A Systems Approach to Measuring
Short Duration Acceleration Transients

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Introduction

It is common for failures to occur when attempting to acquire acceleration structural response measurements during crash, impact, and pyrotechnic testing. The structural response of a mechanical system to severe transient loading is commonly measured by accelerometers which are less than ideal. In particular, their amplitude-frequency response has one or more resonant peaks so that the output of the accelerometer may not be an exact replica of the input. If the transient input stimulus contains frequencies near these resonant peaks, signal distortion, over-ranging of signal conditioning electronics, or even failure of the sensing element may occur (Reference 1). These and other problems have spurred the development of a new acceleration-measuring system (Reference 2) which incorporates the following features:

1. Transduction Element.

    Quartz: Extremely rugged, high yield stress, piezo-electric constant holds over very wide stress range.

2. Connectors.

    Solder pins: Mechanically simpler and more rugged than coaxial connectors.

3. Mounting.

    Integral Stud: Simpler and more rugged than separate stud, allows transducer to be smaller.

4. Electronics. and transducer resonance.

    Integral Amplifier: Low impedance output allows coaxial connector elimination, no cable noise, high signal levels.

5. Transducer Resonance.

> Filtered: Low-pass filter between quartz crystal and internal amplifier reduces effect of induced ringing in transducer element. (Only frequencies below 10,000Hz are typically of value for structural modeling.)

PCB Piezotronics was the successful bidder to a development specification (Appendix A) containing these features and placed by competitive bidding by Sandia National Laboratories. The accelerometers developed to this specification use the basic seismic system of the standard PCB 305A shock accelerometer. Probably the most interesting design feature is the two-pole active Butterworth filter between the quartz element and internal FET amplifier. A block diagram of the internal electronic configuration is shown in Figure 1. A photograph of the accelerometer is shown in Figure 2.

Performance Verification Program

Standard accelerometer performance properties, such as thermal shift, base strain sensitivity, etc. were measured and are listed in Appendix B for completeness. These properties are peripheral to the shock-related characteristics that are to be discussed here.

The design criteria for the filtered accelerometer, designated Model 305M23 and ranged for 20,000g, required that the frequency response be flat to 10kHz and roll-off at 12dB per octave thereafter. This indicates that the -3dB point should occur at about 17kHz. In fact, the -3dB breakpoint occurs at

approximately 25kHz as shown in Figure 3. Figure 4 shows the amplitude portion of the frequency response of an unfiltered 305A to 50kHz. There is a minor resonance at about 38kHz in this accelerometer. Figure 5 superimposes the responses of Figures 3 and 4 on a linear vertical scale and makes the comparison between these two accelerometers more vivid.

The phase response of the filtered Model 305M23 was measured from 60Hz to 21kHz and found to be linear within this frequency region corresponding to the 0.7 damping of the Butterworth filter.

Shock testing was next performed to introduce high frequencies and high acceleration levels into the test accelerometers and to compare their output with that obtained from conventional shock accelerometers. In particular, a piezoresistive accelerometer having a 50,000g range and a PCB Model 305A piezoelectric accelerometer were used as standards for comparison. Two series of shock tests were performed. In the first series an 18"x18"x2" aluminum plate was suspended by a cable and one and two pound projectiles were fired at it from an airgun. Impact was at the center of the plate. The test accelerometer was mounted on the side of the plate opposite the impact and near the edge of the plate. The piezoresistive accelerometer was mounted one inch from the test accelerometer. Although the two mounting locations will not provide identical results, the plate response should be similar for each set of measurements. A photograph of the test equipment is shown in Figure 6.

The output from both transducers was recorded at various impact velocities. Figures 7 and 8 are time histories of one such event recorded respectively by a PCB 305M23 and the piezoresistive accelerometer. It is evident that the time histories of these two transducers are not comparable: that of the piezoelectric accelerometer having a maximum amplitude of about 40,000g compared to 6,000g for the filtered device. Figure 9 represents the Fast Fourier Transform of the output of the piezoresistive accelerometer and shows a large resonance at about 170,000Hz. This is the resonance of the transducer seismic system which has been excited by corresponding frequencies in the input impulse. The magnification produced at the resonant frequency of the seismic system of the transducer effectively masks the structural response and can also over-range the data channel.

Since the two-pole filter built into the accelerometer being reported on has a -3dB point at about 25,000Hz, digital filtering of the time history of Figure 8 with a filter of the same character should extract information similar to that shown in Figure 7 if the two transducers see nominally the same acceleration stimulus. The result of digital filtering using a two-pole filter having its -3dB point at 25,000Hz is shown in Figure 10.

Figure 11 superimposes these two filtered time histories and clearly demonstrates the similarity of the two responses. The
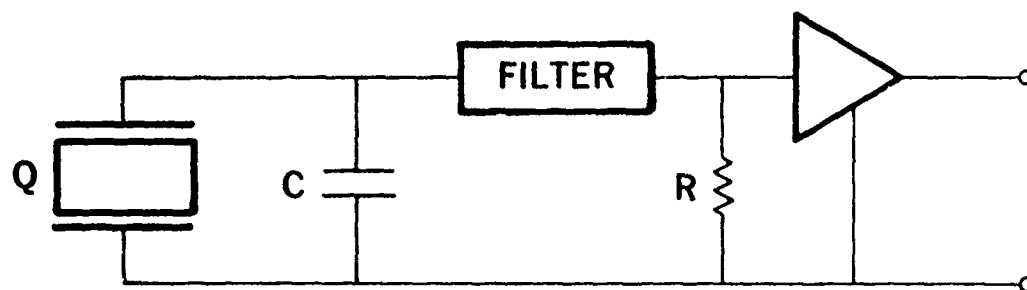
shaded area of this figure emphasizes the region of primary interest. Exact correspondence could not be expected considering the slightly differing locations of the transducers and the many high frequency vibrational modes possible in the plate.

Another overlay (Figure 12) - this time of the Fast Fourier Transforms of the two outputs - demonstrates the very close correspondence in frequency content at frequencies below 10,000Hz.
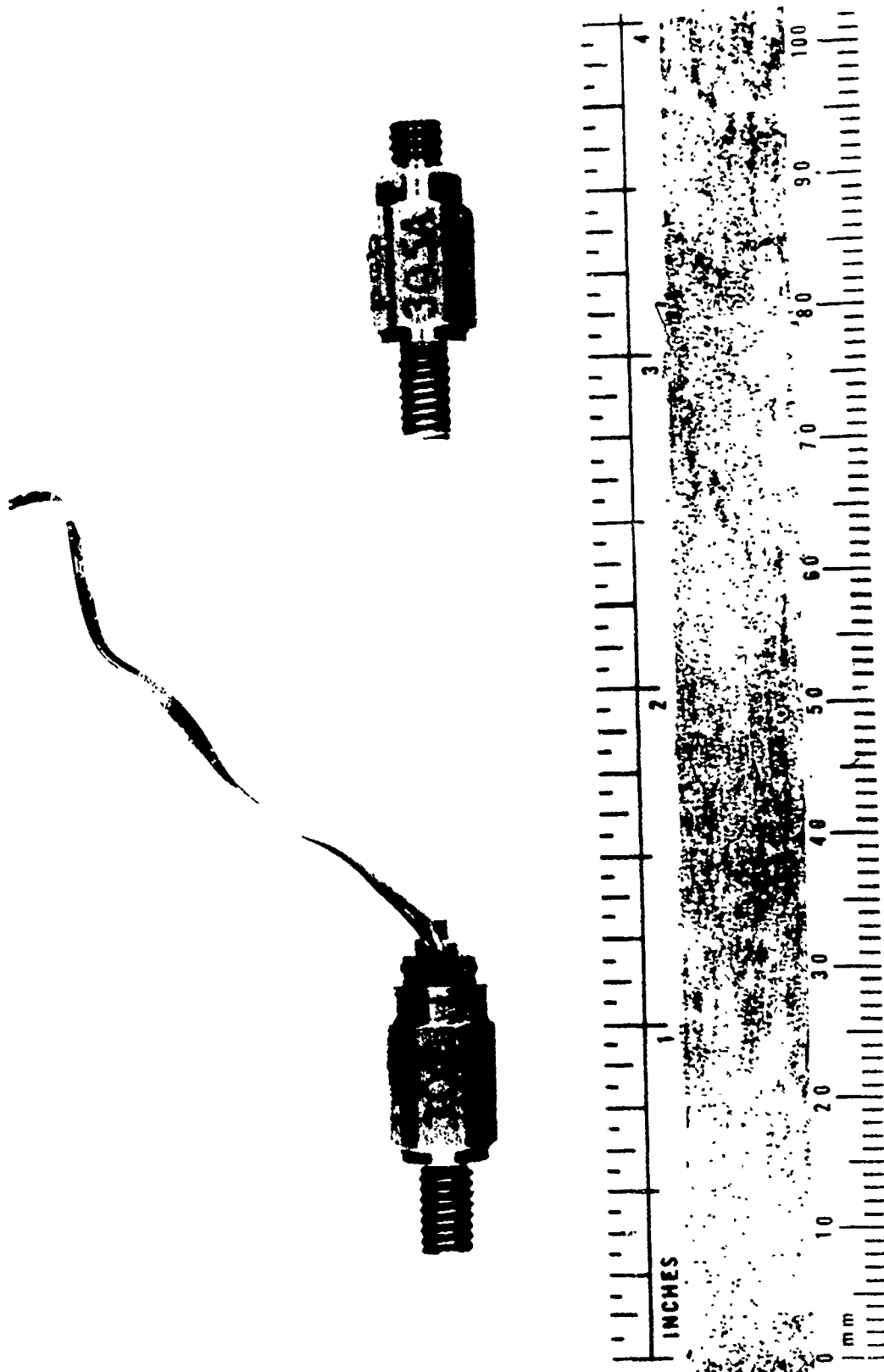
Further experiments were made with a Hopkinson bar consisting of a 2"x2"x48" bar of aluminum. The test and reference transducers (usually a PCB305A) were mounted on one end of the bar and the device was impacted by a projectile at the other end. The bar was also instrumented by strain gages at the center. A photograph is shown in Figure 13. The Hopkinson bar has several virtues for shock testing these devices: a) it permitted survival testing at 100,000g; b) the high frequency content of the shock pulse was low enough that the reference accelerometers could make a measurement of the pulse amplitude without being excited at resonance; and c) the relatively uncomplicated bar motion allowed better comparison with the reference accelerometer output. The strain gages provided further corroboration of the shock levels reached.

The PCB Model 305M23, developed to Sandia's specifications, has proved cabable of obtaining data comparable to that of standard piezoelectric and piezoresistive accelerometers when high frequencies are absent. In the presence of high frequency stimuli, the accelerometer has obtained data without over-ranging its data channel and without introducing error signals from excitation of the resonant frequency of its seismic system. It should, therefore, be especially useful for impact and pyrotechnic measurements.

These shock accelerometers are in the process of being fielded in earth penetrator vehicles; in shale rubblization experiments, and in flyer plate tests. Final results from these experiments will soon be available. It appears this joint development effort and test program has greatly enhanced the probability of acquiring successful structural measurements in harsh mechanical loading environments.

FIGURE 1. BASIC INTERNAL ELECTRONIC CIRCUIT OF INTERNALLY FILTERED
ACCELEROMETER (PCB 305M23)

FIGURE 2. INTERNALLY FILTERED ACCELEROMETER
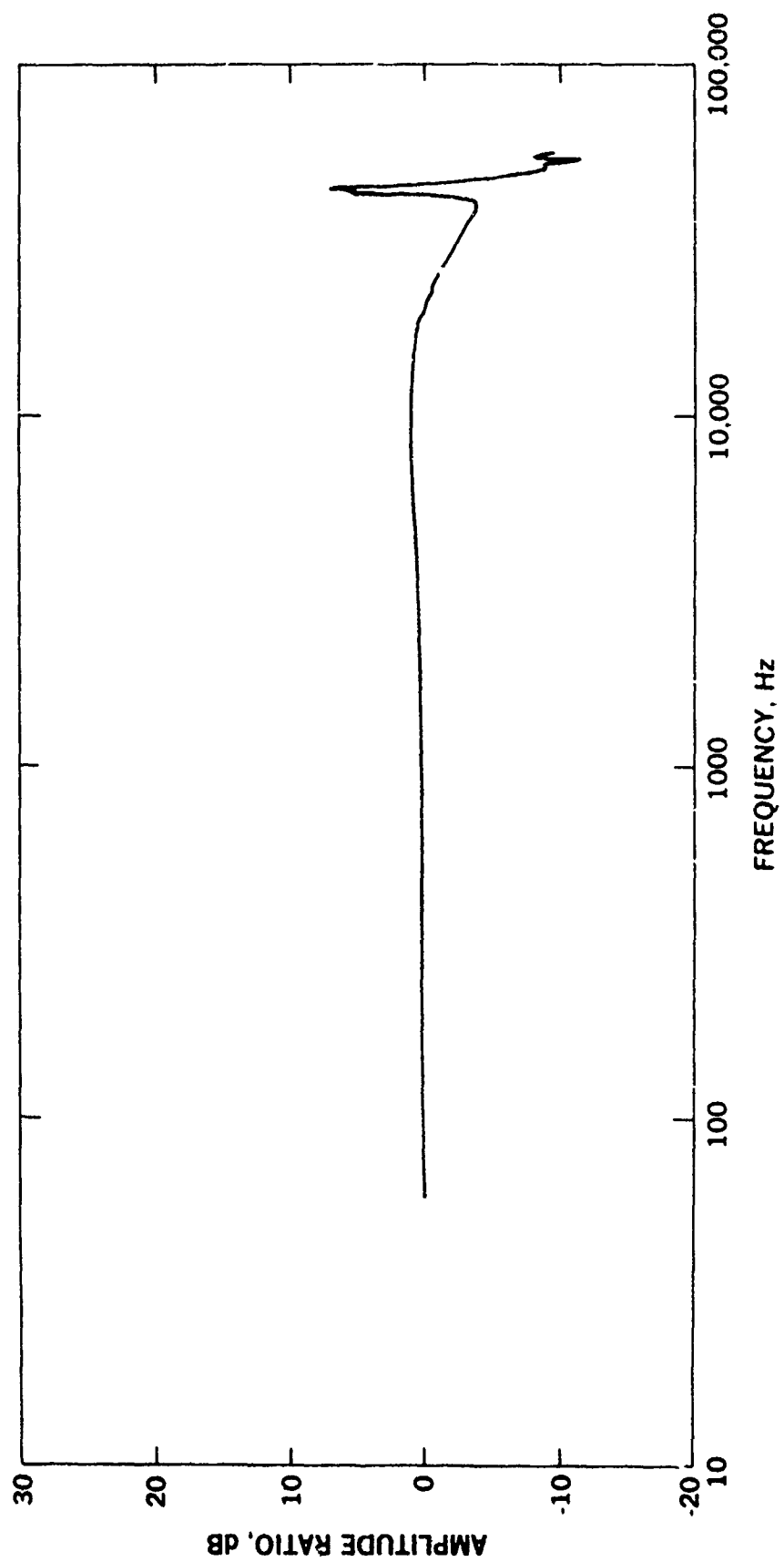(PCB 305M23), LEFT, AND UNFILTERED
ACCELEROMETER (PCB 305A), RIGHT

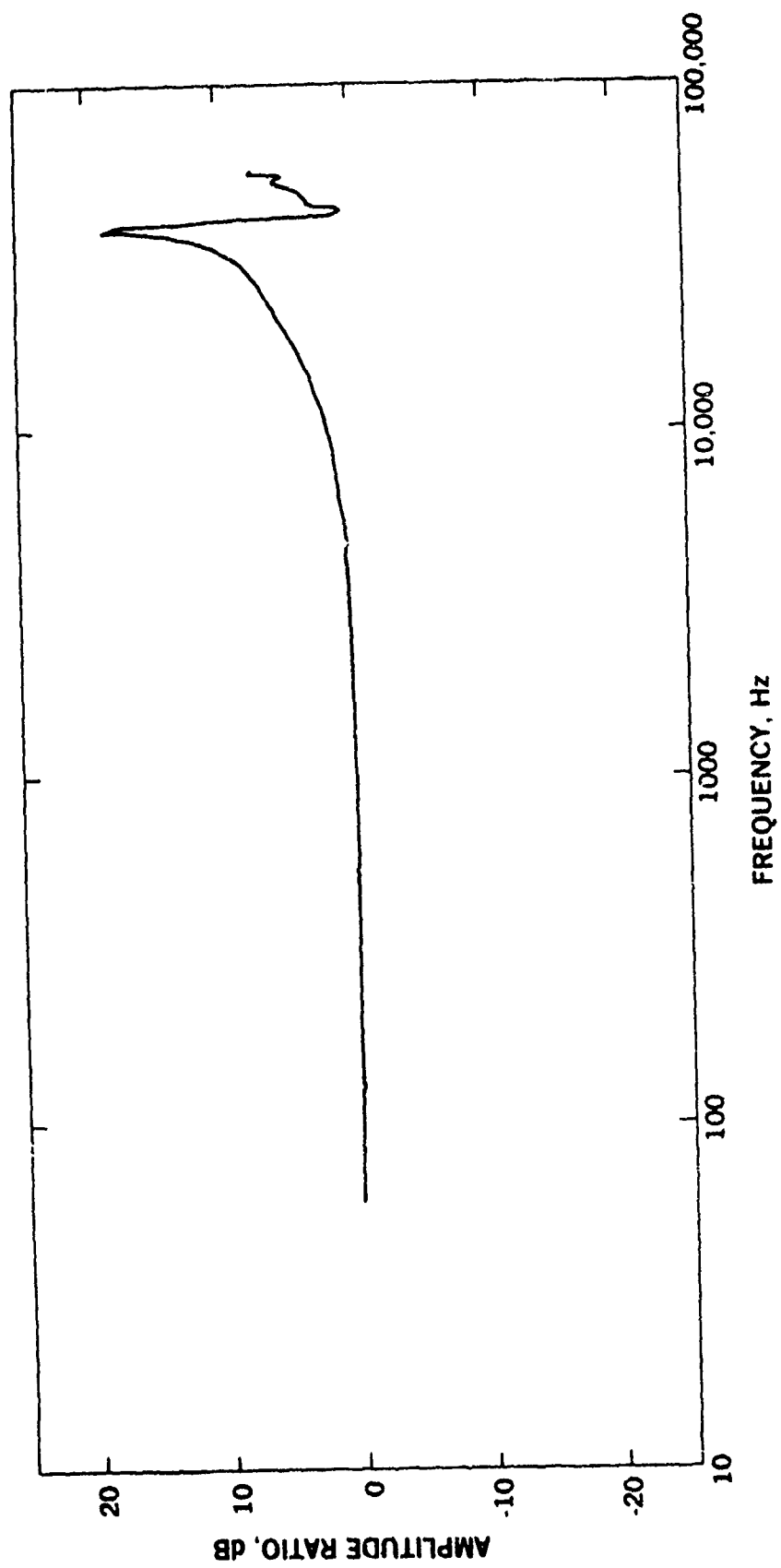FIGURE 3. FREQUENCY RESPONSE OF INTERNALLY FILTERED ACCELEROMETER (PCB 305M23)

FIGURE 4. FREQUENCY RESPONSE OF ACCELEROMETER WITHOUT AN INTERNAL FILTER (PCB 305A)
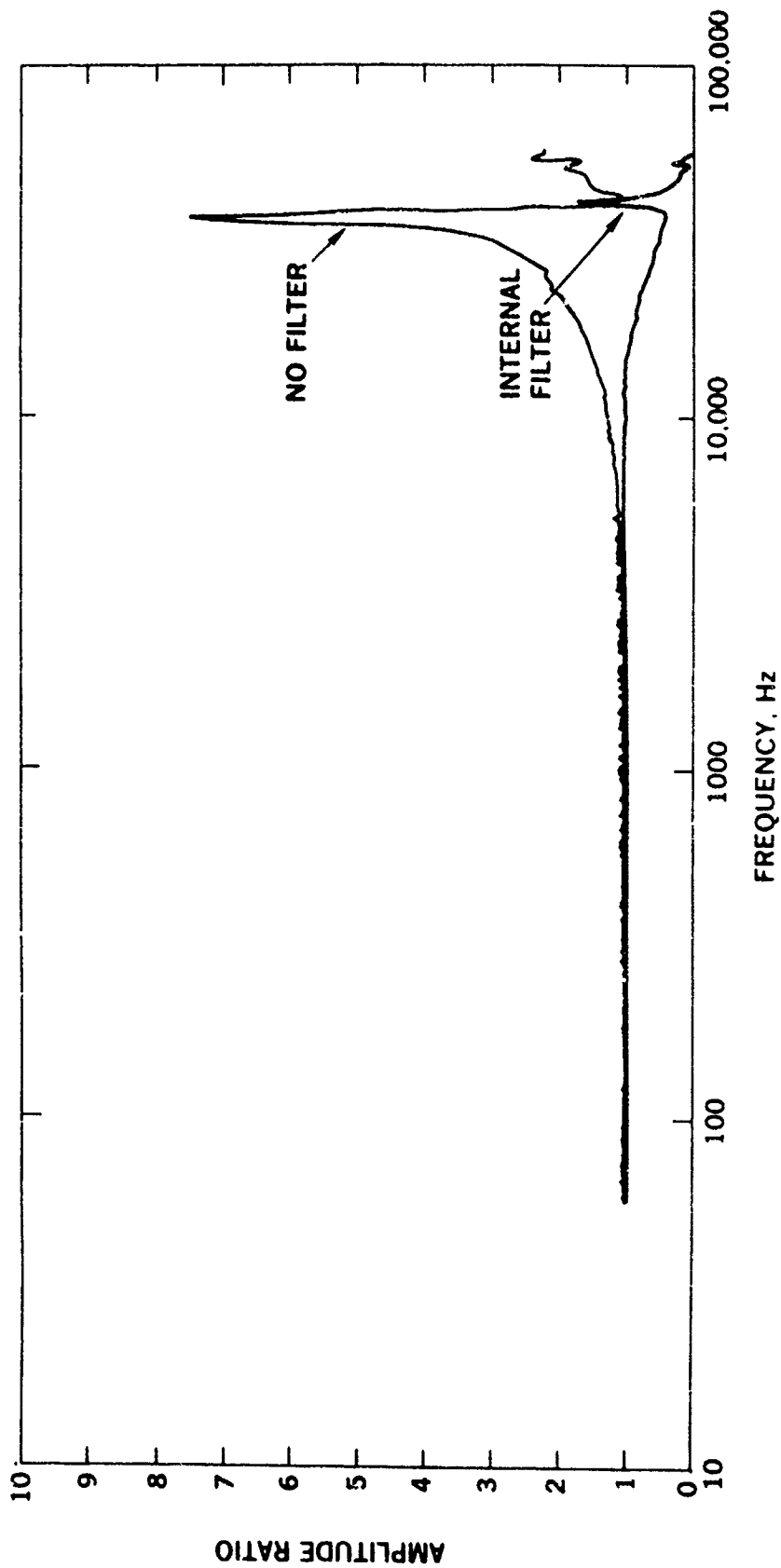
FIGURE 5. ACCELEROMETERS WITH AND WITHOUT AN INTERNAL FILTER USING A LINEAR
AMPLITUDE RATIO VERTICAL SCALE   (PCB 305M23 AND PCB 305A)

FIGURE 6. IMPACT SIDE OF 18" X 18" X 2" PLATE

FIGURE 7. RESPONSE OF ACCELEROMETER WITH INTERNAL FILTER
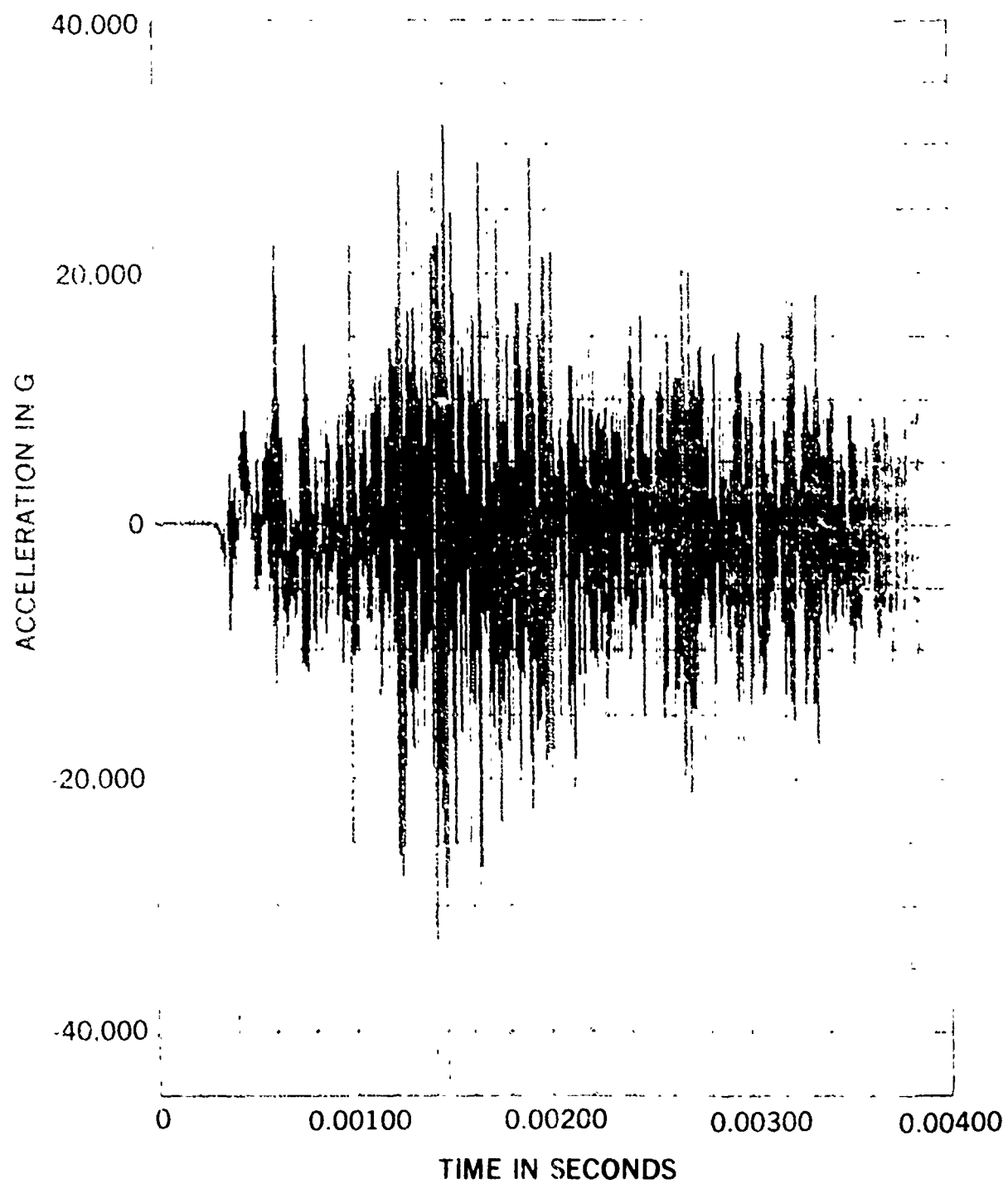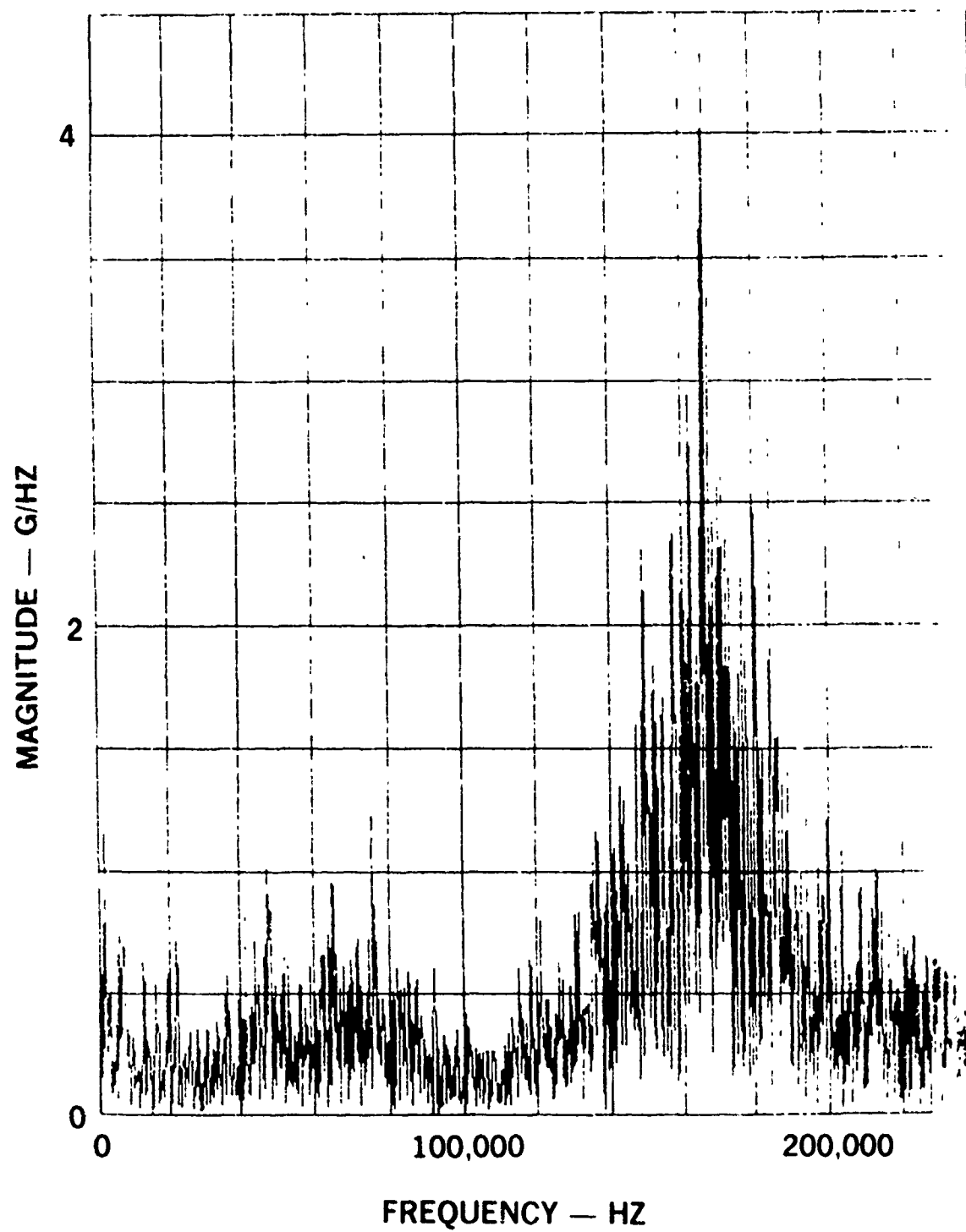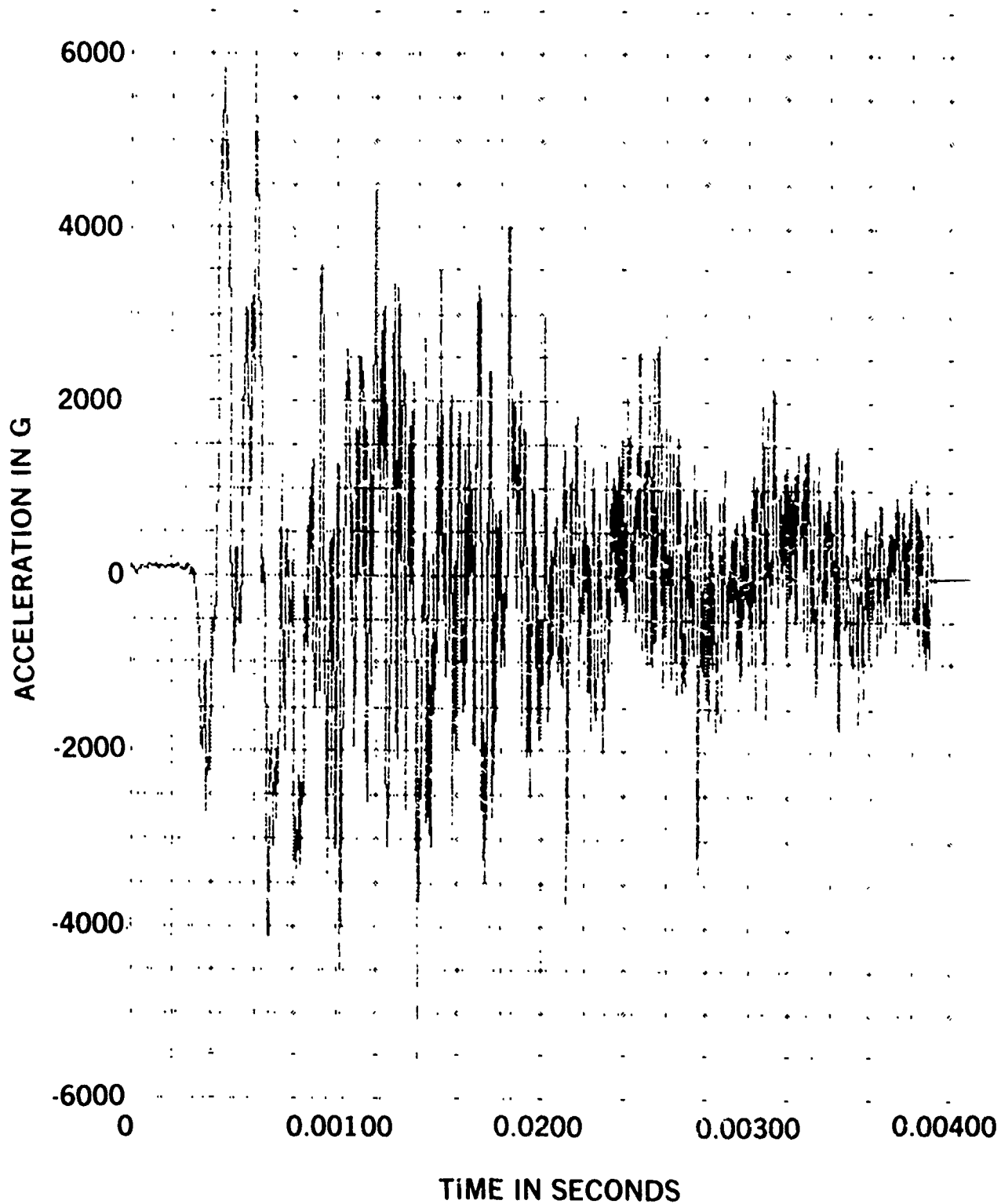(PCB 305M23) TO VIBRATING PLATE

FIGURE 8. RESPONSE OF UNFILTERED PIEZORESISTIVE ACCELEROMETER TO VIBRATING PLATE

FIGURE 9. FAST FOURIER TRANSFORM OF THE RESPONSE OF UNFILTERED PIEZORESISTIVE ACCELEROMETEP TO VIBRATING PLATE

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FIGURE 10. RESPONSE OF EXTERNALLY FILTERED PIEZORESISTIVE
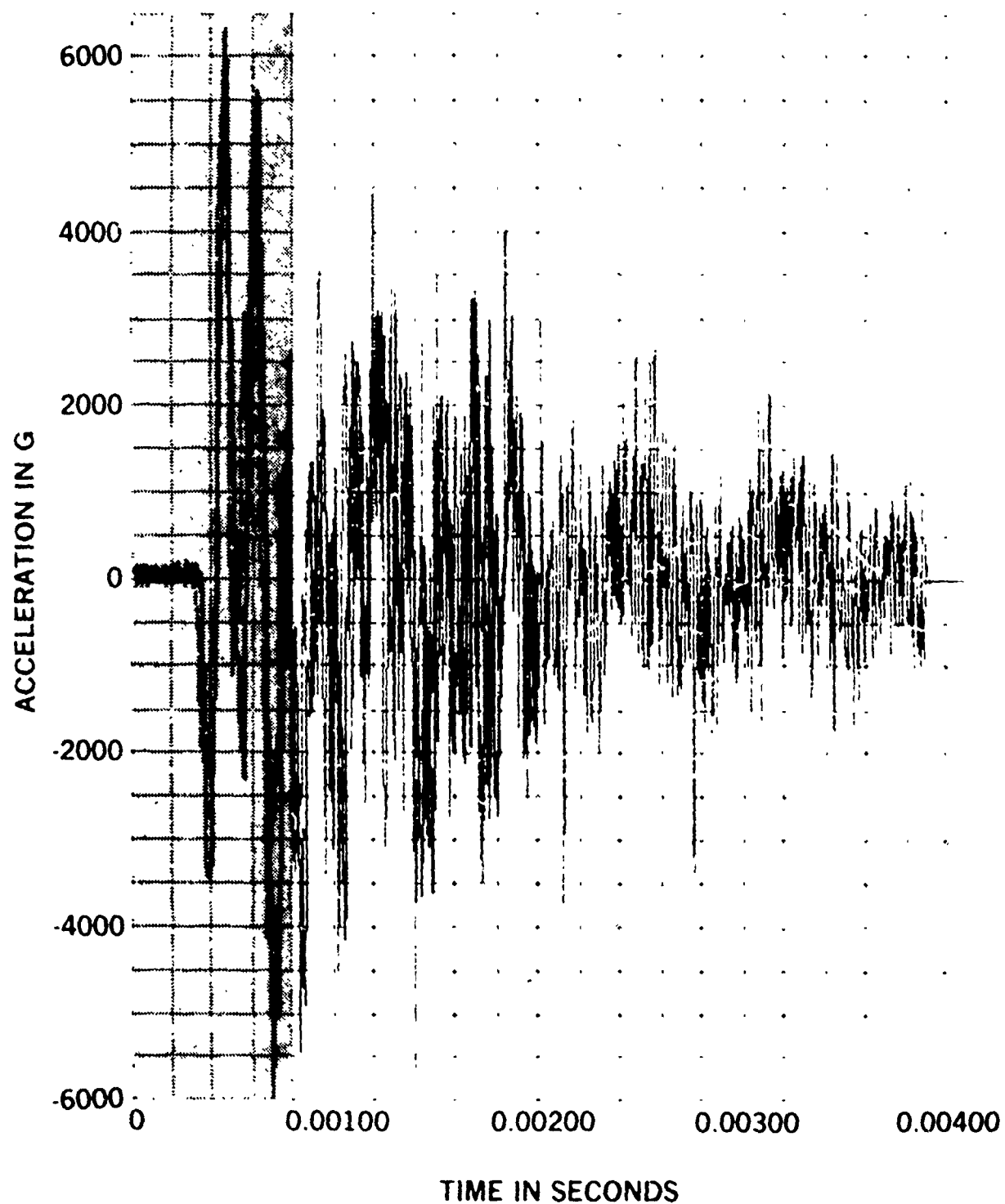ACCELEROMETER TO VIBRATING PLATE

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FIGURE 11. RESPONSE OF ACCELEROMETER WITH INTERNAL FILTER
(PCB 305M23) SUPERIMPOSED ON RESPONSE OF EXTERNALLY
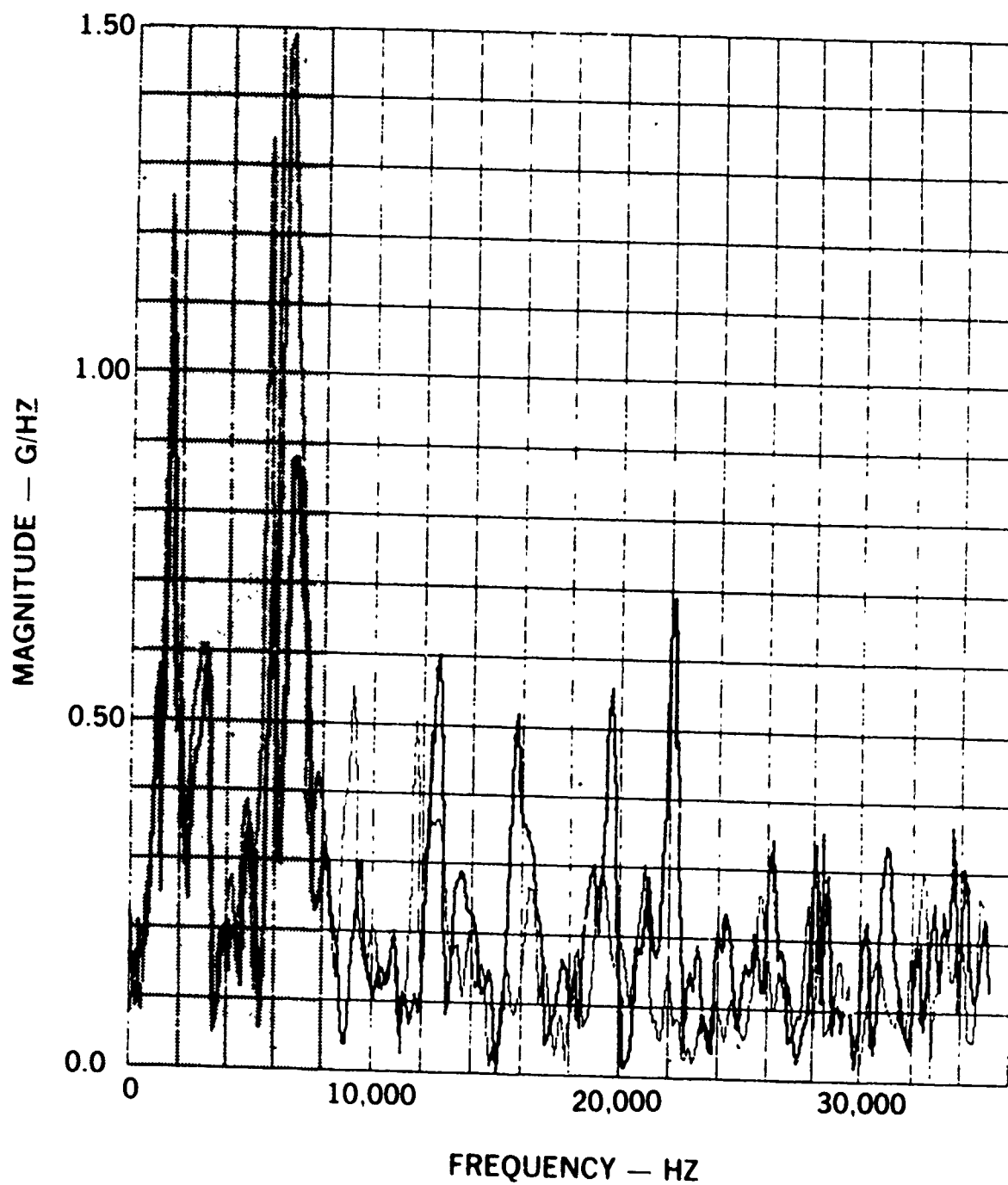FILTERED PIEZORESISTIVE ACCELEROMETER. VIBRATING PLATE
TEST

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FIGURE 12. FAST FOURIER TRANSFORM OF ACCELEROMETER WITH INTERNAL FILTER (PCB 305M23) SUPERIMPOSED ON FAST FOURIER TRANSFORM OF PIEZORESISTIVE ACCELEROMETER. VIBRATING PLATE TEST
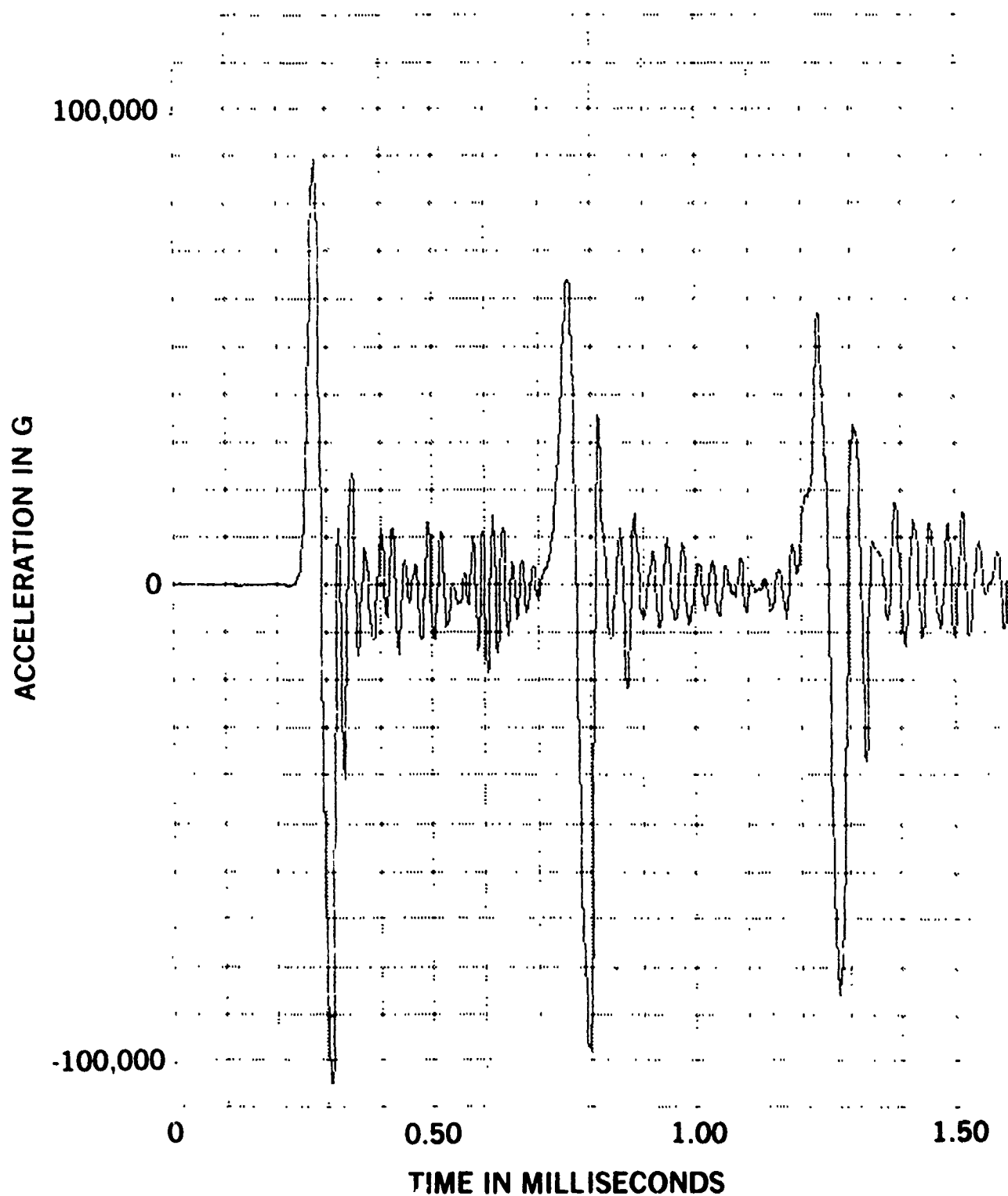
FIGURE 13. HOPKINSON BAR SHOWING TEST AND REFERENCE ACCELEROMETERS

Figures 14 and 15 show the results of one high level test on the Hopkinson bar. From Figure 14, the maximum amplitudes were 90,000g for the compression pulse and slightly more than 100,000g for the reflected pulse. This data is from the reference accelerometer and was confirmed by strain gage data. The test accelerometer which was ranged to produce ±5 volts at ±20,000g clipped before these extreme levels were reached, as shown in Figure 15, but did survive this environment.
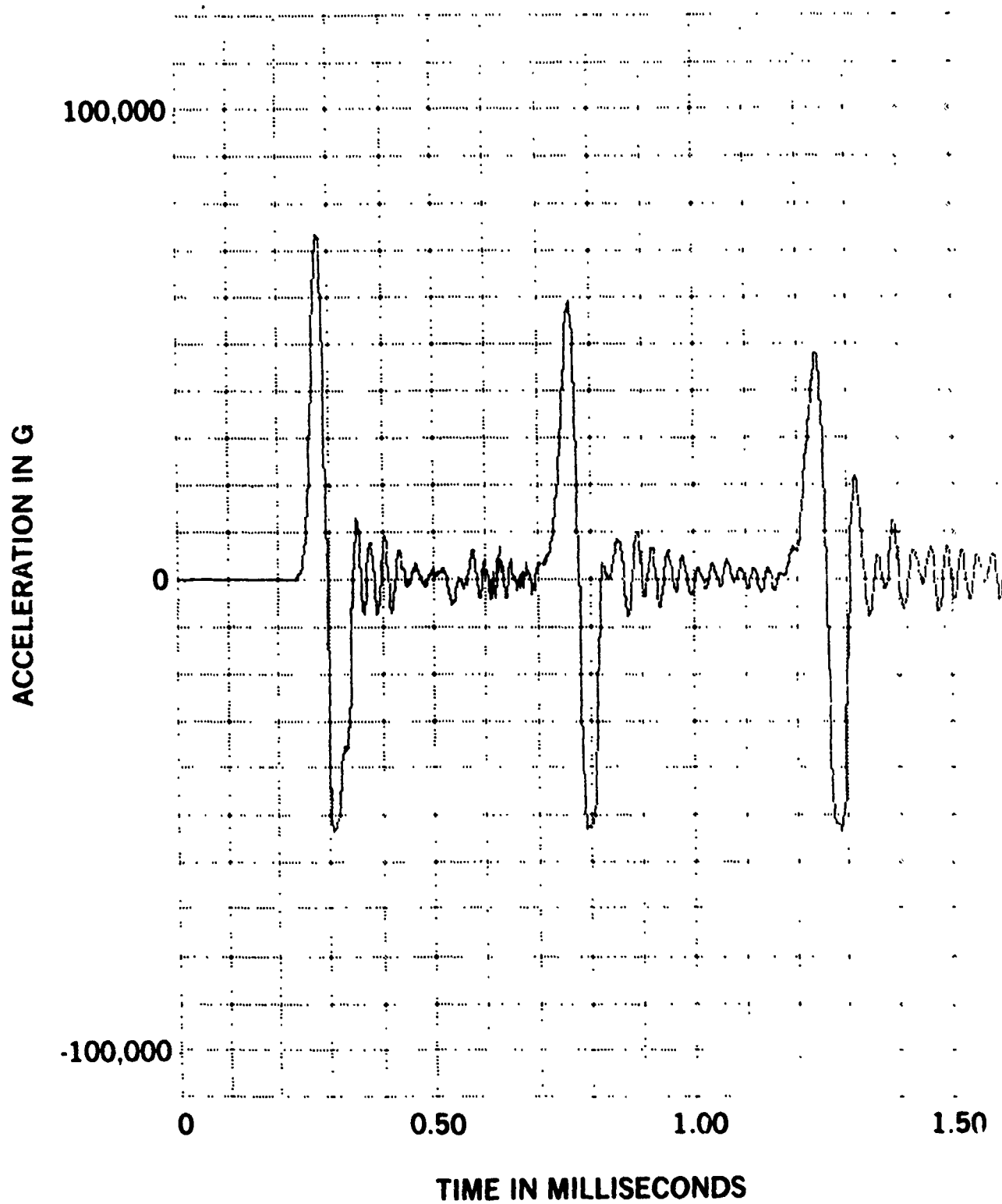
Lower amplitude pulses of about 25,000g peak are shown in Figures 16 and 17 for the reference and test accelerometers respectively. The outputs of the two accelerometers are within 6% of each other indicating that under these conditions of moderately long pulses (about 0.7 milliseconds) and moderate peak amplitudes both transducers are capable of producing consistent, verifiable amplitude data.
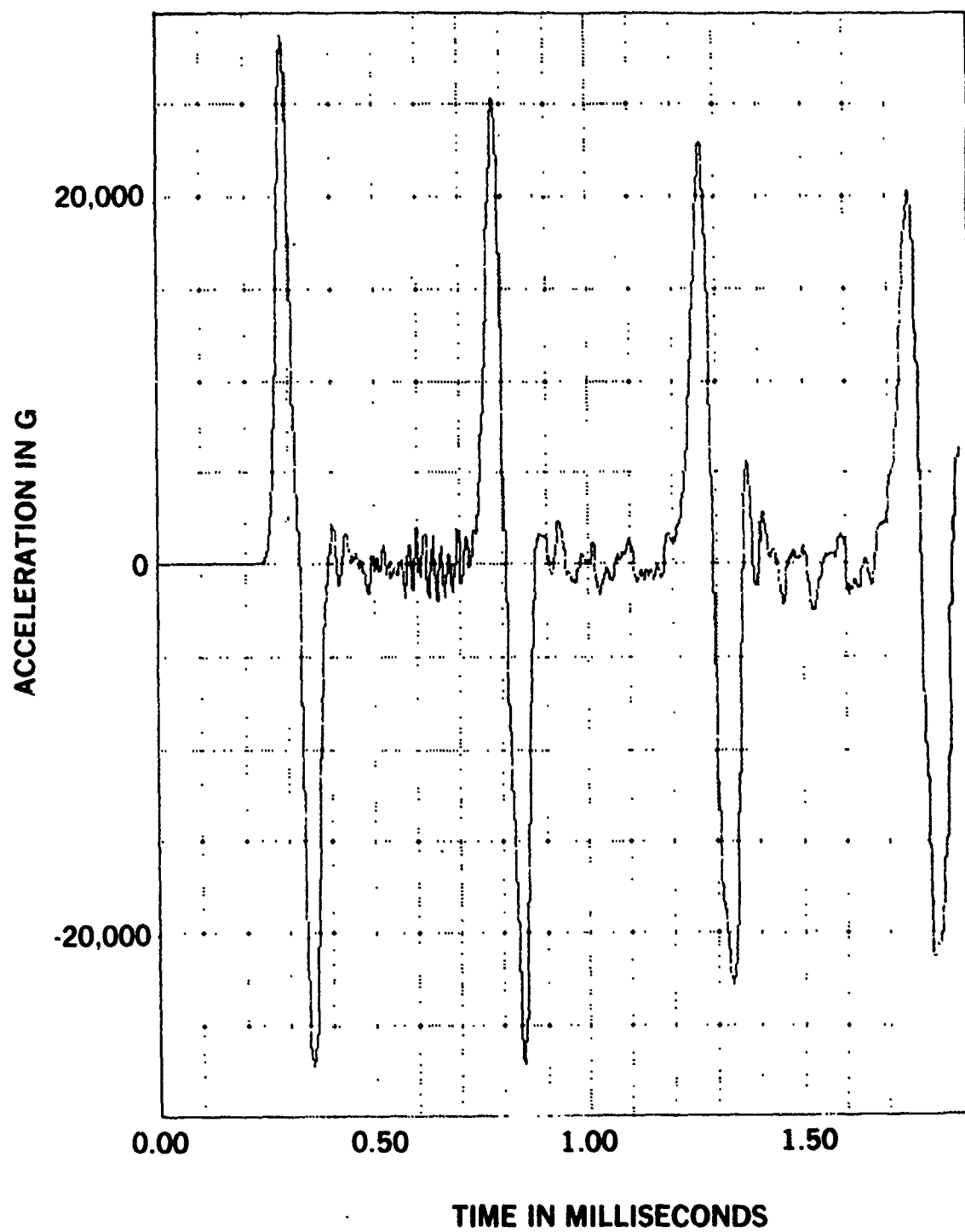
Conclusion

A shock measurement system has been developed in which the quartz seismic system, two-pole active filter and an FET source follower are incorporated in a transducer housing measuring 5/16"hex.x5/8". Tests have shown that the system will survive ±100,000g without damage. Although the results reported here are for accelerometers ranged to ±20,000g, there is no reason to limit the accelerometers to that range and PCB can supply different ranges as required.
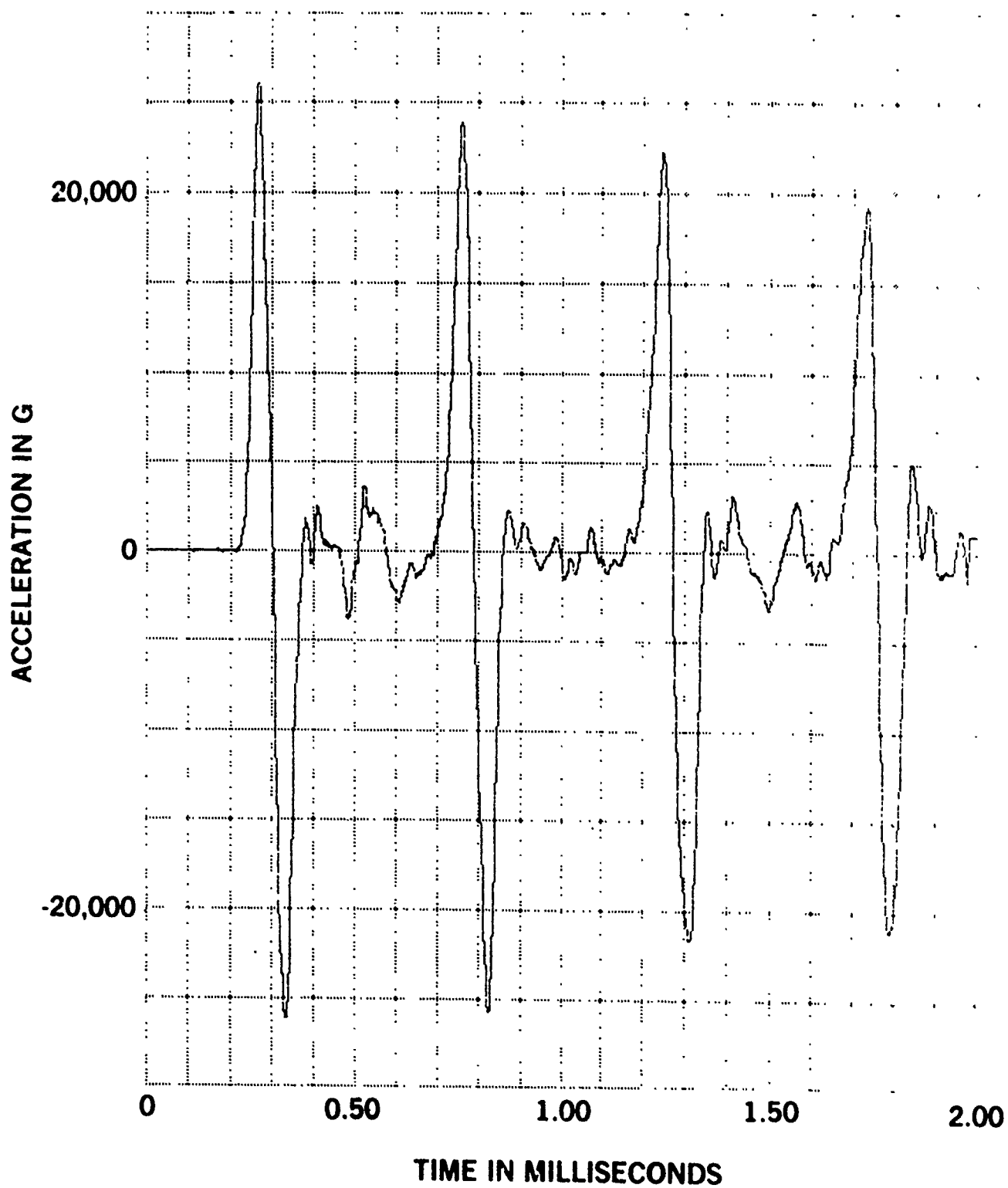
FIGURE 14. RESPONSE OF UNFILTERED PIEZOELECTRIC ACCELEROMETER
(PCB 305A) TO HOPKINSON BAR IMPULSE

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FIGURE 15. RESPONSE OF FILTERED PIEZOELECTRIC ACCELEROMETER
(PCB 305M23) TO HOPKINSON BAR IMPULSE

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FIGURE 16. RESPONSE OF UNFILTERED PIEZORESISTIVE ACCELEROMETER TO
LOW LEVEL HOPKINSON BAR IMPULSE

FIGURE 17. RESPONSE OF FILTERED PIEZOELECTRIC ACCELEROMETER
(PCB 305M23) TO LOW LEVEL HOPKINSON BAR IMPULSE

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Bibliography

1. P. L. Walter and H. D. Nelson, "Limitations and Corrections in Measuring Structural Dynamics," Experimental Mechanics, 19 (9) 309-316, Sept. 1979.

2. F. Schelby to Distribution, Internal Memo, "Developments in High g Shock Measurement at SNLA," Oct. 14, 1982

Appendix A

Specification for High G
Shock Accelerometer

These specifications define a high-g shock accelerometer using a quartz crystal transduction element followed by an internal filter section and internal amplifier. It is required that the filter precede the amplifier in order to preclude electrical overload due to high frequency "ringing" of the crystal. These devices are intended for use in crash, impact, and explosive environments and are subjected to very harsh treatment. A family of transducers of various ranges are envisioned but even the lowest ranges may see, and must survive, up to 20,000g transverse shock.

Short duration precursor stress waves present in the vehicle at impact may cause the crystal to "ring" and, therefore, it is conceivable that as much as 100,000 equivalent g's may stress the transduction element even though the base input is much lower.

Range (FS)	± 2000 g to $\pm 20,000$ g
Output	± 5 v FS
Sensitivities (10%)	2.5 mv/g to 0.25 mv/g
Time constant	2 seconds minimum
High frequency response	flat within +5% to 10,000 Hz with roll off commencing so as to achieve as much attenuation as possible of the accelerometer resonant frequency
Filter	2 pole, Butterworth response
Amplitude linearity	$\pm 1\%$ FS
Transverse sensitivity	$\leq 5\%$
Transverse limit	20,000 g
Polarity	positive output for acceleration directed into base
Signal ground	either case or solder terminal
Seal	hermetic

Operating Temperature Range	-40deg.F to +200deg.F
Power Supply	4 ma constant current
Size	as small as possible, comparable to Kistler 805A or PCB305A
Mounting	integral stud

Appendix B

Measured Standard Performance Properties

Range (for ±5v output)	±20,000g
Time constant	2 seconds
Sensitivity	.19 mv/g
Transverse sensitivity	5.3%
Thermal sensitivity shift	.02%/deg.F
Temperature range	-40 to 250deg.F
Frequency response	flat within ±5% to 25kHz
Base strain	0.2 eq.g/microstrain