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Evaluation of a Hopkinson bar Fly-away Technique for High Amplitude Shock Accelerometer Calibration*

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A split Hopkinson bar technique has been developed to evaluate the performance of accelerometers that measure large amplitude pulses. An evaluation of this technique has been conducted in the Mechanical Shock Laboratory at Sandia National Laboratories (SNL) to determine its use in the practical calibration of accelerometers. This evaluation consisted of three tasks. First, the quartz crystal was evaluated in a split Hopkinson bar configuration to evaluate the quartz gage's sensitivity and frequency response at force levels of 18,000, 35,000 and 53,000 N at ambient temperature, -48°C and +74°C. Secondly, the fly-away technique was evaluated at shock amplitudes of 50,000, 100,000, 150,000 and 200,000 *G* ($1G$=9.81 m/s^2) at ambient temperature, -48°C and +74°C. Lastly, the technique was performed using a NIST calibrated reference accelerometer. Comparisons of accelerations calculated from the quartz gage data and the measured acceleration data have shown very good agreement. Based on this evaluation, we expect this split Hopkinson fly-away technique to be certified by the SNL Primary Standards Laboratory.

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INTRODUCTION

This Hopkinson bar fly-away technique was developed to evaluate the performance of accelerometers for peak acceleration amplitudes up to 200,000*G* ($1G$=9.81 m/s^2). Other Hopkinson bar experiments are capable of such amplitudes but the evaluation is not a direct comparison of acceleration. Sill [1,2] used elementary bar theory to show that an integration of the accelerometer output is proportional to strain measured on the bar surface. Bateman [3] showed that by taking the derivative of the strain measured on the bar surface, a comparison could be made to the accelerometer output without the loss of high frequency information. This fly-away technique is a comparison of acceleration without integrating the accelerometer output or taking the derivative of a strain measurement. This technique was adequate for a comparison of two independent acceleration measurements but as a calibration application, it was not traceable to an acceleration standard or reference. This evaluation was an attempt to determine the feasibility of this technique for the practical calibration of accelerometers.

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The primary focus of this evaluation was on the sensitivity, linearity and frequency response characteristics of an x-cut quartz gage at various stress amplitudes and temperatures. A split Hopkinson bar apparatus was used for this task. The second task of was to evaluate the fly-away method at temperatures of +74°C and -54°C. The final task of this evaluation was to compare the quartz gage output with a Kistler 805A accelerometer using the fly-away technique. This accelerometer was calibrated by NIST for use as a reference accelerometer. The following sections present the experimental apparatus, procedures and results.

HOPKINSON BAR FLY-AWAY METHOD

Figure 1 is a diagram of the Hopkinson bar fly-away apparatus. In this technique, a long aluminum bar is impacted with a spherical nose projectile such that a non-dispersive, one-dimensional stress wave propagates down the bar. This stress wave interacts with a steel disk mounted on the opposite end of the bar. A thin x-cut quartz gage is bonded to the steel disk to measure the stress at the interface between the steel disk and incident bar. The acceleration at the free end of the disk is measured with an Endevco 7270A or Kistler 805A accelerometer.

As long as the rise time of the incident stress pulse is sufficiently long and the disk length is sufficiently short, the response of the disk can be approximated as rigid-body motion. An experimentally verified analytical model supported this assumption for steel and tungsten disks [4]. Using the effective accelerated mass of the disk and the cross-sectional area of the quartz gage, the rigid body acceleration of the steel disk is calculated using the quartz gage stress measurement and Newton's Second Law.

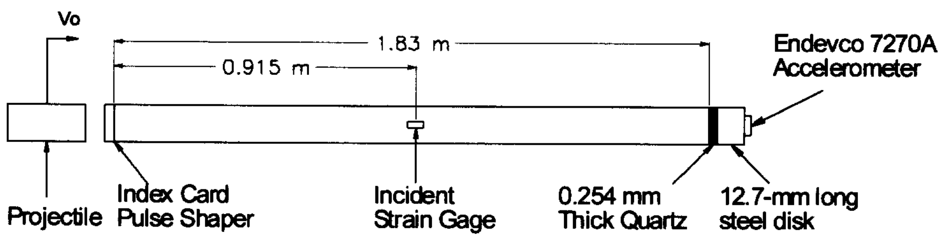

Figure 1. Split Hopkinson Bar Fly-Away Apparatus

HOPKINSON BAR FLY-AWAY APPARATUS DESCRIPTION AND PROCEDURE

The 1.83-m-long, 19.0-mm-diameter, 7075-T651 aluminum bar has strain gages mounted diametrically opposed at mid-length. Opposite the impact end is a 12.7-mm-long, 19.0-mm-diameter steel disk. At the interface between the bar and the disk is a 0.254-mm-thick, 19.0-mm-diameter x-cut quartz gage[5] and on the opposite face of the disk is the accelerometer. An Endevco 7270A was used for much of the fly-away evaluation but a Kistler 805A was also used as an acceleration reference for the final task of this evaluation. The 7270A was mounted to the steel disk following the manufacturer's directions[6], but the 805A had to be bonded to the steel disk because the case on the 805A was not isolated from the measurement circuit. The steel disk and the incident bar are electrodes for the quartz gage measurement and therefore had to be isolated from all other electrical circuits.

When the steel disk was mounted to the end of the bar, a small amount of acoustic couplant was used at the interface to ensure intimate contact with the incident bar. Light vacuum grease was used for the ambient and hot temperatures, while ethylene glycol was used for the cold temperatures. A vacuum collar was also used to keep the steel disk in intimate contact with the incident bar. The temperature conditioned environments were maintained by placing the steel disk and approximately 10-cm of the Hopkinson bar into a temperature chamber.

Several index cards were placed at the impact end of the incident bar to obtain the desired stress pulse shape and duration. A steel spherical nosed projectile was fired at the end of the incident bar with velocity V_o. The impact creates a sine-squared stress pulse that propagates down the length of the bar. When the stress wave interacts with the steel disk, a compression wave reflects back along the incident bar. The quartz gage measures the sum of the incident and reflected stress wave. The magnitude of the incident stress wave eventually decreases and the stress at the quartz interface becomes tensile. At this point, the steel disk, quartz gage, and accelerometer separate from the incident bar like a momentum trap. The steel disk, quartz gage and accelerometer are referred to as the fly-away assembly. The fly-away assembly is caught in a foam catcher after a few centimeters of travel.

SPLIT HOPKINSON BAR DESCRIPTION AND PROCDURE

Figure 2 is a diagram of the split Hopkinson bar apparatus. Two 1.83-m-long, 19.05-mm-diameter, 7075-T651 aluminum rods were precisely aligned with two strain gages mounted diametrically opposed at mid-length. A 0.254-mm-thick, 19.0-mm-diameter x-cut quartz gage was bonded to the transmitted bar at the interface. A light vacuum grease was used at the quartz gage interface as an acoustic couplant to minimize any distortion to the stress wave as it passed through the interface. As the stress wave interacts with the quartz gage, the quartz gage produces a charge proportional to the forces applied. The incident and transmitted bars had to be electrically isolated from the air gun and strain gage measuring circuit because they acted as the electrodes for the quartz gage.

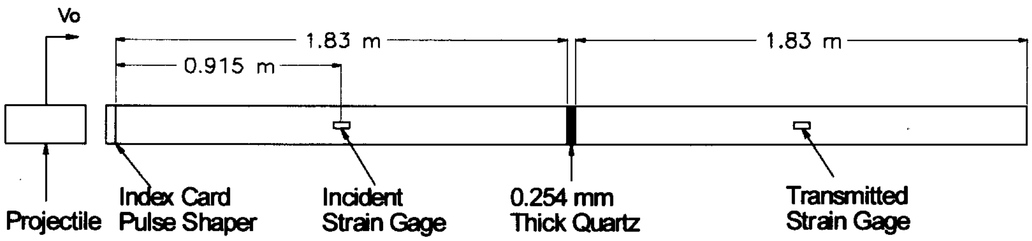

Figure 2. Split Hopkinson Bar Apparatus

A spherical-nose projectile is fired from a gas gun and impacts the pulse shaper shown in Figure 2. The amplitude and duration of this stress pulse are controlled by the projectile impact velocity and an index card pulse shaper [3]. The impact generates a non-dispersive sine-squared stress pulse that propagates down the rod. The incident strain gage measures the incident and reflected stress pulse. The reflected pulse was viewed to determine bar alignment since a large reflected pulse would indicate poor interface alignment. The stress pulse propagates through the quartz disk with little distortion because the impedance of quartz is nearly identical with aluminum [4]. The quartz gage measures the stress at this interface and is then compared to the strain measurement from the transmitted strain gage. This evaluation was performed for force levels of 18,000, 35,000 and 53,000 N at ambient temperature, -48°C, and +74°C. A small insulated box enclosed a 20-cm long area around the quartz interface such that a temperature conditioner could maintain the hot and cold environments as required. The extreme temperatures required two materials to be used as acoustic couplants. Light vacuum grease was used at ambient and hot temperatures, but the vacuum grease did not flow at the cold temperatures so ethylene glycol was used instead.

The frequency response characteristics of the quartz crystal were evaluated using the transmitted strain gage measurement as a reference and the quartz data as the input. The magnitude and phase of the frequency response functions were then evaluated using the techniques described by Bateman [7]. The quartz gage data and the transmitted strain data were shifted in time to preserve the phase characteristics. The time shift corresponded to the stress wave travel time between the quartz gage and the transmitted strain gage locations.

SPLIT HOPKINSON BAR RESULTS

A total of 45 shots were performed on the split Hopkinson bar apparatus at ambient, +74°C and -46°C temperatures. At each temperature, five shots were performed at force input levels of 18, 36 and 53 kN. The results of the split Hopkinson bar apparatus showed that the sensitivity of the quartz crystal was fairly stable throughout the test series. The +74°C conditions had the best agreement and the ambient conditions had the worst agreement. Very good agreement was obtained at the elevated temperatures because the grease flowed from the interface resulting in a very thin grease layer. The ethylene glycol also resulted in a very thin layer which is why the cold environment had better agreement than the ambient conditions. Preparation of the quartz interface was key in obtaining good agreement between the quartz gage and the strain gage measurement. Any particulate material at the interface would result in a gap at the interface or a stress concentration that would affect the quartz gage measurement.

Figure 3 shows a force-time history comparison of the transmitted strain gage and the quartz gage measurements at +74°C. The data shown is unfiltered, 100 kHz data. Table 1 is the average agreement for peak amplitudes for five shots at each temperature and input level. Overall, the agreement between the strain gage and quartz gage was good considering the sensitivity of the quartz gage to bar misalignment and foreign material at the quartz interface.

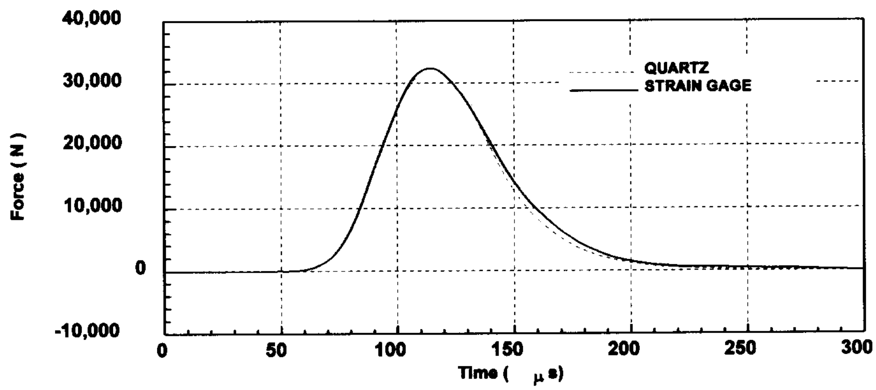

Figure 3. Force-Time History Comparison for the Split Hopkinson Bar Evaluation at +74°C.

	Amplitude Comparison at Various Temperatures		
Input Force (N)	Ambient Temp. (% difference)	+74°C (% difference)	-46°C (% difference)
18,000, 5 shot avg.	5.66	0.80	-3.40
36,000, 5 shot avg.	5.47	0.53	-3.56
53,000, 5 shot avg.	4.94	1.41	-3.43
Series Avg., 15 shots	5.36	0.91	-3.42

Table. 1 Peak Amplitude Comparison of Quartz and Strain Gage data for the Split Hopkinson Bar Evaluation.

Figures 4, 5 and 6 are the frequency response magnitudes for the three input levels at ambient, +74°C and -46°C. All three temperatures indicate the same general trend; good agreement up to approximately 3 kHz, 3-6% amplification from 3-7 kHz, and 8-18% amplification from 8-10 kHz.

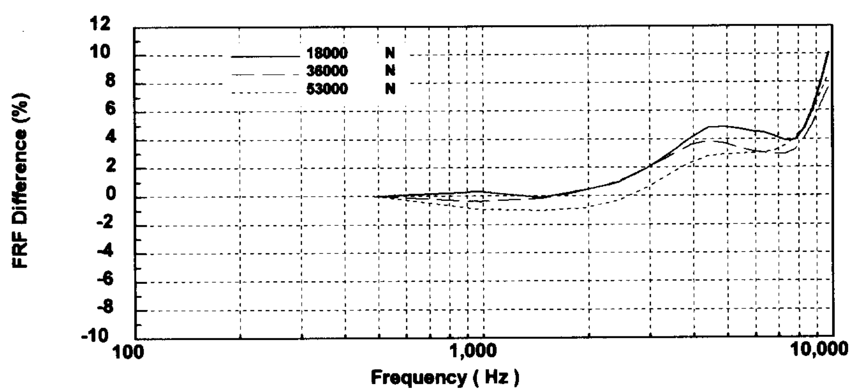

Figure 4. Frequency Response Function Magnitude Comparison at Ambient Temperature

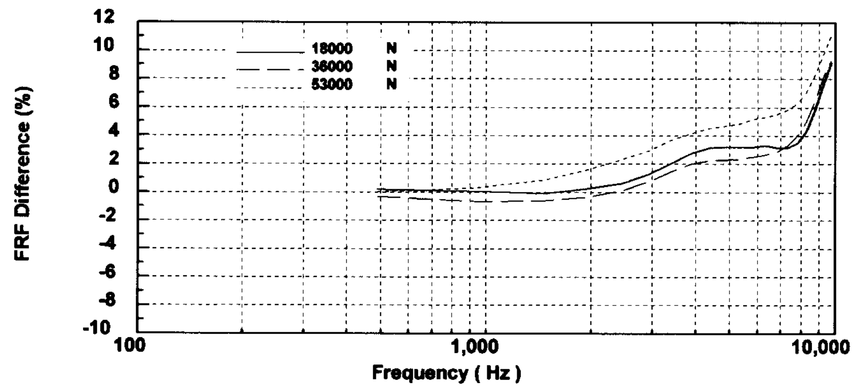

Figure 5. Frequency Response Function Magnitude Comparison at +74°C

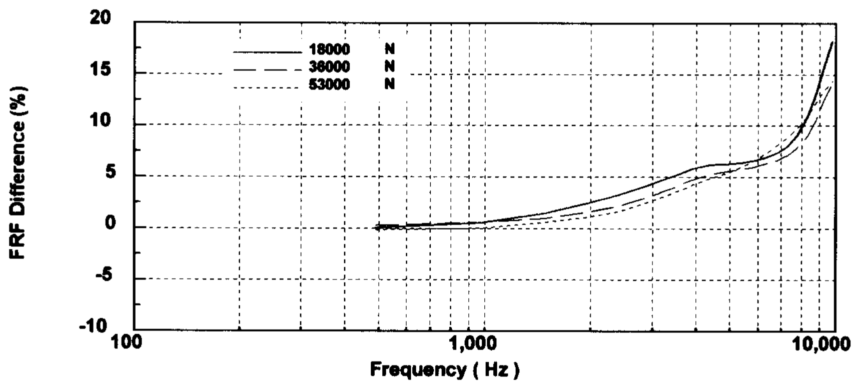

Figure 6. Frequency Response Function Magnitude Comparison at -46°C

Figures 7, 8 and 9 show the phase lag for the three input levels at the three different temperatures. There was minimal lag between the quartz gage measurement and the strain gage measurement. The phase lag at ambient and +74°C was generally within 6° up to 10 kHz. The largest lag of 8° occurred at the -46°C condition. The coherence was found to be greater than 0.999 up to 10 kHz for all three input levels and temperature conditions.

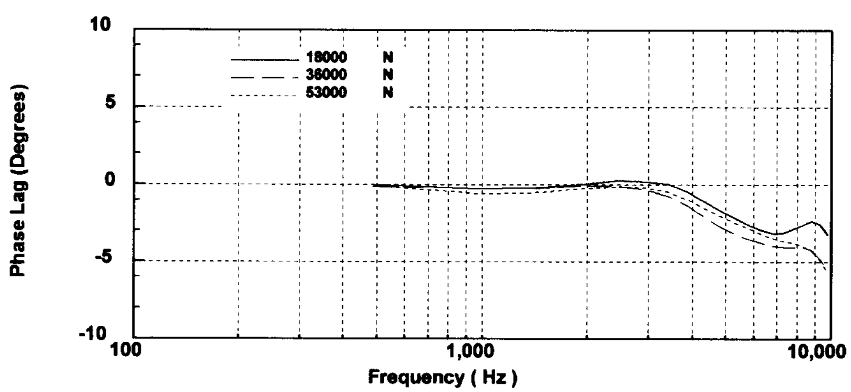

Figure 7. Frequency Response Function Phase Comparison at Ambient Temperature

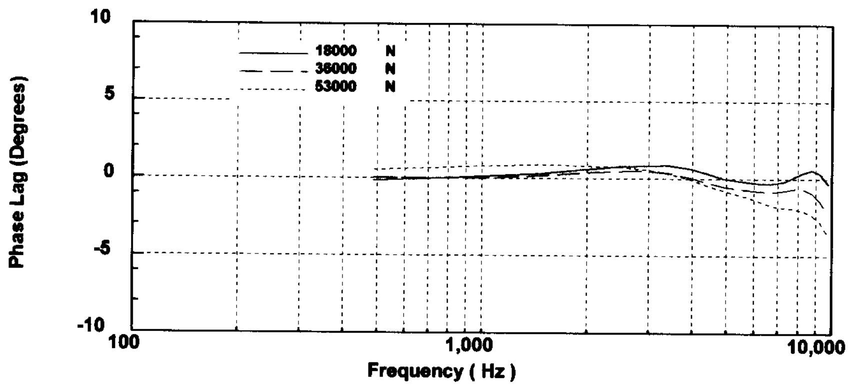

Figure 8. Frequency Response Function Phase Comparison at +74°C

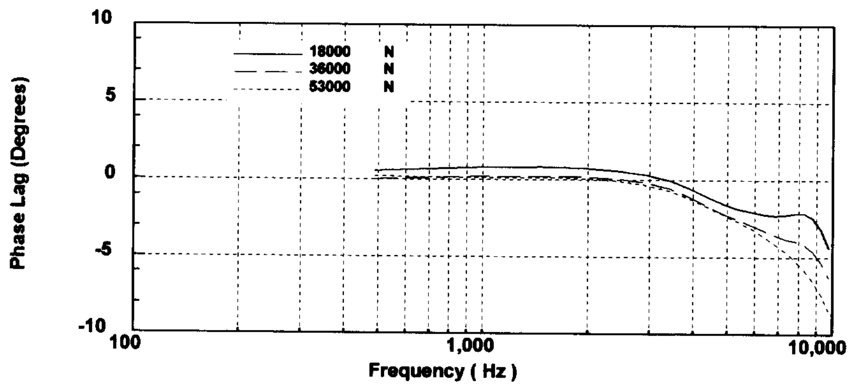

Figure 9. Frequency Response Function Phase Comparison at -46°C

FLY-AWAY TECHNIQUE EVALUATION RESULTS

The fly-away technique was evaluated at ambient temperatures using the Endevco 7270A-200K accelerometer. The peak acceleration amplitudes measured by the accelerometer and the quartz gage are shown in Table 2. The average difference between the accelerometer and the quartz gage was 4.34% and the maximum difference was 8%.

Shot	Rise Time (μs)	A_{quartz} (*G*)	A_{accel} (*G*)	% Difference
1	49	12,247	12,900	5.33
2	48	26,089	26,540	1.73
3	49	53,193	57,448	8.00
4	43	97,255	101,746	4.62
5	41	138,925	144,680	4.12
6	35	205,235	209,865	2.26

Table 2. Data Summary for the Endevco 7270A-200K at Ambient Temperatures

The accelerometer used for the temperature evaluation was the Endevco 7270A-60K and the input acceleration levels were maintained at the full scale value of 60,000*G*. Typical time histories are shown in Figures 10 and 11. The only cold temperature test is shown in Figure 12. The time histories are wide band, unfiltered data. The cold temperature evaluation was not completed due to difficulties found in preparing the fly-away. The cold temperature also caused the vacuum collar to freeze to the incident bar and fly-away.

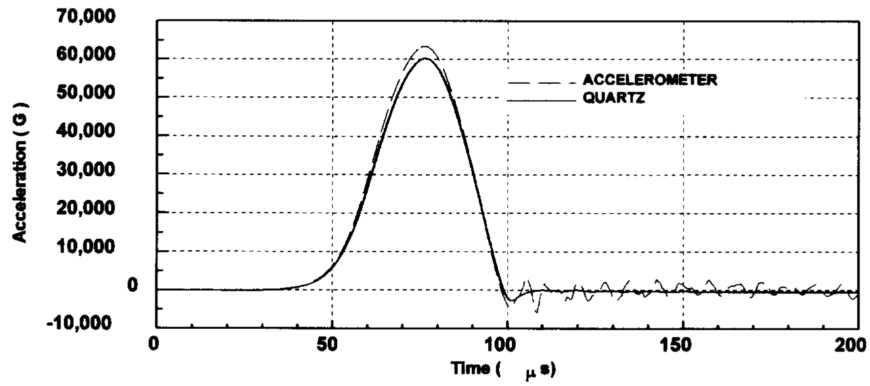

Figure 10. Acceleration-Time Comparison at Ambient Temperature.

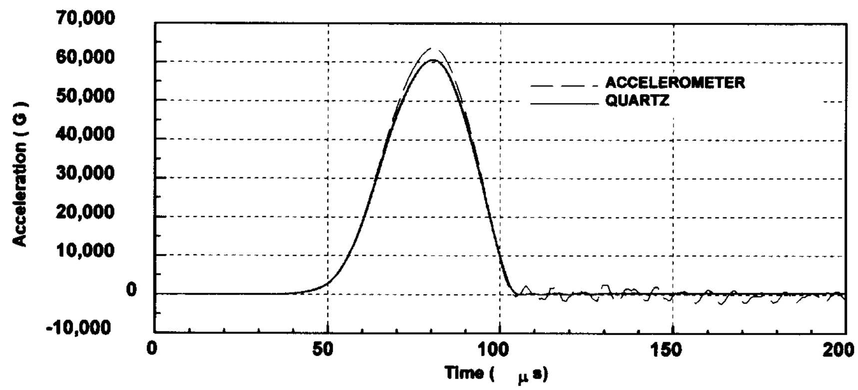

Figure 11. Acceleration-Time Comparison at +74°C

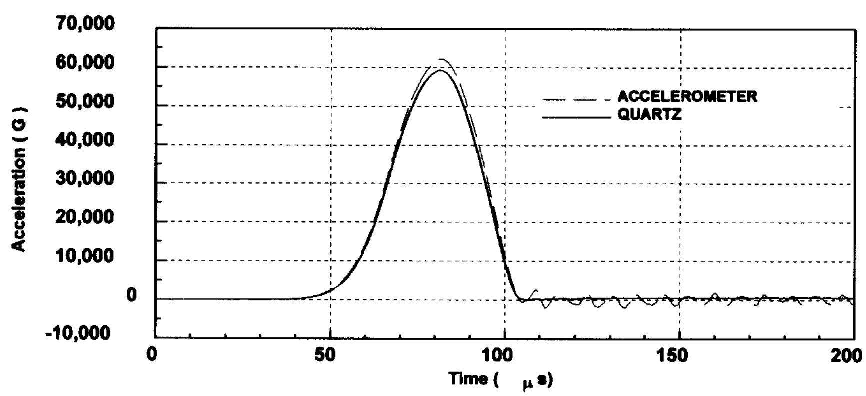

Figure 12. Acceleration-Time Comparison at -54°C

Only one shot was performed at the -54°C environment due to ice forming at the end of the bar and around the vacuum collar. The comparison at -54°C did show very good agreement but the apparatus had some issues that have to be resolved before more shots can be made successfully. At the end of the acceleration pulse it is observed that the quartz gage undergoes tensile loads due to the acoustic couplant. The release of the tensile load excites the resonant behavior of the Endevco 7270A accelerometer but the amplitude of the resonant response is so small that it was not considered a significant problem. The results of the ambient and +74°C temperature tests are tabulated in Tables 3 and 4 respectively.

Shot	Rise Time (μs)	A_{quartz} (G)	A_{accel} (G)	% Difference
1	47	25,196	26,750	5.8
2	47	26,126	27,415	4.7
3	45	25,685	26,870	4.4
4	50	34,295	36,380	5.7
5	50	35,169	37,439	6.1
6	49	34,029	35,987	5.4
7	47	60,158	63,304	4.9
8	47	59,465	62,721	5.2
9	47	59,064	63,282	6.7

Table 3. Data Summary for Endevco 7270A-60K at Ambient Temperature

Shot	Rise Time (μs)	A_{quartz} (G)	A_{accel} (G)	% Difference
1	46	24,633	26,533	7.2
2	45	24,931	26,659	6.5
3	45	25,365	26,596	4.6
4	49	34,953	37,432	7.4
5	50	35,194	36,753	1.2
6	51	32,545	35,283	7.7
7	48	59,519	63,610	6.4
8	47	60,538	63,556	4.7
9	49	54,995	59,236	7.1

Table 4. Data Summary for Endevco 7270A-60K at +74°C

KISTLER 805A REFERENCE EVALUATION RESULTS

A Kistler 805A accelerometer was certified at NIST for use as a reference accelerometer for this evaluation. The 805A was epoxied to the steel disk because the case of the 805A was not isolated from the accelerometer measuring circuit. If the stud mount had been used, the input to the charge amplifier for the quartz gage would have been shorted. The resonant behavior of the 805A was excited by the stress wave input so an analog filter had to be used in the comparison. A low-pass 30 kHz analog filter was used for the quartz gage data and the 805A accelerometer data shown in Figure 13. The results for the 805A series are tabulated in Table 5.

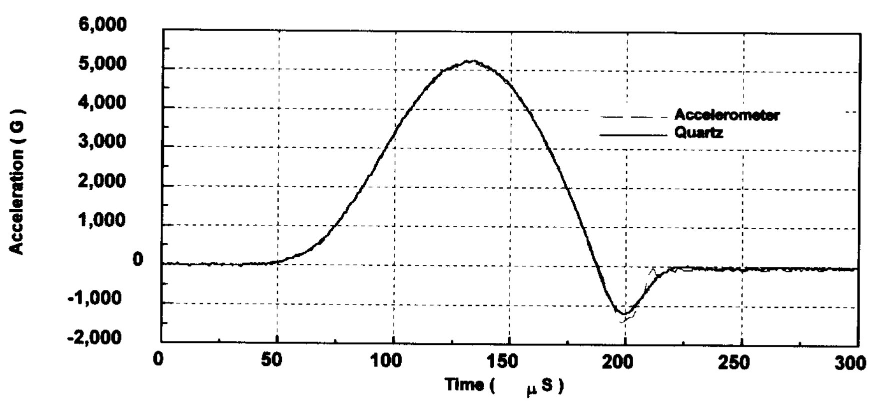

Figure 13. Acceleration-Time Comparison with Kistler 805A Reference, 30 kHz data.

Shot	$A_{quartz}(G)$	$A_{accel}(G)$	% Difference
1	4,720	4,753	0.7
2	4,869	4,901	0.6
3	5,240	5,196	0.8

Table 5. Results of Kistler 805A Reference Accelerometer Evaluation

CONCLUSIONS

This Hopkinson bar Fly-away technique does show potential for use as a practical calibration technique for high *G* accelerometers. The cold temperature conditioning has fixturing issues that need to be resolved, but that should be completed shortly. Efforts are underway to improve the cold temperature procedures to obtain repeatable results. The technique showed excellent agreement with the Kistler 805A reference accelerometer but was limited to peak acceleration amplitudes of 5,000 *G* by the resonant response of the Kistler 805A accelerometer. The 5,000*G* amplitude is well short of what is required for a calibration technique that has a full scale level of 200,000*G*. A different reference accelerometer may have to be found or the input pulse may have to be tailored so as not to excite the resonant behavior of the 805A.

This evaluation showed that the quartz gage interface was extremely sensitive to alignment and the type of acoustic couplant used. Care must be given to this interface in order to obtain good measurements from the quartz gage. Once the subtleties of this technique are addressed in the experimental set-up, this technique can be very repeatable. Overall, this technique does have the potential to be used for the practical calibration of high amplitude accelerometers. It is expected that with further improvements, this technique will be employed at the SNL Primary Standards Laboratory in the near future.

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