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# TESTING TECHNIQUES INVOLVED WITH THE DEVELOPMENT OF HIGH SHOCK ACCELERATION SENSORS

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## INTRODUCTION

This paper describes testing techniques and equipment used in the development of the Endevco Model 7270 Shock Accelerometer, having a range beyond 100,000 g and a mounted resonant frequency on the order of a megahertz. Conventional testing techniques proved inadequate for thorough evaluation. A new calibration system based on the Hopkinson bar has been developed to give rigorous and accurate tests to determine sensitivity, amplitude linearity and zero shift due to accelerations beyond the transducer's designed full scale acceleration level. A related but smaller apparatus was developed to determine resonant frequency and also, although to a very rough degree, the frequency response of the accelerometer. It provided the means to create sub-microsecond rise time strain waves to excite an accelerometer's resonant frequency.

## THE TRANSDUCER

It is instructive first to discuss the transducer to illustrate the need for new testing techniques. Inside the transducer's rectangular steel case is the sensing element, depicted in Figure 1 (patent applied for). The chip of silicon, one millimeter square, incorporates the entire spring, mass, and four-arm piezoresistive strain gage bridge assembly. It is sculpted from single crystal silicon using anisotropic etching and microelectronic fabrication techniques. Strain gages are formed by a pattern of dopant in the originally flat silicon. Subsequent etching of channels frees the gages, and simultaneously defines the "masses" as simply regions of silicon of original thickness. The monolithic structure and extremely small size assures large strength-to-weight ratio; the freed gages maximize linearity and sensitivity. The structure's megahertz resonance and linear range of more than 100,000 g promise to severely challenge (and appear to exceed) the limits of amplitude and precision of the historical methods for calibration and test of shock accelerometers.

## THEORY OF CALIBRATION USING THE HOPKINSON BAR

The short pulse durations associated with high acceleration shock cause errors in calibration when using back-to-back standard and test accelerometers. Relative motion between the test and standard accelerometers becomes significant when the pulse wavelength approaches the fixture/accelerometer dimensions. Reducing these errors by increasing pulse duration or by decreasing dimensions is not always practical, thus the alternate approach of the Hopkinson bar becomes attractive.*

In contrast to the short fixtures of comparison techniques, a mounting fixture in the form of a Hopkinson bar (a long and slender elastic cylindrical bar) is deliberately made longer than the wavelength of the pulse. The entire pulse becomes embodied as a compression wave which travels toward the accelerometer mounted on the end. This allows measurement of the wave free of reflections and distortion. That is, provided that the assumption described in the next paragraph is true.

A one dimensional theoretical model of such a bar of constant cross-sectional area results in the prediction that the pulse travels without distortion or attenuation. A one-dimensional model is fairly simplistic, however. Analysis of cylindrical bars using Pochhammer's equations, which take into account radial displacements due to Poisson's expansion, show that

* Comparison techniques suffer other difficulties, not the least of which is establishing the linearity of the standard transducer [1,2]. The technique is most often used at acceleration levels below about 15,000 g.

a wave travels essentially unchanged as long as the wavelength is long compared to the diameter of the bar.[3,4] This condition can be fairly easily met. Dispersion and attenuation generally occurs to very high frequency components of a wave. Production of high frequency components in a test pulse is therefore to be avoided, and those that are created are allowed to decay, hopefully to have negligible contribution to the total wave after a few diameters of travel.

By using strain gages mounted near the middle of the bar, the wave at that point is well established and will change little thereafter. It can be monitored in full, free from reflections as it travels toward the accelerometer provided that the bar is sufficiently long. Thus the pulse is known, and the sensitivity of the accelerometer can be derived by comparison of its output to the strain gage output.

The fundamental relation for the calibration is:

$$a = 2c \frac{d\varepsilon}{dt} \qquad (1)$$

where acceleration a, as experienced by the accelerometer mounted on a free end, is proportional to the propagation velocity c and $d\varepsilon/dt$, the time rate of change of strain. More useful is the integrated form of the equation, in which the integrated accelerometer output is compared to the magnitude of the strain.* This is the basis of the calibration using the Hopkinson bar. The measurement of a high level acceleration pulse is reduced to the straightforward strain measurement at levels well within the verifiably linear regions of strain gage operation.

## CALIBRATION APPARATUS

Figure 2 shows the schematic of the apparatus, which is described thoroughly in Reference 5. In summary, a projectile with a parabolically pointed tip (based on the work of Brown and Drago[6]) is propelled by air pressure when a paper diaphragm ruptures. It impacts an aluminum mitigator on the end of

* This provides an averaged sensitivity value over the acceleration levels of the pulse. If the accelerometer is nonlinear, correction factors are necessary to determine amplitude linearity.[2,5] Such correction factors are negligible for the small degree of amplitude nonlinearity observed in the tests described in this paper.

the compliantly supported titanium bar, which is 5 feet long and 5/8" in diameter. A compression wave is established and travels to the accelerometer mounted on the other end of the bar, monitored on the way by the two strain gages. Usually the accelerometer is mounted on a "breakaway", allowing it to fly free from the bar so that any zero shift occurring to the transducer output would be visible during that period of zero-g flight. The waveforms of the strain gages and the accelerometer are stored in a Nicolet 4094 Digital Storage Oscilloscope. Digital integration of the accelerometer output is possible using Nicolet-supplied software. Figure 3 shows the capabilities of the system, where peak acceleration and corresponding pulse widths are shown as a function of projectile shape and driving pressure.

## CALIBRATION RESULTS

Extensive calibrations at "low" acceleration levels ( 10,000 g) were performed on several models of shock accelerometers on both the Hopkinson bar and on the comparison-based Endevco 2965C Shock Calibrator (described in Reference 1). Agreement in sensitivity values from the two radically different systems was good: a bias between the two of less than a percent and a standard deviation of two percent in the data from the Hopkinson bar. Figure 4 is an example of the waveforms in a test of sensitivity on the new system. Note that the acceleration pulse occurs 150 μs after the strain gages detect the pulse, since it takes that long for the wave to travel the distance between the gages and the accelerometer. Note also that the integration is performed over the first positive acceleration pulse, and that the several strain gage signals after the initial pulse are from reflections of the strain wave in the bar which the accelerometer does not experience because it is flying free.

Figures 5 and 6 are examples of how zero shift is measured. The lower waveform of Figure 5 is the output of the Endevco Model 7270 to 150,000 g; the upper waveform is the same output digitally integrated. In this figure the integration is extended over a millisecond for determination of zero shift. This is a typical result for the 7270. The near-zero slope during free flight corresponds to a shift less than 0.1 percent of the peak value of 100 mV. Figure 6 shows the effect of integrating a 0.3 percent shift which occurred in a more conventional accelerometer due to a 100,000 g shock.

In the study of amplitude linearity, it was found that the sensitivity of five 7270 accelerometers at 150,000 g differed from sensitivity as measured at 10,000 g, (using the comparison technique) by a maximum of 4 percent. Calibration uncertainty on the Hopkinson bar is calculated to be approximately 6% in the realm of 100,000 g.[5] It appears from these and many other tests that the amplitude linearity of the 7270 exceeds the capabilities of the calibration technique.

## SHOCK SURVIVABILITY

Besides calibration of shock accelerometers, the Hopkinson bar can be used to a limited degree to study shock survivability. Although the high frequency content of pyrotechnic shock cannot be well simulated, high acceleration levels can be attained fairly easily and with safety. Another bar was manufactured to this end, tapped so that the accelerometer could be mounted directly. As the strain wave reflects from end to end the attached accelerometer is subjected to repeated couples of positive and negative accelerations.

Figure 7 shows the output of a 7270, subjected to a pulse causing an indicated 250,000 g and 150,000 g in the positive and negative directions, respectively. The decay of the pulse is due to the rubber suspension system holding the bar. Admittedly this pulse is less severe than some pyrotechnic shocks. Were the bar of smaller diameter and shorter, and had the projectile had a ragged point rather than the smoothly sloping tip that was used, the pulse would have had higher frequency content. Each of these possible variations, however, would make support of the bar difficult.

A short small diameter bar has had application in the transmission of pulses of high frequency content, as described below, but at very much lower acceleration levels.

## DETERMINATION OF FREQUENCY RESPONSE

Just as with sensitivity, the determination of frequency response of the 7270 required a transient method, since with no continuous motion could signals of sufficient amplitude or bandwidth be generated.

The first consideration was to determine the resonant frequency. Although fast rise time impacts can be used to excite the resonance of a conventional shock accelerometer, in most cases it was exceedingly difficult to excite the 7270's resonance with impact.

Figure 8 depicts the apparatus with which the resonance of all 7270's has been readily excited, by breaking 2 millimeter diameter glass capillary tubing against the end of an 18" long, 1/2" diameter high purity alumina rod. The breakage includes sub-microsecond steps, since resonances of 1.6 MHz and higher have been excited.

The glass is broken when in static compression. Ideally, the load would be released in a single step. From equation 1, the resultant step strain wave would correspond to a negative impulse acceleration for the accelerometer mounted on the end. With an ideal impulse input, by taking the Fourier Transform of the response, the frequency response could be obtained.[7]

Instead, the breakage is probably a series of smaller steps, causing trains of impulses. The actual shape of the strain wave is not known, since strain levels are too low to measure accurately. Despite this fact, the fast rise time causes accelerations of thousands of gs, and the output of the acceleration can be readily captured and analyzed by FFT. An example of this process is shown in Figure 9. The result shows major features of the frequency response: a 1.34 MHz resonance and minor resonances between 500 and 800 kHz probably associated with the thickness of the case.* Using results such as this, the performance of the 7270 can be summarized in Figure 10, a plot of the resonant frequency versus each unit's sensitivity from a family of prototype 7270's. All have the basic geometry shown in Figure 1.

* The variability in the low frequency response is the result of poor resolution of the fast digitizer used for this test.

## CONCLUSION

Two sets of apparatus were built to evaluate and calibrate a new model of shock accelerometer. For the determination of accelerometer sensitivity and amplitude linearity, a Hopkinson bar was incorporated to create pulses at accelerations to greater than 100,000 g. Strain gage measurement of the pulse provides a standard for calibration of the accelerometer.

Zero shift due to accelerations greater than the designed full scale is measured by integration of the output of an accelerometer allowed to fly free from the bar after the initial positive pulse.

Resonant frequency is measured by performing an FFT of the output due to a submicrosecond rise time stress wave in a smaller version of the Hopkinson bar. Breakage of glass capillary tubing provides the pulse. The wave is not monitored, so the resultant "frequency response" is only approximate.

The calibration techniques described in this paper provide accurate and versatile means to evaluate the performance of shock accelerometers at levels to 100,000 g and above, a task not possible with conventional techniques. The quality of performance of the accelerometer with the extremely small monolithic silicon sensing element was found to be excellent.

## REFERENCES


1. "Comparison Shock Motion Calibrations", Technical Paper No. 240, Endevco Corp.

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3. Kolsky, H., Stress Waves in Solids, Oxford University Press, 1953, pg 87.

4. Redwood, M. Mechanical Waveguides, Pergamon Press, 1960, pg. 143.

5. Sill, R.D., "Shock Calibration of Accelerometers at 100,000 g Using Compression Waves", 29th International Instrumentation Symposium, ISA, Albuquerque, New Mexico, May 1983.

6. Brown, G. and Drago, G., "Shock Calibration of Accelerometers Using Hopkinson's Bar", University of California, Berkeley, College of Engineering, No. 77.3, March, 1977.

7. Eller, E. "Response of Transducers to Fast Transient Motion Inputs", Tenth Transducer Workshop, Telemetry Group, Inter-range Instrumentation Group, Range Commander Council, White Sands, New Mexico, June, 1979, Colorado Springs, Colorado.

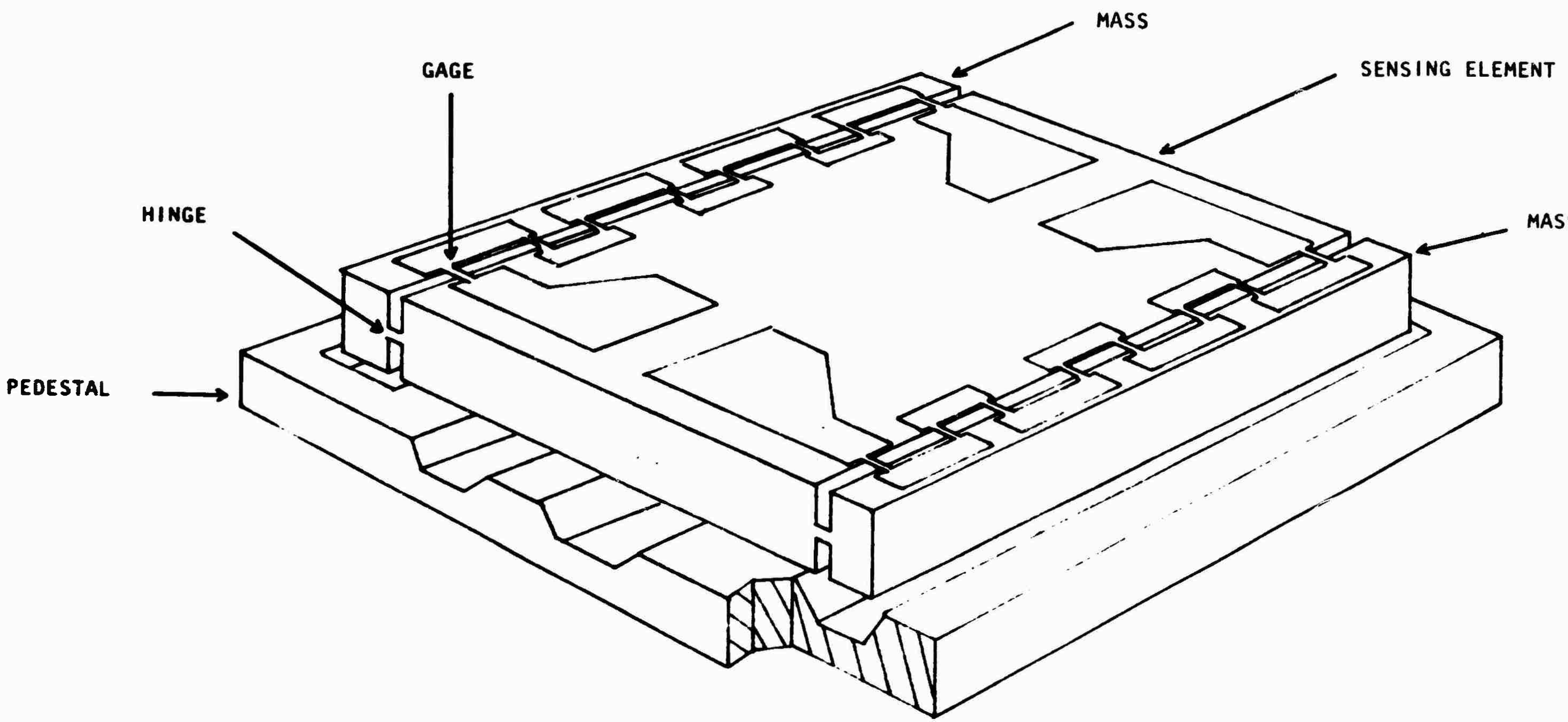


Figure 1. Monolithic silicon sensing element for Endevco® model 7270 accelerometer.

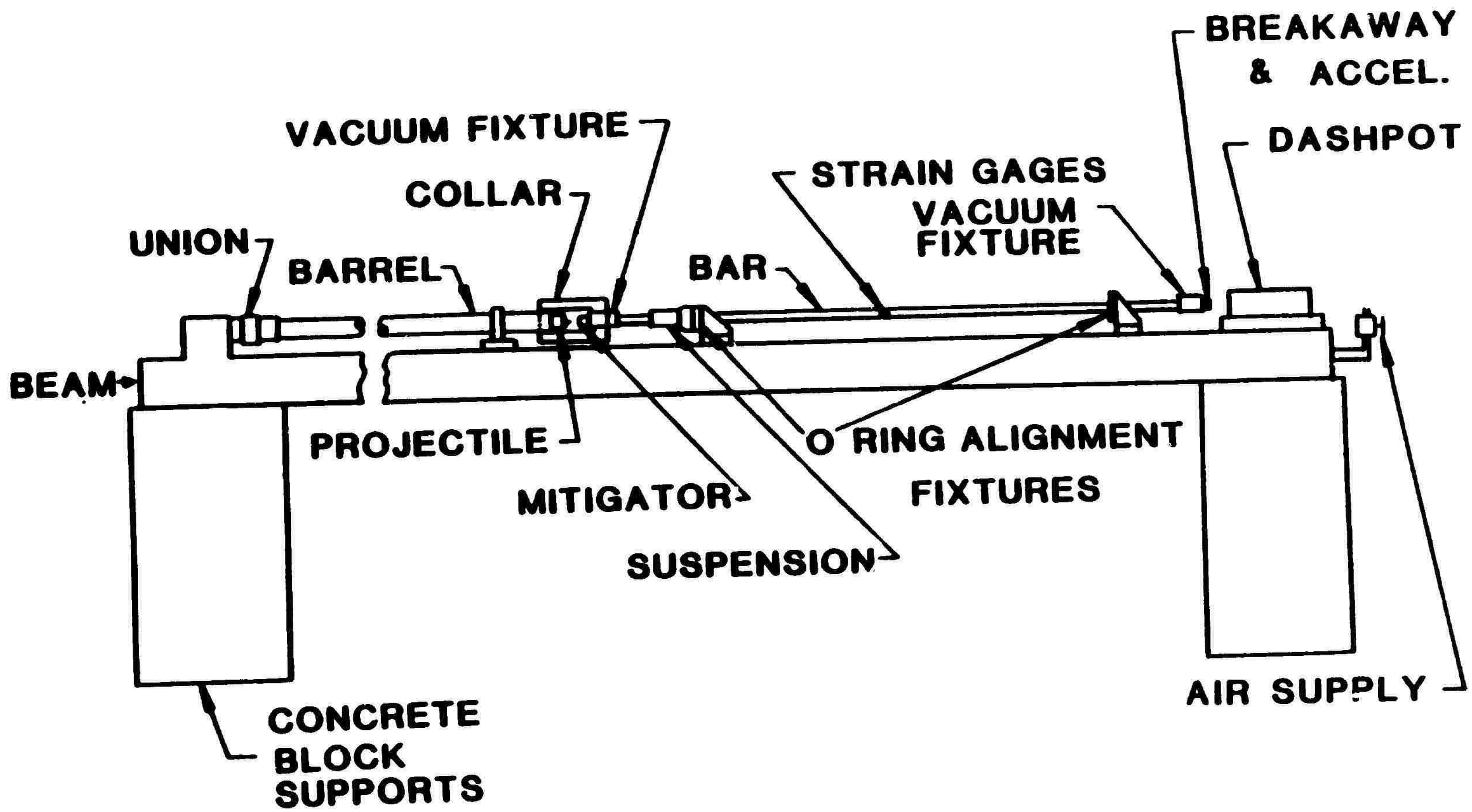


Figure 2. Schematic of apparatus.

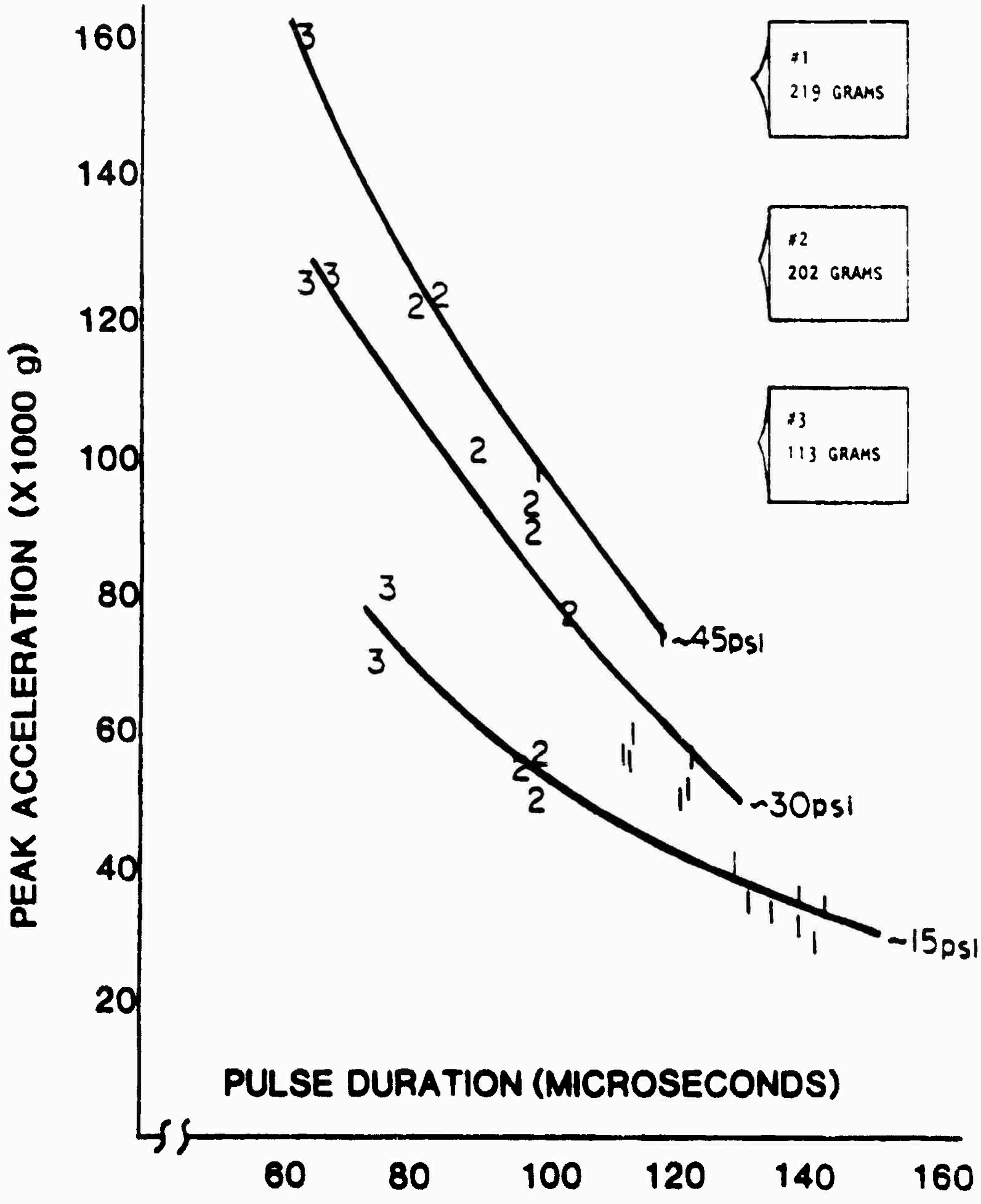


Figure 3. Peak acceleration vs pulse duration using each of three projectiles at three driving pressures.

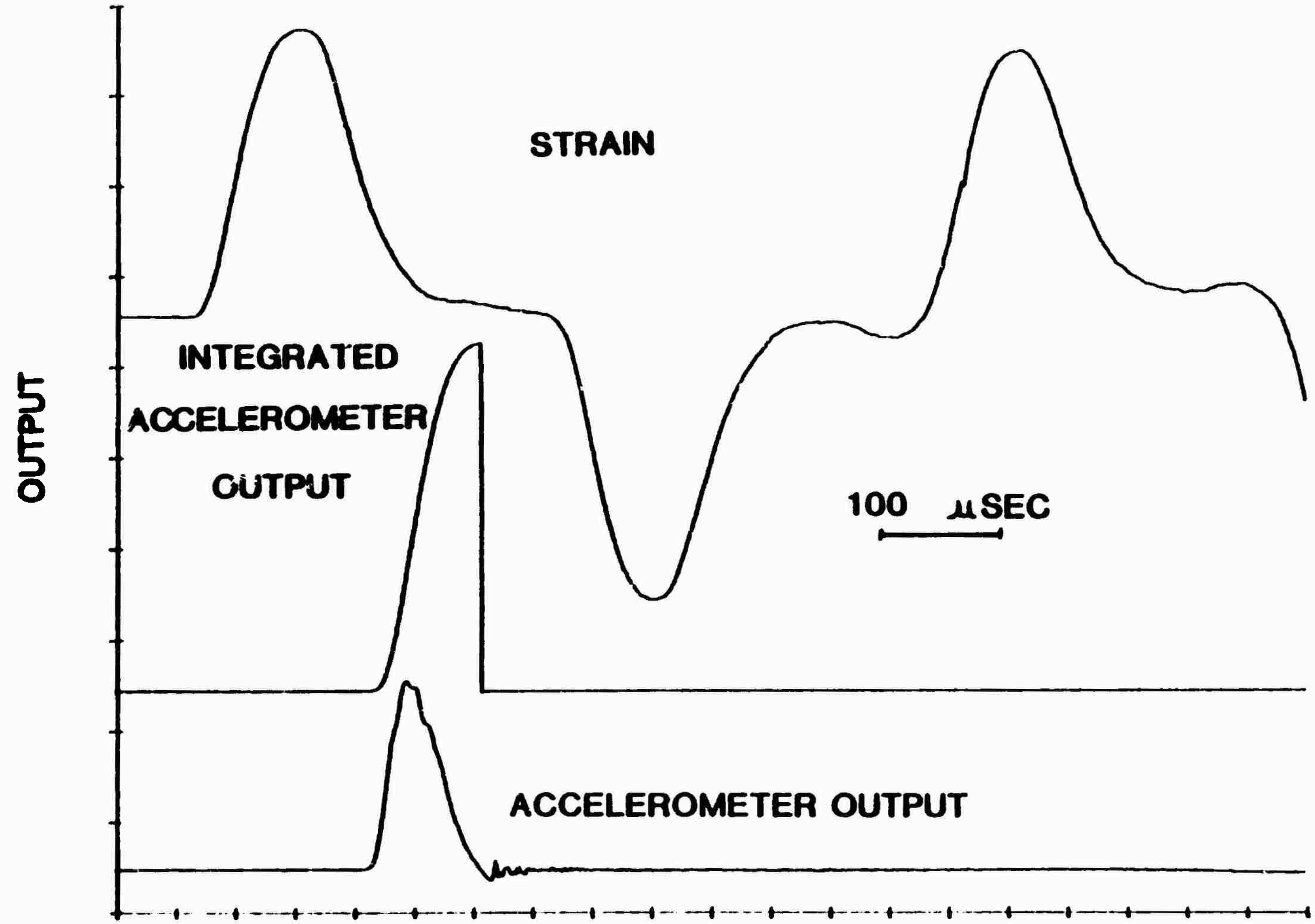


Figure 4. Test waveforms.

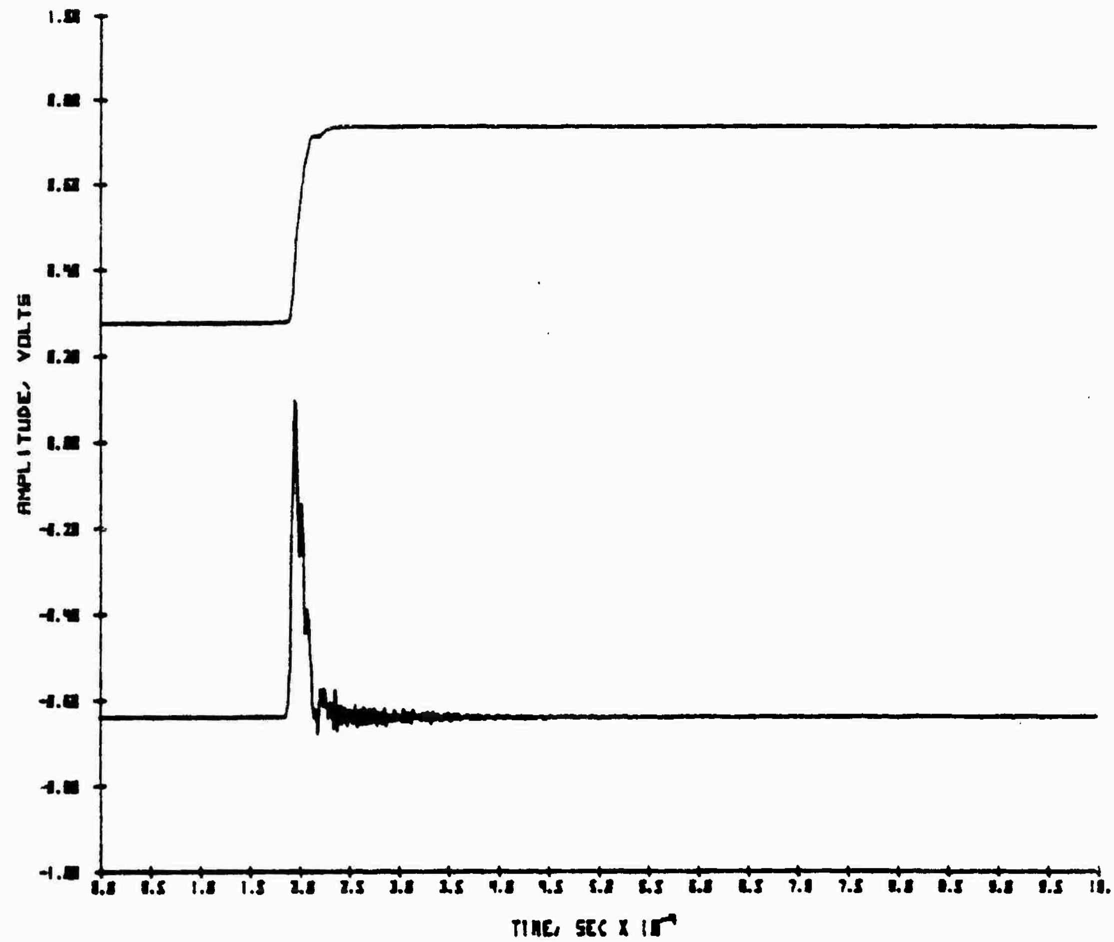


Figure 5. Output of 7270 from 150,000 G, lower waveform, integrated output, upper waveform.

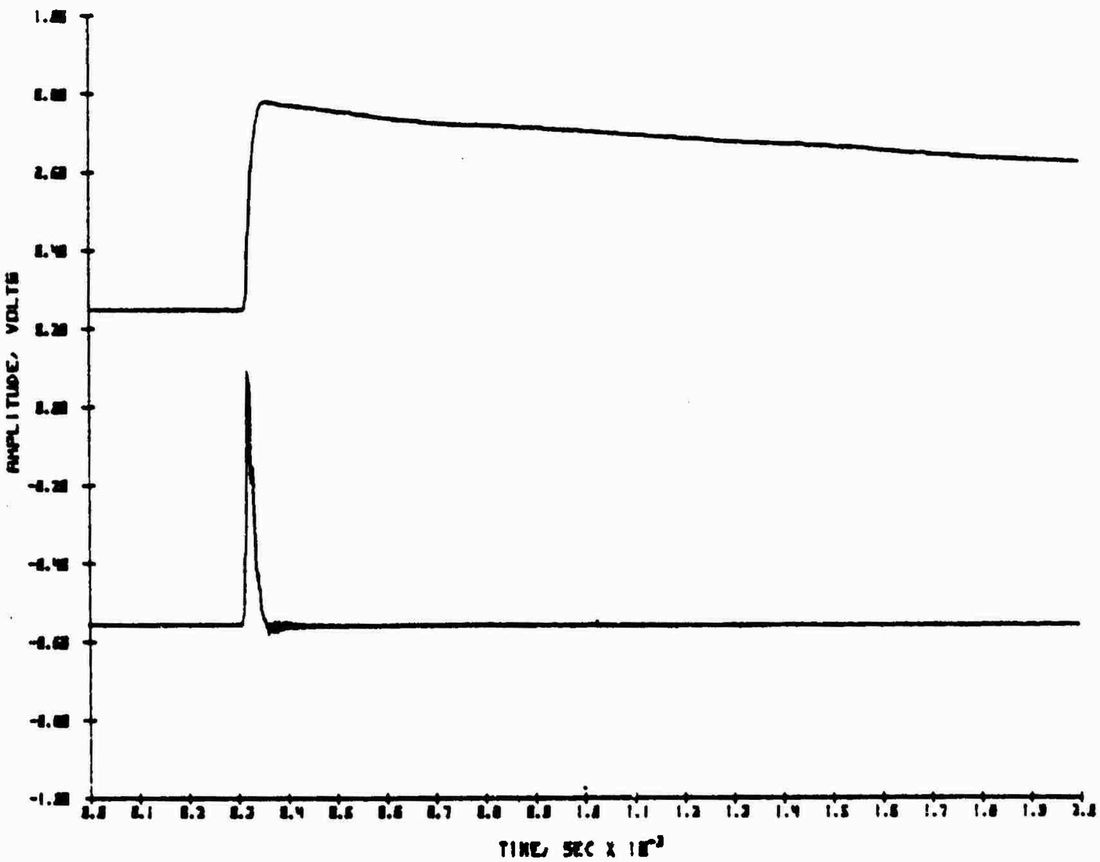


Figure 6. Output of conventional accelerometer to 100,000 G, lower waveform: integrated output showing 0.3% zero shift, upper waveform.

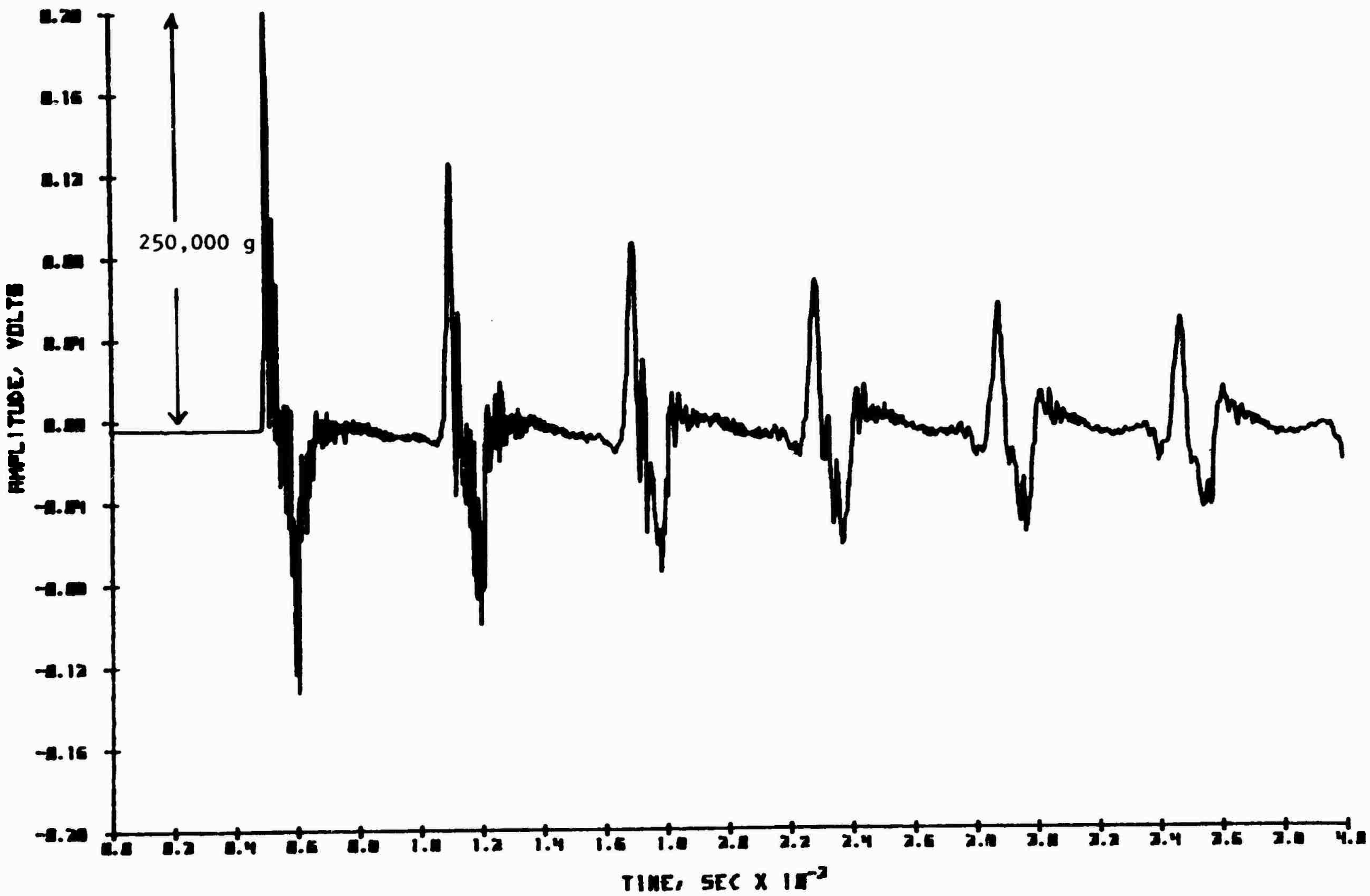


Figure 7. Accelerometer output when attached to Hopkinson Bar.

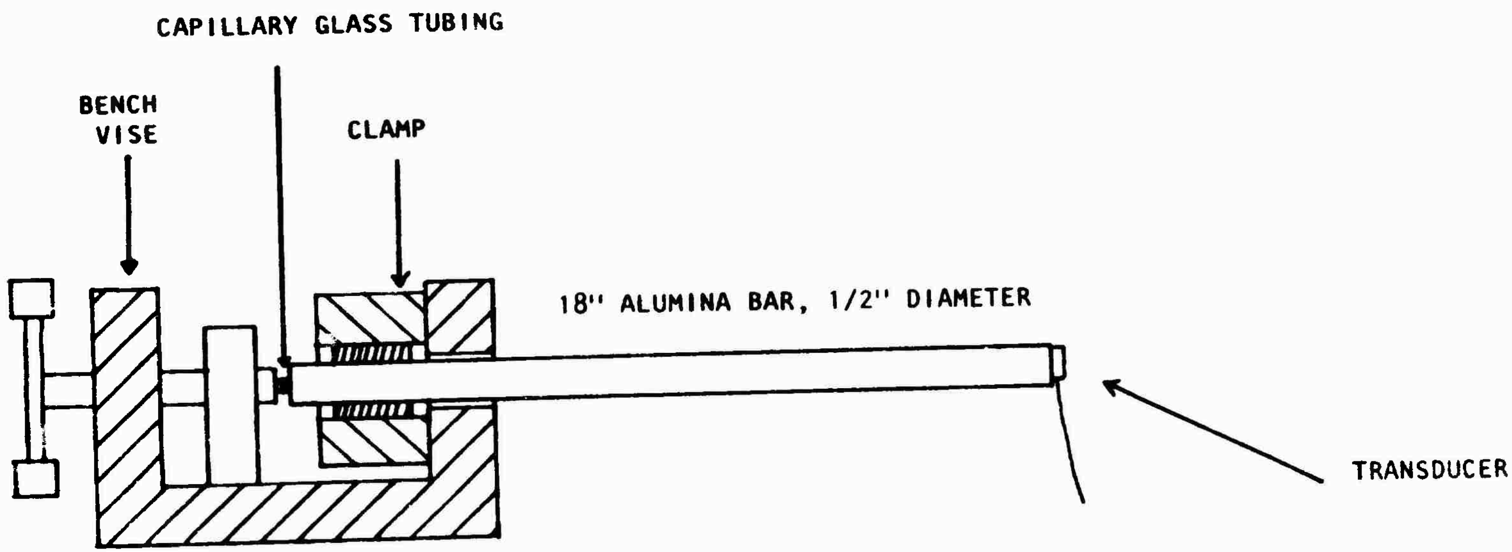


Figure 8. Apparatus for determining mounted resonant frequency.

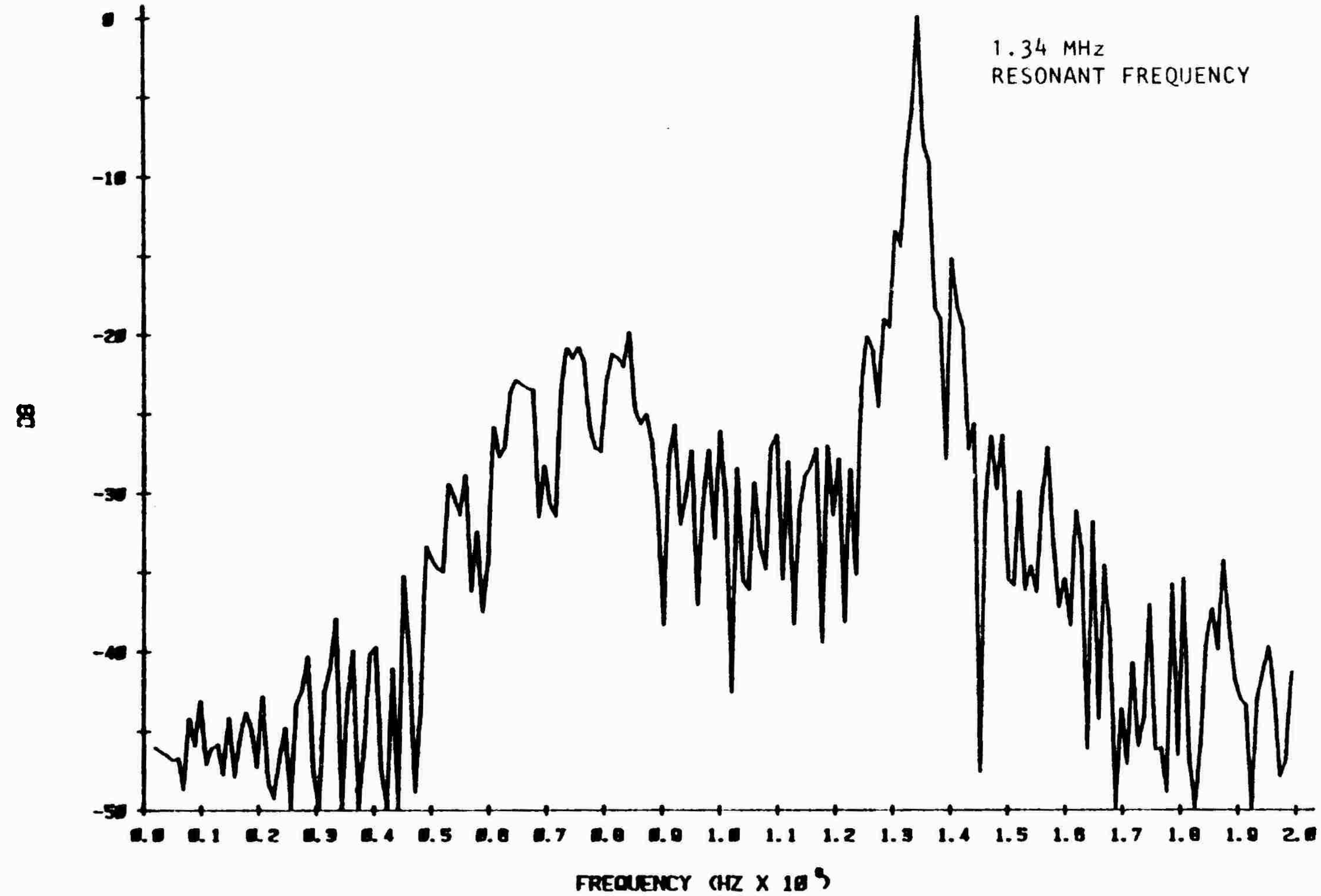


Figure 9. FFT of 7270 response to broken glass capillary.

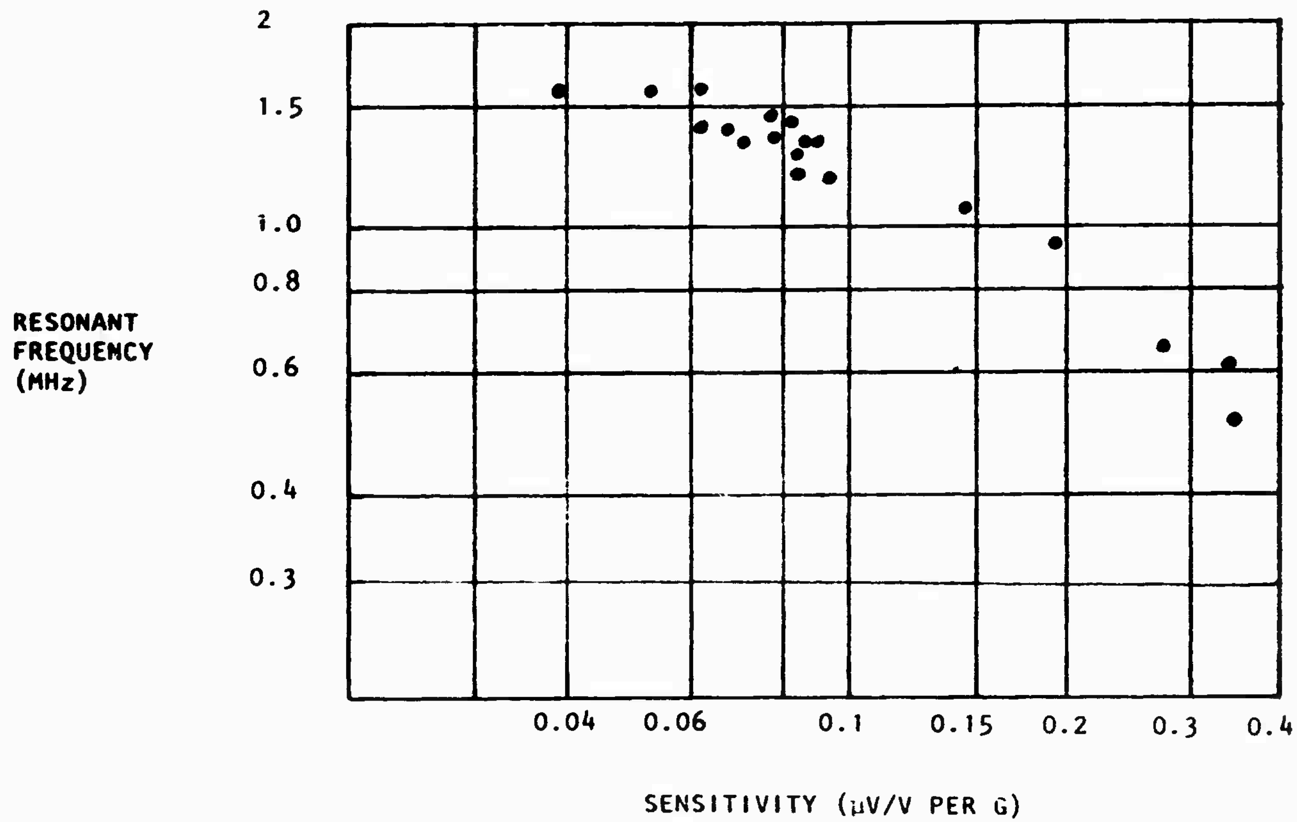


Figure 10. Resonant frequency vs sensitivity of the Endevco® model 7270.