purchase amplifiers that can detect vibrations up to 30 kHz, but because of cost they were not used in this study. Lastly, all measurements must be performed in the dark, preferably at a time when the building is quiet, so as to keep any unwanted external vibration to a minimum.

System Equations

Consider the consequences of the slider in Figure 5 translating purely in a vertical direction. A laser beam reflects off the top surface of the slider, which is lying in a horizontal plane, and strikes an optical detector normally. The angle between the incoming laser beam and the horizontal plane is ψ, and from basic optics laws it can be shown that ψ is also the angle between the reflected beam and the horizontal plane. If the slider translates vertically, the distance travelled by the reflected laser beam relative to the optical detector (Δ_t) can be shown through geometry to be:

$$\Delta_t = 2\Delta z \cos\psi \qquad (2.1)$$

Aside from vertical translation, the slider was also assumed to rotate about the x and y axes. The distance between the detector and the slider is designated to be R (see Figure 6). If the slider has a rotation of ϕ about the x axis, the angle between the reflected beam and the horizontal will be $\psi + 2\phi$. The reflected beam, represented by the vector $\vec{R}$, can now be broken into its y and z components:

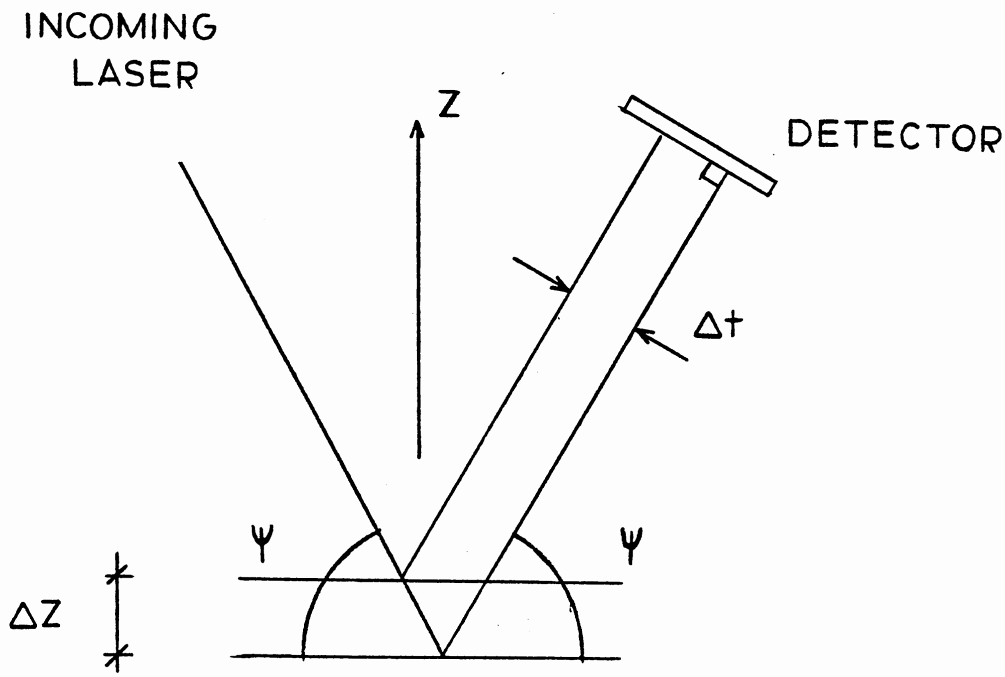

Figure 5. Reflected Beam Displacement Due to Pure Vertical Translation of the Slider

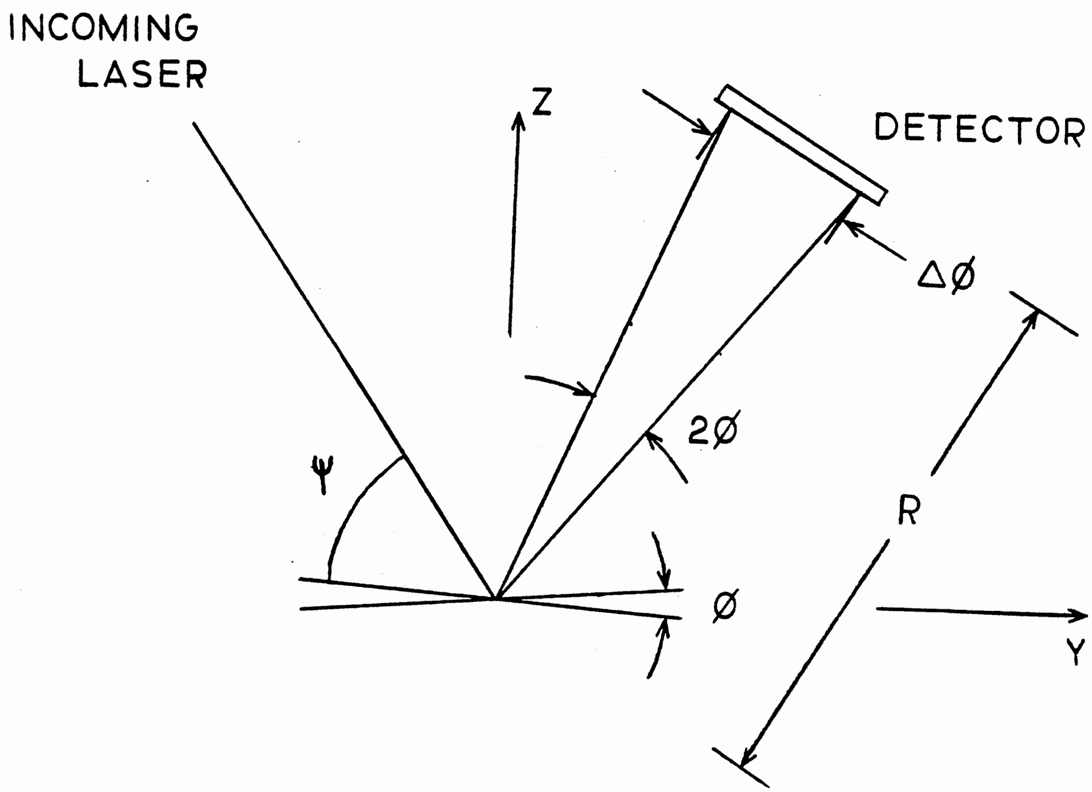

Figure 6. Reflected Beam Displacement Due to the Slider's Rotation about the X-axis

$$\vec{R} = \frac{R\cos(\psi + 2\phi)\,\hat{j}}{\cos 2\phi} + \frac{R\sin(\psi + 2\phi)\,\hat{k}}{\cos 2\phi} \tag{2.2}$$

It is also possible for the slider to rotate around the y axis. If the slider is rotated an angle θ about the y axis, as depicted in Figure 7, $\vec{R}$ is rotated about the y axis by an angle of 2θ. As a result, $\vec{R}$ acquires an x component and has its z component modified:

$$\vec{R} = \frac{R\sin(\psi + 2\phi)\ \sin 2\theta\,\hat{i}}{\cos 2\phi} + \frac{R\cos(\psi + 2\phi)\,\hat{j}}{\cos 2\phi} + \frac{R\sin(\psi + 2\phi)\ \cos 2\theta\,\hat{k}}{\cos 2\phi} \tag{2.3}$$

For this Equation to be useful it must be transformed into the local coordinates of the optical detector (x' and y' coordinate system). With the Equation in this form it will be possible to determine the rotations of the slider by analyzing the movements of the reflected laser beam relative to the optical detector. The transformed reflected laser beam will be referred to as the vector $\vec{P}$, which lies in the x', y' system and has the form:

$$\vec{P} = \frac{-R[\sin(\psi + 2\phi)\ \sin 2\theta]\,\hat{i}'}{\cos 2\phi} + \frac{R[\sin(\psi + 2\phi)\ \cos 2\theta\ \cos\psi - \cos(\psi + 2\phi)\ \sin\psi]\,\hat{j}'}{\cos 2\phi} \tag{2.4}$$

Because the above Equation is a result of rotations of the slider, it can be concluded that the term associated with the y' axis is the re-

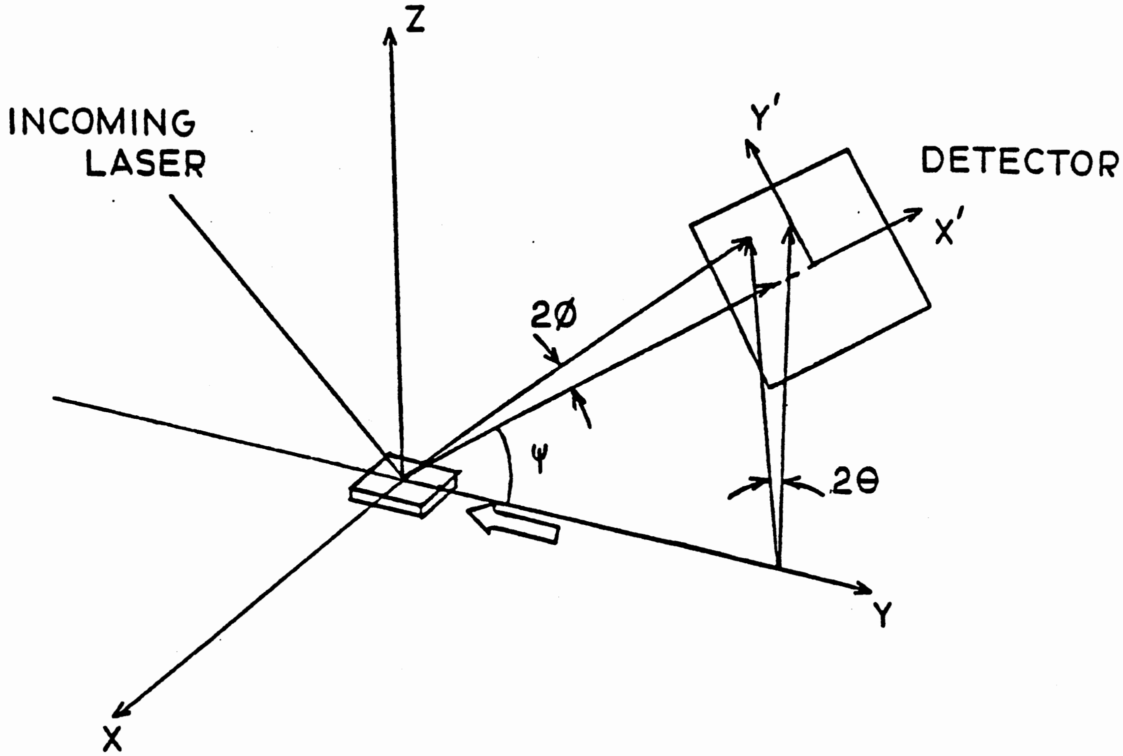

Figure 7. Reflected Beam Displacement Due to the Slider's Rotation about the X and Y axes

sult of the rotation ϕ. Similarly, it can be concluded that the term associated with the x' axis is the result of the rotation Θ, thus 2.4 can be broken into two parts. Equation 2.5 is the portion of Equation 2.4 that results from a rotation ϕ, and Equation 2.6 is the portion of 2.4 that results from a rotation Θ:

$$\Delta_\phi = \frac{R[\sin(\psi + 2\phi)\cos 2\theta \cos\psi - \cos(\psi + 2\phi)\sin\psi]\hat{j}'}{\cos 2\phi} \quad (2.5)$$

$$\Delta_\theta = \frac{-R[\sin(\psi + 2\phi)\sin 2\theta]\hat{i}'}{\cos 2\phi} \quad (2.6)$$

To simplify Equation 2.5 and Equation 2.6, the angle sum relationships for sineand cosine were substituted in yielding Equations 2.7 and 2.8, respectively:

$$\Delta_\phi = \frac{R[(\sin\psi \cos 2\phi + \cos\psi \sin 2\phi)\cos 2\theta \cos\psi}{\cos 2\phi}$$

$$- \frac{(\cos\psi \cos 2\phi - \sin\psi \sin 2\phi)\sin\psi]}{\cos 2\phi} \quad (2.7)$$

$$\Delta_\theta = \frac{-R(\sin\psi \cos 2\phi + \cos\psi \sin 2\phi)\sin 2\theta}{\cos 2\phi} \quad (2.8)$$

Because the angular displacements encountered in this type of research are very small, the following small angle assumptions were made:

$$\sin 2\phi \doteq 2\phi$$

$$\cos 2\phi \doteq 1$$

$$\sin 2\theta \doteq 2\theta$$

$$\cos 2\theta \doteq 1$$

Substituting these assumptions into Equation 2.7 produces:

$$\Delta_{\phi} = R[\sin\psi \cos\psi + 2\phi\cos^2\psi - \sin\psi \cos\psi + 2\phi\sin^2\psi] \qquad (2.9)$$

Simplifying:

$$\Delta_{\phi} = 2R\phi \qquad (2.10)$$

Applying the same small angle approximations to Equation 2.8 yields:

$$\Delta_{\theta} \cong -2R\theta\sin\psi - (2\phi)(2\theta) \cos\psi \qquad (2.11)$$

If the higher order term is neglected 2.11 becomes:

$$\Delta_{\theta} \cong -2R\theta\sin\psi \qquad (2.12)$$

It is possible for the slider to translate vertically and rotate around the x axis simultaneously. Thus Equations 2.1 and 2.10 must be added together to accurately represent the movement on the optical detector at any given time:

$$\Delta_{\phi t} = 2R\phi + 2\Delta z \cos\psi \qquad (2.13)$$

Equation 2.13 contains two unknowns Δz and ϕ . This is the rational behind the LR employing two optical detectors instead of one. If two optical detectors are used, Equation 2.13 can be applied to each detector and the two equations can be solved for the two unknowns. Referring to Figure 4 and applying Equation 2.13 to detectors 1 and 2 respectively, yields:

$$\Delta_{\phi t1} = 2R_1\phi + 2\Delta z \cos\psi_1 \qquad (2.14)$$

$$\Delta_{\phi t2} = 2R\phi_2 + 2\Delta z \cos\psi_2 \tag{2.15}$$

If $R_1 = R_2$ then 2.15 can be subtracted from 2.14 and manipulated algebraically producing:

$$\Delta z = \frac{\Delta_{\phi t1} - \Delta_{\phi t2}}{2(\cos\psi_1 - \cos\psi_2)} \tag{2.16}$$

Substituting this back into Equations 2.14 and 2.15 respectively, yields:

$$\phi = \frac{\Delta_{\phi t1}}{2R} - \frac{[\Delta_{\phi t1} - \Delta_{\phi t2}]\cos\psi_1}{2R[\cos\psi_1 - \cos\psi_2]} \tag{2.17a}$$

$$\phi = \frac{\Delta_{\phi t2}}{2R} - \frac{[\Delta_{\phi t1} - \Delta_{\phi t2}]\cos\psi_2}{2R[\cos\psi_1 - \cos\psi_2]} \tag{2.17b}$$

Equations 2.17a and 2.17b are equivalent mathematical expressions, thus ϕ could be found by using either expression. θ could be determined by Equation 2.12. If Equation 2.12 is applied to both optical detectors it generates the following two independent equations:

$$\theta = \frac{\Delta_{\theta 1}}{2R\sin\psi_1} \tag{2.18a}$$

$$\theta = \frac{\Delta_{\theta 2}}{2R\sin\psi_2} \tag{2.18b}$$

Theoretically, both of these equations will generate equivalent θ's. In reality, the results from Equations 2.18a and 2.18b might differ somewhat, a comparison of the two could give one an idea of the accuracy of the measurement system.

CHAPTER III

EXPERIMENTAL PROCEDURE

In this study an attempt was made to determine the movements of two Winchester drive read/write head sliders using laser reflectometry. The sliders studied are associated with the WREN IV and WREN V read/write head assemblies, which are produced by the Control Data Corporation. Throughout this report the terms type 4 and type 5 will be used synonymously with WREN IV and WREN V, respectively. It was not known whether the LR was capable of determining the dynamics of a slider operating in a Winchester drive because of the small amplitudes and high frequencies of the vibrations encountered. A system was constructed to record the pitch, roll, and vertical translation of a slider relative to its media during normal operation and, using the same system, some miscellaneous measurements were made regarding the slider's frequency spectrum, and also the slider's activity while moving radially from track to track. This chapter describes the use of this measurement system, and gives a description of all the steps taken in preparation for and during experimentation.

WREN IV and WREN V Read/Write Head Assemblies

The WREN IV and WREN V read/write head assemblies both have similar load arms and sliders; the difference between the two assemblies lies in the gimbals. Figures 8a and 8b illustrate the type 4 and

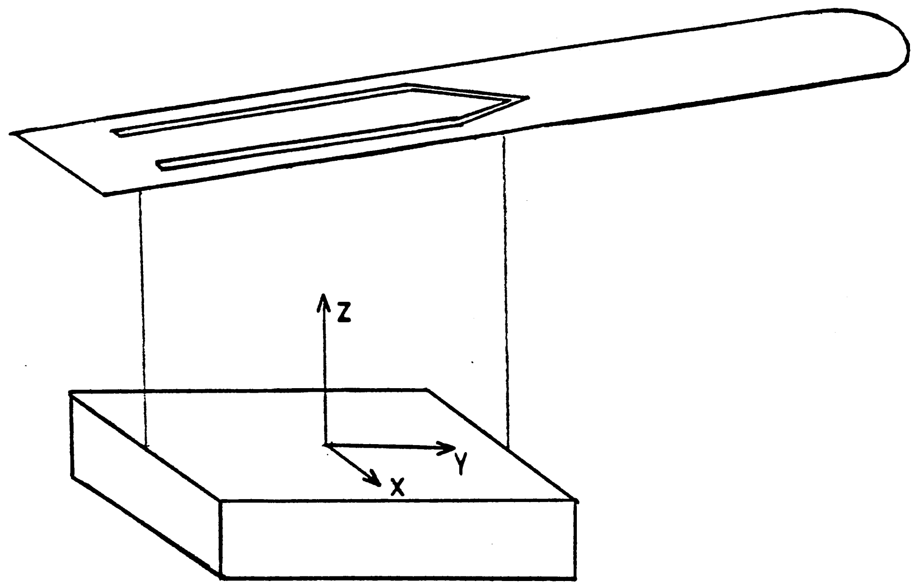

Figure 8a. Type 4 Gimbal and Slider

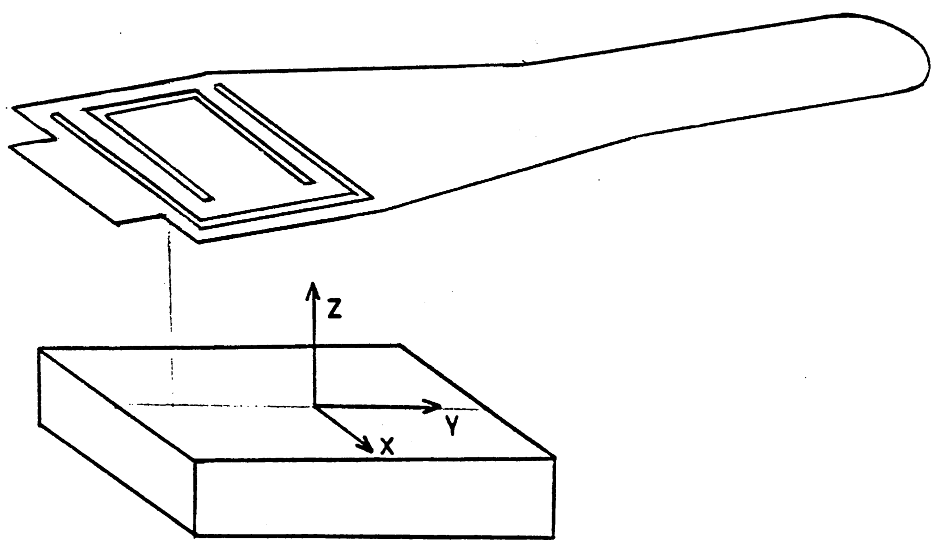

Figure 8b. Type 5 Gimbal and Slider

type 5 gimbals, respectively, and how each one is attached to its respective slider. As alluded to earlier, it was necessary to mount a small mirror on each slider so its movements could be monitored. The specific locations of these mirrors for the type 4 and type 5 sliders are shown in Figures 9a and 9b, respectively.

System Calibration

The only parts of the system that required calibration were the lateral effect photodiodes. The specific detectors used were the United Detector Technology model PIN-SC/10D, one of which is depicted in Figure 10 with its local coordinate system. The detector's active area is 0.4in. x 0.4in., with the origin of the local coordinate system located approximately at the center of the detector. Each of these photodiodes required two UDT 301-DIV transimpedance amplifiers. The detectors determine the centroidal location of an incoming beam of light, and according to where the center of the beam strikes the detector, a current is generated for both x and y positions. The currents produced are proportional to the respective x and y coordinates at which the beam strikes the detector. This means, theoretically, for the infinite number of locations a beam of light could strike the detector, an infinite number of currents could be produced. Both of these currents are converted to voltages by the amplifiers; this explains the need for two amplifiers per one detector.

All four of the detectors used in this study were of the same model; however, two of these detectors were the same exact detectors used in [8]. These two detectors were extensively tested by Miller to determine the detectors' sensitivities. Sensitivity is defined as

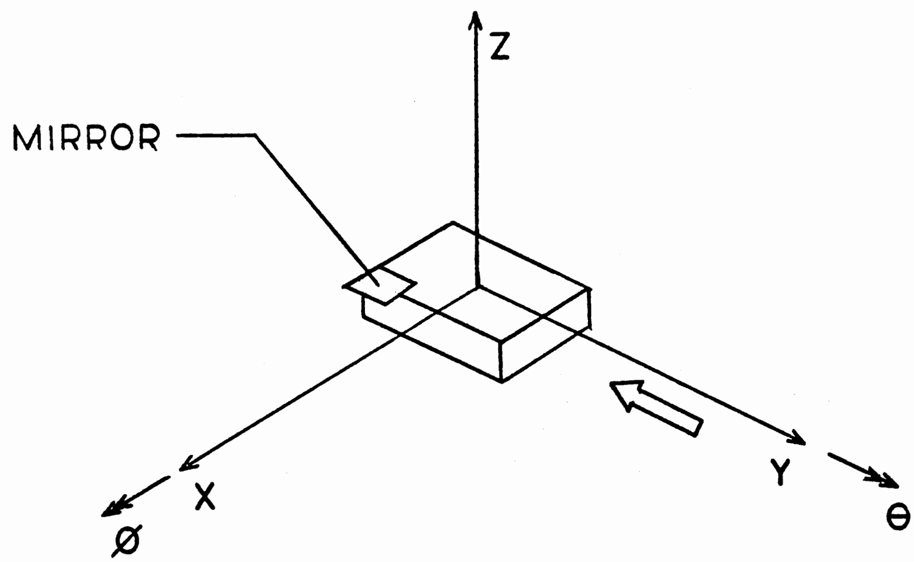

Figure 9a. Mirror Location on the Type 4 Slider

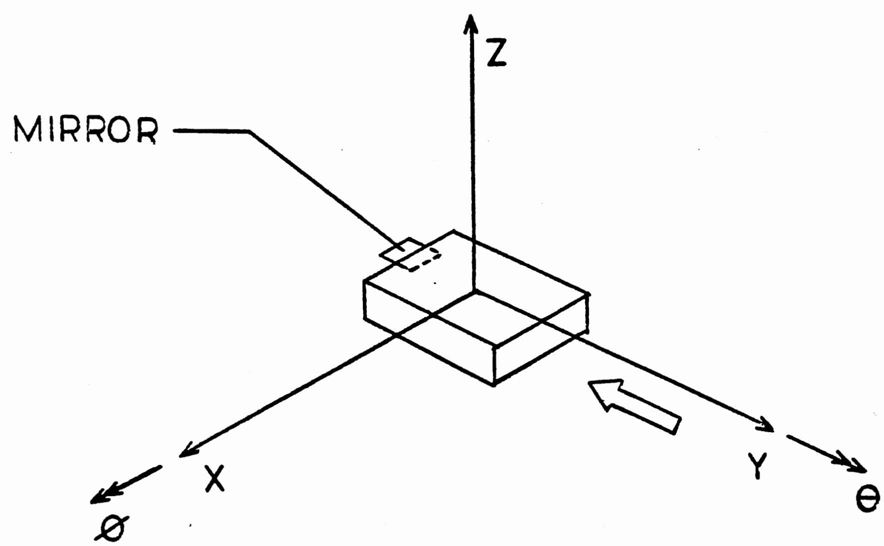

Figure 9b. Mirror Location on the Type 5 Slider

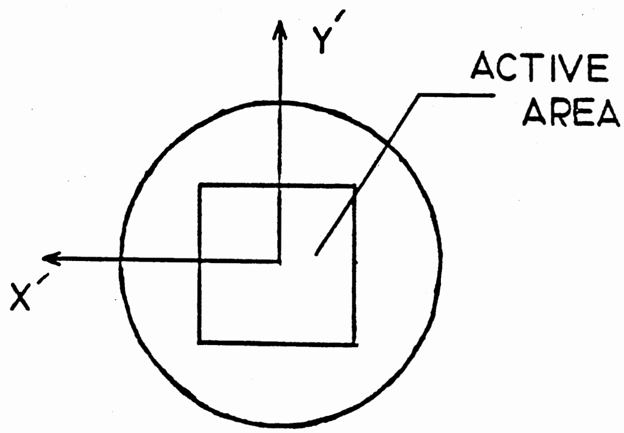

Figure 10. United Detector Technology PIN-SC/10D
Two Axis Lateral-Effect Photodiode

being the change in output voltage of the detector divided by the relative change in distance the light beam moves across the detector face. If the sensitivities are known for the given detectors and the voltages associated with the initial and final positions of the incoming laser beam are also known, the distance the beam travelled across the face of the detector can be calculated.

Each detector was tested by mounting it on a micrometer table and directing an incoming laser beam normally at incremented locations on its face. The output voltages at these locations were recorded and analyzed. The results indicated that the voltage output was not linear with respect to the displacement of the laser beam on the outer portions of the detector; however, in the central 0.06in. x 0.06in. area of the detector a linear relation between voltage output and beam displacement was exhibited for both the x and y directions, and after a statistical analysis of the results, 71 volts/inch was determined to be the average sensitivity for each detector in this interior region.

Analysis using Laser Reflectometry

To determine the flying height and the pitch and roll angles of the slider relative to the media, it was necessary to monitor the movements of the slider and media simultaneously. Thus, two of the previously described LR systems were required. It was not possible to observe the media directly beneath the slider; as an alternative, the media approximately 2 mm off the inside edge of the slider was monitored. It was assumed that the two different media locations possessed approximately the same contour. Figure 11 illustrates the optical portion of the system. The setup portrayed in Figure 11 was

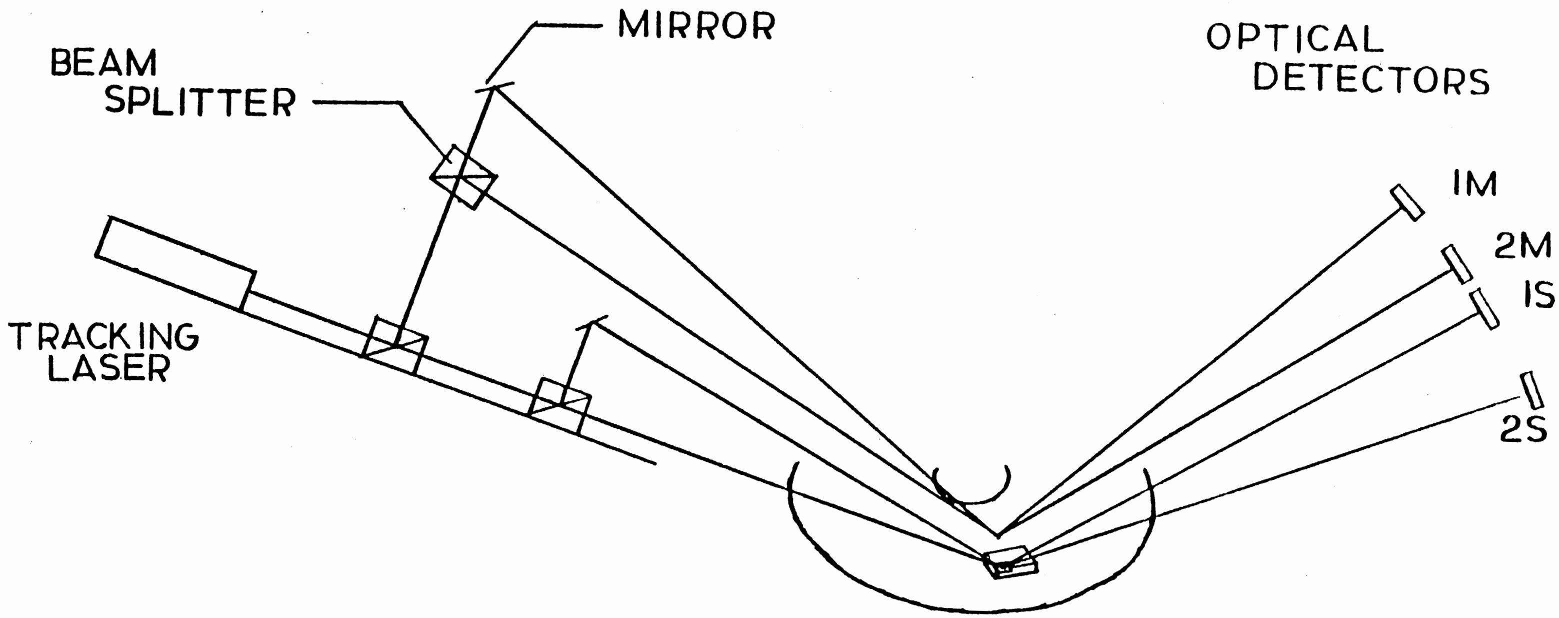

Figure 11. Schematic Representation of the Optical Portion of the Measurement System

encased entirely in an airtight "clean box". This clean box was necessary to prevent any small particulate from settling on the media or entering the internal mechanisms of the disk drive.

Figure 12 represents, schematically, the instrumentation used to record the data taken. The equipment portrayed in Figure 12 required handling; thus it was necessary to place it outside the clean box. The four "tracking" laser beams required four optical detectors, which in turn required eight amplifiers. The wiring connecting the detectors to the amplifiers was run through holes drilled in the side of the clean box. To prevent any air leaks, these holes were sealed using silicone rubber sealant. The eight amplifiers produce eight channels of voltage output. It was necessary to record all eight of these channels of voltage output so they can be analyzed using Equations 2.16, 2.17, and 2.18. To accomplish this task, a DATA 6000 waveform analyzer and a DATA 6100 waveform analyzer were used. Both of these devices are produced by the Data Precision Division of the Analogic Corporation and each has the capability of recording four channels of data simultaneously at a sampling rate of 25 kHz. The data was recorded and displayed as a waveform containing 512 data points. The device used to record the waveforms to floppy disk was a disk drive also produced by the Analogic Corporation.

The time required for a Winchester disk drive operating at 3600 rpm to make one revolution is 0.0167 seconds, and thus it was deemed necessary to obtain at least 0.0167 seconds of data for each set of data taken to examine the continuity of the waveforms. Although the time necessary for 512 data points to be taken at 25 kHz is 0.02048 seconds, which would have been adequate for recording the data

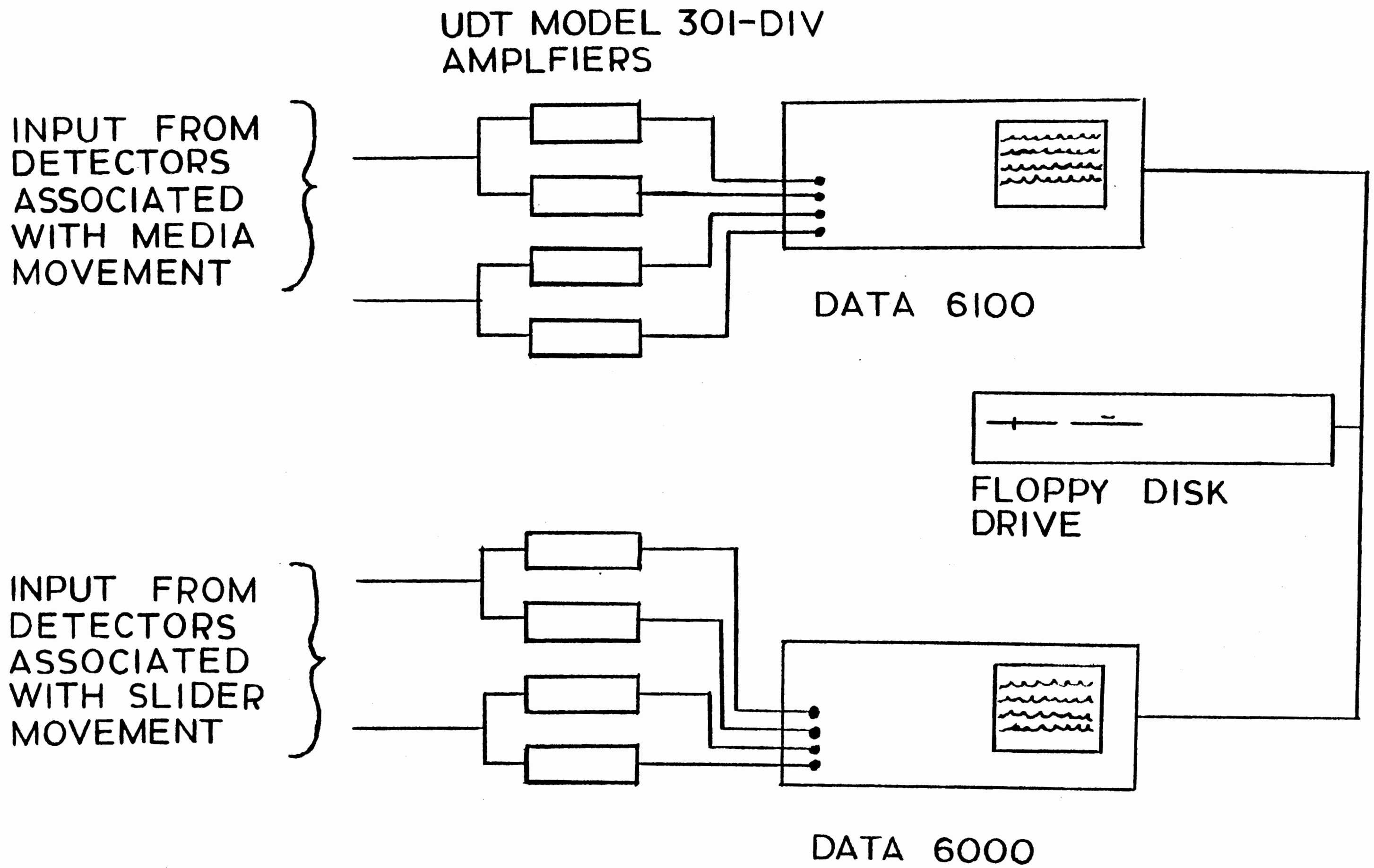

Figure 12. Schematic Representation of the Instrumentation Portion of the Measurement System

pertaining to one revolution, a sampling rate of 20 kHz was used for all data taken to acquire a broader picture of the recorded waveforms. The DATA 6000 and DATA 6100 each has a 14-bit A/D converter, which has three different input settings: 0.5, 5.0, and 50.0 volts. The sliders examined in this study have previously verified flying heights of 11 microinches. To determine the accuracy of the measurement system, it would be appropriate to operate with 1 microinch resolution. Referring to Equation 2.16, the DATA 6000 and DATA 6100 are each capable, theoretically, of ascertaining about 3.2 microinch vertical translation resolution when each machine's ordinate axis is set on the 0.5 volt scale. This resolution is not optimal, but it should be adequate enough to determine the accuracy of the system.

In this study data was taken concerning the average and peak-to-peak flying attitudes of the type 4 and type 5 sliders. Therefore, to compare these flying attitudes at the same circumferential locations, it was necessary to establish a standard location to trigger the system. A triggering device was established by placing a small mirror on the spindle, as illustrated in Figure 13. A second laser, or "triggering" laser, located outside the clean box, was then directed through the front plexiglass cover of the clean box and onto the mirror mounted on the spindle. The laser beam reflected off the mirror and struck a photoresistor located on the interior of the clean box. The laser beam only reflected off the mirror once per revolution, thus providing a reference point. The photoresistor was placed in a conventional ballast circuit, with the varying voltage across the photoresistor used to trigger the DATA 6000 and DATA 6100. When taking a standard set of data, a piece of tape was placed in front of the

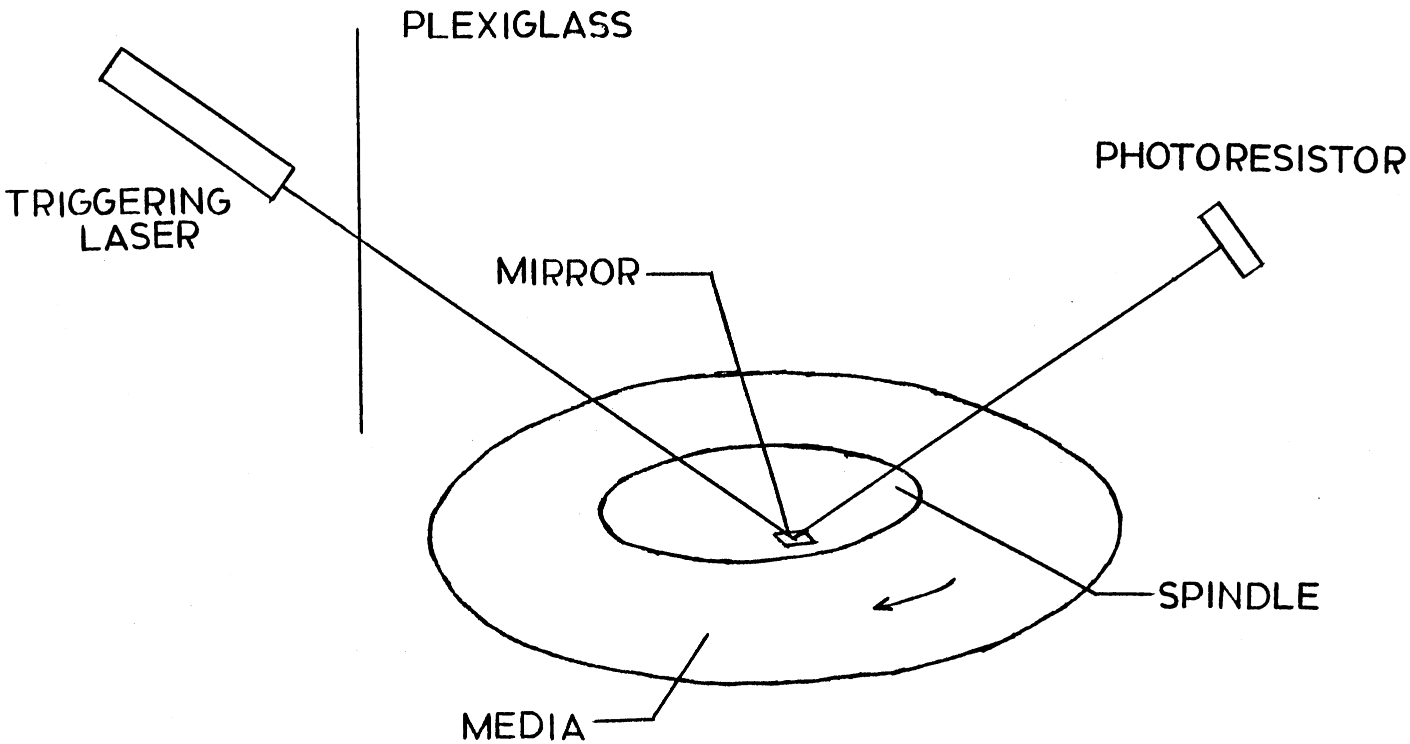

Figure 13. Schematic Representation of the Triggering Mechanism used during Experimentation

triggering laser beam on the plexiglass cover, and the Winchester drive was allowed to come up to speed normally. Once the slider was placed on a chosen track, the tape was removed, allowing the laser beam to reflect off the mirror at the reference point, and vary the voltage across the photoresistor. This would theoretically trigger the system at the same exact location for every set of data that was obtained.

Data was collected while the type 4 and type 5 assemblies were each installed in the Winchester drive. The data was obtained while the drive was operating at three different track locations: tracks 625, 335, and 000. The media velocities associated with these track locations were approximately 19.1, 21.9, and 25.1 m/s, respectively. The specific drive examined had 988 tracks, with track 988 being the innermost track and track 000 being the outermost track. The corresponding radii for tracks 988 and 000 were approximately 1.625 and 2.625 inches, respectively.

The experimental procedure used to determine the vertical translation of the type 4 and type 5 sliders relative to the media was as follows. First, with the media <u>not</u> rotating, and the media rotated to the reference point, the read/write head assembly being measured was moved manually from the parking track to the track at which the flying height measurement was about to be made. At this point, the slider was assumed to be lying perfectly flat on the media surface with no flying height whatsoever. Next, while the tracking laser beams were targeted at the slider and media, the voltages associated with this static position for the slider and media, on all 8 channels, were recorded for use at a later time. Hereafter, these voltages will be referred to as the static voltages. The head assembly was then returned to the parking track, and the drive was powered up and allowed to reach operating speed. The head assembly was then returned to the track of interest through use of a disk drive exerciser provided by the Control Data Corporation. The system was then triggered as explained previously, and the waveforms were recorded to floppy disk. The waveforms recorded on the floppy disk were stored by graphics characters, so it was necessary to convert these characters to digital data by means of a program, written in IBM basic, supplied by the Analogic Corporation. Once the digital voltage records from the data set were available on floppy disk, it was possible to use a computer to handle the massive amount of calculations involved with finding the flying height and relative rotations of the slider at all 512 points recorded. The technique used to determine the flying heights involved assuming the reference point was located at the highest point on the media. The reference point was located by: (a) manually rotating the media and observing the peaks and valleys in the media contour and (b) qualitatively placing the triggering mirror at a location on the spindle corresponding to the highest peak in the media. The Equation used to determine the flying heights was found by equating the two distances as illustrated in Figure 14:

$$\Delta M + T + \Delta H = \Delta Y + T' + FH \quad (3.1)$$

where ΔM is the vertical change in height of the media as the media rotates, T is the thickness of the slider, ΔH is the flying height of the slider at the reference point, ΔY is the vertical change in height of the slider from the reference to the point at which the flying

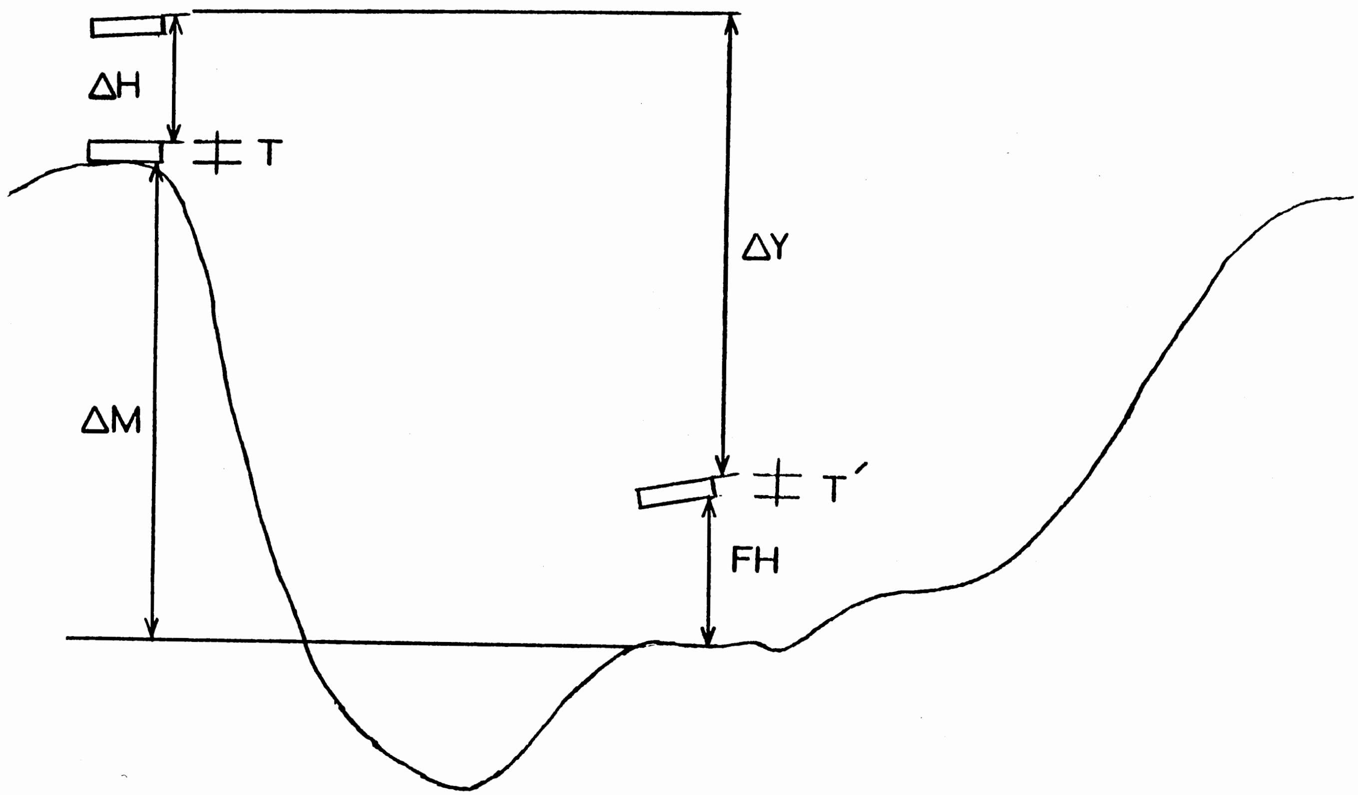

Figure 14. Flying Height Diagram

height is desired, T' is the distance from the mirror mounted on the slider to the bottom of the slider on its trailing edge, and FH is the actual flying height at the point in question. ΔM can be obtained from the initial static voltages of the media recorded at the reference point, and the voltages of the media recorded at the point in question using Equation 2.16. T is a constant known to be 0.033 inches. ΔH can be found from: (a) the initial static voltages of the slider, recorded at the reference point, and (b) the voltages recorded while the slider is flying at the reference point, also using Equation 2.16. ΔY can be found from the voltages recorded while the slider is flying at the reference point and the voltages recorded while the slider is flying at the point in question, once again using Equation 2.16. From inspection of Figure 14 it becomes apparent that T' is a function of the roll of the slider:

$$T' = T\cos(\Theta) \tag{3.2}$$

If the roll of the slider is assumed to be small, then:

$$T' = T \tag{3.3}$$

Rearranging Equation 3.1 and substituting 3.3 yields the equation used to calculate the flying heights:

$$FH = \Delta M + \Delta H - \Delta Y \tag{3.4}$$

As mentioned earlier, the media surface was not perfectly flat. Therefore, in order to examine the angular rotations of the slider relative to the media, it was necessary to subtract the slope of the media from the rotations of the slider. Figure 15 helps explain this

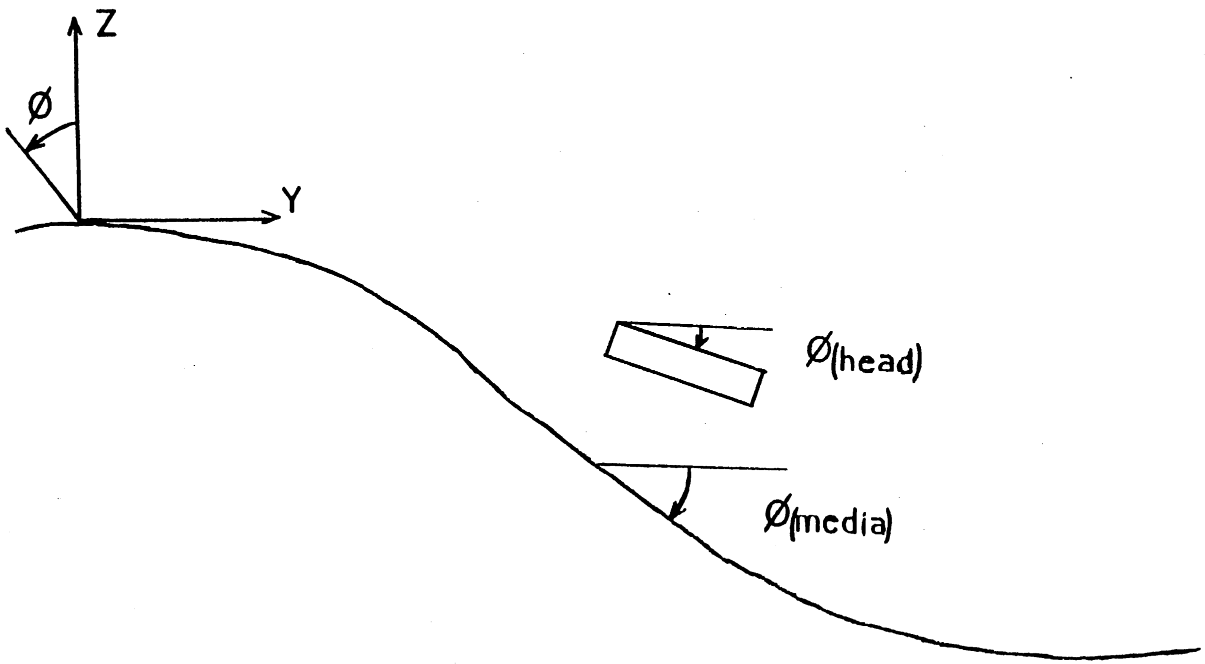

Figure 15. Relative Rotation Illustration

concept. Using Equations 2.17 and 2.18, the equations for the relative rotations are as follows:

$$\text{Relative Pitch} = \phi(\text{head}) - \phi(\text{media}) \tag{3.5}$$

$$\text{Relative Roll} = \theta(\text{head}) - \theta(\text{media}) \tag{3.6}$$

Because it was assumed the slider was lying perfectly flat on the media when the static voltages were being recorded, the relative rotations are assumed to be zero while the slider was in this position. Using the static voltages as a reference, the relative rotation of the slider could be determined at any point in question.

It was not always possible to align the system so the read/write head assembly was in the same vertical plane as the incoming and reflected laser beams. This created a problem, as illustrated in Figure 16, because the rotations yielded from Equations 2.17 and 2.18 are in a "global" coordinate system (XYZ) associated with the plane of the laser beams, and the rotations desired are those of the slider in its local coordinate system (X'Y'Z). To extract the local rotations of the slider it was necessary to conduct a coordinate transformation. Figure 17 illustrates the offset angle ζ and the coordinate systems involved. The coordinate transformations for the local pitch and roll are:

$$\phi' = \phi \cos\zeta + \theta \sin\zeta \tag{3.7}$$

$$\theta' = -\phi \sin\zeta + \theta \cos\zeta \tag{3.8}$$

The computer program which calculated the flying heights and relative rotations of the type 4 and type 5 sliders was written in BORLAND

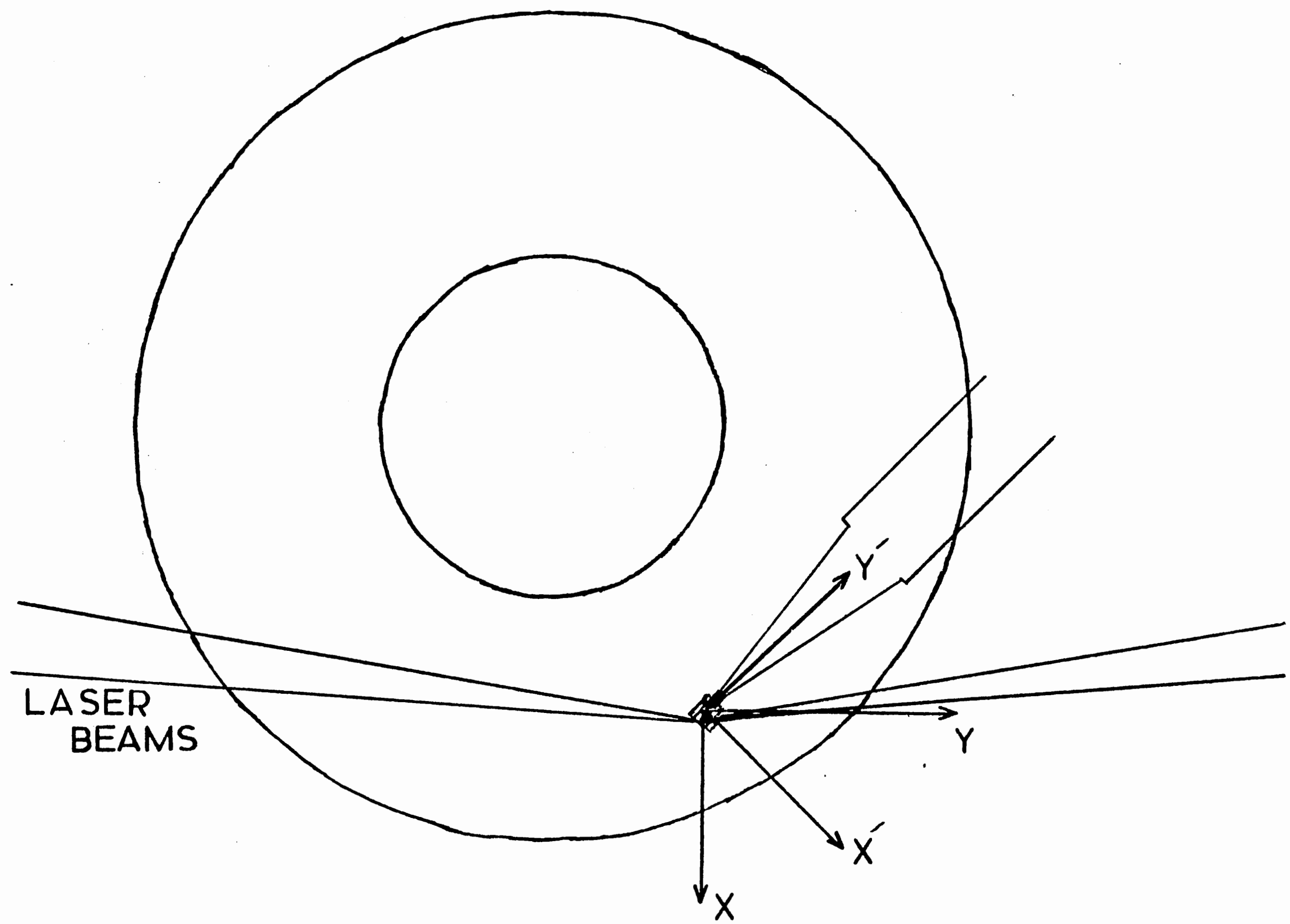

Figure 16. Angular Offset of the Read/Write Assembly from Global Coordinates

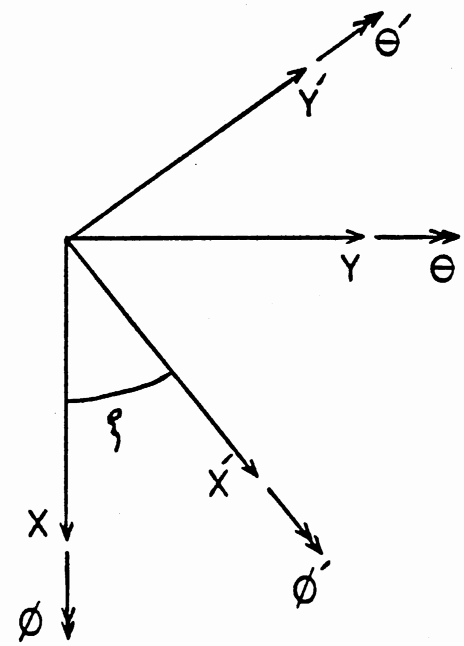

Figure 17. Coordinate Transformation Diagram

TURBO PASCAL. A hard copy of the program can be viewed in the Appendix. The program initially requires the input of all eight of the static voltages. Next, all of the digital voltage data obtained in a data set is read into the computer along with the four angles ψ associated with the four tracking laser beams, and the angle ς for the particular data set. At this point, the flying heights and the relative rotations in global coordinates are calculated using the previously discussed equations. Finally, the relative rotations are converted to the local coordinates of the slider, and an output file is created on floppy disk containing the flying heights and the converted relative rotations.

Both the type 4 and type 5 read/write head assemblies were modelled using finite elements on NASTRAN. The first natural frequencies were both verified by actually exciting the mode shapes on a shaker and observing them with the help of a stroboscope. Once the finite element models were verified the higher resonant frequencies were compared against the experimentally acquired frequencies to determine if there was a relationship between the two.

Besides attempting to determine the flying heights and relative rotations of the type 4 and type 5 sliders during normal operation using laser reflectometry, an effort was made to study some other aspects of the Winchester drives characteristics. For example, an attempt was made to determine the type 5 slider's flying attitudes while the exerciser alternated the read/write assembly between two tracks spaced five tracks apart. Also, an experiment was conducted that compared the frequency spectrum of the media to the frequency spectrum of both sliders. Depending on which of the slider's frequency spectrums (type 4 or type 5) matched more closely the frequency spectrum of the media, and how well each of the sliders performed on the previous tests, some definitive answers could be established regarding which read/write head assembly followed the media runout more closely.

CHAPTER IV

EXPERIMENTAL RESULTS

The voltage traces collected in this study that relate to the normal operation of the media as well as to the type 4 and type 5 read/write head assemblies, exhibited low-frequency periodicity accompanied by what appeared to be some higher-frequency random vibration. Figures 18 and 19 contain typical voltage traces obtained while monitoring the slider and media, respectively. The voltage traces were recorded using the DC coupling on the DATA 6000 and DATA 6100 to retain the DC bias of the signals. The DC biases are important, because without them the relative distances between the slider and media would be impossible to obtain.

The traces in Figure 18 labeled Channel 1 and Channel 2 are output from detector 2S (see Figure 11), and the traces labeled Channel 3 and Channel 4 are output from detector 1S. In Figure 19 the traces labeled Channel 5 and Channel 6 are output from detector 2M, and channel 7 and channel 8 are output from detector 1M. The odd-numbered channels are the traces that pertain to the output for the Y'-Y' axes on all four detectors, while the even-numbered channels are the traces that pertain to the respective X'-X' axes. As stated earlier, the Winchester drive examined rotates at 3600 rpm; thus, the time required for one full revolution is 16.67 milliseconds. Upon close examination of Figures 18 and 19 it becomes apparent that the eight traces

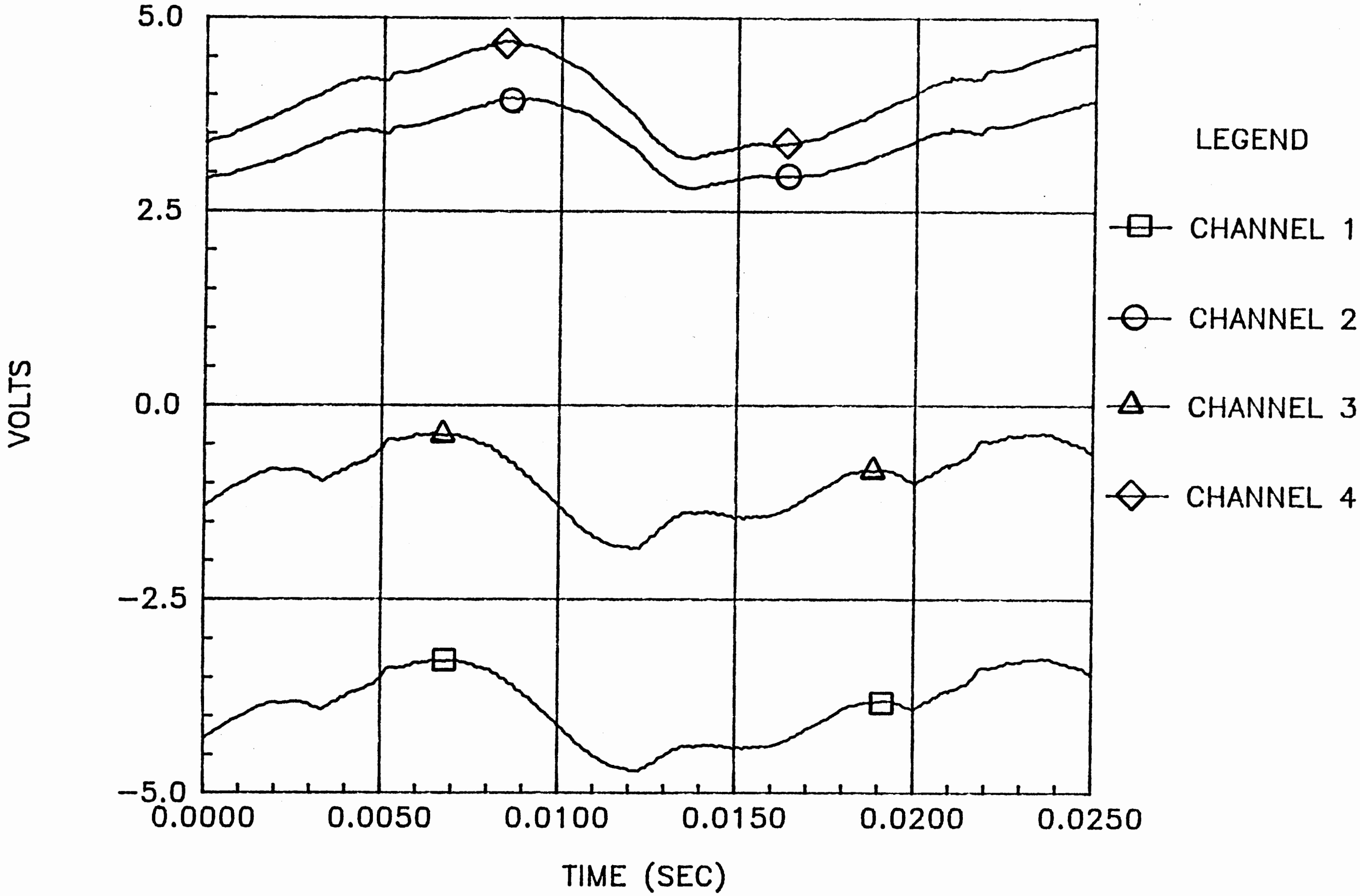

Figure 18. Typical Slider Voltage Traces

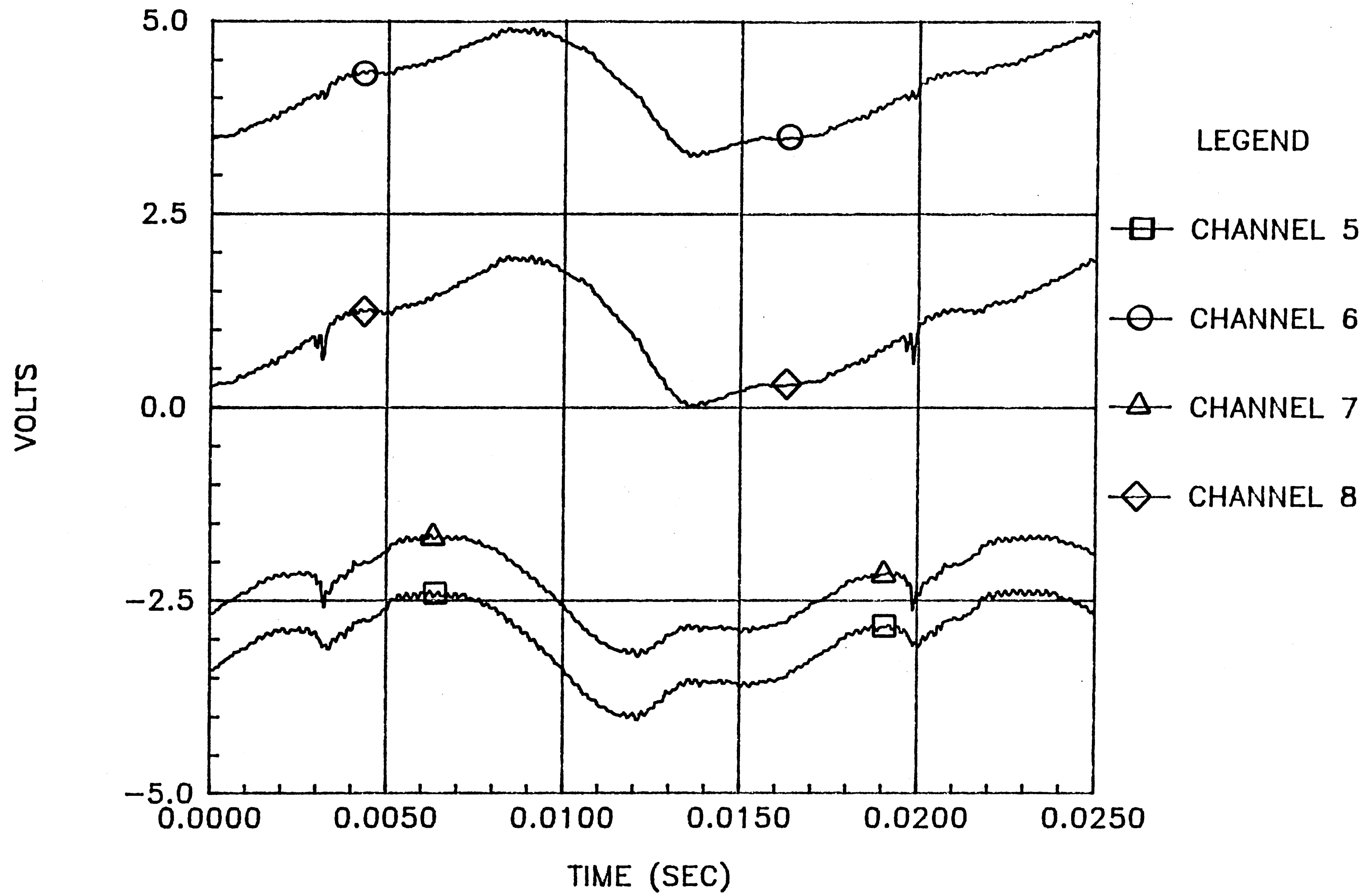

Figure 19. Typical Media Voltage Traces

involved contain a vibrational component with a period of 16.67 milliseconds. Hence, the low frequency of the traces can be attributed to the rotation of the media. At this point, it should be noted that both the odd and even-numbered traces associated with the slider are very similar to the corresponding traces associated with the media. This is an indication that both data recorders were triggered at precisely the same time and the activity of the slider and the media closely parallel each other.

Another characteristic of the traces associated with the Y'-Y' output of the detectors are the three "humps" which appear per revolution of the media. It is believed that the six bolts that clamped the media to the spindle were responsible for deforming the contour of the media, and that the amplitude of the humps was a function of the torques used to install the bolts.

Figure 20 illustrates how similar the traces concerning the slider and media actually are. Channels 4 and 6 are both output for the X'-X' axis for the slider and the media, respectively. The only differences between the two traces are the slightly different amplitudes, which can be credited to the two different detectors being located at different angles with respect to the horizontal plane, and the high frequency random vibration, which seems more prominent in the trace associated with the media. The high-frequency random vibration visible in the media traces appears to be attenuated somewhat in the slider traces. This suggests that the high-frequency vibration originates in the media, either from its asperities or vibration.

The peak-to-peak amplitudes of the voltage traces in Figure 20 are larger than 1 volt. This is of importance because the DATA 6000

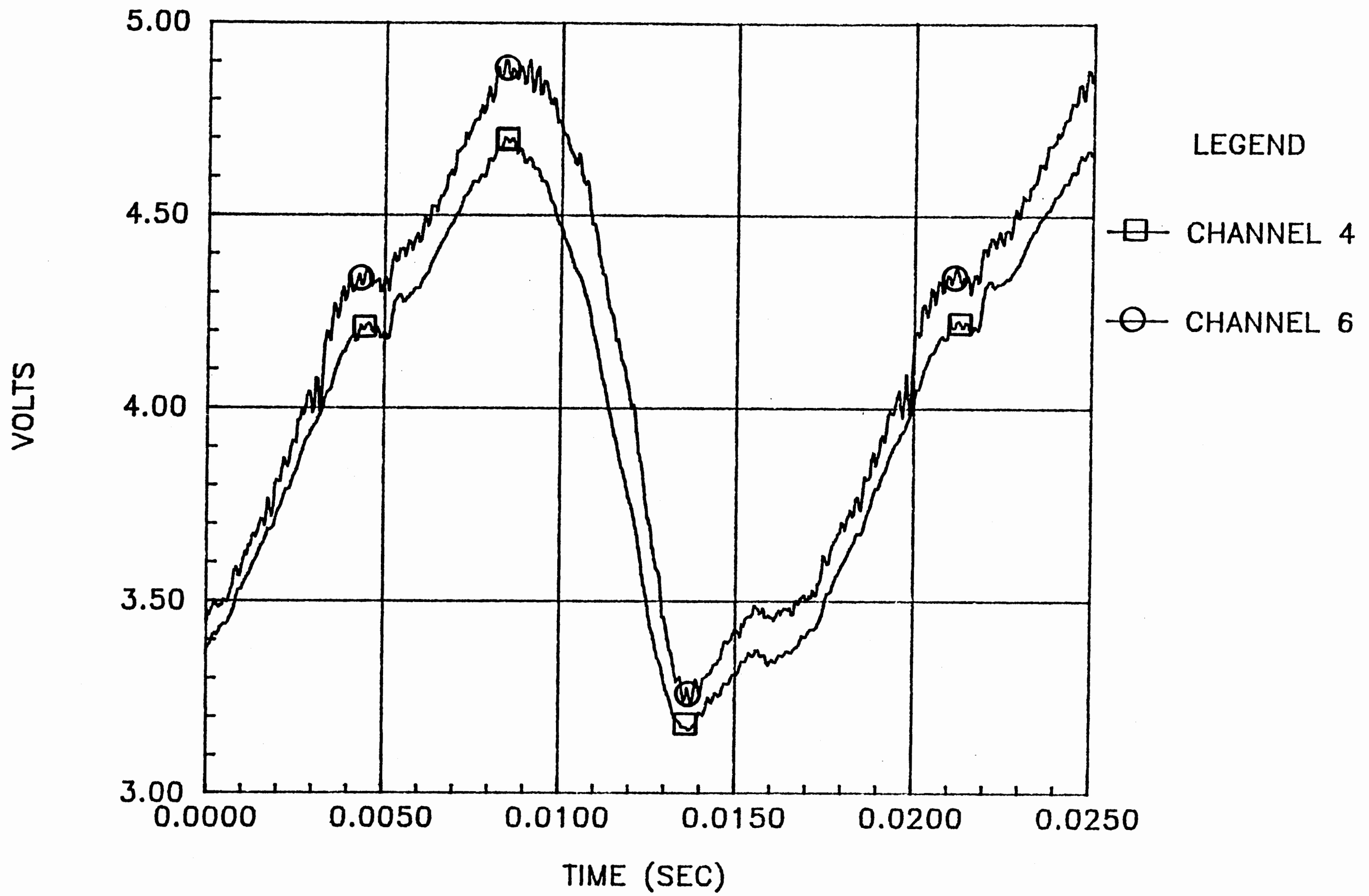

Figure 20. Comparison of Slider and Media Voltage Traces

and DATA 6100 were set to record data on an input scale for the ordinate axis of 0.5 volts (zero to peak). If this setting is used, regardless of how the laser beams are positioned initially, the entire waveform cannot be recorded. If the entire waveform cannot be recorded, it is impossible to determine the flying height and relative rotations of the slider through an entire rotation of the media. Because determining the relative displacements was a prime motivation of this study, an alternative was sought. One possibility considered was decreasing the distance from the media and slider (R) to their respective detectors. This would in turn reduce the amplitude of the signals obtained. Reducing R was not effective because when the distance was reduced to sufficiently record the signals in a 1.0 volt range (peak-to-peak), it was impossible for the reflected laser beams to reach their respective reoriented optical detectors. As a result, the DATA 6000 and DATA 6100 were both set to receive an input on a 5.0 volt scale (zero to peak). At this setting, theoretically, the flying height resolution was 32 microinches (from Equation 2.16). This resolution was unacceptable to detect a flying height of 11 microinches, but because the 5.0 volt scale was the only alternative available, it was used to obtain the first few data sets on a "trial" basis.

Five different performance aspects of the Winchester drive were examined in this study. To get a broad view of what was occurring on the entire disk surface, data were taken on three different track locations: tracks 625, 335, and 000. Unless otherwise mentioned, all of the experiments attempted were performed on these three tracks. The first aspect of this study was concerned with determining the flying height of the type 4 and type 5 sliders. The second aspect examined the rotations of the type 4 and type 5 sliders relative to the media. The maximum rotation amplitudes of the sliders were also of importance, and were taken note of. The third aspect explored was the movements of the type 5 slider as it alternated track locations. This portion of the study was performed while the slider was alternating between tracks spaced 5 tracks apart (about 0.005"). The fourth aspect dealt with a comparison of the frequency spectrums of the type 4 and type 5 head assemblies relative to the media's frequency spectrum. Finally, the fifth aspect investigated was the variation in runout of the media at different track locations.

Flying Heights of the Type 4 and Type 5 Sliders

As mentioned earlier, the flying height measurements were attempted while the ordinate axis was set on a 5.0 volt (zero to peak) scale. This means that the data obtained had only 32 microinch resolution, which was not accurate enough to confirm the already known flying height of 11 microinches. Nonetheless, data were collected, and it was expected that it would yield flying height measurements that varied between 50.0 and -50.0 microinches. Once the data were analyzed, this was not the case. The data indicated that the slider was flying in the milli-inch region. The procedure through which the data were taken and analyzed was rechecked, and more data were taken that produced similar invalid results. The system and procedures used were reexamined and two problems surfaced. The first problem involved the sensitivity of the optical detectors. According to the engineers at UDT, the optical detector that monitored the laser beam movements relative to the detector face was only capable of ascertaining movements of 1 micrometer under average conditions, with somewhat better resolution possible if the experiments were conducted in the absence of any background light. Calibration tests in which a laser beam was reflected from a mirror mounted atop a MB electromagnetic calibration shaker were performed that indicated the detectors were capable of detecting a 20 microinch movement of the reflected laser beam relative to the detector. Finer calibration could not have been attempted without first isolating the shaker head and detector, as building vibrations were apparent. This obviously had a drastic effect on the flying height resolution. If each of the readings taken from the detectors were off by 20 microinches the resolution of the system for discerning flying heights would be, according to Equations 2.16 and 3.4, 450 microinches.

The second problem encountered with the system concerned the accuracy of the static voltages. The static voltages were observed to vary while they were manually recorded. As a result, it was only possible to record the static voltages to the hundredth place because the thousandth place was, in some cases, changing perpetually. Frequently, the voltages would not vary at all, other times the voltages would vary between 0.00 and 0.05 volts and on one particular data set, the static voltages varied, on the average, nearly 0.5 volts. The source of the varying static voltages was not known, but it was believed to be caused by building vibration or possibly the media deforming under the load of the read/write assembly. Finally, it was necessary to record a mentally obtained "running average" of the static voltage.

If the static voltages recorded were all in error by 0.1 volts, the error could have altered the flying height measurement by as much as 16,000 microinches, according to Equations 2.16 and 3.4. A solution could not be found to solve the problem of the unstable static voltages, and the data that were obtained gave very erratic flying heights in the milli-inch region; as a result of this, the flying height measurements were no longer pursued.

Rotations of the Type 4 and Type 5 Sliders Relative to the Media

The problems discovered regarding the flying height measurements obviously raised questions concerning the accuracy of the relative rotation measurements. According to [6], on a 5 1/4-inch drive, a typical average relative pitch rotation of a similar slider under conditions similar to the sliders examined in this study, varies from 80 to 120 microradians around the leading edge of the slider. The 80-microradian rotation pertained to the slider being exposed to the media velocity (15.56 m/s) on the inside track of the media, and the 120 microradian rotation pertained to the slider being exposed to the media velocity (25.14 m/s) on the outside track of the media. If the measurement system used in this study was to be of any value, it was necessary that it have at least a 8-12 microradian resolution when measuring the pitch rotations. The relative pitch rotation resolution of the system due to the optical detectors' limited ability to discern the laser beam movement was found using Equation 2.17, and yielded a system resolution of nearly 8 microradians. Using the same procedure, and assuming the static voltages were all in error by 0.1 volts due to fluctuation, the relative pitch rotation resolution was 280 microradians.

The system's relative roll resolution was also affected by the problems with the optical detectors and the static voltages, and although the effects were not as significant, they are worth mentioning. Due to the problem with the optical detectors, the error introduced into the relative roll calculation was found to be 2 microradians using Equation 2.18. The error due to the static voltages varying by 0.1 volts could vary the relative roll calculation by as much as 64 microradians. Because the static voltages affected the resolution of the system considerably more than the problems with the detectors, acquiring the static voltages was assumed to be the primary problem with the system.

When contrasted to the relative rotations found in the literature search, the resolution of the system does not appear to be copacetic; however, it is important to note that the static voltages did not always vary by 0.1 volts, at times they did not even vary by 0.01 volts. The system's relative pitch resolution was 280 microradians if all of the static voltages which pertained to pitch measurement were off by 0.1 volts. In a standard data set, usually the static voltages as a whole were relatively stable and rarely did all of the voltages that were used in the pitch calculations vary on the average by more than 0.02 volts. Because the manner in which the static voltages behaved was so random, it was impossible to determine the exact resolution of the system; however, it still seemed likely that the system could provide some assistance in determining the relative rotations of the sliders in question.

To study the uncertainties regarding how many decimal places are necessary to store when recording the static voltages, it was necessary to consider the error introduced into the system when just recording two decimal places. If the static voltages recorded were in error by 0.005 volts (which is possible when only recording the static voltages to the hundredth digit), theoretically, the maximum error possible when calculating relative pitch rotation was 7 microradians (using Equation 2.17), and the maximum error introduced into the relative roll calculation due to the recording method was approximately 2 microradians (using Equation 2.18). These errors were insignificant compared to the other problems with the system and were considered negligible.

For purposes of comparison, the roll angles of the slider were calculated by the program in the Appendix using input from both detectors 1S and 2S. For the specific cases in which the program was verified by hand, the two different roll rotations were equivalent to four or five digits of accuracy. The minor discrepancy between the two roll angles was attributed to the disregarding of the higher-order terms in the derivation of the roll angle. In both cases, for media and slider, the roll rotations were found using both detectors and averaged to obtain the final roll rotation.

The triggering system used appeared to trigger the system adequately each time a set of data was recorded. The previously illustrated voltage traces seem to indicate that both the DATA 6000 and the DATA 6100 were triggered at exactly the same instant. This was rigorously checked each time a set of data was recorded to floppy disk. If the two recording devices did not trigger at exactly the same instant, the data set would have been useless. One item that should be mentioned regarding the triggering system, was the fact that when the object blocking the triggering laser was removed and the laser was allowed to strike the triggering mirror, the system at times took several seconds to trigger, and at other times the system would trigger instantly. Considering the media makes a full revolution every 16.67 milliseconds, a pause of several seconds could not be explained. One possibility was that the bearings that support the media had a small amount of "slop." If this is the case, the entire media disk could translate vertically in a random fashion, thus causing the system to trigger at sporadic intervals.

The pitch and roll of the type 4 slider relative to the media on tracks: 625, 335, and 000 in the time domain are plotted on Figures 21, 22, and 23, respectively. Unfortunately, the data for track 625 bears few similarities to what was expected of the type 4 slider. According to Figure 21, the average recorded relative pitch rotation was about 350 microradians. The media velocity on track 625 was 19.1 m/s, and according to [6] the relative pitch rotation should have been approximately 100 microradians. Although [6] concerns an assembly of very similar dimensions and loads to that of the type 4 and type 5 assemblies, the likeness was not close enough for an exact comparison. Nonetheless, the relative pitch rotations from [6] were still valuable information because they gave a general idea if the results from this study were in the "ballpark." Figure 21 also indicates the relative roll of the slider was positive using the coordinate system outlined in Figure 2. According to [2], a similar slider under like conditions was observed to have slightly negative roll rotation using the same coordinate system outlined in Figure 2. Because of these

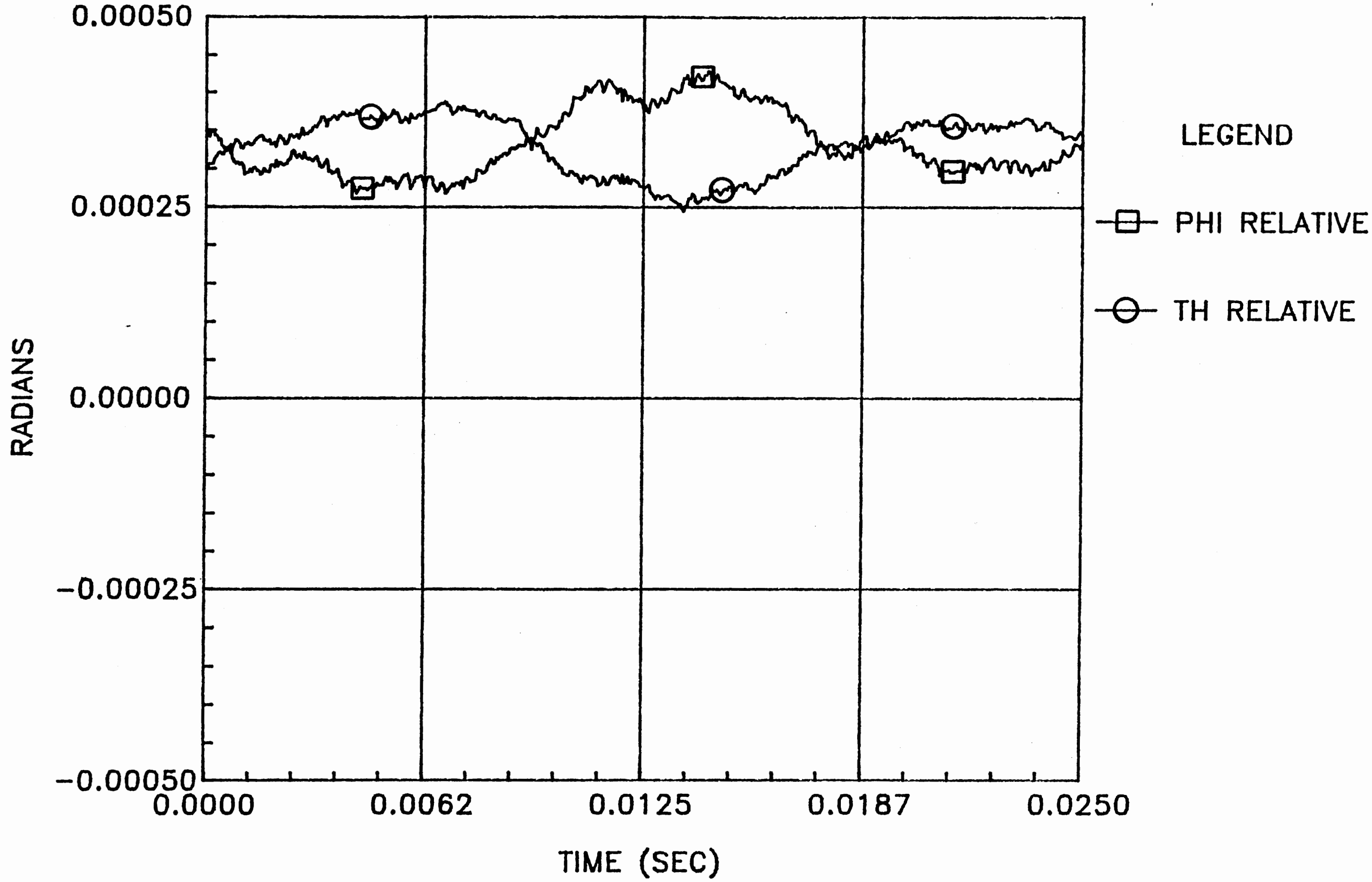

Figure 21. Relative Rotations of the Type 4 Slider on Track 625

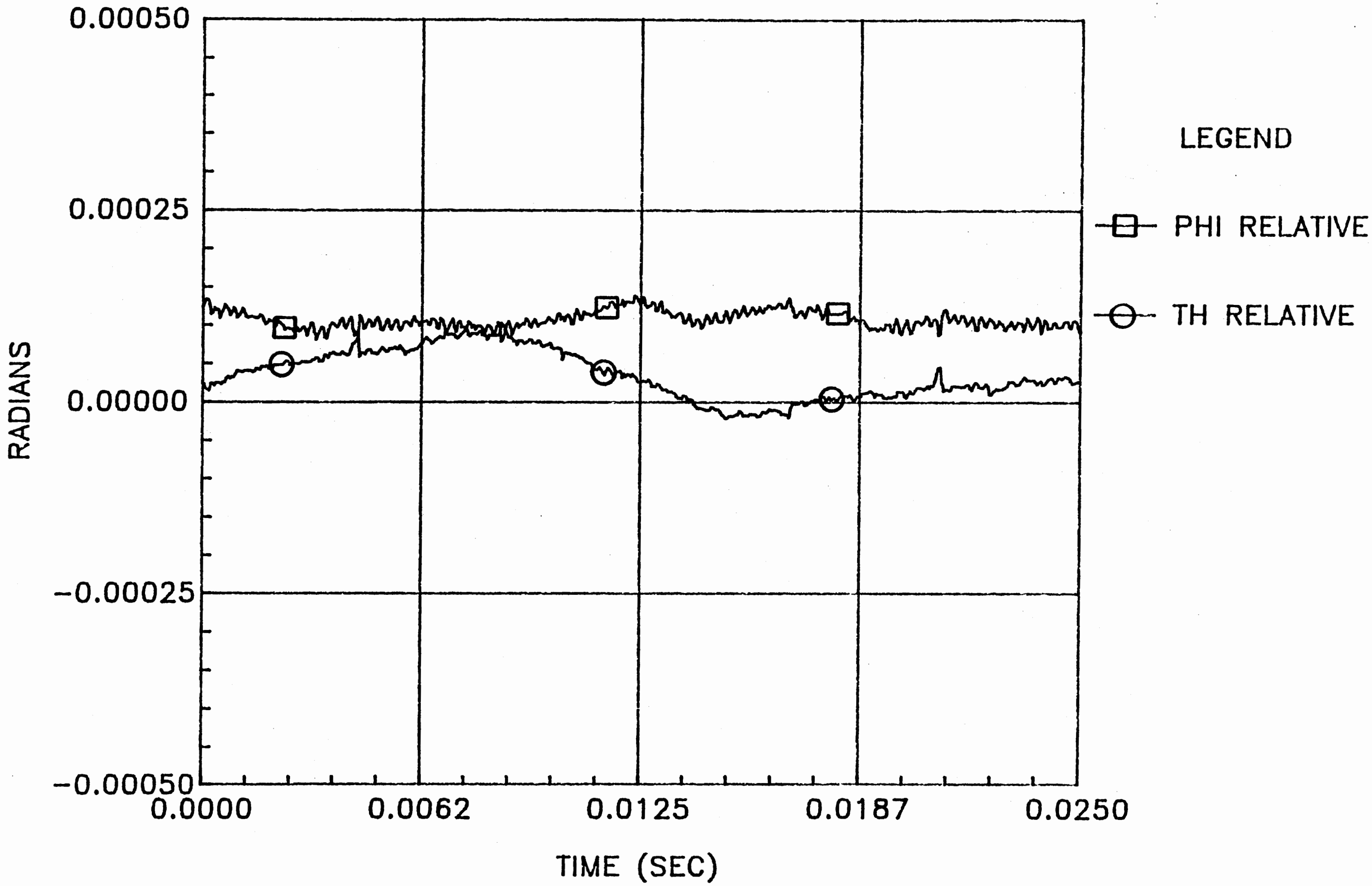

Figure 22. Relative Rotations of the Type 4 Slider on Track 335

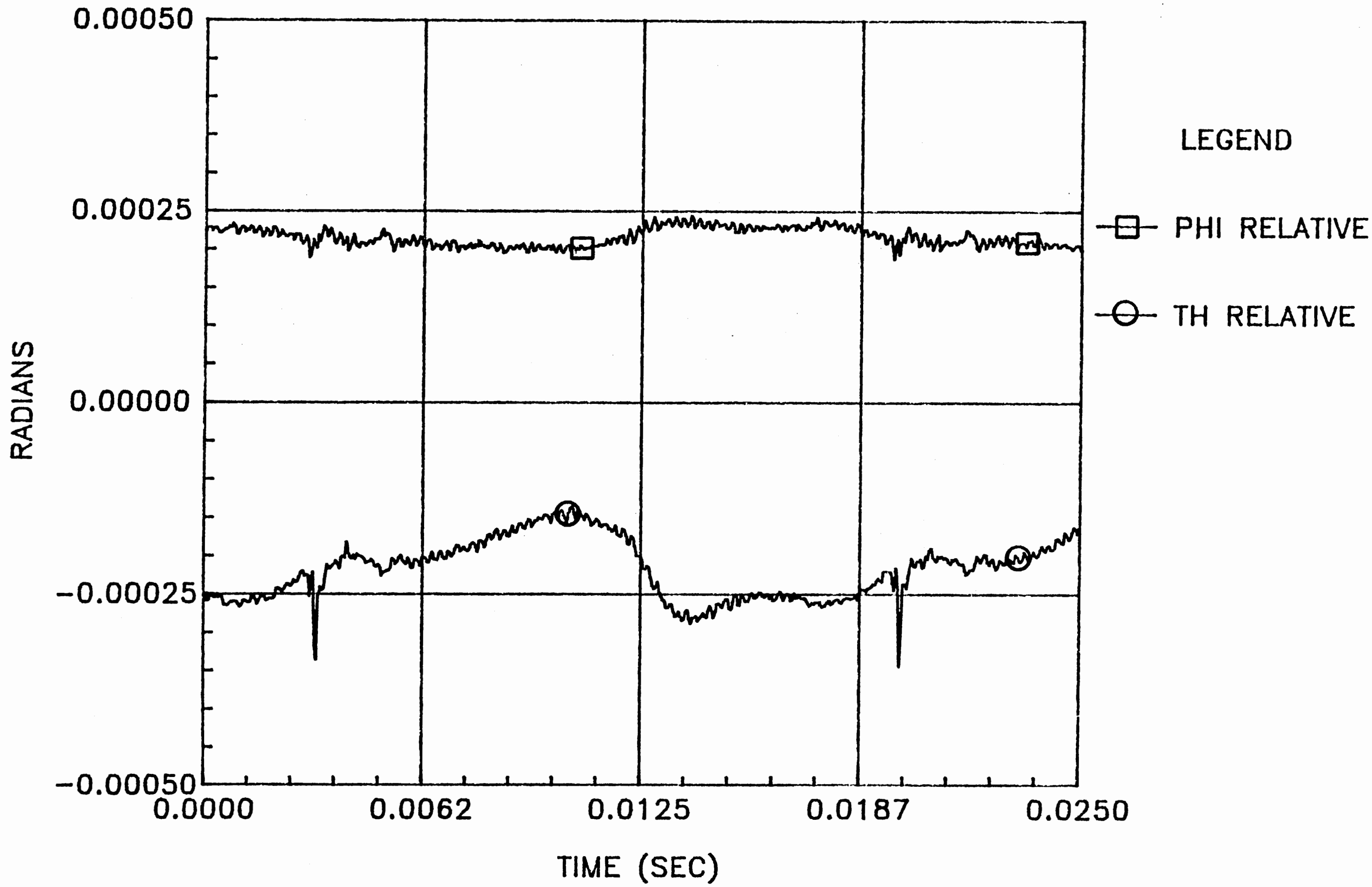

Figure 23. Relative Rotations of the Type 4 Slider on Track 000

discrepancies, and the fact that the data for the type 4 slider on track 625 differed from the bulk of the remaining data collected (this point will be addressed later), the data set pertaining to the relative pitch rotation was disregarded.

The data collected for the type 4 assembly on tracks 335 and 000 resembled more closely what was expected of the assembly. Figure 22 contains the data collected for track 335. At this location, the media velocity was nearly 22.0 m/s and, the average relative pitch angle was approximately 110 microradians. The data presented in [6] indicates the average relative pitch angle for a slider under these conditions should be about 108 microradians. The relative roll of the slider, according to Figure 22, was on the average about 25 microradians. This is not a slightly negative rotation as expected, but it is in the proximity.

The velocity of the media beneath the type 4 slider while on track 000 was about 25.1 m/s, and [6] predicted a relative pitch rotation of about 120 microradians. Figure 23 illustrates the data collected for the type 4 slider on track 000. The average pitch angle recorded for this location appears to be approximately 225 microradians. This was a bit larger than expected, but not entirely out of the question. The relative roll associated with track 000 was -200 microradians, which complied with what was stated in [2], and had a distinct period of 16.67 milliseconds. This was the first obvious sign of periodicity in the recorded slider movements. Upon closer examination of the previous waveforms, which represent the slider's relative pitch and roll, a period of 0.0167 ms. is noticeable, but because of small amplitudes and other components of vibration in the data, it was previously difficult to detect. The periodicity is a good sign that the measuring system and the program which manipulates the data were operating correctly. The spikes visible in the relative roll data were due to a scratch in the media surface and have no significance regarding the movements of the slider.

Figures 24, 25, and 26 represent the relative rotations of the type 5 slider in the time domain on tracks: 625, 335, and 000, respectively. Figure 24 indicates the average relative pitch on track 625 was about 30 microradians, as compared to 100 microradians from [6]. The average roll was an acceptable rotation of about -50 microradians. Figure 25 illustrates the results for the slider's relative rotations on track 335. According to [6], the relative pitch rotation for the slider at this location is 110 microradians, the average relative pitch recorded was approximately 80 microradians, whereas the average recorded relative roll was about -100 microradians. Finally, the relative pitch rotation of the type 5 slider on track 000 according to Figure 26 was nearly -25 microradians with an average relative roll of about -20 microradians. Once again, the spikes are attributed to a visible scratch in the media and have no significance to the slider movements. The average pitch for the type 5 slider on track 000 was negative unlike all of the preceding relative pitch rotations, but the waveform still maintained a similar pattern and amplitude to the previous relative pitch data, thus the abnormality was attributed to incorrect static voltages. All of the average recorded rotations for the type 4 and type 5 sliders are presented on Table 1. A point worthy of mentioning was the visible periodicity of the relative roll signals as the type 4 and type 5 assemblies were moved outward on the media.

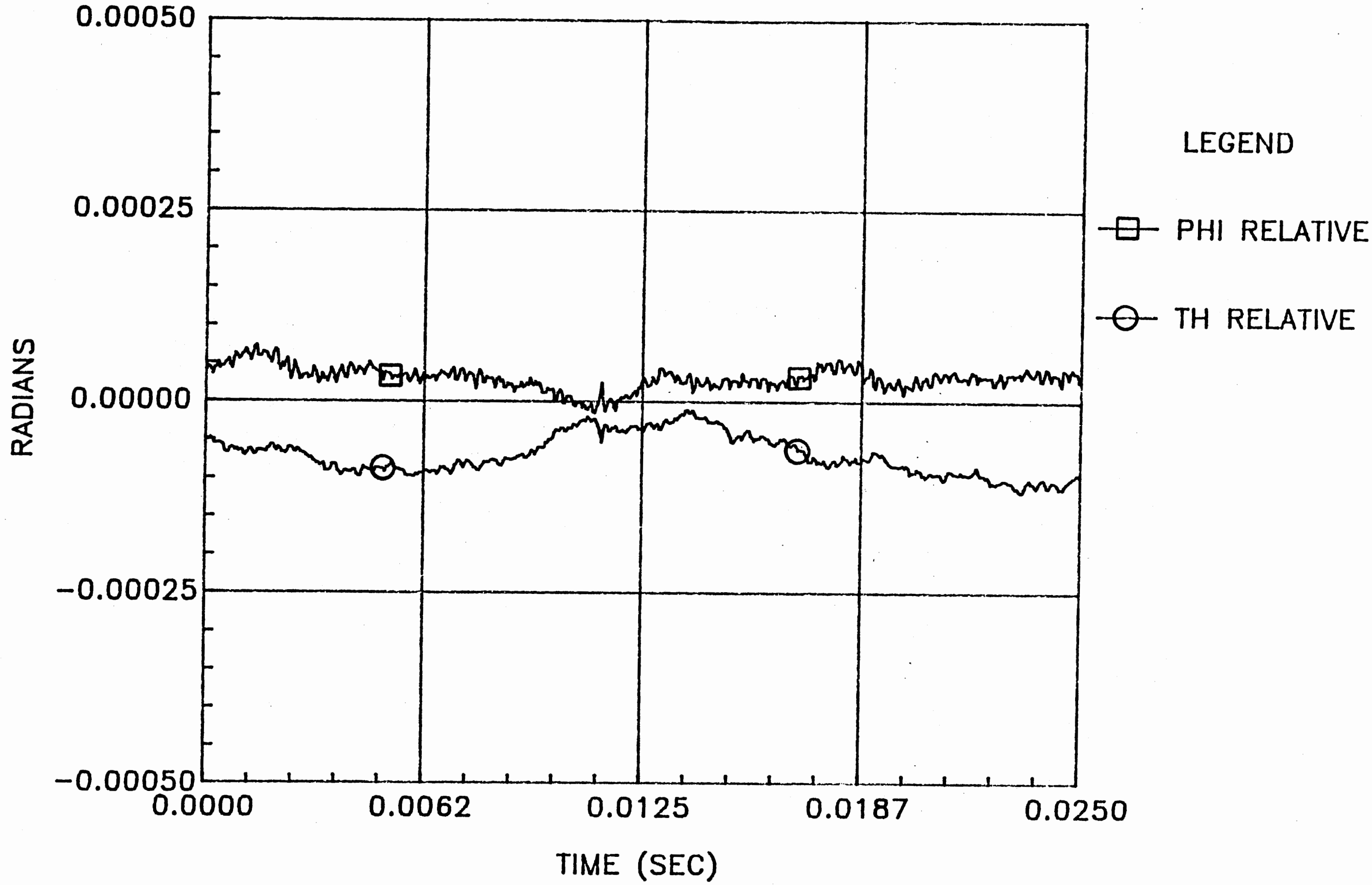

Figure 24. Relative Rotations of the Type 5 Slider on Track 625

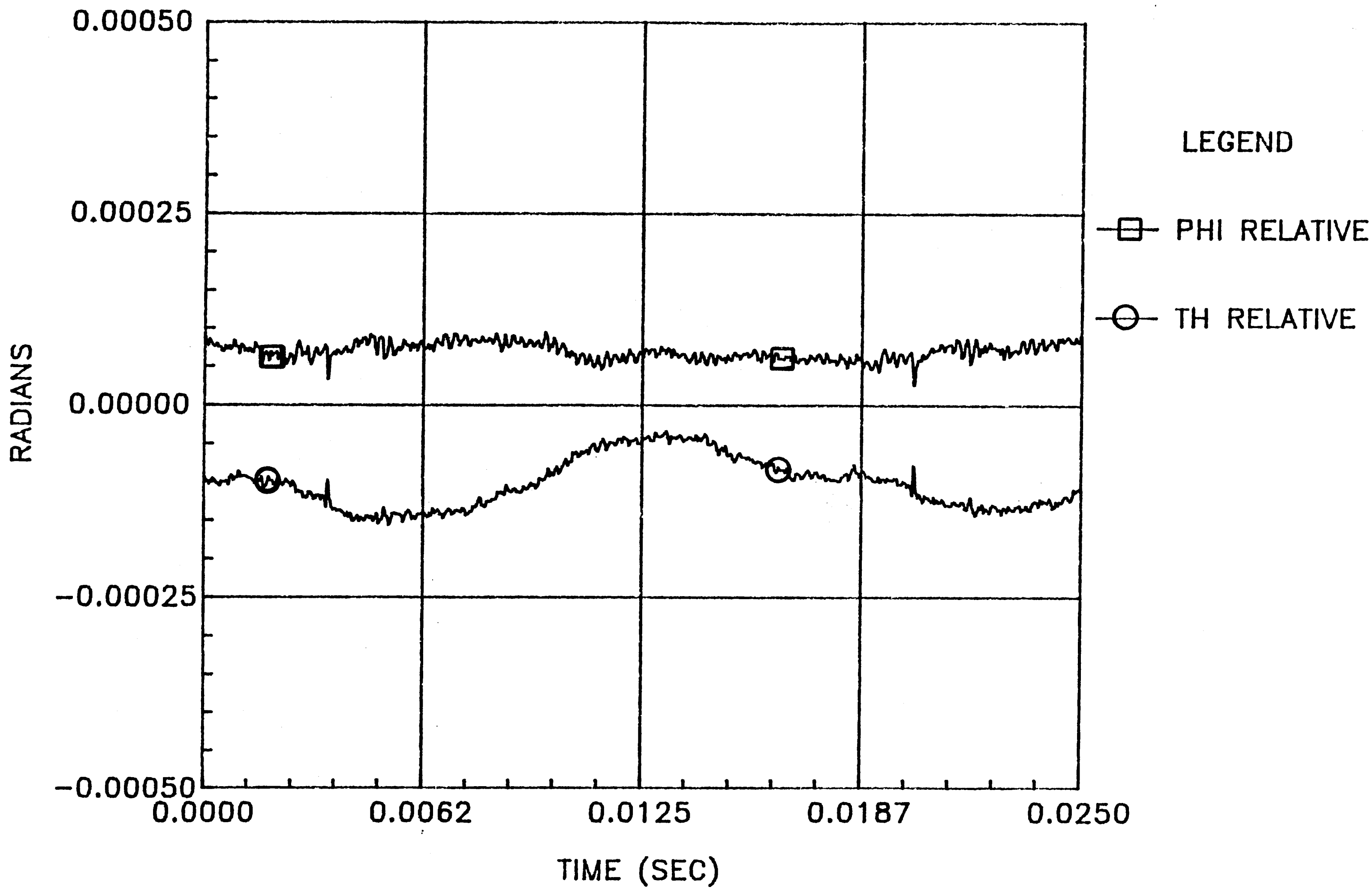

Figure 25. Relative Rotations of the Type 5 Slider on Track 335

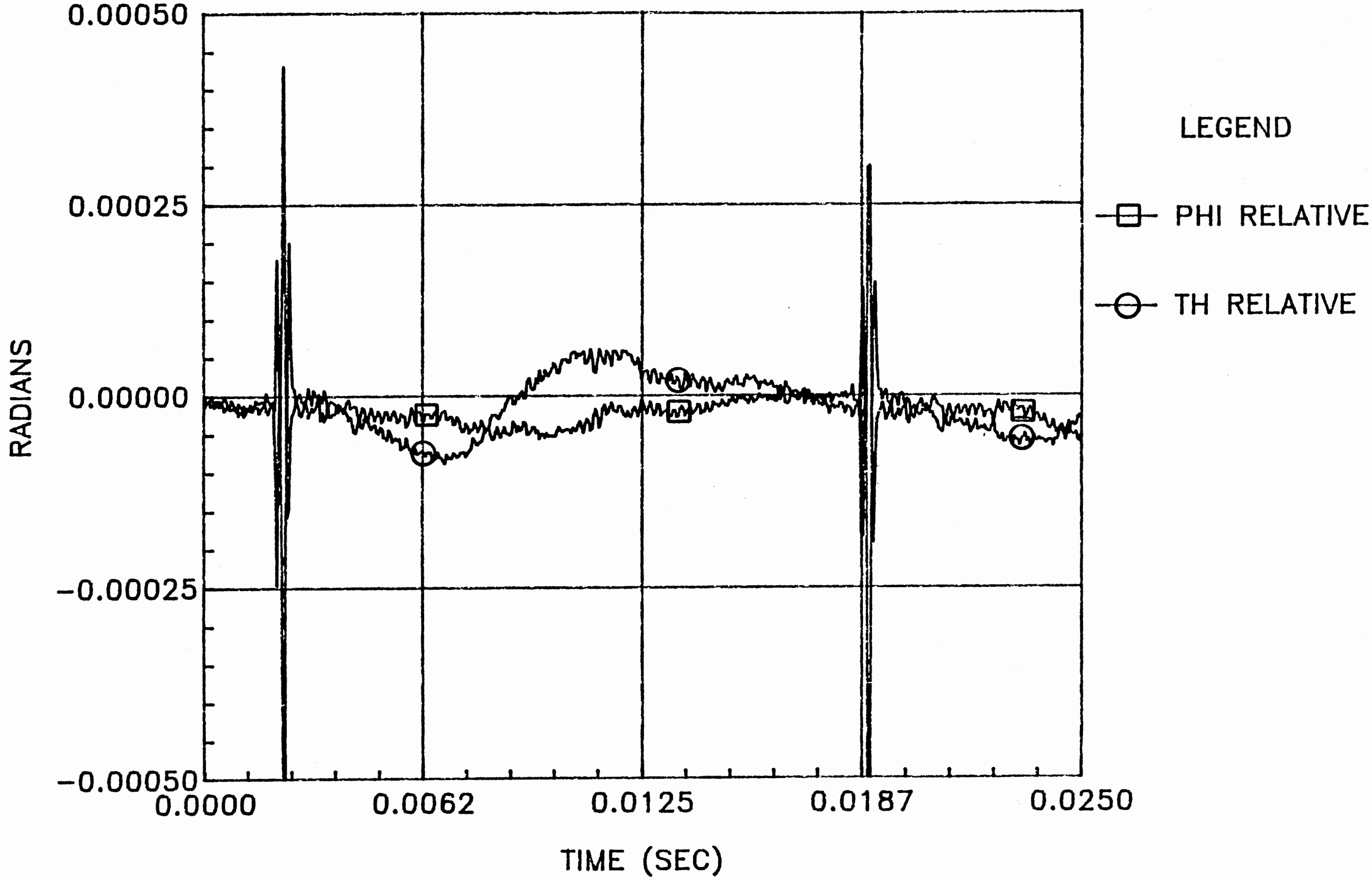

Figure 26. Relative Rotations of the Type 5 Slider on Track 000

TABLE I

APPROXIMATE AVERAGE RELATIVE ROTATIONS OF THE TYPE 4 AND TYPE 5 SLIDERS

Type 4

Track	Pitch (Microradians)	Roll (Microradians)
625	350	275
335	110	25
000	225	-200

Type 5

Track	Pitch (Microradians)	Roll (Microradians)
625	30	-50
335	80	-100
000	-25	-20

Because the periodicity became prevalent on the outer tracks of the media, it was attributed to the increase in media velocity and possibly increased radial distance.

Barring the data pertaining to the type 4 slider on track 625, and the data concerning the relative pitch rotation of the type 5 slider on track 000, the data collected were not entirely unrealistic. Unfortunately, it was impossible to verify the exact accuracy of the results because of the previously mentioned problems with the measurement system, and all that could be gathered from comparing the results to the data found in the literature search was that the system appears to produce output in the vicinity of previously published data.

Incorrect static voltages, certainly in the case of relative roll rotations, and principally, in the case of relative pitch rotations, have a "biasing" effect on the output rotations. Thus, theoretically, the relative rotations could have been in error on an absolute scale; however, the rotations relative to each other, theoretically, should have been very accurate. With this in mind, the peak-to-peak relative rotations of the types 4 and type 5 sliders were found for all three track locations, and can be viewed on Table II. This data essentially disregards the possibly incorrect static voltages, and deals with the waveforms as if their DC biases were removed.

At this point, the differences between the relative pitch data for the type 4 slider on track 625 and the remainder of the data become apparent. The relative peak-to-peak pitch rotation of the type 4 slider on track 625 is clearly out of place in comparison to the other peak-to-peak relative pitch rotations. Without the data pertaining to track 625, the average peak-to-peak pitch rotation for both sliders

TABLE II

APPROXIMATE RELATIVE PEAK-TO-PEAK PITCH AND ROLL ROTATIONS FOR THE TYPE 4 AND TYPE 5 SLIDERS

Type 4

Track	Pitch (Microradians)	Roll (Microradians)
625	162	143
335	60	124
000	52	149

Type 5

Track	Pitch (Microradians)	Roll (Microradians)
625	88	107
335	67	120
000	66	148

was 67 microradians, and the peak-to-peak relative pitch rotation seems to decrease as the sliders are moved outboard on the media. The average peak-to-peak relative roll rotation for both sliders was 132 microradians.

As stated earlier, [3] indicated the slider's pitch rotation is typically around its trailing edge. With this information and the dimensions of the slider, it was possible to calculate the flying height variation of the leading edge of the slider. This was achieved by multiplying the length of the slider (about 0.160") by the peak-to-peak relative pitch rotation. The flying height variations of the leading edge of the type 4 and type 5 sliders are presented in Table III. The variational peak-to-peak displacements of the leading edge, excluding the data from the type 4 slider on track 000, average about 10.6 microinches. This seems within reason, because [3] discussed a situation where the leading edge of a slider had an amplitude on the order of 6 microinches, while the average recorded amplitude of the leading edge in this study was 5.3 microinches (10.6/2).

Dynamics of the Type 5 Slider while Alternating Tracks

The examination of the type 5 slider while it was alternating tracks at a high frequency, was expected to yield larger relative roll peak-to-peak rotations than the relative roll peak-to-peak rotations of the slider while operating normally. This was not the case, as illustrated by the voltage traces in Figure 27. The trace recorded while the Winchester drive was operating normally can be identified by its periodicity and constant peak-to-peak voltage. The other voltage

TABLE III

FLYING HEIGHT VARIATION OF THE LEADING EDGE
DUE TO RELATIVE PITCH ROTATIONS

Type 4

Track	Flying Height Variation (Microinches)
625	25.7
335	9.5
000	8.2

Type 5

Track	Flying Height Variation (Microinches)
625	14.0
335	10.6
000	10.5

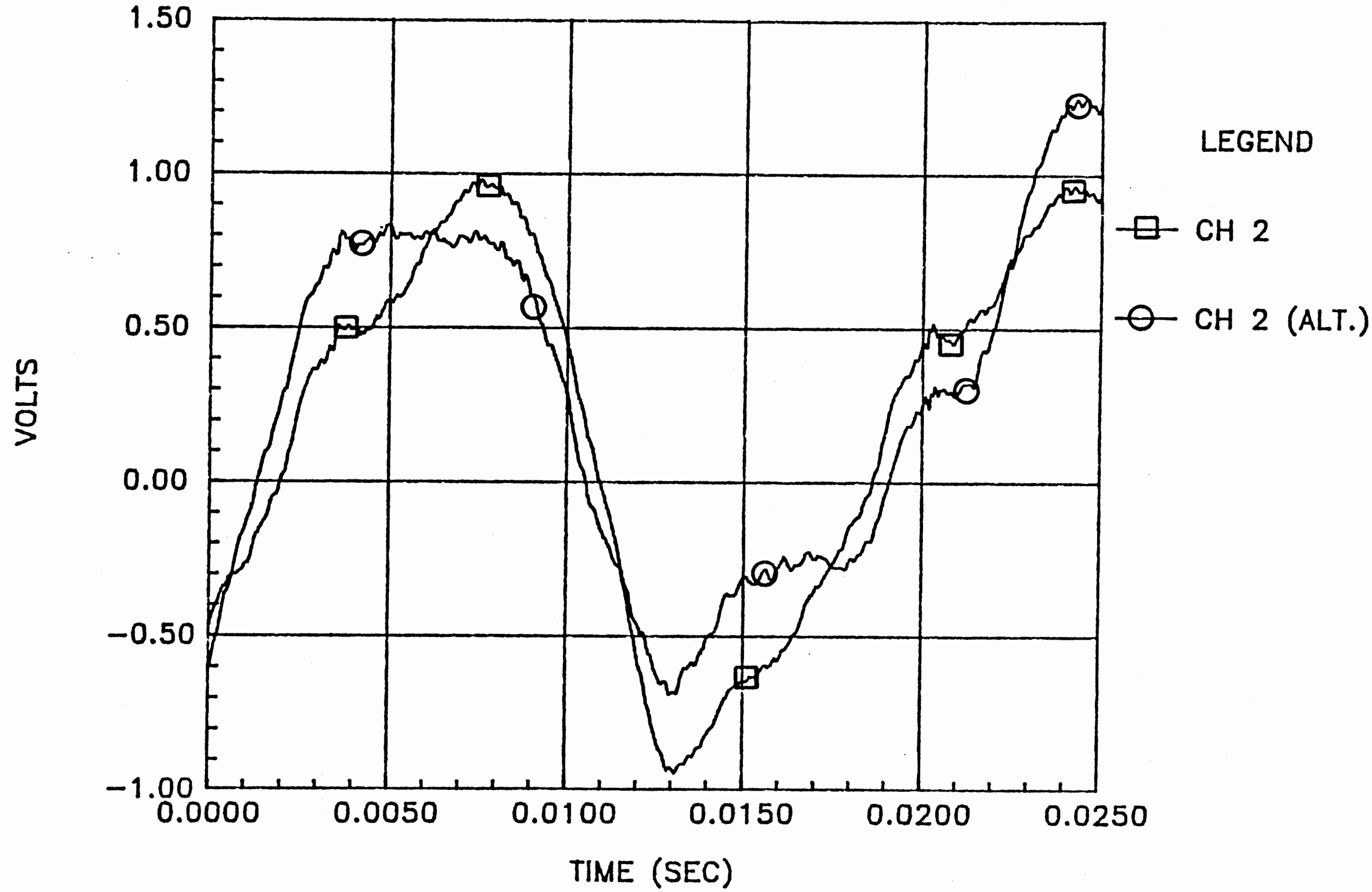

Figure 27. Comparison between Slider Voltages Associated with Roll Rotation Recorded while the Slider was Operating Normally and while the Slider was Alternating Tracks

trace, recorded while the slider was alternating between two tracks, which were spaced five tracks apart, displays a less conspicuous periodicity and an apparently random peak-to-peak voltage.

Figures 28, 29, and 30 represent the relative pitch and roll rotations of the type 5 slider while alternating between tracks: 625-630, 335-340, and 000-005, respectively. In contrast to the previously set forth standards of a positive relative pitch rotation and a slightly negative relative roll rotation, the rotations obtained while the type 5 slider was alternating tracks appeared to be satisfactory. Figure 28 indicates that the average relative pitch of the slider while oscillating between tracks 625 and 630 was slightly negative (probably because of static voltage problems), with what appears to be a period of about 11.25 milliseconds. The relative roll, strangely enough, was about what was expected of the slider while the drive was operating normally; however, when the assembly was alternating tracks some periodicity and an increased rotational amplitude were expected. The alternating radial motion of the type 5 assembly was expected to induce these relative roll characteristics, while the characteristics of the relative pitch were expected to remain about the same as the characteristics of the relative pitch of the slider during normal operation. The only explanation for the 11.25-millisecond period and increased amplitude of the relative pitch rotation was that the alternating motion of the assembly was exciting one of the assembly's resonant frequencies. The small peak-to-peak radial distance travelled by the slider, about 0.005", coupled with the rigidity of the air bearing could have been the reasons why no increased relative roll amplitudes were experienced by the slider.

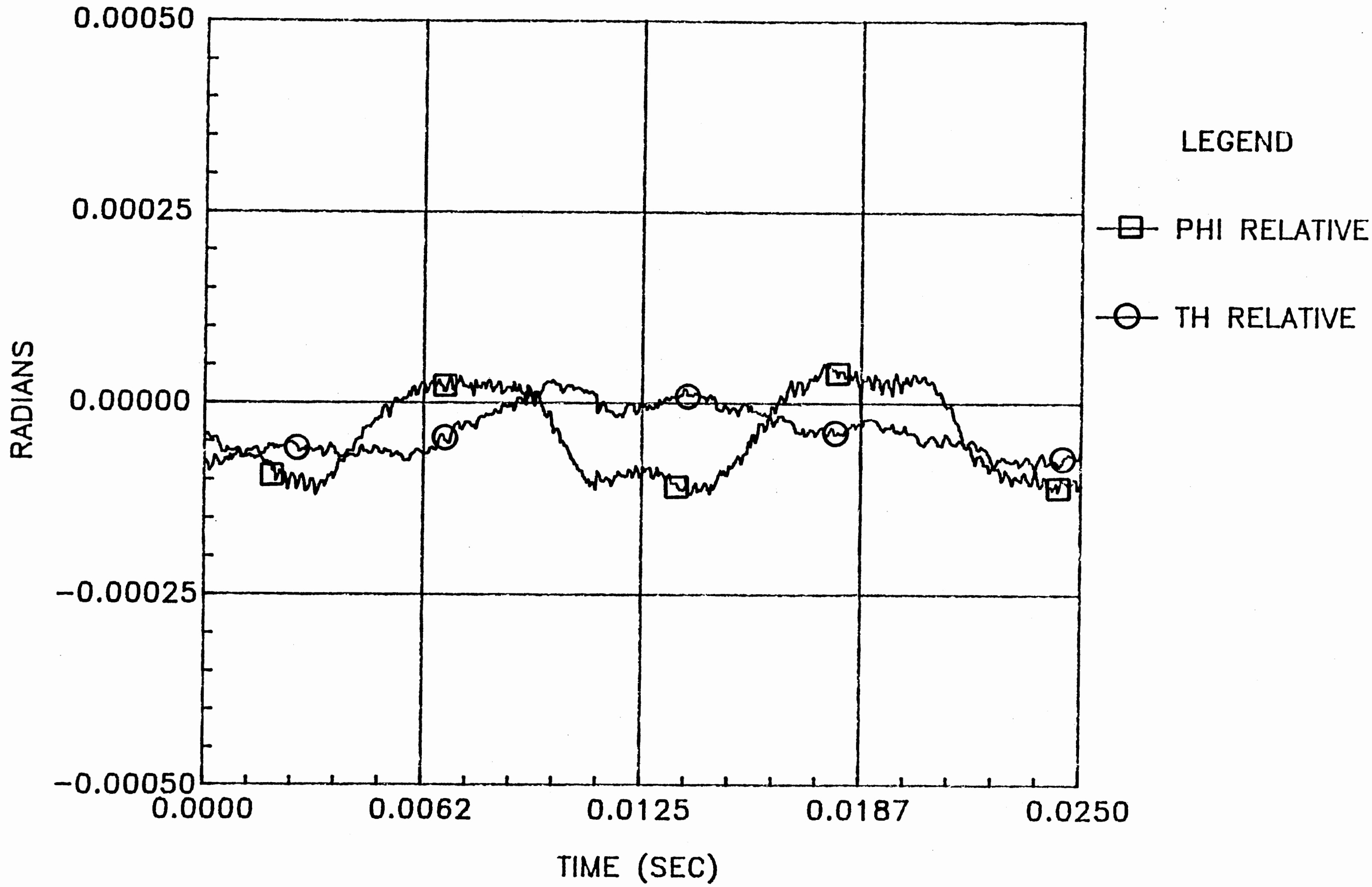

Figure 28. Relative Rotation of the Type 5 Slider while Alternating Between Tracks 625 and 630

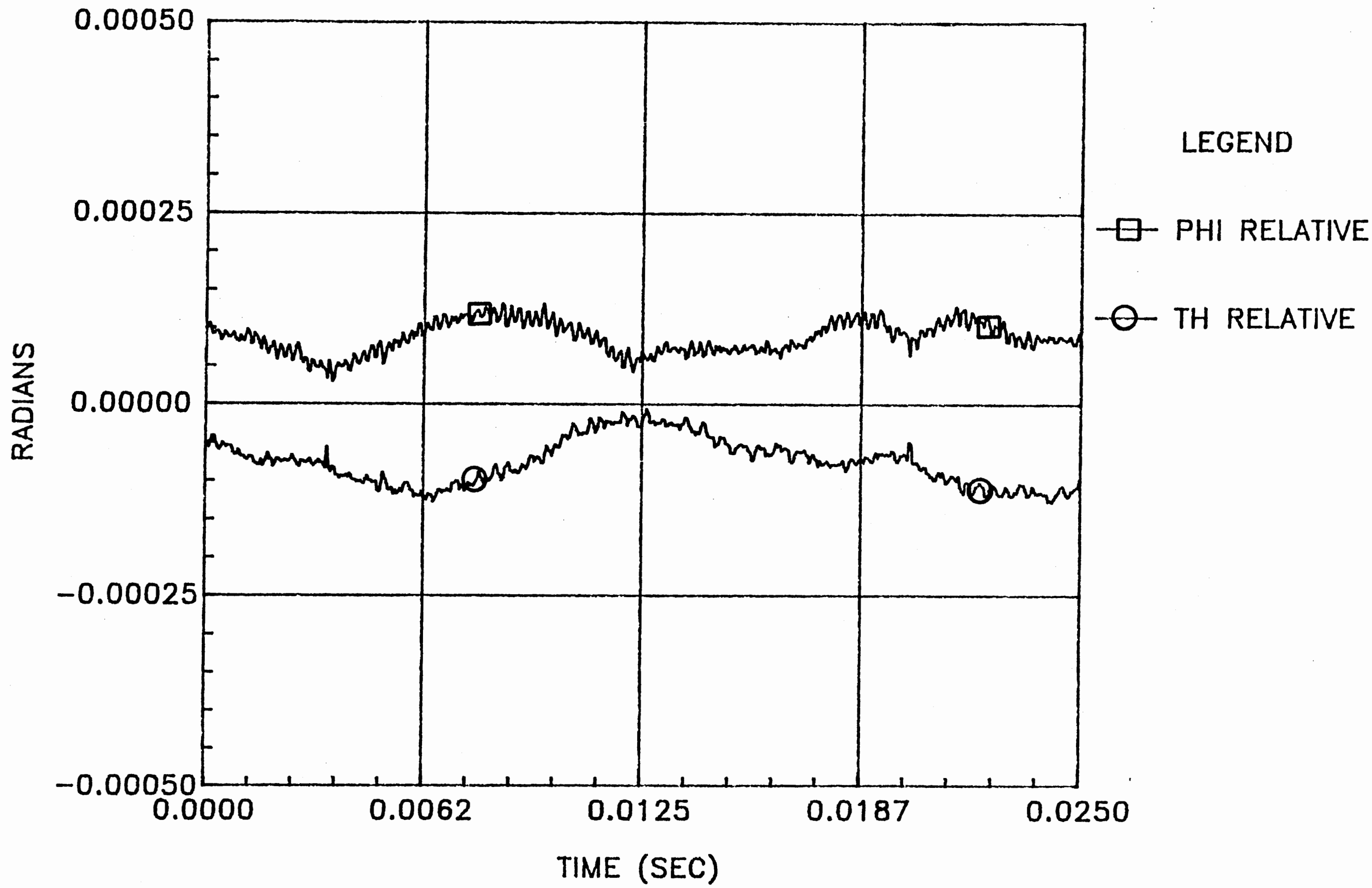

Figure 29. Relative Rotation of the Type 5 Slider while Alternating Between Tracks 335 and 340

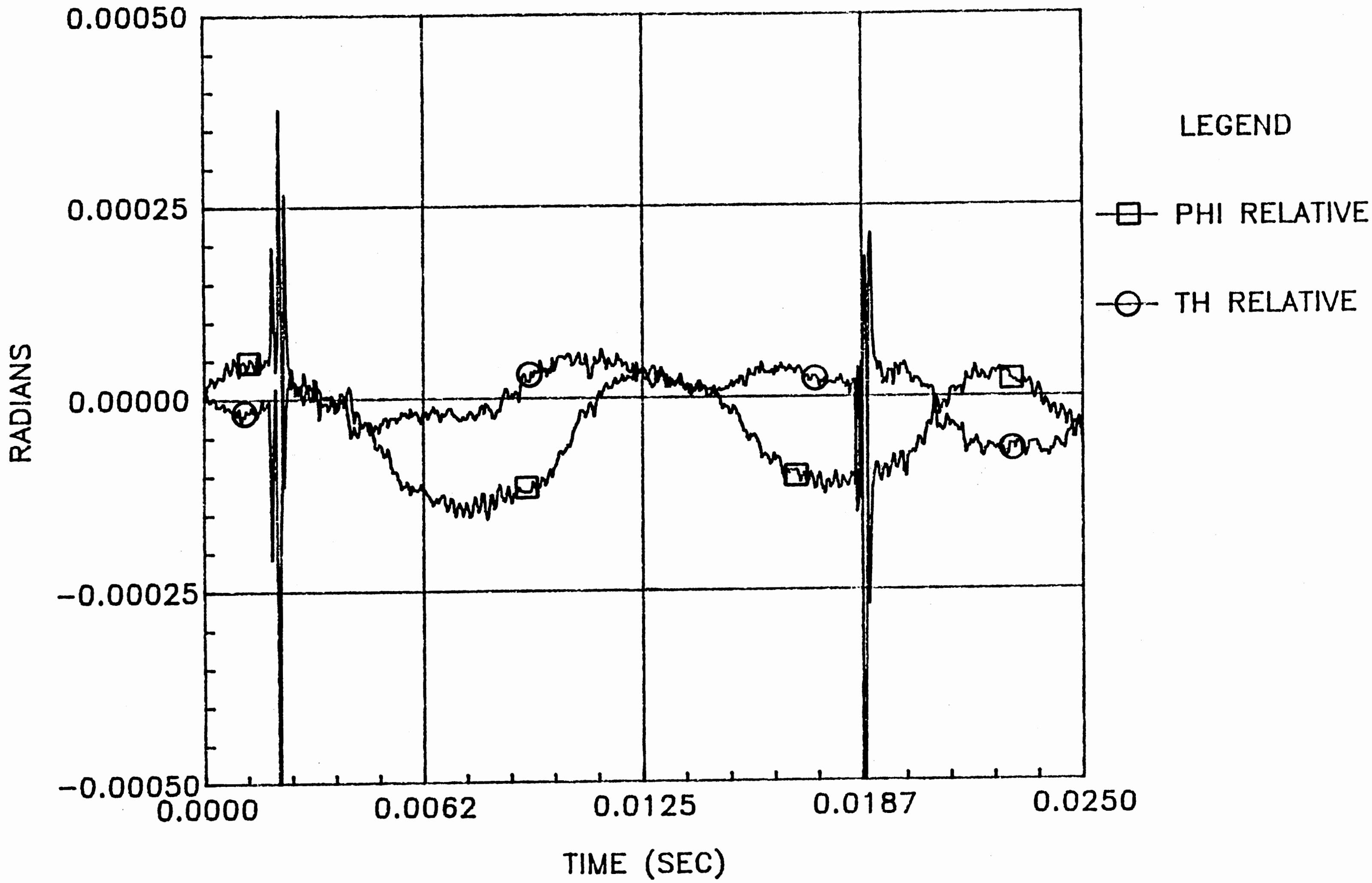

Figure 30. Relative Rotation of the Type 5 Slider while Alternating Between Tracks 000 and 005

The results recorded while the type 5 slider was alternating between tracks 335 and 340 were favorable. The relative pitch rotation was, on the average, about 100 microradians, and the relative roll was about -50 microradians. One point of significance was the similarities between the data collected from the type 5 slider while it was operating normally on track 335 (Figure 25), and the data collected when the type 5 slider was alternating between tracks 335 and 340 (Figure 29). Once again, the relative roll of the slider was similar in both cases except for the minor biasing offset, and the relative pitch exhibited a larger rotational amplitude when the slider was alternating tracks.

The relative pitch and roll of the type 5 slider while alternating between tracks 000 and 005 are illustrated in Figure 30. In comparison to Figure 26, which illustrated the relative rotations of the type 5 slider under normal operation on track 000, the relative roll in both situations again seems to be similar. The relative pitch again gained periodicity and amplitude when the assembly was alternating tracks. The most prevalent frequency visible again was about 87 Hz, which has a period of approximately 11.5 milliseconds. It is questionable if one of the assembly's resonant frequencies was the cause of the relative pitch vibrations in the alternating data recorded on tracks 625-630 and 000-005. The lessened activity in the alternating data pertaining to tracks 335-340 implies that it was not. In any event, some phenomenon, not necessarily related to media velocity, was causing the relative pitch to oscillate at approximately 88 Hz.

The results from the NASTRAN models are illustrated in Figures 31 through 42. Figures 31 through 36 are the mode shapes of the type 4 assembly, while Figures 37 through 42 are the mode shapes for the type 5 assembly. The eigenvalues for each mode shape are included on each plot. The finite element models did not include the air bearing models suggested in [7]; however, an effort was made to simply support the slider to simulate the rigidity of an air bearing. Because the simple support did not yield a substantial change in the eigenvalues, barring the cantilever mode, the air bearing simulation was not pursued any further.

The first natural frequencies of the type 4 and type 5 assemblies in Figures 31 and 37, respectively, were both experimentally verified using a mechanical shaker and a stroboscope. The remaining mode shapes had higher frequencies and smaller amplitudes, which made their experimental verification difficult. However, there were indications that at least the first three resonant frequencies of each assembly were valid. According to the NASTRAN results, the type 4 assembly exhibited its pitch and roll modes at just under 1000 Hz, whereas the rolling mode of the type 5 assembly was around 1100 Hz, and the pitching mode of the type 5 assembly was about 1400 Hz. The significance of these resonant frequencies will be addressed in the following section that deals with the frequency spectrums of the type 4 and type 5 assemblies. The measurement system used in this study was sensitive to vibration up to 5000 Hz, thus, for completeness, all of the remaining eigenvalues up to about 5000 Hz are presented with their respective eigenvectors.

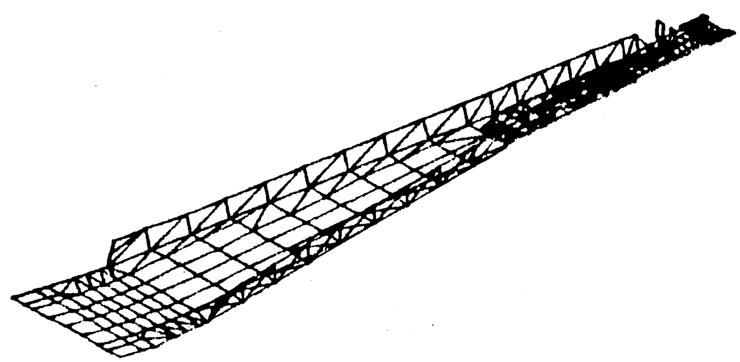

Figure 31. Type 4 Mode Shape (Frequency 89.8 Hz.)

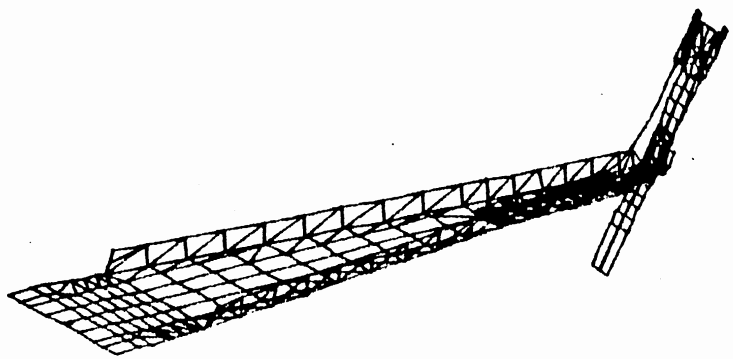

Figure 32. Type 4 Mode Shape (Frequency 969.0 Hz.)

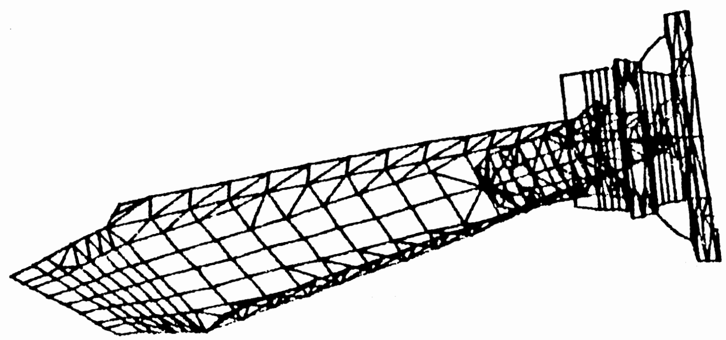

Figure 33. Type 4 Mode Shape (Frequency 991.1 Hz.)

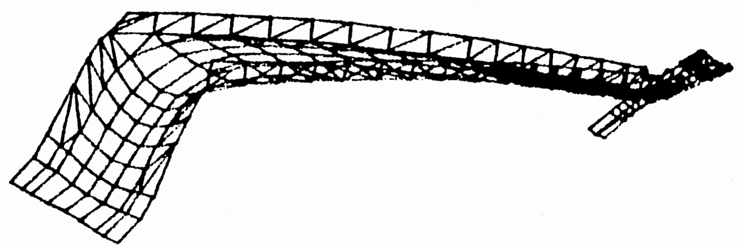

Figure 34. Type 4 Mode Shape (Frequency 2384.2 Hz.)

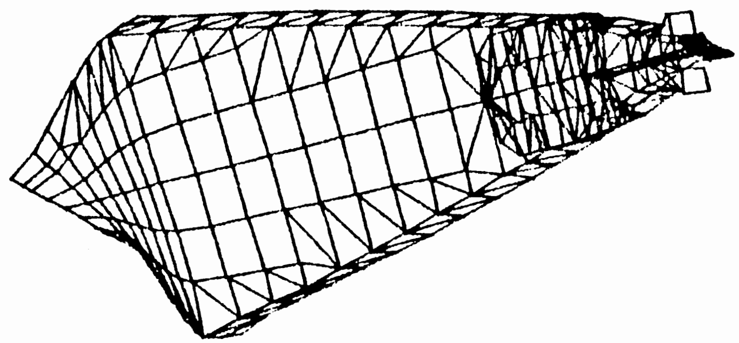

Figure 35. Type 4 Mode Shape (Frequency 2747.2 Hz.)

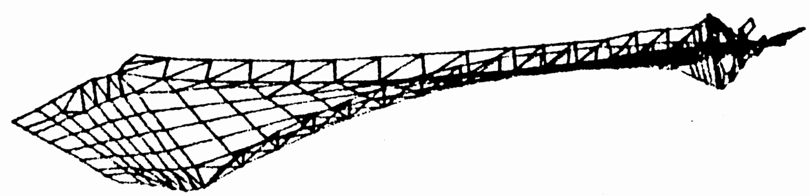

Figure 36. Type 4 Mode Shape (Frequency 5551.6 Hz.)

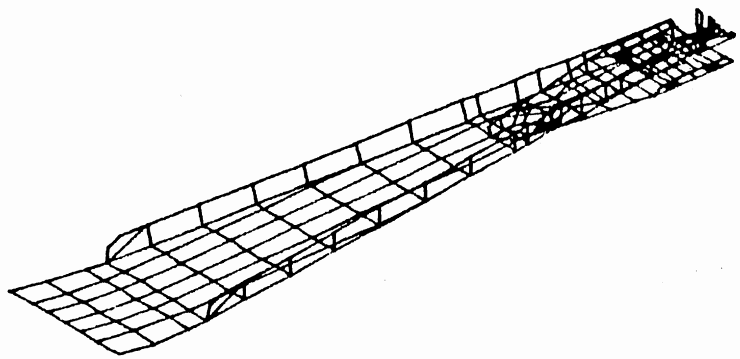

Figure 37. Type 5 Mode Shape (Frequency 86.2 Hz.)

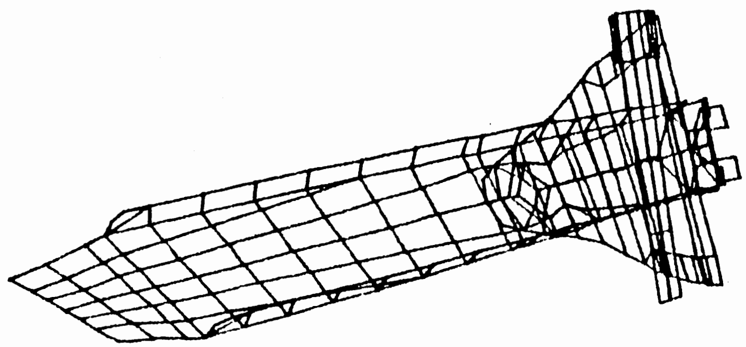

Figure 38. Type 5 Mode Shape (Frequency 1094.0 Hz.)

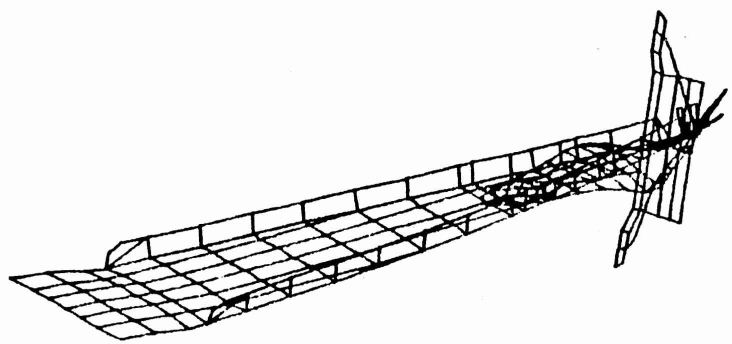

Figure 39. Type 5 Mode Shape (Frequency 1399.2 Hz.)

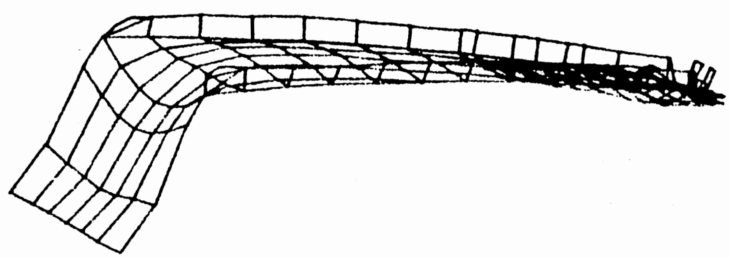

Figure 40. Type 5 Mode Shape (Frequency 2364.0 Hz.)

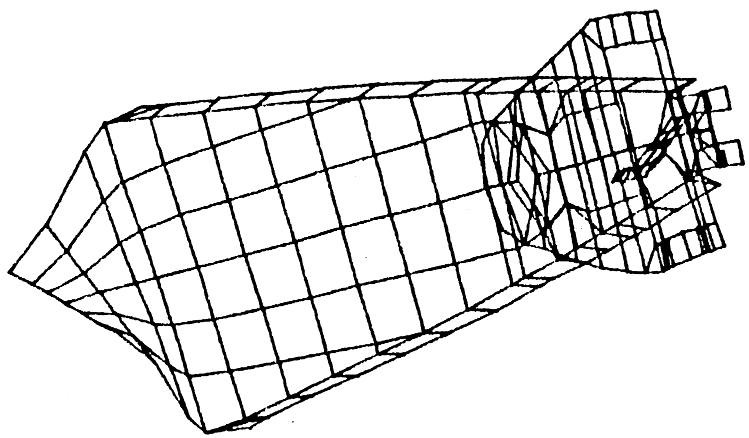

Figure 41. Type 5 Mode Shape (Frequency 2612.4 Hz.)

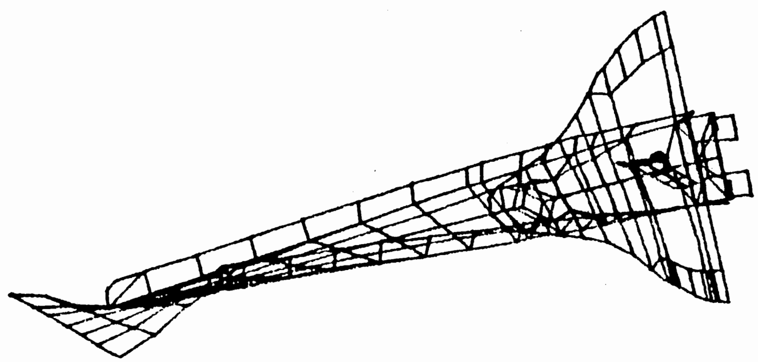

Figure 42. Type 5 Mode Shape (Frequency 5165.1 Hz.)

Comparison of the Type 4 and Type 5 Head Assembly Frequency Spectra's Relative to the Media's Frequency Spectrum

This portion of the research was performed by inserting a filter between the photodiode amplifiers and the waveform recorder/analyzers (see Figure 12). The filter was set to pass signals with a frequency of 400 Hz or greater. The primary motivation behind the 400 Hz setting was to eliminate the a 60 Hz component, which was associated with the media rotation, and a 360 Hz component, which was thought to be a product of six radial "waves" created by the six bolts that clamped the media to the spindle. Without the filter, the 60 Hz and 360 Hz components dwarfed all of the other signals detected, thus making it difficult to study the more obscure vibrational components.

During normal operation, the type 4 and type 5 head assemblies were monitored on tracks: 625, 335, and 000. The signals related to the Y'-Y' axis on the optical detectors 1S and 2M (see Figure 11) were recorded, and then analyzed by examining their frequency spectrums. The frequency spectrums were obtained by use of the fast fourier transform capability of both the DATA 6000 and DATA 6100. It was assumed that the signals recorded regarding the slider were a combination of the slider's pitching and vertical translation while following the media's runout, while the signals recorded associated with the media were assumed to depict its circumferential contour. To determine which of the read/write assemblies follows the media contour more closely, a comparison was made between the FFTs of each slider and its respective media. The FFT of the slider which simulated the FFT of its respective media the closest was selected to be the better assembly.

Figures 43, 44, and 45 represent the FFTs of the filtered data pertaining to tracks 625, 335, and 000, respectively, for the type 4 assembly. Figures 46, 47, and 48 represent the same respective data related to the type 5 assembly. The aforementioned low frequency components (60 and 360 Hz) still appeared in the frequency spectrums after filtering, as the response of the filter in the frequency domain is a ramp in the region of the set frequency of 400 Hz., thus the low frequency components still remain, but with greatly reduced amplitudes. Upon examination of the frequency spectrums of both the type 4 and type 5 assemblies, the high frequency activity of the slider (3200 to 4300 Hz), which has been apparent in nearly every waveform thus far in this study, appears to originate in the media, while some of the lower frequency vibration, around 1000 Hz, appears to originate in the read/write assembly.

The high frequency activity of the media was mentioned in [2] and [6] as being the result of surface roughness. The data collected in this study seems to reinforce this idea. The FFTs relating to track 625 display some components in the media at about 3200 to 3800 Hz, while the FFTs regarding track 335 exhibit some components in the media between 3800 and 4200 Hz. Lastly, the FFTs pertaining to track 000 display some components around 4300 Hz. The frequency of these components seem to increase with media velocity, which in turn suggests that the high frequency activity was in fact caused by asperities in the media. The activity of the read/write assemblies in the 1000 Hz region was credited to their pitch and roll modes as depicted

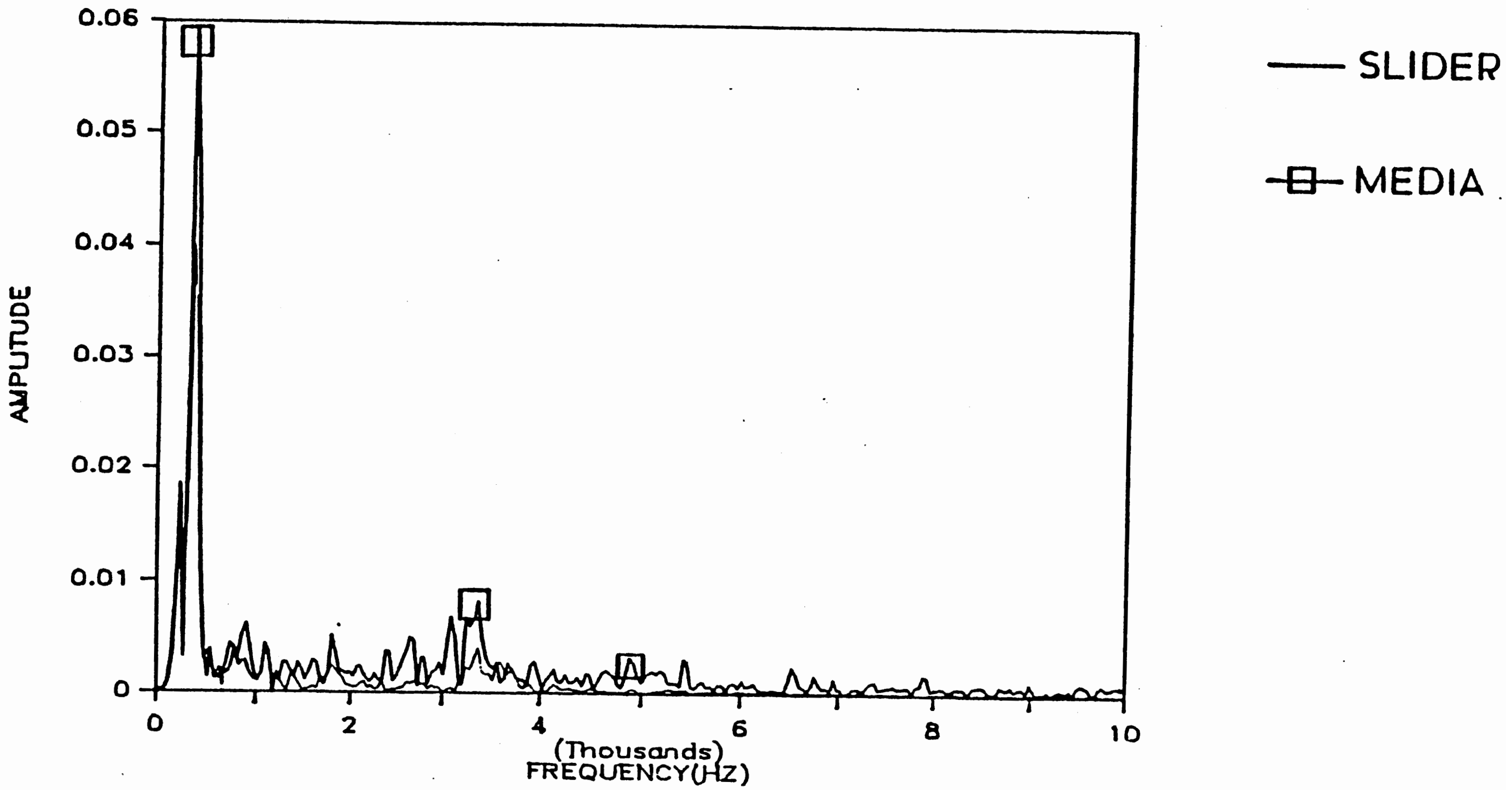

Figure 43. FFT of Filtered Data for the Type 4 Slider on Track 625

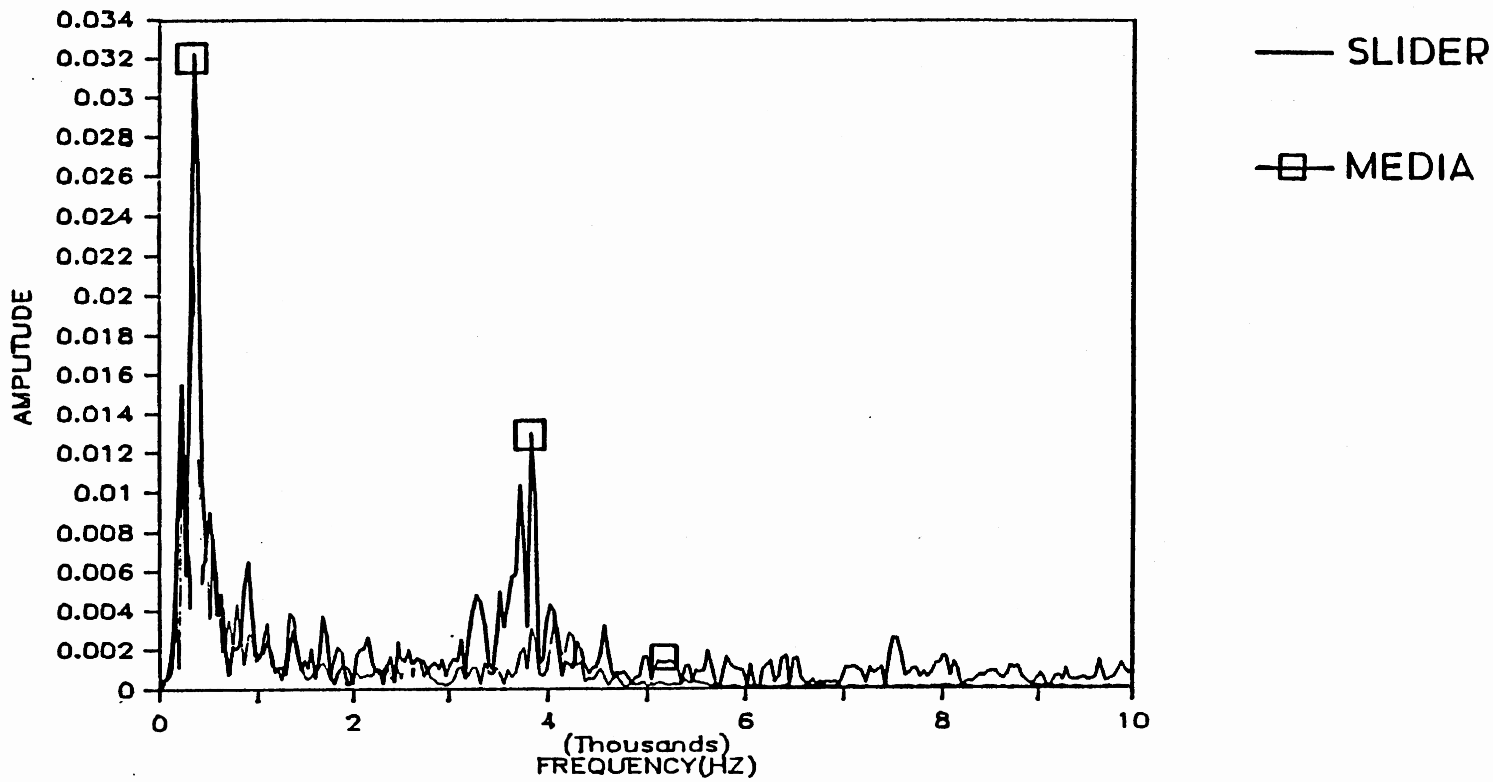

Figure 44. FFT of Filtered Data for the Type 4 Slider on Track 335

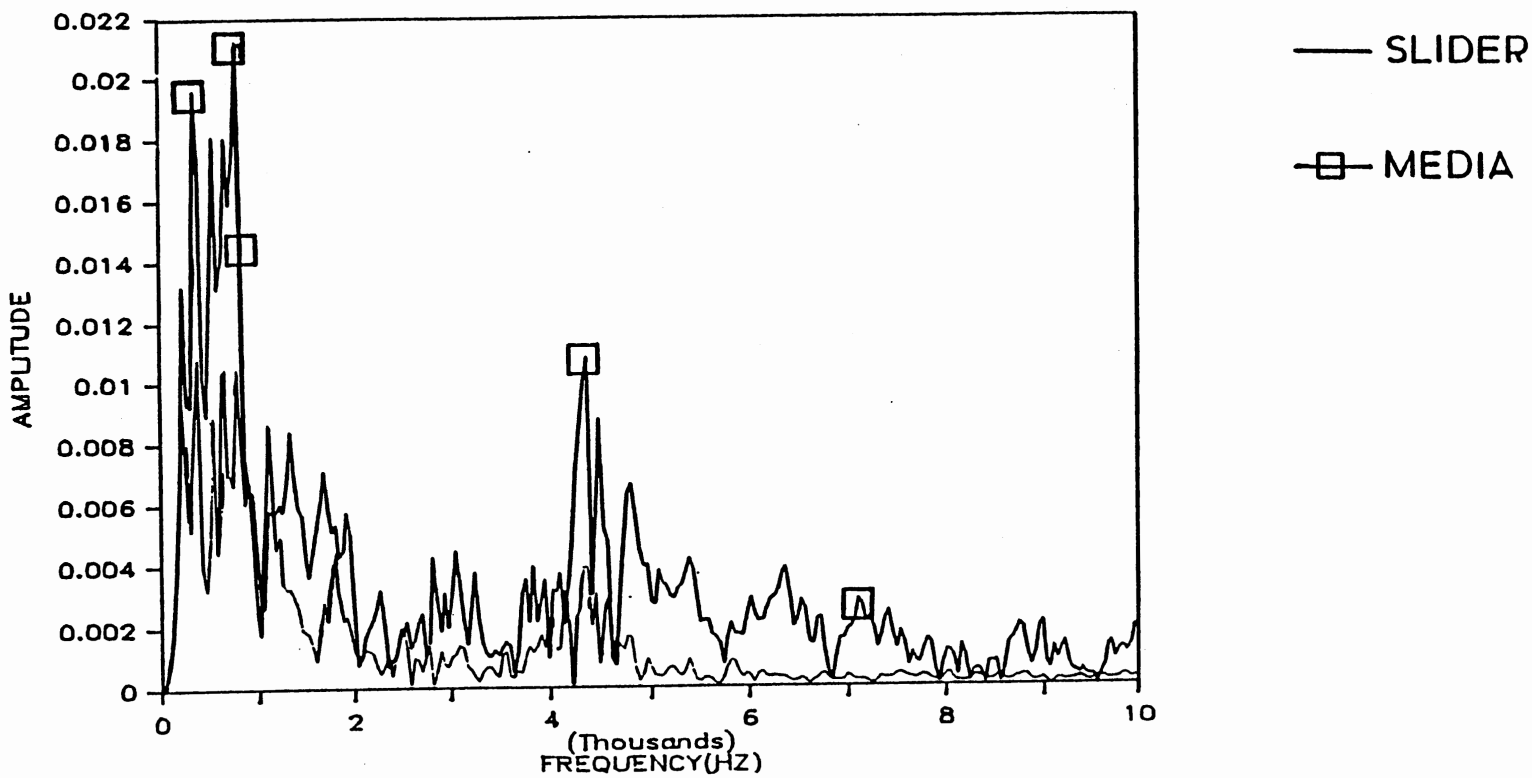

Figure 45. FFT of Filtered Data for the Type 4 Slider on Track 000

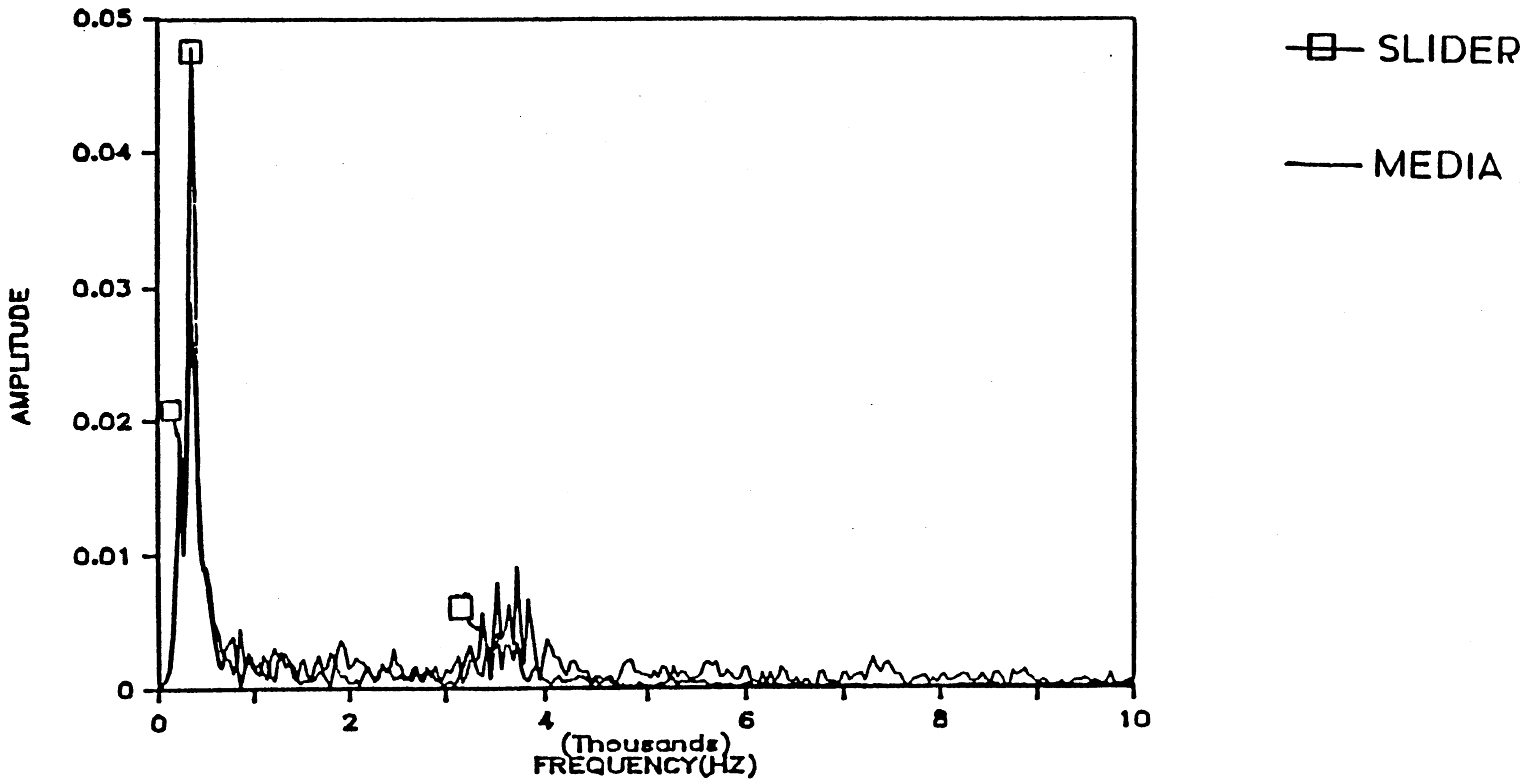

Figure 46. FFT of Filtered Data for the Type 5 Slider on Track 625

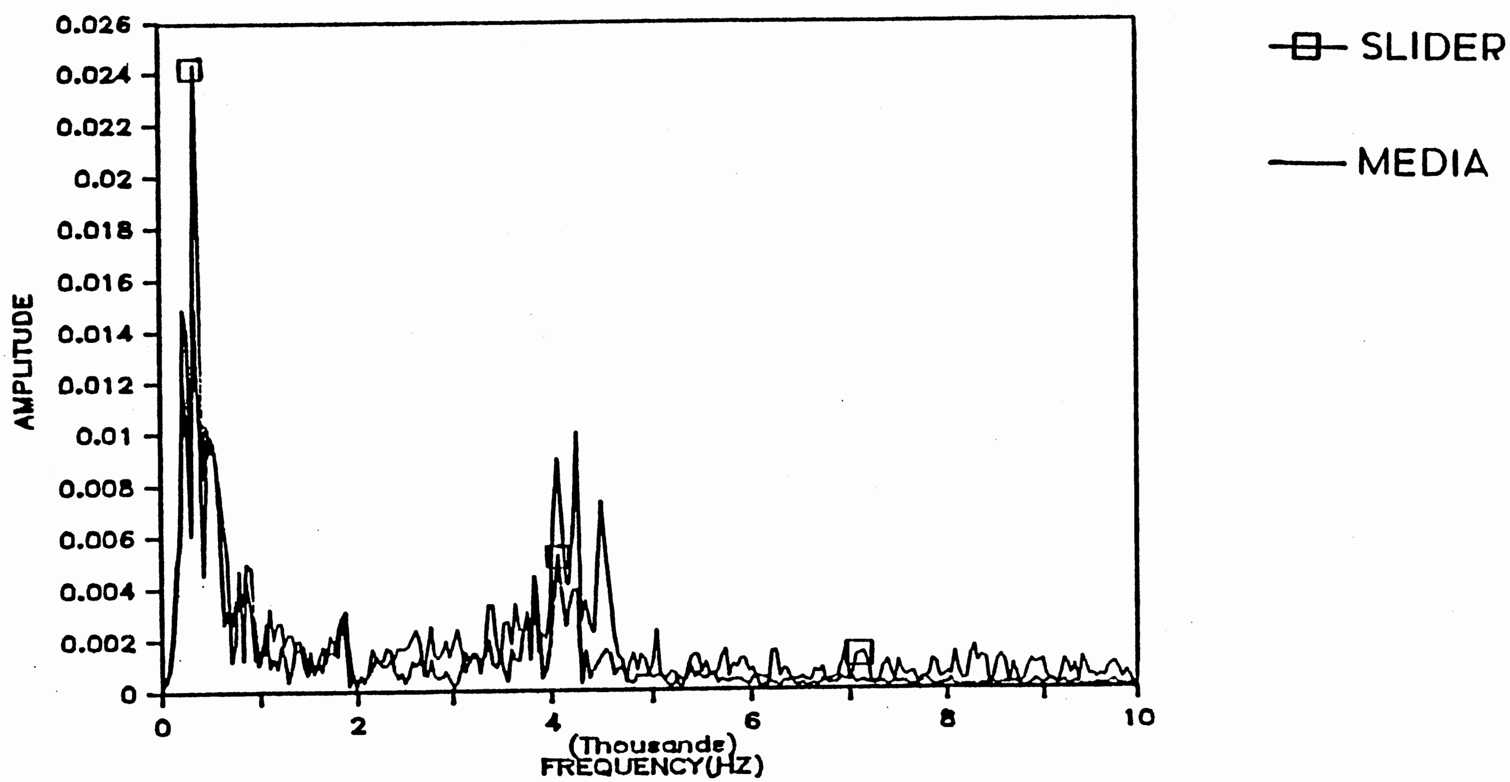

Figure 47. FFT of Filtered Data for the Type 5 Slider on Track 335

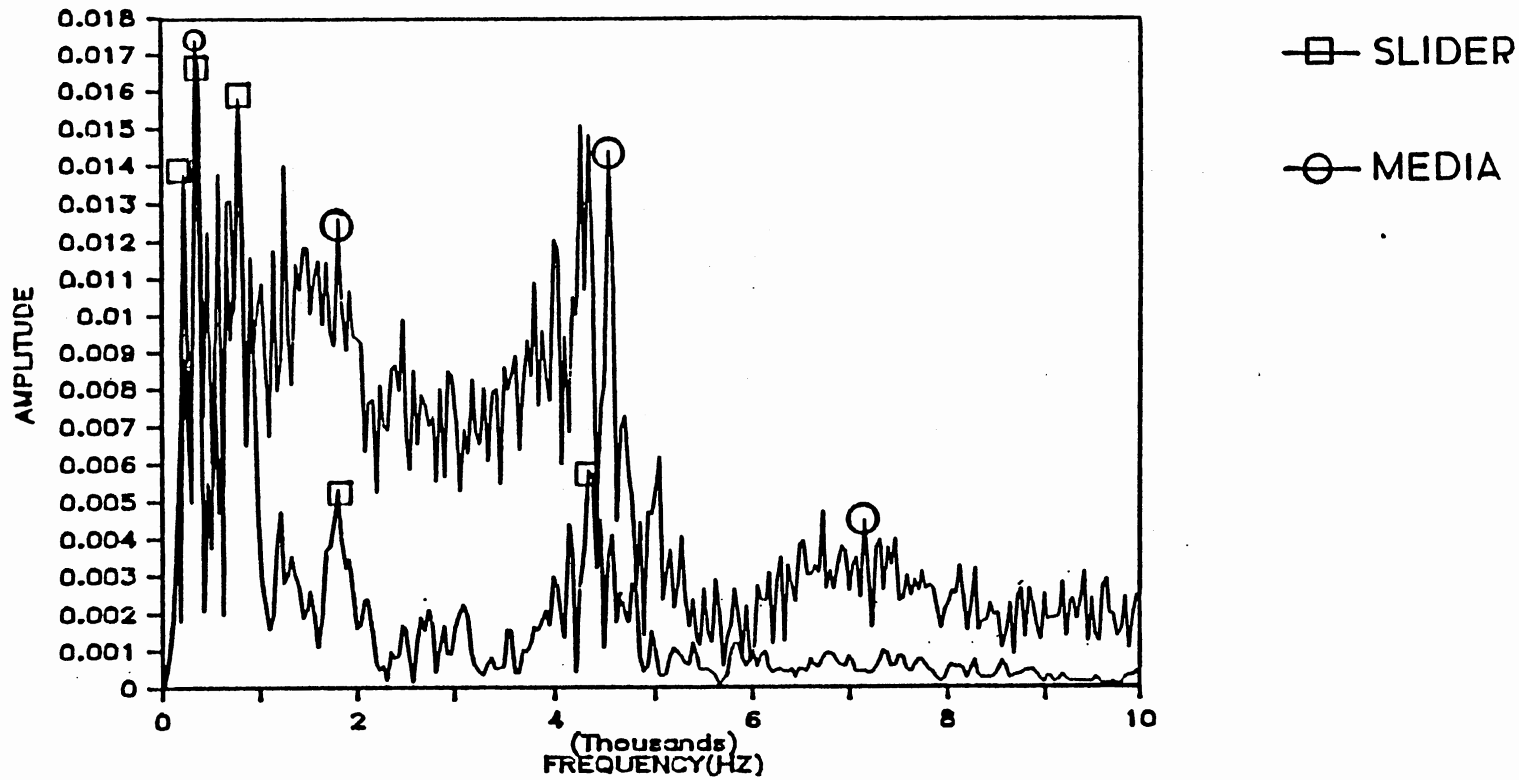

Figure 48. FFT of Filtered Data for the Type 5 Slider on Track 000

by Figures 32, 33, 37, and 38. Evidently these pitch and roll modes were being excited somewhat, and this, at some frequencies, resulted in slightly higher slider activity than media activity.

It was assumed that the activity in the 3.5 to 4.5 kHz range was a result of surface roughness. Ideally, to get an indication of how well the type 4 and type 5 assemblies followed the asperities in the media, the intervals of area under the media's FFT should be compared to the intervals of area under the slider's FFT. Unfortunately, this was not feasible so a simpler comparison was made to check to slider's ability to comply with the asperities on the disk. This was done by calculating the amplitude ratios (amplitude of the slider peak divided by the amplitude of the media peak) of the type 4 and type 5 slider in the 3.5 to 4.5 kHz range. These amplitude ratios are shown in Table IV. The higher amplitude ratio indicates that the slider was following the media more closely, with an amplitude ratio of one meaning that the slider followed the media exactly. While viewing Figures 43 through 48, it should be kept in mind that the system could measure a maximum frequency of 5.0 kHz and any activity which emerges above this ceiling should be disregarded.

According to Table IV, the type 5 slider appears to consistently maintain a higher amplitude ratio than the type 4 slider, thus it seems that if the assumptions involved with this data were correct the type 5 slider complied with the media better than the type 4 slider.

Variation of the Media Runout as Track Location was Varied Radially

The final aspect of the Winchester drive that was examined was

TABLE IV

AMPLITUDE RATIOS OF THE TYPE 4 AND TYPE 5 ASSEMBLIES AT VARIOUS TRACK LOCATIONS IN THE 3.5 TO 4.5 kHz REGION.

Track Location	Type 4	Type 5
000	0.36	0.55
335	0.25	0.51
625	0.53	0.60

the variation in media runout at different locations on the disk. The runout was examined on tracks: 625, 335, and 000.

Figures 49, 50, and 51 illustrate the media runout on track 625, 335, and 000, respectively. The runout appears to increase from 2.5 milli-inches, on track 625, to about 5 milli-inches, on track 000. These data appear to be consistent with the idea that the clamping bolts are the source of the radial waves in the media, which increase in amplitude as the radius increases. The data also seems to be somewhat consistent with the 1-to-2 milli-inch media runout mentioned in [2].

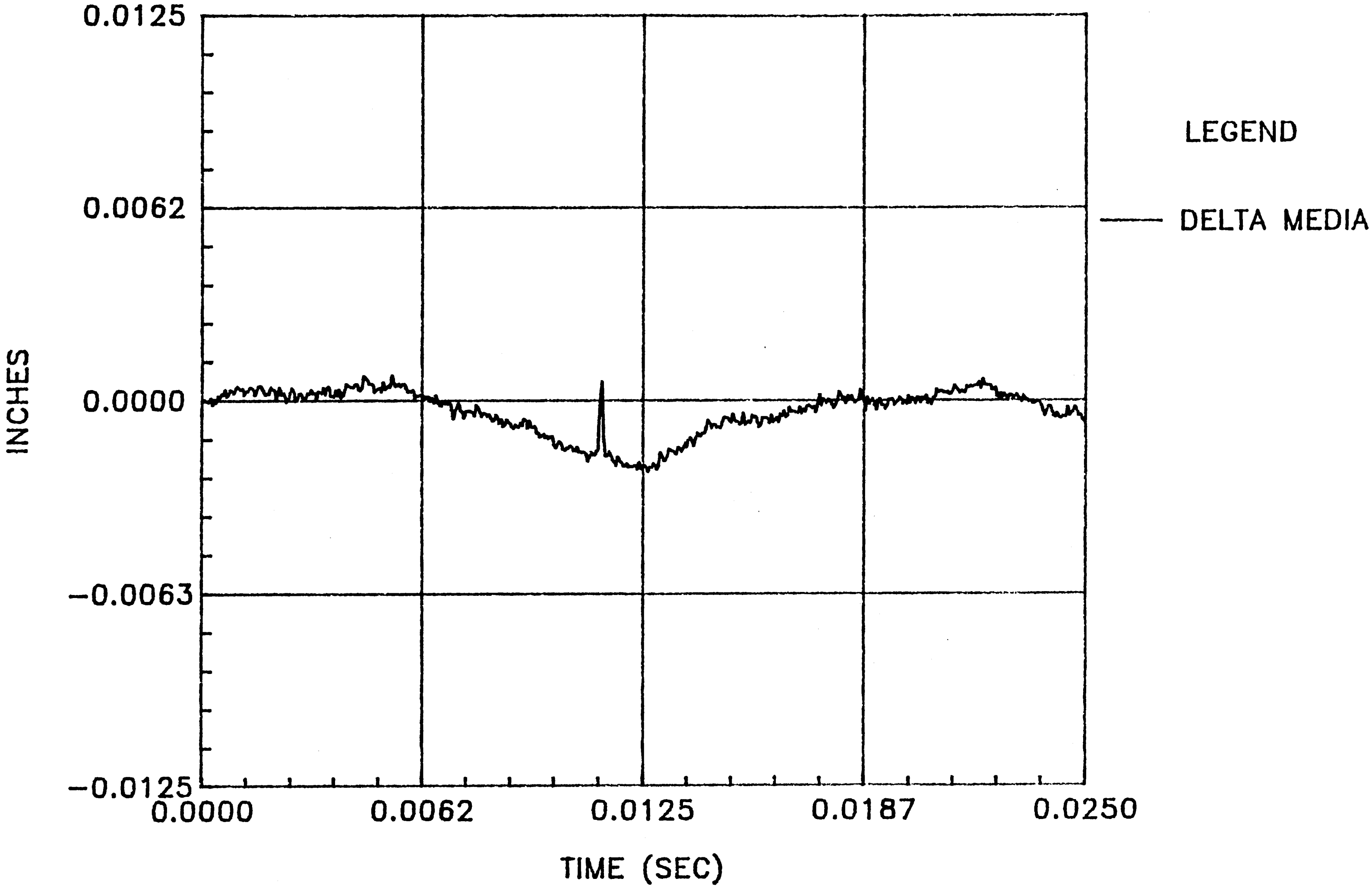

Figure 49. Vertical Translation of the Media on Track 625

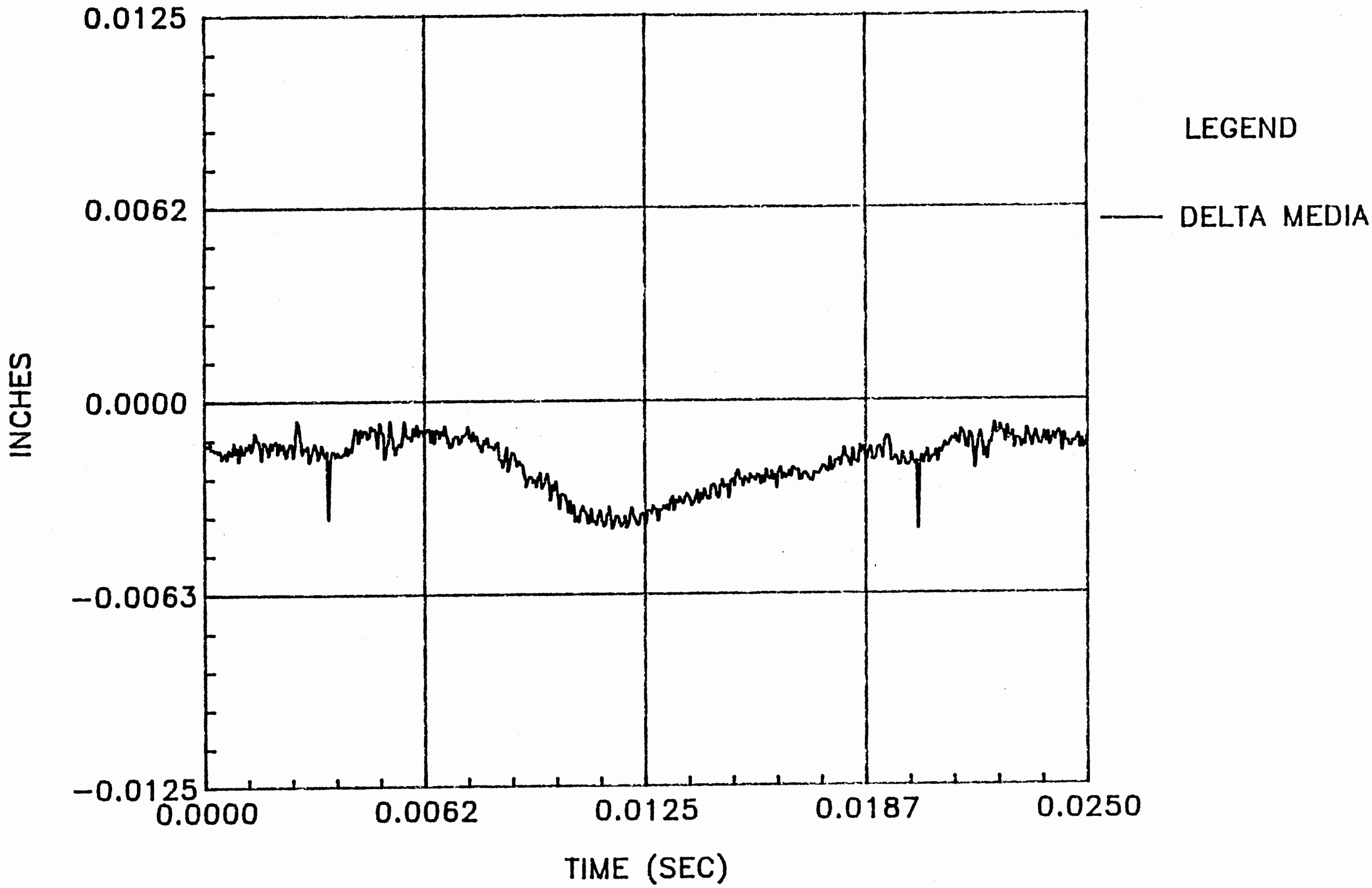

Figure 50. Vertical Translation of the Media on Track 335

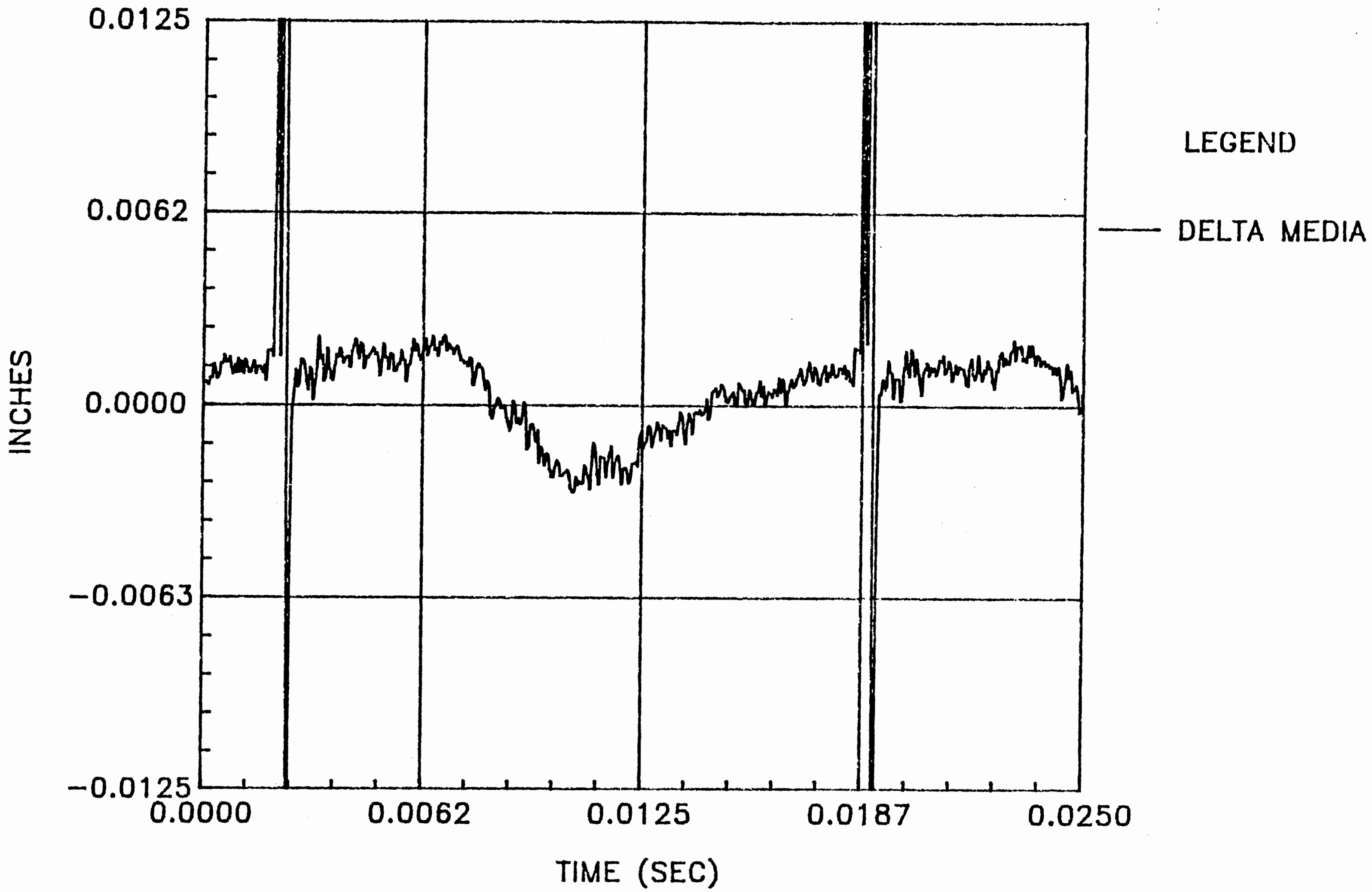

Figure 51. Vertical Translation of the Media on Track 000

CHAPTER V

CONCLUSIONS

In concluding this study, it was necessary to discuss two separate topics. The first topic discussed covers the conclusions that can be drawn regarding the data collected, and the second topic entails recommendations regarding the improvement of the measurement system used in this study.

Conclusions Regarding Collected Data

Although the attempts of measuring flying heights in this study were not successful, there is some evidence in reference to the data obtained, that the system is capable of ascertaining relative angular rotations in the 100-microradian range. Unfortunately, these measurements could not withstand a great deal of scrutiny because of the erratic reference static voltages used in their calculation. Obtaining accurate static voltages was the main problem associated with the measurement system, and because a method could not be found to obtain the static voltages accurately, information pertaining to the movements of the sliders examined that did not depend on the accuracy of the static voltages was sought.

The mean value of the movements calculated were definitely contingent on the reference static voltages; however the amplitude of these movements were not. Thus, theoretically, the amplitude of the rela tive pitch rotation around an unknown average relative pitch rotation could be found accurately using the measurement system. The same thing can be said for the relative roll rotations of the sliders. With this in mind, coupled with the fact that the data collected were comparable to data found in the literature search, the data pertaining to the amplitude of rotation of the two sliders appeared reliable enough for purposes of comparison.

The high frequency data obtained showed signs of being reliable because the frequency spectra obtained for the slider and the media paralleled each other closely. The frequency spectra were fast fourier transforms of the signals gathered from the Y'-Y' channels associated with the media and the slider. In the 1000 Hz. region both the type 4 and type 5 sliders exhibited some activity, and in the 3500 and 4500 Hz. region the media also displayed some activity, which was complemented by some attenuated motion of the sliders.

The portions of data obtained in this study that were thought to be reliable, including the relative rotation amplitudes and the amplitude ratios obtained in the high frequency study, gave somewhat mixed indications as to which read/write assembly performed better overall. The conclusions which can be drawn regarding the relative rotation amplitudes are as follow:

1. The type 4 assembly had a smaller relative pitch amplitude, on the average, than the type 5 assembly (excluding the data collected on track 625 for the type 4 assembly).

2. The type 5 assembly had a smaller relative roll amplitude, on the average, than the type 4 assembly.

Because the pitch rotation was assumed to be about the trailing edge of each slider, and the component that reads and writes information to the media is located in the trailing edge of the slider, a smaller roll amplitude is probably a more favorable characteristic than a smaller relative pitch amplitude. In this instance, the data seem to indicate that the type 5 assembly had the smaller average relative roll rotation, although the difference between the average relative roll rotations of the two assemblies was small.

The conclusion that can be drawn regarding the high frequency data is obvious after viewing Table IV in Chapter 4. It is believed that the activity of the media in the 3.5 to 4.5 kHz range is caused by asperities in the media, and an assembly that follows the asperities closely would exhibit similar activity in the same frequency range. Because the type 5 assembly appears to emulate the frequency spectrum of the media in the mentioned range more closely than the type 4 assembly, it is believed that the type 5 assembly follows the media more closely.

A considerable amount of time was spent modelling the type 4 and type 5 assemblies using NASTRAN. One conclusion that could be drawn from the results was that the activity observed in the FFTs of both the type 4 and type 5 assemblies around 1000 Hz was probably caused by the pitching and rolling resonance frequencies of the assemblies which ranged from about 970 to 1400 Hz. In some cases the eigenvalues found for the assemblies did not exactly match the frequency of the peaks on the respective assemblies FFT, two possible explanations for this were:

1. It was not possible to include the wiring on the assemblies in the mathematical models.

2. Neither of the assemblies were modelled with an accurate mathematical representation of an air bearing.

As a result of these differences, the output of the mathematical models would differ somewhat from the results in reality.

It is recommended for future research that the media be mathematically modelled, as to obtain its resonant frequencies. Knowledge of these resonant frequencies would obviously be helpful when distinguishing between vibrations that arise during operation and vibrations that arise due to the excitation of a resonant frequency.

The data collected pertaining to the media suggests that the lower frequency disturbances in the media originate at the bolts, which clamp the media to the spindle, and propagate radially. The bolts did not create six distinct depressions in the media, because of the manner in which they are installed; however, it is believed that as the media thickness is decreased, more problems pertaining to consistent flying heights will arise, and more attention will need to be given to the manner in which the clamping bolts are installed and the torques used to install them.

Recommendations Regarding System Improvement

The measurement system used in this study demonstrated the ability to obtain the frequency spectra of slider and media movements, and also demonstrated some ability to measure relative rotation amplitudes. Many improvements could be made on the system to enhance its ability to measure flying heights and relative rotations, and some of these improvements will be listed; however, none of the improvements will add a substantial amount of accuracy to these measurements without a method to obtain accurate reference static voltages. Some of the aforementioned improvements are as follows:

1. Decrease the distance the reflected laser beams travel so as to enable the recorded signals to fit in a 1.0 volt peak-to-peak amplitude.

2. Measure the sliders dynamics relative to the media directly beneath the slider. This could be done by monitoring the slider at a given location, then moving the slider and monitoring the media at the same location (it should be kept in mind that any effects caused by the slider/media interaction will not be present in these data).

3. Isolate the measurement system and disk drive from external vibration. It was possible that exterior vibration could have had an adverse effect on the measurements. This could be accomplished by placing the measurement system and Winchester drive on a damping setup.

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APPENDIX

```
PROGRAM CALC;
{-----------------------------------------------------------------------------}
{                                                                             }
{                  Dynamic Analysis of Winchester Drive                       }
{                        Read/Write Head Designs                              }
{                      Using the Laser Reflectometer                          }
{                                                                             }
{                Relative Pitch and Roll Calculation Program                  }
{                                                                             }
{          This program was used to calculate the relative pitch and         }
{     roll angles of the slider using data obtained by utilizing the         }
{     laser reflectometer.                                                    }
{          The program initially requests the user to enter all eight         }
{     of the static voltages which pertain to the data set being reduced }
{     by the program.  Next, the program requests the names of all            }
{     eight files that contain the digital voltage data obtained by the }
{     DATA 6000 and DATA 6100.  Subsequently, all of the angles ψ are         }
{     requested for each of the four detectors.  Once the file names are }
{     known, the digital voltage data is read into the computer.  At          }
{     this point the program requests the angle ζ and the file the user }
{     wishes to write the relative pitch and roll angles to.  Next, the }
{     program uses equations 2.17 and 2.18 to calculate the pitch and         }
{     roll angles of both the media and the slider in the global              }
{     system of the laser beams as illustrated in figure 16.  Finally,        }
{     the angles are converted into the local coordinate system of the        }
{     slider and the rotation of the media is subtracted from the             }
{     rotation of the slider to yield the rotation of the slider              }
{     relative to the media.                                                  }
{                                                                             }
{     INPUT VARIABLES:                                                        }
{          STHY2 - STATIC VOLTAGE FOR THE Y'-Y' AXIS ON DETECTOR 2S           }
{          STHY1 - STATIC VOLTAGE FOR THE Y'-Y' AXIS ON DETECTOR 1S           }
{          STHX2 - STATIC VOLTAGE FOR THE X'-X' AXIS ON DETECTOR 2S           }
{          STHX1 - STATIC VOLTAGE FOR THE X'-X' AXIS ON DETECTOR 1S           }
{          STMY2 - STATIC VOLTAGE FOR THE Y'-Y' AXIS ON DETECTOR 2M           }
{          STMY1 - STATIC VOLTAGE FOR THE Y'-Y' AXIS ON DETECTOR 1M           }
{          STMX2 - STATIC VOLTAGE FOR THE X'-X' AXIS ON DETECTOR 2M           }
{          STMX1 - STATIC VOLTAGE FOR THE X'-X' AXIS ON DETECTOR 1M           }
{          PSI2H - THE ANGLE FROM THE HORIZONTAL TO DETECTOR 2S               }
{          PSI1H - THE ANGLE FROM THE HORIZONTAL TO DETECTOR 1S               }
{          PSI2M - THE ANGLE FROM THE HORIZONTAL TO DETECTOR 2M               }
{          PSI1M - THE ANGLE FROM THE HORIZONTAL TO DETECTOR 1M               }
{          ZETA  - THE ANGULAR OFFSET OF THE LOCAL COORDINATE SYSTEM          }
{                  FROM THE GLOBAL COORDINATE SYSTEM                          }
{          VOLT  - A TWO DIMENSIONAL ARRAY STORING ALL OF THE DIGITAL         }
{                  VOLTAGES DATA RECORDED                                     }
{          TIME  - A TWO DIMENSIONAL ARRAY STORING THE TIMES AT WHICH         }
{                  ALL OF THE DIGITAL VOLTAGE DATA WAS STORED                 }
{                                                                             }
{     VARIABLES USED IN MAIN PROGRAM:                                         }
{          THH   - THE ROLL ROTATION OF THE SLIDER IN THE SLIDERS             }
{                  LOCAL COORDINATE SYSTEM                                    }
{          THM   - THE SLOPE OF THE MEDIA ALONG THE X' AXIS IN THE            }
{                  SLIDERS LOCAL COORDINATE SYSTEM                            }
{          PHIH  - THE PITCH ROTATION OF THE SLIDER IN THE SLIDERS            }
{                  LOCAL COORDINATE SYSTEM                                    }
{          PHIM  - THE SLOPE OF THE MEDIA ALONG THE Y' AXIS IN THE            }
{                  SLIDERS LOCAL COORDINATE SYSTEM                            }
{          DEL1  - A VARIABLE USED IN CALCULATING THE THE GLOBAL              }
{                  PITCH ANGLES                                               }
{          DEL   - A VARIABLE USED IN CALCULATING THE VERTICAL                }
{                  TRANSLATION OF THE OBJECT IN QUESTION                      }
```

```
{               TH      - THE ROLL ROTATION OF THE SLIDER IN THE GLOBAL          }
{                         COORDINATE SYSTEM                                      }
{               TM      - THE SLOPE OF THE MEDIA ALONG THE X AXIS IN THE         }
{                         GLOBAL COORDINATE SYSTEM                               }
{               PH      - THE PITCH ROTATION OF THE SLIDER IN THE GLOBAL         }
{                         COORDINATE SYSTEM                                      }
{               PM      - THE SLOPE OF THE MEDIA ALONG THE Y AXIS IN THE         }
{                         GLOBAL COORDINATE SYSTEM                               }
{               DY      - THE VERTICAL DISPLACEMENT OF THE SLIDER FROM THE       }
{                         REFERENCE POINT TO THE POINT IN QUESTION (SEE FIG. 14) }
{                                                                                }
{          CONSTANTS:                                                            }
{               R       - THE DISTANCE FROM THE POINT AT WHICH THE LASER BEAM    }
{                         IS REFLECTED TO THE DETECTORS                          }
{               SENH1 - THE SENSITIVITY OF DETECTOR 1S                           }
{               SENH2 - THE SENSITIVITY OF DETECTOR 2S                           }
{               SENM1 - THE SENSITIVITY OF DETECTOR 1M                           }
{               SENM2 - THE SENSITIVITY OF DETECTOR 2M                           }
{                                                                                }
{          OUTPUT VARIABLES:                                                     }
{               PR      - THE RELATIVE PITCH ANGLE OF THE SLIDER WITH RESPECT    }
{                         TO THE MEDIA                                           }
{               TR      - THE RELATIVE ROLL ANGLE OF THE SLIDER WITH RESPECT     }
{                         TO THE MEDIA                                           }
{               DM      - THE VERTICAL DISPLACEMENT OF THE MEDIA FROM THE        }
{                         REFERENCE POINT TO THE POINT IN QUESTION (SEE FIG. 14) }

CONST

  R=34.0;
  SENH1=71.0;
  SENH2=71.0;
  SENM1=71.0;
  SENM2=71.0;

TYPE

  S=ARRAY[1..8] OF STRING[20];
  T=ARRAY[1..8,1..512] OF REAL;

VAR

  STHY2,STHY1,STHX2,STHX1,STMY2,STMY1,STMX2,STMX1,PSI2H,PSI1H,PSI2M,
  PSI1M,THH,THM,PHIH,PHIM,ZETA,DEL1,DEL,TH,TM,PH,PM,DM,DY,PR,TR      :REAL;
  INFILE                                                             :S;
  FLAG                                                               :BOOLEAN;
  DATA_FILE                                                          :TEXT;
  TIME,VOLT                                                          :T;
  K                                                                  :INTEGER;
  FILENAME                                                           :STRING[20];
{                                                                                }
{                                                                                }
{               PROCEDURE STATIC PROMPTS THE USER TO INPUT ALL EIGHT OF THE      }
{          STATIC VOLTAGES.                                                      }
{                                                                                }
{                                                                                }
PROCEDURE STATIC;
BEGIN
  WRITELN('  DETECTOR 1 IS THE DETECTOR WITH THE LARGER ANGLE PSI AND      ');
  WRITELN('DETECTOR 2 IS THE DETECTOR WITH THE SMALLER ANGLE PSI.  AT THE  ');
  WRITELN('TIME THIS PROGRAM WAS WRITTEN DETECTOR 2 FOR THE HEAD AND THE   ');
  WRITELN('AND FOR THE MEDIA RECEIVED DATA FOR CHANNELS 1 AND 2 AND DETECTOR');
  WRITELN('AND DETECTOR 1 FOR THE HEAD AND MEDIA RECIEVED DATA FOR CHANNELS ');
  WRITELN('3 AND 4.');
  WRITELN('  ');
  WRITELN('  ');
```

```
    WRITELN('ENTER THE STATIC Y-Y READING ON DETECTOR 2 FOR THE HEAD');
    READLN(STHY2);
    WRITELN('ENTER THE STATIC X-X READING ON DETECTOR 2 FOR THE HEAD');
    READLN(STHX2);
    WRITELN('ENTER THE STATIC Y-Y READING ON DETECTOR 1 FOR THE HEAD');
    READLN(STHY1);
    WRITELN('ENTER THE STATIC X-X READING ON DETECTOR 1 FOR THE HEAD');
    READLN(STHX1);
    WRITELN('ENTER THE STATIC Y-Y READING ON DETECTOR 2 FOR THE MEDIA');
    READLN(STMY2);
    WRITELN('ENTER THE STATIC X-X READING ON DETECTOR 2 FOR THE MEDIA');
    READLN(STMX2);
    WRITELN('ENTER THE STATIC Y-Y READING ON DETECTOR 1 FOR THE MEDIA');
    READLN(STMY1);
    WRITELN('ENTER THE STATIC X-X READING ON DETECTOR 1 FOR THE MEDIA');
    READLN(STMX1);
END;
{                                                                          }
{                                                                          }
{            PROCEDURE INPUT PROMPTS THE USER FOR THE NAMES OF ALL EIGHT OF}
{        THE FILES THAT CONTAIN THE DIGITAL VOLTAGE DATA OBTAINED DURING   }
{        EXPERIMENTATION.  THEN THE USER IS PROMPTED FOR THE    ANGLES     }
{        FOR EACH DETECTOR.                                                }
{                                                                          }
{                                                                          }
PROCEDURE INPUT;
  BEGIN
    WRITELN('  ');
    WRITELN('REMEMBER DETECTOR 1 IS THE DETECTOR WITH THE LARGER ANGLE PSI');
    WRITELN('AND DETECTOR 2 IS THE DETECTOR WITH THE SMALLER ANGLE PSI.');
    WRITELN('AT THE TIME THIS PROGRAM WAS WRITTEN DETECTOR 2 FOR THE HEAD');
    WRITELN('AND THE MEDIA RECEIVED DATA FOR CHANNELS 1 AND 2 AND DETECTOR');
    WRITELN('1 FOR THE HEAD AND MEDIA RECEIVED DATA FOR CHANNELS 3 AND 4.');
    WRITELN(' ');
    WRITELN('ENTER THE FILE THE DATA FOR HEAD,DETECTOR 2,Y-Y IS IN');
    READLN(INFILE[1]);
    WRITELN('ENTER THE FILE THE DATA FOR HEAD,DETECTOR 2,X-X IS IN');
    READLN(INFILE[2]);
    WRITELN('ENTER THE FILE THE DATA FOR HEAD,DETECTOR 1,Y-Y IS IN');
    READLN(INFILE[3]);
    WRITELN('ENTER THE FILE THE DATA FOR HEAD,DETECTOR 1,X-X IS IN');
    READLN(INFILE[4]);
    WRITELN('ENTER THE FILE THE DATA FOR MEDIA,DETECTOR 2,Y-Y IS IN');
    READLN(INFILE[5]);
    WRITELN('ENTER THE FILE THE DATA FOR MEDIA,DETECTOR 2,X-X IS IN');
    READLN(INFILE[6]);
    WRITELN('ENTER THE FILE THE DATA FOR MEDIA,DETECTOR 1,Y-Y IS IN');
    READLN(INFILE[7]);
    WRITELN('ENTER THE FILE THE DATA FOR MEDIA,DETECTOR 1,X-X IS IN');
    READLN(INFILE[8]);
    WRITELN(' ');
    WRITELN(' ');
    WRITELN('ENTER PSI2 FOR THE HEAD IN RADIANS');
    READLN(PSI2H);
    WRITELN('ENTER PSI1 FOR THE HEAD IN RADIANS');
    READLN(PSI1H);
    WRITELN('ENTER PSI2 FOR THE MEDIA IN RADIANS');
    READLN(PSI2M);
    WRITELN('ENTER PSI1 FOR THE MEDIA IN RADIANS');
    READLN(PSI1M);
END;
{                                                                          }
{                                                                          }
{            PROCEDURE GETDATA READS ALL OF THE DIGITAL VOLTAGE DATA WITH  }
{        ITS CORRESPONDING TIMES FROM FLOPPY DISK INTO THE ARRAYS VOLT AND }
{        TIMES.                                                            }
```

```
{                                                                              }
{                                                                              }
PROCEDURE GETDATA;
VAR
  I,J,K        :INTEGER;
    BEGIN
      FOR I:=1 TO 8 DO
        BEGIN
          ASSIGN(DATA_FILE,INFILE[I]);
          RESET(DATA_FILE);
          FOR J:=1 TO 512 DO
            BEGIN
              READLN(DATA_FILE,TIME[I,J],VOLT[I,J]);
            END;
          CLOSE(DATA_FILE);
        END;
    END;
{                                                                              }
{                                                                              }
{              PROCEDURE DELTA CALCULATES THE VERTICAL TRANSLATION AND PITCH }
{        ANGLES OF THE OBJECT IN QUESTION.                                     }
{                                                                              }
{                                                                              }
PROCEDURE DELTA(D1,D3:REAL;VAR DEL,P:REAL);
VAR
  A,B,C,D,SEN2,SEN1,PSI1,PSI2,STAT1,STAT3,P1,P2      :REAL;

  BEGIN
    IF FLAG=TRUE THEN
      BEGIN
        STAT1:=VOLT[1,1];
        STAT3:=VOLT[3,1];
        SEN2:=SENH2;
        SEN1:=SENH1;
        PSI1:=PSI1H;
        PSI2:=PSI2H;
      END
    ELSE
      BEGIN
        STAT1:=STMY2;
        STAT3:=STMY1;
        SEN2:=SENM2;
        SEN1:=SENM1;
        PSI1:=PSI1M;
        PSI2:=PSI2M;
      END;
    A:=(D3-STAT3)/SEN1;
    B:=(D1-STAT1)/SEN2;
    C:=2*(COS(PSI1)-COS(PSI2));
    DEL:=(A-B)/C;
    P1:=(D3-STAT3)/(SEN1*2*R)-(DEL*COS(PSI1))/R;
    P2:=(D1-STAT1)/(SEN2*2*R)-(DEL*COS(PSI2))/R;
      IF FLAG=TRUE THEN
        BEGIN
        A:=(D3-STHY1)/SEN1;
        B:=(D1-STHY2)/SEN2;
        C:=2*(COS(PSI1)-COS(PSI2));
        DEL1:=(A-B)/C;
        P1:=(D3-STHY1)/(SEN1*2*R)-(DEL1*COS(PSI1))/R;
        P2:=(D1-STHY2)/(SEN2*2*R)-(DEL1*COS(PSI2))/R;
        END;
    P:=(P1+P2)/2;
END;
{                                                                              }
{                                                                              }
{              PROCEDURE DELM CALLS PROCEDURE DELTA TO CALCULATE THE VERTICAL}
```

```
{         DISPLACEMENTS AND SLOPE OF THE MEDIA ALONG THE Y AXIS.              }
{                                                                             }
{                                                                             }
PROCEDURE DELM(I:INTEGER;VAR D,P:REAL);
  BEGIN
    FLAG:=FALSE;
    DELTA(VOLT[5,I],VOLT[7,I],D,P);
  END;
{                                                                             }
{                                                                             }
{              PROCEDURE DELY CALLS PROCEDURE DELTA TO CALCULATE THE VERTICAL}
{         DISPLACEMENTS AND PITCH ROTATION OF THE SLIDER.                     }
{                                                                             }
{                                                                             }
PROCEDURE DELY(I:INTEGER;VAR D,P:REAL);
  BEGIN
    FLAG:=TRUE;
    DELTA(VOLT[1,I],VOLT[3,I],D,P);
  END;
{                                                                             }
{                                                                             }
{              PROCEDURE DELH CALCULATES THE FLYING HEIGHT OF THE SLIDER AT   }
{         THE REFERENCE POINT.                                                }
{                                                                             }
{                                                                             }
PROCEDURE DELH(VAR D:REAL);
VAR
  A,B,C           :REAL;
  BEGIN
    A:=(VOLT[3,1]-STHY1)/SENH1;
    B:=(VOLT[1,1]-STHY2)/SENH2;
    C:=2*(COS(PSI1H)-COS(PSI2H));
    D:=(A-B)/C;
  END;
{                                                                             }
{                                                                             }
{              PROCEDURE ANGLE CALCULATES THE ROLL ANGLES OF THE OBJECT IN    }
{         QUESTION.                                                           }
{                                                                             }
{                                                                             }
FUNCTION ANGLE(D2,D4:REAL):REAL;
VAR
  T1,T2,SEN2,SEN1,PSI1,PSI2,STAT2,STAT4    :REAL;

  BEGIN
    IF FLAG=TRUE THEN
      BEGIN
        STAT2:=STHX2;
        STAT4:=STHX1;
        SEN2:=SENH2;
        SEN1:=SENH1;
        PSI2:=PSI2H;
        PSI1:=PSI1H;
      END
    ELSE
      BEGIN
        STAT2:=STMX2;
        STAT4:=STMX1;
        SEN2:=SENM2;
        SEN1:=SENM1;
        PSI2:=PSI2M;
        PSI1:=PSI1M;
      END;
    T1:=-((D2-STAT2)/SEN1)/(2*R*SIN(PSI2));
    T2:=-((D4-STAT4)/SEN2)/(2*R*SIN(PSI1));
    ANGLE:=(T1+T2)/2;
```

```
END;
{                                                                    }
{                                                                    }
{                        MAIN PROGRAM                                }
{                                                                    }
{                                                                    }
BEGIN
  STATIC;
  INPUT;
  GETDATA;
  WRITELN('ENTER THE ANGLE ZETA(IN RADIANS)');
  READLN(ZETA);
  WRITELN('ENTER THE FILE YOU WISH TO WRITE THE OUTPUT TO');
  READLN(FILENAME);
  ASSIGN(DATA_FILE,FILENAME);
  REWRITE(DATA_FILE);
  FOR K:=1 TO 512 DO
    BEGIN
      DELM(K,DM,PM);
      DELY(K,DY,PH);
      FLAG:=TRUE;
      TH:=ANGLE(VOLT[2,K],VOLT[4,K]);
      FLAG:=FALSE;
      TM:=ANGLE(VOLT[6,K],VOLT[8,K]);
      PHIH:=PH*COS(ZETA)+TH*SIN(ZETA);
      THH:=-PH*SIN(ZETA)+TH*COS(ZETA);
      PHIM:=PM*COS(ZETA)+TM*SIN(ZETA);
      THM:=-PM*SIN(ZETA)+TM*COS(ZETA);
      PR:=PHIH-PHIM;
      TR:=THH-THM;
WRITELN(DATA_FILE,TIME[1,K]:10:8,' ',PR:10:8,' ',TR:10:8,' ',DM:10:8);
    END;
 CLOSE(DATA_FILE);
 END.
```

VITA

Robert K. Brown

Candidate for the Degree of

Master Of Science

Thesis: DYNAMIC ANALYSIS OF WINCHESTER DRIVE READ/WRITE HEAD DESIGNS USING THE LASER REFLECTOMETER

Major Field: Mechanical Engineering

Biographical:

Personal Date: Born in Stillwater, Oklahoma, July 29, 1964, the son of Larry T. and Ausma V. Brown.

Education: Graduated from Stillwater High School, Stillwater, in May, 1982; received Bachelor of Science Degree at Oklahoma State University in May, 1987; completed requirements for the Master of Science degree at Oklahoma State University in December, 1988.

Professional Experience: Engineer Trainee, OG&E, Sooner Generating Plant, Red Rock, Oklahoma, 1985, 1986; Research Assistant, School of Mechanical and Aerospace Engineering, Oklahoma State University, 1987-1988.

Professional Organization: Tau Beta Pi, Pi Tau Sigma, American Society of Mechanical Engineers, American Institute of Aeronautics and Astronautics.