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**GYROSCOPIC TESTING OF ACCELEROMETERS  
TO DETERMINE CONING ANGLE**

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## I. Introduction

Accelerometer usage at the Ballistic Research Laboratory ranges from measuring in-bore projectile accelerations<sup>1</sup> to monitoring relative phase between liquid oscillations and cylinder positions in a three-degree-of-freedom flight simulator.<sup>2</sup> An interesting application was made by the Raytheon Company when they mounted an accelerometer off the central axis of a Carco table (gyroscope) and calculated components of acceleration through rigorous mathematical techniques.<sup>3</sup>

However, in-flight measurements of fast and slow precession for spin-stabilized projectiles currently include only yawsonde data to track yaw and spin histories.<sup>4</sup> The yawsonde is basically used to determine if the yaw is growing. Yawsondes employ two optical sensors to determine the motion of the projectile with respect to the sun. The data are telemetered to a ground station. The raw yawsonde data are a series of pulses (positive and negative) that measure times at which the optical sensors are aligned with the sun. These data yield a solar aspect angle (Sigma-N) (Figure 1) and the Eulerian roll rate of the projectile (Phi-Dot) (Figure 2).<sup>5</sup> The yawsonde is restricted to use during nearly cloudless weather and also has limitations on the relative position of the sun and on firing azimuth and QE.

The yawsonde gives a planar representation of the yawing motion about the trajectory. Although this representation is planar, the projectile is at an angle of attack roughly equal to the sum of the peak magnitudes of the fast and slow motion. By filtering the trajectory and slow mode, the fast mode planar representation can be obtained (dotted line, Figure 3). The demodulation of this motion is representative of the fast mode amplitude (solid line, Figure 3). Other yawsonde data have been reduced by this method and display fast mode damping with yaw induction, negligible fast mode motion, and slow mode damping.

To supplement the yawsonde data, an on-board accelerometer could also provide insight into projectile flight characteristics. An accelerometer might be used to determine spin rates, yaw rates, and amplitudes of motions. In addition, acceleration data could be collected in any kind of lighting or firing conditions.

## II. Description of the Experiment

To show that this method has the potential to supplement the yawsonde, simple mathematical derivations and laboratory experiments were carried out to see if the angle of attack could be correctly verified in a laboratory gyroscope.

### 1. Physical Setup

The mechanical portion of this project involved the mounting of a sensitive, crystal, AC accelerometer (see Appendix) in the canister of a gyroscope (Figure 4).<sup>6</sup> The axis of the accelerometer was centered perpendicular to the vertical axis of the canister 14.6 cm ( $5\frac{3}{4}$  in) above the pivot center (Figure 5). A dense sponge material with a small cavity to hold the accelerometer was used to mount the device in the top of the cylinder. The coning

plate, located at the bottom of the apparatus, predetermined the coning angle (Figure 6). In addition, a slip ring at the top of the gyroscope enabled the accelerometer signal to be connected to a signal analyzer. This signal analyzer provided an ICP current through these same two input and output lines to power the accelerometer (Figure 7). The gyroscope was equipped with two optical sensors. One measured the inertial spin and the other the inertial coning of the gyroscope. Two frequency counters provided a visual output of each frequency. The spin was limited to 30 Hz and the coning was limited to 13 Hz to avoid fixture vibrations.

## 2. Constraints

Figure 8 represents the geometric configuration of the accelerometer in the gyroscope. This representation is only useful for earth-fixed, single-mode, coning motion where the accelerometer is placed on the spin axis with the sensitive axis oriented perpendicular to the long axis of the projectile ( $l$ ). It does not include components for off-axis accelerometer placement, epicyclic motion, or coriolis forces. In essence, only centripetal acceleration is under consideration.

## 3. Geometrical Interpretation

The following three basic equations are used:

$$|\vec{a}_r| = r(2\pi\dot{\phi}_1)^2 \quad (1)$$

$$|\vec{a}_m| = |\vec{a}_r| \cos\alpha \quad (2)$$

$$\alpha = \sin^{-1} \left( \frac{r}{l} \right) \quad (3)$$

where:

$ \vec{a}_m $	= magnitude of maximum acceleration along sensitive axis of accelerometer
$ \vec{a}_r $	= magnitude of maximum acceleration along r
$r$	= radius of circular motion of accelerometer
$\alpha$	= coning angle
$l$	= length from the accelerometer to the gimbal axis
$\dot{\phi}_1$	= earth-fixed inertial coning rate (Hz)

Raw voltage output is converted to  $|\vec{a}_m|$  by:

$$|\vec{a}_m| = \frac{(g)(\sqrt{2})(S)}{cal} \quad (4)$$

where:

$cal$  = calibration of accelerometer (milli-volts/g)  
 $S$  = accelerometer output (rms milli-volts)  
 $g$  = gravitational conversion factor

Eq. (3) is then solved in terms of the coning rate and measured acceleration:

$$\alpha = \frac{1}{2} \sin^{-1} \left( \frac{|\vec{a}_m|}{(2)(l)(\pi\phi_1)^2} \right) \quad (5)$$

### III. Output

Most spin-stabilized projectiles have the spin and yaw rotations in the same directional sense (prograde motion). Since the accelerometer is on the spinning frame, responses from the accelerometer for circular, single-mode, prograde motion occur at a frequency:

$$f = p - \dot{\phi}_1 \quad (6)$$

where:

$p$  = earth-fixed inertial spin rate (Hz)  
 $f$  = frequency of response with respect to body-fixed frame (Hz)

The typical spectrum output of the accelerometer is shown in Figure 9. The response occurs at the expected  $f = p - \dot{\phi}_1 = 11.63$  Hz. The amplitude of this response represents the peak acceleration in mVrms resulting from the sensitive axis aligned toward the center of rotation (along  $r$ , Figure 4).

### IV. Discussion

Table 1 represents data from six spin and coning sets at a constant coning angle of 1.97°. The estimated error for this angle is 0.10%. This angle was mechanically measured using a cathometer and dial indicators.

Table 1. Data with 1.97° Coning Plate.

Counter readings		Analyzer readings					
$p$ (Hz)	$\dot{\phi}_1$ (Hz)	$p - \dot{\phi}_1$ (Hz)	$f$ (Hz)	$S$ (mVrms)	$ \ddot{a}_m $ (m/s <sup>2</sup> )	$r_{calc}$ (m)	$\alpha_{calc}$ (deg)
29.1	10.0	19.13	19.13	142.1	19.5	0.0050	1.96
28.8	8.3	20.50	20.75	98.3	13.5	0.0050	1.95
26.04	10.8	15.24	15.13	175.0	24.0	0.0052	2.05
19.86	8.2	11.63	11.63	98.7	13.6	0.0051	1.99
17.64	12.6	5.05	5.13	240.7	33.1	0.0053	2.08
13.55	9.3	4.25	4.25	125.2	17.2	0.0050	1.98

The differences between the coning plate angle and  $\alpha_{calc}$  give a probable error of 2%. There are three sources of inaccuracy in the mechanical setup of the accelerometer. First, the accelerometer was not rigidly fixed within the cavity. Any unrestrained movement of the accelerometer within the cavity causes variations in the output. Second, the vertical height ( $l$ ) was measured with a straight edge. And third, the manufacturer's precision in the calibration was not completely correct. It is expected that a more stable and measurable mount would provide more accurate results. Table 2 shows the uncertainty in each term.

Table 2. Uncertainty in Variables.

Variable	Uncertainty
$cal$	$\pm 1$ mV/g
$l$	$\pm 0.508$ cm
$S$	$\pm 1.0$ mVrms
$\dot{\phi}_1$	$\pm 0.2$ Hz

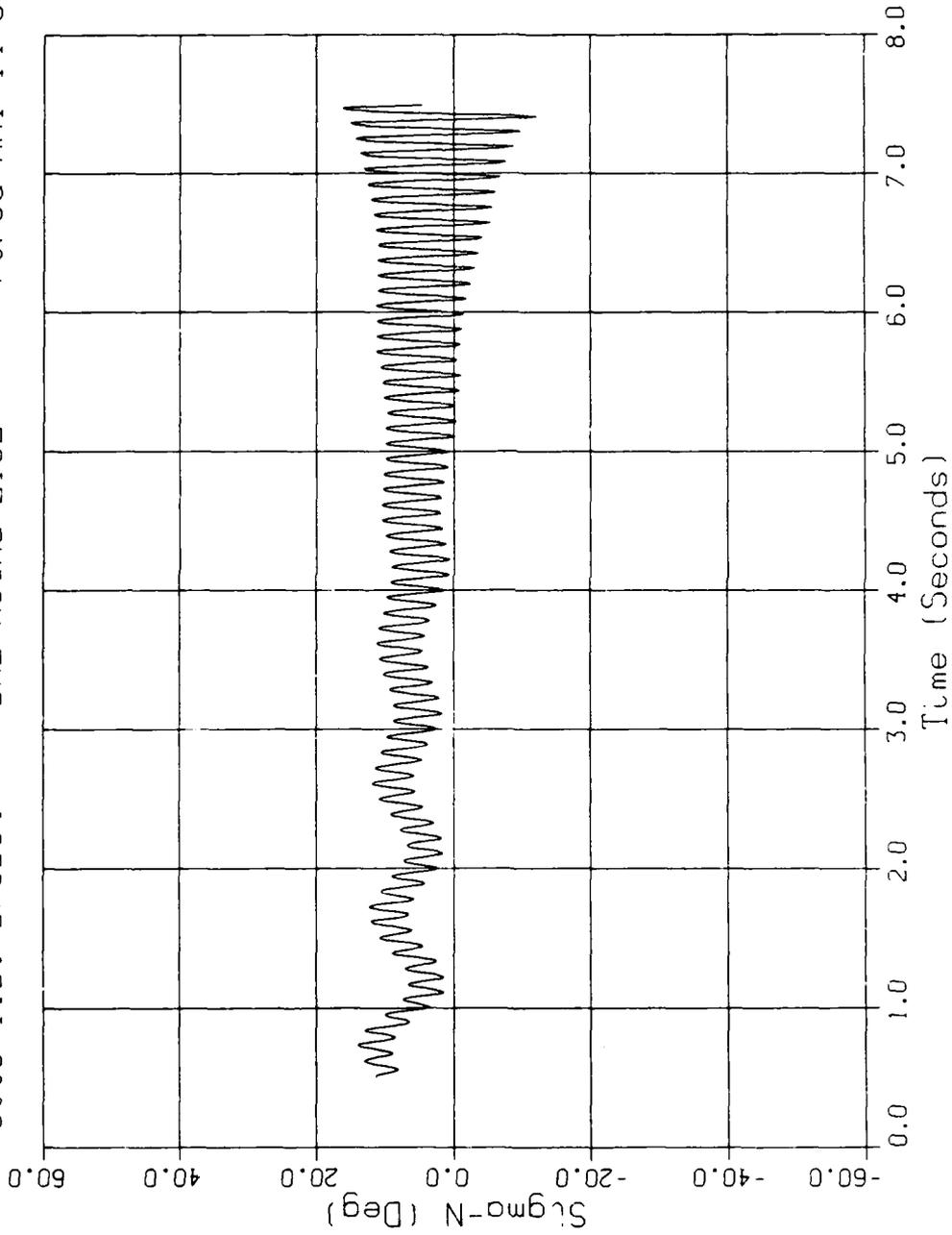
The uncertainties in the elements listed in Table 2 combine in the propagation of error technique to determine an uncertainty in  $\alpha_{calc}$  of 6%. Thus the true error in  $\alpha_{calc}$  is estimated to be between 2 and 6%. The propagation of error also shows that the estimated error of 6%, in the present experiment, can be significantly reduced by a more accurate determination of  $\dot{\phi}_1$  and  $l$ .

## V. Conclusion and Recommendations

The experiment showed that using simple geometrical principles, accelerometers can accurately measure the coning angle on a gyroscope. In this laboratory experiment, the accelerometer can measure the coning angle to within 6% of its actual value. The inaccuracies that were generated in the setup may not occur when the accelerometer is actually mounted on a more suitable fixture. The Ballistic Flight Simulator can be used to provide complex motions required for more advanced laboratory testing. Experience must be gained in determining which method is better for finding fast and slow mode rates found

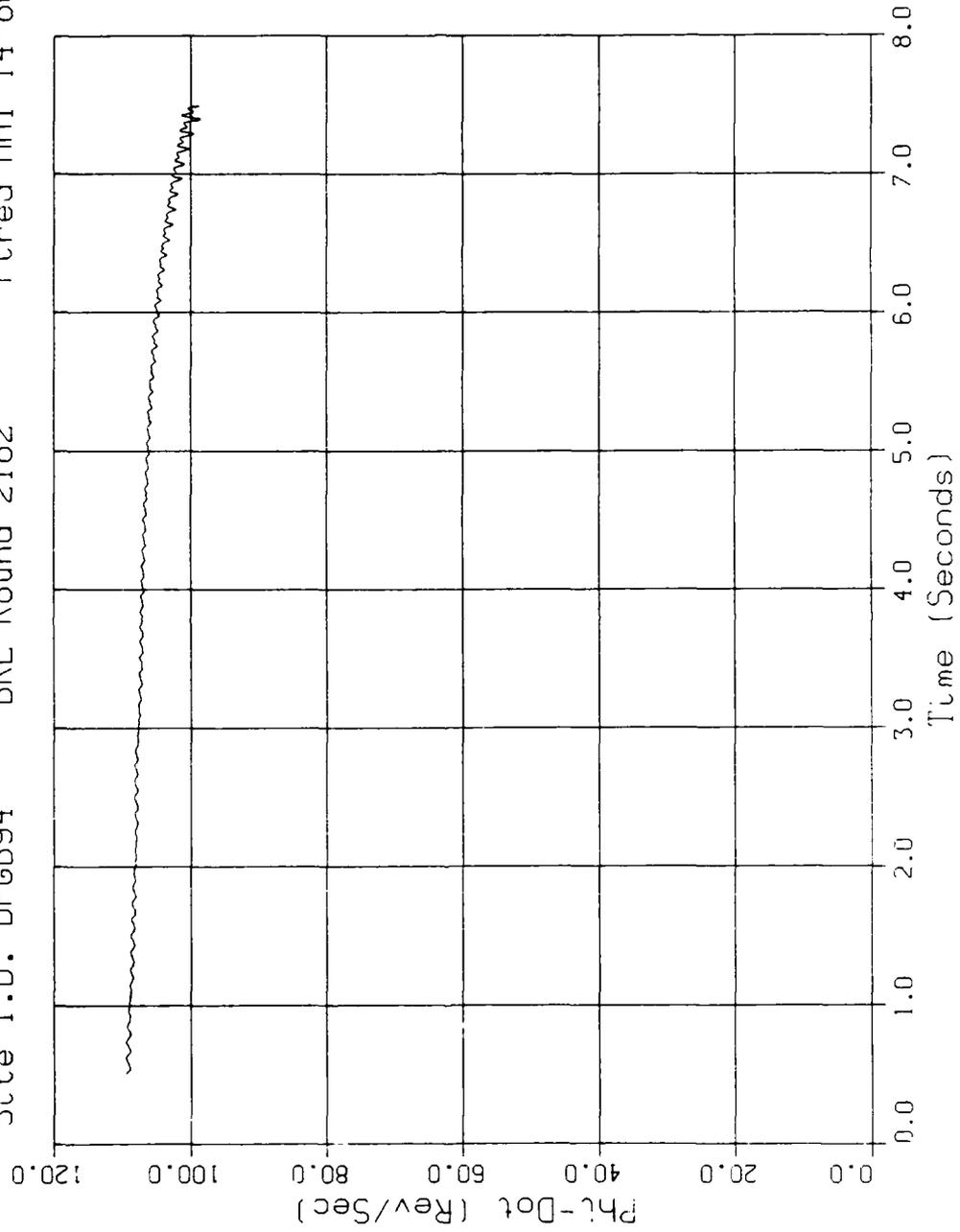
in actual flight cases. Flight testing of the device may be required to determine additional problems with the measurement technique, including launch failure or calibration variation, effects of coriolis and dynamic range of instrumentation required to effectively yield both fast and slow mode rates and a wide range in yaw amplitudes. This method of measuring yaw rates and amplitudes has the potential to be used in conjunction with or in place of the yawsonde.

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**Figure 1.** Sigma N versus time for DPG B94 M825 PIP for low QE and transonic launch with yaw induction

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**Figure 2.** Phi dot versus time for DPG B94 M825 PIP for low QE and transonic launch with yaw induction

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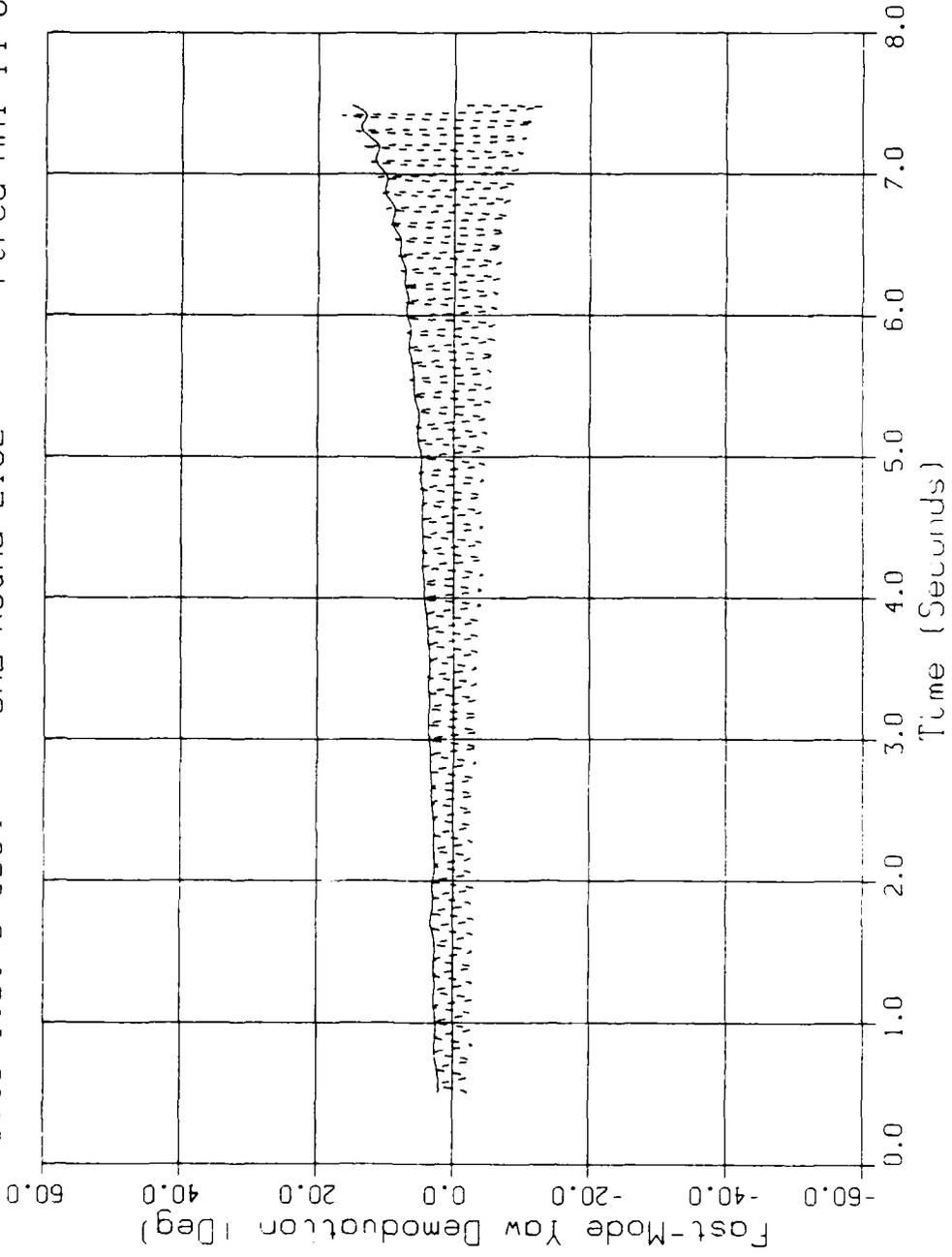


Figure 3. Fast mode yaw demodulation of DPG B94 (0.5-7.5 sec.).

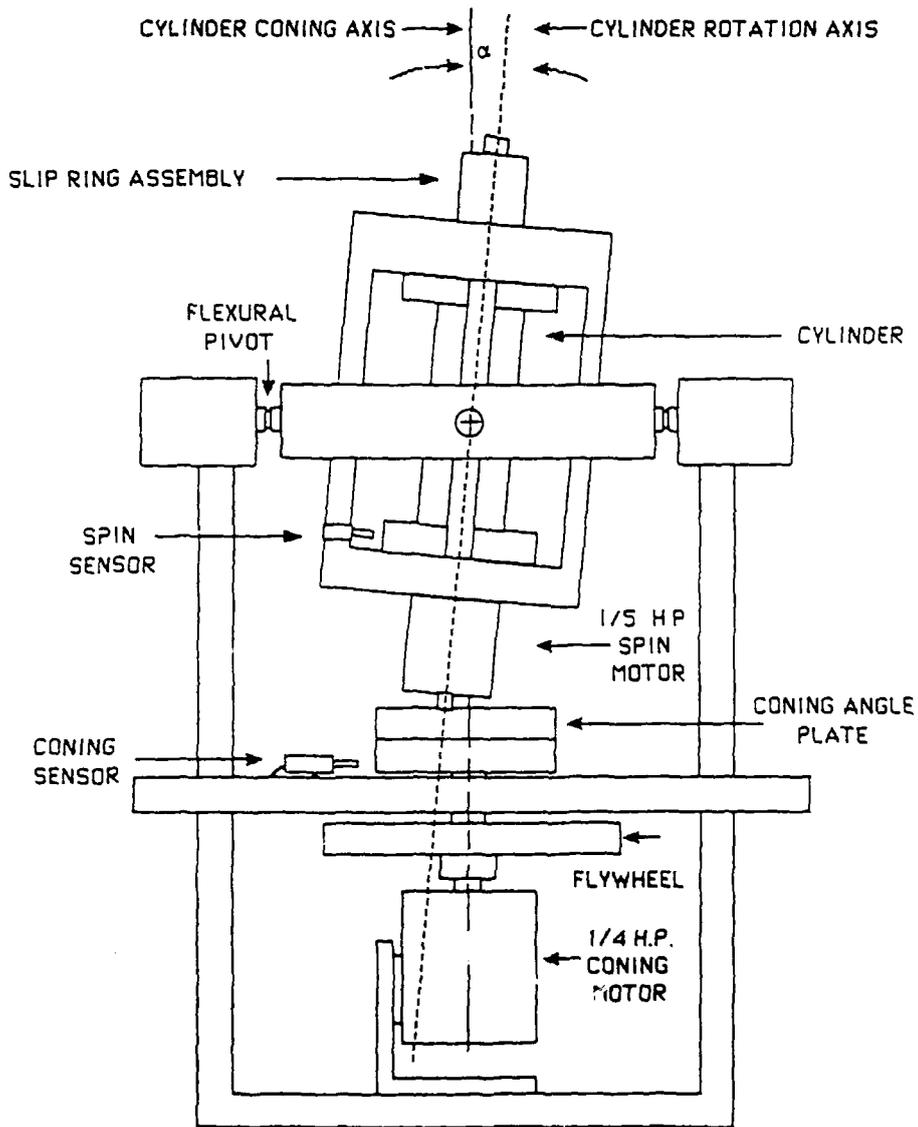


Figure 4. Forced precession gyroscope apparatus.

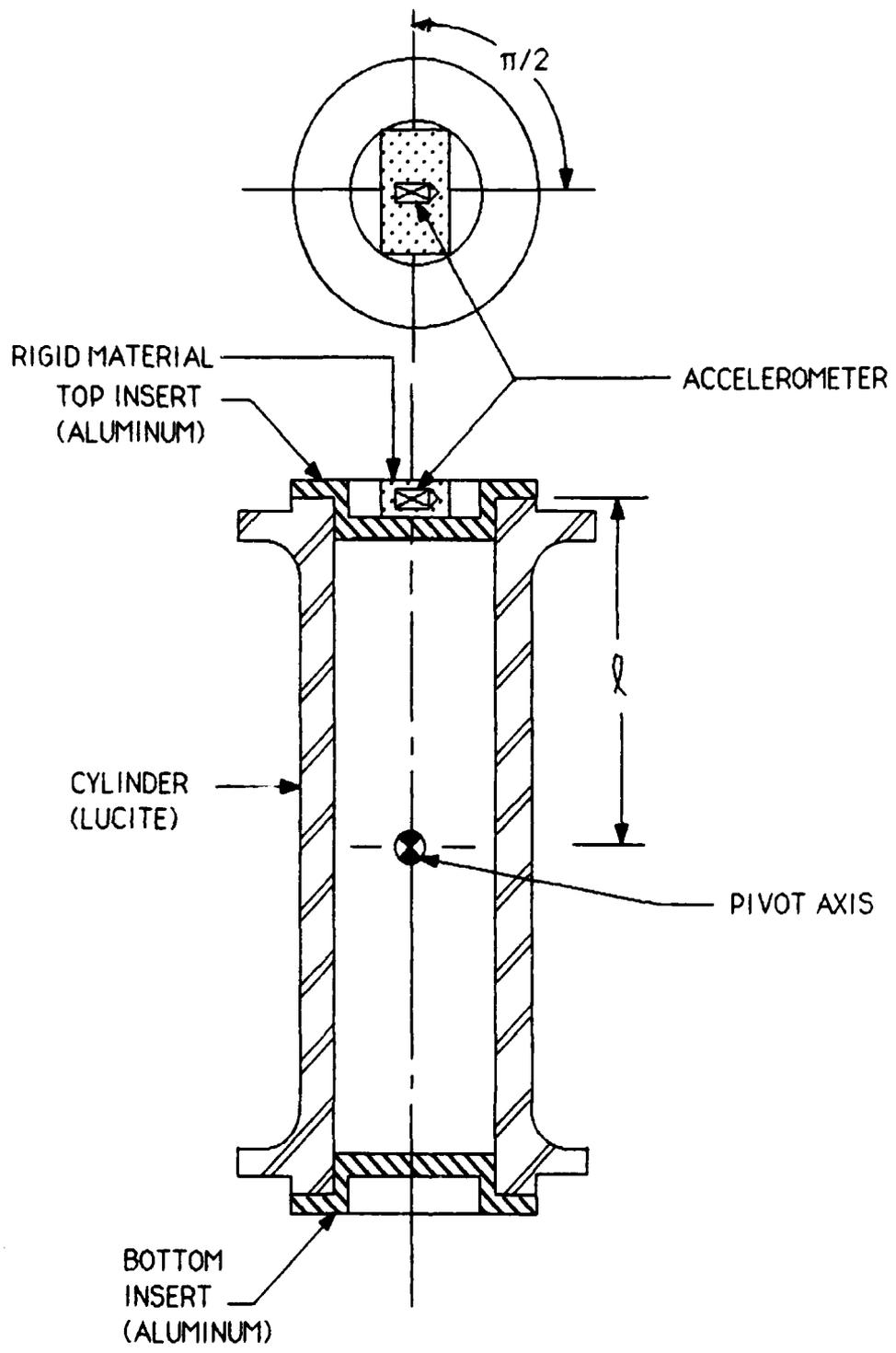


Figure 5. Location of accelerometer in cylinder.

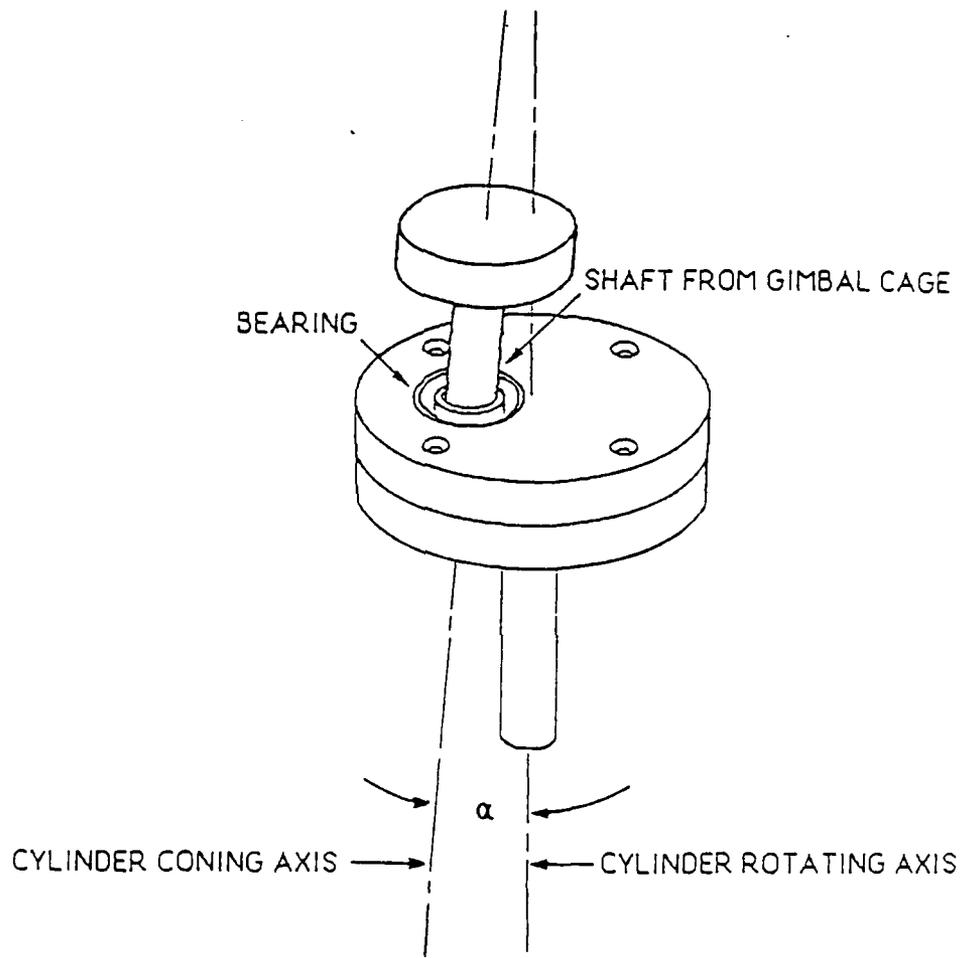


Figure 6. Predetermined coning angle plate.

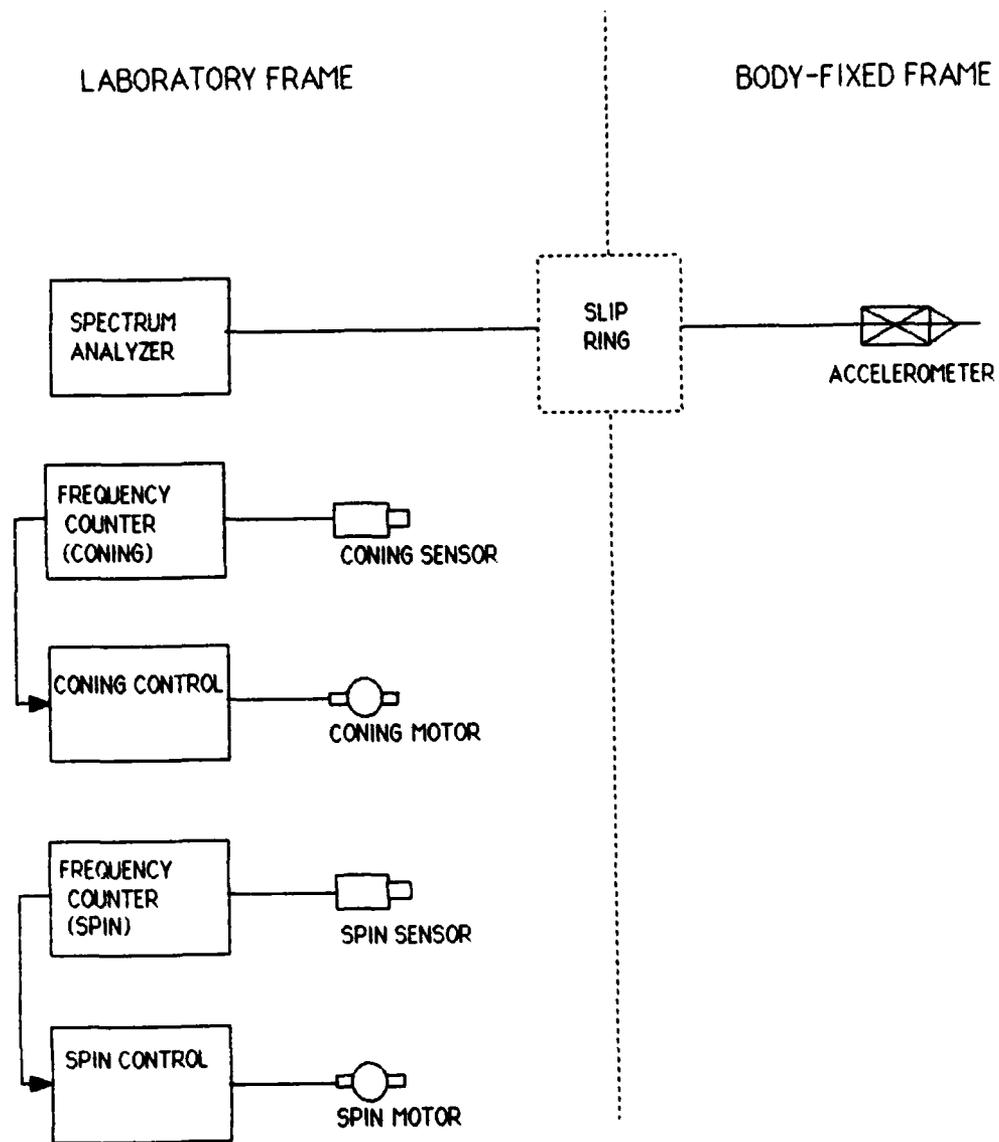
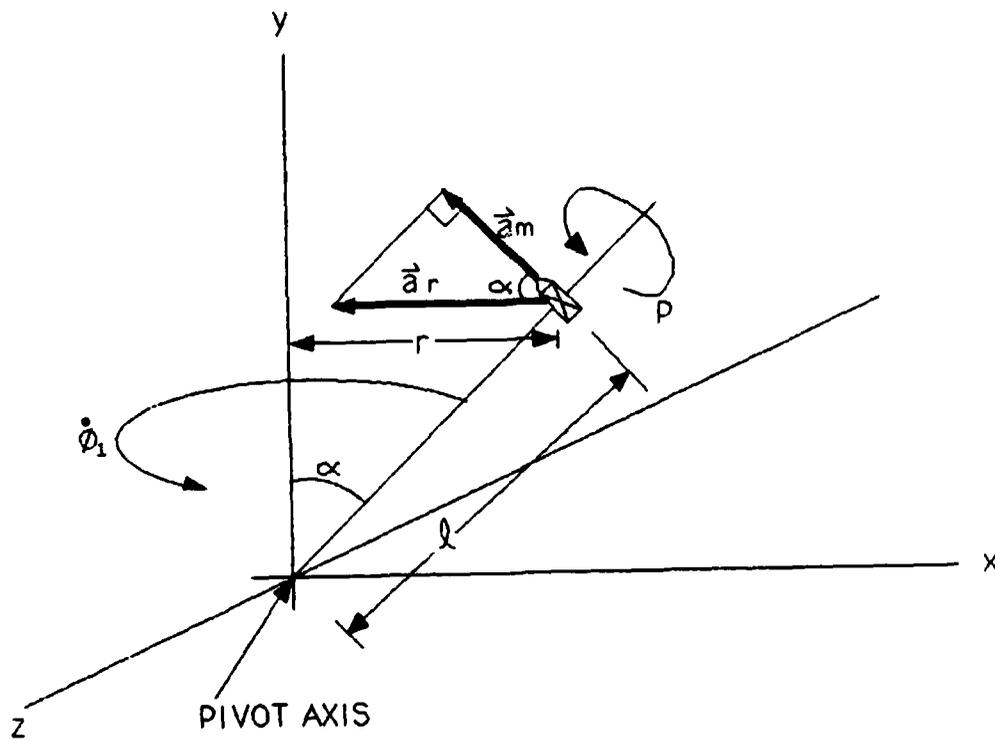


Figure 7. Block diagram of setup.



**Figure 8.** Acceleration components at  $|\vec{a}_m|$  max.

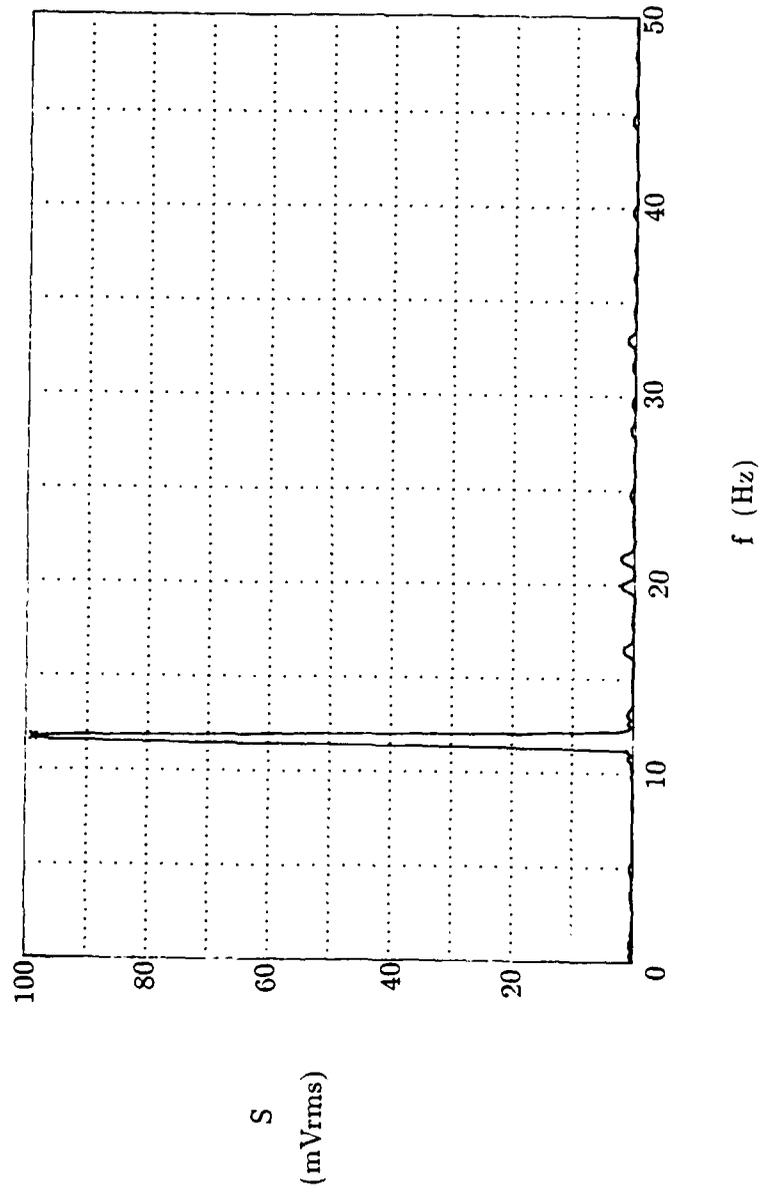


Figure 9. Spectral display for,  $\alpha = 1.97^\circ$ ,  $\rho = 19.86$  Hz,  $\phi_l = 8.23$  Hz.

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## List of Symbols

$ \vec{a}_m $	maximum magnitude of acceleration along sensitive axis of accelerometer
$ \vec{a}_r $	maximum magnitude of acceleration along $r$
$cal$	calibration of accelerometer
$f$	frequency of response with respect to body-fixed frame
$l$	length from the accelerometer to the gimbal axis
$p$	earth-fixed inertial spin rate
$r$	radius of circular motion of accelerometer
$S$	accelerometer output
$\alpha$	coning angle
$\dot{\phi}_1$	earth-fixed inertial coning rate

Appendix  
Calibration Data for Accelerometer



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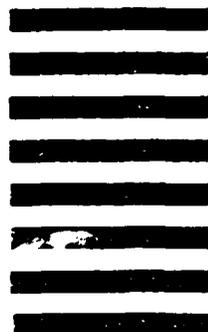
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