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High Shock, High Frequency Characteristics of a Mechanical Isolator for a Piezoresistive Accelerometer, the ENDEVCO 7270AM6*

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High Shock, High Frequency Characteristics of a Mechanical Isolator for a Piezoresistive Accelerometer, the ENDEVCO 7270AM6*

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Abstract

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 Sandia National Laboratories (SNL). An Extended Technical Assistance Program (ETAP) with the accelerometer manufacturer has resulted in a commercial mechanically isolated accelerometer that is available to the general public, the ENDEVCO 7270AM6*, for three shock acceleration ranges of 6,000 g, 20,000 g, and 60,000 g. The in-axis response shown in this report has acceptable frequency domain performance from DC to 10 kHz (± 10%) over a temperature range of -65°F to +185°F. Comparisons with other isolated accelerometers show that the ENDEVCO 7270AM6 has **ten times** the bandwidth of any other commercial isolator. ENDEVCO 7270AM6 cross-axis response is shown in this report. Finally, pyroshock and ballistic shock measurements, performed by international organizations, show extended applicability of the ENDEVCO 7270AM6.

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

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Introduction

Sandia National Laboratories (SNL) conduct impact testing for a variety of structures. For example, penetrator structures are propelled at velocities of 1000 fps (nominal) into earth or rock, and nuclear transportation casks are dropped from 30 feet onto a hard concrete targets at a 10° slapdown orientation as shown in Figure 1. The impact environment is a high frequency, high shock environment. During an impact test, metal to metal contact may occur within the structure internally and produce an additional high frequency, high shock environment. The SNL Mechanical Shock Testing Laboratory developed a

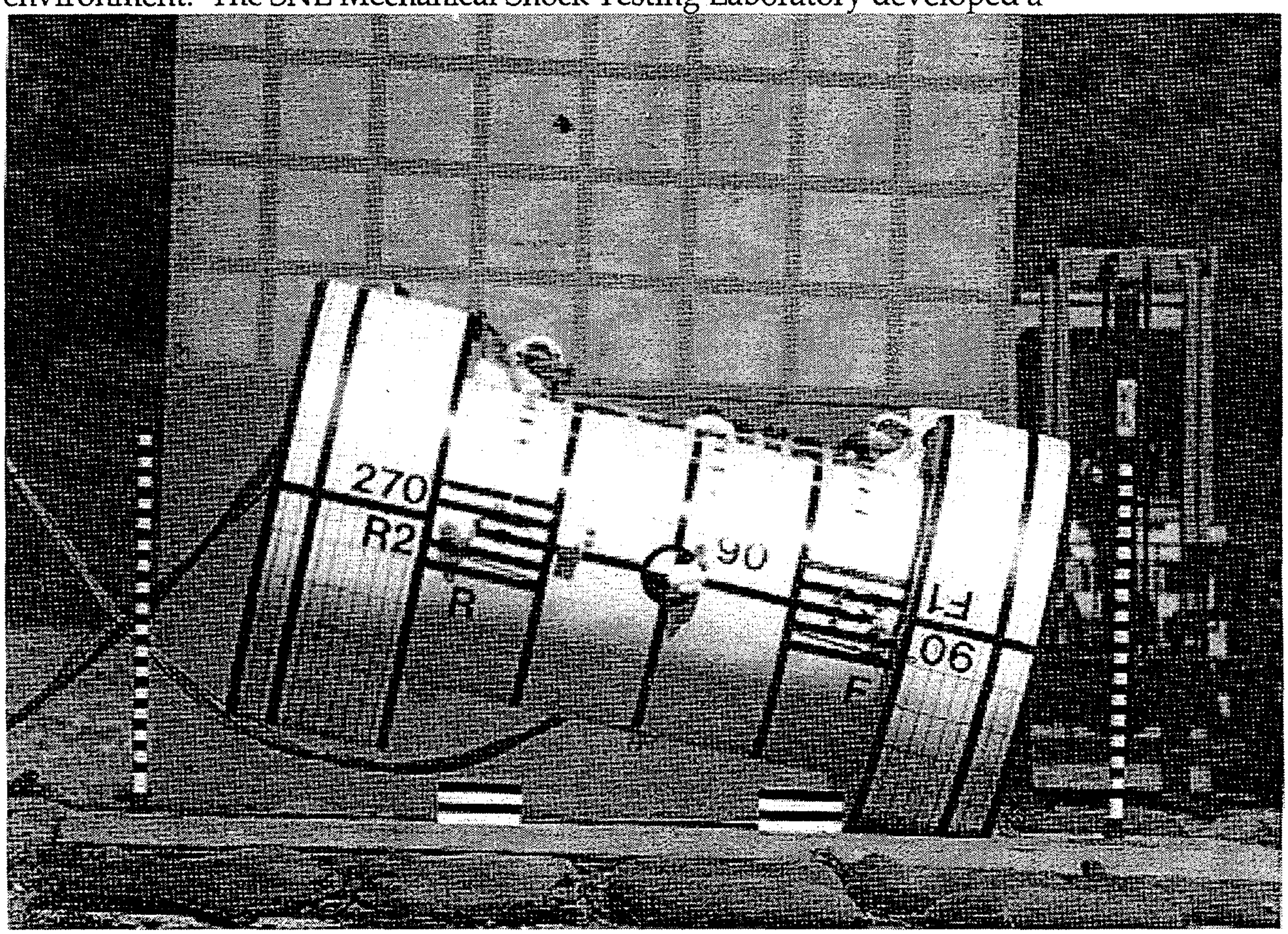

Figure 1: Slapdown Test Impact for a Nuclear Transportation Cask.

mechanical isolator for a piezoresistive accelerometer in response to impact test and pyroshock measurement requirements for various SNL structures. The mechanical isolator development was initiated by the impact test of a nuclear transportation cask in an end-on orientation. All the accelerometers resonated or broke during the impact. The resonant response of the accelerometers that did not break was so large that the data was clipped and rendered useless. No useable accelerometer responses were recorded for the test. Although the physical damage to the structure could be discerned from the impact, the more sophisticated analyses of the structural response as measured by the accelerometers could not be performed because the accelerometer data were lost. The accelerometers were subsequently isolated with a mechanical isolator design for the slapdown impact shown in Figure 1, and data were successfully obtained. The development of the mechanical isolator continued for other programs at SNL, and the characteristics of mechanical isolator have been reported previously for frequencies of DC-10 kHz and shock magnitudes of up to 15,000 g [1,2,3,4]. When technology transfer funds became available to transfer SNL technology to private industry, a proposal was accepted for an Extended Technical Assistance Program (ETAP) with the accelerometer manufacturer, ENDEVCO*, to transfer the mechanical isolator technology.

The ETAP for the mechanical isolator consists of four phases. The first phase was to determine if the rubber material in the isolator was the most appropriate elastic material. The second phase was to determine how the elastic material would be obtained by the commercial manufacturer. For the third phase, the shock magnitudes applied to the isolator were increased so that the upper limit of the shock magnitudes for the mechanical isolator could be determined. The SNL Mechanical Shock Laboratory has been developing test and data analysis capabilities to extend our understanding of the mechanical isolator assembly in the high frequency, high shock environments where measurements are being made during impact and pyroshock tests. In-axis results for up to 70,000 g and a frequency bandwidth of DC-30 kHz with a Hopkinson bar test configuration are described [5]. The last phase of the ETAP is the testing and evaluation of the mechanical isolator prototypes made by ENDEVCO. The piezoresistive accelerometer is now available as the ENDEVCO 7270AM6 for three shock acceleration ranges of 6,000 g, 20,000 g, and 60,000 g.

Further characterization of the ENDEVCO 7270AM6 has been directed by other SNL programs so that the high frequency in-axis (DC-30 kHz) and the cross-axis response have been characterized as shown in Tables I and II [6]. These wide-bandwidth characterizations are needed for many applications because more sophisticated analyses are being performed with the field data. Also,

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requirements have been written to qualify components for frequency ranges of 10 kHz. For example, recent Army research has found that armored vehicle components can be damaged by the high frequency content of ballistic shock [7,8,9]. To enhance survivability of the new generation of combat vehicles, the Army has specified a minimum frequency range of DC to 10 kHz for the design and qualification test of components. 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 Tables I and II. Additionally, results from SNL shock environments other than impact and international explosive tests have been made available to the authors for publication by Aberdeen Proving Grounds.

Table I: In-Axis ENDEVCO 7270AM6 Accelerometer Experiments.

	Low Amplitude (up to 20,000 g)	**High Amplitude (up to 70,000 g)**
Low Frequency (dc-10 kHz)	Titanium	Titanium
High Frequency (dc-30 kHz)	Beryllium	Beryllium

Table II: Cross-Axis ENDEVCO 7270AM6 Accelerometer Experiments.

Environment	**Experimental Configuration**
Static Compression	Beryllium Cylinder
Static Strain	Steel Beam
Dynamic strain	Steel Beam
Compressive Mechanical Shock	Beryllium Cylinder in a Split Hopkinson Bar Configuration

Selection of the Elastic Material for the Mechanical Isolator

The material used in the mechanical isolator is polysulfide rubber which is sold as an adhesive in semi-solid form. This material was used for historical reasons because early mechanical isolator designs used a layer of polysulfide rubber between two plates. The accelerometer was then mounted on the top plate with screws in the usual manner, and the assembly was mounted on the structure with a 10-32 stud in the bottom plate. Polysulfide rubber has been made at SNL for many years in small plaques with a thickness of 0.010 in. However, ENDEVCO wanted a commercial source for the polysulfilde material, but no commercial supplier of this rubber in 0.010 in. thick plaques could be found. Consequently, several alternative materials were considered for the mechanical isolator. These materials were chosen using the criteria: Shore A durometer in the range of 50-90; temperature range of -65°F and +185°F, and easy formability into 0.010 thick plaques. The materials chosen were: Silicone (GE RTV 511), Adiprene, Adhesive Film (3M), and Ethylene Propylene (EPDM) rubber. Two mechanical isolators were assembled with each material candidate. Initially, all mechanical isolator assemblies were calibrated with both a shaker calibration and a dropball calibration. From previous experience, the shaker calibration at 30-50 g's must have less than ±5% deviation over a bandwidth of DC-10 kHz in order for the isolator to be a candidate for high shock levels. A comparison of shaker calibrations for the ENDEVCO 7270AM6 isolator and a commercial isolator, Bruel & Kjaer Model 0559, is shown in Figure 2 and indicates the superior performance of the ENDEVCO 7270AM6 isolator. For the shaker calibration, an ENDEVCO 7270A-6K was mounted on the Bruel & Kjaer Model 0559 isolator to maximize the performance of the Bruel & Kjaer Model 0559. Heavier accelerometers, greater than 1.5 grams, will lower the resonant frequency of the Bruel & Kjaer Model 0559. Shaker calibrations were also performed at -65°F and +185°F with similar results.

Additionally, the dropball calibration should be flat (±3%) for shock levels up to the maximum peak magnitude of the dropball apparatus, 20,000 g. If the material performed adequately during these calibrations, then the evaluation continued with Hopkinson bar testing at ambient temperatures. The Hopkinson bar test configuration is shown in Figure 3. This titanium Hopkinson bar configuration for in-axis characterizations has a 0.75 in. diameter and a DC-10,000 Hz non-dispersive bandwidth. This apparatus and the associated data analyses performed in the SNL Mechanical Shock Laboratory are described in subsequent sections of this report [1-6, 10]. The advantage of Hopkinson bar testing is that shorter pulse durations (and consequently high frequency content) can be applied to the test item and the data is available for analysis. Only two of these materials, silicone and adiprene, performed adequately at ambient

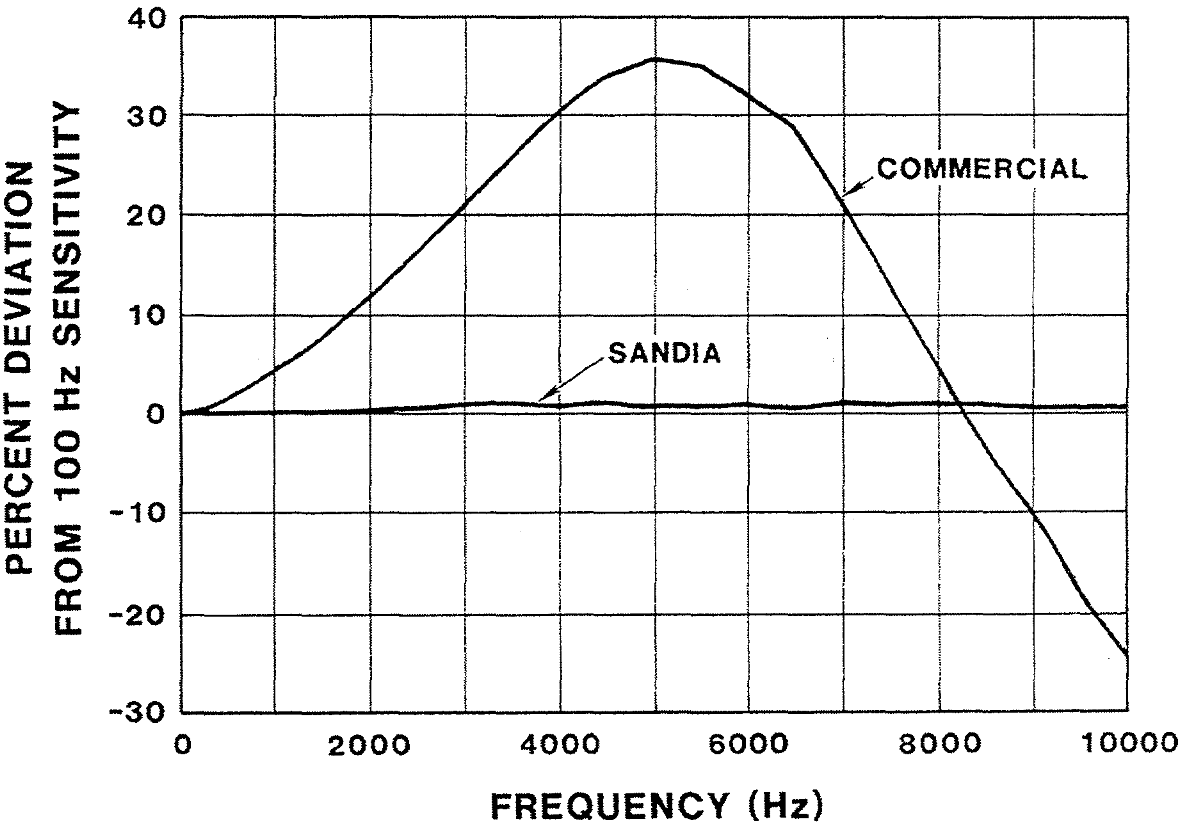


Figure 2: Shaker Calibration Comparison of SNL Mechanical Isolator and a Commercial Isolator, Bruel & Kjaer Model UA559.

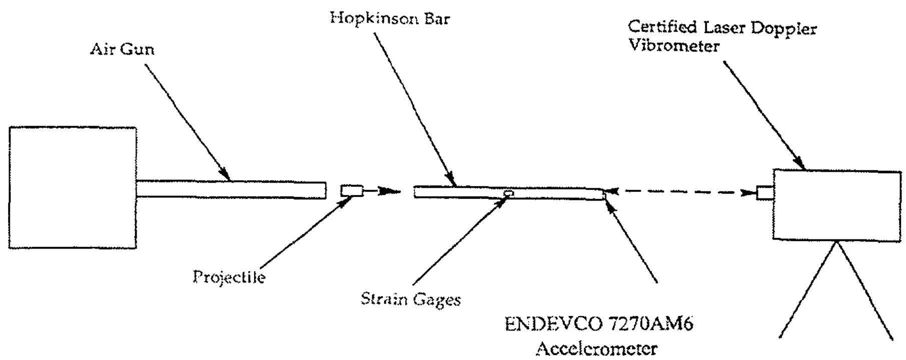


Figure 3: Hopkinson Bar Configuration for In-Axis Isolated Accelerometer Characterizations.

temperatures at shock amplitudes up to 15,000 g. Adequate performance has two criteria: the isolator peak acceleration amplitude must not differ significantly from the peak acceleration amplitude derived from a reference measurement and the accelerometer must not show resonant response. If the isolator and its elastic material have good agreement with the acceleration derived from the strain gages at these low shock amplitudes, then the material had adequate stiffness. If the accelerometer did not resonate, then the material had adequate shock mitigation with its impedance mismatch characteristics. The next evaluation was on the Hopkinson bar at -65°F, and neither material performed satisfactorily at this cold temperature. Consequently, the search for an another elastic material was abandoned, and polysulfide rubber remained the elastic material in the mechanical isolator.

Polysulfide rubber is purchased as a liquid and is not available commercially in the 10 mil thick plaques required for the isolator. In order for the commercial manufacturer to have an adequate supply of the polysulfide rubber, a simple circular fixture was constructed to make rubber plaques with a four inch diameter. As shown in Figure 4, this fixture consists of a circular housing and a circular piston that fits in the housing. The piston has three O-rings on it that allow a vacuum to be drawn on the area below the piston using a fitting in the side of the housing. The piston is forced down onto stops at the top of the housing with an arbor press. Six bolts are put in place to hold the piston in the correct position during the 24 hours required for the polysulfide rubber to solidify. The rubber is cured for an additional 48 hours after it is removed from the fixture.

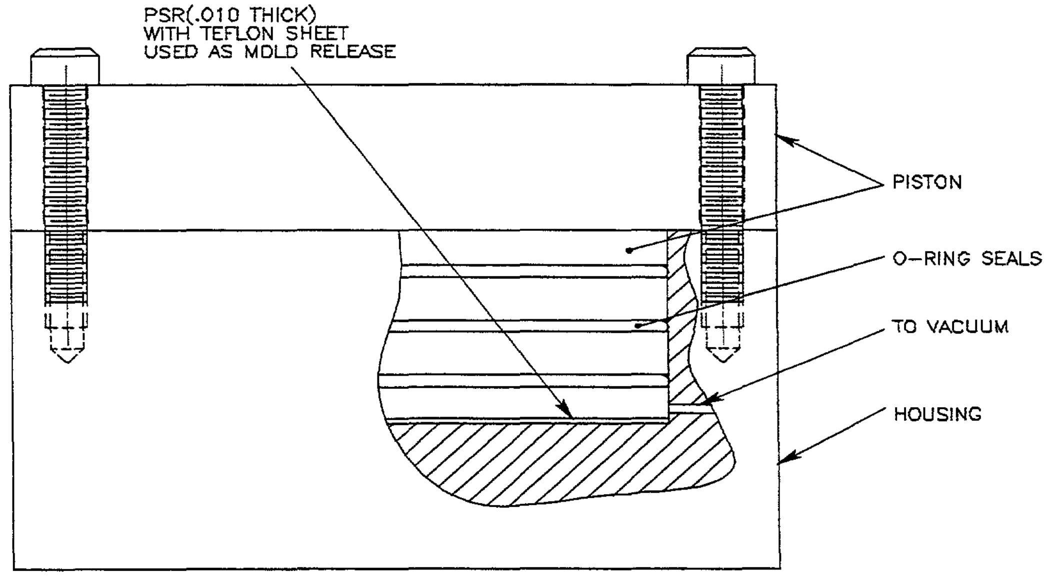


Figure 4: Simple Fixture to Make Polysulfide Rubber Plaques.

Development of the ENDEVCO 7270AM6 Mechanical Design

As part of the ETAP, twelve accelerometers were assembled in the mechanical isolator shown in Figure 5 as an exploded view. Since the accelerometer is available in five acceleration ranges, all ranges (except the lowest range of 2,000 g) were used: two with 6,000 g range; six with 20,000 g range, two with 60,000 g range, and two with 200,000 g range. The mechanical isolator has never been used with the 2,000 g accelerometer because the resonance of the isolator (≈30-50 kHz) tends to excite the resonance of the accelerometer at 90 kHz. Testing was planned for each accelerometer up to its maximum acceleration range. Testing of the 6,000 g accelerometers in the mechanical isolators was conducted at 5,000 g to confirm previous results. Testing continued with the 20,000 g accelerometers at 10,000 g to confirm previous results and at 20,000 g. Although the isolator performed acceptably at 10,000 g, the performance at 20,000 g was clearly unacceptable as shown in Figure 6. The acceleration time history shows a nonlinear response at the end of the Hopkinson bar pulse that was not evident at lower acceleration levels. The Fourier transform in Figure 6 shows several peaks that are not usually present and a high peak for the accelerometer resonance at almost 400 kHz. For acceptable isolator performance in the Fourier transform, the accelerometer resonance should have a magnitude that is at least two decades below the low frequency asymptote. The observation of this unacceptable performance led to a redesign of the isolator with six major changes as shown in Figure 7. First, the mounting stud was changed from a 10-32 to a 1/4-28 to increase the stiffness of the stud and to allow a larger torque value to be used (75 in-lb instead of 25 in-lb). The thickness of the isolator top was increased by 1/16 in. and the width of the slot for the accelerometer was decreased from 0.375 in. to 0.305 in. to raise the frequency of any modes in the plate-like top. Four 2-56 screws replaced the previous two 3-48 screws to clamp the top tighter to the bottom. This screw configuration allowed a decrease in the diameter from 0.745 in. to 0.675 in. Finally, the brass pins that were originally press-fit into the isolator bottom were replaced with two 3-48 screws that have shrink tubing over the threads to prevent metal-to-metal contact between the screws and the accelerometer. The elimination of the brass pins simplifies the machining and assembly considerably because the press fit requires tight tolerances and an extra operation for assembly. With these design changes, the ENDEVCO 7270A in the mechanical isolator respond correctly at acceleration levels up to 70,000 g without significantly increasing the weight of the isolator (9.5 grams as compared to the original 7.5 grams). Above 70,000 g, the nonlinear response appears and is similar to that shown in Figure 6. The nonlinear response is amplitude dependent and may be caused by small gaps opening in the isolator assembly. A finite element analysis has been made of the new

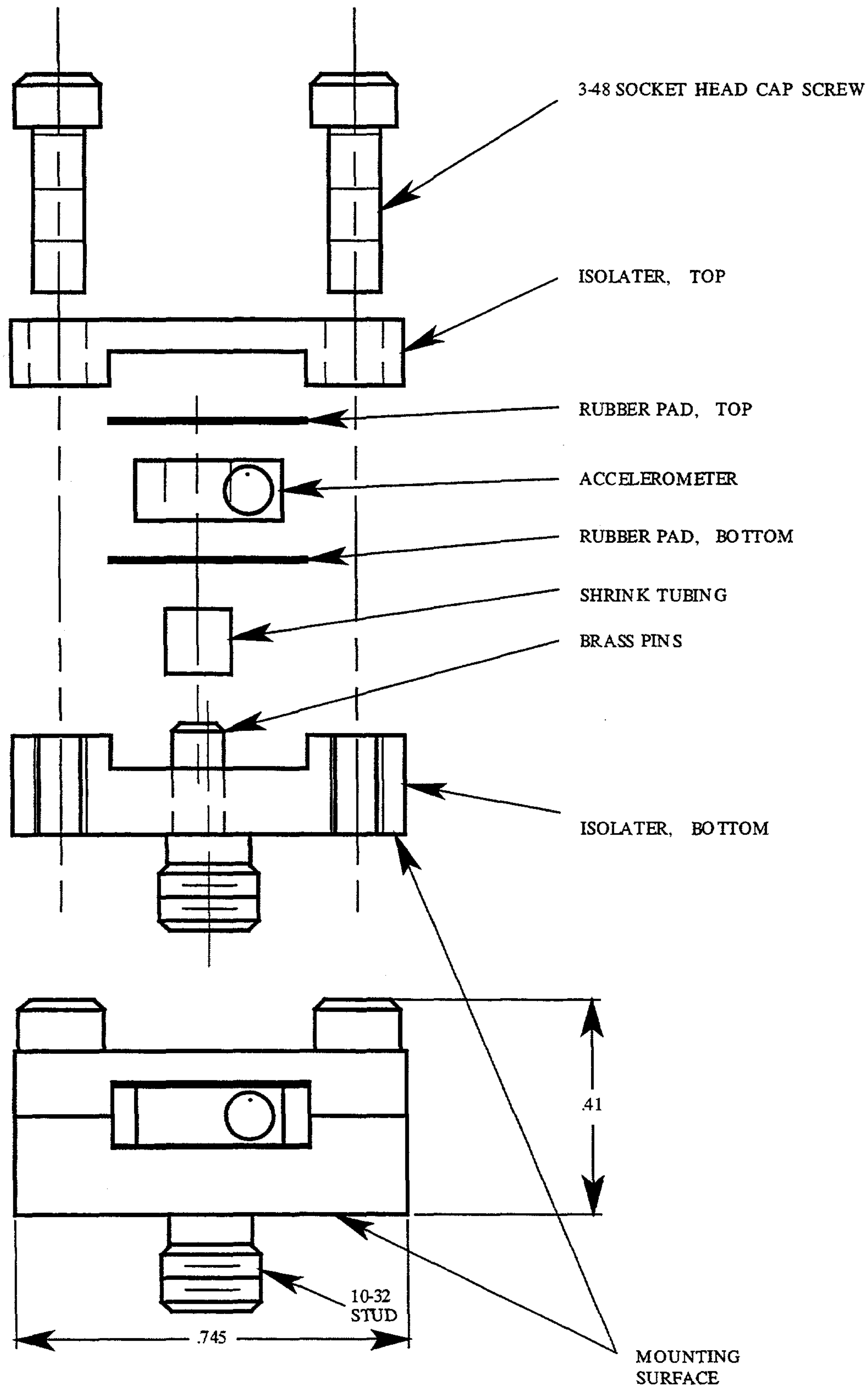
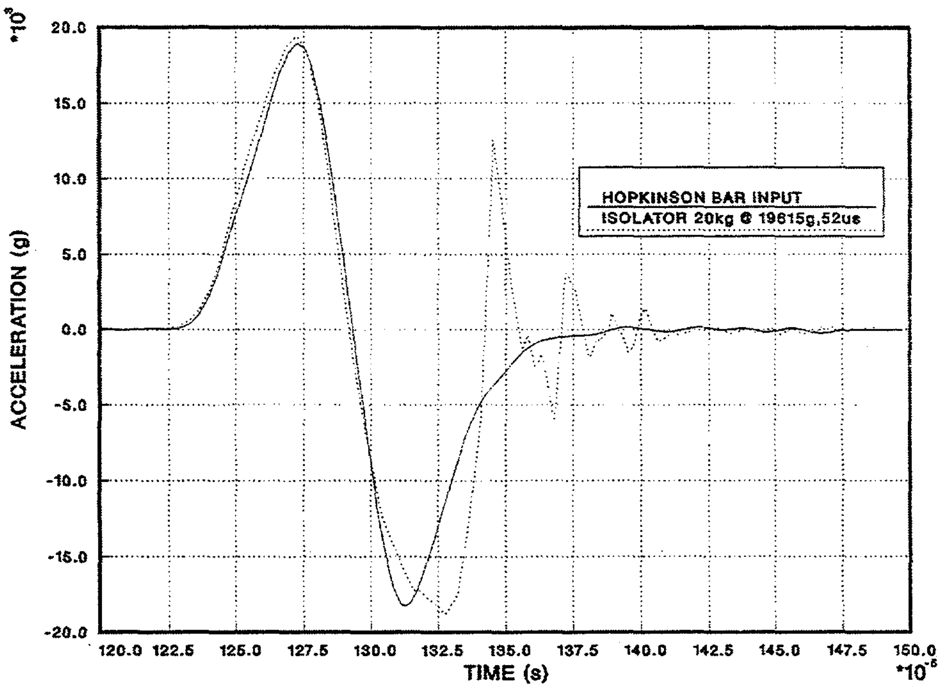
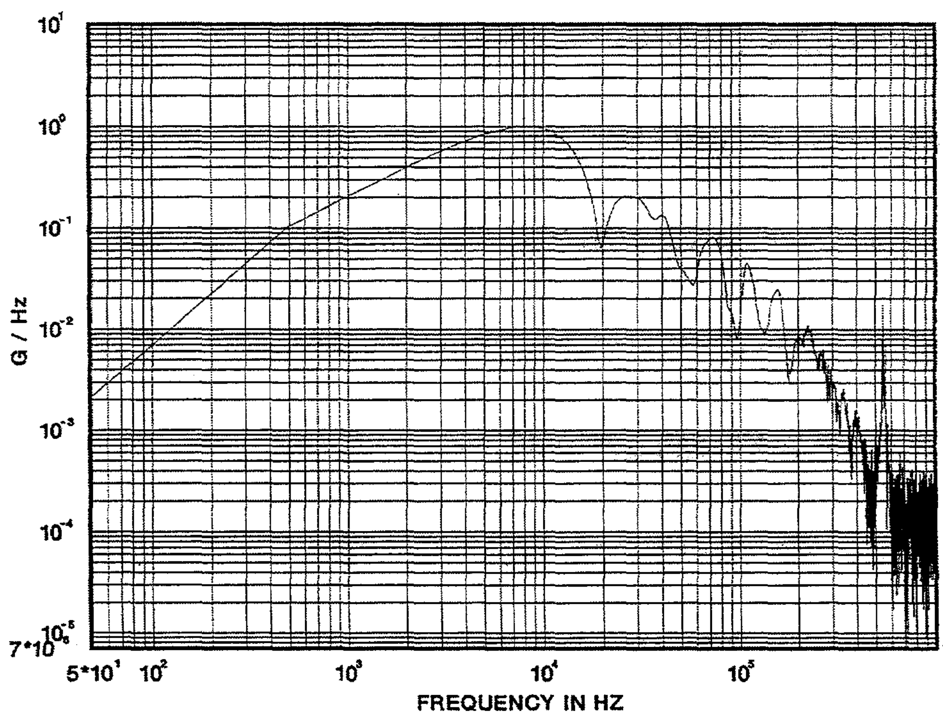


Figure 5: Exploded View of Initial SNL Mechanical Isolator Design.



a) Acceleration Time History



b) Fourier Transform

Figure 6: Unacceptable Response of Initial SNL Mechanical Isolator Design.

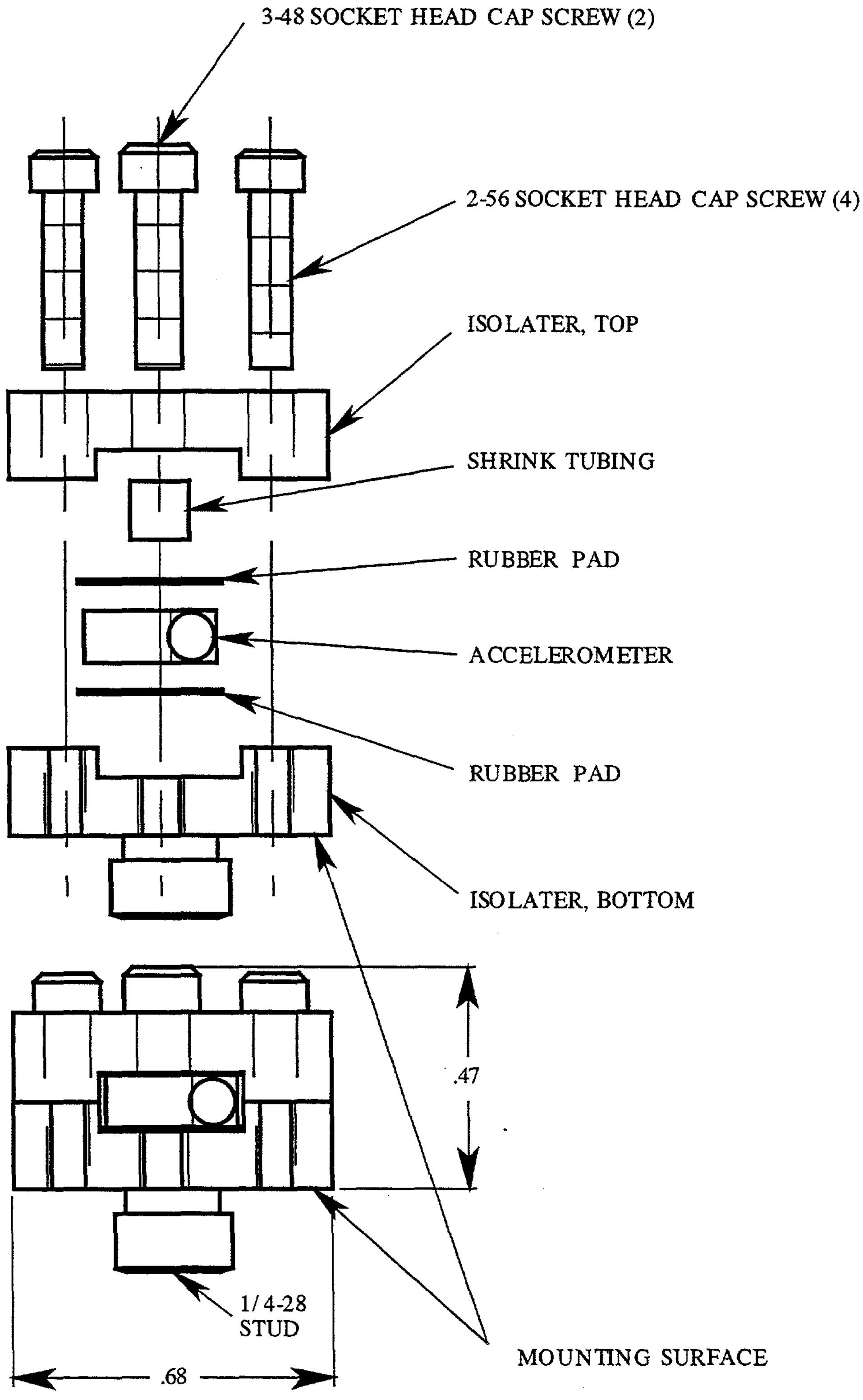


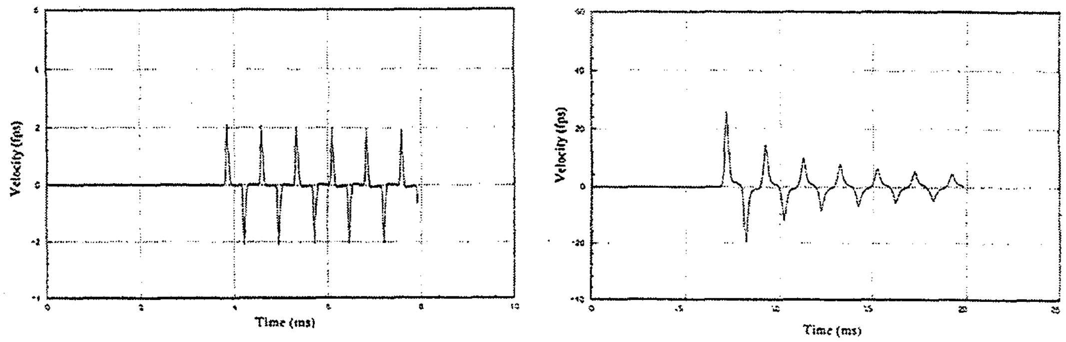
Figure 7: Exploded View of Improved SNL Mechanical Isolator with Acceptable Performance to 60,000 g for DC-10 kHz.

isolator design, and no resonance was identified in the frequency range of 30-50 kHz where resonance response has been observed experimentally for the ENDEVCO 7270AM6. All resonance frequencies identified by finite element analyses are above 100 kHz. The characterization of the ENDEVCO 7270AM6 for the conditions shown in Tables I and II and results from shock environments other than impact comprise the remainder of this report.

Hopkinson Bar Configurations

The Hopkinson bar configuration for characterizing accelerometers for in-axis input is shown in Figure 3. Both titanium and beryllium materials were used for the ENDEVCO 7270AM6 characterization. In-axis input in this configuration is an acceleration that is normal to the mounting surface or parallel to the sensing axis and the integral mounting stud. A maximum shock magnitude of 200,000 g is used for the titanium bar to insure that the 6 AL, 4V titanium alloy (6% aluminum and 4% vanadium) does not yield. In this study, the titanium Hopkinson bar has a 0.75 in. diameter, 72 in. length, and a non-dispersive bandwidth of DC-10 kHz. Strain gages are used as the reference measurement for the titanium Hopkinson bar and have an uncertainty of +6% [11]. This titanium capability has been used to characterize the ENDEVCO 7270AM6 at acceleration levels up to 200,000 g [5].

A maximum shock magnitude of 70,000 g is used for the beryllium bar to insure that the beryllium (99% pure) does not yield because it is a health hazard in particle form. In this study, the beryllium Hopkinson bars have a 50 in. length, 0.75 and 2.0 in. diameters, and a non-dispersive bandwidth of DC-50 kHz. A Laser Doppler Velocimeter (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. The LDV 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. Since these piezoresistive accelerometers have resonance at these high frequencies of 100's of kHz, the LDV is a useful diagnostic tool. Ref. [12] gives the details of the certification process. Strain gages cannot be used as the reference measurement for the beryllium bar because its response exhibits two anomalies that are shown in Figure 8: the high rate of damping and the non-return to zero of the stress time history.



Titanium Bar **Beryllium Bar**

Figure 8: Beryllium Hopkinson Bar Strain Anomalies.

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 a bar was investigated [13] for use with the beryllium bar. However, it was found that the Hopkinson bar material for this configuration is limited to aluminum that closely matches the impedance of the quartz crystal.

Cross-axis sensitivity of the piezoresistive accelerometers has been studied with the beryllium split Hopkinson bar configurations shown in Figure 9. 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 but is perpendicular to the to the direction of the shock. With beryllium's Poisson's ratio of 0.07, the cross-axis performance is obtained with negligible motion in the accelerometer's sensitive axis. No special preparations of the beryllium Hopkinson bar interfaces with the inserts are made other than insuring that the surfaces are flat and polished. Strain gages are used as the reference measurement for the cross-axis Hopkinson bar configuration and have an uncertainty of +6% [11]. A picture of the beryllium insert with instrumentation is in Figure 10.

Another configuration for cross-axis characterizations with the accelerometers mounted normal to the stress wave at the end of the bar was investigated [4]. However, this approach was abandoned because the resonance at the end of the bar is about 120 kHz and caused the accelerometers to resonate and break. The split Hopkinson bar configuration avoids the resonance at the end of the bar and is easily modified to accommodate different mounting requirements for a variety of sensors.

Careful alignment of the bars with projectiles and/or inserts is required. All Hopkinson bars used for the results shown in this paper are freely supported. A low pressure air gun is used to fire a 3 inch long hardened tool steel (for titanium) or magnesium (for beryllium) projectile at the end of the bar. This impact creates a stress pulse that propagates toward the opposite end of the Hopkinson bar. Regulating the air gun pressure that determines the impact speed controls the amplitude of the velocity pulse. Placing a number of index cards on the impact surface controls the shape (approximately a half sine) and duration of the velocity pulse.

All accelerometers in this study were calibrated in the SNL Calibration Laboratory using two methods: 1) shaker calibration and 2) dropball calibration. The two methods are traceable to the National Institute of Standards and Technology, NIST, formerly National Bureau of Standards (NBS) as described elsewhere [14].

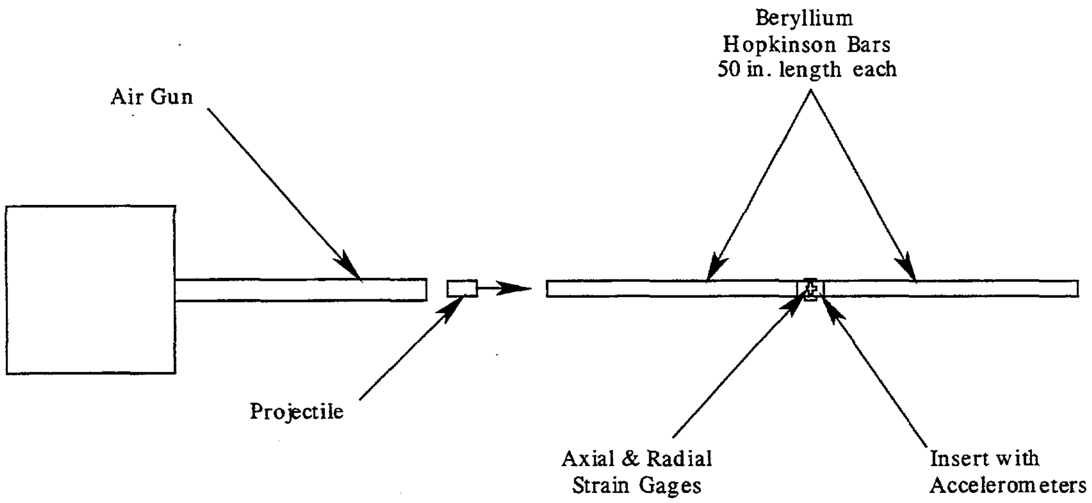
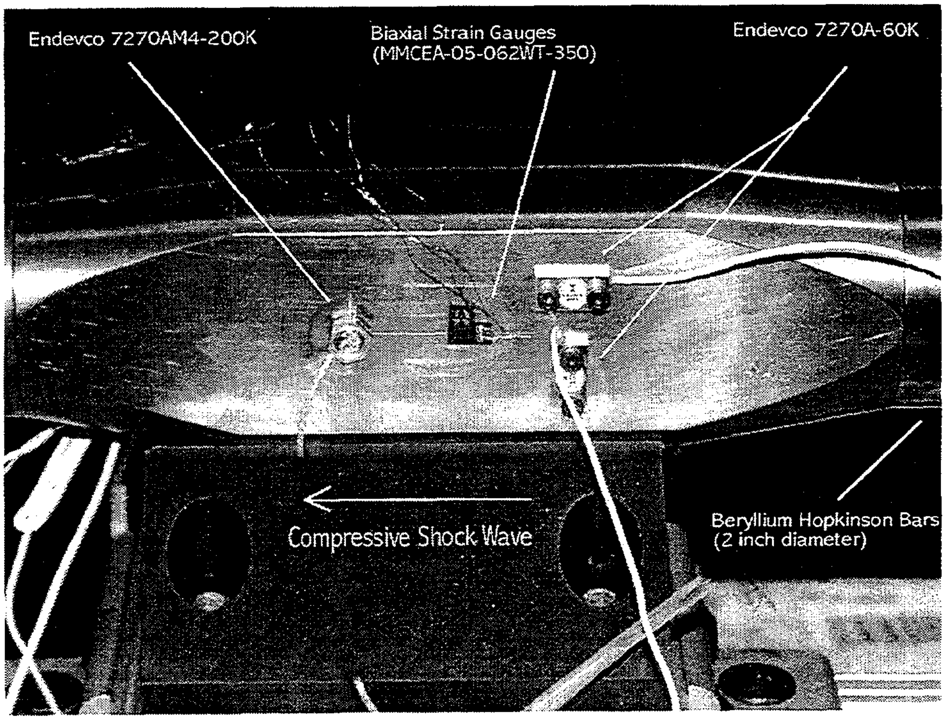


Figure 9: Split Beryllium Hopkinson Bar Configuration for Cross-Axis Input (2.0 in. Diameter).



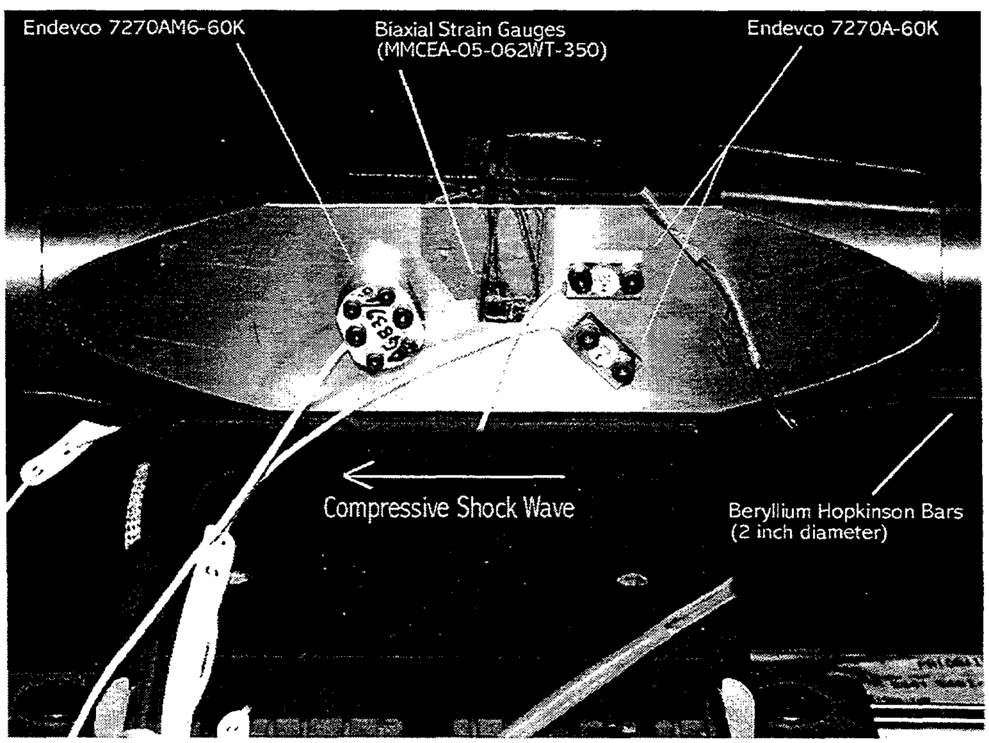


Figure 10: Two Flats on the Beryllium Insert for Static Compression and Mechanical Compressive Shock Cross-Axis Experiments (2 in. Diameter).

Hopkinson Bar Analysis for In-Axis Response

The theory of stress wave propagation in a Hopkinson bar is well documented in the literature [15, 16]. 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:
>
> $$v = 2c\varepsilon \tag{1}$$
>
> or,
>
> $$a = 2c\frac{d\varepsilon}{dt} \tag{2}$$
>
> where,
>
> $$c = \sqrt{\frac{E}{\rho}} \tag{3}$$
>
> 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 is 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.

Both time domain calculations, as a percent difference from the reference measurement (LDV or strain gages), and frequency domain calculations, as frequency response functions, are made with the Hopkinson bar data.

The magnitude, phase and coherence of frequency response functions were calculated so that a quantitative evaluation could be made of the frequency response for the ENDEVCO 7270AM6. The reference acceleration data, calculated from either strain gages or the LDV, and the accelerometer response data were used to calculate a frf, H(jω), using the equations below [17].

$$H(j\omega) = \frac{H_1 + H_2}{2} \tag{4}$$

where,

$$H_1(j\omega) = \frac{\sum_{n=1}^{5} G_{xy}}{\sum_{n=1}^{5} G_{xx}} \tag{5}$$

and

$$H_2(j\omega) = \frac{\sum_{n=1}^{5} G_{yy}}{\sum_{n=1}^{5} G_{yx}} \tag{6}$$

and where G_{xy} is the cross-spectrum between the reference acceleration, x, and the accelerometer response, y; G_{yx} is the cross-spectrum between the accelerometer response, y, and the reference acceleration, x; G_{yy} is the auto-spectrum of the accelerometer response, y; and G_{xx} is the auto-spectrum of the reference acceleration, x. The frf, H_1 is biased by the error on the reference acceleration, and the frf, H_2 is biased by the error on the accelerometer response. The Hopkinson bar data for these frf calculations have noise on both the reference acceleration and the accelerometer response, so the average of the two frf's in (4) is used. The summations are performed for the ensemble of five reference accelerations and their corresponding accelerometer responses. The coherence, $\gamma^2_{xy}(j\omega)$, was also calculated for an ensemble of five data sets according to the equation [17],

$$\gamma^2_{xy}(j\omega) = \frac{H_1}{H_2} \tag{7}$$

as a measure of the linearity between the reference acceleration and the accelerometer response and of the noise in these data.

Hopkinson Bar Analysis for Cross-Axis Response

The axial motion, a, at a location in the Hopkinson bar other than the free end is [18]

$$a = c\frac{d\varepsilon}{dt} \quad (8)$$

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

$$y = r\varepsilon_r \quad (9)$$

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

$$\varepsilon_r = \mu\varepsilon \quad (10)$$

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

$$a_y = \frac{\mu r}{c}\frac{da}{dt}. \quad (11)$$

A prediction of the axial and radial acceleration for the beryllium Hopkinson bar using the equations above is shown in Figure 11. Strain measurements co-located with the ENDEVCO 7270AM6 on insert of Fig. 10 in the split Hopkinson bar configuration are shown in Figures 12 and 13 and indicate a Poisson's ratio of about 0.07.

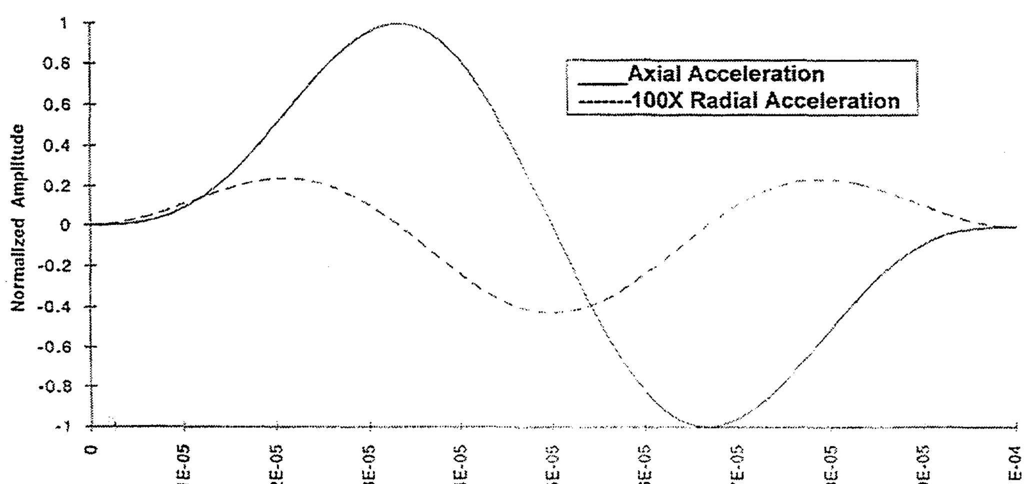


Figure 11: Theoretical Prediction of Axial and Lateral Accelerations for the Beryllium Hopkinson Bar.

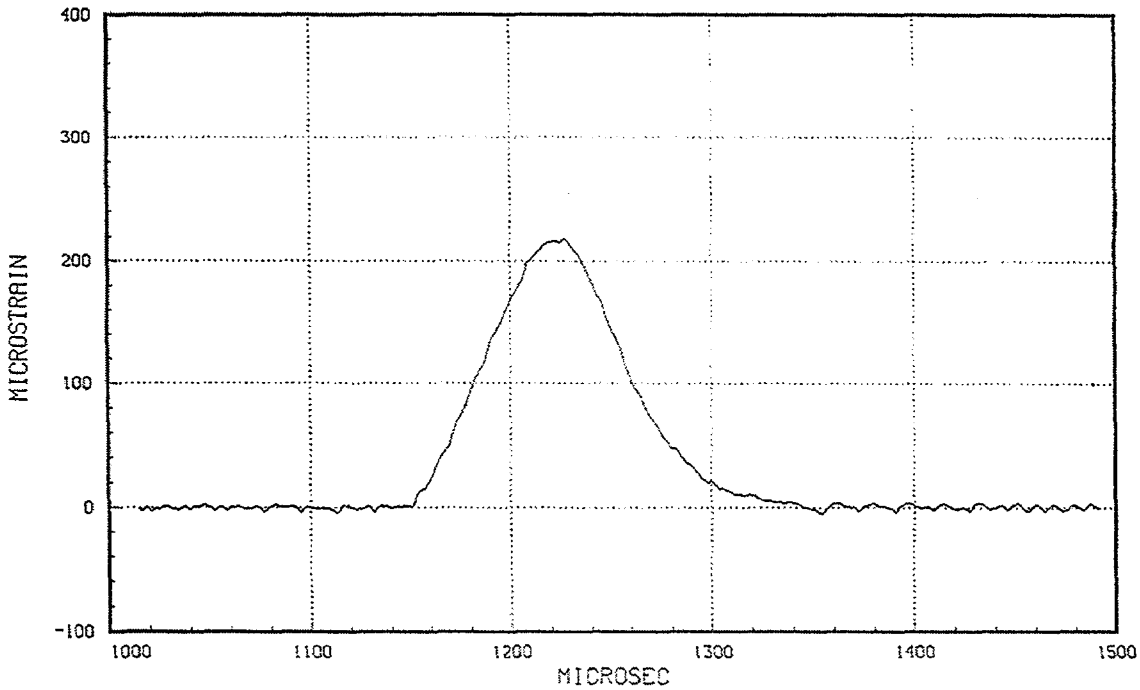


Figure 12: Axial Strain on the Beryllium Insert.

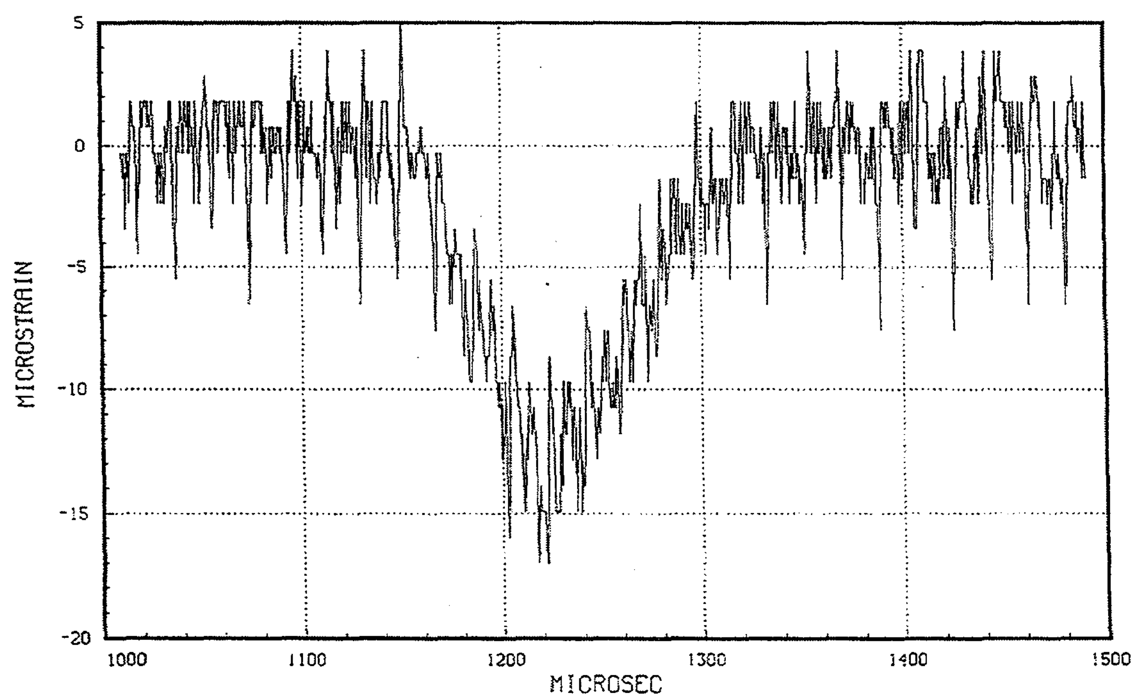


Figure 13: Lateral Strain on the Beryllium Insert.

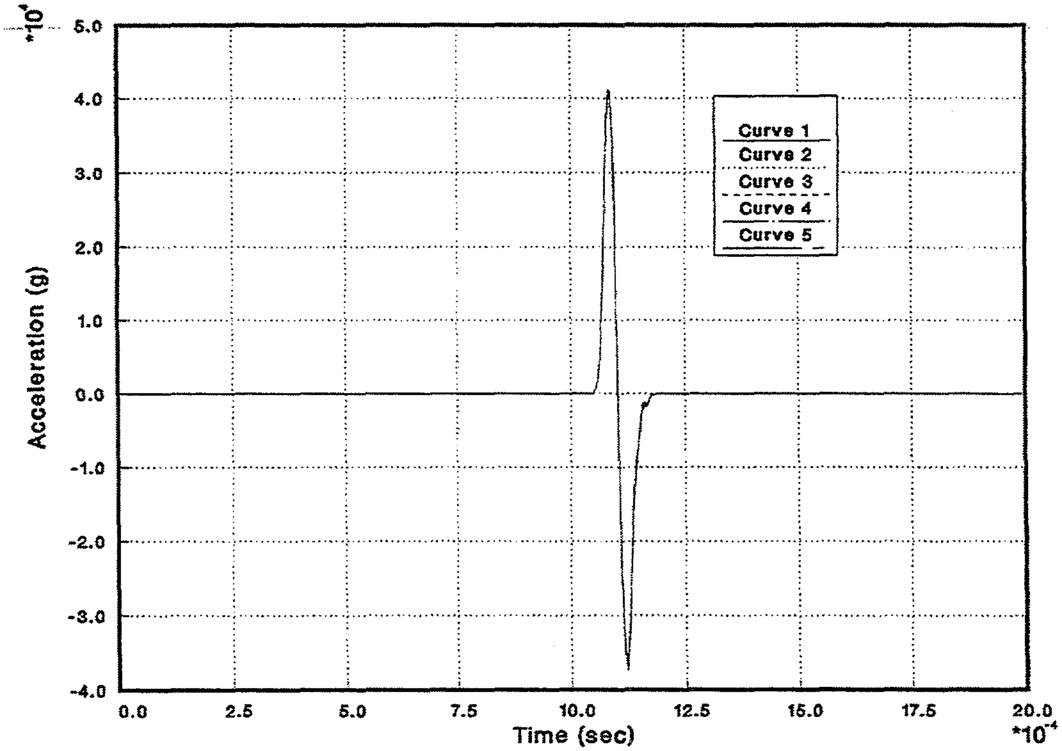
In-Axis Isolated Accelerometer Performance

The in-axis titanium Hopkinson bar testing was conducted for the final mechanical isolator design at shock levels of 20,000 g, 40,000 g, and 60,000 g for a duration of about 40 μs and for temperatures of -65°F, ambient (70°F), and +185°F. Figure 14 shows the consistent time history data that is required for the frequency response function analyses of these data. Appendix A shows the frequency response functions for temperatures of -65°F, ambient (70°F), and +185°F, respectively, with a non-dispersive bandwidth of DC to 10 kHz. The frequency response function magnitudes show less than four percent deviation for the three temperatures and the three shock levels. For these same conditions, the frequency response function phase changes are minimal.

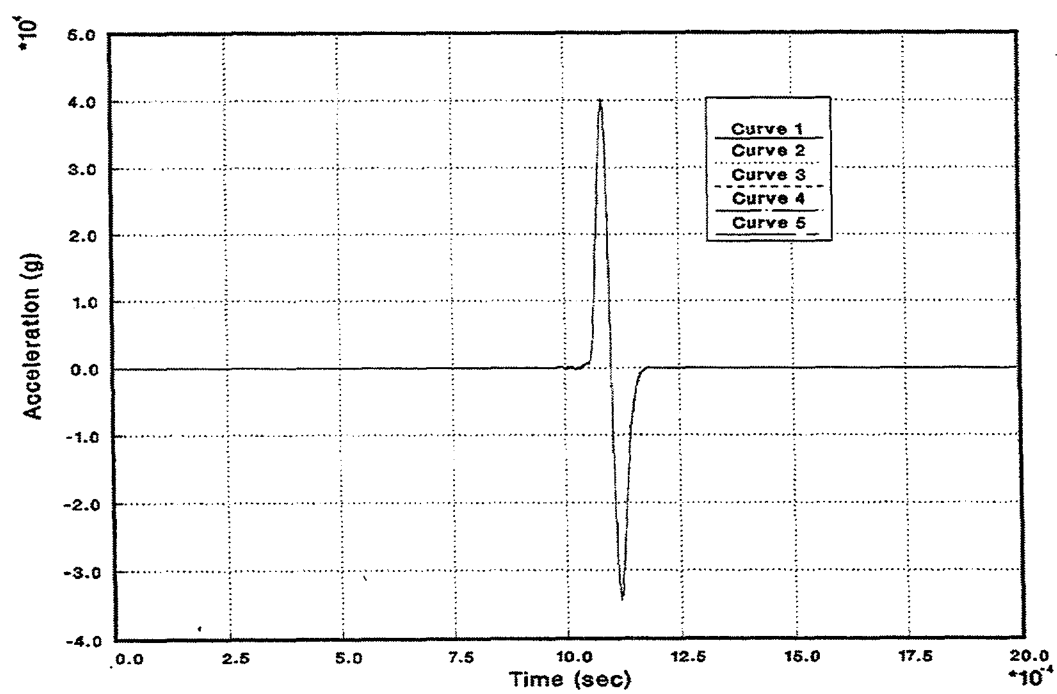
The frequency response function coherence plots confirm the quality of the data, and the coherence is acceptable to 20 kHz. The large deviations in magnitude and phase that occur above 10 kHz, are due to the loss of coherence at higher frequencies. The frequency at which the loss of coherence starts to effect the frequency response function is not known, but the large excursions in these functions above 10 kHz are not due to the ENDEVCO 7270AM6. Rather, the excursions occur because of differences between small numbers at these frequencies in the autospectrum for the Hopkinson bar acceleration and the cross-spectrum for the Hopkinson bar acceleration and the isolator response. These computational anomalies have been noted and discussed previously [1-6, 10-12], and the frequency response functions are useable to at least 10 kHz and above.

Even though additional testing was conducted with acceptable results up to 70,000 g at ambient temperature, the acceleration level of 60,000 g is the maximum recommended upper limit for this isolator design over the temperature range of -65°F to +185°F. The original intention was to reach levels of 200,000 g, but the 200,000 g acceleration level does not appear to be achievable with this design approach. In order to reach 200,000 g, an increase in the isolator weight and consequently, a decrease of the useable frequency range would be required.

In an attempt to characterize the resonance for the ENDEVCO 7270AM6, it was mounted on the end of a 2.0 in. diameter beryllium Hopkinson bar with a ¼-28 threaded hole in the in-axis orientation as shown in Figure 3. 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. 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



a) Hopkinson Bar Acceleration



b) ENDEVCO 7270AM6 Response

Figure 14: Consistent Hopkinson Bar Time History Data Used for Frequency Response Function Calculations (40,000 g at Ambient Temperature).

ENDEVCO 7270AM6 that has a higher weight of 8.4 grams. The corresponding frequency response functions are shown in Appendix A.

Although the first (lowest) ENDEVCO 7270AM6 resonance was not identified in these beryllium Hopkinson tests, a resonance has been observed in other experiments. Experiments conducted in Germany subjected the ENDEVCO 7270AM6, mounted on a steel plate, to shock from 50 grams of C-4. The ENDEVCO 7270AM6 exhibited a resonance at 48 kHz. The ENDEVCO 7270AM6 was also subjected to explosive shock from 1000 grams of C-4 in the same configuration. The explosive tests are described in Appendix B that shows excellent performance and survival for the ENDEVCO 7270AM6 in ballistic shock environments.

The performance of two isolated accelerometers, the Bobkat Isolator for the ENDEVCO 7270A [19] and the ENDEVCO 7255 are presented in the form of frf's in Appendix C. The frf's were calculated from Hopkinson bar in-axis tests using the configurations and equations described above. The tests were conducted on steel for the Bobkat and titanium for the ENDEVCO 7255 Hopkinson bars with peak amplitudes shown on the plots. Both isolators have resonance below 10kHz. The resonance *changes value with shock magnitude*, so both isolators are *non-linear* for the frequency range of DC-10kHz. Their useable frequency range is a maximum of DC to 1 kHz. Both the Bobkat Isolator for the ENDEVCO 7270A [19] and the ENDEVCO 7255 are available commercially.

TNO Building and Construction Research in The Netherlands performed an unsolicited, independent evaluation of the ENDEVCO 7270AM6. TNO evaluated the in-axis response for four isolators for the ENDEVCO 7270A, one of which was the ENDEVCO 7270AM6. TNO wants to measure structural response to underwater explosions that have high frequency content. The conclusion of their evaluation is that the ENDEVCO 7270AM6 performed the best for their applications. The evaluation report is in Appendix D. Finally, the performance specification for the ENDEVCO 7270AM6 is in Appendix E.

Cross-Axis Isolated Accelerometer Performance

The characterization of the cross-axis response of the ENDEVCO 7270AM6 accelerometer continued in the four environments of static compression experiments up to 82 με; static strain on a beam of 250 με; dynamic beam strain experiments at 250 με (as per ISA-RP 37.2, Paragraph 6.6); and mechanical compressive shock with a 2 in. diameter split Hopkinson bar configuration. The orientation of the sensors for the static compression and mechanical compressive shock cross-axis experiments are shown in Figure 10. Radial strain measurements verified the performance of the beryllium. Figure 15 shows the in-axis and Poisson strain as a function of applied load, and Figure 16 shows the 7270AM6-20K response (nominal 10 μV/g sensitivity) as a function of strain. For the static and dynamic base strain experiments, a steel beam as specified in ISA-RP 37.2, Paragraph 6.6 was used that creates maximum surface strain at the fixed end of a cantilever beam. The transducers mounted at this location are subjected to base strain. The base strain is one-dimensional surface strain because the beam has a very large radius of curvature that minimizes the motion at the transducer and the centrifugal acceleration, $r\omega^2$. The results of the static compression, static beam, and dynamic beam strain are shown in Tables III-V, respectively. The ENDEVCO 7270A-60K (flat package) and ENDEVCO 7270AM4-200K (can package) [6] results are included for comparison. The response of the ENDEVCO 7270A and ENDEVCO 7270AM4 accelerometers in these three environments is a base strain response and is consistent with the manufacturer's specifications of <0.5 mv output for a strain of 250 με. The response of the ENDEVCO 7270AM6 is much lower in these three environments because the ENDEVCO 7270A in the isolator mechanical case is essentially decoupled from the mounting surface.

The compressive acceleration shock applied to the ENDEVCO 7270AM6 is derived from the strain gages co-located with the ENDEVCO 7270AM6 as shown in Figure 10. The time history compressive acceleration shock has a magnitude of approximately 25,000 g as shown in Fig. 17. The ENDEVCO 7270AM6 response to compressive shock measured on the insert is $\pm$ 750 g or less for three, randomly chosen, orientations of 0°, 45°, and 55° as shown in Figs. 18-20. The cross-axis responses are 3% (30,000 Hz bandwidth) of the compressive perpendicular shock magnitude and are very consistent for the three orientations of the isolator perpendicular to the compressive shock. The frequency content of the ENDEVCO 7270AM6 cross-axis response is predominantly 20,000 Hz and 40,000 Hz. These two frequencies have not been observed for any other test conditions and are assumed to be rocking motion of the ENDEVCO 7270AM6, in the absence of other information. Since these frequencies are significantly beyond the specified bandwidth of DC-10kHz for the ENDEVCO 7270AM6 and the magnitude is a very small percentage of the compressive shock, the cross-axis response is considered minimal.

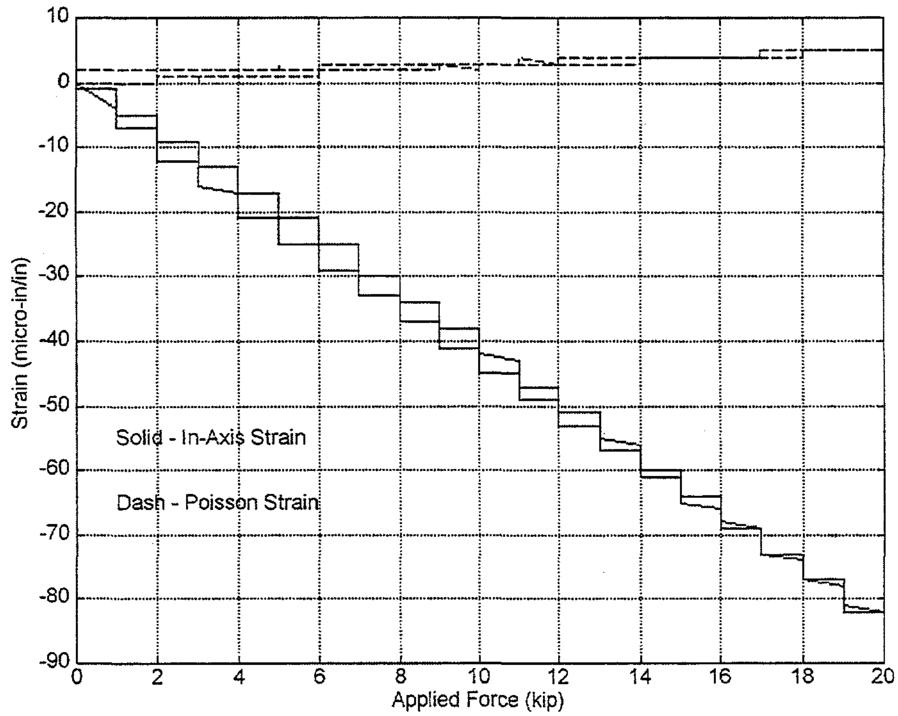


Figure 15: Strain Response on the Beryllium Insert (2 in. Diameter) Used for the Static Compression Experiments.

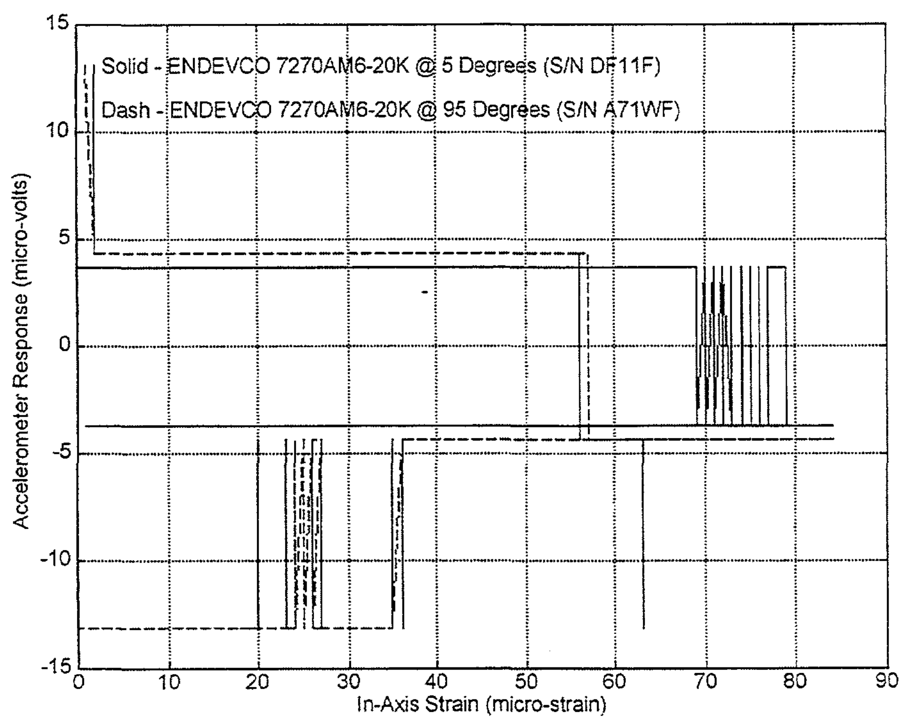


Figure 16: ENDEVCO 7270AM6 Response on the Beryllium Insert (2 in. Diameter) Used for the Static Compression Experiments.

Table III: Static Base Strain Results.

Accelerometer Type	Orientation	Torque (in-lb)	Strain Sensitivity (g/με)	Voltage output at 250 με (mv)
7270AM4-200K	80°	75	0.5816	0.187
7270AM4-200K	25°	75	0.0612	0.019
7270AM6-20K	5°	75	0.0188	0.045
7270AM6-20K	95°	75	0.0188	0.045
7270A-60K	In Line	9	0.1531	0.064
7270A-60K	45°	9	0.4184	0.166
7270A-60K	90°	9	0.3061	0.124

Table IV: Static Beam Results.

Accelerometer Type	Orientation	Torque (in-lb)	Strain Sensitivity (g/με)	Voltage output At 250 με (mv)
7270AM4-200K	In Line*	75	3.2260	1.090
7270AM4-200K	15°	75	0.2368	0.080
7270AM6-60K	15°	75	0.0070	0.006
7270A-60K	In Line	9	0.4232	0.175
7270A-60K	45°	9	0.6772	0.280
7270A-60K	90°	9	0.0943	0.039

* 0.009 in shim

Table V: Dynamic Beam Strain Results.

Accelerometer Type	Orientation	Torque (in-lb)	Strain Sensitivity (g/με)	Voltage output At 250 με (mv)
7270AM4-200K	In Line*	75	3.1370	1.060
7270AM4-200K	15°	75	0.5387	0.182
7270AM4-200K	15°	30	0.1717	0.058
7270AM6-60K	15°	75	0.0147	0.012
7270A-60K	In Line	9	0.3918	0.162
7270A-60K	90°	9	0.0435	0.018
7270A-60K	45°	9	0.5804	0.240

* 0.009 in shim

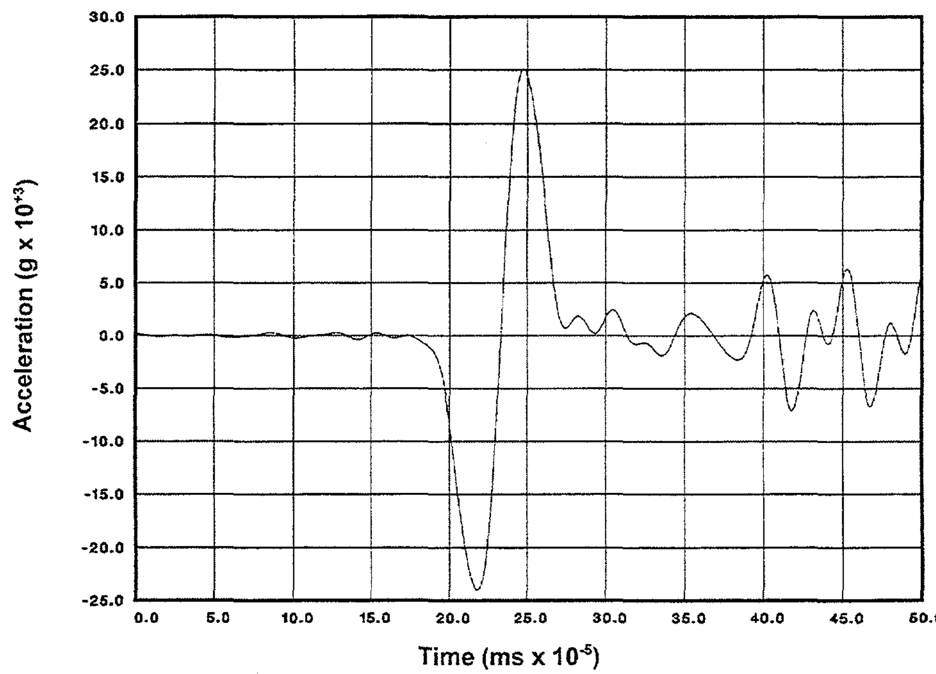


Figure 17: Compressive Acceleration Shock Measured on the Beryllium Insert.

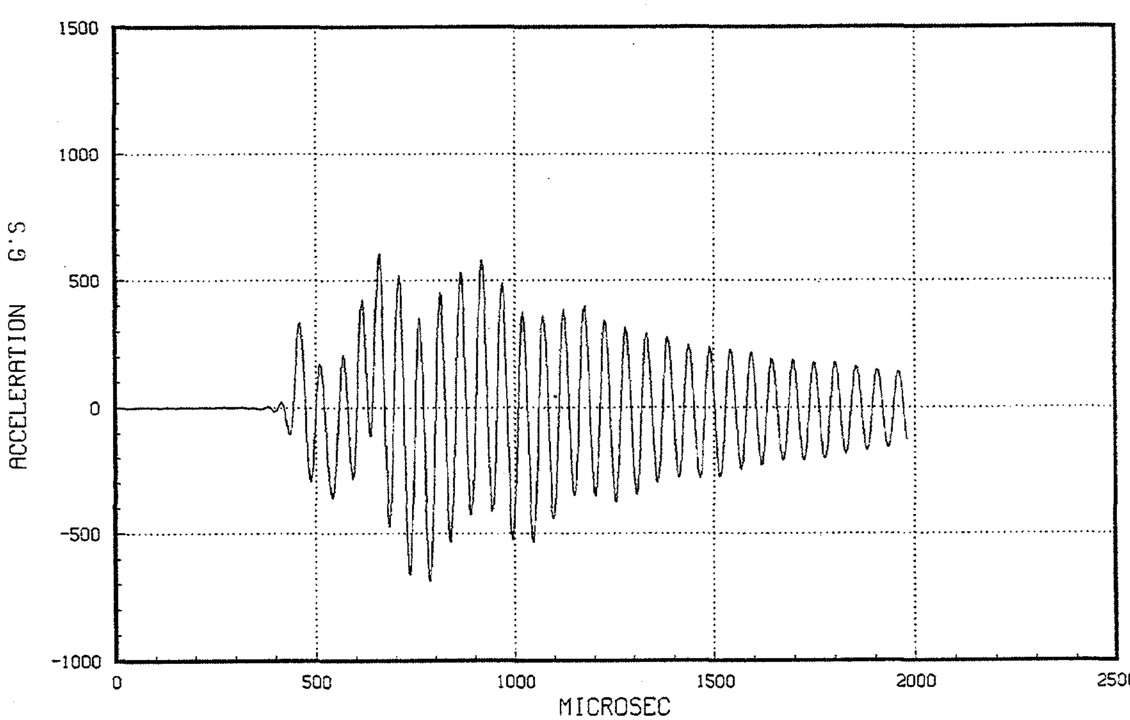


Figure 18: ENDEVCO 7270AM6 Compressive Shock Responses Measured on the Beryllium Insert (0 Degree Orientation).

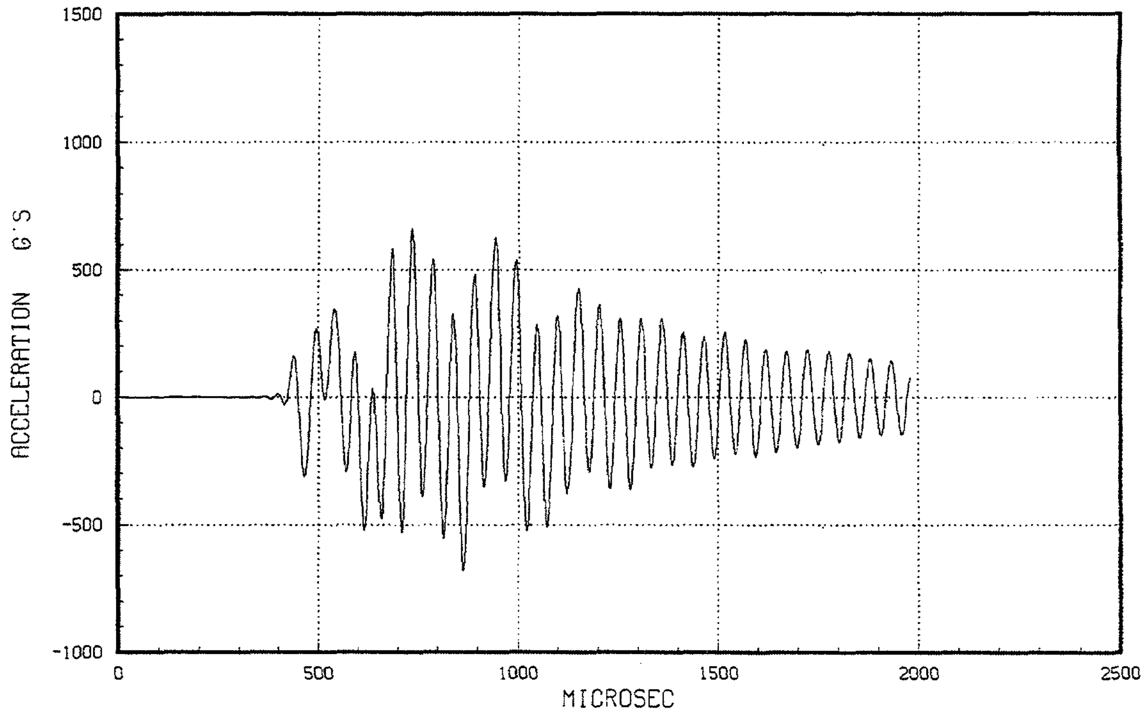


Figure 19: ENDEVCO 7270AM6 Compressive Shock Responses Measured on the Beryllium Insert (45 Degree Orientation).

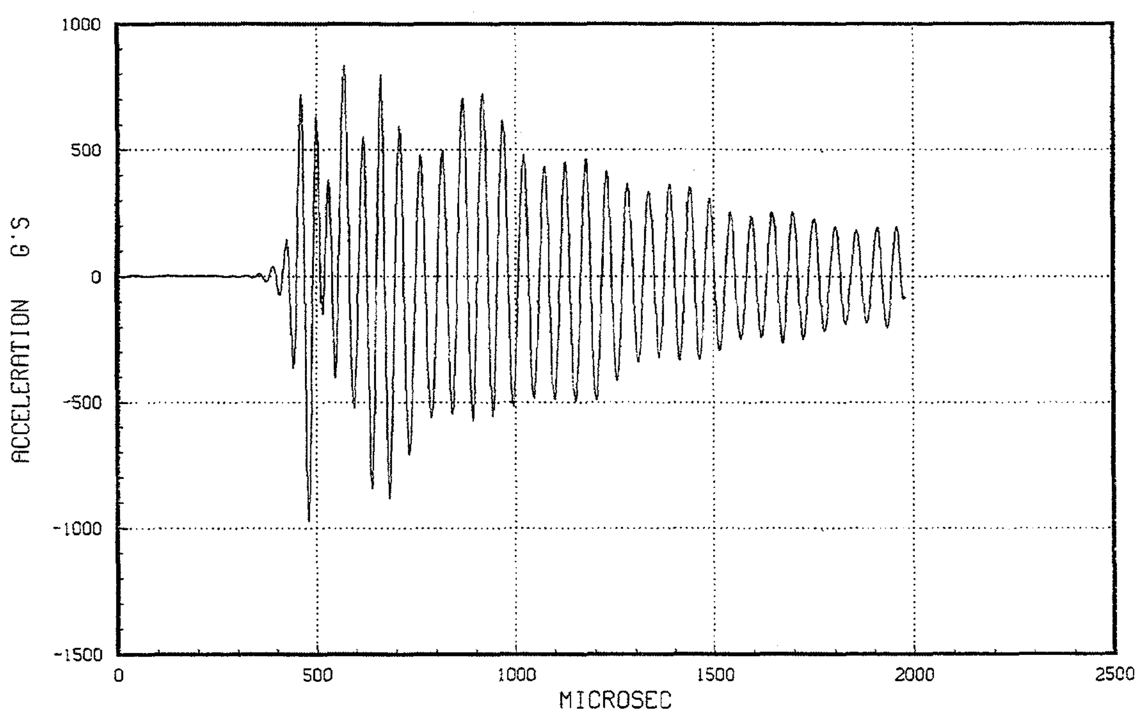


Figure 20: ENDEVCO 7270AM6 Compressive Shock Responses Measured on the Beryllium Insert (55 Degree Orientation).

Uncertainty Analysis

The uncertainty in these measurements and results are attributed to: uncertainty in the sensors, the reference measurement (strain gages or LDV), the data acquisition system, and accelerometer response due to variation in mounting torque. The sensor and data acquisition uncertainty is monitored on a continual basis in the SNL Mechanical Shock Laboratory as required by the SNL Specification 9958003 [13]. These requirements include the performance of both the hardware (sensors, amplifiers, digitizers etc.) and the IMPAX software that controls the data acquisition system through a computer [13,14,15]. The 9958003 specification allows an accuracy of $\pm$10% for amplitude, $\pm$5% for duration, and $\pm$8% for rise and fall time for any measured pulse greater than 50 μs in duration. The current data acquisition system and software meet these requirements within $\pm$0.5%, and documentation of these results is maintained in the Mechanical Shock Laboratory. Consequently, the uncertainty in these measurements is the uncertainty in the accelerometer calibration, $\pm$5% [14], the uncertainty of the reference measurement 6% [11, 12], and the uncertainty in the torque wrench calibration, $\pm$5% [6]. These three uncertainties are considered random, so they may be combined in an uncertainty analysis with a 95% confidence level as [24-25].

$$w_T = \sqrt{w_s^2 + w_{rf}^2 + w_t^2} \qquad (1)$$

where: w_T = total uncertainty,
w_s = accelerometer calibration uncertainty, 5%,
w_{rf}= uncertainty of the reference measurement, 6%, and
w_t = torque wrench calibration uncertainty, $\pm$5%.

The value of the total uncertainty, w_T, is $\pm$ 8% and is typical for the measurements made in the SNL Mechanical Shock Laboratory.

Conclusions

A mechanical isolator for a piezoresistive accelerometer, the ENDEVCO 7270AM6, has been developed at SNL , and has been transferred to ENDEVCO. The isolator has acceptable performance for shock levels of 20,000 g, 40,000 g, and 60,000 g and for temperatures of -65°F, ambient (70°F), and +185°F with a frequency bandwidth of DC to 10 kHz. The performance was determined by the magnitude, phase and coherence of frequency response functions calculated from in-axis Hopkinson bar data and cross-axis response in four environments. This mechanical isolator has <u>ten times</u> the bandwidth of any other commercial isolator as shown in Figure 2 and Appendix C. The mechanical isolator technology, that was developed in response to SNL impact and pyroshock test requirements shows an extended capability in some explosively generated ballistic and underwater shock environments as shown in Appendices B and D. The performance specifications for the ENDEVCO 7270AM6 are in Appendix E.

Acknowledgements

The authors would like to acknowledge the expertise of the SNL personnel in the Organic Materials Department, Mathew Donnelly and David Zamora, who developed a process and constructed the fixture for making the polysulfide rubber plaques. The authors would also like to thank Thomas J. Baca who provided a starting point, and R. Glenn Bell III, Neil T. Davie, and Patrick L. Walter for their contributions during the development of the isolator.

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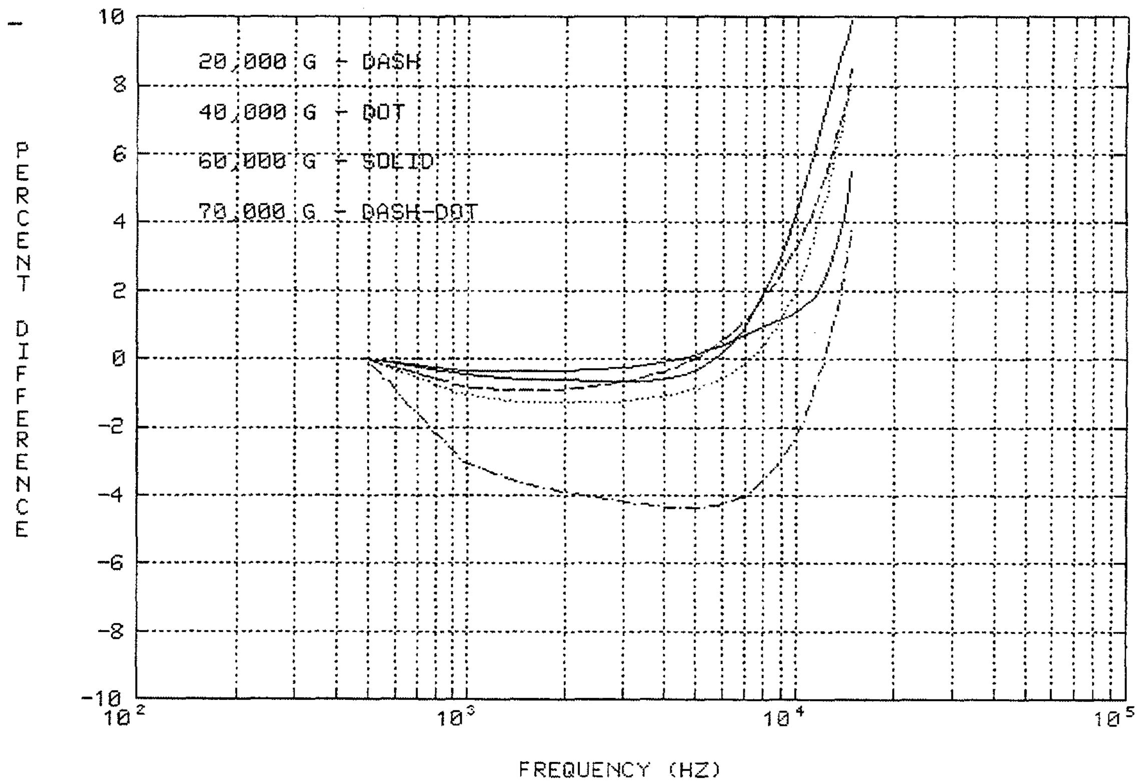
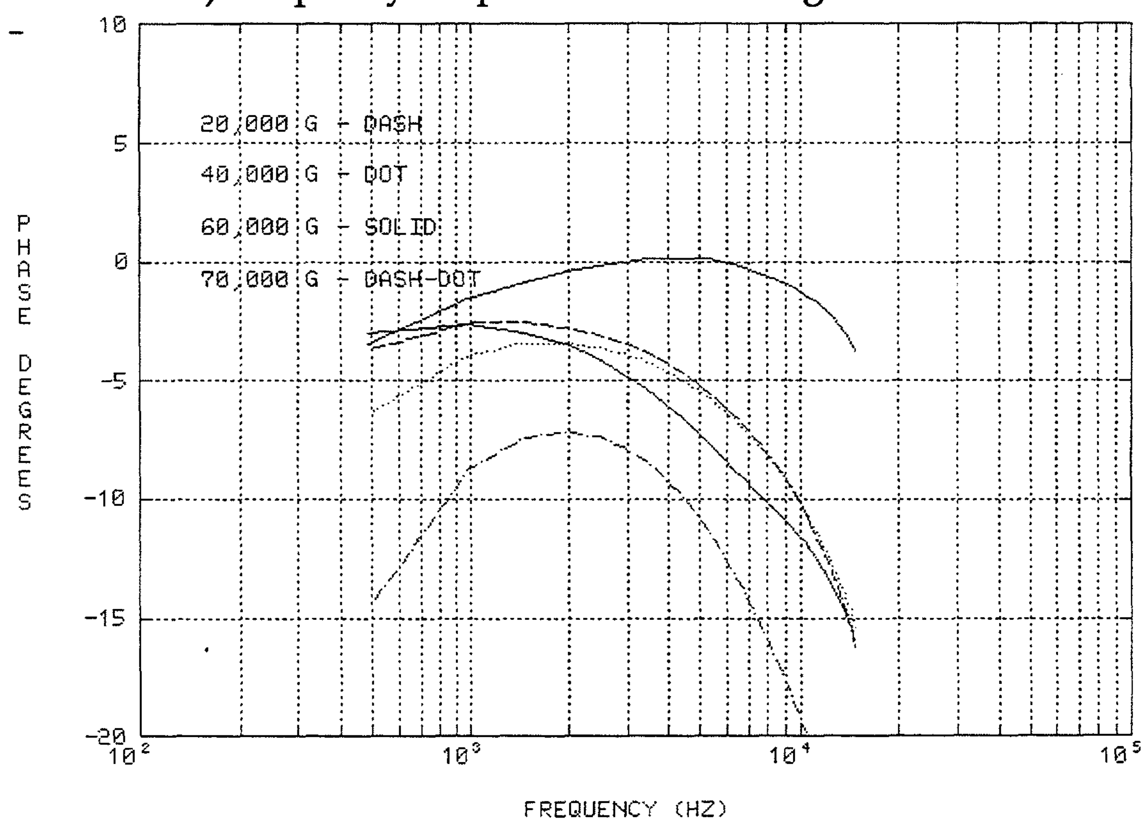
Appendix A

ENDEVCO 7270AM6

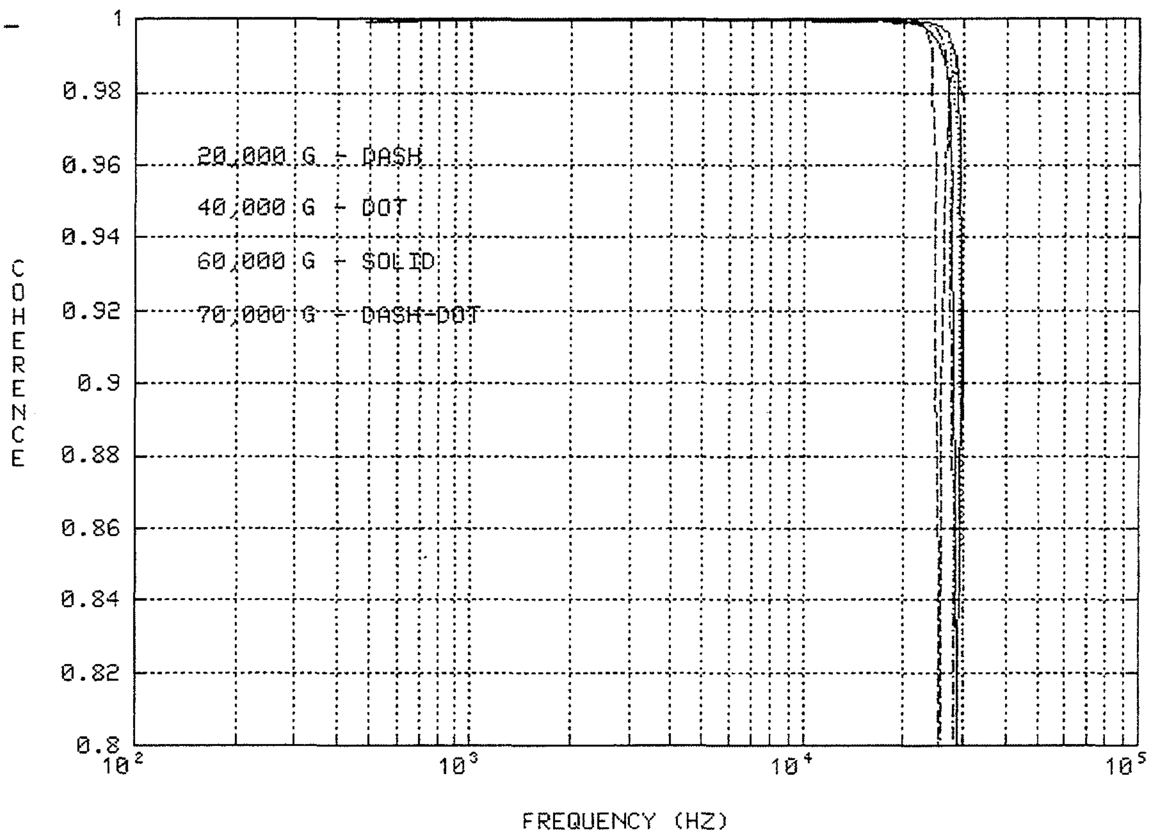
Frequency Response Functions



a) Frequency Response Function Magnitude

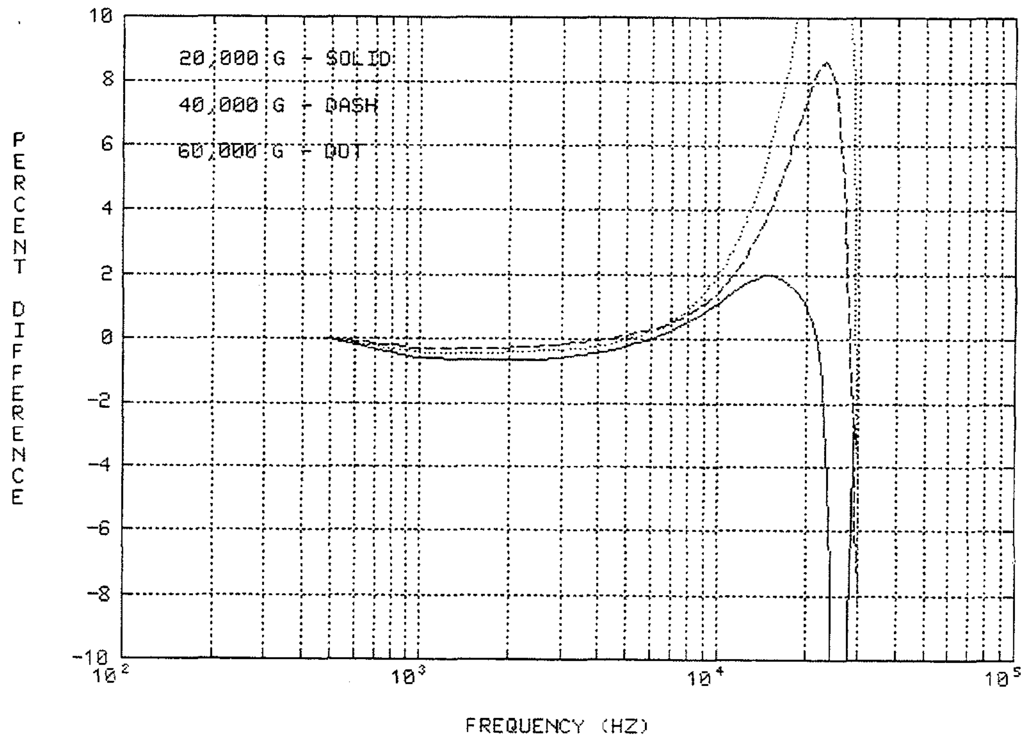


b) Frequency Response Function Phase

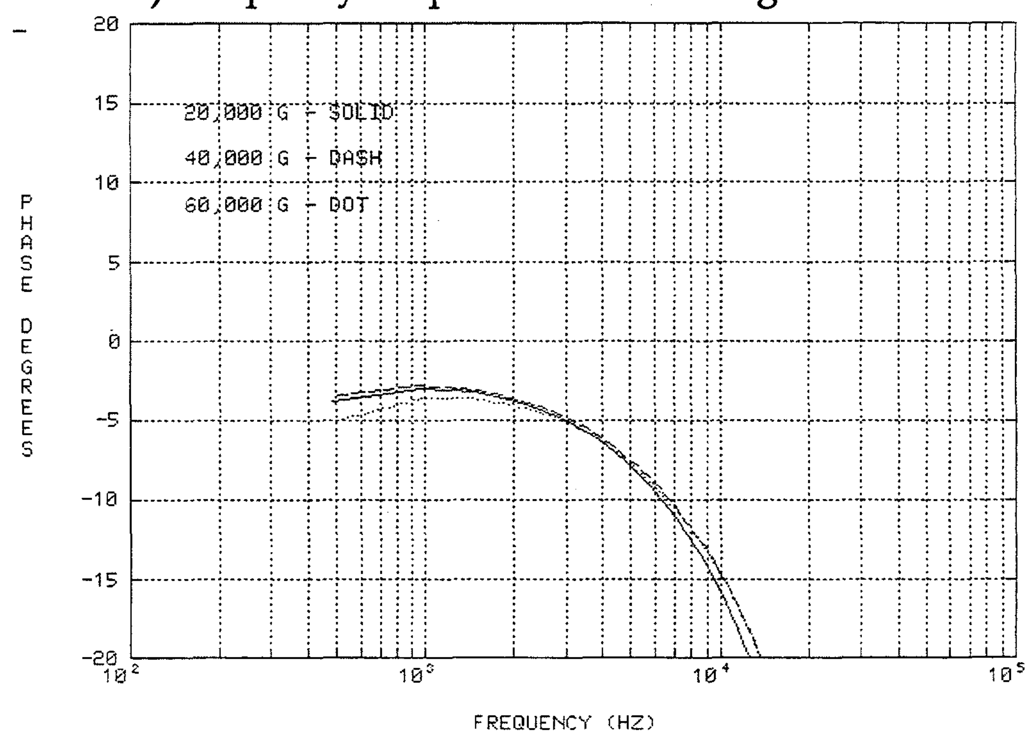


c) Frequency Response Function Coherence

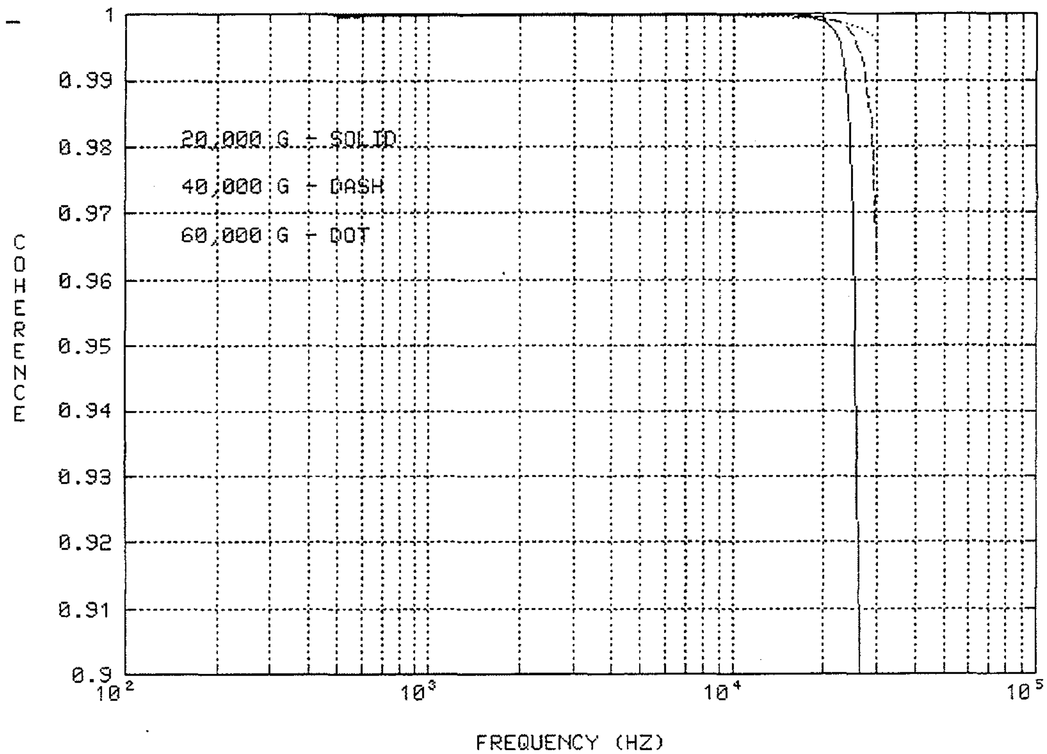
Frequency Response Functions at Ambient, 70°F as Measured with a Titanium Hopkinson Bar (DC-10 kHz Non-Dispersive Bandwidth).



a) Frequency Response Function Magnitude

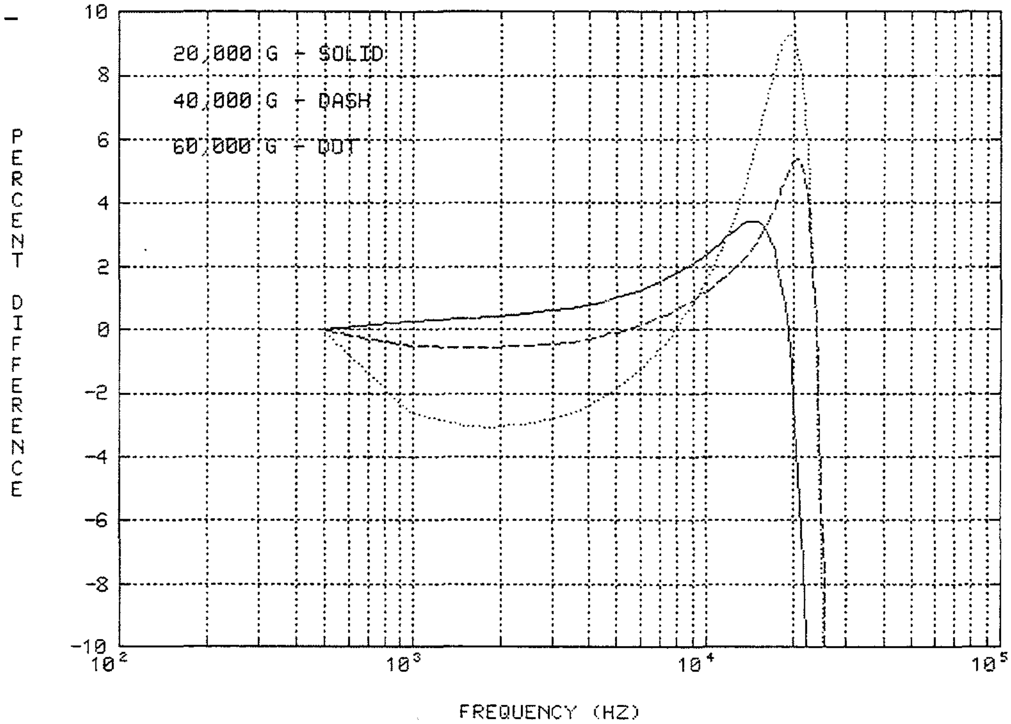


b) Frequency Response Function Phase

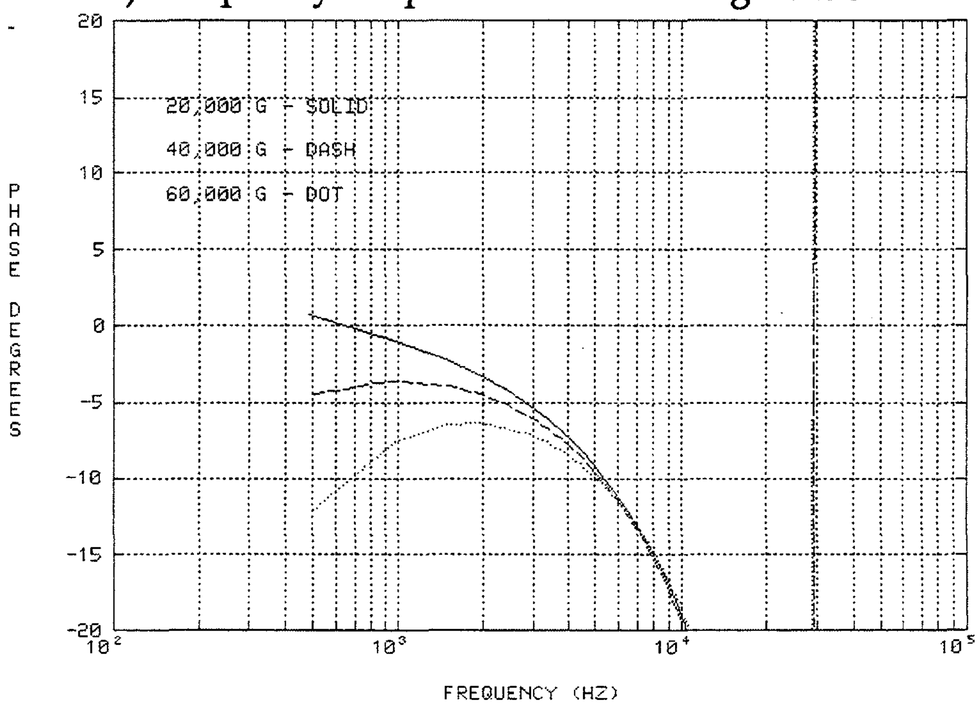


c) Frequency Response Function Coherence

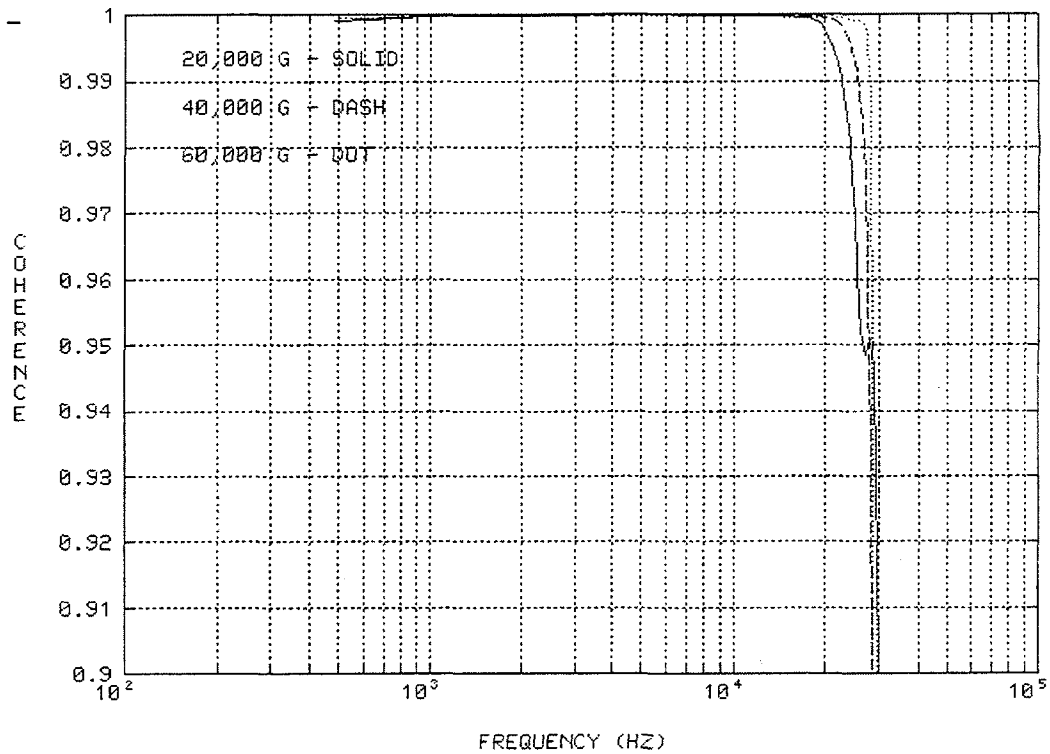
Frequency Response Functions at -65°F as Measured with a Titanium Hopkinson Bar (DC-10 kHz Non-Dispersive Bandwidth).



a) Frequency Response Function Magnitude

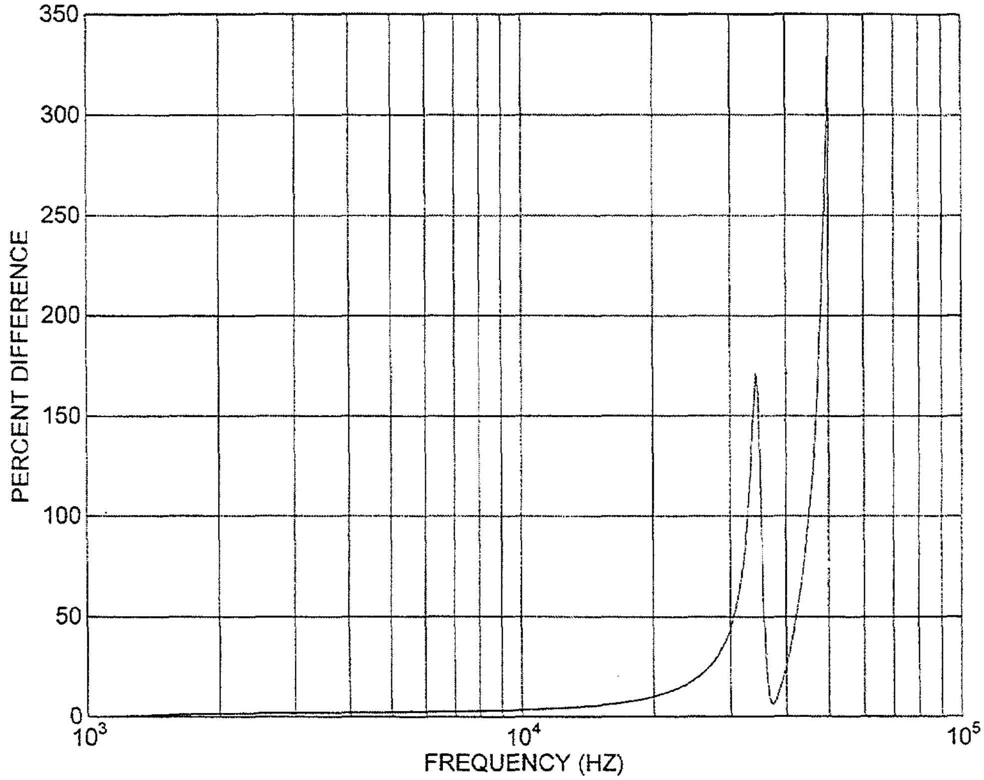


b) Frequency Response Function Phase

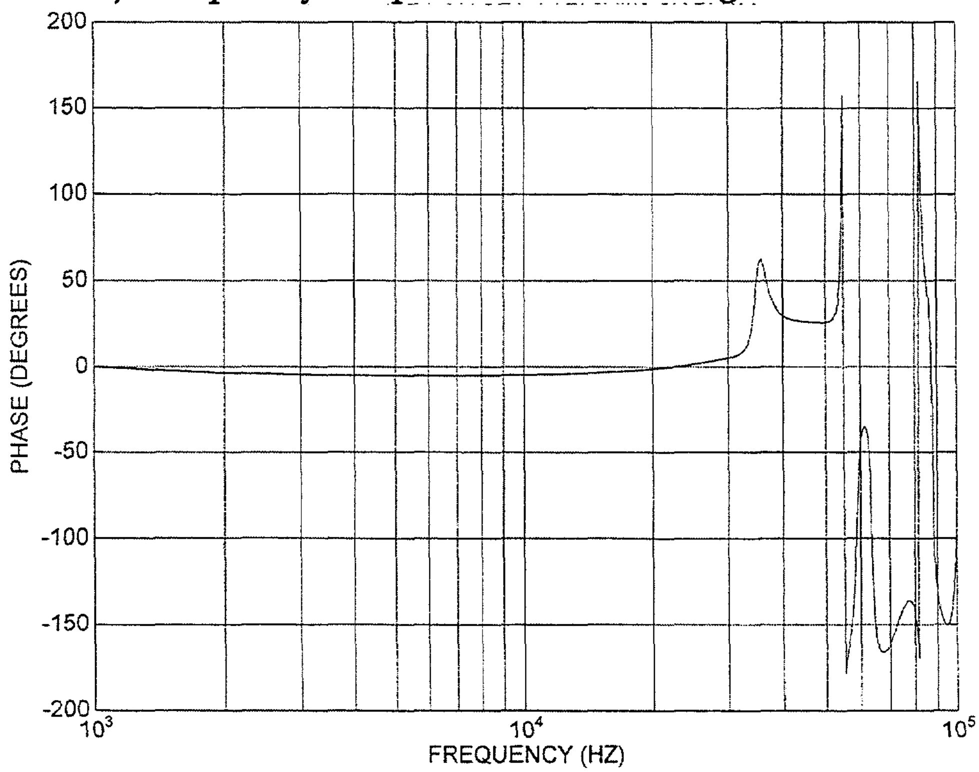


c) Frequency Response Function Coherence

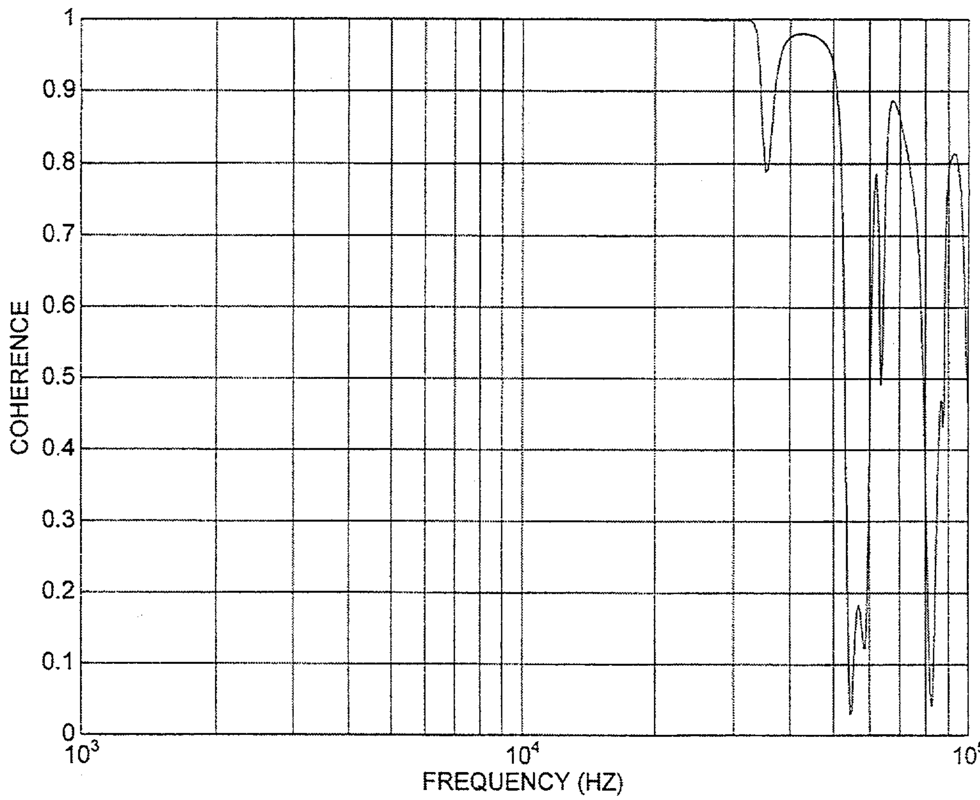
Frequency Response Functions at +185°F as Measured with a Titanium Hopkinson Bar (DC-10 kHz Non-Dispersive Bandwidth).



a) Frequency Response Function Magnitude



b) Frequency Response Function Phase



c) Frequency Response Function Coherence

Frequency Response Functions for the ENDEVCO 7270AM6 Mounted on a 2.0 in. Diameter Beryllium Hopkinson Bar (Ambient Temperature, DC-30 kHz Non-Dispersive Bandwidth).

Appendix B

ENDEVCO 7270AM6 in a Ballistic Shock Environment
International Explosive Tests in Germany

DEPARTMENT OF THE ARMY
U. S. ARMY ABERDEEN TEST CENTER
400 COLLERAN ROAD
ABERDEEN PROVING GROUND, MARYLAND 21005-5059

February 27, 1997

REPLY TO
ATTENTION OF

Ballistics Division

Dr. Vesta Bateman
Sandia National Laboratories
P.O. Box 5800, Mail Stop 0555
Albuquerque, NM 87185-5800

Dear Dr. Bateman:

The Aberdeen Test Center would like to thank you for fabricating a mechanical isolator for the 7270 accelerometer. This device was used to measure explosively generated "ballistic shock" at levels which are known to destroy hard mounted 7270 accelerometers and other standard, commercially available accelerometers.

The mechanically isolated accelerometer that you provided survived 5 test shots in Lechtenau, Germany and 7 test shots at Aberdeen Proving Ground without failure. Mr. Scott Walton (410-278-3396) and Mr. Michael Clark (410-278-5120) can provide further technical details.

Sincerely,

Jerold L. Nook
Director, Engineering Directorate

EXPLOSIVE TEST RESULTS FROM LICHTENAU, GERMANY

Sandia National Labs

TEST DESCRIPTIONS

1. The data on the SRS plot labeled "50 gram Germany" were generated in Germany on 22 May 96. The actual test was 50gm of C-4 with a 90mm standoff from the center of a small, flat steel plate. Dimensions of the plate were 460mm x 460mm x 40mm. All gages were mounted radially equidistant (127mm) from the center of the plate. The LOFFI record was generated by a mechanically filtered (600-Hz roll off) Endevco 2262A-2000. The BOBKAT record was generated from a mechanically filtered (8-kHz roll off) Endevco 7270A-6K. The ATC Velocity gage is Scott Walton's velocity gage design.

2. The data on the SRS plot labeled "1000 gram Germany" were generated in Germany on 22 May 96. The test consisted of detonating 1000gm of C-4 placed directly against the German Ballistic Shock Simulator (SBS). The explosive charge was placed against the front plate (which was perpendicular to the ground) of the simulator. The gages were mounted on a plate (parallel to the ground) that butted into the plate the explosive was placed against. The mass and geometry of the SBS is roughly equivalent to a turret of a main battle tank.

INSTRUMENTATION FOR EXPLOSIVE TESTS IN LICHTENAU, GERMANY

Sandia National Labs

50gm Against Flat Plate, 95mm Stand-off

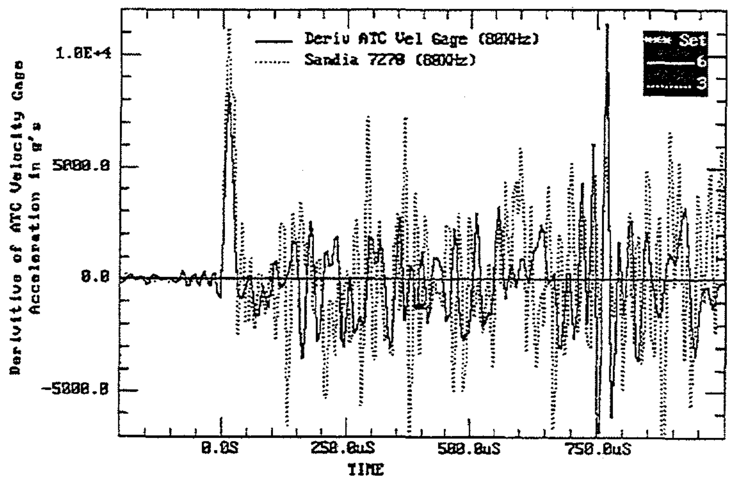
Gage Type	Gage Factor	Sample Rate	Anti-Alias
ATC Velocity Gage	9.56 $\frac{m/s}{V}$	200,000	80-kHz
BOBKAT (7270A)	36,032 g/V	200,000	80-kHz
LOFFI (2262A)	3,084 g/V	200,000	80-kHz
Sandia (7270A)	670,691 g/V	200,000	None

1000gm Against German Ballistic Shock Simulator (SBS), No Stand-off

Gage Type	Gage Factor	Sample Rate	Anti-Alias
ATC Velocity Gage	12.70 $\frac{m/s}{V}$	200,000	80-kHz
BOBKAT (7270A)	36,032 g/V	200,000	80-kHz
LOFFI (2262A)	3,084 g/V	200,000	80-kHz
Sandia (7270A)	599,520 g/V	200,000	None

ACCELERATION COMPARISON 50 GRAM TEST, 80 KHZ FILTER

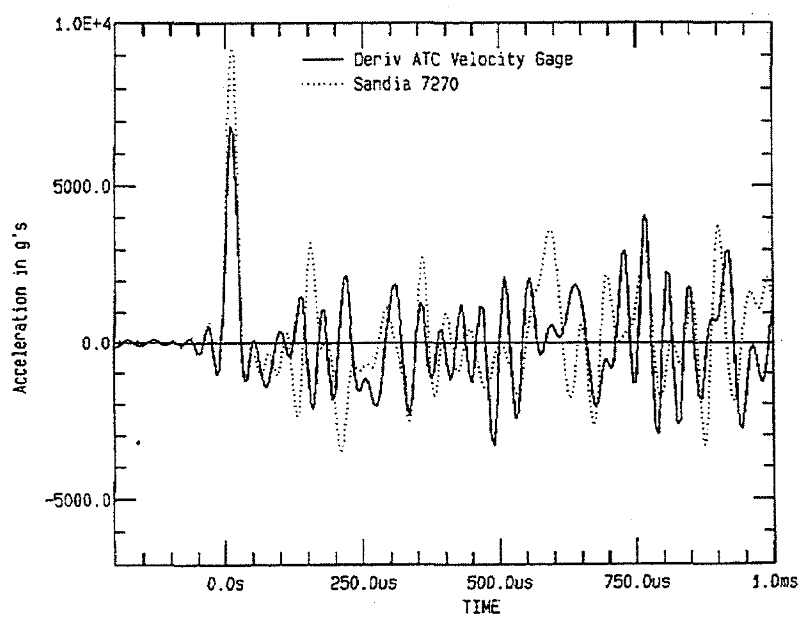
Sandia National Labs



Note: High Frequency on 7270A-AM6 is at 48 KHz.

ACCELERATION COMPARISON 50 GRAM TEST, 30 KHZ FILTER

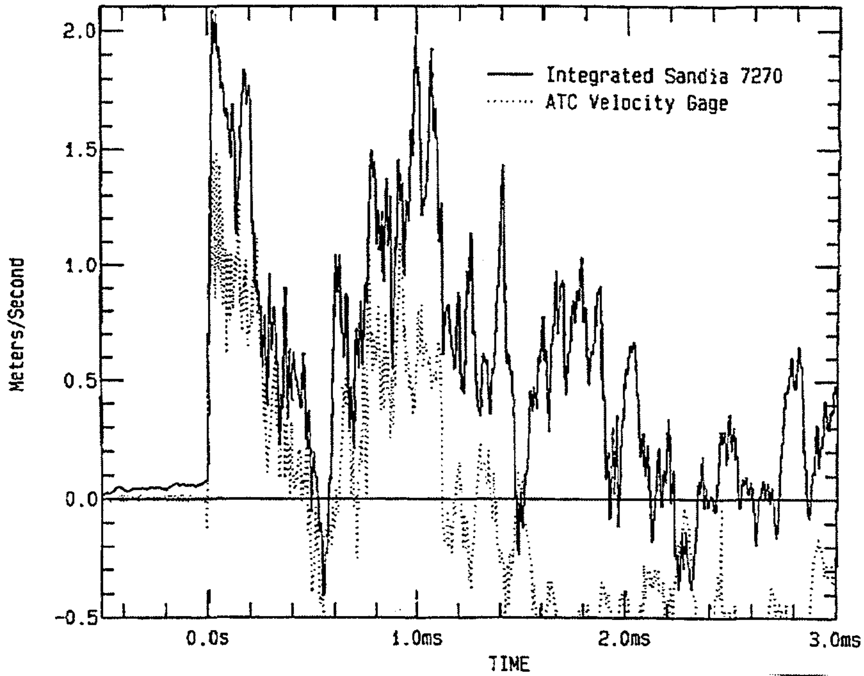
Sandia National Labs



For a bandwidth of 30 KHz, both signals are reasonable.

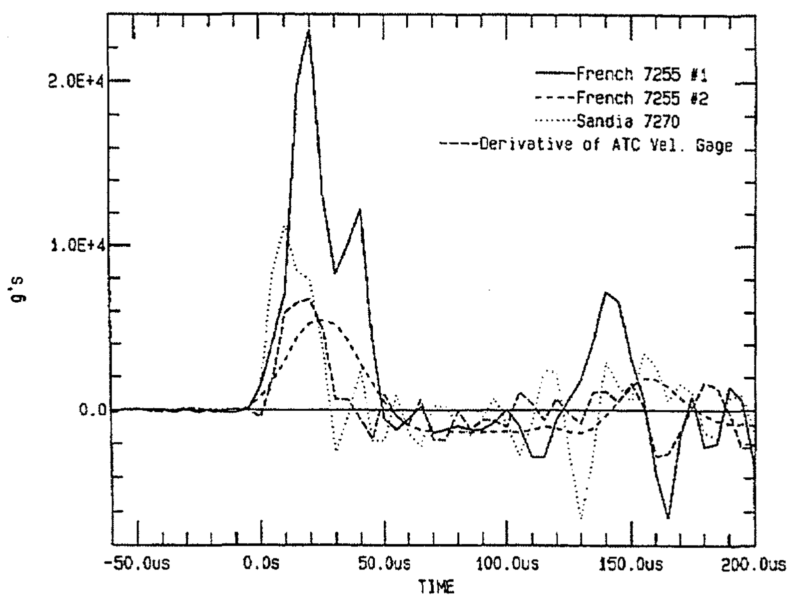
WIDEBAND VELOCITY COMPARISON - 50 GRAM TEST

Sandia National Labs



ACCELERATION COMPARISON 50 GRAM TEST, 30 KHZ FILTER

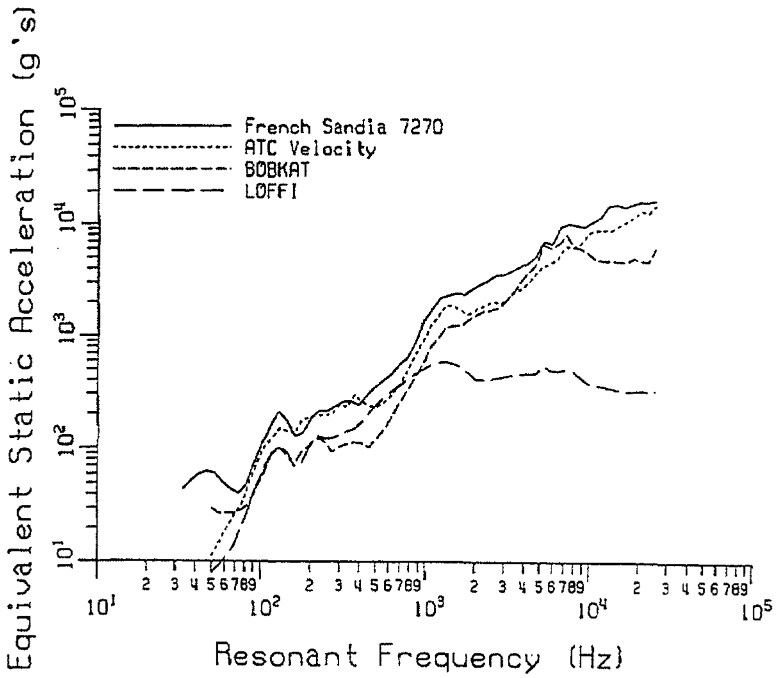
Sandia National Labs



Comparison shows 7255 #1 is clear outlier.

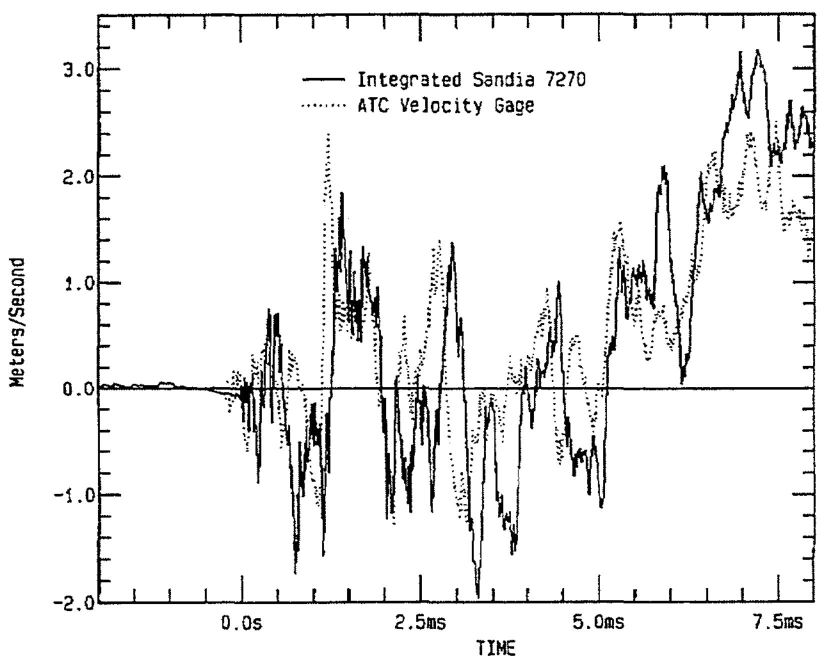
WIDEBAND SHOCK SPECTRA COMPARISON - 50 GRAM TEST

Sandia National Labs



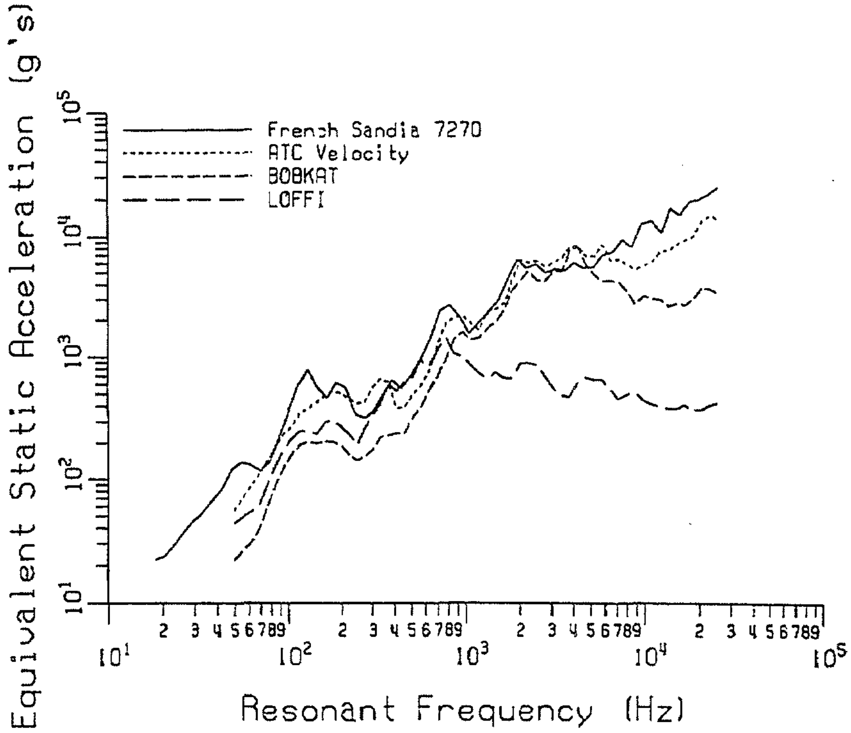
WIDEBAND VELOCITY COMPARISON - 1000 GRAM TEST

Sandia National Labs



WIDEBAND SHOCK SPECTRA COMPARISON - 1000 GRAM TEST

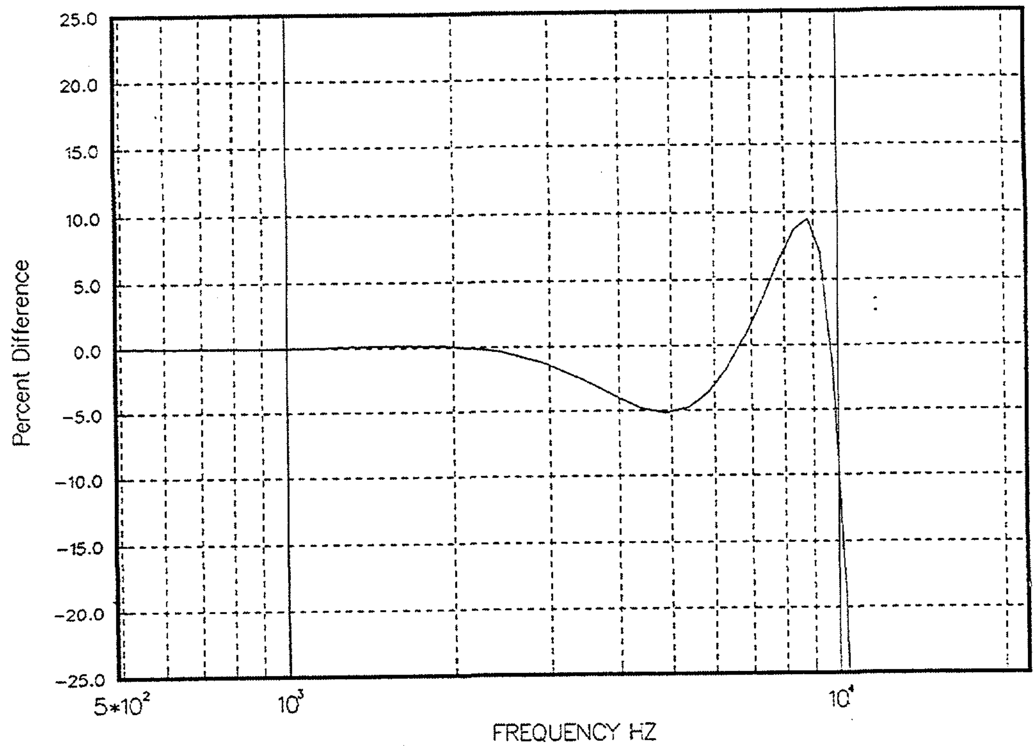
Sandia National Labs



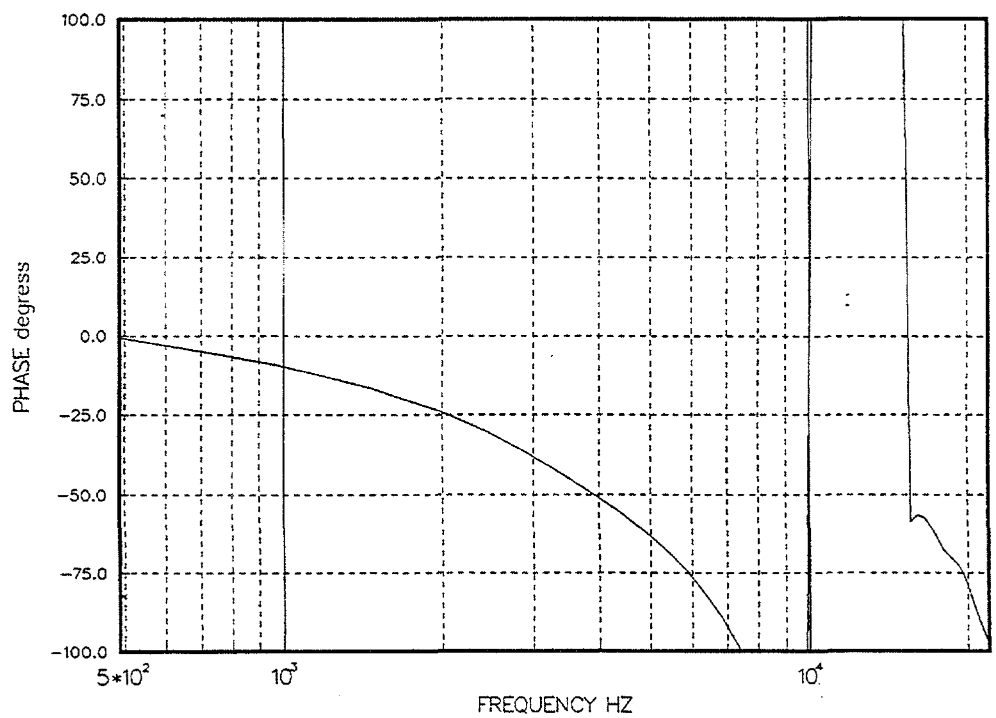
Appendix C

Bobkat Isolator and the ENDEVCO 7255

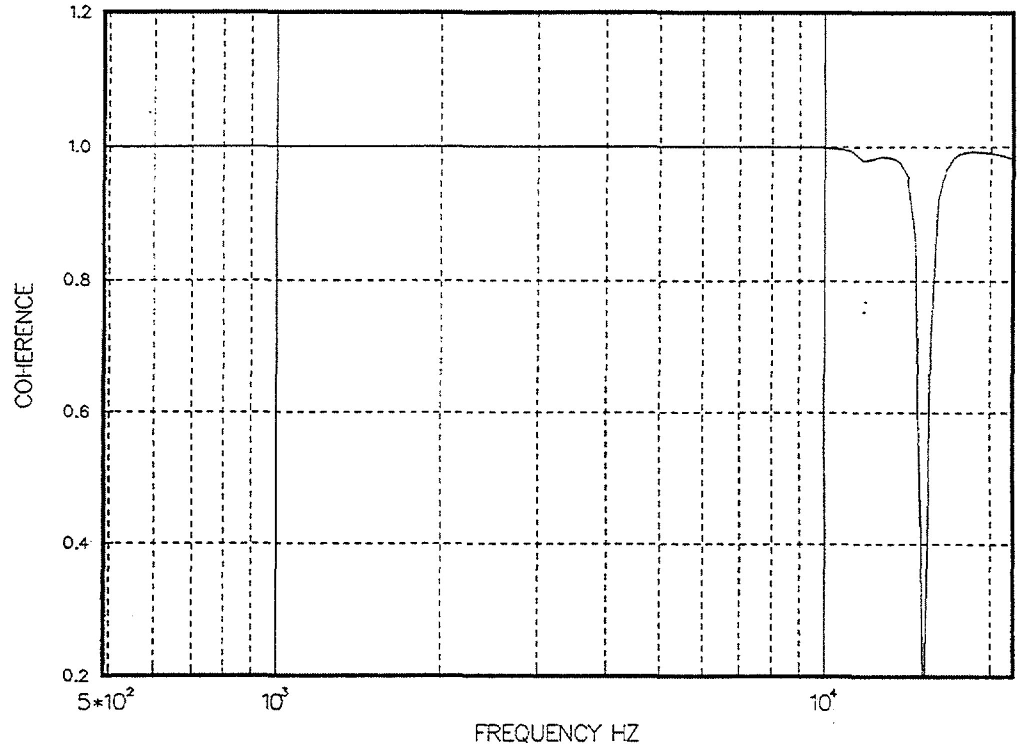
Frequency Response Functions



a) Frequency Response Function Magnitude

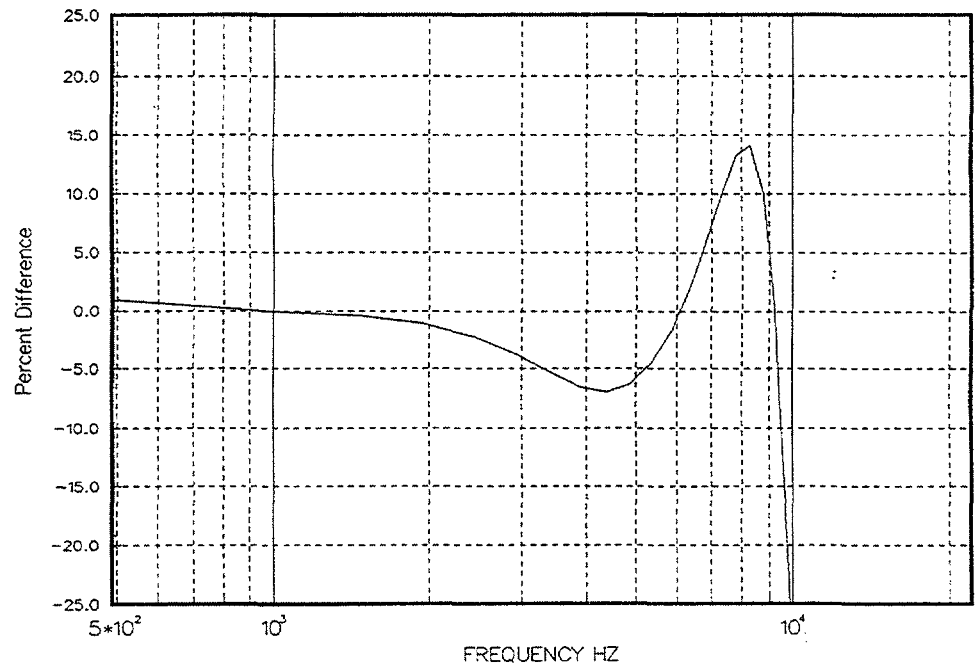


b) Frequency Response Function Phase

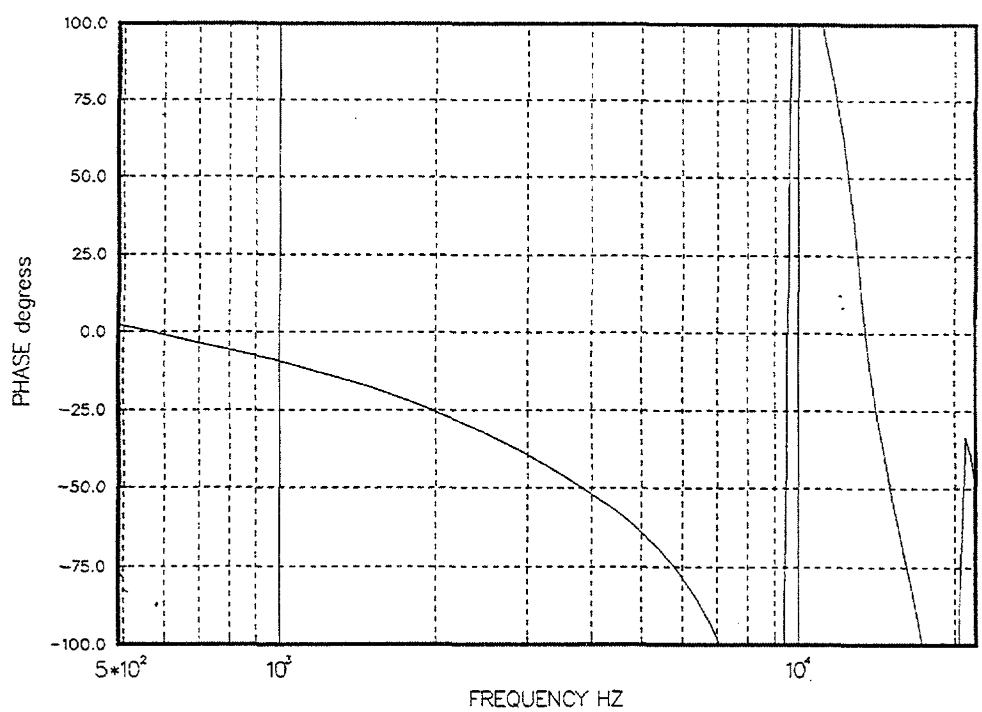


c) Frequency Response Function Coherence

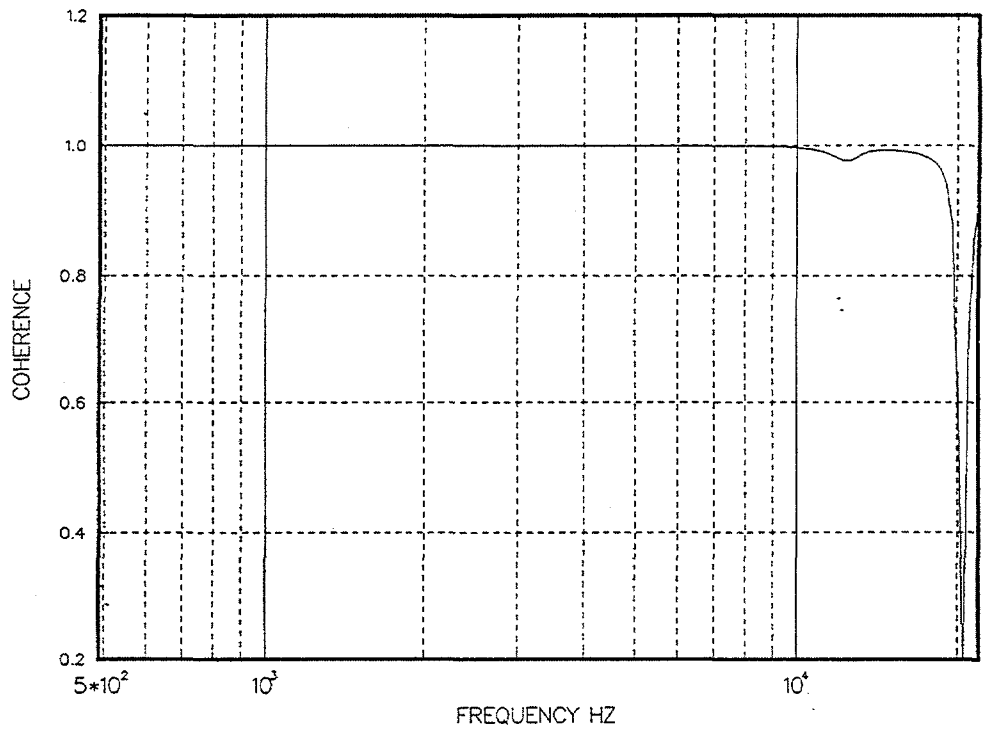
Bobkat Isolator Frequency Response Functions at 5000 g Amplitude and Ambient (70°F) (DC-10 kHz Non-Dispersive Bandwidth).



a) Frequency Response Function Magnitude

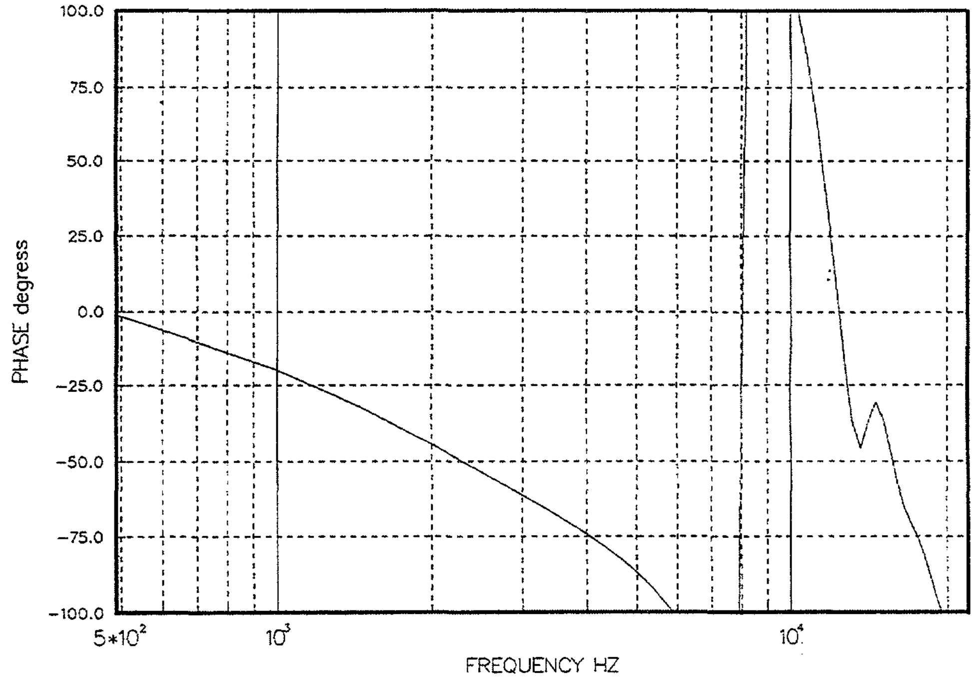


b) Frequency Response Function Phase

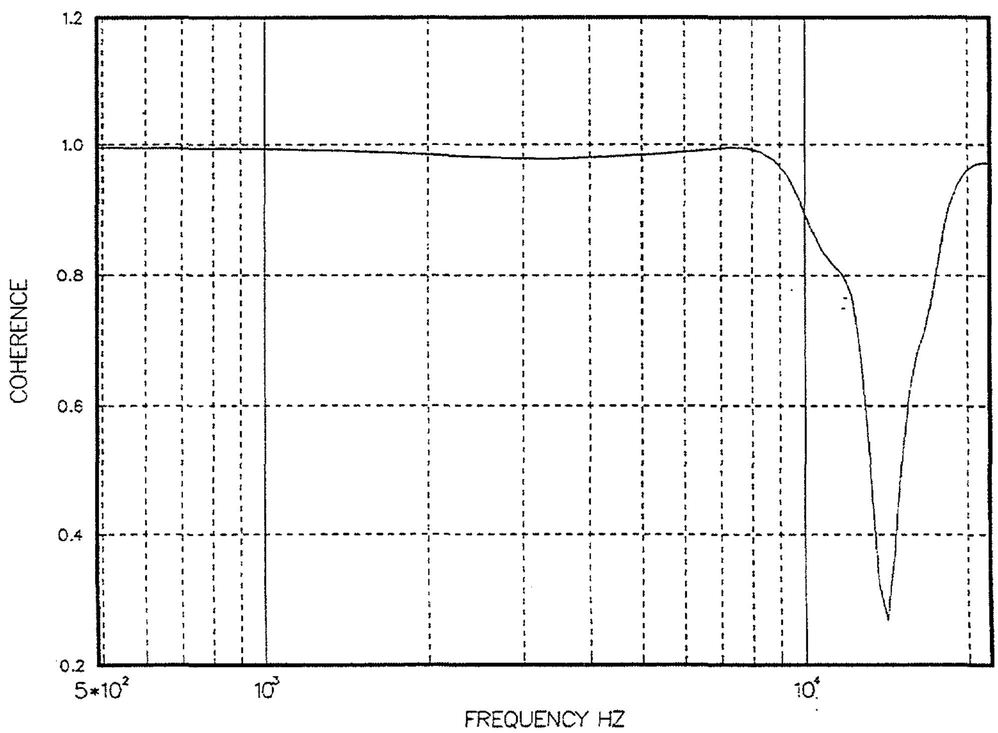


c) Frequency Response Function Coherence

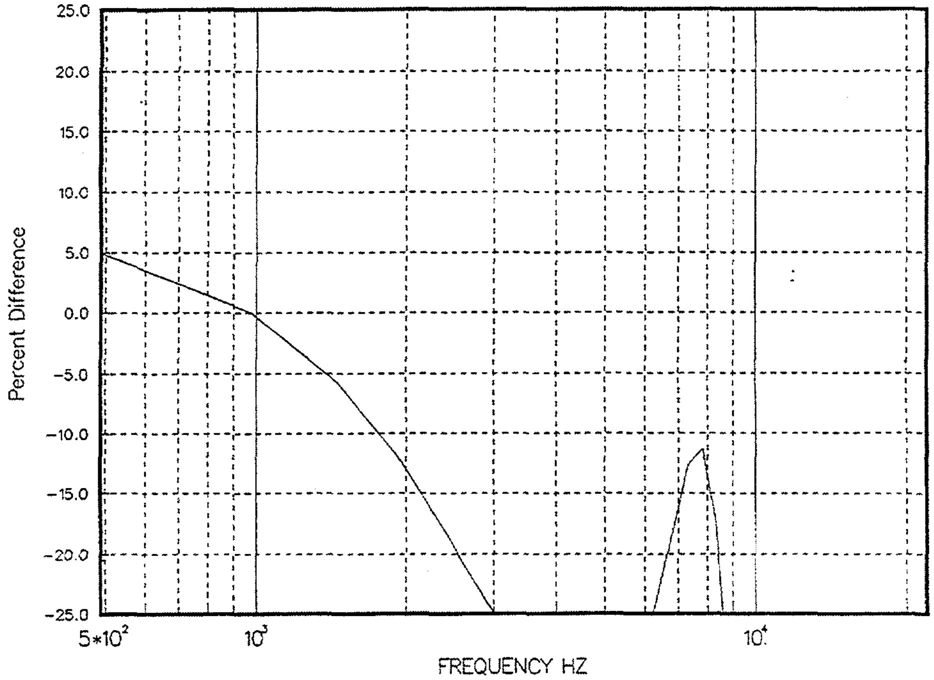
Bobkat Isolator Frequency Response Functions at 10,000 g Amplitude and Ambient (70°F) (DC-10 kHz Non-Dispersive Bandwidth).



a) Frequency Response Function Magnitude

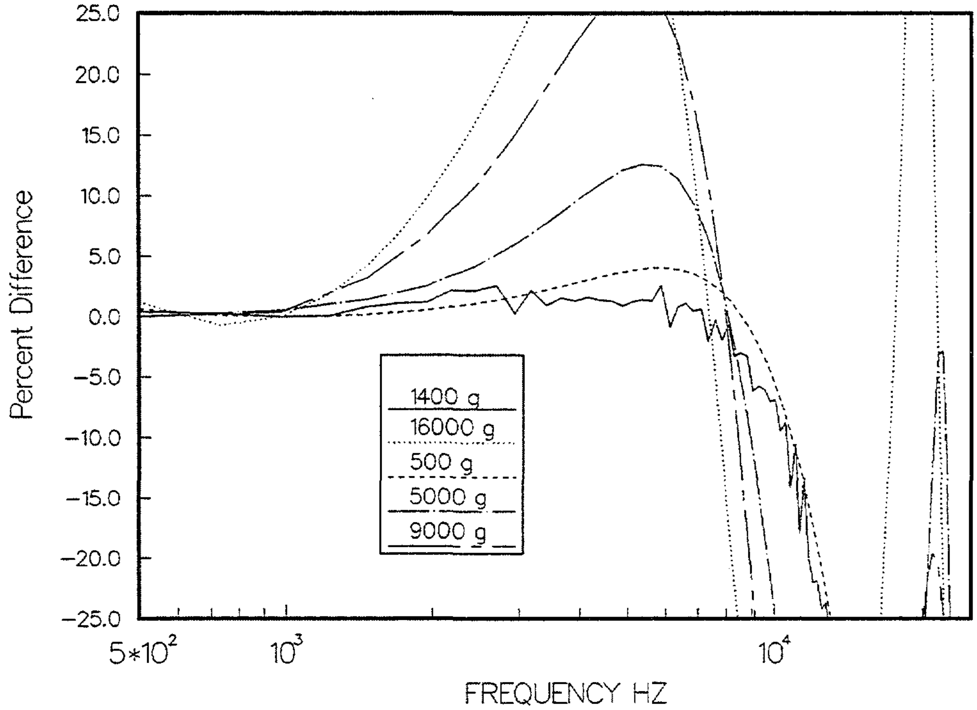


b) Frequency Response Function Phase

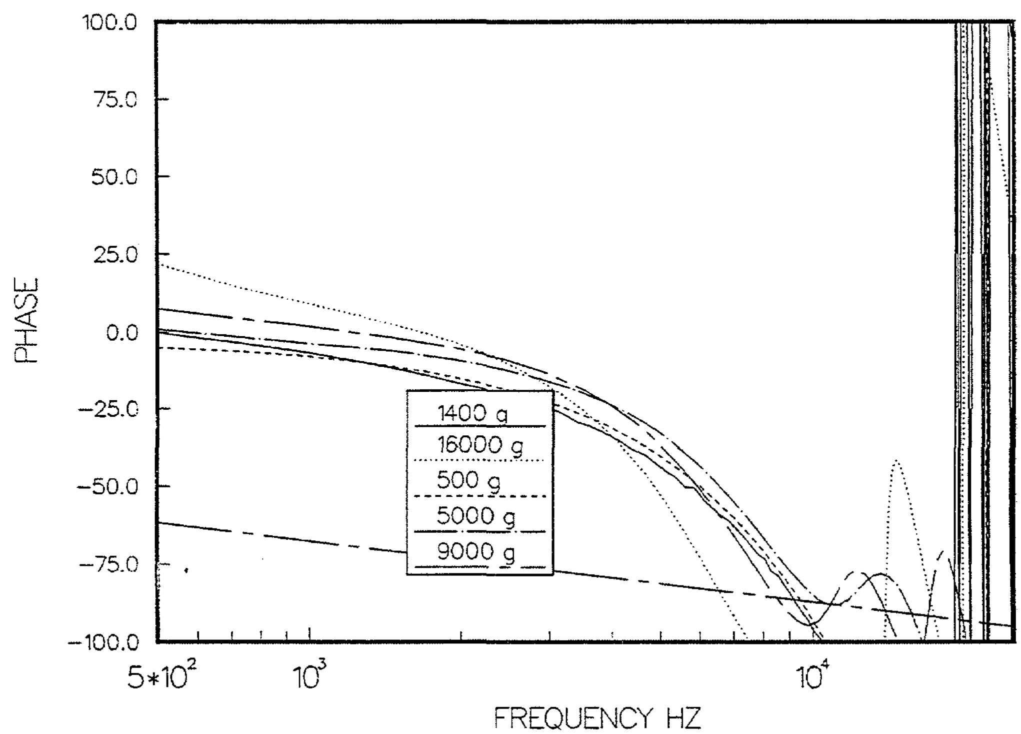


c) Frequency Response Function Coherence

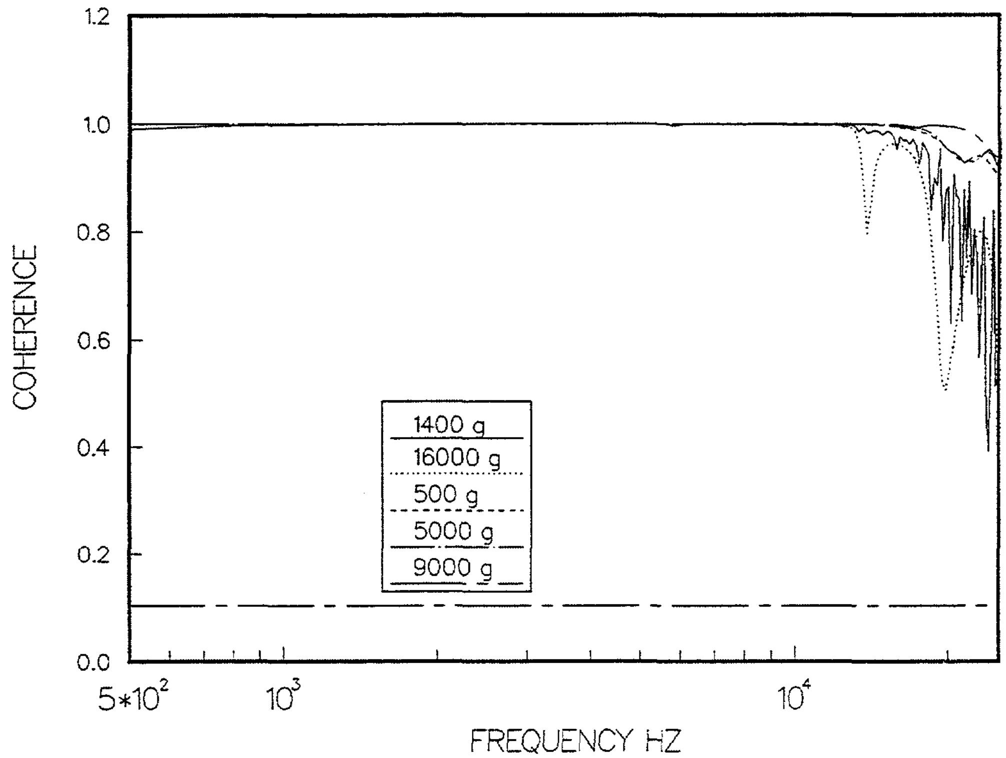
Bobkat Isolator Frequency Response Functions at 15,000 g Amplitude and Ambient (70°F) (DC-10 kHz Non-Dispersive Bandwidth).



a) Frequency Response Function Magnitude



b) Frequency Response Function Phase



c) Frequency Response Function Coherence

ENDEVCO 7255 Frequency Response Functions at Ambient, 70°F (DC-10 kHz Non-Dispersive Bandwidth).

Appendix D

TNO Building and Construction Research
The Netherlands

TNO Report 94-CMC-R1366, Mechanical Isolators

TNO report

94-CMC-R1366 Mechanical filters

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Date 30 November 1994

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Monitoring Agency : TNO Defence Research

Classified by : ir. P.J. Keuning, RNlN.
Classification date: 30 November 1994

Project number	: 42774613 - A92/KM/122
Author	: ing. B. Bosman
Approved	: ir. A.W. Vredeveldt
Visa	: ir. G.T.M. Janssen
Pages	: 23 (excl. RDP & Distr. List)
Classification	: ONGERUBRICEERD

The classification designation 'ONGERUBRICEERD' is equivalent to 'UNCLASSIFIED'.

Managementuittreksel

Titel	: Mechanical filters
Auteur	: Ing. B. Bosman
Datum	: 30-11-'94
Opdr.nr.	: 42774613 - A92/KM/122
IWP nr.	: 792
Rapportnr.	: 94-CMC-R1366

Een viertal mechanische filters, te gebruiken voor de Endevco 7270A versnellingsopnemers, zijn beproefd.
De frequentiekarakteristiek (zowel in meetrichting als dwars daarop), de lineairiteit en de temperatuursinvloeden zijn tot een frequentie van 10 kHz geëvalueerd.
Het is mogelijk om, met gebruikmaking van speciale mechanische filters, zware schoksignalen in een frequentiegebied tot 10 kHz juist te registreren.
De geëvalueerde mechanische filters vertonen kleine niet lineairiteiten.
Van de geëvalueerde mechanische filters heeft het Disk-isolation-technique filter de beste karakteristieken.
Om het bruikbare frequentiegebied van een mechanisch filter te bepalen dienen de werkelijk opgetreden omstandigheden (zoals amplitude, temperatuur, etc.) in beschouwing te worden genomen.

Contents

1. SUMMARY

Four different mechanical filters, to be used with Endevco 7270A accelerometers, have been tested.
The frequency characteristic (measurement direction and transverse), linearity and influence of temperature have been evaluated till 10 kHz.
It is possible to measure high level shock signals in a frequency range up to 10 kHz properly, using special mechanical filters.
The evaluated mechanical filters show a small nonlinearity.
Of the evaluated mechanical filters the Disk-isolation-technique mechanical filter shows the best characteristics.
One has to consider the actual circumstances (such as amplitude, temperature, etc.) to define the usable frequency range.

2. INTRODUCTION

The calculation methods for the effects of underwatershock on a construction are improving strongly.
Of course there is a need for verification by experiments.
Because of the strong improvements in the calculation methods the frequency contents of the experimental data has to be much higher than in the past.
Several accelerometers with a very high natural frequency are commercially available. TNO experience is that in practice those accelerometers can be excited in resonance and fail, even though this resonance is 180 kHz.
The only way to avoid failure, due to excitation in resonance, is the use of mechanical filters or internaly damped transducers.
The aim of this investigation is to design a mechanical filter for the Endevco 7270A transducer with a usable frequency bandwidth of 10 kHz.
For the usable frequency bandwidth a maximum amplitude deviation of 5%, a maximum phase deviation of 5 degrees and a maximum transverse sensitivity of 5% is acceptable.

3. EVALUATED MECHANICAL FILTERS

Four different mechanical filters, to be used with Endevco 7270A accelerometers, have been tested.
The first one is the filter as used by TNO in the past at full scale experiments and small scale experiments. For small scale experiments a large bandwidth is necessary. This filter will be called TNO-old filter. This filter is shown in figure 1a.
The second one is the modified filter of the previous one (thinner rubber). This filter is called TNO-new filter and is shown in figure 1b.
The third is a further modified filter called TNO-new-round filter. This filter is shown in figure 1c.
The fourth is a filter developed by Sandia National Laboratories and made available by Endevco. This filter is called Disk-isolation-technique filter. [1],[2]
Endevco stated that this filter was not the best they had of this type.
The rubber of the first two filters (TNO-old and TNO-new) were glued on the steel surface. The rubber of the TNO-new-round filter was glued on the aluminium surface. The accelerometer was clamped between two rubber layers at the Disk-isolation-technique filter.
The TNO-new-round filter and the Disk-isolation-technique filter both has a stud for attachment to the test structure.
The TNO-old filter and TNO-new filter were glued to the test structure.

4. EXPERIMENTAL SETUP AND MEASUREMENT SYSTEM

4.1 Transducer calibration

The accelerometers used for this study were calibrated by TNO using two methods; a shaker calibration according to ISO 5347 part 3 "Secondary vibration calibration" and a dropball calibration according to ISO 5347 part 4 "Secondary shock calibration". [3],[4],[5]
Figure 2 shows a dropball calibration data record.

4.2 Executed measurements

Some measurements took place on the MIL 901D light weight shock machine at a temperature of 20 degrees Celcius. Different shock levels were used (200 g, 300 g, 500 g and 3000 g).
All other measurements were carried out using a hopkinson bar.
On the hopkinson bar some different amplitudes, pulse durations and temperatures were used.
The hopkinson bar (made of AISI-304) is shown in figure 3.
The support allows free movement of the bar in axial direction.
The hopkinson bar easily lends itself to temperature conditioning because the end of the bar can simply be inserted into a temperature chamber. In literature the theory of stress wave propagation is well documented. [6],[7],[8]
A controlled impact of a projectile against the bar generates a repeatable one-dimensional elastic stress wave in the bar which results in a motion at the free end of the bar of : $v = 2 c \epsilon$
with v the velocity at the end of the bar.
c the wave propagation speed in the bar.
ϵ the strain measured in the bar and not affected by reflections.
The shape (approximately a half sine) and duration of the pulses are controlled by impact speed and interface.
Acceleration amplitudes of 2500 g, 6000 g and 15000 g and pulse durations of 45 μs, 55 μs and 70 μs were used at temperatures of 20 and 50 degrees Celcius. The pulse durations were measured at the 10% level of the first peak in the acceleration signal.
The four mechanical filters as well as a hard mounted accelerometer were measured.
On the hopkinson bar also transverse measurements were performed.
For transverse measurements an accelerometer mounted at the end of the bar was used as the reference acceleration.

4.3 Used Equipment

All transducers used for this evaluation were Endevco 7270A-20K (range 20,000 g) accelerometers.
For the measurements on the MIL 901D light weight shock machine and on the hopkinson bar a Scadas-II frontend with PDFA-ETD modules and 16 bits ADC (make Difa) was used.
A sampling frequency of 125 kHz and a analogue low pass filter of 41.7

5. DATA ANALYSIS

For the MIL 901D light weight shock machine the frequency response functions of the mechanical filters were calculated, using the data of transducers mounted on the mechanical filters and a hard mounted transducer. The frequency resolution for this calculation was 6.25 Hz. For the calculation of the frequency response functions 18 averages were used.

For the hopkinson bar considerable preparations of the data was required before frequency response functions could be calculated. First the data had to be corrected for the time delay of the acceleration record compared to the strain record (this time delay is equal to the time for the wave to propagate from the strain gage to the end of the bar).
Then the acceleration was integrated to obtain velocity and the strain record was converted to velocity using the factor 2c.
From these data the frequency response functions were calculated using a impact window to prevent leakage errors. The frequency resolution for this calculation is 488 Hz.
For the calculation of the frequency response functions 5 averages were used.

6. RESULTS

6.1 Tests on the MIL 901D light weight shock machine

Figure 4 shows a time history measured on the MIL 901D light weight shock machine. The amplitude spectrum of this data is shown in figure 5. The frequency response function of the TNO-new filter, using 3000 g shock level and 18 averages, is shown in figure 6.
At frequencies higher than 3000 Hz the coherence is low. The transducers are mounted directly next to each other at the centerline. Figure 5 shows that the high frequencies are present in the measured acceleration signal. Apparently the data is very place dependent for the high frequencies.
The signals generated by the MIL 901D light weight shock machine can not be used to judge the functioning of the mechanical filters at high frequencies.

6.2 Tests on the hopkinson bar

A time history of a 2500 g shock pulse (pulse duration of 70 μs) on the hopkinson bar is shown in figure 7.
Figure 8 shows the integrated and time shifted acceleration signal combined with the velocity signal of the strain gages.
The amplitude spectrum of the 2500 g, 70 μs acceleration pulse is shown in figure 9 and the amplitude spectrum of the 15000 g, 45 μs acceleration pulse is shown in figure 10. It is clear that these signals can be used for evaluating the filter response in the frequency range from 1 to 10 kHz very well.
The coherence functions are calculated for the hopkinson bar data. The calculated coherence functions are unity in the presented frequency range (1 to 10 kHz).
The frequency response functions of the different mechanical filters, for a shock level of 2500 g (70 μs) at a temperature of 20 as well as 50 degrees Celcius, are shown in figures 11 to 18.
All mechanical filters show more or less acceptable characteristics at 20 degrees Celcius.
A temperature of 50 degrees Celcius proves to high for the TNO-new-round mechanical filter.
The transverse sensitivity of the TNO-new-round mechanical filter is shown in figure 19. The transverse sensitivity of each mechanical filter is given in table 1.

mechanical filter	transverse sensitivity [%]
TNO-old (worst direction)	6
TNO-new (worst direction)	7
TNO-new-round	5
Disk-isolation-technique	3.5

Table 1. Transverse sensitivity

The frequency response function of the TNO-new-round mechanical filter at a shock level of 15000 g (45 μs) and a temperature of 20 degrees Celcius is shown in figure 20.
The frequency response function of the Disk-isolation-technique mechanical filter at a shock level of 15000 g (45 μs) and a temperature of 50 degrees Celcius is shown in figure 21.
Both filters show a small nonlinearity.

7. CONCLUSIONS

It is possible to measure high level shock signals in a frequency range up to 10 kHz properly, using special mechanical filters.

The signals generated by the MIL 901D light weight shock machine can not be used to judge the functioning of the mechanical filters at high frequencies.

A temperature of 50 degrees Celcius is to high for the TNO-new-round mechanical filter.

The transverse sensitivity of the TNO-old and TNO-new mechanical filters are too high.

The evaluated mechanical filters show a small nonlinearity.

Of the evaluated mechanical filters the Disk-isolation-technique mechanical filter shows the best characteristics.

One has to consider the actual circumstances (such as amplitude, temperature, etc.) to define the usable frequency range.

8. REFERENCES

[1] Bateman V.I., Bell R.G., Davie N.T.; Evaluation of shock isolation techniques for a piezoresistive accelerometer.
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The Shock and Vibration Bulletin, No.61 Vol.4, Oct.1990.

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Oxford at the Clarendon press 1953.

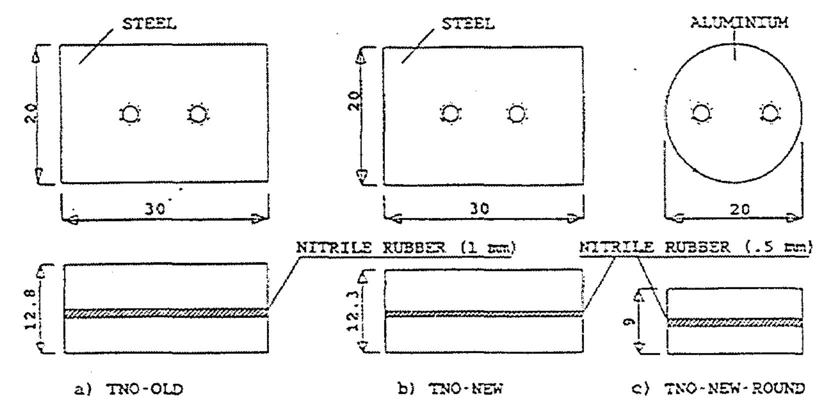
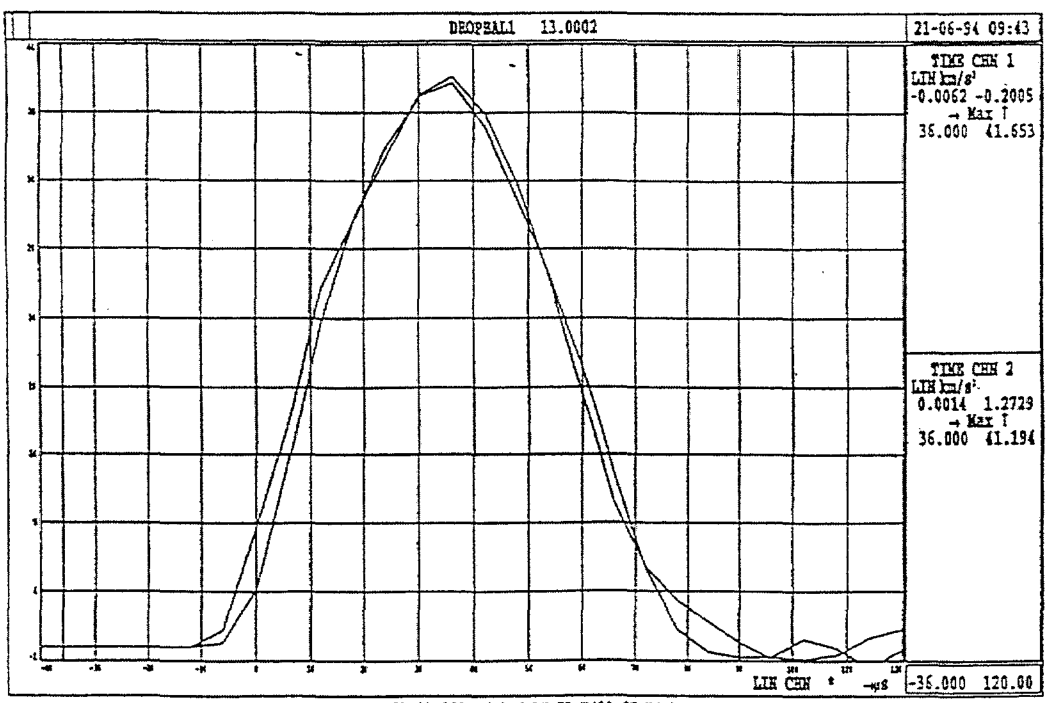


FIGURE 1. MECHANICAL FILTERS



BH 62 (2.062pC/g) / BK 53 F(10.65uV/g)

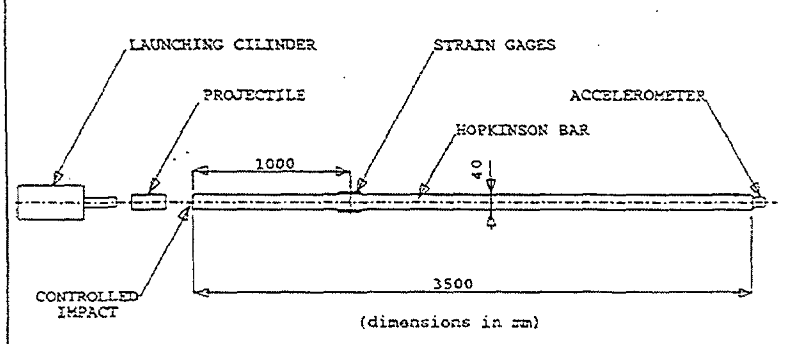


FIGURE 3. HOPKINSON BAR

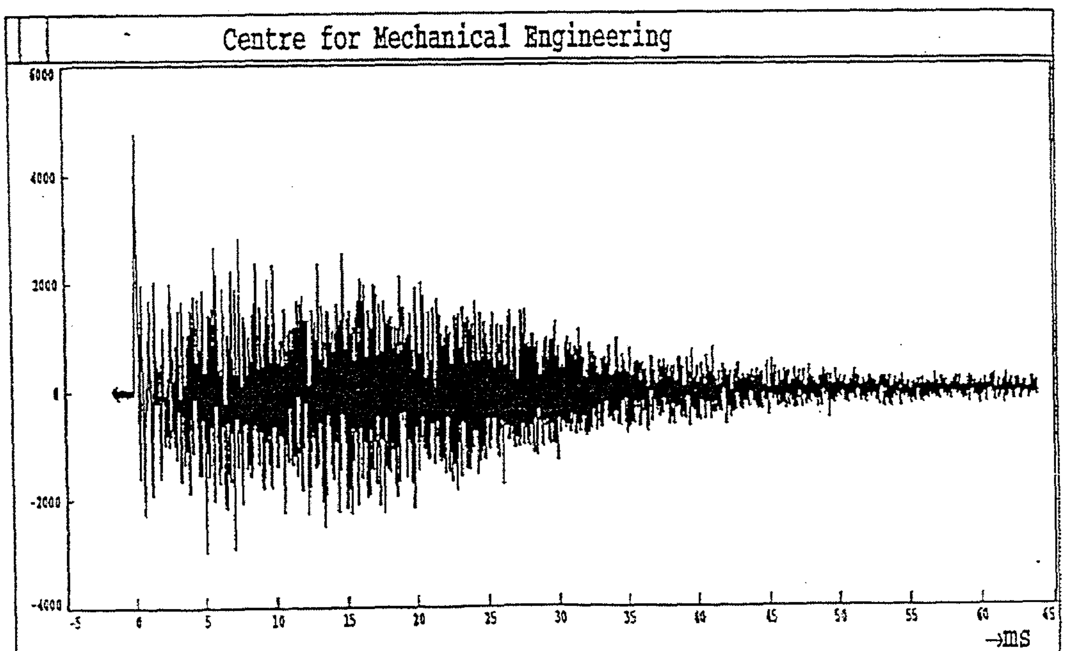


FIGURE 4. Time history measured on the MIL 901D LWS [m/s2]

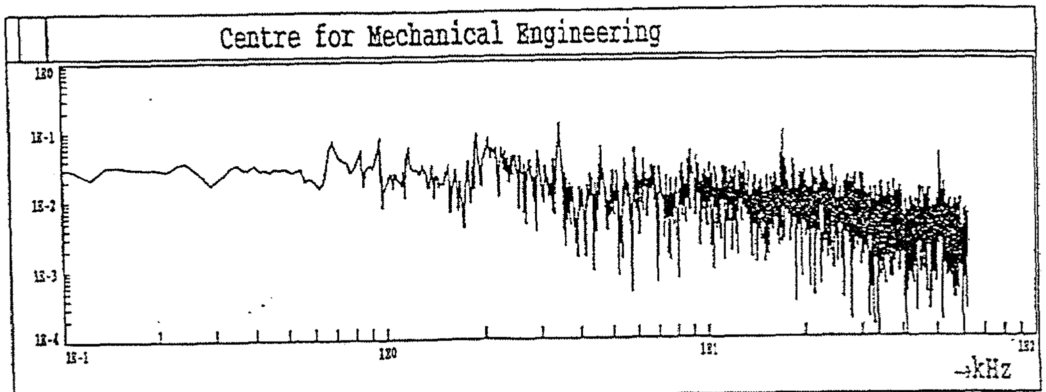


FIGURE 5. Amplitude spectrum measured on the MIL 901D LWS [m/s2]

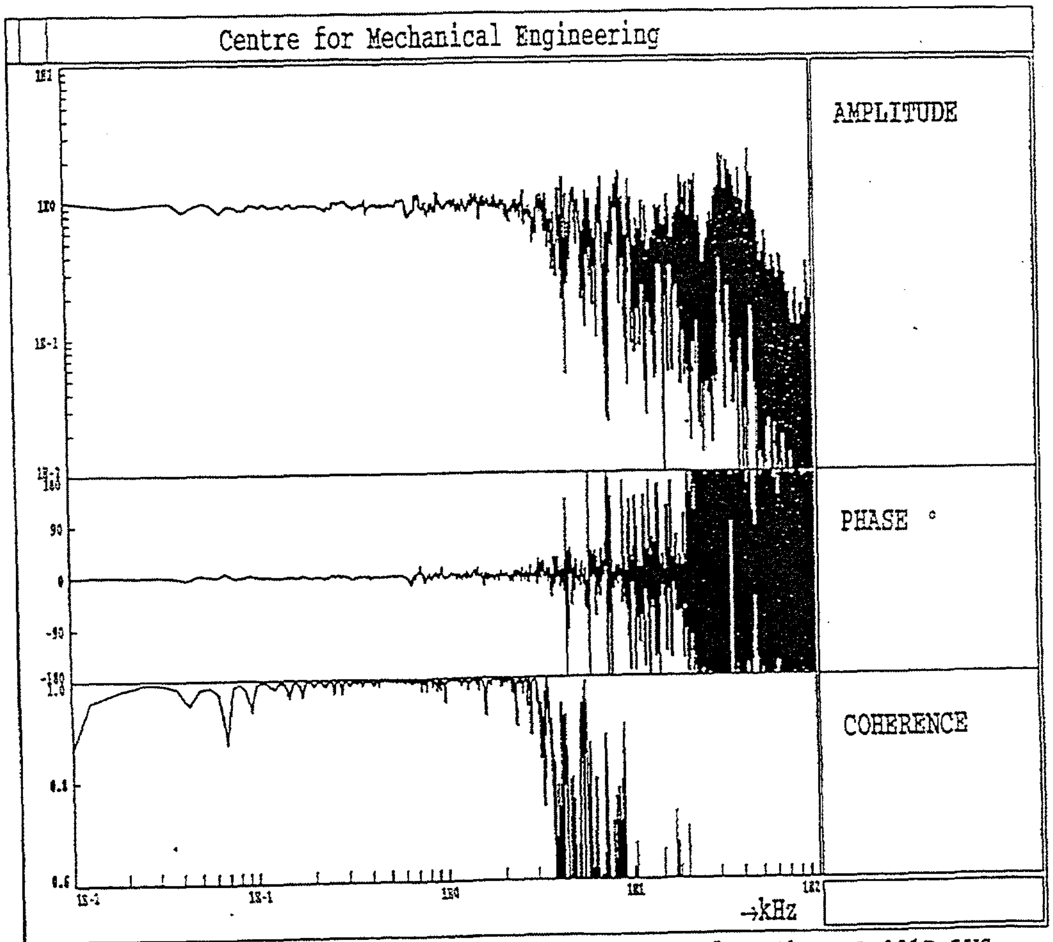


FIGURE 6. FRF of TNO-new mechanical filter measured on the MIL 901D LWS

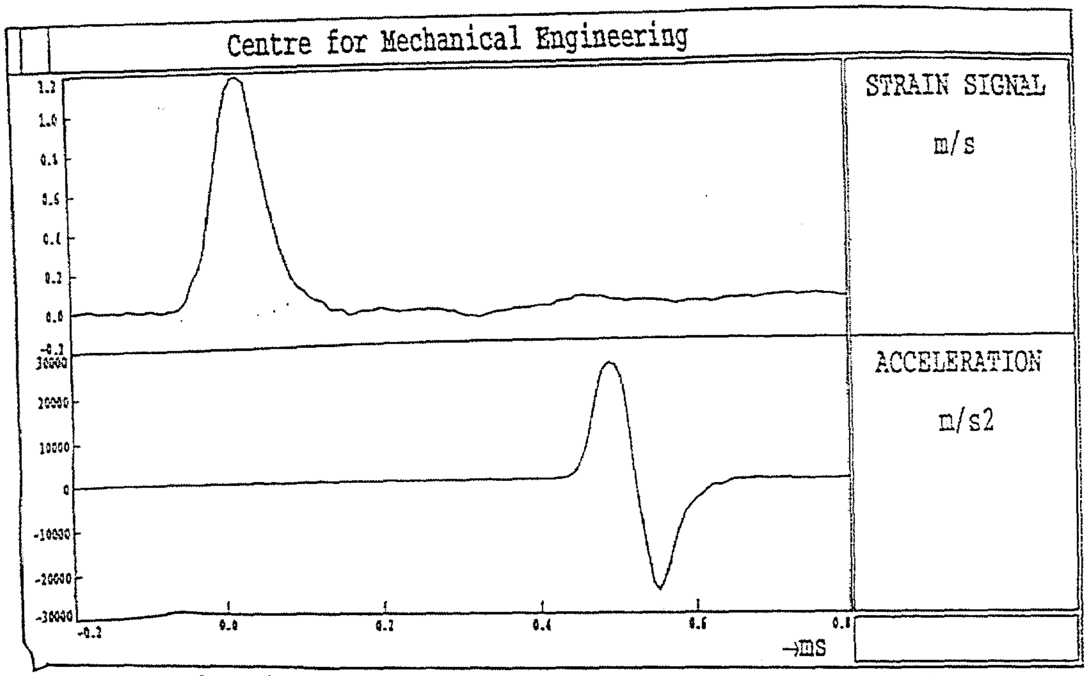
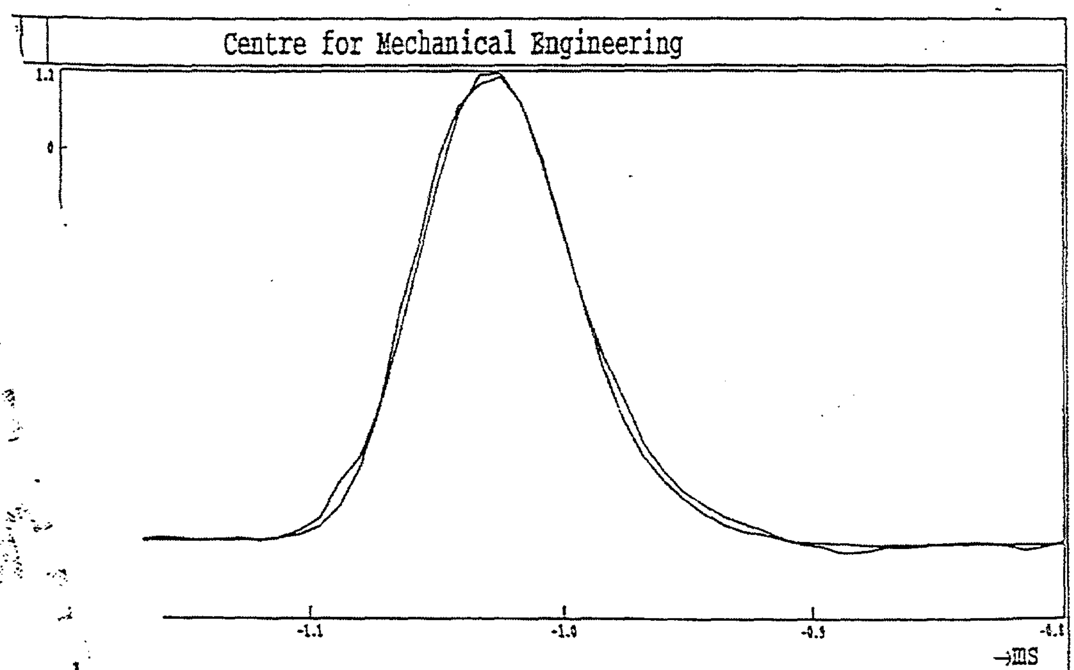


FIGURE 7. Time history of hopkinson bar 2500 g shock pulse (70 microsec)



train signal and integrated and time shifted acceleration [m/s]

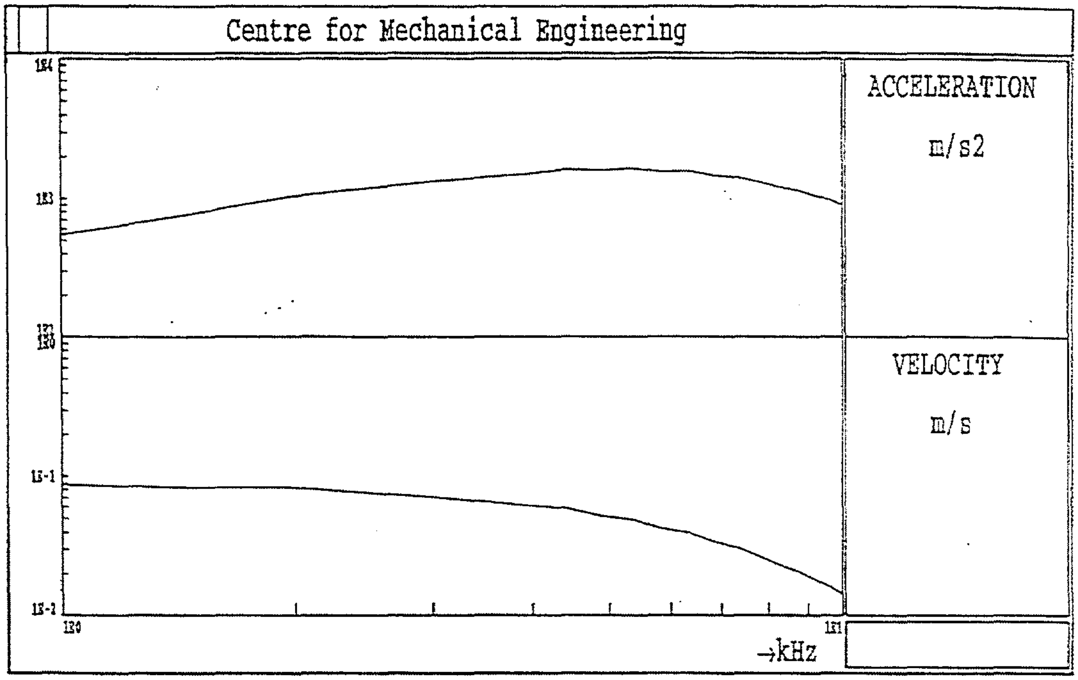


FIGURE 9. Amplitude spectrum of 2500 g (70 microsec) acceleration pulse

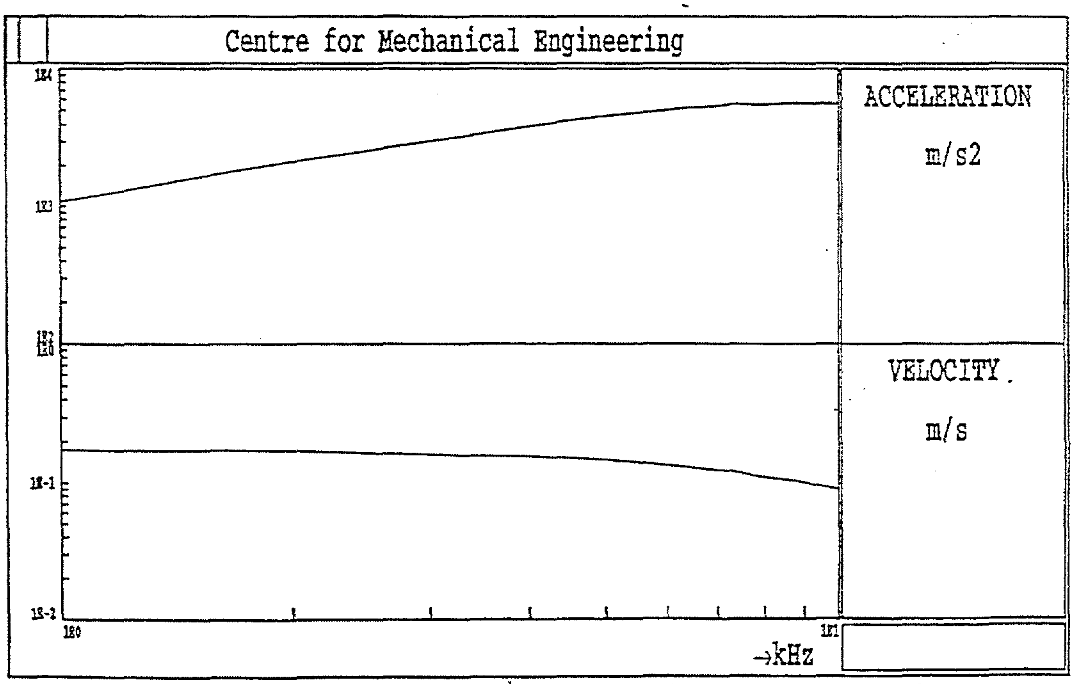


FIGURE 10. Amplitude spectrum of 15000 g (45 microsec) acceleration pulse

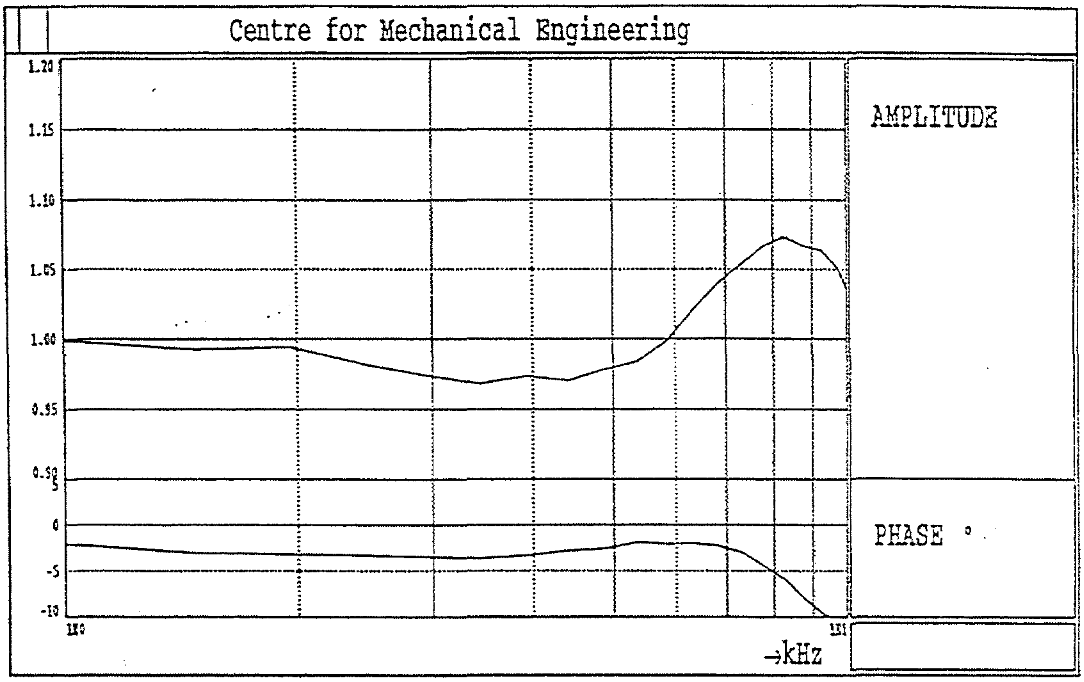


FIGURE 11. FRF of TNO-old (2500 g, 20 degrees Celcius)

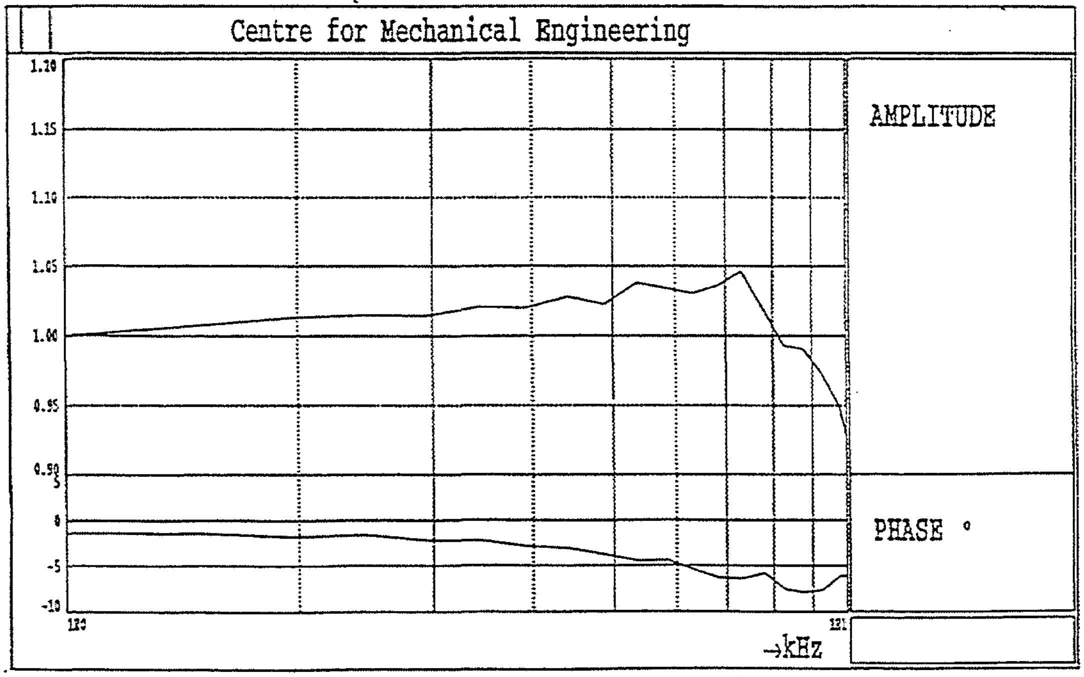


FIGURE 12. FRF of TNO-old (2500 g, 50 degrees Celcius)

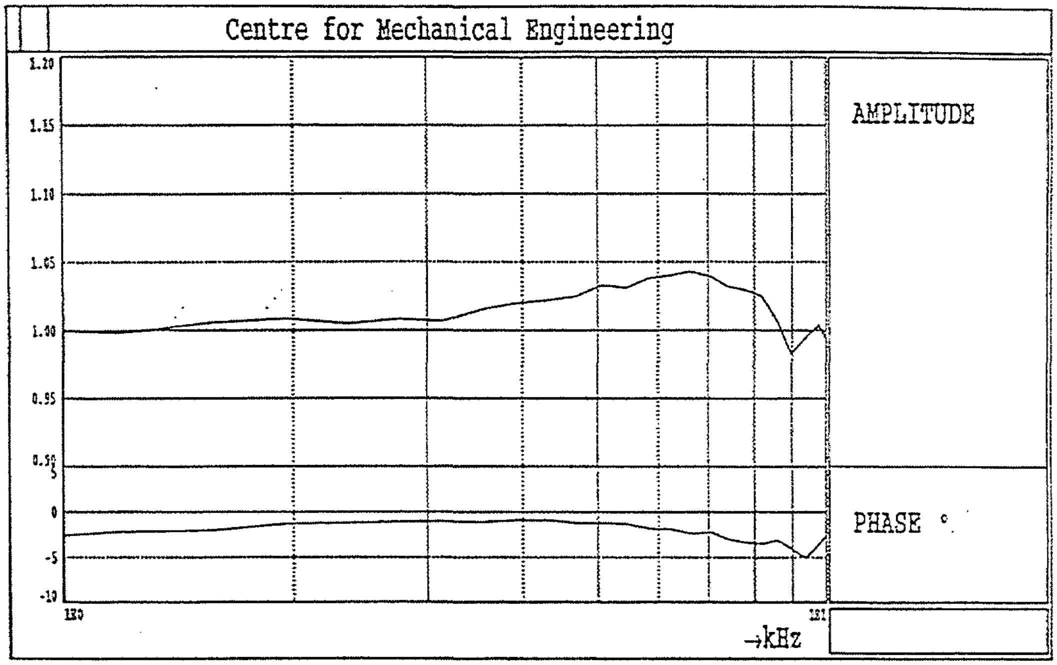


FIGURE 13. FRF of TNO-new (2500 g, 20 degrees Celcius)

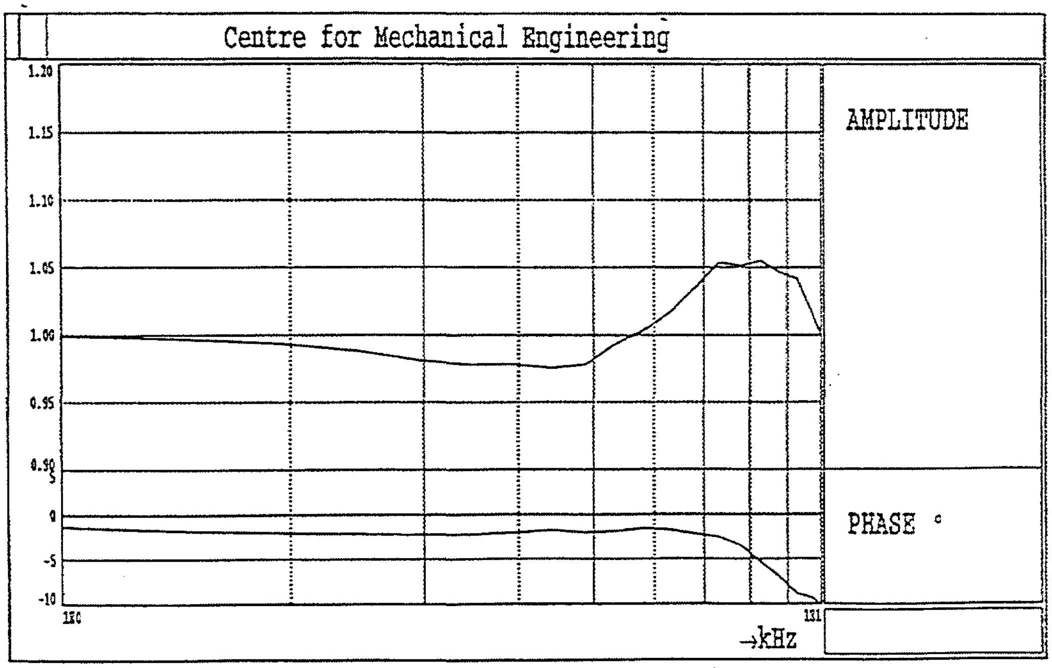


FIGURE 14. FRF of TNO-new (2500 g, 50 degrees Celcius)

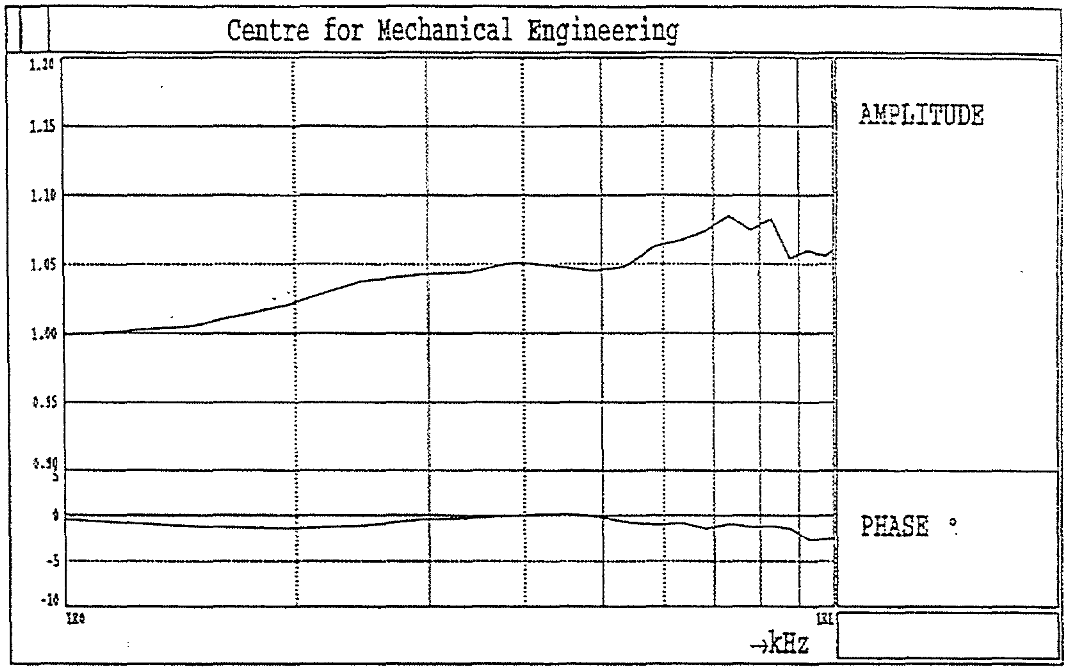


FIGURE 15. FRF of TNO-new-round (2500 g, 20 degrees Celcius)

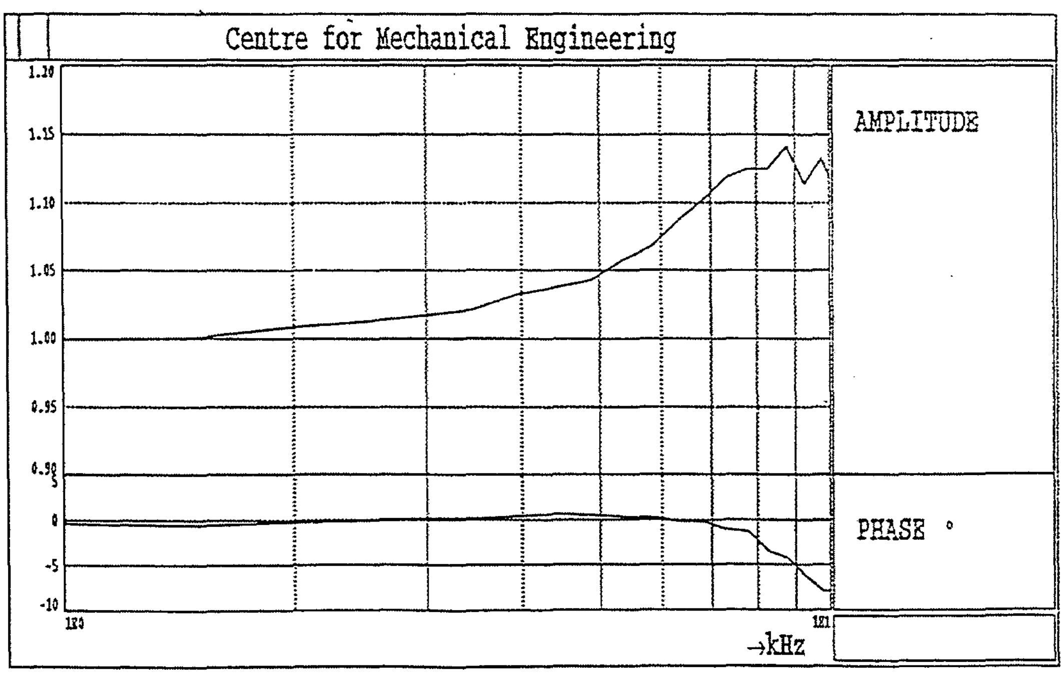


FIGURE 16. FRF of TNO-new-round (2500 g, 50 degrees Celcius)

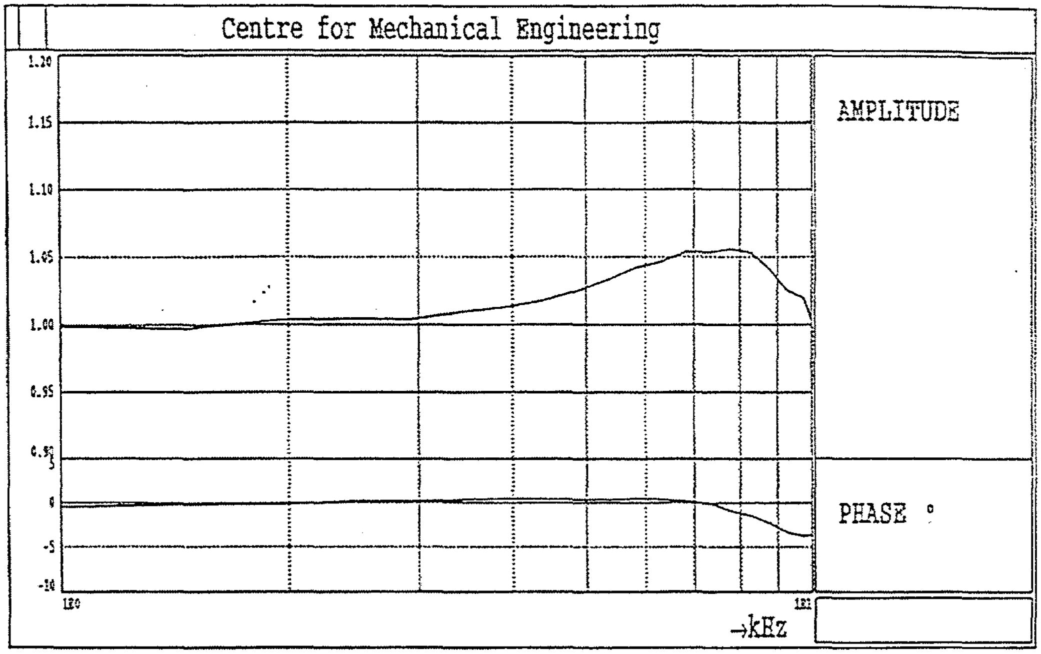


FIGURE 17. FRF of Disk-isolation-technique (2500 g, 20 degrees Celcius)

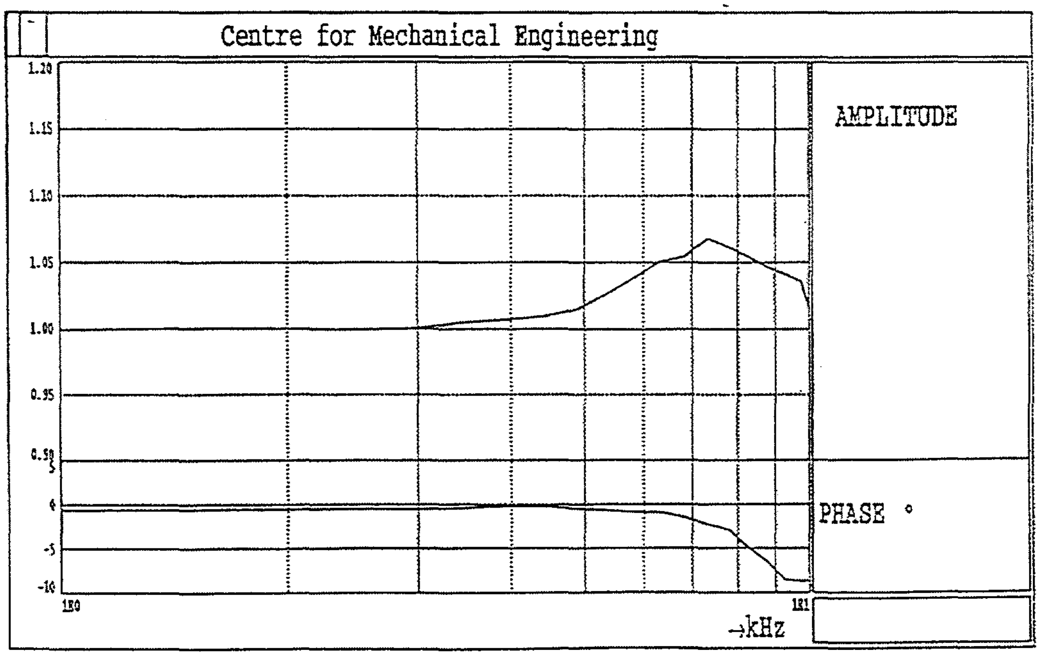


FIGURE 18. FRF of Disk-isolation-technique (2500 g, 50 degrees Celcius)

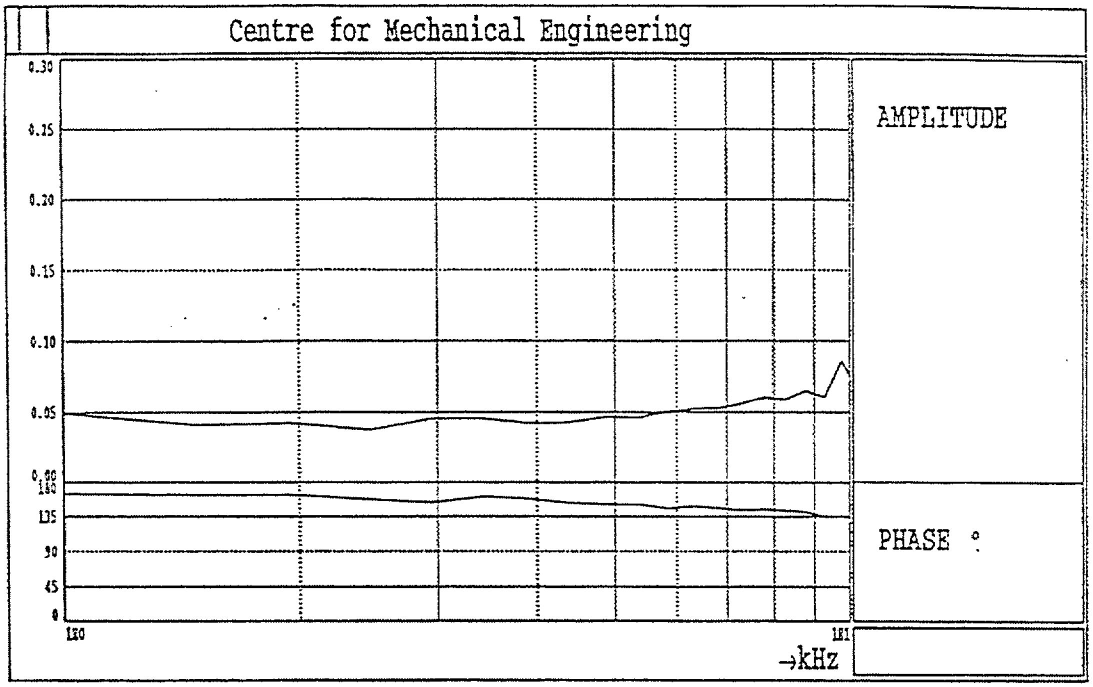


FIGURE 19. FRF of TNO-new-round in transverse direction (2500 g, 20 deg.C)

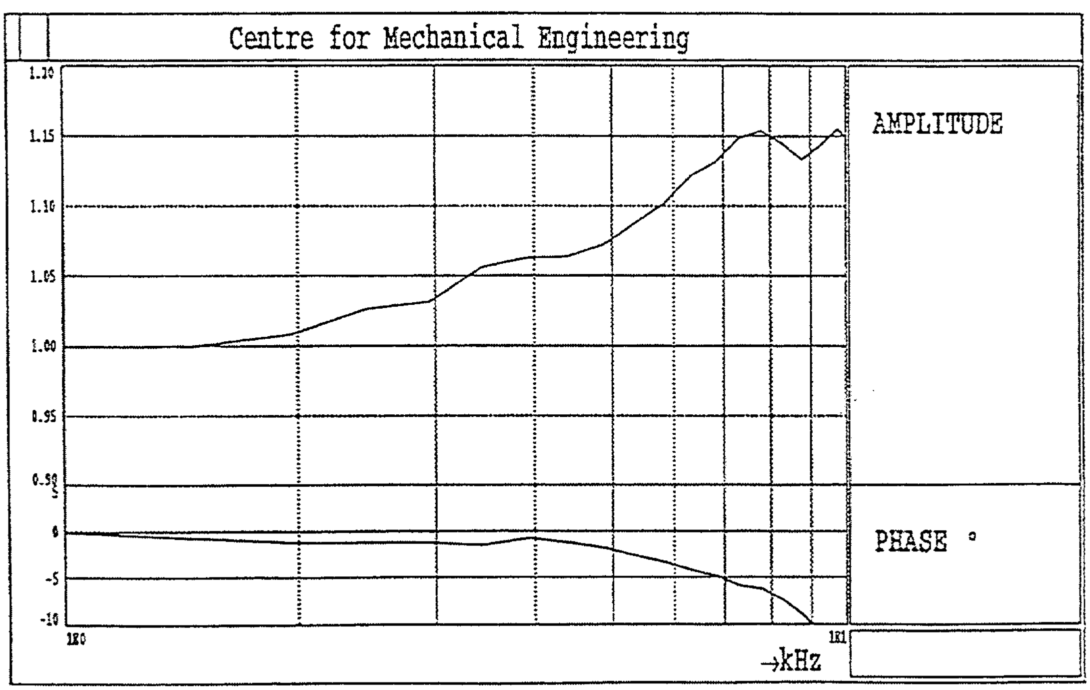


FIGURE 20. FRF of TNO-new-round (15000 g, 20 degrees Celcius)

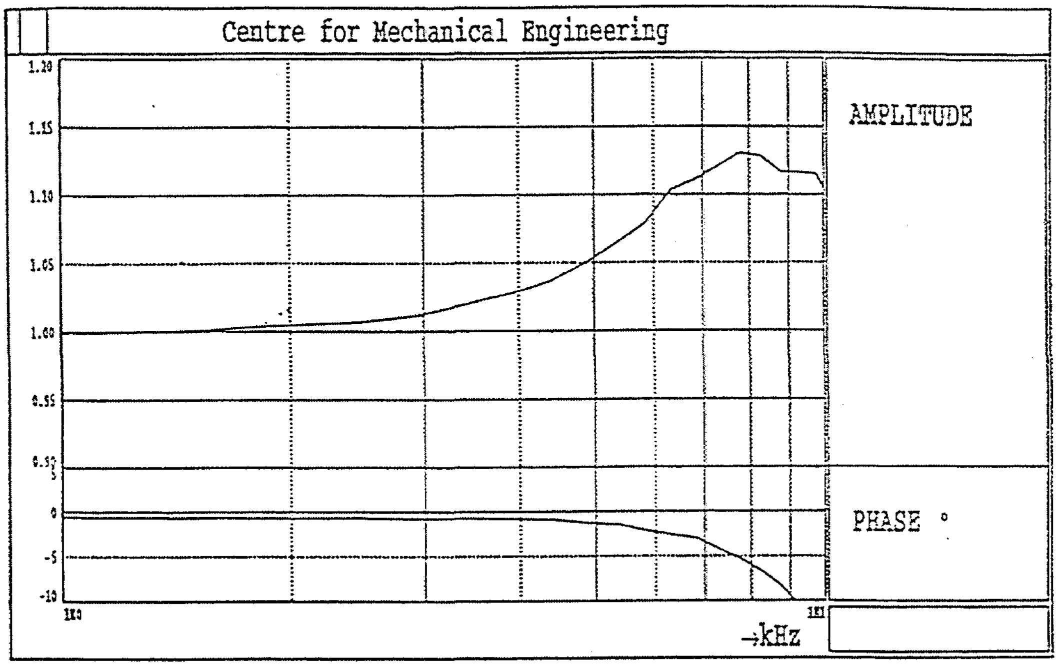


FIGURE 21. FRF of Disk-isolation-technique (15000 g, 50 degrees Celcius)

Appendix E

ENDEVCO 7270AM6

Performance Specifications

Piezoresistive Accelerometer

Model 7270AM6

- **Mechanical Filter**
- **6000 to 60 000 g Full Scale**
- **DC Response**
- **Rugged**

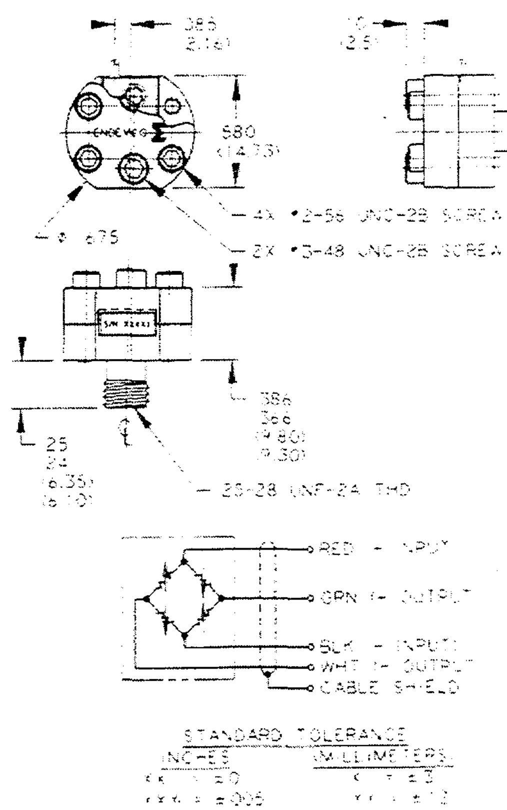
DESCRIPTION

The ENDEVCO® Model 7270AM6 series of piezoresistive accelerometers are rugged units with built-in mechanical filters designed for shock measurements. The mechanical filter assembly is designed to mitigate the high frequency content of a shock pulse in order to protect the accelerometer sensor from high g, high frequency inputs that would otherwise exceed the over-range limits. The Model 7270A-XXM6 is available in ranges of 6000 to 60 000 g Full Scale.

Developed by Sandia National Laboratories, the mechanical isolator consists of an aluminum housing lined with two layers of elastomer filter that cushions the Model 7270A Piezoresistive Accelerometer. With the elastomer on both sides of the accelerometer, the response is the same to both positive and negative accelerations. The mechanical filter used in the Model 7270A-XXM6 features a damped output with a linear phase shift. The unit is usable over the frequency range from DC to 10 kHz for the temperature range of -30 to +150°F (-34 to +66°C).

The Endevco Model 136 Three-Channel Signal Conditioner, Model 68207 BCAS Computer Controlled System or Model 4430A Bridge Signal Conditioner are recommended as signal conditioner and power supply.

U.S. Patents 4,498,229, 4,605,919 and 4,689,600



SPECIFICATIONS

PERFORMANCE CHARACTERISTICS: All values are typical at +75°F (+24°C) and 10 Vdc excitation unless otherwise stated. Calibration data, traceable to the National Institute of Standards (NIST), is supplied.

	Units	Model -6KM6	-20KM6	-60KM6
RANGE [1]	g pk	±6000	20 000	±60 000
SENSITIVITY	μV/g	30 +20/-15	10 ±5	3 +2/-1.5
FREQUENCY RESPONSE [2] (±10% max, ref. 100 Hz)	kHz	0 to 10	0 to 10	0 to 10
MOUNTED RESONANCE FREQUENCY	kHz Typ	TBD	TBD	TBD
NON-LINEARITY (% of reading, to full range)	% Max	±2, up to acceleration corresponding to the recommended range. Measurement uncertainties prevent stating this as a specification limit above 10 000 g.		
TRANSVERSE SENSITIVITY	% Typ	5	5	5
ZERO MEASURAND OUTPUT	mV Max	±100	±100	±100

Piezoresistive Accelerometer

SPECIFICATIONS—continued

PERFORMANCE CHARACTERISTICS–continued

	Units	Model -6KM6	-20KM6	-60KM6
THERMAL ZERO SHIFT From -30°F to +150°F (-34°C to +66°C)	mV Max	±50	±50	±50
THERMAL SENSITIVITY SHIFT From -30°F and +150°F (-34°C and +66°C)	% Max	±10	±10	±10
OVERRANGE LIMIT	g pk	±18 000	±60 000	±100 000
WARM-UP TIME	Minutes Max Seconds (Typ)	2 (15)	2 (15)	2 (15)

ELECTRICAL

EXCITATION	10.0 Vdc, 12 Vdc maximum
INPUT RESISTANCE	550 ±200 ohms
OUTPUT RESISTANCE	550 ±200 ohms
INSULATION RESISTANCE	100 megohms minimum at 100 Vdc; between sensor, cable shield and case

PHYSICAL

CASE, MATERIAL	Stainless Steel (17-4 PH CRES)
ELECTRICAL, CONNECTIONS	Integral cable, 4 conductor No. 36 AWG Teflon® insulated leads, braided shield, flourocarbon jacket
IDENTIFICATION	Manufacturer's logo, model number and serial number
MOUNTING/TORQUE [1]	75 lbf-in (8.4 Nm)
WEIGHT	8.4 grams excluding cable (cable weighs 3.6 grams/meter)

ENVIRONMENTAL

ACCELERATION LIMITS	±100 000 g half sine pulse or three times the recommended range, in any direction, whichever is smaller. Pulse duration should be the greater of 20 microseconds or five periods of the resonance frequency
TEMPERATURE Operating Storage	 -30°F to +150°F (-34°C to +66°C) -65°F to +250°F (-54°C to +121°C)
HUMIDITY	Unaffected. Unit is epoxy sealed
ALTITUDE	Unaffected

CALIBRATION DATA SUPPLIED

SENSITIVITY [5]	μV/g at 5000 g

ACCESSORY
31290 Wrench

OPTIONAL ACCESSORIES
25034 4 Conductor Shielded Cable
32103 Tri-axial Mounting Block

NOTES
1. Removable Loc-Tite should be applied to 10-32 stud before installation. Recommended mounting torque should be applied to bottom half of unit.

0997

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