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THE USE OF A BERYLLIUM HOPKINSON BAR TO CHARACTERIZE IN-AXIS AND CROSS-AXIS ACCELEROMETER RESPONSE IN SHOCK ENVIRONMENTS*

Vesta I. Bateman
Principal Technical Staff
Sandia National Laboratories
P.O. Box 5800, MS0555
Albuquerque, New Mexico 87185-0555

Fred A. Brown
Principal Technician
Sandia National Laboratories
P.O. Box 5800, MS0555
Albuquerque, New Mexico 87185-0555

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KEYWORDS

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ABSTRACT

The characteristics of a piezoresistive accelerometer in shock environments are being studied at Sandia National Laboratories in the Mechanical Shock Testing Laboratory. A beryllium Hopkinson bar capability has been developed to extend our understanding of the piezoresistive accelerometer, in two mechanical configurations and with and without mechanical isolation, in the high frequency, high shock environments where measurements are being made. In this paper, recent measurements with beryllium single and split-Hopkinson bar configurations are described. The in-axis performance of the piezoresistive accelerometer in mechanical isolation for frequencies of dc-30 kHz and shock magnitudes of up to 6,000 g as determined from measurements with a beryllium Hopkinson bar with a certified laser doppler vibrometer as the reference measurement are presented. Results of characterizations of the accelerometers subjected to cross-axis shocks in a split beryllium Hopkinson bar configuration are also presented.

INTRODUCTION

Sandia National Laboratories (SNL) conduct impact testing for a variety of structures. These impact tests include earth and rock penetrator tests in which a penetrator structure is propelled at velocities of 1000 fps (nominal) into earth or rock. During an impact test, metal to metal contact may occur within the structure and produce high frequency, high amplitude shocks. The piezoresistive accelerometer, which is frequently used for field tests of various high reliability structures, must withstand these severe shock environments. The piezoresistive accelerometer has several desirable characteristics: dc response, low power requirements, minimal zero shift, and high resonant frequency. A bandwidth of at least 10 kHz is needed for many applications because more sophisticated analyses are being performed with the field data. Additionally, requirements are being made to qualify components for frequency ranges of 10 kHz. For example, recent Army research has found that armored vehicle components can be damaged

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by the high frequency content of ballistic shock [1,2,3]. To enhance survivability of the new generation of combat vehicles, the Army has specified a minimum frequency range of 10 kHz for the design and qualification test of components. Qualification to even higher frequencies is desired, if reasonably possible. Since there is no capability to calibrate or characterize accelerometers with shock inputs for frequencies above 10 kHz, the SNL Mechanical Shock Laboratory has been given the task of characterizing accelerometers for the conditions shown in Table 1. The two areas of high frequency performance and high amplitude shock (acceleration level) performance for the piezoresistive accelerometer are being pursued because measurements are being made in these environments.

Table 1: Test Matrix for In-Axis Accelerometer Study.

	Low Amplitude (up to 20,000 g)	**High Amplitude (up to 200,000 g)**
Low Frequency (dc-10 kHz)	Titanium	Titanium
High Frequency (dc-50 kHz)	Beryllium	Beryllium

The SNL Mechanical Shock Laboratory has a titanium Hopkinson bar capability to test accelerometers up to 200,000 g that has been used to determine the characteristics of a piezoresistive accelerometer at these high acceleration levels [4]. The SNL titanium Hopkinson bar with strain gages as the reference measurement has been calibrated for a bandwidth of dc to 10 kHz with an uncertainty of + 6% [5].

The piezoresistive accelerometers are being characterized over the extended bandwidth of dc to 50 kHz to provide better interpretation of high frequency measurements. To achieve this goal, a beryllium Hopkinson bar capability has been developed to extend the upper limit of the frequency range for Hopkinson bar calibration and characterization of accelerometers. The reference measurement for the beryllium Hopkinson bar in a single bar configuration is a commercial laser doppler vibrometer (LDV) that has been certified by the SNL Primary Electrical Standards Laboratory [6]. The LDV is the Polytec PI Model OFV-3000 controller and Model OFV-302 sensor head*. The in-axis performance of the piezoresistive accelerometer for frequencies of dc-50 kHz and shock magnitudes of up to 70,000 g as determined from measurements with a beryllium Hopkinson bar have been presented [7]. The results of both in-axis studies [4,7] of the two mechanical configurations shown in Figure 1 confirm the manufacturer's performance specifications for the accelerometers that were previously unconfirmed. The rectangular package that uses two #4-40 screws for mounting will be referred to as the flat package in this paper. The cylindrical package that uses a single #1/4-28 mounting stud will be referred to as the can package. This accelerometer is the Model 7270A manufactured by ENDEVCO*. Both configurations are being studied to determine if there are any differences in the performance characteristics between the two accelerometers. In some cases, it has been suspected that the flat package exhibited beam mode (with fixed end conditions) response in high frequency environments. It has been hypothesized that the can package might eliminate this beam response and the subsequent frequency content in the measured accelerometer response data. Results to date indicate the two packages are similar in response with the exception of a resonance noted in the can package at about 100 kHz that is not apparent in the flat package.

*Reference to a commercial product implies no endorsement by SNL or the Department of Energy or lack of suitable substitute.

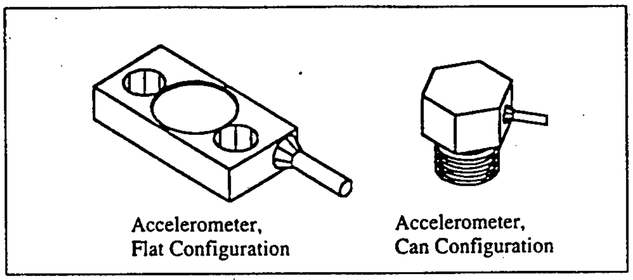

Figure 1: Two Mechanical Configurations for a Piezoresistive Accelerometer.

Others have tried to extend the frequency range of the Hopkinson bar by removing dispersion effects from the data [8,9]. However, this technique is not a valid approach to extend the bandwidth because there is no coherence in the data above ~15 kHz for the typical Hopkinson bar materials of aluminum, steel and titanium. A beryllium Hopkinson bar allows measurement of frequencies in the bandwidth of dc to 50 kHz with acceptable coherence because the beryllium's high stress wave speed can create a shorter pulse duration without dispersion than other Hopkinson bar materials that are used for the current accelerometer studies.

BERYLLIUM HOPKINSON BAR CONFIGURATIONS

The beryllium Hopkinson bar configuration for characterizing accelerometers for normal or in-axis input is shown in Figure 2. Normal input in this configuration is an input that is normal to the mounting surface or parallel to an integral mounting stud. A maximum shock magnitude of 70,000 g is used for the beryllium bar to insure that the beryllium will not yield because it is a health hazard. Both of the mechanical configurations for the piezoresistive accelerometer have been tested with the normal input. The reference measurement is the LDV as shown. Strain gages cannot be used as the reference measurement because the beryllium bar's response exhibits two anomalies that have been presented previously [7]: the high rate of damping and the non-return to zero of the stress time history. A configuration that uses a quartz crystal to directly measure the acceleration applied to an accelerometer mounted on a flyaway device at the end of the bar was investigated [10]. However, it was found that the Hopkinson bar material is limited to aluminum that matches the impedance of the quartz crystal.

Cross-axis sensitivity of the piezoresistive accelerometers is being studied with the beryllium Hopkinson bar configurations shown in Figures 3 and 4. An in-axis response is the response of an accelerometer whose sensitive axis is in the direction of the shock. An out-of-axis or cross-axis response is the response of an accelerometer whose sensitive axis is not in the direction of the shock and is obtained with the configurations in Figures 3 and 4. A cross-axis configuration with the accelerometers mounted normal to the stress wave on the end of the bar was proposed previously [4] but was abandoned because the end-modes at 120 kHz in the Hopkinson bar caused the accelerometers to resonate and break. No special preparations of the beryllium Hopkinson bar interfaces with the inserts are made other than insuring that the surfaces are flat and polished. All Hopkinson bars used for the results shown in this paper are freely supported. Both time domain calculations, as a percent difference from the reference LDV measurement, and frequency domain calculations, as frequency response functions, are made with the Hopkinson bar data.

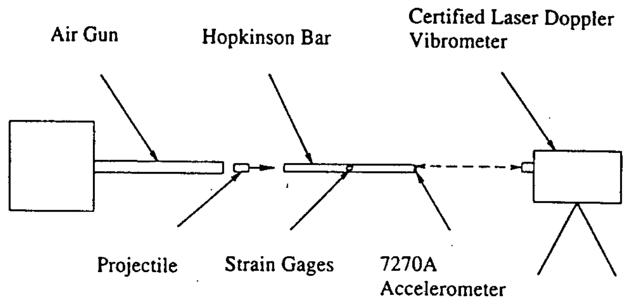

Figure 2: Beryllium Hopkinson Bar Configuration for Normal Input

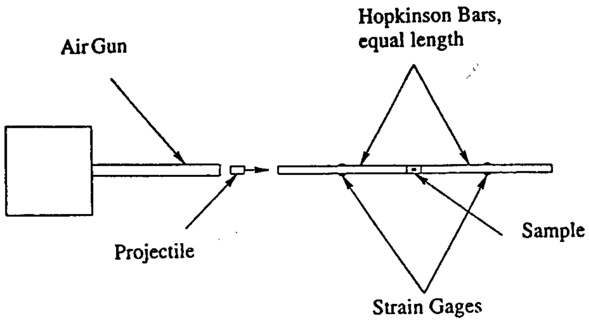

Figure 3: Split Beryllium Hopkinson Bar Configuration for Cross-Axis Input.

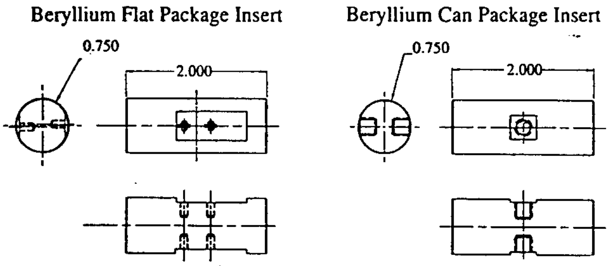

Figure 4: Sample Configuration for Split Beryllium Hopkinson Bar for Cross-Axis Input.

HOPKINSON BAR ANALYSIS

The theory of stress wave propagation in a Hopkinson bar is well documented in the literature [11,12]. The results of this theory are summarized as follows:

A Hopkinson bar is defined as a perfectly elastic, homogeneous bar of constant cross-section.

A stress wave will propagate in a Hopkinson bar as a one-dimensional elastic wave without attenuation or distortion if the wavelength, λ, is large relative to the diameter, D, or $10D \leq \lambda$.

For a one-dimensional stress wave propagating in a Hopkinson bar, the motion of a free end of the bar as a result of this wave is:

$$v = 2c\varepsilon \qquad (1)$$

or,

$$a = 2c\frac{d\varepsilon}{dt} \qquad (2)$$

where,

$$c = \sqrt{\frac{E}{\rho}} \qquad (3)$$

and v and a are the velocity and acceleration, respectively, of the end of the bar, c is the wave propagation speed in the bar, E is the modulus of elasticity, ρ is the density for the Hopkinson bar material, and ε is the strain measured in the bar at a location that is not affected by reflections during the measurement interval.

The motion of an accelerometer mounted on the end of the bar will be governed by equations (1) and (2) if the mechanical impedance of the accelerometer is much less than that of the bar or if the thickness of the accelerometer is much less than the wavelength. The requirement on the strain gage is that the gage length (g.l.) be much less than the wavelength or $\lambda \geq 10$ g.l.

The Mechanical Shock Laboratory beryllium Hopkinson bar for accelerometer in-axis testing is made of beryllium (99% pure) with a 0.75 inch diameter and a 50 in. length. The bar is supported in a way that allows it to move freely in the axial direction. A low pressure air gun is used to fire a 2 inch long hardened tool steel projectile at the end of the bar (maximum velocity is about 28 fps). This impact creates a stress pulse which propagates toward the opposite end of the Hopkinson bar. The amplitude of the pulse is controlled by regulating the air gun pressure, which determines the impact speed. The shape (approximately a half sine) and duration of the pulse are controlled by placing various thickness of paper (3x5 index cards) on the impact surface. The LDV is located at the end of the bar on which the accelerometer is mounted and measures velocity at a point next to the accelerometer. This LDV with high frequency (up to 1.5 MHz) and high velocity (10 m/s) capability was purchased from a commercial source and has been certified by the Primary Electrical Standards Department at SNL. For the 1000 mm/s/V range (positive velocity), the total uncertainty with approximately a 95% confidence level for the velocity is 5%. When the LDV is used over 90% of its range, this LDV has a 2-3% uncertainty for all specified frequencies and velocities. The uncertainty decreases for decreasing velocity scales. The LDV provides a reference velocity measurement for velocities up to 10 m/s and for frequencies up to 1.5 MHz. This reference measurement provides information in a bandwidth that is not available from strain gages that are generally considered to have a bandwidth of no greater than dc-40 kHz. The details of the certification process are described in [8].

Once recorded, the velocity (LDV) and acceleration (accelerometer) records can be compared by converting to either velocity or acceleration as shown in (1) and (2). Hopkinson bar accelerometer calibration methods documented in the literature [13-16] generally use velocity, in which case the accelerometer record is integrated and compared directly to the strain record converted to velocity by the factor 2c. This provides smooth curves for comparison of time histories, however much of the higher frequency information is lost due to the integration process. Since it was desired to preserve the frequency response of the data, acceleration is used for the comparison of the data. Consequently, the time derivative of the strain records was required, and the resulting signal may be contaminated by high frequency noise created in the process of calculating the derivative. This problem was essentially eliminated by: 1) adequate sample rate of 500 kHz or higher; 2) low pass digital filtering with a cutoff frequency well above the frequency range of interest (10 kHz); and most importantly, 3) an accurate differentiation algorithm which was derived using the Fourier series reconstruction techniques in [16]. This algorithm results in an exact derivative of the digitized signal providing the Sampling Theorem has not been violated, that is, the data is not aliased [17].

IN-AXIS MECHANICALLY ISOLATED ACCELEROMETER PERFORMANCE

A mechanical isolator has been developed for a piezoresistive accelerometer. The purpose of the isolator is to mitigate high frequency shocks before they reach the accelerometer because the high frequency shocks may cause the accelerometer to resonate. Since the accelerometer is undamped, it often breaks when it resonates. The mechanical isolator was developed in response to impact test requirements for a variety of structures at SNL. An Extended Technical Assistance Program with the accelerometer manufacturer has resulted in a commercial isolator that is available to the general public. This mechanical isolator has **ten times** the bandwidth of any other commercial isolator and has acceptable frequency domain performance, as measured with a single titanium Hopkinson bar configuration, from DC to 10 kHz (± 10%) for shock magnitudes up to 60,000 g over a temperature range of -65°F to +185°F [18]. The mechanical isolator assembly is shown in Figure 5 and is ENDEVCO Model 7270AM6. The isolator is available for ENDEVCO 7270A ranges of 6,000 g, 20,000 g, and 60,000 g.

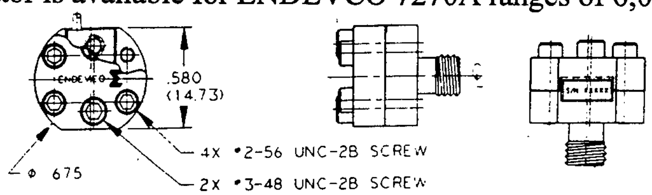

Figure 5: ENDEVCO 7270AM6 Mechanical Isolator Assembly.

In an attempt to characterize the resonance for the ENDEVCO 7270AM6, it was mounted on the end of a beryllium Hopkinson bar with a ¼-28 threaded hole in the normal orientation as shown in Figure 2. A low amplitude shock pulse of ~6,000 g with a 15 μs duration was created, and the frequency response functions (magnitude and coherence) were calculated with the response of five pulses as shown in Figure 6. A higher magnitude shock pulse was not used because the duration of the shock pulse at 15 μs causes the mechanical assembly to resonate. Although this configuration was used successfully to characterize the 1.5 gram ENDEVCO 7270A for a bandwidth of 50 kHz, the coherence is not acceptable past 30 kHz for the ENDEVCO 7270AM6 with a higher weight of 8.4 grams. A 2.0 in. diameter beryllium Hopkinson bar configuration is being implemented to obtain coherence for a DC-50 kHz bandwidth. Figure 7 shows the time history and the corresponding Fourier transform for the ENDEVCO 7270AM6 response with a isolator resonance at ~75 kHz. Other testing, in which the ENDEVCO 7270AM6 was mounted on a steel plate and subjected to shock from 50 grams of C-4 detonated on the other side of the plate with a 90 mm standoff, have shown a resonance at 48 kHz.

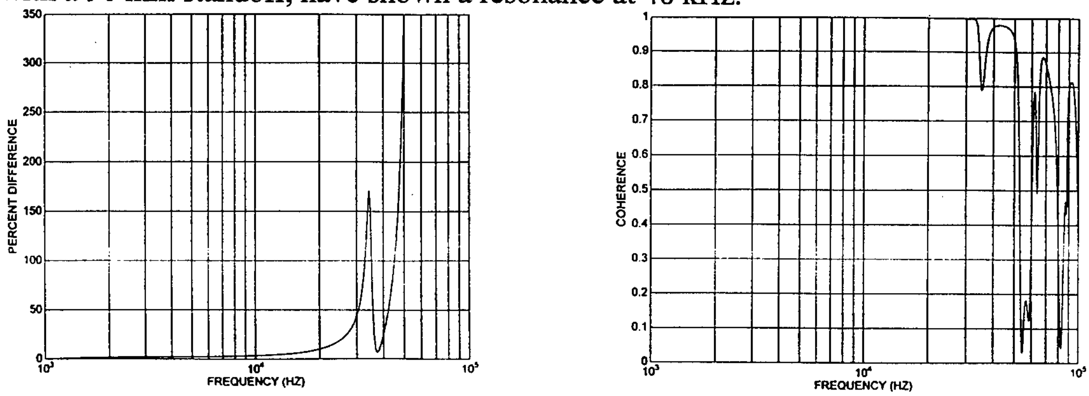

Figure 6: Frequency Response Functions for the ENDEVCO 7270AM6 Mounted on a 0.75 in. Diameter Beryllium Hopkinson Bar (Phase calculated but not shown).

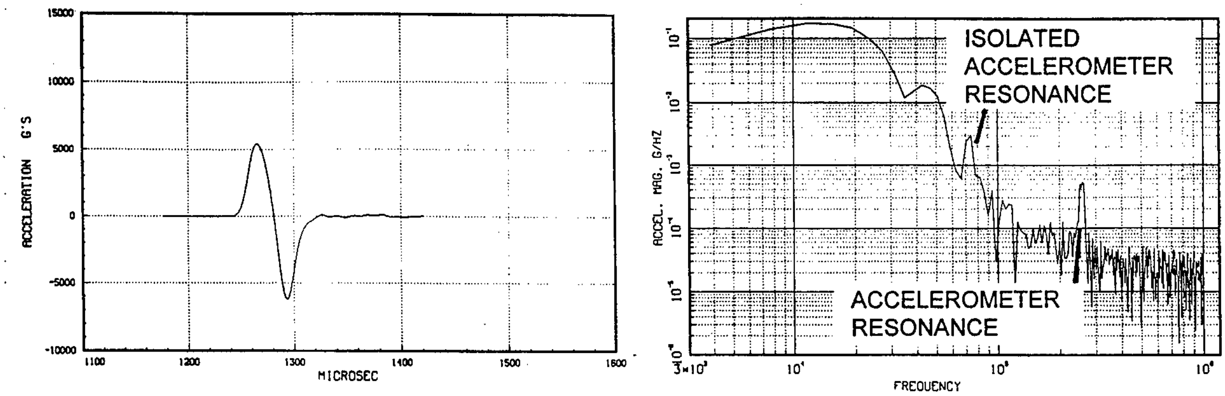

Figure 7: ENDEVCO 7270AM6 Response in a 0.75 in. Diameter Beryllium Hopkinson Bar Configuration.

CROSS-AXIS ACCELEROMETER PERFORMANCE

The axial motion, a, at a location in the Hopkinson bar other than the free end is

$$a = c\frac{d\varepsilon}{dt} \qquad (4)$$

where ε is the axial strain. The radial motion, y, is

$$y = r\varepsilon_r \qquad (5)$$

where r is the radius of the Hopkinson bar and ε_r is the radial strain. Since the relationship between axial and radial strain is

$$\varepsilon_r = \mu\varepsilon \qquad (6)$$

where μ is Poisson's ratio, then the final expression for radial acceleration, a_y, is

$$a_y = \frac{\mu r}{c}\frac{da}{dt}. \qquad (7)$$

A prediction of the axial and radial acceleration for the beryllium Hopkinson bar using the equations above is shown in Figure 8. Strain measurements co-located with the accelerometers for the flat package insert of Fig. 4 in the split Hopkinson bar configuration are shown in Figures 9 and 10 and indicate a Poisson's ratio of about 0.07. Two accelerometer responses measured on the insert are shown in Fig. 11. This response is base strain dominated because it does not correspond to either of the curves in Fig. 8 but follows the general shape of the lateral strain response in Fig. 10. A compressive static load was applied to the insert with the results shown in Figs. 12 and 13. Since the sensitivity of the accelerometer is approximately 1 μV/g and the applied strain was about 250 $\mu\varepsilon$, these results are consistent with the manufacturer's specifications of <0.5 mv output for a strain of 250 $\mu\varepsilon$. The orientations of the sensor in the two mechanical packages is shown in Figure 14. The precise orientation in the 7270AM4 allowed orientation of the sensor with the beams in line with the shock and oriented at 90° to the shock, and the results are shown in Figure 15.

CONCLUSIONS AND FUTURE WORK

The ENDEVCO 7270AM6 was originally designed for impact shock, but is showing acceptable response in some ballistic shock and pyroshock applications with explosives. Characterization of the ENDEVCO 7270AM6 resonance will continue with the new 2.0 in. beryllium single Hopkinson bar

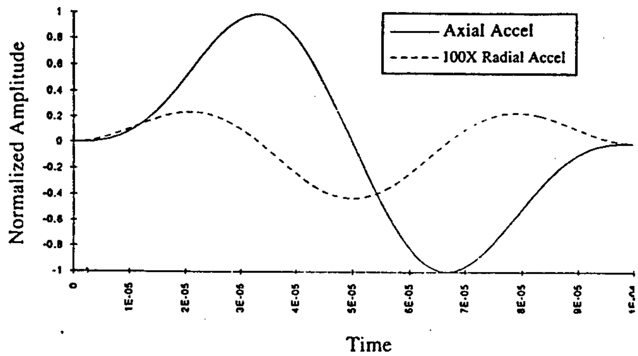

Figure 8: Theoretical Prediction of Axial and Lateral Accelerations for the Beryllium Hopkinson Bar.

configuration. The cross axis response of the ENDEVCO 7270A is base strain sensitive, but the cross-axis response of the ENDEVCO 7270AM4 may be either base strain or acceleration. Additional characterization of the piezoresistive accelerometer's cross-axis sensitivity will be conducted with the 2.0 in. diameter beryllium split-Hopkinson bar configuration. These characterizations, accomplished at the high frequencies and high shock levels, will permit better interpretation of data measured in the presence of high frequency, high shock environments.

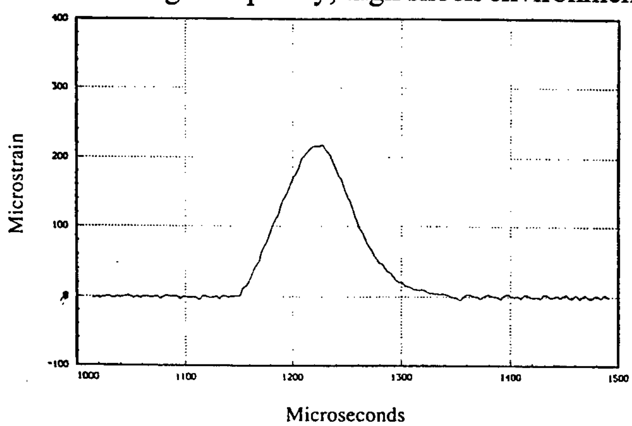

Figure 9: Axial Strain on the Beryllium Insert.

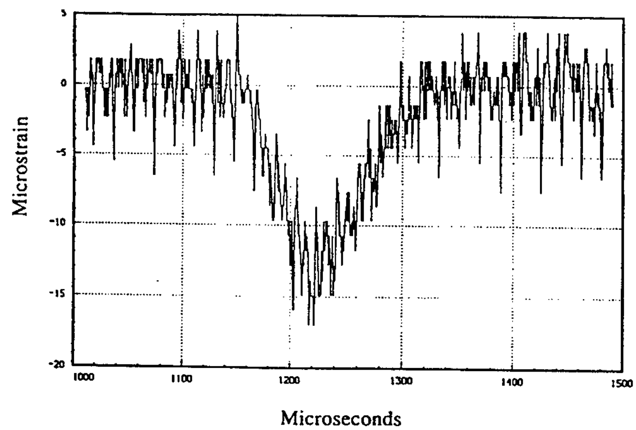

Figure 10: Lateral Strain on the Beryllium Insert.

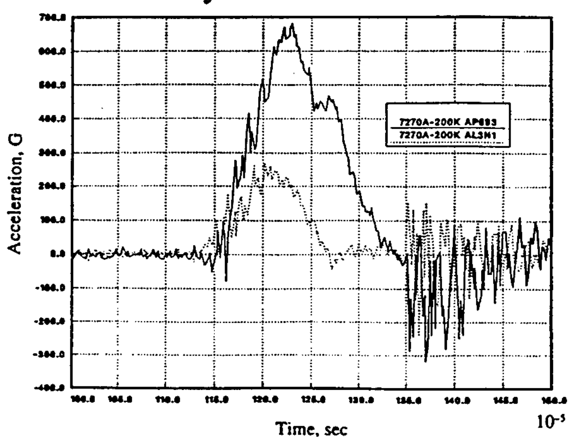

Figure 11: Two Accelerometer Responses Measured on the on the Beryllium Insert.

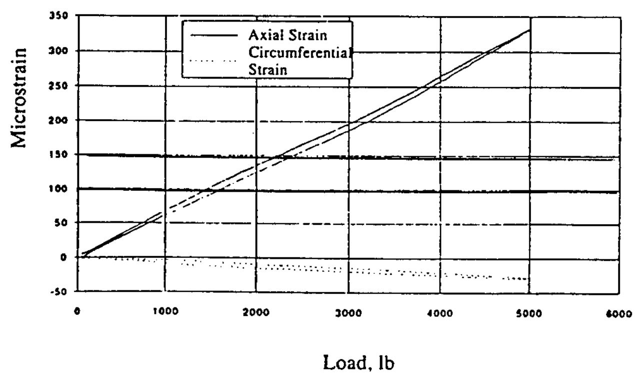

Figure 12: Strain Response for a Compressive Test of the Beryllium Insert.

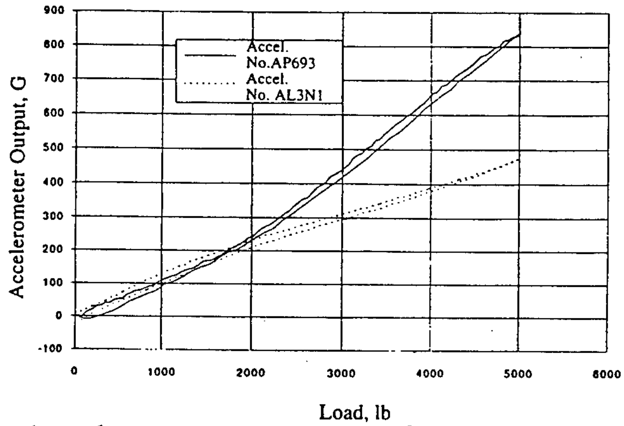

Figure 13: Accelerometer Response for a Compressive Test of the Insert.

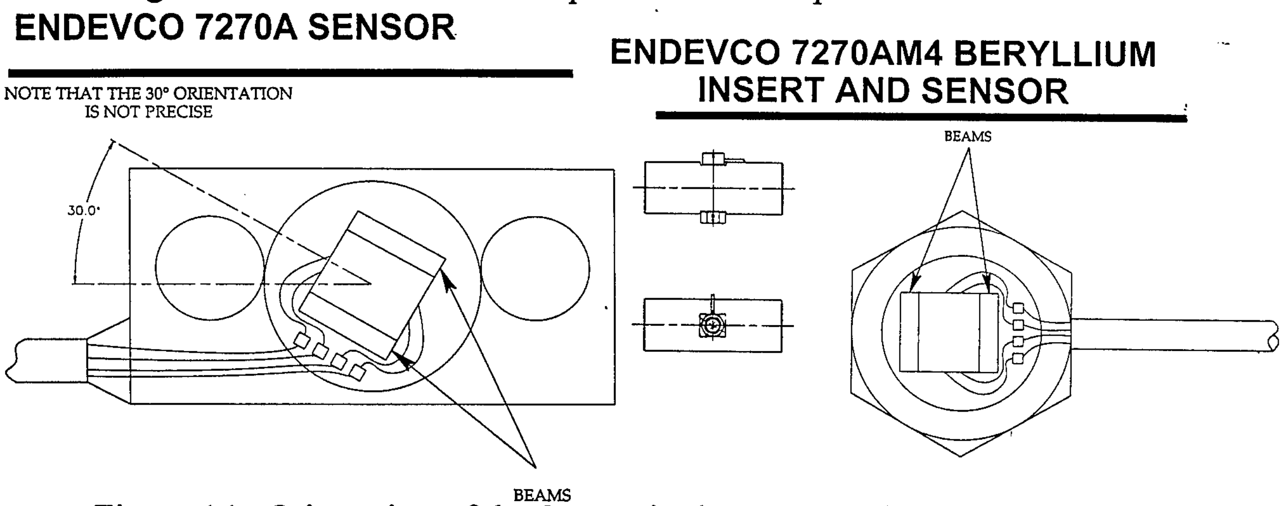

Figure 14: Orientation of the Sensor in the Two Mechanical Packages of the ENDEVCO 7270A

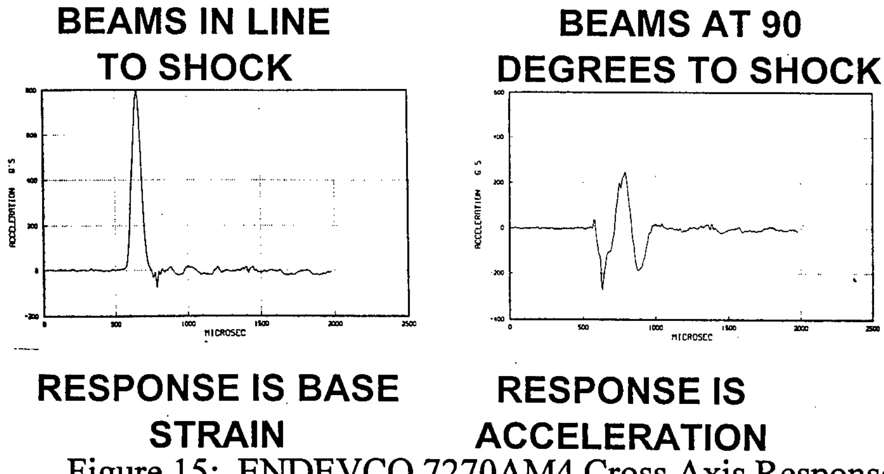

Figure 15: ENDEVCO 7270AM4 Cross Axis Response

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