OCULAR TORSION DURING LINEAR ACCELERATION IN SPACE

by

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Abstract

Tests were conducted to investigate the effects of weightlessness on otolith function in humans while undergoing linear acceleration. Two subjects were used in the Vestibular Sled on the German Spacelab D1 life sciences experiments. A sled system was used to induce ocular torsion in the subjects by imposing a side to side oscillatory motion on them while keeping the head fixed relative to the shoulders. The tests were repeated at periods prior to weightlessness and twice during weightlessness.

Using a linear accelerometer model for the otolith organs, it is expected that rotational cues induced under constant gravity by the resultant gravito-inertial force would be re-interpreted or subdued during weightlessness. All tests were conducted at two different sled frequencies to investigate the frequency dependence of otolith response.

The results of the D1 experiments are outlined and analyzed. The sensitivity and phase of response relative to input stimulus are found to be consistent with those of earlier tests [Lichtenberg 79], [Arrott 85], [Arrott and Young 86]. Otolith response is reduced during weightlessness in three of the four test sets, but is increased in one subject at low frequency. Sensitivity is significantly higher during high frequency oscillations in comparison to low frequency tests. Sufficient data was not available to provide conclusive evidence of otolith re-interpretation under zero gravity.

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Chapter 1

Introduction

The perception of motion by the human body depends on cues taken from a number of sensory inputs. These cues include visual stimulus, tactile stimulus and signals from the vestibular system. While visual and tactile senses respond to external inputs and can be relatively easy to isolate and investigate, inputs to the vestibular system are generated within the body and are difficult to isolate. The vestibular system is primarily responsible for sensing information about the position and acceleration of the head with respect to the shoulders and for transmitting the sensed signals to the motor system. However, this perception takes place in conjunction with visual and tactile cues. Various studies have investigated the function of the vestibular system by isolating one or more of the sensory inputs.

Two sets of organs are largely responsible for detecting motion in the vestibular system: The semicircular canals and the otolith organs. It has been determined that the semicircular canals detect angular rotation of the head with respect to inertial space, while the otolith organs sense linear accelerations of the head. The response of the vestibular system to linear motion has been investigated subjectively by measuring threshold levels of detection when a subject is undergoing different magnitudes of horizontal linear acceleration under constant gravity [Mach 75], [Young 84], [Jongkees and Groen 46], [Lansberg 54] and [Walsh 62]. Alternatively, it is desirable to obtain a more direct measurement of otolith response without passing through voluntary mechanisms. One method of achieving this is by measuring the involuntary compensatory rotation of the eyeballs when the body is under linear acceleration. This phenomenon is known as ocular torsion, or ocular counterrolling. Ocular torsion is defined as rotation of the eyeballs in a
direction opposite to the leftward or rightward tilted position of the head with respect to the shoulders [Graybiel 52]. Ocular torsion can also be elicited by stimulating the vestibular system in such a way that angular rotation of the head is perceived.

When a person undergoes horizontal linear acceleration under gravity, the gravitoinertial force acting on the head is the resultant of the accelerating force and the pull of gravity. For a time-varying linear acceleration, this combined effect produces pendulum-swing rotation of the gravitoinertial force. Based on the theory of relativity, the otolith organs would not be able to detect the difference between rotation of the gravitoinertial force resulting from rotation of the head, and that resulting from actual motion of the vector itself in space. By isolating input from the semicircular canals (which normally detect angular acceleration), Young and Meiry [Young and Meiry 68] showed that ocular torsion could be produced in vestibular normal subjects when the subjects are placed in a linearly accelerating sled. By fixing the head with respect to the shoulders, it was shown that the observed response resulted mainly from otolith function.

Further tests have been conducted which have determined the response of otolith organs to step accelerations and to various modes of periodic accelerations using the linear sled [Lichtenberg 79], [Arrott 85]. The frequency response of the otolith organs has been investigated by Young [Young and Oman 69] and Arrott [Arrott 85] under constant gravity conditions, during periods of weightlessness resulting from parabolic flight, and after a period of weightlessness [Arrott and Young 86]. These studies showed that ocular torsion is significantly reduced as a result of weightlessness. The first study of otolith response to sinusoidal acceleration input under prolonged weightlessness was conducted by Young and a team from the MIT Man-Vehicle Laboratory with the D1 space shuttle mission. These tests investigated the effect of prolonged weightlessness on ocular torsion at two input frequencies, as well as the duration of these effects after six days of weightlessness. Tests were conducted on two subjects at various times pre-flight, in-flight (weightless condition), and post-flight.
This thesis presents the results and analysis of experiments conducted on human subjects under linear acceleration. Subjects were placed in an upright sitting position on a linear sled designed at the MIT Man-Vehicle Laboratory (see Figure 1-1). The sled was set in sinusoidal linear motion and the response of the subject’s eyes to the input stimulus was observed using photographs taken at a constant firing rate. Under conditions where the gravitational vector is acting vertically downward parallel to the subject’s spine, this motion produces a response in ocular motion similar to that when the head of the subject is rotated relative to the shoulders and in the plane of the face. In experiments conducted by Lichtenberg, Arrott and Young, the amount of rotation of the eyeballs (ocular torsion) was found to depend on the acceleration of the sled, the frequency of motion, and the magnitude of the lateral component of the gravitational vector (g-vector). Based on the results of earlier work, further studies were made to investigate the response of otolith functions under zero gravity conditions, and to determine the effects of frequency of motion on the response.

The results of this and other studies bear significantly on achieving an understanding of the mechanism through which humans adapt to zero-gravity conditions. Such conditions may occur while traveling in a vehicle under non-terrestrial gravitational forces, such as traversing the deck of a space station. It will also assist in explaining the short length of time required for the otolith functions to adapt to changing g-vectors while the body is undergoing linear acceleration. While otolith response is only one of many inputs to the sensory mechanism in perception of motion, it is one of the primary determinants [Lichtenberg 79]. The cues given by the study of ocular counterrolling play an important role in understanding the functions of the vestibular organs, and the interplay between different sensory inputs in humans.

This study presents the results of the D-1 Spacelab Vestibular Schlitten (VS), or sled experiments conducted between March and November 1985 by a team from the MIT Man-
Figure 1-1: Postural setup for the D1 sled experiments.
Vehicle Laboratory. The Introduction provides the basis for the D-1 VS experiments, and for the study of perception of motion in general. Chapter Two reviews current literature on the subject of ocular torsion and provides the physiological basis of otolith adaptation. A model that has been developed to predict the response of vestibular organs is presented. Previous studies on the dynamic response of ocular counterrolling will also be reviewed and their results summarized. Chapter Three describes the Spacelab experiments and the technical specifications of the equipment used as well as the design protocols. Chapter Four explains and justifies the method of analyzing data from the experiments. Chapter Five presents the results of the analysis from the experiments. Chapter Six covers the discussion of the experimental results, and includes an analysis of the limitations of the experimental and analytical procedures. Areas in which further work could be done are pointed out to enable more detailed findings on otolith function to be made.
Chapter 2
Background

The study of the otolith response to dynamic stimulus, and specifically to changes in the magnitude and direction of the gravito-inertial force (GIF) through the head is important in understanding the mechanisms governing the vestibular system as a whole. Various studies have been performed to investigate the response of the sensory system by isolating one or more input stimuli. These include tests performed by B. Lichtenberg [Lichtenberg 79], A. Arrott [Arrott 82], and Young and Oman [Young and Oman 69]. The response of the otolith organs to a stimulus can be detected by measuring induced ocular torsion, the compensatory rotation of the eyeballs of a subject undergoing linear motion in three-dimensional space.

2.1 Gravito-inertial force

When a body is subjected to linear acceleration, the perceived motion is determined by the magnitude and direction of the gravito-inertial force. The GIF is the resultant of the applied force and any other static forces that may be acting upon that body, such as gravity under terrestrial conditions. For an externally applied acceleration, the force experienced by the body acts in a direction opposite to the applied acceleration. Under the constant downward force due to earth gravity, \( g=9.81\text{ms}^{-2} \), a body in horizontal acceleration of \( a \) will experience a net force proportional to \( (g-a) \) and acting in a direction, \( \theta \), away from the vertical depending on the magnitude of acceleration, \( a \). The effect of a horizontal linear acceleration on the GIF is shown in Figure 2-1.

For human subjects undergoing linear acceleration, the coordinate system adopted in this work is identical to that defined by Hixson et al. [Hixson 66], and is shown in Figure
Figure 2-1: The effect of horizontal linear acceleration on the gravito-inertial force (a) under gravity, and (b) under weightlessness.
2.2 Motion sensors

The role of the vestibular organs in motion perception was shown at the turn of the century by Mach [Mach 75]. By comparing the responses of vestibular impaired subjects with those of vestibular normal subjects, Guedry and Harris [Guedry 74] determined that the vestibular detection of motion is predominant over the perception through visual, tactile and other cues. The response of otolith organs in humans to linear acceleration in the presence of visual stimulus has been investigated by Arrott [Arrott 85].

The vestibular system consists of a set of organs within the inner ear as shown in Figure 2-3. The two active organs in motion perception are the semicircular canals and the otolith organs. The semicircular canals are a set of three interconnected fluid-filled tubes located in the temporal bone. The tubes form closed loops which merge within a larger tube, the utricle. The spatial orientation of the canals is such that they lie in roughly mutually orthogonal planes (see Figure 2-4). The sensory element within the canal comprises the cupula and crista, both located within the ampulla. A range of hair cells of the cupula floating in the endolymph fluid transmit motion sensations into the sensory system.

The semicircular canals are responsible for detecting angular accelerations of the head. Directionality of the detection is produced by virtue of the spatial orientation of the tubes to cover the three space dimensions. The ability of the human body to detect the direction of rotation of an applied acceleration would depend upon the combination of semicircular canals being stimulated by the applied acceleration.
Figure 2-2: Coordinate system used in D1 Sled experiments. Adapted from Hixson et al.
Figure 2-3: Schematic diagram of the ear showing the inner ear, semicircular canals and the otolith organs (From Noback, C. and Demarest, R., *The human nervous system: basic principles of neurobiology*).
Figure 2-4: Spatial arrangement of the semicircular canals (From Lindsley, D. and Holmes, E., *Basic human neurophysiology*).
Each ear contains two otolith receptors in humans, one in the utricle and the other in the saccule. The otolith organs are located within the utricular and succular regions of the inner ear. In conjunction with the semicircular canals, these organs provide a means of detecting linear accelerations and changes in vertical orientation of the head [Young and Oman 69]. The sensory maculae consist of hair cells covered by a layer of calcite crystals and are surrounded by endolymph fluid. The density of the crystals is about 2.7 times higher than the surrounding fluid [Guedry 74].

Functionally, the otolith organs behave like linear accelerometers. In the presence of an applied acceleration, the hair cells are set into motion in the less-dense surrounding endolymph fluid. The motion of the hair cells and the otolith membrane is transferred to gelatinous strata containing sensory hairs in the sensory epithelium, the sensory hairs in the epithelium in turn transmit sensory information to receptor cells [Graybiel 52].

2.2.1 Mechanical otolith model

A model to approximate the function of the otolith organs as linear accelerometers was developed by Young [Young and Meiry 68]. A diagram of the model is shown in Figure 2-5. The sensory maculae is modeled as a mass-spring-dashpot system. For a single hair, the calcite crystal is represented by a mass $M$, surrounded by endolymph fluid of density $\rho$. The virtual mass of the crystal and surrounding fluid moving at the same velocity as the crystal-membrane structure is represented by $M'$. Using the proposed model, the otolith organs would not be able to distinguish between the downward vertical force due to gravity, and an equal and opposite upward motion of the body with an acceleration of 9.81 ms$^{-2}$ (g).

Using the above model, the motion of the crystal in an accelerating reference frame is given by Equation (2.1).

$$\ddot{x} + \frac{B}{M'} \ddot{x} + \frac{k}{M'} x = \frac{1}{M'} (M-\rho V)g - acos\theta$$  \hspace{1cm} (2.1)
Figure 2-5: Model of the otolith organs as a linear accelerometer, developed by L. Young.
The hair cells in the otolith organs are free to deflect in any direction over the plane of the otolith membrane. As a result, they are able to detect accelerations in three dimensions.

2.3 Ocular Counterrolling

Under normal terrestrial conditions with gravity acting vertically downward, sensory inputs are taken from the retina and from the vestibular sensory organs when the head is subjected to a change in position or velocity. Signals from the vestibular system are fed to the eye muscles to provide compensatory motion of the eyeballs for stabilization of the visual field. In the case of rotation of the head, the eye compensates for the change in acceleration by rolling in a direction opposite to that of the perceived motion. This compensatory movement of the eyeball is known as ocular counterrolling and is achieved through a combination of muscles around the eyeball. These muscles control rotational ocular motion in the plane of the face and into the head as shown in Figure 2-6.

Ocular counterrolling is observed in response to both step and periodical inputs, classified as static and dynamic ocular counterrolling, respectively. In static ocular counterrolling (SOCR), the eyes respond to a tilt of the head by rotating in a direction opposite to the tilt. The amount of rotation bears a strong relationship to the angle of tilt, as investigated by Kellogg [Kellogg 71]. Ocular torsion was observed to increase with tilt and peak at a point corresponding to a head angle of 60° from the vertical. Beyond this point, the angle of rotation declined significantly for larger angles of tilt as shown in Figure 2-7.

2.3.1 Dynamic response

Ocular counterrolling is also observed when the head is subjected to linear acceleration in inertial space. In contrast with SOCR, in which the head is actually rotated with respect to the shoulders, dynamic ocular torsion fixes the head and stimulates the
Figure 2-6: Muscular arrangement for the control of ocular rotation. (From A. Arrott.)
Figure 2-7: Variation of Ocular torsion with angle of head tilt (from H. Kellog).
otolith organs by rotating the gravito-inertial acceleration vector with respect to the head. The threshold levels of detection of such accelerations were investigated through studies by Meiry [Meiry 65] and Melville-Jones and Young [Melville Jones 52]. Significant differences were observed between the threshold levels of subjects in the upright position subjected to horizontal linear acceleration steps, and those in the same position subjected to vertical acceleration. When subjected to horizontal acceleration, the threshold levels were more consistent, over a range of magnitudes of acceleration and also from subject to subject.

Using the magnitude of ocular torsion elicited by applying a linear acceleration to the body as a means of detecting linear accelerations instead of voluntary judgment of the subject, it has been shown that there indeed exists a relationship between the magnitude of acceleration and the degree of ocular counterrolling [Lichtenberg 79]. Ocular torsion was observed in subjects undergoing horizontal accelerations while positioned in the upright and supine conditions.

2.4 Sled Experiments

The relationship between ocular counterrolling and periodic linear motion of the head has been investigated by Hannen [Hannen 66], Smiles [Smiles 75] and others. Within the constraints of possible frequencies at which human subjects can safely be oscillated (generally less than 1 Hz), these tests revealed that the amplitude of ocular torsion decreased with increasing frequency, while the phase difference between the input signal and the eye motion response was observed to increase directly with frequency. Lichtenberg [Lichtenberg 79] observed a time constant of approximately 3 seconds for the linearized system.

In the upright position under gravity, a subject undergoing left-right linear acceleration in inertial space experiences an acceleration that is a combination of the
imposed force and the force due to gravity. If the imposed acceleration is linear time varying, then the effect of the imposed motion is to produce a rotating force vector with respect to the head of the subject. This rotating g-vector is interpreted as rotation of the head with respect to the shoulders when no other sensory inputs are available in this case, the head is stationary.

Under conditions of zero gravity (weightlessness), however, the resultant acceleration arises from the imposed force alone. For a subject in left-right horizontal motion, the resultant g-vector also changes direction from left to right. The difference between conditions of 1g and those of weightlessness are illustrated in Figure 2-1.

While studies performed by Young [Young 84], Lichtenberg [Lichtenberg 79], and Arrott [Arrott 85] were able to determine the relationship of ocular torsion under sinusoidal input in 1g conditions, the effect of weightlessness on otolith function has not been thoroughly investigated. In particular, the human body has shown rapid adaptation to conditions of zero or fractional gravity. This is not necessarily predictable using a model that is calibrated to terrestrial conditions. Experiments conducted using the MIT sled on board the D1 spacelab provided the opportunity to investigate (1) the effect of prolonged weightlessness on ocular torsion response due to sinusoidal input, and (2) the variation of this effect with time before, during and after days of weightlessness.
Chapter 3
Methodology

3.1 Setup and procedures

The investigation of ocular counterrolling under linear acceleration was conducted using a sled based on the MIT-designed sled facility [Lichtenberg 79], [Arrott 85] by a team led by L. Young and A. Arrott. The Spacelab sled was built according to the specifications of the European Space Agency (ESA). Preflight tests were conducted using this sled at the Johnson Space Center in the US, and at the Spacelab facility in Cologne, Germany. Inflight tests were made on board the space shuttle using identical equipment. The sled is designed to provide sinusoidally varying linear acceleration in the y-z plane of the subject as shown in Figure 3-1. The subject is placed on a seat mounted on a metal frame. The superstructure is supported and guided by two steel rails. Motion of the seat is in the left-right direction with the subject facing forward. The seat is driven through a winch system connected to a torque motor. Control of the motion of the sled and the generation of motion profile signals is obtained by means of a computer.

During the experiment, the subject is seated and the head is strapped to a helmet and secured relative to the shoulders. This ensures that the directionality of the g-vector with respect to the head is fully predictable and maintained. In addition, since the semicircular canals respond to angular accelerations of the head, steps are taken to ensure that the ocular torsion response elicited is not a result of roll motion of the head. Under lateral accelerations of less than 6 ms⁻² (about 0.6g), it has been determined that the inertial force induced by the acceleration is not large enough to produce roll motion of the head while the restraints described above are in place [Lichtenberg 79]. Since all the Spacelab experiments were conducted using sinusoidal oscillations of maximum acceleration
amplitude 1.96 ms\(^{-2}\) (0.2g), it is assumed that the semicircular canals are not sufficiently stimulated during the D-1 linear acceleration tests to adversely affect the lateral acceleration response [Arrott 85]. As a result, any cues of rotation detected in the subject result primarily from the effect of the rotating g-vector on the otolith organs.

The subject is placed in the seat of the sled facing forward. The seat and its structural box frame are moved along the rails by the motor-winch system according to the input profile provided by the computer’s signal generator. In the D1 experiments, all the inputs to the sled were sinusoidal. Limitations on the size of the driving motor and the optimal firing rate of the camera to detect ocular torsion determined the major constraints in the design of the experiment. The experiments were aimed at studying the effects of prolonged weightlessness on the response of the otolith functions at ‘high’ and ‘low’ rates of oscillation of the cart. High frequency was a rate of 0.8 Hertz and low frequency was at 0.18 Hertz. Two sets of tests were conducted using two subjects: The pre-flight tests conducted on ground under gravity prior to weightlessness, the in-flight tests conducted during weightlessness, and the post-flight tests conducted again on ground after a period of weightlessness. All experiments were conducted with sinusoidal motion profile and a peak acceleration of 0.2g of the cart.

Rotations of both eyeballs were monitored simultaneously using a Nikon 35mm F3 camera specially adapted for use in space at the Johnson Space Center with a 55mm lens mounted into the subject’s helmet attachment. The helmet was shrouded around the camera to prevent outside visual disturbances from interfering with ocular torsion. Illumination of the eyes was provided by a ring flash mounted inside the helmet and approximately 15 cm away from the eyes. The ring flash was chosen to minimize any rotational cues that may be apparent to the subject during the test. The subjects were asked to stare down the barrel of the camera for the entire duration of the experiment. The firing rate of the camera was determined to be high enough to prevent aliasing of the eye motion signal. At the
Figure 3-1: View of the ESA sled used in the D1 experiments showing the directions of motion.
maximum sled frequency of 0.81 Hz, this corresponds to a camera firing rate of 1.62 Hz corresponding to the Nyquist frequency, or higher. Two camera firing speeds were used during the D1 experiments. Some runs were shot at 0.256 second intervals while others were at 0.4 second intervals.

Detection and measurement of ocular torsion was facilitated in two ways during the tests. First, since it is difficult to secure the head rigidly during the experiment, the reference points for measuring eye position were taken from the head itself, rather than from the surrounding sled frame. The subject was asked to place a specially molded bite board firmly between his teeth. An extension of the bite board reached up until just below the eyes and bore markings that enabled straight reference lines to be taken as shown in Figure 3-2. Second, contact lenses with reference marks were worn by the subjects. This allowed eye position to be measured even when natural iral landmarks were difficult to obtain. Measurement of ocular torsion requires that a given set of landmarks on the eyeball are tracked throughout a given run of the tests. The amount of slippage between the contact lens and the eyeball is not large enough to introduce significant error in the position readings.

3.2 Subjects

Of nine crewmembers A, B, C, D, E, F, G, H and I used during the D-1 experiments, subjects E and H were selected for the Vestibular Sled tests. The same two subjects were used in both phases of data collection; pre-flight and in-flight. The equipment used in all cases was identical. Subjects were chosen based on vision and balance tests conducted prior to the experimentation to ensure that they had normal vestibular function. Both subjects used in the tests were middle aged males.
Figure 3-2: Arrangement of biteboard for sled subject.
3.3 Sled construction

The MIT sled used in the D-1 experiments consists of a box frame mounted on two circular guide rails. The box frame has a seat for the subject that could be fixed in the upright (y-z) or supine (y-x) positions with respect to the subject for the investigation of different orientations of motion. In this set of experiments, the seat was mounted perpendicular to the rails so that the subject is upright and oscillated from left to right. The box frame cart is attached to the rails through bearings and is driven by a steel cable connected by a winch drum to the torque motor. The rails are two parallel 1 inch (2.54cm) diameter steel rods positioned at a distance of 1.7m from each other. The total length of the rods is 5m and the effective track length of the box cart is 4.7m. The layout and dimensions of the sled are described by Arrott [Arrott 85]. In order to permit some tolerance and adjustment during motion of the sled, one of the rails is rigidly fixed at both ends while the other is fixed at one end only.

Traction of the sled and frame is provided by the winch system described above. The cart is driven by a 3.5 horsepower permanent magnet DC motor. Signals for the motion profiles are provided by a pulse width modulated (PWM) velocity controller. The computer, in combination with a series of digital to analog converters monitors the experimental parameters, generates the desired motion profiles, and activates the camera firing and flash. Using the setup described for a sinusoidal input to the sled, the motion of the sled can be described as shown in Equation (3.1). A sled run consists of 34 motion cycles at 0.8 Hz followed by 8 cycles at 0.18 Hz.

\[
v(t) = \frac{A}{2\pi f_s} \sin(2\pi f_s t) \quad 0 < t < N/f
\]  

(3.1)

A = Peak acceleration
\(f_s\) = sled frequency
N = total number of cycles
The sled used for in-flight experiments was identical to the ground equipment in terms of its major dimensions and characteristics. The space sled was mounted on the floor of Spacelab's aisle within the payload capsule. Other monitoring equipment for the VS-NS 102 experiments including the computer and controllers was also mounted in Spacelab.

3.4 Scanning

Photographs of the eye positions taken during the experiments were processed at the Kodak Laboratories. In cases where lighting was poor, the film was pushed up to three stops during developing to ensure that the iral landmarks could be traced easily. Positive slide images were received as uncut rolls from the developers and each frame was numbered and tagged.

The equipment used to read positions and reference point on the film was a Hermes Senior Film Analyzer originally designed to perform bubble chamber measurements. The analyzer is capable of projecting a 64cm by 64cm image from the 35mm transparent film on a horizontal screen in front of the operator. A planar motion light cursor on the screen allows any position on the image to be targeted and recorded by the analyzer.

An Apple IIe computer linked to the analyzer enables such functions as film advance/rewind and projector selection can be performed from the operator's position. In addition, the Apple computer reads the targeted cartesian coordinates from the light cursor and performs calculations on them to produce the angle between two given points as well as statistical parameters of a given set if data points. The program for performing these routines was developed under the supervision of A. Arrott and is written in BASIC. The complete listings of the programs used in this analysis are given in the Appendix.

When the image of the eye is projected on to the screen, the operator selects a set of two points on each eye as reference marks. The pair of points should be as close to the line
of the diameter of the pupil as possible, and at a reasonable distance apart in order to minimize errors in the calculated slope. The reference points will be maintained throughout a given run. The operator first measures the head angle with respect to the film by taking the coordinates of two points on the fiducial marks of the biteboard. All angles are measured with respect to the fixed axes of the cursor. The fiducial reference points are taken once for each eye and the angle of the head with respect to the film is computed. Using the ural or contact lens marks chosen on the eye, the operator then picks each one of the pair of points alternately four times, resulting in eight single-point readings. The standard deviation of the four measurements corresponding to each point is then calculated. If the standard deviation falls within a predefined range of the mean, the computer proceeds to find the mean measured value of each point and from this calculates the angle between the chosen points and the fiducial marks taken initially. This gives the angle of the eye with respect to the head. The process is repeated for the right and left eye separately, and over the entire run of the experiment.

3.4.1 Calculation of slopes

The procedure for resording and calculating the angle of ocular torsion was developed by A. Arrott [Arrott 85] and is adopted here. If the fiducial points taken have coordinates \((X_0, Y_0)\) and \((X'_0, Y'_0)\), then the slope of the reference line can be obtained from equation (3.2).

\[
T_0 = \tan^{-1} \left( \frac{Y_0 - Y'_0}{X_0 - X'_0} \right)
\]  

(3.2)

The mean positions of the two landmarks chosen on the eye, \((x_{1i}, y_{1i})\) and \((x_{2i}, y_{2i})\), are obtained from equations (3.3) [Arrott 85].
The variance of the slope is given in Equation (3.4).

\[
\sigma^2 = \frac{s_{X_2}^2 + s_{Y_2}^2}{(X_2 - X_1)^2} + \frac{s_{Y_2}^2 + s_{Y_1}^2}{(Y_2 - Y_1)^2}
\]

Using the two mean values of the positions calculated on the eye, the slope or angle of the eye position relative to the coordinate system can be obtained from Equation (3.5).

\[
T_1 = \tan^{-1}\frac{Y_1 - Y'_1}{X_1 - X'_1}
\]

Combining Equations (3.2) and (3.5), the angular position of the eye relative to the head can be obtained as shown in Equation (3.6).

\[
T = T_1 - T_0
\]
Each angular position, together with the corresponding standard deviation of measurement is stored into the computer as it is read.
Chapter 4

Data Analysis

The results of the scanning process are a two-dimensional array with one column containing angular positions and the second consisting of the corresponding measurement standard deviations. The data is first transferred from the Apple IIe system into DOS-readable format, which is more compatible with the signal processing software used for the analysis.

In analyzing the results of the D1 Spacelab experiments, a C language program was used to sort the data from each run into two separate files, each containing the angular positions and measurement standard deviations for one eye only. The files were then manually checked to ensure that errors made during the scanning process were corrected. Repeated measurement points were removed, and absent points were replaced with a special "eye-closed" tag, normally used to signify when a particular eye frame could not be read during scanning. Other scanning information including the dates and roll numbers were removed. Complete code listings developed for this work are given in the Appendix.

4.1 Theoretical Foundation

The variables obtained from the scanning procedure were as follows:

\[\theta_r\] Right eye angular position (degrees)
\[\theta_l\] Left eye angular position (degrees)
\[s_r\] Right eye standard deviation
\[s_l\] Left eye standard deviation

Since the motion profile of the sled and the frequency at which photographs were taken are both known, the time and phase of each set of data points can be deduced. For each frame, the following parameters are defined:
\( t_i \) Time at which photograph was taken.
\( \Phi_i \) Phase of motion stimulus at frame i.
\( (i = 1, 2, 3, ..., N) \)

The phase positions are obtained by assuming that the first frame was photographed at time \( t=0 \), and that the sinusoidal sled motion begins at the end of the sled track as shown in equation (4.1).

\[
y(t=0) = Y \\
y'(t=0) = -\omega^2; \quad Y = 0.2g
\] (4.1)

For simplicity, the following conventions are used during the analysis. Variables are given for one eye only, and are valid for both left and right eyes.

\( t_i \) time at which photograph was taken
\( x_i \) eye position
\( s_i^2 \) measurement variance
\( \Phi_i \) phase
\( (i = 1, 2, 3, ..., N) \)

4.1.1 Offset removal

For each set of \( n \) frames, the constant offset within the ocular positions is removed in order to make the mean position zero. This was done by subtracting the mean eye position from each measurement as shown in Equation (4.2).

\[
x_i = x_i - \frac{\sum_{j=1}^{N} x_j}{\sum_{j=1}^{N} \frac{1}{s_j^2}}
\] (4.2)

The quality of all the photographs as indicated by the magnitude of their standard deviations can be quantified using the harmonic mean of their variances [Arrott 85].
\[ s_h^2 = \frac{N}{\sum_{j=1}^{N} 1_j} \quad (4.3) \]

In order to verify that the dominant frequency of the measured signal corresponds with the stimulus (sled) frequency, the power spectrum of the response was evaluated using the Fourier transform (FFT) (Equation (4.4)).

\[ X = \text{fft}(x) \]
\[ P_{xx} = X \ast X \quad (4.4) \]

The plot of the power spectrum, \( P_{xx} \), against frequency shows a peak at the dominant frequency as illustrated in Figure 4-1.

4.1.2 Filtering

A simple \( M \)-point moving average is used to filter out the low frequencies from the response signal, \( x \). These included the offsets and any drift in eyeball motion that may be present during the test. The number of points, \( M \), used in the averaging corresponds to the minimum number of frames within a single cycle of sled motion. This can be obtained using the camera firing rate, \( f_f \) and the sled frequency, \( f_s \) as shown in equation (4.5).

\[ M = \frac{f_f}{f_s} \quad (4.5) \]

Filtering was employed for the purpose of displaying the response without low frequency noise. The actual data points were not altered during other parts of the analysis.
Figure 4-1: Determination of dominant frequency using the power spectrum, measured in (deg)$^2$. The power spectrum is plotted over the entire frequency range present during the test.
4.2 Calculation of cross-correlation

Assuming that the model of the vestibular system described in Chapter 2 behaves in a linear fashion, the response signal is expected to be sinusoidal also. The sensitivity of otolith response is measured by the ratio of output to input signal amplitudes. The output response can therefore be described in terms of its amplitude and phase, where the amplitude correspond to the sensitivity in degrees per unit lateral acceleration. Since the frequency of the response is known to be equal to that of the stimulus, the most reliable means of measuring the amplitude and phase is by cross-correlating the stimulus with the response.

The analysis method used for cross correlation is based on a derivation by Ljung [Ljung 87]. The time base of the response signal is calculated using the stimulus frequency, $f_s$. The stimulus signal can be formulated as shown in Equation (4.6).

$$ u(t) = a\cos(\omega t), \quad t = 0, 1, 2, ... $$

where

$$ \omega = 2\pi f_s \quad (4.6) $$

The response, $x(t)$, can be predicted in the form of Equation (4.7).

$$ x(t) = aH(e^{i\phi})\cos(\omega t + \phi) + v(t) + \text{transient} $$

$$ \beta = \angle H(e^{i\omega}) \quad (4.7) $$

During the measurement, photographs were begun only after the third stimulus cycle, the transient term in Equation (4.7) can be ignored as a result. The cross-correlation sums are formed from the two signals as shown in Equation (4.8).

$$ P_c(N) = \frac{1}{N} \sum_{t=0}^{N-1} x(t)\cos(\omega t), $$

$$ P_s(N) = \frac{1}{N} \sum_{t=0}^{N-1} x(t)\sin(\omega t) \quad (4.8) $$
Substituting for \( x(t) \) from Equation (4.7) into Equations (4.8), the cross correlation can be simplified into Equation (4.9) as follows using the cosine term of the cross correlation only.

\[
P_c(N) = \frac{1}{N} \sum_{i=0}^{N-1} a H(e^{i\omega}) \cos(\omega t + \beta) \cos(\omega t) + \frac{1}{N} \sum_{i=0}^{N-1} v(t) \cos(\omega t)
\]  

(4.9)

For a large number of sample points, \( N \) (usually \( N>100 \)) and provided the noise term, \( v(t) \) does not contain any harmonics of the stimulus frequency \( f_s \), Equation (4.8) can be approximated by Equation (4.10).

\[
P_c(N) = \frac{a}{2} |H(e^{i\omega})| \cos(\beta)
\]  

(4.10)

Similarly, the sine term of the cross correlation function can be approximated closely to Equation (4.11).

\[
P_s(N) = \frac{a}{2} |H(e^{i\omega})| \sin(\beta)
\]  

(4.11)

Using Equations (4.10) and (4.11), an estimate of the gain and phase between stimulus and response signals can be formulated respectively by Equations (4.12) and (4.13).

\[
H = |H(e^{i\omega})| = \frac{\sqrt{P_c^2(N) + P_s^2(N)}}{a/2}
\]  

(4.12)

\[
\beta_N = -\tan^{-1}\left(\frac{P_c(N)}{P_s(N)}\right)
\]  

(4.13)

Calculation of the gain, \( H \) and the phase, \( \beta \), can be used to construct the response of the vestibular system under linear acceleration. For most of the runs in the D1 experiments, there were at least 200 data points, which puts the above method well within the limits of accuracy desired.
4.3 Justification of procedure

The standard deviation figures provide a useful means of identifying how accurate particular readings are during scanning. Thus when the angle positions are weighted inversely according to their variances, a relative scaling between points can be obtained. This method was used in the previous analysis of SL1 data performed by Anthony Arrott [Arrott 85]. However, using this weighting method means that all the measurements with relatively large standard deviations would have low values during the analysis whereas the true angular position lies within the entire range of the standard deviation. Since there is no means of determining whether the true position lies above or below the measured mean, the use of variance weighting was discarded during the analysis. For presentation purposes, error bars are indicated on the charts to indicate the actual range of values for the angular position.

4.3.1 Replacement of bad data points

During the experiments, there were instances in which the subject blinked while a photograph was being taken, or in the case of the post-flight runs, the subject was drowsy and not able to keep his eyes open throughout the experiment. Such measurements were read as bad data points during the scanning process, and were labeled with a special code for the analysis. The same code was used to represent points that could not be accurately read by the scanner due to poor lighting of the eye or poorly detectable iral landmarks.

During the analysis, these points were taken into account by replacing each bad point with the nearest good point that was an integral number of stimulus cycles away. The number of points per cycle was found using Equation (4.5), and a short Matlab macro was employed to determine the nearest good point and insert both the eye position and standard deviation of the good measurement at the bad one. In this way, accuracy of the analysis and the cross correlation was not severely compromised when there was a large number of bad points.
4.4 Error estimates of the cross correlation method

The variance of calculation of the gain and phase using the cross correlation method was calculated as shown in Equation (4.14). The method used is similar to that given by Arrott [Arrott 85], with the exception that the variance of measurement, \( s_1^2 \), is not used in this instance.

\[
S_H^2 = \sum_{i=1}^{N} \left[ \frac{\partial H}{\partial x_i} \right]^2
\]

\[
= \sum_{i=1}^{N} \left[ \frac{1}{P_c^2 + P_s^2} \right] \frac{1}{N} (P_c \cos \phi_i + P_s \sin \phi_i)^2
\]

\[
S_B^2 = \sum_{i=1}^{N} \left[ \frac{\partial B}{\partial x_i} \right]^2
\]

\[
= \sum_{i=1}^{N} \left[ \frac{(P_c \cos \phi_i + P_s \sin \phi_i)}{P_c^2 + P_s^2} \right] (4.14)
\]

The above equations give an estimate of the accuracy and consistency of the calculated gain and phase values.
Chapter 5

Results

5.1 Format

Using the cross-correlation method, values of gain and phase were obtained for each of the experimental runs. The phase values were used to deduce the relative phase of the response to the stimulus cycle by plotting all the sample points over a single period [Arrott 85]. The gain, or sensitivity, gives a measure of the maximum ocular torsion evoked per unit acceleration using an input amplitude of 0.2g, while the phase indicates the lag between stimulus and response measured in degrees. The units of sensitivity are degrees per g.

Motion of the sled to the right implies that the GIF vector is directed to the left. This will produce ocular torsion in the counterclockwise direction. The value of phase obtained is representative of the time interval between the maximum acceleration of the sled (maximum displacement) and the maximum torsion of the eyeball during each cycle. Positive phase values mean that the sled motion leads the eye motion by the ratio of the phase to the total period of oscillation. The precise relationship used to obtain the time interval between stimulus and response for a given phase angle $\beta$ is given in Equation (4.13). $T_s$ is the period of oscillation of the sled.

$$\tau = \frac{\beta}{360^\circ} T_s$$

Ocular torsion for a representative run of the experiment is shown in Figure 5-1. The upper plot is the input sinusoid measured in units of acceleration, g. The lower plot is the variation of ocular torsion over time, measured in degrees. Direct response, or linearity, is
apparent between the two signals, especially when the initial transients and scanning errors are accounted for. A cubic spline was used to smooth the response in order to obtain a closer approximation to ocular motion.

The results for the two subjects, E and H, are compared for the various parameters monitored during the tests. These parameters are the left and right eye variations, frequency variations, and pre-flight and in-flight results.

5.2 Eye to eye variations

The results for the left and right eyes of each subject are compared in Table (eye-to-eye). Values of gain are the average readings pre-flight and in-flight.

5.3 Frequency variations

Tests conducted at high frequency (0.8Hz) and low frequency (0.18Hz) were used to determine the effects of input frequency on the response. From Table 5-I, it can be seen that the response at low frequencies was generally lower than that at high frequency for both subjects. This variation can be attributed to the longer time available during low frequency runs which permits greater drift motion of the eyeballs.

5.4 Pre-flight and in-flight sensitivity

The pre-flight test results showed that gain was greater under terrestrial conditions than during weightlessness. This was true for both high and low frequency tests on Subject H and for the high frequency tests of Subject E. An increase in sensitivity was observed for subject E at low frequency (see Figure 5-3). Data was taken at both high and low frequencies and in both of the subjects. The results of the remaining test runs at different points prior to launch and during launch are depicted in Figures 5-2 to 5-5.
Figure 5-1: Representative plot of ocular response to linear acceleration. The sampling points have been folded into a single cycle to reveal the dominance of the stimulus frequency.
Table 5-I: Variation of sensitivity in left and right eyes for both subjects. Gain is measured in degrees of eye rotation per unit lateral acceleration.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Right eye gain (deg/g)</th>
<th>Left eye gain (deg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High freq. preflight</td>
<td>3.5837</td>
<td>3.9988</td>
</tr>
<tr>
<td>High freq. inflight</td>
<td>3.0400</td>
<td>2.3500</td>
</tr>
<tr>
<td>Low freq. preflight</td>
<td>1.0977</td>
<td>0.3817</td>
</tr>
<tr>
<td>Low freq. inflight</td>
<td>3.2410</td>
<td>0.9570</td>
</tr>
<tr>
<td>Subject H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High freq. preflight</td>
<td>1.1272</td>
<td>1.1483</td>
</tr>
<tr>
<td>High freq. inflight</td>
<td>0.4435</td>
<td>0.6307</td>
</tr>
<tr>
<td>Low freq. preflight</td>
<td>1.5010</td>
<td>1.2196</td>
</tr>
<tr>
<td>Low freq. inflight</td>
<td>.5258</td>
<td>.5005</td>
</tr>
</tbody>
</table>

5.5 Phase variations

The folded plots for some sample runs are shown in Figures 5-6 to 5-9. A description of the folding procedure is given by A. Arrott [Arrott 85]. The angle of best fit to reproduce a cosine shape is the phase angle between the motion stimulus and the response. The plots are made for the input sinusoid at the calculated phase of the response signal. The solid line represents the input signal, while the scatter plot is the response data points.
Subject E
High Frequency Sled
$s = 0.2g$, $f_s = 0.8Hz$

Right eye
Left eye

Figure 5-2: Variation of gain over time prior to launch and during weightlessness for subject E at high frequency.
Subject E
Low Frequency Sled
\( a = 0.2g, f_s = 0.18Hz \)

Figure 5-3: Variation of gain over time prior to launch and during weightlessness for subject E at low frequency.
**Subject H**

High Frequency Sled

\[ a = 0.2g, \quad f_s = 0.8Hz \]

Figure 5-4: Variation of gain over time prior to launch and during weightlessness for subject H at high frequency.
Figure 5-5: Variation of gain over time prior to launch and during weightlessness for subject H at low frequency.
Figure 5-6: 'Folded' data for Subject E. Ocular torsion response is plotted as a function of relative phase difference between the input and response at high frequency.
Figure 5-7: ‘Folded’ data for Subject E. Ocular torsion response is plotted as a function of relative phase difference between the input and response at low frequency.
Figure 5-8: 'Folded' data for Subject H. Ocular torsion response is plotted as a function of relative phase difference between the input and response at high frequency.
Figure 5-9: 'Folded' data for Subject H. Ocular torsion response is plotted as a function of relative phase difference between the input and response at low frequency.
5.6 General Results

The values obtained from all the scanned and analyzed results to date is given in Table 5-II.

<table>
<thead>
<tr>
<th>Subject E, High Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day ((L = \text{Launch}))</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>L-217</td>
</tr>
<tr>
<td>L-217</td>
</tr>
<tr>
<td>D0 (day 1)</td>
</tr>
<tr>
<td>D5 (day 6)</td>
</tr>
<tr>
<td>D5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-217</td>
</tr>
<tr>
<td>L-217</td>
</tr>
<tr>
<td>D0</td>
</tr>
<tr>
<td>D5</td>
</tr>
</tbody>
</table>

**Table 5-II:** Results of gain and phase for subject E. *Abnormally high gain values were obtained where large sections of data were not scannable.

5.7 Experimental accuracy and errors

The results were consistent in their values and agreed with previous studies performed by A. Arrott [Arrott 85], B. Lichtenberg [Lichtenberg 79], and L. Young [Arrott and Young 86]. The large errors in many of the test measurements can be attributed to the difficulties in maintaining the chosen ural landmarks during scanning. Small errors in these measurements would lead to large variations in the angle readings due to the magnitude of ocular torsion present. Although these errors were reduced by keeping the standard deviation of measurement below 4°, they produced the most significant errors in the results.
Subject H, High Frequency

<table>
<thead>
<tr>
<th>Day (L=launch)</th>
<th>Right eye Gain (deg/g)</th>
<th>Right eye Phase (deg)</th>
<th>Left eye Gain (deg/g)</th>
<th>Left eye Phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-256</td>
<td>0.86</td>
<td>34</td>
<td>0.84</td>
<td>68</td>
</tr>
<tr>
<td>L-254</td>
<td>1.41</td>
<td>16</td>
<td>1.39</td>
<td>31</td>
</tr>
<tr>
<td>L-254</td>
<td>0.48</td>
<td>49</td>
<td>2.13</td>
<td>40</td>
</tr>
<tr>
<td>L-217</td>
<td>1.15</td>
<td>21</td>
<td>0.69</td>
<td>30</td>
</tr>
<tr>
<td>L-217</td>
<td>1.26</td>
<td>77</td>
<td>1.1</td>
<td>1</td>
</tr>
<tr>
<td>L-204</td>
<td>0.50</td>
<td>85</td>
<td>0.52</td>
<td>80</td>
</tr>
<tr>
<td>L-204</td>
<td>0.37</td>
<td>46</td>
<td>0.44</td>
<td>42</td>
</tr>
<tr>
<td>L-195</td>
<td>0.46</td>
<td>54</td>
<td>1.26</td>
<td>74</td>
</tr>
<tr>
<td>L-194</td>
<td>1.76</td>
<td>50</td>
<td>1.61</td>
<td>48</td>
</tr>
<tr>
<td>D5 (day 6)</td>
<td>0.44</td>
<td>85</td>
<td>0.63</td>
<td>84</td>
</tr>
</tbody>
</table>

Low Frequency

<table>
<thead>
<tr>
<th>Day (L=launch)</th>
<th>Right eye Gain (deg/g)</th>
<th>Right eye Phase (deg)</th>
<th>Left eye Gain (deg/g)</th>
<th>Left eye Phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-256</td>
<td>2.13</td>
<td>19</td>
<td>2.76</td>
<td>26</td>
</tr>
<tr>
<td>L-256</td>
<td>1.95</td>
<td>33</td>
<td>1.79</td>
<td>76</td>
</tr>
<tr>
<td>L-254</td>
<td>0.92</td>
<td>30</td>
<td>0.91</td>
<td>84</td>
</tr>
<tr>
<td>L-217</td>
<td>2.84</td>
<td>44</td>
<td>0.67</td>
<td>43</td>
</tr>
<tr>
<td>L-217</td>
<td>1.67</td>
<td>63</td>
<td>1.65</td>
<td>25</td>
</tr>
<tr>
<td>L-204</td>
<td>0.27</td>
<td>56</td>
<td>0.24</td>
<td>49</td>
</tr>
<tr>
<td>L-204</td>
<td>0.72</td>
<td>30</td>
<td>0.77</td>
<td>32</td>
</tr>
<tr>
<td>L-194</td>
<td>1.96</td>
<td>58</td>
<td>2.79</td>
<td>60</td>
</tr>
<tr>
<td>D5 (day 6)</td>
<td>0.53</td>
<td>14</td>
<td>0.50</td>
<td>17</td>
</tr>
</tbody>
</table>

**Table 5-III**: Results of gain and phase for subject H.

The inconsistency in phase measurements can be attributed to inaccuracies in determining the exact point over the run at which initial transients die off completely. The frequency response is meaningful only within the steady state region.

Although the study conducted by B. Lichtenberg [Lichtenberg 79] determined that head roll was not significant at lateral accelerations less than 0.6g, these tests were not performed on the ESA equipment used during the D-1 Spacelab experiments. There is a
possibility that head roll did indeed have an effect on the measured ocular torsion. It would be necessary to obtain measurements of head roll for the D-1 data also in order to determine upper bounds of head motion that occurred during those tests.

Another source of inconsistency in the results was the fact that only two sets of comparable measurements were obtained during weightlessness. Moreover, the nature of the voyage was such that both subjects were exhausted during the runs, and this resulted in a significant number of lost data points, particularly for subject E.
Chapter 6

Discussion

The Young model of otolith organs as linear accelerometers outlined in Chapter 2 of this thesis leads to the hypothesis that otolith function would be affected by weightlessness because they are normally subjected to a constant downward acceleration due to gravity. Based on this, the inflight data was expected to indicate that perception of linear acceleration in space would be reinterpreted in terms of the new surrounding environment. The results of the tests were also expected to provide clues on the mechanism by which adaptation to weightlessness takes place. The wide discrepancies between the various tests, and in some instances the inconsistencies between similar tests make it difficult to develop the evidence in support of this hypothesis. The procedure of using still photographs to track eye movements and later scanning and analyzing the results raises the possibility of measurement errors significantly. Using a method that provides better sampling of the output signal at smaller time intervals as well as a means of assimilating and analyzing the results directly, possibly in real time, would allow for greater control over errors and greatly enhance the results.

For both subjects, the sensitivity to linear acceleration was reduced on the first day of weightlessness compared to the preflight ground tests. Comparison between the first and fifth days of weightlessness, while inconclusive because of the small number of data points available, appears to indicate a further reduction in ocular torsion response with increasing duration of weightlessness. Post-flight tests were not conducted for the D1 mission, but these results complement the findings of Young and Arrott [Arrott and Young 86] during the spacetlab 1 Vestibular Tests. Those findings indicated that otolith response sensitivity is reduced immediately following weightlessness, and increases gradually in the days
following. The D1 results confirm that response is indeed reduced during weightlessness, and that the reduction in sensitivity begins soon after leaving normal gravity conditions.

Reduction in response during weightlessness indicates that otolith tilt cues are reinterpreted when the gravito inertial force undergoes nearly instantaneous reversal in direction, as was the case during sled runs. In part, the variation between results may be attributed to inconsistent signals being fed from the otolith organs into other parts of the sensory system.

The frequency tests of otolith response to linear acceleration suggest that the otolith functions are more sensitive to higher frequency oscillations than to lower frequencies. However, aberrations in the results, as well as the small number of data points available for examination render these findings inconclusive.

The current results could be improved by employing a band filter instead of the high pass filter used for this analysis. This would provide cleaner signals for comparison and possibly improve the values of sensitivity obtained. A Fourier transform could also be used to verify the results from the correlation method, since the frequency of interest is known. At the time of writing, complete results of the analysis for all the preflight and inflight tests have not been obtained. Addition of these results will provide a broader basis for comparison and allow for better fit to be obtained between data sets.
Appendix A
Sample Results

Figures A-1 to A-8 show some typical patterns of ocular response to linear acceleration at sled frequencies of 0.8Hz (high) and 0.18Hz (low).
Figure A-1: High frequency plots for subject E. The upper plot is the sled acceleration and the lower is the ocular torsion response.
Figure A-2: High frequency plots for subject H. The upper plot is the sled acceleration and the lower is the ocular torsion response.
Figure A-3: Low frequency plots for subject E. The upper plot is the sled acceleration and the lower is the ocular torsion response.
Figure A-4: Low frequency plots for subject H. The upper plot is the sled acceleration and the lower is the ocular torsion response.
Figure A-5: Preflight fitted sinusoid for subject E. The upper plot is the sled acceleration and the lower is the ocular torsion response.
Figure A-6: Preflight fitted sinusoid for subject H. The upper plot is the sled acceleration and the lower is the ocular torsion response.
Figure A-7: Inflight fitted sinusoid for subject E. The upper plot is the sled acceleration and the lower is the ocular torsion response.
Figure A-8: Inflight fitted sinusoid for subject H. The upper plot is the sled acceleration and the lower is the ocular torsion response.
Appendix B

Computer Programs

The following is a listing of the computer programs used in the analysis of ocular torsion data. Sort.c is the C-language code used to sort the data into separate files for the left and right eyes. The other programs are MATLAB codes used to perform filtering, cross-correlation and curve-fitting.

B.1 Program Sort.c

/* This program takes as input the raw data from Ocular Torsion */
/* Experiments and transfers the data into four new files; R1 and R2 */
/* contain the eye angles and standard deviations for the right eye */
/* while L1 and L2 contain those for the left eye. The input file */
/* should contain only measured values and frame numbers. */

FILE *fp,*fopen();
N16 nblines,i,j;
fp=fopen(filnam,"r");
j=0;
while (fscanf(fp,"%8x",i) != EOF) j=j+i;
fclose(fp);
*/
#include "stdio.h"

main()
{
    char input[20];
    int i, k, n;
    float r_ang, r_dev, l_ang, l_dev;
    FILE *infile, *r1, *r2, *l1, *l2;

    printf("Enter the name of input file: ");
    scanf("%s", input);

    infile = fopen(input, "r");
    if (infile == (FILE *) NULL) {
        printf("Could not open file - %s - for input\n", input);
    }
exit(1);

*/

printf("Enter the names of output files:\n\n");
printf("Right eye positions:\n ");
scanf("%s", R1);
printf("Right eye S.D.s \n ");
scanf("%s", R2);
printf("Left eye positions:\n ");
scanf("%s", L1);
printf("Left eye S.D.s \n ");
scanf("%s", L2);
*/

r1 = fopen("ra.dat", "w");
r2 = fopen("rs.dat", "w");
l1 = fopen("la.dat", "w");
l2 = fopen("ls.dat", "w");

printf("\n\n sorting %s....\n", input);
n=0;
while(fscanf(infile, "%d", &i) != EOF)
{
    printf("%d\n", i);
    fscanf(infile, "%f%f%d%f%f", &r_ang, &r_dev, &k, &l_ang, &l_dev);
    fprintf(r1, "%f\n", r_ang);
    fprintf(r2, "%f\n", r_dev);
    fprintf(l1, "%f\n", l_ang);
    fprintf(l2, "%f\n", l_dev);
    n += 1;
}
printf("\n...Done. %s has %d points.\n", input, n);

fclose(infile);
fclose(r1);
fclose(r2);
fclose(l1);
fclose(l2);
B.2 Matlab Programs

% This is the main routine for determining the transfer function and
% phase difference of OCR data. The user is prompted for the method of
% analysis; (cross-correlation, fourier or both) and the results are
% stored in separate files for each eye.

!sort;

% load the sorted files into matlab as variables
load ra.dat;
load rs.dat;
load la.dat;
load ls.dat;
fprintf('
All files loaded.

Fs = input('Sled Freq (Hz): ');
Fp = input('Frame Freq (Hz): ');

% fprintf('

Select a method of analysis:
')
% fprintf(' 
[1] Cross-correlation
[2] Fourier
[3] Spectral (both)
[0] Quit

)c = input('Enter selection and hit <CR> : ');

while(c ~= 1 & c ~= 2 & c ~= 3 & c ~= 0)
  fprintf('Please enter 1, 2 or 3')
  c = input('Enter selection and hit <CR> : ');
  if c == 0,
    break
  end
end

c=1;
if c == 1,
  clg, subplot(211)
  M = max(size(la));
  fprintf(' ******* RIGHT EYE *******
  correl2(ra(10:M),rs(10:M)',Fs,Fp);
  fprintf(' ******* LEFT EYE *******
  correl2(la(10:M),ls(10:M)',Fs,Fp);
  % print('linus')

  return;
elseif c == 2
  fprintf(' *******RIGHT EYE*******
  fourier2(ra',f,rs');
}
fprintf(' *******LEFT EYE*******
')
fourier2(la',f,ls');
return

elseif c == 3
fprintf(' *******RIGHT EYE*******
')
analyze(ra',f,rs');
fprintf(' *******LEFT EYE*******
')
analyze(la',f,ls');
return
else
return
end
function [H,B] = correl2(xl,s,Fs,Fp)
%CORREL cross-correlation macro to perform analysis of scanned
% data using the method shown in A. Arrott's thesis.
% The raw angles are first filtered and offsets removed.
% Input values are the angle positions, phase stimulus
% and the corresponding variances.
% x1=ocular pos.; s=std. dev.; Fs=sled freq; Fp=Picture freq.

g = 0.2; % Sled acceleration = 1.96m/s^2 = 0.2g
f = Fp/Fs; % Find # of frames per cycle; Fp=2.5Hz or 3.84Hz

[x, s] = inter(xl, s, Fs, Fp);

x = scanfilt2(x, s, Fs, Fp);

s = ones(x); %Test: no weighting
s2 = s.*s;

t=1/Fp;
N = max(size(x));
T = [0:t:(N-1)*t];

u = 2*pi*Fs*T;

T2=0:.1:max(T);
x2=spline(T,x,T2);
plot(T,x,'+',T2,x2,T,cos(u)+5),
grid
xlabel('Time (s)')
ylabel('Torsion (deg)')

pc = x.*(cos(u));
ps = x.*(sin(u));
pcs = pc./s2;
pss = ps./s2;
m = sum(s2.^2);
ic = sum(pcs)/m;
is = sum(pss)/m;
H = 2*sqrt(ic*ic + is*is)/g;
b = -atan(is/ic);
B = 180/pi*b;
fprintf('Gain = %g deg/g\n', H)
fprintf('Phase shift = %g deg\n', B)
title('Ocular torsion')
clg
P = acos(cos((u+b)/2));
plot(2*P,cos(u+b),'o',2*P,x,'+')
title('Fitted Sinusoid'),xlabel('Relative phase (deg)'),ylabel('Torsion')
print('medea')
%clg
save trans-funct H B T x
B.4 Filtering program

function x2 = scanfilt(x,s,Fs,Fp)

%SCANFILT Function to perform offset removal and filtering of input
%signal. R is the range of points to be used in filtering (R=ff/fs)
%

f=Fp/Fs;

s = ones(x); %Test: no weighting
s2 = s.*s;
rs = s2.\1; %convert s.d to variance, find reciprocal
xrs = x.*rs;
os = sum(xrs)/sum(rs);
x1 = x - os;
N = max(size(x));
st = N/sum(rs);

%Filtering

R = fix(f); %find no. of points for filtering
M = fix((R+1)/2);
x0 = [zeros(1,M) x1 zeros(1,M)];
r0 = [zeros(1,M) rs zeros(1,M)];

for i = (M+1):(N+M)
    k = 1;
    for j=(i-M):(i+M)
        w(k) = x0(j).*r0(j);
        v(k) = r0(j);
        k = k+1;
    end
    x2(i) = x0(i) - sum(w)/sum(v);
end
if f==2.56/.8,
    x2=1.22\times x2(M+1:N+M);
else
    x2=1.03\times x2(M+1:N+M);
end
save filtered_data x2
B.5 Interpolation program

function [q, s] = inter(Q,S,f,fp)
%This function replaces missing data points
%within an array with the value of the next valid
%point at the same phase.

q = Q;
s = S;
m = max(size(Q));

s = ones(q); % Test: no weighting

if f == 0.8,
    if fp == 2.5, % Set the phase length, depending on
        k=25; % the sled and frame freqs.
    elseif fp == 3.84,
        k=24;
    end
else
    if f == .18,
        if fp == 2.5,
            k=14;
        elseif fp == 3.84,
            k=21;
        end
    else
        fprintf('error: unspecified sled frequency');
    end
end

% Perform first pass to remove "eye closed" points

for i=1:(m-k),
    n=0;
    while abs(q(i+n*k)) > 180 & (i+(n+1)*k)<m,
        q(i+n*k) = q(i+n*k+1);
        s(i+n*k) = s(i+n*k+1);
        n=n+1;
    end
    if abs(q(i)-q(i+1)) > 10,
        q(i) = q(i+k);
        s(i) = s(i+k);
    end
end

for i=(m-2*k):m,
n=0;
while abs(q(i+n*k)) > 180 & (i+(n+1)*k)<m, 
  q(i+n*k) = q(i+n*k-1); 
  s(i+n*k) = s(i+n*k-1); 
  n=n+1;
end
if abs(q(i)-q(i-1)) > 10, 
  q(i) = q(i-k); 
  s(i) = s(i-k);
end

%run through again to check
if q(1) > 180 | abs(q(1)-q(2))>15, 
  q(1) = q(1+k);
end
for i=2:m, 
  if q(i) > 180, 
    if i>k & abs(q(i)-q(i-1))>10, 
      q(i) = q(i-k); 
      s(i) = s(i-k);
    end
    if i<(m-k) & abs(q(i)-q(i-1))>10, 
      q(i) = q(i+k); 
      s(i) = s(i+k);
    end
  end
end
save interpolated q s
BASIC Program used for scanning. Developed by A. Arrott.

LOAD DIGITIZER CHECK
LIST

10 XB = PEEK (49313) ; XT = PEEK (49314) ; IF (V) = 1B + 25b * XT
20 XB = PEEK (49315) ; XT = PEEK (49316) ; IF (X) = 25b * XT
30 PRINT X(0) ; Y(0)
40 GOTO 10

LOAD EYEPALL-1-MOD2
FILE NOT FOUND

LOAD EYEPALL-1-MOD2
LIST

5 DIM X(100) ; Y(100) ; Z(100)
7 PRINT "X = "; X
9 Y = 12 ; Z = 2.125865
11 A = C = S = "A" ; BEG = D = "C" ; C = "I"
13 S = "A" ; Tofilens = "***"
15 S = A + S
17 LET FN = 2 ; A = A + (180 / PI)
30 PRINT "FILE NOT FOUND"
40 PRINT "OPEN F:OO" ; PRINT ":CLOSE F:"
40 INPUT "DATE (MMDD): " ; TOD; A = 274 ; GOSUB 135 ; IF F = 1 THEN GOTO 40
50 IF LEN (OD) < 7 THEN PRINT "MISSING, TRY AGAIN" ; GOTO 40
60 PRINT "TIME (HHMM): " ; TIM; A = T; GOSUB 135 ; IF F = 1 THEN GOTO 50
70 PRINT "ROLL #? " ; ROL; A = R ; GOSUB 135 ; IF F = 1 THEN GOTO 70
80 PRINT "ROLL LABEL? " ; ROLL; A = R ; GOSUB 135 ; IF F = 1 THEN GOTO 80
90 PRINT "SCANNER #? " ; SCAN; A = S ; GOSUB 135 ; IF F = 1 THEN GOTO 80
90 PRINT
95 FILE = "F" + A + B
97 PRINT D$ := "OPEN" ; FILE
99 PRINT D$ := "CLOSE" ; FILE
110 PRINT D$ := "APPEND" ; FILE
115 PRINT D$ := "WRITE" ; FILE
120 PRINT DT$; PRINT TI$; PRINT RN$; PRINT RL$; PRINT SCR$
125 PRINT D$
130 K = PEEK (49312)
135 INPUT "FRAME#": FR$; AF$ = FR$; GOSUB 185: IF F = 1 THEN GOTO 155
140 HOME : HTAB 17: PRINT FR$
145 HTAB 1: VTAB 2: PRINT "PLEASE ZERO THE DIGITIZER": PRINT "AND CHECK USING FLAG '1 7'
150 O$ = "FID1": PRINT O$: VTAB 2
155 F = 0: IF LEN(AF$) = 0 THEN F = 1: PRINT : PRINT "PLEASE ENTER A NON-
160 ZERO VALUE"
170 RETURN
180 FOR J = 1 TO 0: STEP -1
190 B(J) = 0
200 IF B(J) = 2 AND J < 0 THEN B(J) = 0: GOTO 270
210 B = B - 2: J = J
220 NEXT J
230 RETURN
300 B = PEEK (49312)
305 IF B = 0 THEN DACK = 1: GOTO 340
310 YB = PEEK (49313): IT = PEEK (49314): I1(U) = YB - 256 + IT
315 XB = PEEK (49315): X1(U) = PEEK (49316): X1(U) = XB + 256 = X1
320 GOSUB 190
325 IF WJ = J AND B(J) = 1 THEN DACK = 0: GOSUB 500
330 GOSUB 400
335 IF E(R) = -1 THEN DACK = 0: PRINT "ACKNOWLEDGE ERROR"
340 KE$ = (49152)
345 IF KE$ = "FID1": VTAB 2: FID 1 = 1 TO 5: PRINT KE$: NEXT: E(R) = 0
350 KE$ = PEEK (49152)
355 IF KEY > 128 THEN VTAB 2: HTAB 1: VTAB 2: PRINT FL$; R = PEEK (49153): GOSUB 300: FL$ = "0"
360 DACK = 1
370 GOTO 300
400 F = VAL (FR$): IF F = 1: FR$ = STR$ (F)
410 HOME : HTAB 17: PRINT FR$
415 GOTO 450
420 F = VAL (FR$): IF F = 1: FR$ = STR$ (F)
425 HOME : HTAB 17: PRINT FR$
430 F = 1: FCDD = 0: F1 = 0: F2 = 0: PRINT "FID1": VTAB 2
435 GOTO 450
440 HTAB 1: VTAB 2: INPUT "CORRECT FRAME#": FR$
445 HOME : HTAB 17: PRINT FR$: GOSUB 800
450 XBAR = 0: ZBAR = 0
455 F = 1: FCDD = 0: F1 = 0: F2 = 0: PRINT "FID1": VTAB 2
460 RETURN
500 IF FL$ = 28 THEN VTAB 2: IF X(U) > (512 + TO) OR X(U) < (512 - TO)
OR Y(O) > (SIZ + T0) OR Y(O) < (SIZ - T0) THEN GOSUB 630:ERR = 1
506 IF FLX = 2B AND ERR = 1 THEN HTAB 1: VTAB 2: PRINT "ZERO-CHECK FAILED, IF REPEATED": PRINT "FAILURE. SEE SUPERVISOR":FLX = 0: GOTO 570

510 IF FLX = 2B THEN GOSUB 600:FLX = 0: GOTO 570
515 IF F = 1 THEN X(F) = X(O):Y(F) = Y(O)
520 IF F = 2 THEN X(F) = X(O):Y(F) = Y(O):PODD = 1:F1 = 0:F2 = 0
525 IF POOD THEN X1BAR = XBAR + X(O):Y1BAR = YBAR + Y(O):S1X = S1X + X(O):S1Y = S1Y + Y(O):S2 = S2
530 IF POOD THEN S# = "12": VTAB 2: A1(F1) = X(O): Y1(F1) = Y(O): F1 = F1 + 1: GOTO 555
535 X2BAR = XBAR + X(O):Y2BAR = YBAR + Y(O):S2X = S2X + X(O): S2Y = S2Y + Y(O)
540 IF POOD THEN S# = "12": VTAB 2: A2(F2) = X(O): Y2(F2) = Y(O): F2 = F2 + 1
545 POOD = ABS (POOD - 1)
550 F = F + 1
555 GOSUB 600
560 RETURN
565 VTAB 2: HTAB 1: PRINT S#: PRINT S#: PRINT S#
570 PRINT BE#: HTAB 1: VTAB 2
575 PRINT C#: HTAB 2: RETURN
580 VTAB 2: HTAB 1: FOR A = 1 TO 5: PRINT BE#: NEXT : VTAB 2: HTAB 1
585 RETURN
590 PRINT D#: "APPEND" #5
595 PRINT D#: "WRITE" #5
600 PRINT PR#: PRINT ANGLE: PRINT SAMPLE
605 PRINT D#
610 P = 2: POOD = 1:F1 = 0:F2 = 0
615 C# = "11":
620 HME : HTAB 17: PRINT PR#
625 X1BAR = X1BAR + 0:X2BAR = 0:Y2BAR = 0
630 S1X = S1X: S1Y = S1Y: S2 = S2
635 GOSUB 600
640 RETURN
645 ZRCK = 0
650 IF FL# = "C" THEN GOSUB 1000: RETURN
655 IF FL# = "CB" THEN HOME : HTAB 17: PRINT PR#: GOSUB 600: RETURN
660 IF FL# = "E" THEN GOSUB 700: RETURN
665 IF FL# = "ED" THEN GOSUB 900: RETURN
670 IF FL# = "N" THEN GOSUB 950: RETURN
675 IF FL# = "RFA" THEN GOSUB 720: RETURN
680 IF FL# = "1 7" THEN FL# = 29: RETURN
685 IF FL# = "CHFR" THEN GOSUB 430: RETURN
690 IF FL# = "LO" THEN GOSUB 1200: GOTO 1400
695 PRINT "ILLEGAL FLAG": VTAB 2: HTAB 1: RETURN
700 F = F - 1: IF POOD THEN P2 = F2 - 1: C# = "12":
705 IF POOD THEN X2BAR = X2BAR + A2(F2):Y2BAR = Y2BAR + Y2(F2):S2X = S2X + X2(F2):S2Y = S2Y + Y2(F2):PODD = 1:
710 GOTO 925
715 IF NOT POOD THEN F1 = F1 - 1: C# = "11":
720 IF NOT POOD THEN X1BAR = X1BAR - X1(F1):Y1BAR = Y1BAR - Y1(F1):S1X
\[
X_1(F_1) = X_1(F_1) * Y_1(F_1) + Y_1(F_1) * Y_1(F_1)
\]

925 FODD = ABS(FODD) - 1
927 GOSUB 600
930 RETURN
950 P = P + 1: IF FODD THEN PRINT "12": GOTO 960
955 IF NOT FODD THEN PRINT \"11\"
960 FODD = ABS(FODD) - 1
965 RETURN
1000 X1BAR = X1BAR / F1: Y1BAR = Y1BAR / F1
1005 X2BAR = X2BAR / F2: Y2BAR = Y2BAR / F2
1010 S1X = (S1X - F1 * X1BAR - 2) / (F1 - 1) : S1X = ABS(S1X) : S1X = SGR(S1X)
1015 S1Y = (S1Y - F1 * Y1BAR - 2) / (F1 - 1) : S1Y = ABS(S1Y) : S1Y = SGR(S1Y)
1020 S2X = (S2X - F2 * X2BAR - 2) / (F2 - 1) : S2X = ABS(S2X) : S2X = SGR(S2X)
1025 S2Y = (S2Y - F2 * Y2BAR - 2) / (F2 - 1) : S2Y = ABS(S2Y) : S2Y = SGR(S2Y)
1035 VTAB 7: PRINT \"IFL \" : F1R N = 0 TO P1 - 1: HTAB 6: PRINT X1(N):
\"; Y1(N): NEXT
1040 PRINT : PRINT \"AVG \" : X1BAR: \"; Y1BAR: HTAB 22: PRINT X2BAR: \"; Y2BAR
1045 PRINT \"STD \" : S1X: HTAB 14: PRINT S1Y: HTAB 22: PRINT S2X: HTAB 29: PRINT S2Y
1047 IF (X2BAR - X1BAR) = 0 THEN THE = PI / 2: GOTO 1075
1050 MBAR = (Y2BAR - Y1BAR) / (X2BAR - X1BAR)
1055 REM SMBAR = (MBAR + 2) * (S2X - 2 + S1X - 2) + (S2Y - 2 + S1Y - 2)
1060 REM SMBAR = SMBAR / (X2BAR - X1BAR) + 2: SMBAR = SGR(SMBAR)
1065 THE = ATN(MBAR)
1070 IF MBAR < 0 THEN THE = THE + PI
1072 A1 = SY1 * 2 + S2Y * 2: A2 = SX1 * 2 + S2X * 2
1080 SANGLE = SANGLE / ((X2BAR - X1BAR) - 2 + (Y2BAR - Y1BAR) - 2)
1085 SANGLE = SGR(SANGLE)
1088 IF (XF(2) - XF(1)) = 0 THEN HEADANG = PI / 2: GOTO 1098
1090 FID = (YF(2) - YF(1)) / (XF(2) - XF(1))
1095 HEADANG = ATN(FID)
1097 IF FID < 0 THEN HEADANG = HEADANG + PI
1098 THE = THE - PI / 2: HEADANG = HEADANG - PI / 2
1100 ANGLE = THE - HEADANG
1105 ANGLE = FN RTD(ANGLE)
1110 HEADANG = FN RTD(HEADANG)
1115 THE = FN RTD(THE): THE = FN RTD(THE)
1120 SANGLE = FN RTD(SANGLE): SANGLE = FN RTD(SANGLE)
1130 PRINT : PRINT \"HEAD ANG \"; THE; \" DEG"
1135 PRINT \"EYE WRT FILM \"; THE; \" DEG"
1140 PRINT \"EYE WRT HEAD \"; SANGLE; \" DEG"
1145 PRINT \"STD ANGLE \"; SANGLE; \" DEG"
1150 S1X = (S1X * S1X) * (P1 - 1) + P1 * (X1BAR - 2): SY1 = (SY1 * SY1) *
(P1 - 1) * P1 * (Y1BAR) ^ 2
1160 SX2 = (SX2 * SX2) * (P2 - 1) + P2 * (X2BAR) ^ 2; SY = (SY * SY) * 
(P2 - 1) + P2 * (Y2BAR) ^ 2
1170 X1BAR = X1BAR * F1; Y1BAR = Y1BAR * F1
1180 X2BAR = X2BAR * F2; Y2BAR = Y2BAR * F2
1190 RETURN
1200 HOME
1205 INPUT "TIME OUT (HHMM)? "; TF$
1210 PRINT D$; "APPEND"FI$
1215 PRINT D$; "WRITE"FI$
1220 PRINT EN$; PRINT DT$; PRINT TP$;
1225 PRINT D$
1230 PRINT D$; "CLOSE"FI$
1232 GOSUB 600
1235 VTAB 2; HTAB 1; PRINT "BYE"
1240 RETURN
1300 LET EC = PEEK (222)
1302 IF EC < > 133 THEN GOTO 1300
1305 IF EC = 133 THEN VTAB 2; PRINT "DIVISION BY ZERO IN SLOPE"; PRINT
"CALCULATIONS, PLEASE REJECT"; PRINT "FRAME AND REMEASURE POINTS"
1307 ERR = 1
1310 GOTO 340
1320 VTAB 2; PRINT "UNANTICIPATED ERROR, CODE "; EC
1330 STOP
1410 END
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