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CHARACTERISTICS OF A PIEZORESISTIVE ACCELEROMETER IN HIGH FREQUENCY, HIGH SHOCK ENVIRONMENTS*

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Authors' Biographies

Vesta I. Bateman received a B.S. degree from Vanderbilt University and a M.S. and Ph.D. from the University of Arizona, all in Mechanical Engineering. She taught for four years in the Mechanical Engineering Department at Virginia Tech. Since 1980, she has been at Sandia National Laboratories in Albuquerque, New Mexico where she is a Senior Member of the Technical Staff in the Mechanical Shock Testing Laboratory.

Neil T. Davie received a B. A. degree in math and physics from Augustana College in 1976. He received a M. S. degree in Theoretical and Applied Mechanics from the University of Illinois. Since that time, he has been employed by Sandia National Laboratories. He was involved in mechanical modeling and structural analysis until 1982 when he began working in the area of shock testing and pyroshock simulation. Presently, he is a Senior Member of the Technical Staff in the Shock Testing Laboratory.

Fred A. Brown has over twenty years of shock testing experience in the Mechanical Shock Laboratory at Sandia National Laboratories He has participated in the development of many different types of shock-producing mechanisms including resonant fixturing for pyroshock simulation, Hopkinson bar testing for component evaluation, and innovative drop table configurations for specialized shock requirements.

Abstract

The characteristics of a piezoresistive accelerometer in shock environments are being studied at Sandia National Laboratories in the Mechanical Shock Testing Laboratory. A Hopkinson bar capability has been developed to extend our understanding of the piezoresistive accelerometer with and without mechanical isolation in the high frequency, high shock environments where measurements are being made. Two different Hopkinson bar materials are being used: titanium and beryllium. The characteristics of the piezoresistive accelerometer for frequencies of DC-10 kHz and shock magnitudes of up to 4,000 g as determined from measurements with a titanium Hopkinson bar are presented. The SNL uniaxial shock isolation technique has demonstrated acceptable characteristics for a temperature range of -50°F to +186°F and a frequency bandwidth of DC to 10 kHz. These characteristics have been verified by the calibration of the Hopkinson bar used for accelerometer testing. The beryllium Hopkinson bar configuration is described. Preliminary characteristics of the piezoresistive acclerometer at a nominal shock level of 17,000 g for a frequency range of DC-50 kHz are presented.

Keywords
Accelerometer, high shock, high acceleration, high frequency

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 strucuture is propelled at velocities of 1000 fps (nominal) into earth or rock. Another example of an impact test is a slapdown test of a nuclear transportation cask. In a slapdown test, one end of the cask impacts a hard concrete target, then the structure rotates so that the other end of the cask impacts the target [1]. Additionally, impact testing is conducted for a variety of weapon structures [2]. During an impact test, metal to metal contact may occur within the structure and produce high frequency, high amplitude shocks. The high frequency portion of this transient vibration has been observed to excite an accelerometer into resonance even though this resonance exceeds 350 kHz. An accelerometer may fail in this situation. Even if the accelerometer does not fail, the amplitude of the resonating accelerometer response can be so large that

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DISCLAIMER

the data are clipped and rendered useless. If the data are not clipped, a digital filter must be applied to eliminate undesirable accelerometer resonant response. In anticipation of accelerometers' resonating during a test, the data channels may be set to accomodate the large amplitude of the accelerometer resonance. The result is usually an unacceptably small signal to noise ratio. If possible, it is more desirable to prevent excitation of the accelerometer resonance. This may be accomplished by mechanically isolating the accelerometer from the high frequency excitation without degrading the transducer response in the bandwidth of interest.

In the past, several techniques have been used at SNL to mechanically isolate accelerometers and instrumentation packages containing accelerometers from high frequency, high amplitude shock environments. These techniques include various configurations of adiprene, polysulfide rubber, water soluble wax, and urethane rubber [3,4,5]. The techniques have been successful in mechanically isolating the accelerometers but have a limited, useable frequency range of 2 kHz or less. The useable frequency range is specified as those frequencies for which the sensitivity deviation is ±5% or less. In one application, a mechanical isolator was combined with an electrical analog filter, tuned for the isolator resonance, to achieve a useable frequency range of 10 kHz. A commercially available, mechanical isolator has also been evaluated. However, this isolator exhibited nonlinear behavior over its acceleration capability of 1500 g. A commercial piezoelectric accelerometer with integral electronics and mechanical isolation is available but is generally not used in our field testing because of signal conditioning requirements, cable-whip and zero-shift problems, and a limited useable frequency range of about 1 kHz.

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 by the high frequency content of ballistic shock [6,7,8]. 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. Initially, the isolation techniques were designed and evaluated for the desired bandwidth of 10 kHz. These techniques are used with a piezoresistive accelerometer which is frequently used for field tests of various high reliability structures which must withstand severe shock environments. The piezoresistive accelerometer has several desirable characteristics: DC response, low power requirements, minimal zero shift, and high resonant frequency. A major undesirable characteristic is that the piezoresisitive accelerometer is undamped. A high frequency input causes it to resonate, and the resulting large amplitude may exceed the measuring capability of the instrumentation system. The resonant behavior can be prevented with a mechanical isolator that has a damped resonance between the upper limit of the useable frequency range and the accelerometer's resonance. For example, the the uniaxial isolator assembly decribed in this paper has a damped resonance at about 50 kHz. This resonance allows significant attenuation of frequency input at the accelerometer's resonance (90 kHz and greater) and is useable for the piezoresistive accelerometer models with ranges equal to or greater than 6,000 g.

There are several goals in the design of a shock isolation technique. Primarily, the technique must have repeatable response characteristics. Secondly, the technique must allow calibration of the shock isolated accelerometer assembly prior to and after a field test. Lastly, the technique must show linear amplitude and frequency characteristics. These goals have been achieved with the mechanical isolators developed at SNL for a piezoresistive accelerometer [9,10]. Results for the uniaxial isolation technique only are presented below and have been verified by calibration of the Hopkinson bar [11].

Higher frequency measurements (in excess of 10 kHz) and higher frequency measurements at acceleration levels in excess of 20,000 g are being attempted. Recent applications of mechanically isolated accelerometers include pyroshock measurements such as stage separation shock for multistage missile programs (for example, STARS, Strategic TARget System, program) and the USS IOWA explosive accident simulation. Impact and pyroshock phenomena contain high frequencies (up to 100 kHz), and there is no capability to calibrate or characterize accelerometers with shock inputs for frequencies above 10 kHz. Additionally, recent penetrator testing by SNL has used data packages with bandwidths of DC-60 kHz for onboard recording of accelerometer response in excess of 35,000 g during penetration events. These accelerometer measurements are made with bare piezoresistive accelerometers mounted inside a data package with no mechanical isolation other than the data package itself. The piezoresistive accelerometer and the SNL mechanical isolation techniques are being characterized over the extended bandwidth of DC to 30 kHz to provide better interpretation of these high frequency measurements. To achieve this goal, a beryllium Hopkinson bar is being developed to extend the upper limit of the frequency range for Hopkinson bar calibration and characterization of accelerometers. Others have been successful in extending the frequency range of the Hopkinson bar by removing dispersion effects from the data [12,13]. However, our goal is to achieve the additional frequency bandwidth without additional processing of the data. A beryllium Hopkinson bar will allow measurement of frequencies in the bandwidth of 10-30 kHz because of the beryllium's high stress wave speed as compared to the titanium alloys that are used for the current accelerometer calibrations.

Current calibration of accelerometers is conducted for a maximum of 15,000 g. In the applications listed above, the piezoresistive accelerometer is being used to measure accelerations in excess of 15,000 g. In some cases, a 200,000 g accelerometer is being used. The SNL Mechanical Shock Laboratory has a Hopkinson bar capability to test accelerometers up to 100,000 g which can be extended to 200,000 g and will be used to determine the characteristics of a piezoresistive accelerometer at these high acceleration levels. This capability will also be used to determine the maximum acceleration capability for the mechanical isolation technique. The two areas of high frequency performance and high shock (acceleration level) performance for the piezoresistive accelerometer, with mechanical isolation and without (bare), are being pursued because measurements are being made in these environments.

Uniaxial Isolation Technique Design and Calibration

The uniaxial isolation technique is shown in Figure 1. The uniaxial technique consists of an aluminum disk that has a slot for the accelerometer. The disk is divided into two halves that are held together by two screws. A layer of polysulfide rubber compound (PRC-1422) is positioned on each side of the accelerometer in the slot. Brass locator pins (not shown) hold the PRC-1422 and accelerometer layers in place in the slot. An integral stud on the bottom of the disk is used to attach the uniaxial isolator assembly to the test structure (25 in-lbs mounting torque). Shrink tubing is used on the brass pins in the disk technique to prevent metal to metal contact during lateral shocks.

All accelerometers in this study were calibrated in the SNL Calibration Laboratory using three methods: 1) shaker calibration; 2) centrifuge calibration; and 3)

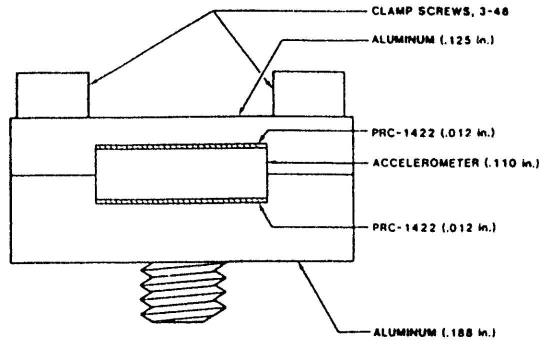


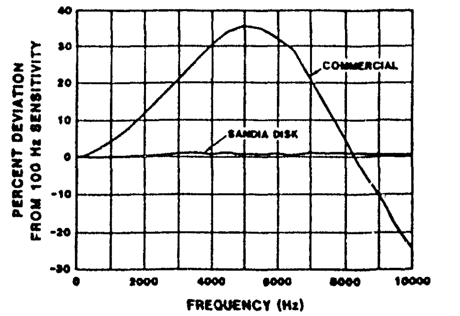
Figure 1: Uniaxial Isolation Technique for a Piezoresistive Accelerometer.

dropball calibration. The three methods are traceable to the National Institute of Standards and Technology, NIST, formerly NBS as described elsewhere [9]. A commercially available mechanical isolator was evaluated using 6000 g piezoresistive accelerometers. Although the dropball and centrifuge calibrations were acceptable, both commercial isolators showed a deviation of 36% at 5 kHz in the shaker calibration at 5 g input as shown in Figure 2a. A uniaxial isolator assembly calibration at 30 g input is also shown for comparison. The damped resonance at 5 kHz is in agreement with the manufacturer's specifcations for the commercial isolator. The shaker data indicates that the useable frequency range, defined as less than 5% deviation from the 100 Hz reference, is about 1 kHz. Additionally, the commercial assemblies were evaluated on the Hopkinson bar, described in a later section, at two levels of 500 g and 1500 g with a pulse duration of 100 μs. These tests showed amplitude nonlinearities in the commercial isolator.

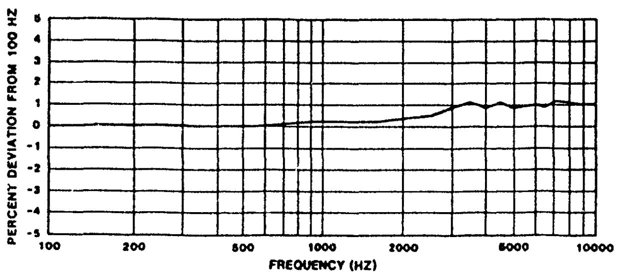
Figure 2b shows a shaker calibration at 30 g input for a uniaxial isolator assembly. This isolator had a sensitivity variation of less than $\pm 0.5\%$ for the ± 5000 g centrifuge calibration (not shown). Figure 2c depicts a dropball calibration of the uniaxial isolator. The calibrations for the piezoresistive accelerometers with no isolation show no deviation over a bandwidth of DC-10 kHz and are not shown here. Since the piezoresistive accelerometers and the SNL isolators were satisfactorily calibrated by all three methods, a more detailed evaluation of the shock isolation techniques has been undertaken to investigate the linearity of amplitude and frequency characteristics on the Hopkinson bar in the SNL Shock Laboratory.

Hopkinson Bar Configurations

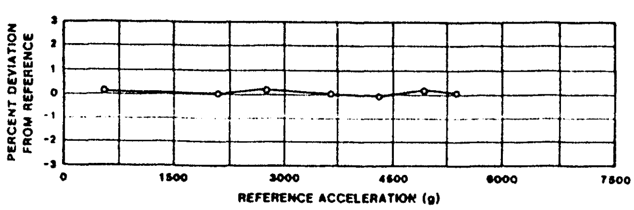
There are two Hopkinson bar configurations used to characterize the response of the piezoresistive



a) **Shaker Calibration Comparison for Uniaxial and Commercial Isolators**



b) Shaker Calibration of Uniaxial Isolator



c) Dropball Calibration of Uniaxial Isolator

Figure 2: Calibrations for Commercial and Uniaxial Isolators.

accelerometer and the isolation technique. The configuration for a normal input is shown in Figure 3. Normal input in this configuration is an input that is normal to the mounting surface and is also parallel to the integral mounting stud. Both the uniaxial technique and the bare piezoresistive accelerometer are tested with the normal input. Cross-axis sensitivity of the piezoresistive accelerometer and the isolated accelerometer are being studied with the split Hopkinson bar configuration in Figure 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 <u>not</u> in the direction of the shock and is obtained with the configuration in Figure 4. Both time domain calculations, as a sensitivity calculation, and frequency domain calculations, as frequency response functions, are made with the Hopkinson bar data. The sensitivity calculation is described below. The frequency response functions are calculated in the same manner as reported previously [9]. Since accelerometer calibrations at temperatures other than ambient can only be conducted with the shaker due to limitations of existing equipment at the SNL Calibration Lab, it is desirable to calibrate shock accelerometers with dropball or with another shock producing technique such as the Hopkinson bar. The Hopkinson bar easily lends itself to temperature conditioning because the end of the bar, where the accelerometer is mounted, is simply inserted into a temperature chamber. For this reason, shock calibrations for the shock isolation techniques at the temperature extremes of -50°F and +186°F were conducted with a Hopkinson bar located in the SNL Shock Laboratory.

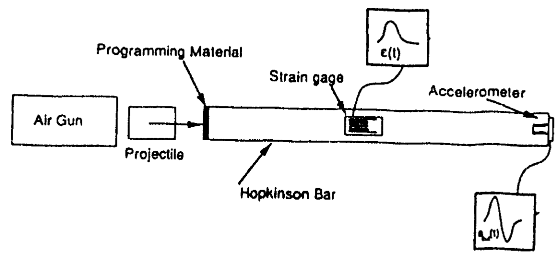


Figure 3: Hopkinson Bar Configuration for Normal Input.

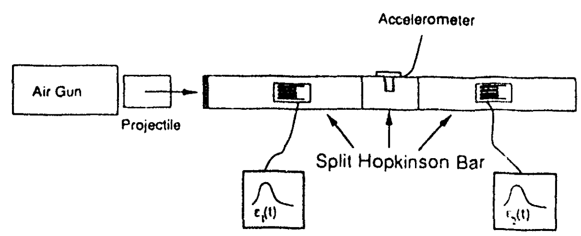


Figure 4: Hopkinson Bar Configuration for Cross-Axis Input.

The theory of stress wave propagation in a Hopkinson bar is well documented in the literature [14,15]. 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 less than the wavelength or $\lambda \geq 10$ g.l.

The Shock Laboratory Hopkinson bar, used for accelerometer testing, is shown schematically in Figures 3-4 and is made of either 6 AL, 4V titanium alloy (6% aluminum and 4% vanadium) or beryllium (99% pure) with a 0.76 inch diameter. The titanium bar is 72 in. long, and the beryllium bar is 50 in. long. 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. 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 thicknesses of paper (3x5 index cards) on the impact surface. The two strain gages are located 49.75 inches from the end on which the accelerometer is mounted and are mounted at diametrically opposite positions on the bar. The 49.75 inch strain gage location is in the mid-portion of the bar and allows a longer incident pulse, if desired. These gages are connected in opposite arms of a Wheatstone bridge to measure the net axial strain.

Once recorded, the strain and acceleration records can be compared by using either velocity or acceleration as shown in (1) and (2). When these comparisons are made, the time delay of the acceleration record, which is equal to the time for the wave to propagate from the strain gage to the end of the bar, must be taken into account. Hopkinson bar accelerometer calibration methods documented in the literature [16-18] 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 [19]. 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 [20].

The selected technique for calculating the sensitivity change at temperatures other than ambient, using the acceleration derived from the Hopkinson bar strain measurements, can be used only to estimate the change in sensitivity due to temperature because of the uncertainties associated with the measurements. Most of the errors are deterministic and will be cancelled when the percentage sensitivity change due to the -50^{O}F temperature is calculated in the following equation [11]:

$$C = \left[\frac{A_{Ac-50}}{A_{Ac-A}} \bullet \frac{A_{Hop-A}}{A_{Hop-50}} - 1\right] \times 100 \qquad (4)$$

where:

C = Percentage sensitivity change at -50^{O}F as compared to ambient,

A_{Ac-50} = Shock amplitude measured by accelerometer at -50^{O}F,

A_{Ac-A} = Shock amplitude measured by accelerometer at ambient,

A_{Hop-A} = Shock amplitude derived from strain gages for ambient test, and

A_{Hop-50} = Shock amplitude derived from strain gages for -50^{O}F test.

A similar equation is used for the sensitivity change at +186°F.

Hopkinson Bar Calibration Results

Three separate operations have been performed to calibrate the titanium Hopkinson bar. First, a calculation of the wave speed for the titanium Hopkinson bar was made at the temperatures of -50°F and +160°F. Secondly, a reference accelerometer, calibrated by NIST traceable standards, was placed on the end of the bar in the same manner as the accelerometers for the calibration tests and was subjected to shock pulses at various amplitudes. The reference accelerometer output was compared to the acceleration calculated from the Hopkinson bar strain gage response. Lastly, a static load test was performed on the Hopkinson bar; and an effective gage factor was calculated from the measured bar sensitivity. The operations are explained in detail in [11] . The sum of the reference uncertainty and the maximum of the three standard deviations were added to obtain the estimated uncertainty of 6%. It is felt that the uncertainty should not change as long as the bar suffers no physical damage and the strain gages are not changed. A similar calibration is planned for the beryllium Hopkinson bar.

Piezoresistive Accelerometer Performance With and Without Isolation

Twelve piezoresistive accelerometers mounted in the uniaxial isolation technique were used to assess the performance of the technique at -50°F and +186°F. Each accelerometer was subjected to five 5000 g pulses with a duration of 100 μs at each of five temperatures: ambient (70°F), -50°F, ambient, +186°F, and ambient. The accelerometers were tested at ambient after each test at a temperature extreme because the temperatures of -50°F and +186°F are beyond the manufacturer's operational range, -30°F to +150°F. The last ambient test ensured that the accelerometer was still operational after exposure to the extreme temperature environment.

The uniaxial isolation technique was characterized in the time domain with equation (2). The data from the strain gages and the accelerometers were digitally filtered at 17 kHz prior to the sensitivity calculation. The average sensitivity change at -50°F was 6.0% or -0.05%/°F. The average sensitivity change at +186°F was -4.3% or -0.04%/°F. These results are lower than the -0.06%/°F quoted in the manufacturer's specifications.

An acceleration-to-acceleration frequency response function was calculated for the uniaxial isolation technique at the two temperature extremes and compared to the frequency response function at ambient temperature. The calculations were made in the same manner as those published previously [9], and the frequency resolution for these calculations is 244 Hz. The magnitudes of the frequency response functions are shown in Figure 5 which shows that the magnitudes at 10 kHz deviate less than 10 percent from the magnitude at low frequency for all three temperature conditions. The frequency response function phase (not shown) varies in an approximately linear manner up to 10 kHz for all three temperature conditions. The deviation in the frequency response function magnitude above 20 kHz can be explained by the coherence functions (not shown) which show the coherence between the input and the output accelerations is less than one above 20 kHz. The computational anomaly, indicated by the lack of coherence, creates an apparent resonance above 20 kHz that is not a mechanical resonance in the uniaxial isolation technique.

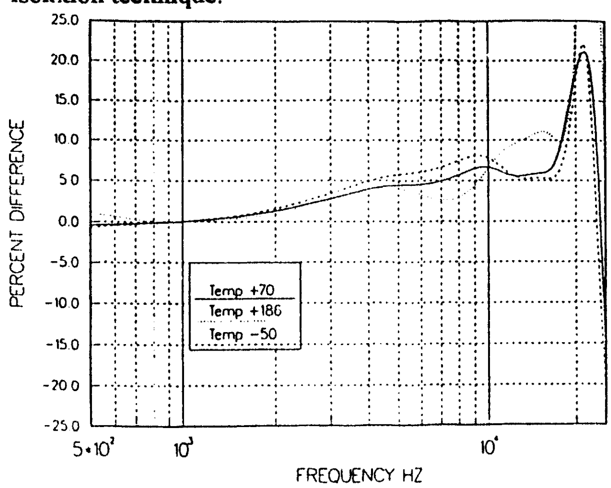


Figure 5: Frequency Response Function Magnitude for the Uniaxial Isolation Technique at -50°F, Ambient (70°F), and+186°F with a 5000 g, 100 μs Input Pulse.

The corresponding frequency response functions for the bare piezoresistive accelerometer, mounted with two #4-40 screws, are shown in Figure 6. Although not shown, the frequency response functions at the temperature extremes of -50°F and +186°F are similar to those shown in Figure 5 and shown deviations within the manufacturer's specifications.

Preliminary results from the beryllium Hopkinson bar for a bare accelerometer mounted with a 1/4 in.-28 stud are shown in Figure 7. The frequency response function is flat to within ±5% over a range of DC-50kHz at the shock level of 17,000 g. This bare accelerometer actually has a flat to response to 150 kHz (manufacturer's specifications), but the 50 kHz limit in Figure 7 represents the capability limit of the beryllium bar. Figure 7 shows that the beryllium bar can be used to characterize accelerometers to a much higher frequency than the titanium bar.

Conclusions and Future Work

A piezoresistive accelerometer with and without the SNL uniaxial isolation technique has been characterized over a bandwidth of DC to 10 kHz with a Hopkinson bar at 4-5,000 g. The uniaxial shock isolation technique has demonstrated acceptable characteristics for a temperature range of -50°F to +186°F. The SNL uniaxial isolation technique has <u>ten times</u> the bandwidth of any commercial isolation technique. The titanium Hopkinson bar has been certified with a transfer standard with an uncertainty of 6%. Preliminary results for a bandwidth of DC to 50 kHz have been shown for a beryllium Hopkinson bar.

The test matrix for evaluation of the piezoresistive accelerometer with and without isolation and for a normal or in axis input is shown below. This test matrix will be performed for two different configurations of the the bare accelerometer: mounted with two #4-40 screws and mounted with a 1/4 in.-28.

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

Additionally, characterization of the piezoresistive accelerometer's cross-axis sensitivity, with and without a mechanical isolator, will be conducted with the beryllium Hopkinson bar because of beryllium's low Poission ratio of 0.035 (average) and the shorter pulse durations allowed by the beryllium as a result of the higher wave speed. The short durations have lower stresses for any acceleration level and consequently, a smaller Poisson effect. The cross-axis tests will be performed at the same levels as the in-axis with the exception of a maximum g

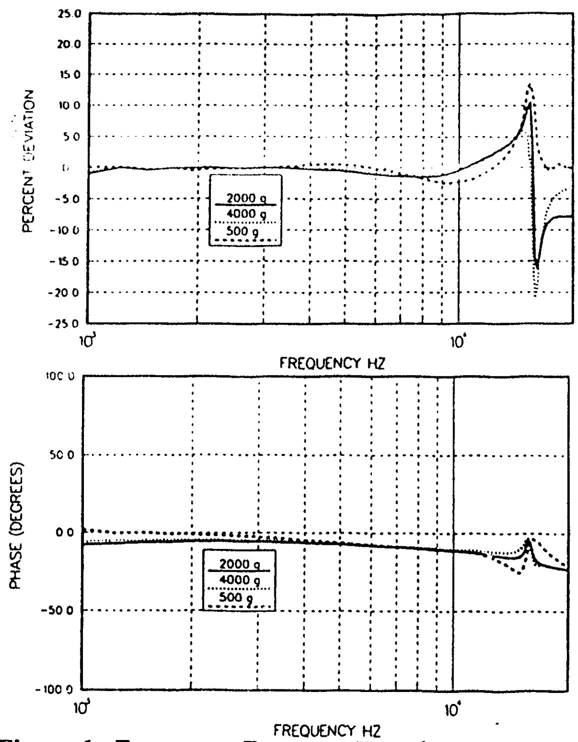


Figure 6: Frequency Response Function Comparison a Piezoresistive Accelerometer and a 50μs Pulse.

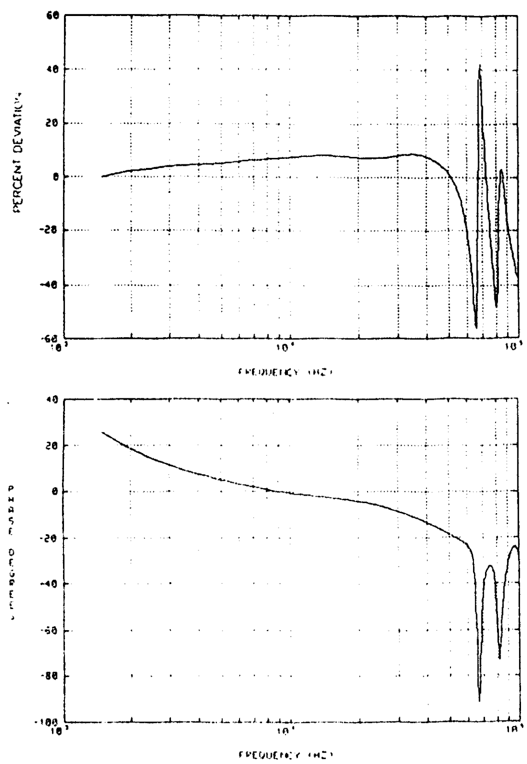


Figure 7: Preliminary Frequency Response Functions for a Piezoresistive Accelerometer (Stud Package) and the Beryllium Hopkinson Bar.

level limitation of 100,000 g. The frequency bandwidth for these characterizations and certifications will be extended to 30-50 kHz by the use of a beryllium Hopkinson bar instead of the titanium bar. 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.

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