IN-AXIS AND CROSS-AXIS ACCELEROMETER RESPONSE IN SHOCK ENVIRONMENTS*

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KEYWORDS

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ABSTRACT

The characteristics of a piezoresistive accelerometer in shock environments have been studied at Sandia National Laboratories (SNL) in the Mechanical Shock Testing Laboratory for ten years The SNL Shock Laboratory has developed a capability to characterize accelerometers and other transducers with shocks aligned with the transducer's sensing axis and perpendicular to the transducer's sensing axis. This unique capability includes Hopkinson bars made of aluminum, steel, titanium, and beryllium. The bars are configured as both single and split Hopkinson bars. Four different areas that conclude this study are summarized in this paper: characterization of the cross-axis response of the accelerometer in the four environments of static compression, static strain on a beam, dynamic strain, and mechanical shock; the accelerometer's response on a titanium Hopkinson bar with two 45° flats on the end of the bar; failure analysis of the accelerometer; and measurement of the accelerometer's self-generating cable response in a shock environment.

INTRODUCTION

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

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DISCLAIMER

[1,2,3]. To enhance survivability of the new generation of combat vehicles, the Army has specified a minimum frequency range of 10 kHz for the design and qualification test of components. 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.

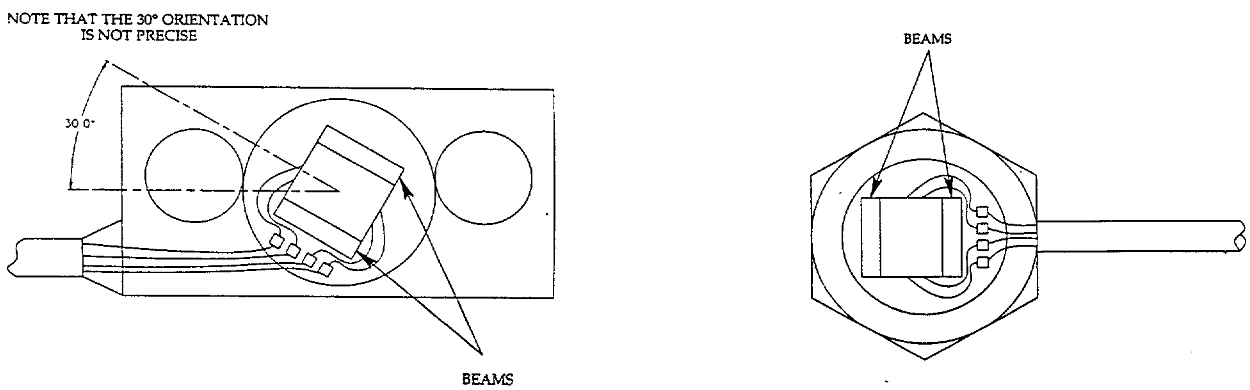
Table I: Experiment Matrix for In-Axis Accelerometer Study.

	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

Table II: Environments for the Cross-Axis and Combined Shock Accelerometer Study.

Environment	Experimental Configuration
Static Compression	Beryllium Cylinder
Static and Dynamic Strain	Steel Beam
Compressive Mechanical Shock	Split Hopkinson Bar with a Beryllium Cylinder
Combined Shock	Titanium Hopkinson Bar with 45° Flats

The results from the in-axis studies for the two mechanical configurations shown in Figure 1 have been reported previously and will not be repeated here [4,5,6,7]. The ***ENDEVCO 7270A**** uses two #4-40 screws for mounting. The ***ENDEVCO 7270AM4**** uses a single #1/4-28 mounting stud. Previous results [4,7] confirm the manufacturer's performance specifications for frequency response and time response that were previously unconfirmed, and show that the two accelerometers perform in a similar



ENDEVCO 7270A with Top Removed

ENDEVCO 7270AM4 with Top Removed

Figure 1: Two Mechanical Configurations for a Piezoresistive Accelerometer, ENDEVCO 7270A and ENDEVCO 7270AM4 (dual beam design).

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

manner for in-axis shocks with the exception of a resonance noted in the can package at about 100 kHz that is not apparent in the flat package. The in-axis characterizations include both time-domain results with a bandwidth of dc to 100 kHz and frequency-domain results with a bandwidth of dc to 50 kHz.

The piezoresistive accelerometers are being characterized in cross-axis environments in Table II to provide better interpretation of high frequency measurements. To achieve this goal, a beryllium split Hopkinson bar capability has been developed because of its low Poisson's ratio, 0.07. The result is that beryllium has negligible response in the accelerometer's sensitive axis, so these cross-axis experiments may be considered pure cross-axis environments. The reference measurement for the beryllium Hopkinson bar in a split bar configuration is a strain gage to measure both axial and lateral response. The SNL strain gages have been certified as a reference measurement with an uncertainty of + 6% [5].

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

HOPKINSON BAR CONFIGURATIONS

Cross-axis sensitivity of the piezoresistive accelerometers has been studied with the beryllium split Hopkinson bar configurations shown in Figures 2 and 3. 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 but is perpendicular 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. A cross-axis configuration with the accelerometers mounted normal to the stress wave on the end of the bar was proposed previously [4] but was abandoned because the end-modes at 120 kHz in the Hopkinson bar caused the accelerometers to resonate and break. Acceleration responses for the ENDEVCO 7270A and 7270AM4 mounted on titanium Hopkinson bars with two 45° flats on the end have been obtained with the configurations shown in Figure 4. A bar was machined to accommodate two accelerometers of the same model at the same time. The 45° flats provide a combined in-axis and cross-axis shock environment.

The Mechanical Shock Laboratory Hopkinson bars, used for accelerometer characterizations, are made of either 6 AL, 4V titanium alloy (6% aluminum and 4% vanadium) or beryllium (99% pure). The titanium bar is 72 in. long with a 0.76 inch diameter, and the beryllium bars are 50 in. long with a 2.0 inch diameter. Each 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 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 pulse. Placing a number of index cards on the impact surface controls the shape (approximately a half sine) and duration of the pulse. No special preparations of the beryllium Hopkinson bar interfaces with the inserts are made other than insuring that the surfaces are flat and polished. Careful alignment of the bars and the insert is required. Time domain evaluations, as a percent difference from a reference measurement (Laser Doppler Vibrometer,. LDV, or strain gages), have been made for both the titanium and the beryllium Hopkinson bars.

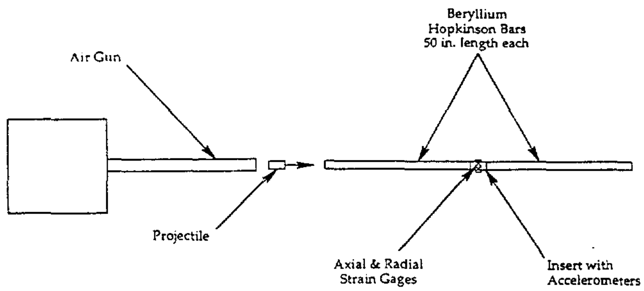


Figure 2: Split Beryllium Hopkinson Bar Configuration for Cross-Axis Input (2.0 in. Diameter).

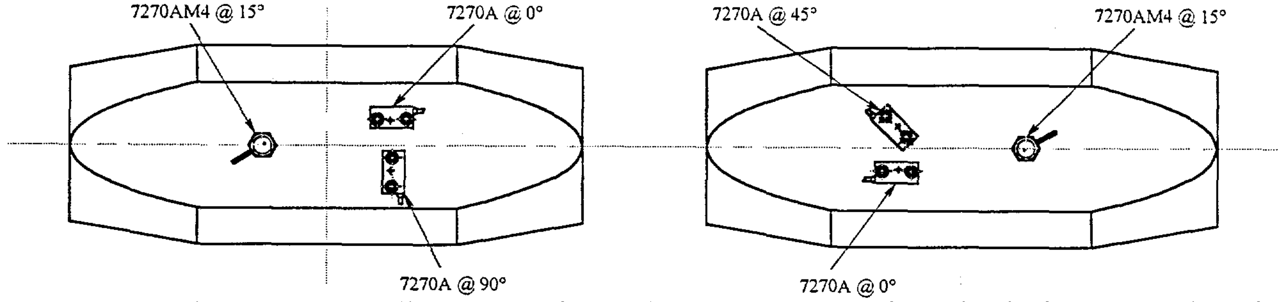


Figure 3: Two Flats on the Beryllium Insert for Static Compression and Mechanical Compressive Shock Cross-Axis Experiments (2 in. Diameter).

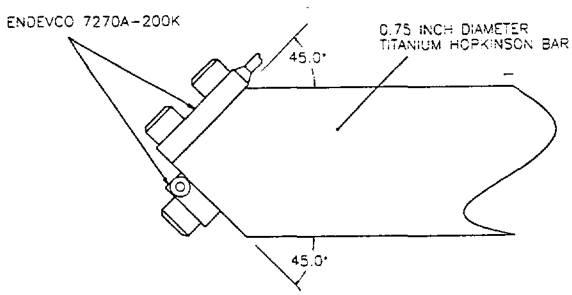
CROSS-AXIS ACCELEROMETER PERFORMANCE

The characterization of the cross-axis response of the ENDEVCO 7270A and 7270AM4 accelerometers in the four environments of static strain on a beam of 250 $\mu\varepsilon$; dynamic beam strain experiments at 250 $\mu\varepsilon$ (as per ISA-RP 37.2, Paragraph 6.6); and static compression experiments up to 100 $\mu\varepsilon$ and mechanical compressive shock with a 2 in. diameter split Hopkinson bar configuration have been completed. The orientation of the sensors for the static compression and mechanical compressive shock cross-axis experiments are shown in Figure 3. Radial strain measurements verified the performance of the beryllium. For the static and dynamic base strain experiments, a steel beam as specified in ISA-RP 37.2, Paragraph 6.6 was used. This recommended practice creates maximum surface strain at the fixed end of a cantilever beam. The transducers are mounted at this location and 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. The results of the static compression, static beam, and dynamic beam strain are shown in Tables III-V, respectively. The response of the 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 $\mu\varepsilon$ except in two cases. In these two cases, a 0.009 in thick shim was used under a 7270AM4 to maintain sensor orientation relative to the compressive shock wave. The shim was abandoned because it caused excessive base strain.

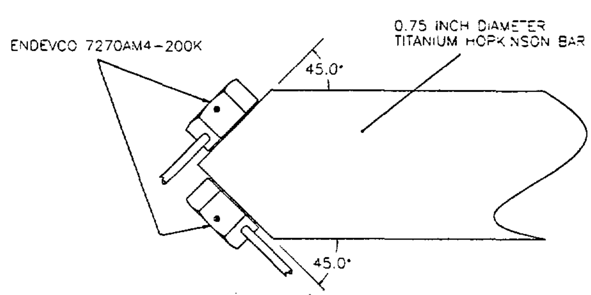
The theory of stress wave propagation in a Hopkinson bar is well documented in the literature [10, 11] and has been summarized previously [4,7]. The cross-axis motion analysis has also been presented [12] and the relationship for the radial acceleration is

$$a_y = \frac{\mu r}{c}\frac{da}{dt}. \qquad (1)$$

where, a_y, is the radial acceleration; μ is Poisson's ratio; a is the axial motion at a location in the Hopkinson bar other than the free end; r is the radius of the Hopkinson bar; and c is the wave propagation speed in the bar.



ENDEVCO 7270A



ENDEVCO 7270AM4

Figure 4: Titanium Hopkinson Bar with Two 45° Flats for the ENDEVCO 7270A and ENDEVCO 7270AM4.

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
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
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/$\mu\varepsilon$)	Voltage output at 250 $\mu\varepsilon$ (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
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

A prediction of the axial and radial acceleration for the beryllium Hopkinson bar using the equations above has been reported previously [12]. As shown in Figures 5-9, the ENDEVCO 7270A shows a base strain response when subjected to a compressive mechanical shock, and the ENDEVCO 7270AM4 shows a base strain response when the beams are in line to the shock or an acceleration response when the beams are in other orientations to the shock. The time history plots of these data have a 20 kHz frequency component that is the first axial mode of the insert. The data cannot be filtered to eliminate this resonant response without severely compromising the rise time of the initial response.

COMBINED SHOCK ENVIRONMENT PERFORMANCE

The ENDEVCO 7270A and 7270AM4 accelerometers were mounted on their respective titanium Hopkinson bar shown in Figure 4. The nominal amplitude of the applied shock pulse was measured with both the references of strain gages and the LDV and agreed within 1%. The results are shown in Table VI and in Figures 10-11. Only one measurement from the 7270AM4 was obtained because the other accelerometer resonated and failed. Both the screws for the 7270A and the stud for the 7270AM4 had backed out after the shock pulse. The loose accelerometers chattered on their flats and caused the accelerometers to resonate. It is hypothesized that the ends modes of the bar caused the screws/stud to loosen. ENDEVCO has donated two accelerometers so that SNL can investigate this problem.

Table VI: Summary of Accelerometer Performance in Combined Shock.

Nominal Amplitude	Accelerometer Model	In-Axis Ampltide	Accelerometer Response	Percentage Error
49,500 g	7270AM4	35,000 g	37,500 g	+ 7.1%
50,000 g	7270A	35,350 g	37,000 g	+ 4.7%
50,000 g	7270A	35,350 g	39,000 g	+10.3%

FAILURE MODE AND SELF-GENERATING CABLE ANALYSES

On June 6, 1998, twenty-seven Model 7270A (flat package) accelerometers were given to ENDEVCO for failure analysis. Eighteen of the twenty-seven accelerometers had equal input/output resistances that indicated that the sensors were intact; their failure mode is assumed to be cable failure. The remaining nine accelerometers had specific complaints, as noted in Table VII. The failure analyses performed in cooperation with ENDEVCO have provided a great insight as to the failure modes of the 7270A. *The overwhelming majority of the failures are due to cable failure that is explained below.*

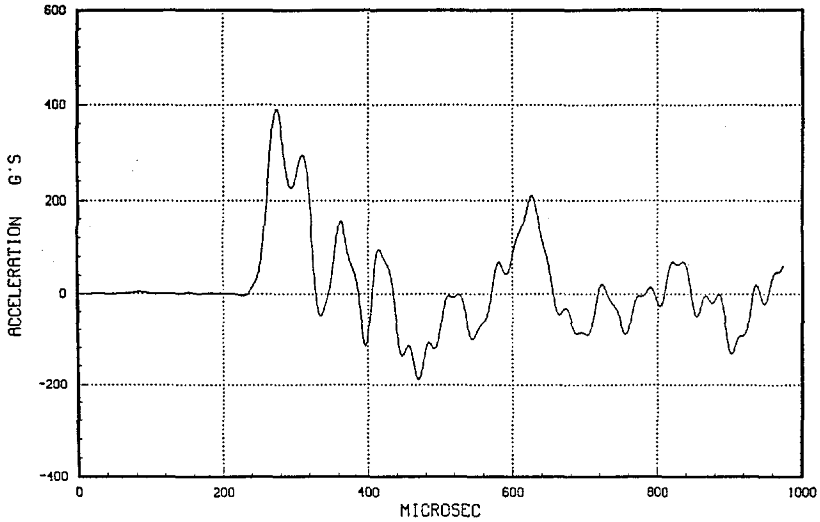


Figure 5: ENDEVCO 7270A-60K Base Strain Response to Cross-Axis Compressive Shock (250 με Amplitude) with 0° Angle and 30 kHz Analog Filter.

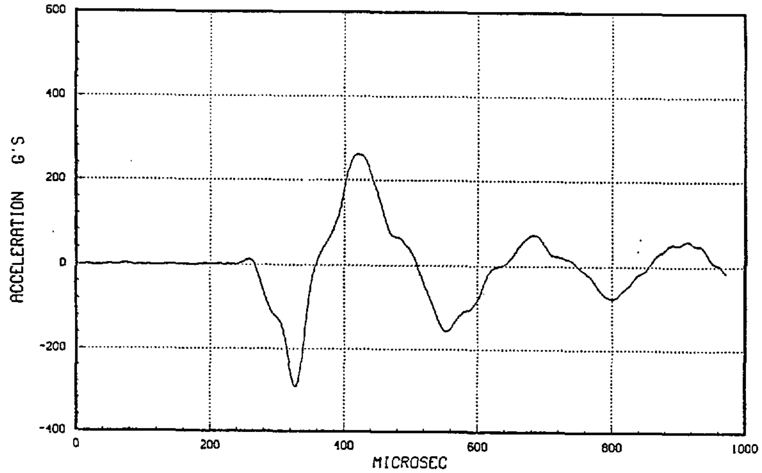


Figure 6: ENDEVCO 7270A-60K Base Strain Response to Cross-Axis Compressive Shock (250 με Amplitude) with 45° Angle and 30 kHz Analog Filter.

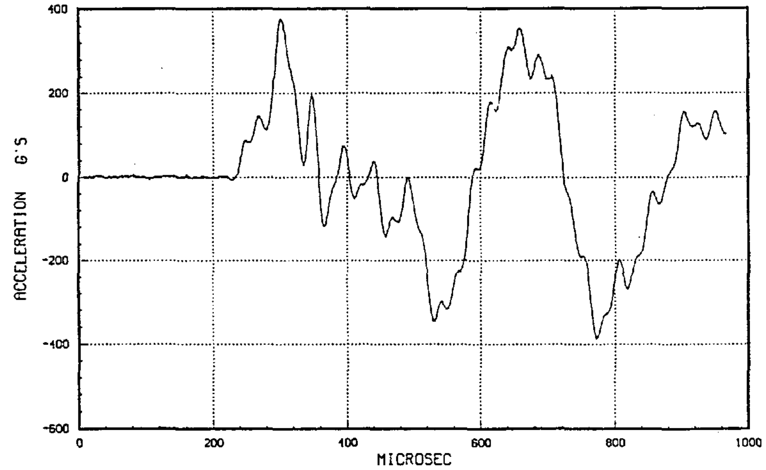


Figure 7: ENDEVCO 7270A-60K Base Strain Response to Cross-Axis Compressive Shock (250 με Amplitude) with 90° Angle and 30 kHz Analog Filter.

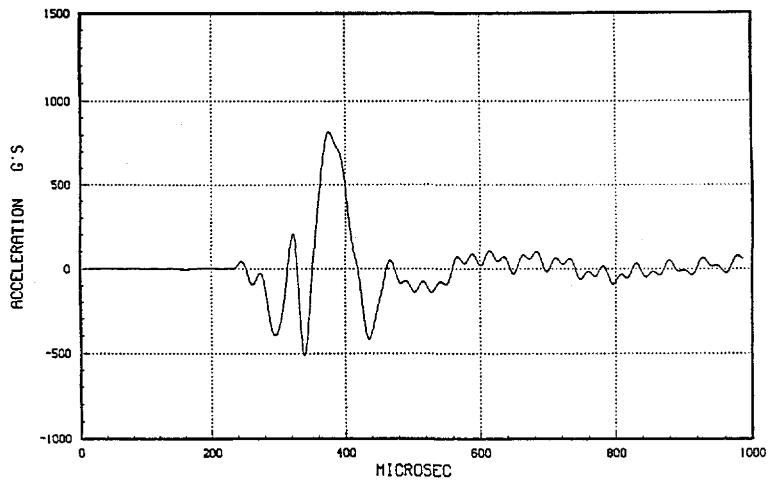


Figure 8: ENDEVCO 7270AM4-200K Base Strain Response to Cross-Axis Compressive Shock (250 με Amplitude) with 15° Angle and 30 kHz Analog Filter.

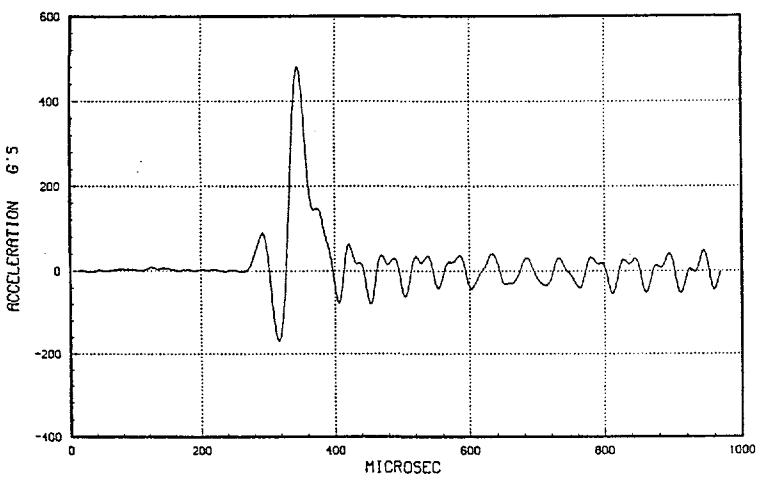


Figure 9: ENDEVCO 7270AM4-200K Base Strain Response to Cross-Axis Compressive Shock (250 με Amplitude) with 65° Angle and 30 kHz Analog Filter.

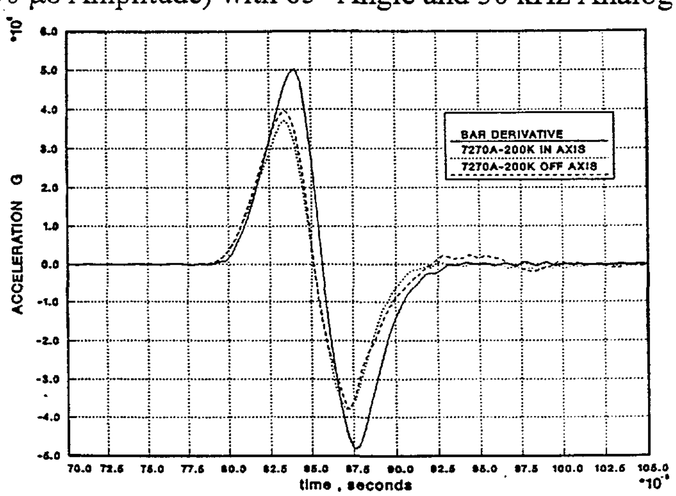


Figure 10: ENDEVCO 7270A-200K Response to Combined Shock at 45° on a Titanium Hopkinson.

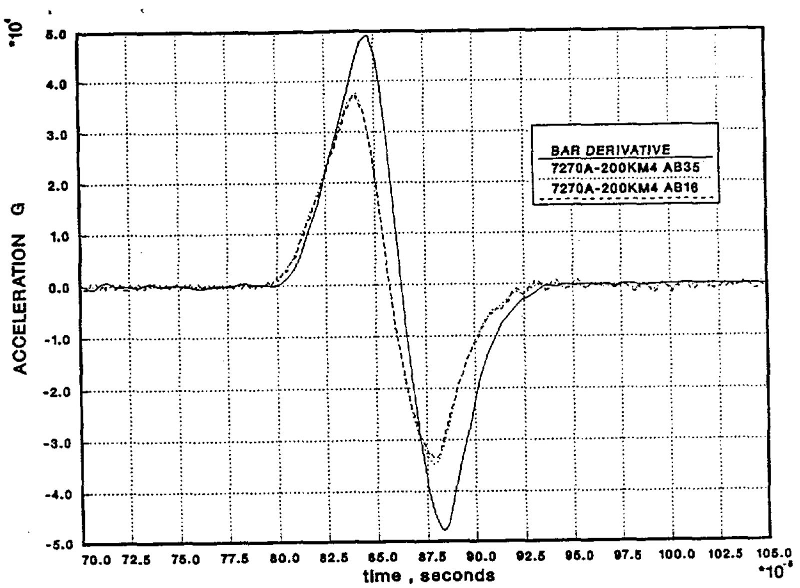


Figure 11: ENDEVCO 7270AM4-200K Response to Combined Shock at 45° on a Titanium Hopkinson.

During a SNL program to develop a transducer with high input impedance, a response was measured that did not appear to originate with the sensor. The cable used with the transducer is the ENDEVCO 7270A cable and is silverplated, 36 gage copper conductors with a silverplated-copper shield and fluorocarbon jacket. The cable was taped to a titanium Hopkinson bar with a 0.75 in. diameter and a 72 in. length as shown in Figure 12. All investigations were conducted at a nominal velocity of 10 fps magnitude and 90 μs duration (measured at 10% amplitude). An amplifier gain of 50 was used unless otherwise noted, and an excitation of 10 V. was provided on the black and red wires unless otherwise noted. The results of this investigation are summarized in Table VIII. These investigations show that the cable generates its own voltage output when it is subjected to a shock in line with the cable and can be as much as 10% of the transducer output. *It is hypothesized that the movement of the wires inside their insulation causes the cable output. The movement of the wires eventually breaks the wires ant can be misinterpreted as sensor failure.* The cable is subjected to shock in most applications because the cables are secured to a structure that undergoes a shock environment. These investigations explain not only the failure mode of the cable, but also mysterious transducer output without transducer excitation in other shock experiments. It has been recommended to ENDEVCO that a methodology for isolating the cable from shock waves be developed in cooperation with SNL.

UNCERTAINTY ANALYSIS

The uncertainty in these measurements and results are attibuted to two sources: uncertainty in the sensors and the data acquisition system and uncertainty in the 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 ±10% for amplitude, ±5% for duration, and ±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 ±0.5%, and documentation of these results is maintained in the Mechanical Shock Laboratory. Consequently, the only uncertainty in these measurements is the uncertainty in the sensor calibration, ±5% [16] and the uncertainty in the torque wrench calibration,

Table VII: Failure Analysis of Nine ENDEVCO 7270A Accelerometers.

Model, S/N	Complaint	Analysis
7270A-20K AG5L3	Resonant frequency ringing during applied shock pulse.	Shock Test at 4908 g; slight after pulse ringing present and is typical output
7270A-20K B91AF	Open	All four gages intact. BW trace on ceramic open.
7270A-20K B72CF	Open	GB links all have tiny pimples at mid-length. Fused one downside gage.
7270A-60K A51KF	Displays ringing during dropball calibration.	Shocked 5 times between 4259 and 4880 g and saw typical after-pulse resonant ringing.
7270A-200K AFFH2	Open	One link of GB fused. Adjacent links & aluminum have been melted.
7270A-200K AP693	Open	One link of WG broken, piece missing. Another edge flaked by shrapnel.
7270A-200K AD288	Open	Masses loose.
7270A-200K A44BF	Open	Failed glassbond. Gross die fracture, additional crack. Inclusion in glassbond.
7270A-200K DN81F	Open	Severe ohmic heating to GB. 6 links vaporized, remaining 2 links shorted by fused Silicon. Traces leadwire to GB deeply melted.

$\pm$5% [6]. These two uncertainties are considered random, so they may be combined in an uncertainty analysis with a 95% confidence level as [17,18]:

$$w_T = \sqrt{w_s^2 + w_{t\&l}^2} \qquad (2)$$

where: w_T = total uncertainty,
w_s = sensor calibration uncertainty, and
w_t = torque wrench calibration uncertainty.

The value of the total uncertainty, w_T, is $\pm$7% and is typical for the measurements made in the SNL Mechanical Shock Laboratory.

CONCLUSIONS AND FUTURE WORK

The characterization of the cross-axis response of the ENDEVCO 7270A and 7270AM4 accelerometers in four environments have been completed. The cross axis response of the ENDEVCO 7270A is base strain sensitive, but the cross-axis response of the ENDEVCO 7270AM4 may be either base strain or acceleration. The accelerometer meets the manufacturer's specifications for base strain and cross axis sensitivity. The ENDEVCO 7270A and 7270AM4 response in a combined shock environment at 45° is amplified by 4% to 10% in comparison to the reference measurement. The amount of amplification depends on both the mechanical package and orientation of the sensor to the shock. Finally, a failure analysis conducted in cooperation with ENDEVCO shows that cable shock is the cause for the

Table VIII: Hopkinson Bar Cable Investigation Summary.

No.	Description	Results
1	Cable and cable shield taped to the bar. Cable conductors connected to amplifier.	Oscillatory output with a period of about 500 μs (2kHz) and peak magnitude of 8.3 V.
2	Same as No. 1 but no excitation voltage.	Similar oscillatory output as No. 1. ***This means the output is self-generated.***
3	Same as No. 1 with green and white wires disconnected and excitation voltage is on.	Similar oscillatory output as No. 1. Output is capacitive coupling through remaining wires.
4	Same as No. 1 but all conductors disconnected but cable shield is connected.	Similar oscillatory output as No. 1.
5	Same as No. 4 but cable shield is also disconnected.	Output is amplifier drift only – magnitude is about 0.8 mV peak, no gain is baseline noise.
6	An ENDEVCO 7270A (350Ω bridge) is powered and hanging in the air. The cable is taped to the bar with shield connected as shown.	Oscillatory output with an irregular period and a peak magnitude of 125 mV peak-to-peak (10% of the transducer response for this stress wave). Baseline noise has dropped to 3 mV.
7	Same as No. 2 with the shield disconnected.	Similar oscillatory output as No. 1.
8	Repeat of No. 2.	Similar oscillatory output as No. 1.
9	Same as No. 8 but cable removed from the bar and hangs by the bar in the air.	Output is amplifier drift only – magnitude is about 100 mV per 1 ms.
10	Same as No. 9 with no bar impact (baseline noise plots).	Output is amplifier drift only – magnitude is 0.8 mV with no amplifier gain.
11	Repeat of No. 2 with a longer duration pulse (169 μs) created with. thick felt.s	Similar oscillatory output as No. 1.

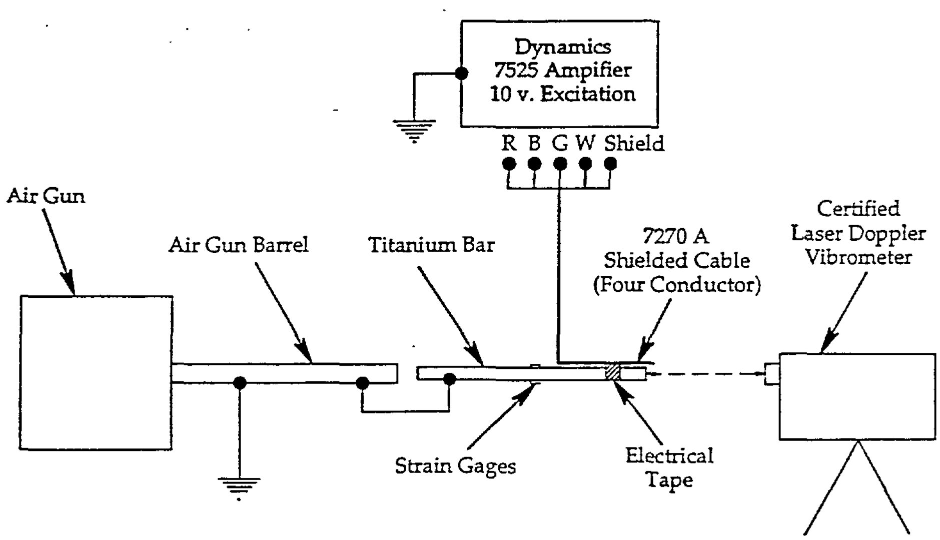


Figure 12: Hopkinson Bar Configuration for Cable Response Investigations.

occasional unexplained failures of this piezoresistive accelerometer. When this analysis is combined with SNL measurements of the cable response in shock environments, a scenario emerges that explains mysterious unpowered accelerometer outputs and accelerometer failures.

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