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HIGH SHOCK, HIGH FREQUENCY CHARACTERISTICS OF A MECHANICAL ISOLATOR FOR A PIEZORESISTIVE ACCELEROMETER*

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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. An Extended Technical Assistance Program with the accelerometer manufacturer has resulted in a commercial isolator that will be available to the general public. This mechanical isolator has ten times the bandwidth of any other commercial isolator and has acceptable frequency domain performance from DC to 10 kHz ($\pm 10\%$) over a temperature range of -65°F to $+185^{\circ}\text{F}$ as demonstrated in this paper.

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

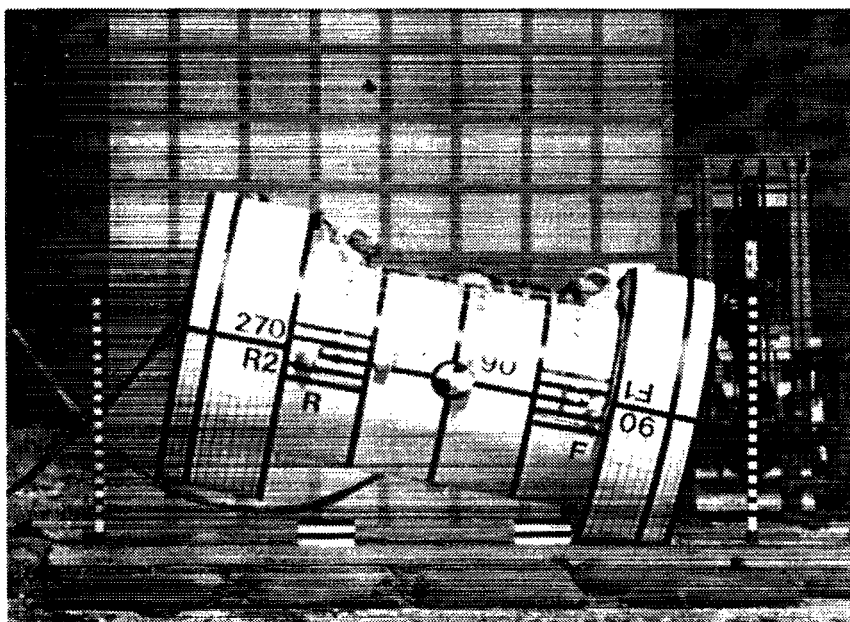


Figure 1: Slapdown Test Impact for a Nuclear Transportation Cask.

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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 mechanical isolator for a piezoresistive accelerometer in response to impact test and pyroshock measurement requirements for a variety of 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 as 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 the piezoresistive accelerometer in the mechanical isolator assembly have been reported previously for frequencies of DC-10 kHz and shock magnitudes of up to 15,000 g [1,2,3,4]. In recent years, technology transfer funds have become available to transfer technology developed for SNL programs to private industry. A proposal was made and accepted for an Extended Technical Assistance Program (ETAP) with the accelerometer manufacturer to transfer the mechanical isolator technology.

The ETAP 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 piezoresistive accelerometer and the mechanical isolator assembly in the high frequency, high shock environments where measurements are being made during impact and pyroshock tests. The results of a test program to characterize the piezoresistive accelerometer with the mechanical isolator for frequencies of DC to 10 kHz and shock magnitudes up to 200,000 g with a Hopkinson bar test configuration are described. The last phase of the ETAP will be the testing and evaluation of the mechanical isolator prototypes made by manufacturer.

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, a commercially available source of the material was desired for the accelerometer company, but no commercial supplier of this rubber in 0.010 in. thin 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 $\pm 5\%$ 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 isolator (Sandia Disk) and a commercial isolator is shown in Figure 2.

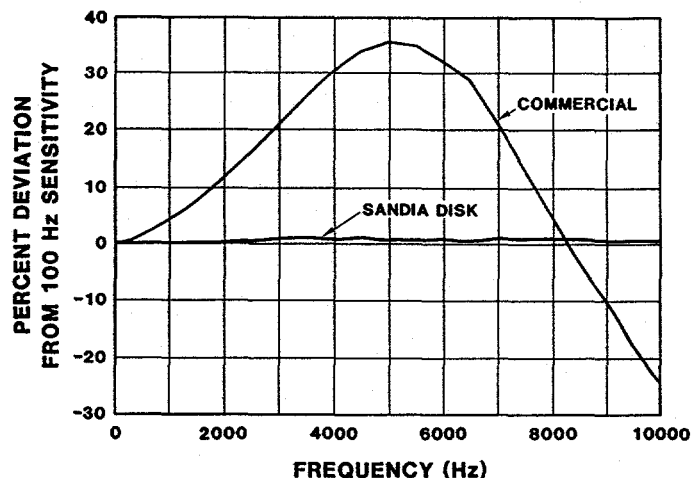


Figure 2: Shaker Calibration Comparison for SNL Mechanical Isolator and a Commercial Isolator

Additionally, the dropball calibration should be flat ($\pm 3\%$) for shock levels up to 20,000 g. Shaker calibrations were also performed at -65°F and $+185^{\circ}\text{F}$. 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 Hopkinson

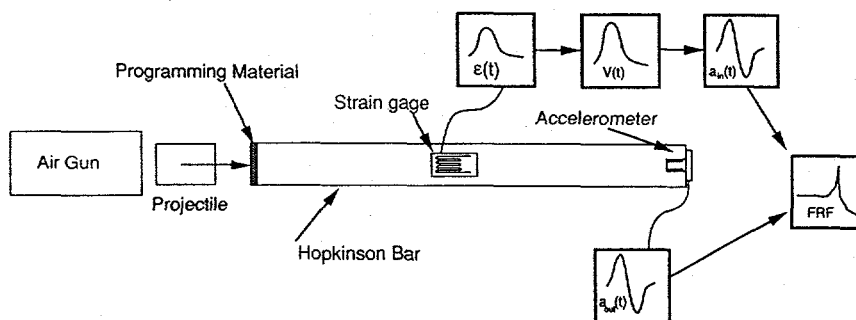


Figure 3: Hopkinson Bar Test Configuration

bar test apparatus and the associated data analyses performed in the SNL Mechanical Shock Laboratory has been described in previous publications [1-5] and will not be described again here. 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 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 the strain gages and the accelerometer must not show resonant response. If the material agreed well 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 (either by impedance mismatch or energy absorption) 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 another elastic material was abandoned, and polysulfide rubber remained the elastic material in the mechanical isolator.

In order for the commercial manufacturer to obtain 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.

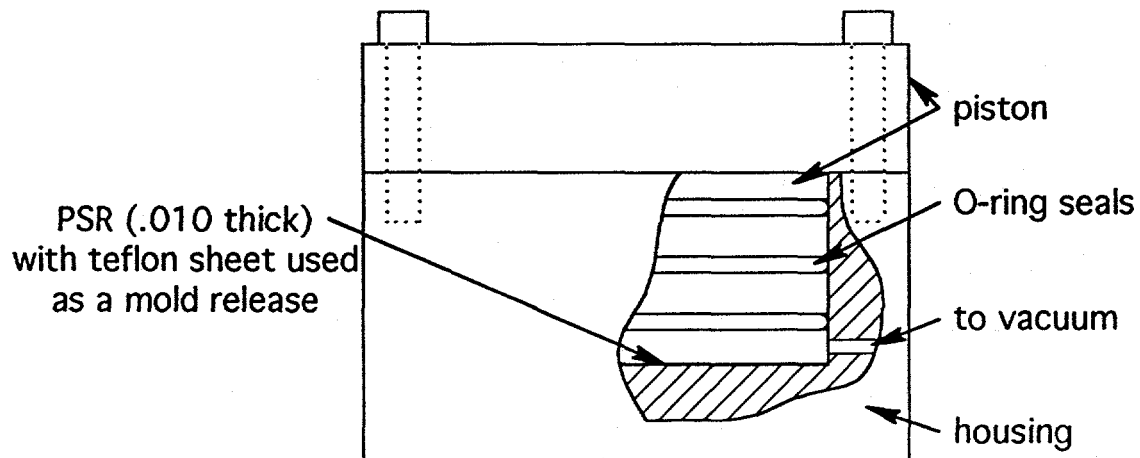


Figure 4: Simple Fixture to Make Polysulfide Rubber Plaques.

SHOCK TESTING OF THE MECHANICAL ISOLATOR

Twelve accelerometers were assembled in the mechanical isolator. An exploded view of the isolator is shown in Figure 5. 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 (approximately 30 kHz) tends to excite the resonance of the accelerometer at 90 kHz. Testing was planned for each accelerometer up to each 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

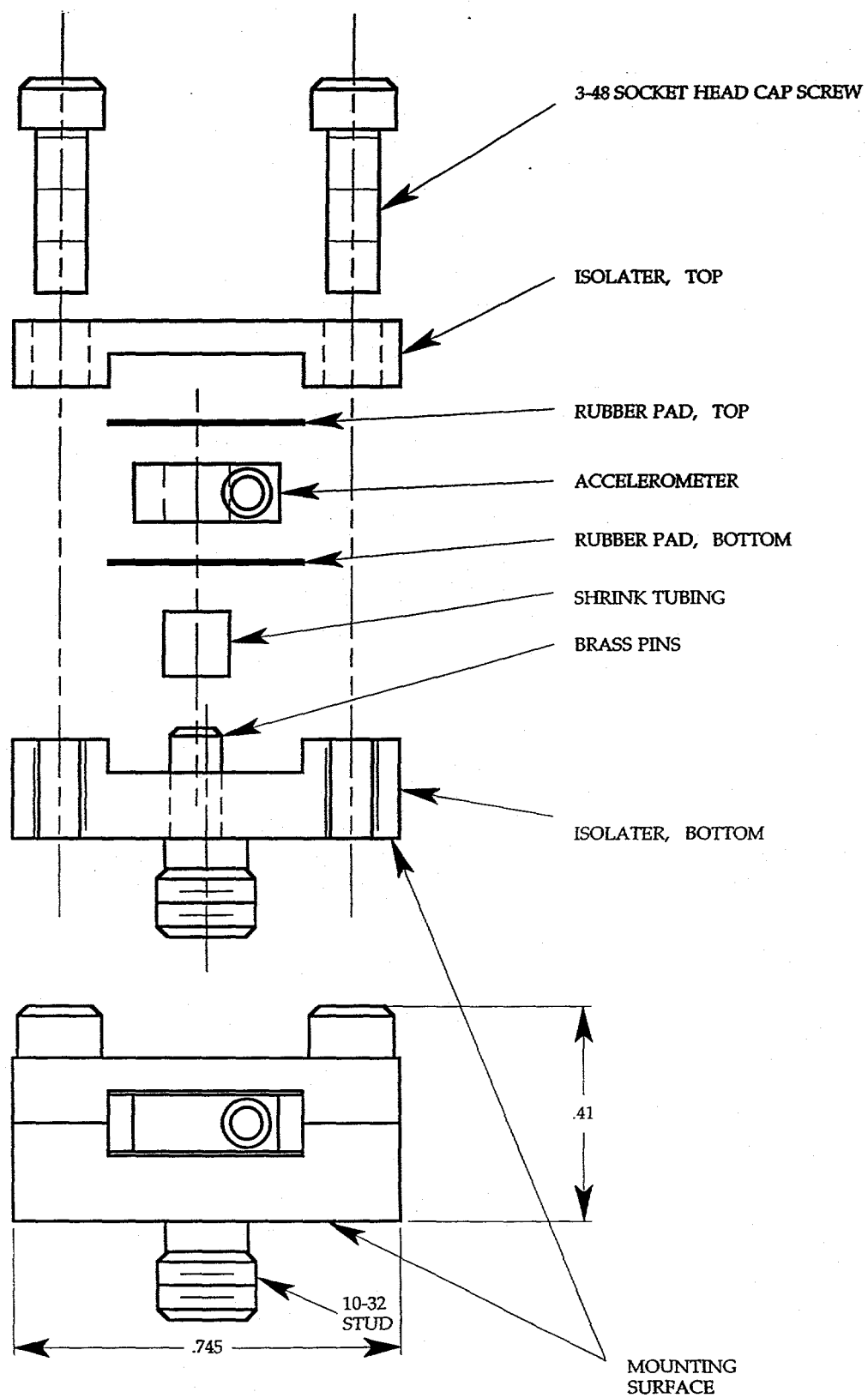


Figure 5: Exploded View of Original Mechanical Isolator.

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 two decades below the low frequency asymptote. The observation of this unacceptable performance led to a

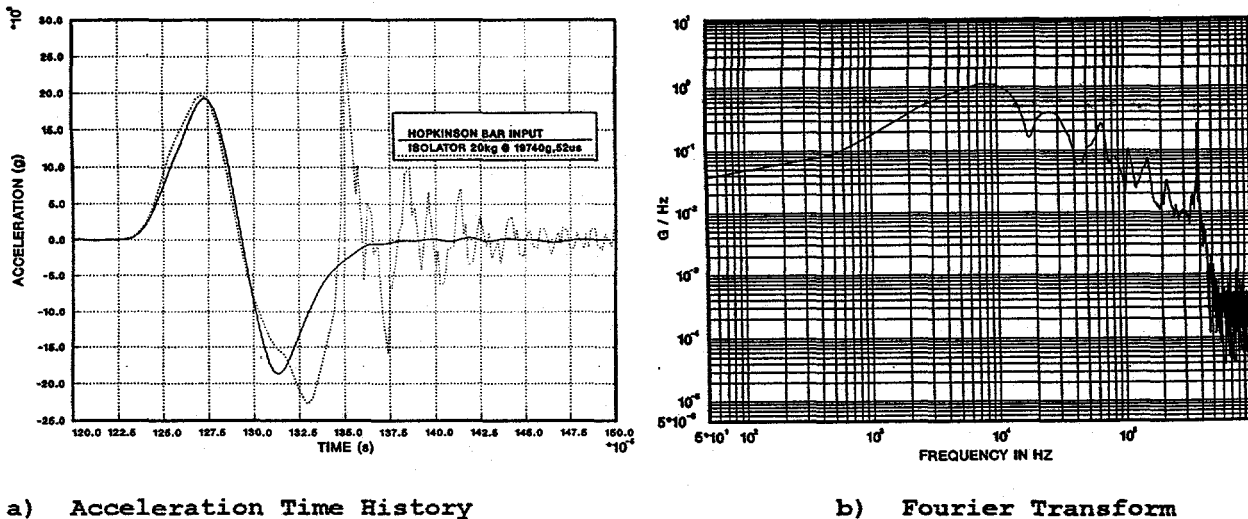


Figure 6: Unacceptable Response of Initial Mechanical Isolator Design.

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-lbs instead of 25 in-lbs). 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 tolerancing and an extra operation for assembly. These design changes allowed the mechanical isolator to respond appropriately at acceleration levels up to 70,000 g before the nonlinear response appears without significantly increasing the weight of the isolator (9.5 grams as compared to the original 7.5 grams). 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 isolator design and no resonance have been found in the frequency range of 30-50 kHz which is the frequency of the response at the end of the Hopkinson bar pulse.

The Hopkinson bar testing continued with the improved mechanical isolator at shock levels of 20,000 g, 40,000 g, and 60,000 g for a duration of about 40 μ s and for temperatures of -65°F, ambient (70°F), and +185°F. Figure 8 shows the consistent time history data that is required for the frequency response function analyses of these data. Figures 9-11 show the frequency response

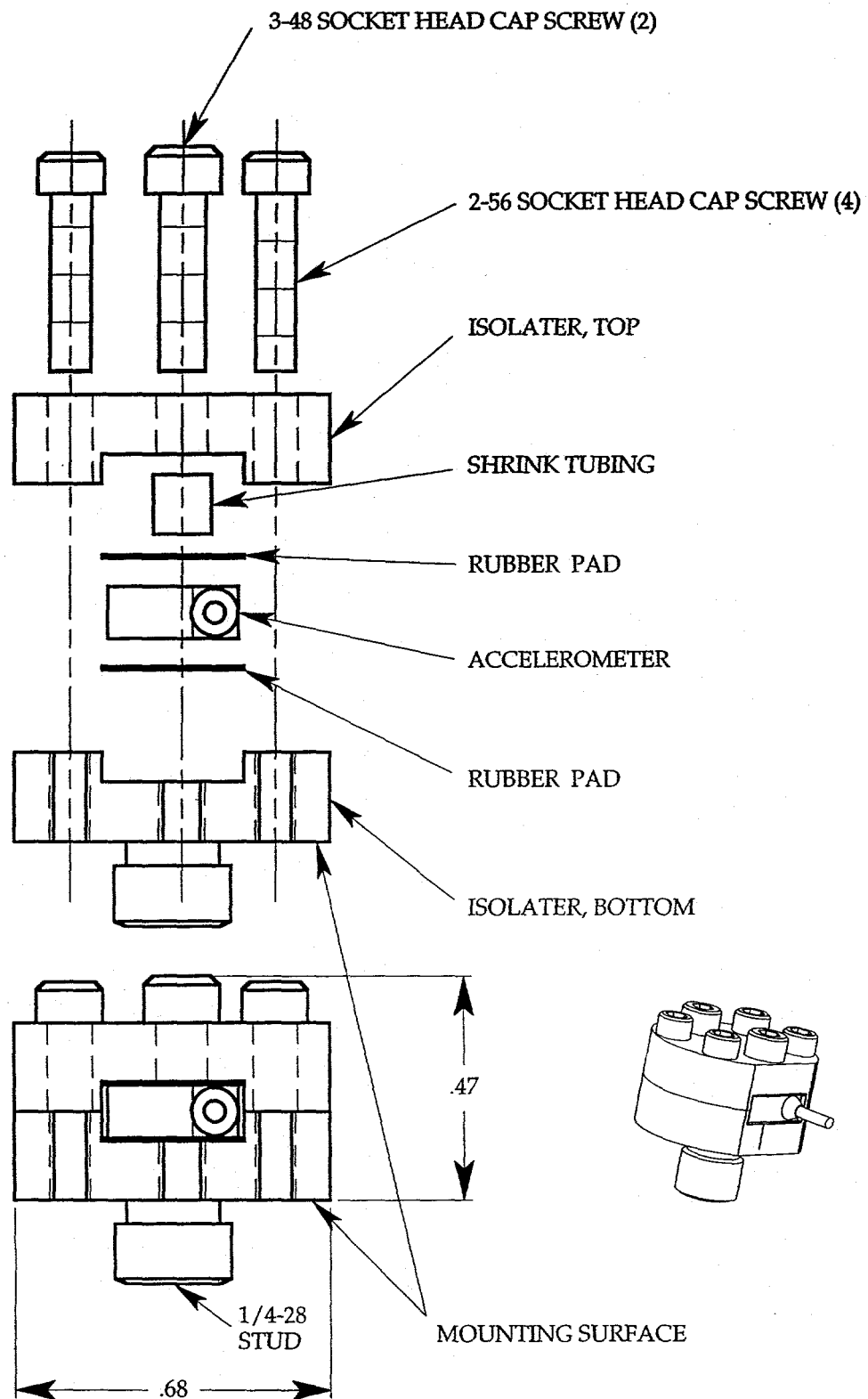
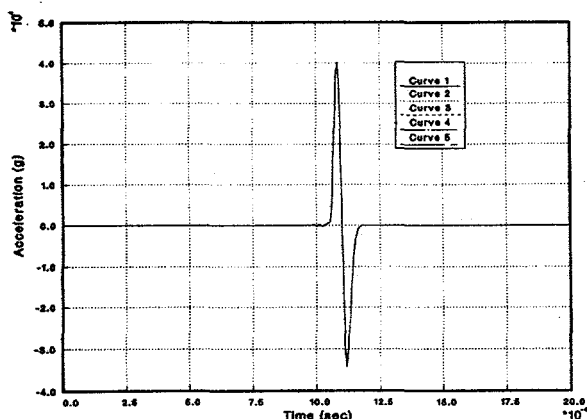
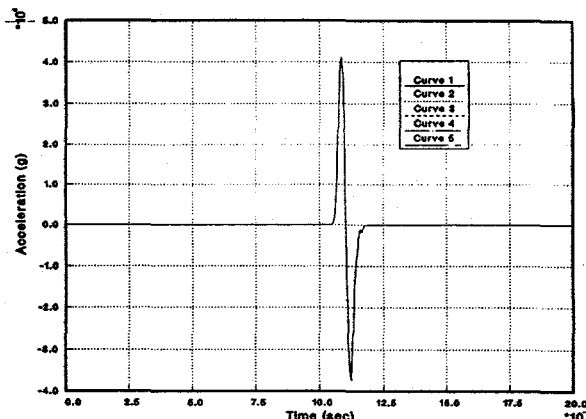


Figure 7: Exploded View of Improved Mechanical Isolator with Acceptable Performance to 60,000 g for DC-10 kHz.



a) Hopkinson Bar Acceleration



b) Mechanical Isolator Response

Figure 8: Consistent Hopkinson Bar Time History Data Used for Frequency Response Function Calculations (40,000 g at Ambient Temperature).

functions for temperatures of -65°F , ambient (70°F), and $+185^{\circ}\text{F}$, respectively. For the 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 the same bandwidth, the frequency response function phase changes are minimal for the same conditions. 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 mechanical isolator. 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 [1-5], and the frequency response functions are useable to at least 10 kHz and above.

Although 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 $+185^{\circ}\text{F}$. 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 the useable frequency range would be required.

CONCLUSIONS

A mechanical isolator for a piezoresistive accelerometer has been developed at SNL. The isolator has acceptable performance as determined by the magnitude, phase and coherence of frequency response functions calculated from Hopkinson bar data for shock levels of 20,000 g, 40,000 g, and 60,000 g and for temperatures of -65°F , ambient (70°F), and $+185^{\circ}\text{F}$ with a frequency bandwidth of DC to 10 kHz. This mechanical isolator has ten times the bandwidth of any other commercial isolator. The mechanical isolator

technology, that was developed in response to SNL impact and pyroshock test requirements, is being transferred to a commercial accelerometer manufacturer.

ACKNOWLEDGMENTS

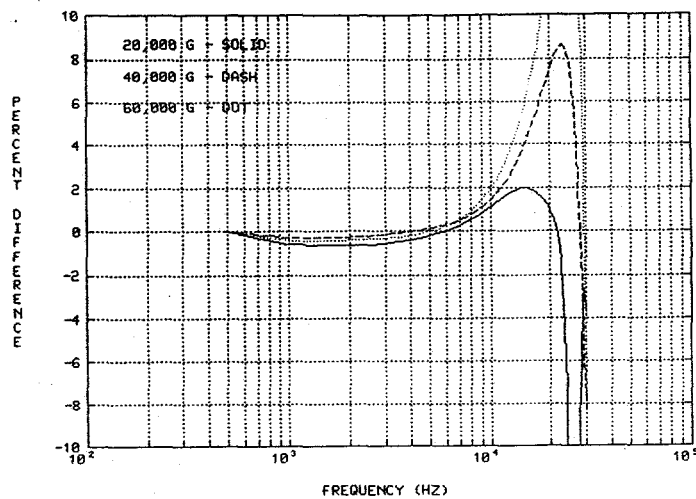
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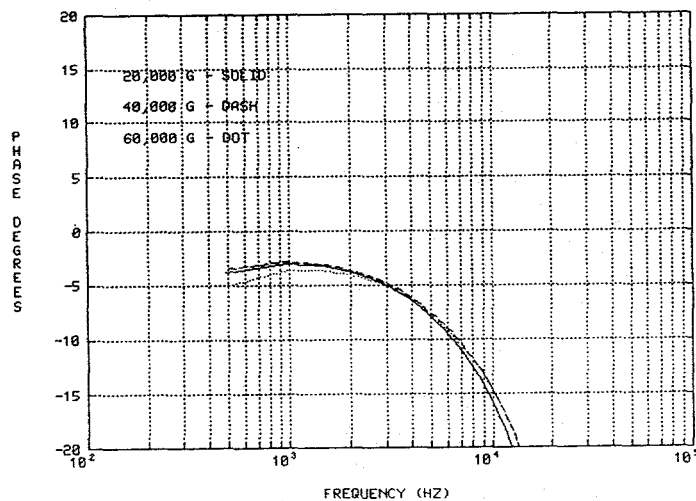
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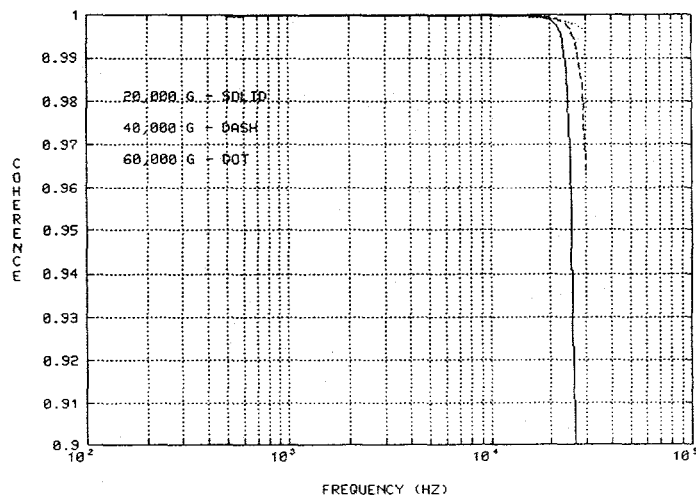
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a) Frequency Response Function Magnitude

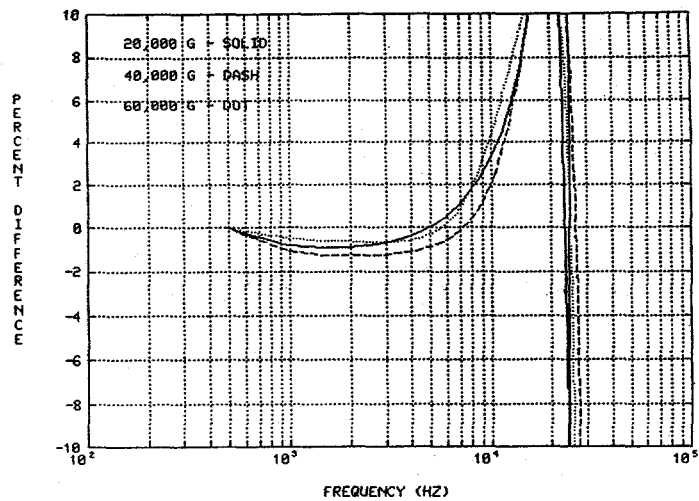


b) Frequency Response Function Phase

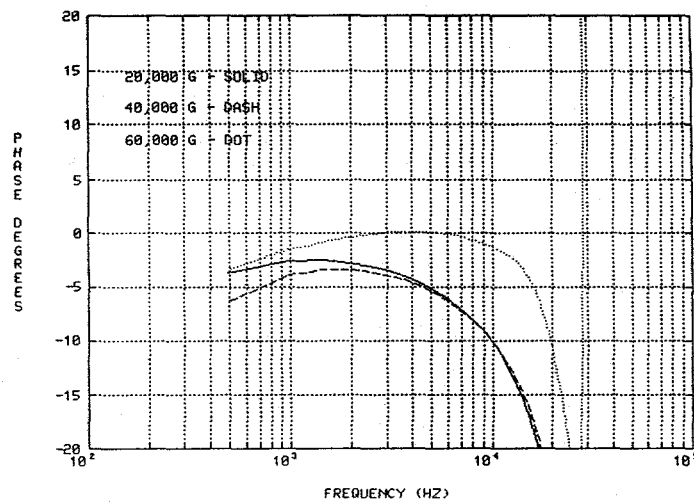


a) Frequency Response Function Coherence

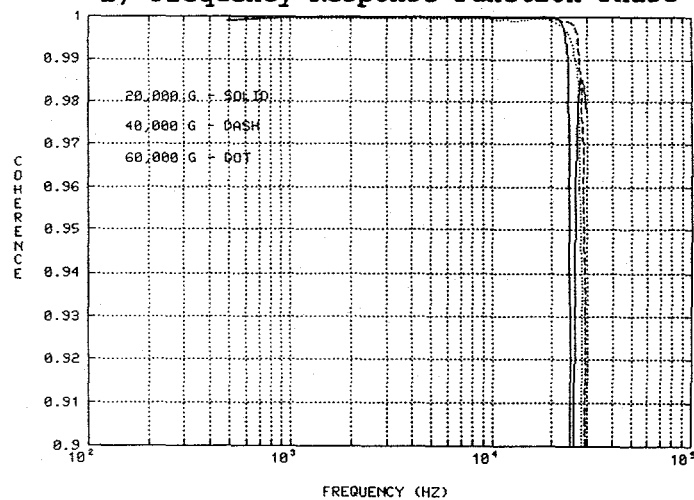
Figure 9: Frequency Response Functions at -65°F.



a) Frequency Response Function Magnitude

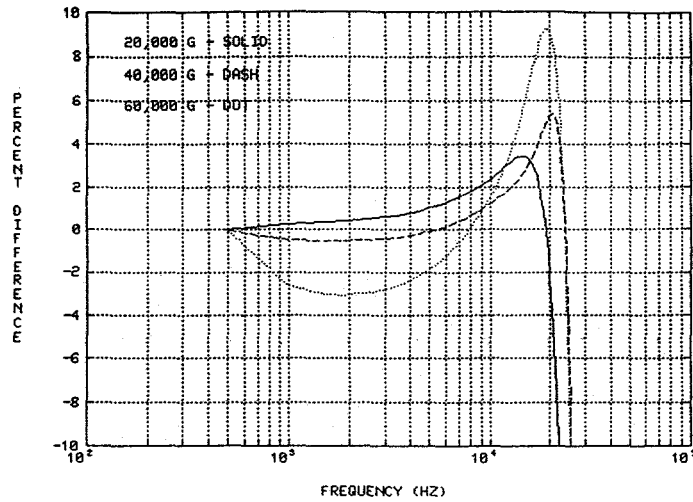


b) Frequency Response Function Phase

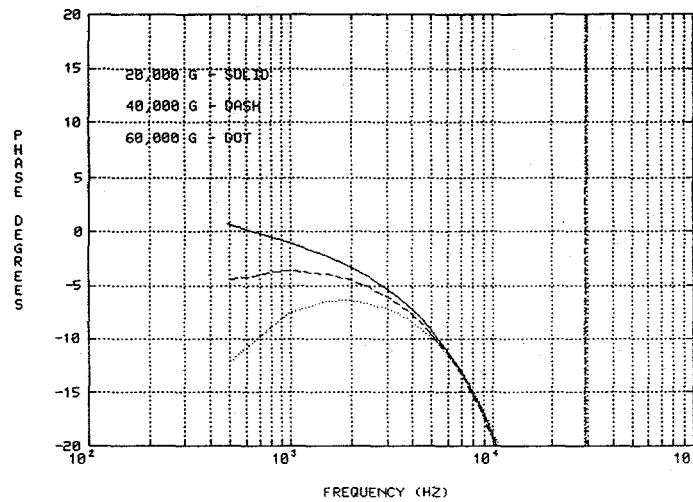


c) Frequency Response Function Coherence

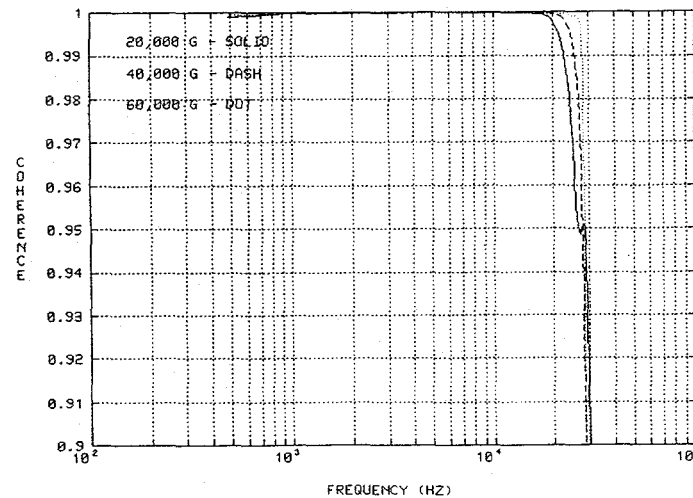
Figure 10: Frequency Response Functions at Ambient (70°F).



a) Frequency Response Function Magnitude



b) Frequency Response Function Phase



c) Frequency Response Function Coherence

Figure 11: Frequency Response Functions at +185°F.