

## PIEZORESISTIVE STRAIN GAGE ACCELEROMETERS WITH SUBCRITICAL DAMPING AND HIGH OVERLOAD CAPABILITIES

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### ABSTRACT

The emergence of semiconductor strain gage accelerometers with their inherent steady state (frequency response to DC) and high shock (250 to 20,000 g) capabilities has created a need for lower range devices of a similar nature. The evolution of a low range, 25 g full scale accelerometer from the recently developed high range units is described. The relatively large inertial displacements found in these devices established a need for extreme overload capability and subcritical damping. Included are details concerning the optimization of damping at temperatures other than ambient, the accomplishing of damping with microinch displacements, the microscopic "adjustment" of overtravel stops and the utilization of new piezoresistive strain elements to increase the sensitivity of the transducer.

### INTRODUCTION

The basic designs of transducers utilizing piezoresistive materials to measure acceleration, pressure, temperature and force are already accomplished. Obstacles such as large non-linear temperature effects, and strain resistance non-linearity have been overcome. Most of these devices have the desirable features of small size, high sensitivity, high natural frequency and response to steady state inputs.

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## INTRODUCTION (continued)

The present efforts of designers of these transducers is to extend the "state-of-the-art" in the following directions:

1. Higher and lower ranges
2. Better response characteristics (e.g., higher natural frequencies)
3. Greater sensitivities
4. Wider temperature envelopes
5. Greater overranging capability
6. Damping where desirable

These efforts, in the field of piezoresistive strain gage accelerometers, are being directed toward higher and lower range instruments.<sup>1</sup> This paper, in particular, describes the extension of existing capability toward three goals: (1) greater sensitivity, (2) viscous damping, and (3) improved overranging capability.

The definition of the specific design goals was brought about by matching the capabilities of the piezoresistive strain gage sensor with a specific instrumentation need. One of the desirable features of the piezoresistive accelerometers already available is their ability to measure sustained accelerations as well as the superimposed shock or vibration spectra with a single transducer. (Previously, such measurement was made typically using a low natural frequency potentiometric device and simultaneously measuring the shock or vibration with a piezoelectric crystal transducer.)

However, previous piezoresistive accelerometers were designed for full scale g levels much higher than the  $\pm 10$  g to  $\pm 50$  g ranges which are frequently employed in the measurement of steady state accelerations and vibrations on launch vehicles.

An additional desirable feature is a flat response to 500 Hz or 1000 Hz to match the band-pass characteristics of typical telemetry systems. This paper describes one such design.

## DESIGN

The original concepts for the design of piezoresistive strain gages were well described by Sanchez.<sup>2</sup> In addition, the specific design of an acceleration transducer<sup>3</sup> and the

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<sup>1</sup> Wall, W. E., "Piezoresistive Strain Gage Accelerometers Increase Spectrum of Shock and Vibration Measurement Capability" The Shock and Vibration Bulletin, Bulletin No. 35 Part 4, January 1966.

<sup>2</sup> Sanchez, J. C., "Semiconductor Strain Gage Evaluation at Extreme Temperatures" Preprint No. 16.2-3-64, ISA, NY 64.

<sup>3</sup> Lovelace, D. E., "Development and Application of a Piezoresistive Strain Gage Accelerometer" Preprint No. 49.2.63, ISA, Chicago 63.

## DESIGN (continued)

optimization of strain gage bridges<sup>4</sup> are equally well illustrated. The transducer design described here is in fact the extension of one design configuration to include those features noted previously; greater sensitivity, viscous damping and improved overranging capability, without sacrificing response (high natural frequency).

More specifically, the original design goals were:

1. Maintain present transducer envelope, 5/8" diameter x 1" high with 5/8" hexagonal base.
2. Weight less than 1 1/2 ounces.
3. Resonant frequency greater than 2000 Hz.
4. Damping factor between 0.4 and 0.7 critical at ambient temperature with reasonable characteristics over temperature range.
5. Linear Range:  $\pm 25$  g.
6. Sensitivity: 1 volt peak at 25 g peak when excited with 28 volts direct current.
7. Overload capability up to positive stops set between 75 g and 150 g, and a shock capability better than 500 g.

## DESIGN EXECUTION AND EVALUATION

The design concept selected as most likely for extension to low range measurement was that of a standard, medium range transducer. This unit (ENDEVCO<sup>®</sup> Model 2261) which has a nominal full scale range of 2500 g, utilizes a simple, cantilevered seismic mass and a transducer frame most suitable for design changes.

The three major features desired were to be accomplished as follows: First, to lower full scale range but at the same time increase sensitivity. These two characteristics are inter-related and were brought about by increasing the radius of gyration and volume of the seismic mass and by incorporating a new strain gage configuration which features a smaller cross-section and increased gage factor. Secondly, viscous damping was incorporated. A closed system was provided to contain the damping fluid, a silicone oil. The closed system maintains a constancy of damping with time and prevents leakage. In order to compensate, in part, for the wide excursions in viscosity with temperature, the thermal expansion of the oil was used to vary the shearing area, increasing it when viscosity is decreasing and the reverse when viscosity increased. Figure 1 illustrates the variations of volume and viscosity of a typical silicone damping fluid. Particular note should be made of the logarithmic viscosity scale and the linear thermal expansion scale.

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<sup>4</sup> Ward, T. L., "Recent Developments in the Application of Semiconductor Strain Gages to Physical and Mechanical Measurements" Preprint No. 17.11-4-65, ISA LA 65.

DESIGN EXECUTION AND EVALUATION (continued)

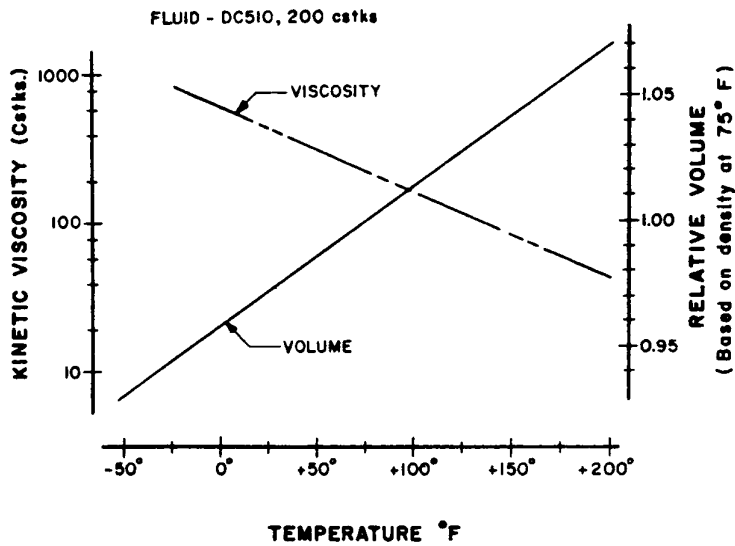


FIGURE 1  
TYPICAL TEMPERATURE CHARACTERISTICS  
SILICONE OIL

The damping effected is viscous; that is, it is a function of viscosity, gap, shearing area and velocity. The design incorporates a proprietary method of multiplying or "amplifying" the apparent velocity.

The need for this increase may be more readily understood if the relative displacements are considered. The full scale deflection of the end of the mass is about 20 microinches double amplitude and the center of mass about 10. With a useful frequency range of 0 to 750 Hz the low velocities available for damping can be appreciated.

$$x = A \sin \omega t$$

$$\dot{x} = \omega A \cos \omega t$$

$$\text{at } f = 500 \text{ Hz}$$

$$\omega = 2 \pi f = 3142 \text{ radians per second}$$

$$x \text{ max.} = \omega A$$

$$= 3142 \times 10 \times 10^{-6} \text{ inches}$$

$$= .0314 \text{ inches per second at the center of mass or } .063 \text{ inches per second at the end.}$$

## DESIGN EXECUTION AND EVALUATION (continued)

A typical aerodynamic transducer has a maximum velocity for damping of 10 inches per second.

The "amplification" of the velocity effect, brought about by the pumping action of the seismic mass within its sealed reservoir affords an increase of about 100% in damping factor, but unfortunately defies straightforward analysis.

Thirdly, the extension of range capability to the low end ( $\pm 25$  g) of the spectrum brought about an imperative requirement for extreme overrange capability. During the normal use and occasional abuse of environmental laboratory or field testing, a transducer may see short shock pulses of 500 g without leaving its storage container and as much as 1000 g when dropped lightly on a hard bench top. These shocks have already been noted as a major cause of failure of similar transducers with an order of magnitude higher range. This characteristic is due to the ability of almost all piezoresistive strain gage transducers to respond to short, harsh transients, a result of their inherently high natural frequencies and sensitivities. The nature and availability of shock pulses normally encountered make force and acceleration transducers the most vulnerable.

The manner of inhibiting the travel of the seismic mass, to prevent this failure mode, was to provide positive mechanical stops. If the full scale displacement, previously noted at about 20 microinches, is extrapolated to the 75 to 150 g stop setting required, this results in the need for stops individually set within approximately  $\pm 14$  microinches. With present day economical machine shop practice, this is well beyond a quarter turn adjustment to an 0-80 screw (about 3000 microinches). As normal mechanical adjustment is not available, it was necessary to develop a unique proprietary method to incorporate and adjust the stops. In spite of the small displacements, this method has proven to be most effective.

Some interesting performance parameters have resulted from the incorporation of these design features. The design resulted in sensitivities approximately 25% higher than the goal but at the same time the resonant frequency of the transducer ( $> 3000$  Hz) was higher than required.

The frequency response characteristics obtained on test are plotted in Figure 2. The damping curves appear to deviate from the true, damped, single-degree-of-freedom system when plotting response versus frequency. This effect is due to the mechanical stiffness of the system varying slightly with temperature, causing the resonant frequency to decrease with increasing temperature. For convenience the response curves of a single-degree-of-freedom system at various damping levels is plotted. This is:

$$(\text{Response}) \frac{x}{x_0} = \frac{1}{\sqrt{\left[1 - \left(\frac{f}{f_n}\right)^2\right]^2 + \left[2\gamma \left(\frac{f}{f_n}\right)\right]^2}}$$

DESIGN EXECUTION AND EVALUATION (continued)

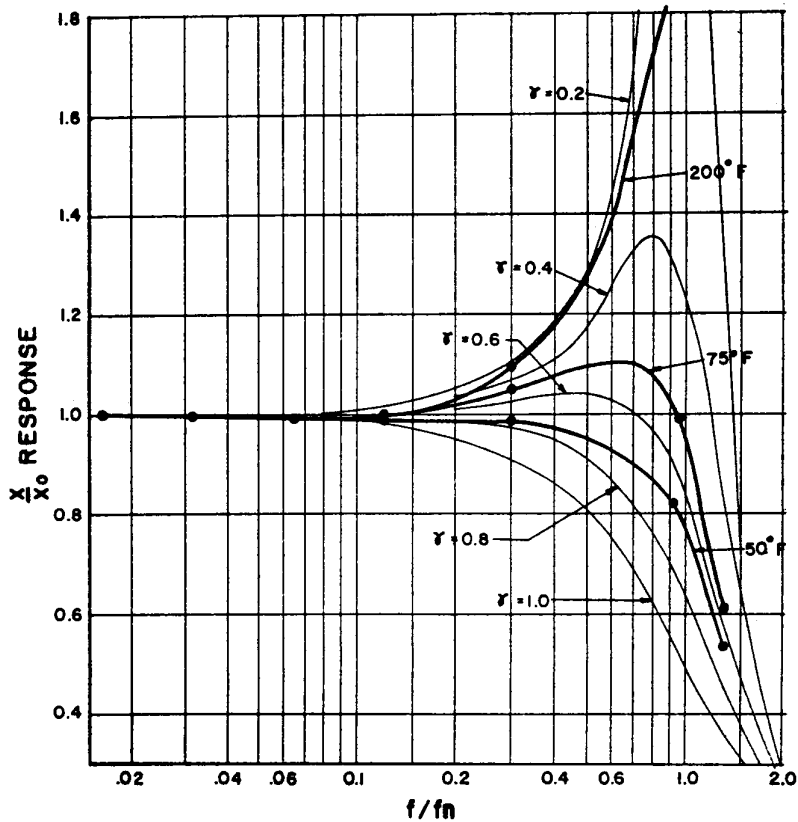


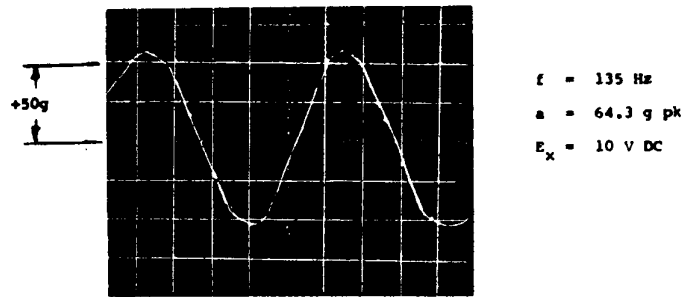
FIGURE 2  
 FREQUENCY RESPONSE  
 ENDEVCO® MODEL 2262 ACCELEROMETER

An interesting feature of the stop system is the manner in which it affects transducer output. Figure 3 shows the electrical output of a transducer operating above rated range with the seismic mass being restrained by the stops. The "clipping" effect and the lack of rebound on contact are of particular interest.

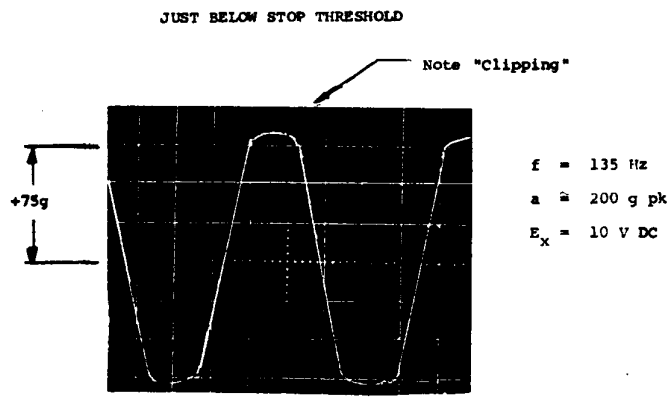
(The performance of the prototype transducers is covered in greater detail in the Results section.)

For greater ease in handling, the transducer incorporates a subminiature six-pin connector to permit the use of a detachable cable. Figure 6 illustrates the transducer and its separate cable.

DESIGN EXECUTION AND EVALUATION (continued)



JUST BELOW STOP THRESHOLD



STOPS ENGAGING AT 75g APPROXIMATELY

FIGURE 3  
EFFECT OF STOP SYSTEM ON ELECTRICAL OUTPUT

A BRIEF HISTORY

The development of the ENDEVCO® Model 2262 Accelerometer can be categorized in three phases. The first was the fabrication of a few preprototype units to prove out, on an individual basis, the feasibility of a 25 g transducer with greater sensitivity, damping and overtravel stops. The second phase was the fabrication and testing of several more finished or prototype units, the performance and design of which is the subject of this paper. Presently, the transducer is in the preproduction or pilot run stage of the development cycle.

RESULTS

The prototype units were tested and found to have the following performance characteristics:

1. Sensitivity: Required 1.0 volt peak full scale at rated voltage. Result, 1.1 to 1.3 volts full scale at rated voltage.
2. Damping: 0.4 to 0.7 at ambient.  
Results: 0.35 to 0.6 at ambient with reasonable temperature shifts. A plot of frequency response for three different temperatures is provided in Figure 2.
3. Overtravel Stops: 75 to 150 g stops have been set between 100 and 200 g. Figure 3 illustrates typical "clipping" of output signal by mechanical stops. One unit was operated without stops at approximately 250 g peak sinusoidal input (10 times overrange) with no apparent waveform distortion. Linearity was not checked.

A more detailed comparison of the design goals and actual instrument performance is provided in Table 1. Particular note should be made in that while the resulting sensitivity of the unit was higher than originally anticipated, the natural frequency was also higher rather than the lower value which might have been anticipated from the higher sensitivity. This is attributed to an increase in gage factor of the new sensor elements available at the time of assembly and a slightly stiffer structure brought about by minor configuration changes.

## RESULTS (continued)

TABLE 1

	<u>Design Goal</u>	<u>Prototype Results</u>
Size:	5/8" hex x 5/8" dia. x 1" high	5/8" hex x 5/8" dia. x 1" high
Weight:	1.5 oz. maximum	1.0 oz. (excluding cable)
Resonant Frequency:	> 2000 Hz	> 3000 Hz
Damping:	.4 to .7 critical at ambient	.35 to .6 critical at ambient
Ranges:	±25 g	±25 g
Excitation Voltage:	28 VDC regulated	28 VDC regulated
Overrange Capability:	Stops at ±75 g to ±150 g	Stops at 100 g to 200 g
Transverse Sensitivity:	3% maximum	1.7%
Bridge Impedance:	Less than 2000 Ω	1550 Ω input; 1200 Ω output (resistive)
Insulation Resistance: (Bridge to Case)	> 1 gigohm at 100 VDC	> 1 gigohm at 100 VDC

During the development of the ENDEVCO® Model 2262 Damped Accelerometer, it became apparent that for some shock measurement applications an undamped configuration would be desirable. This is in part a result of the higher resonant frequency of the final configuration. Figure 4 illustrates the output of a damped Model 2262 Accelerometer compared to a calibration standard.

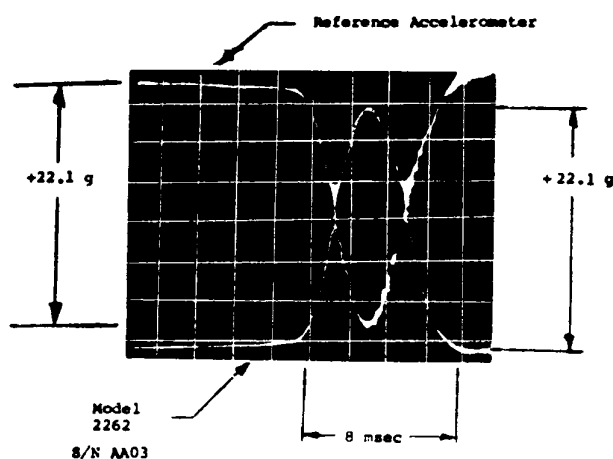


FIGURE 4.  
SHOCK CALIBRATION OF MODEL 2262 - DAMPED

RESULTS (continued)

Figure 5 indicates the performance of the undamped version of the transducer.

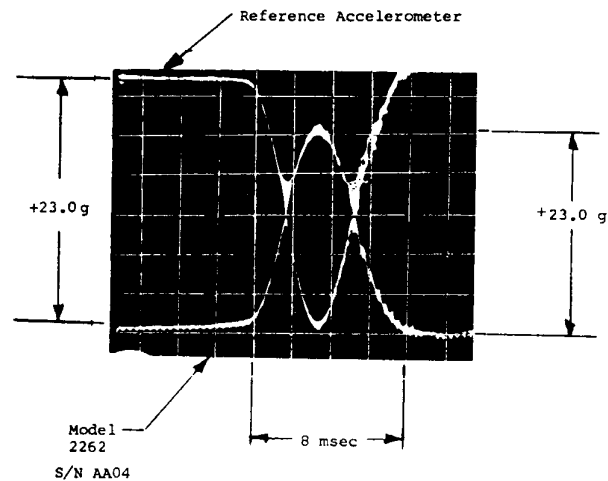


FIGURE 5.  
SHOCK CALIBRATION OF MODEL 2262 - UNDAMPED

A photograph of an ENDEVCO<sup>®</sup> Model 2262 Piezoresistive Strain Gage Accelerometer is shown in Figure 6.

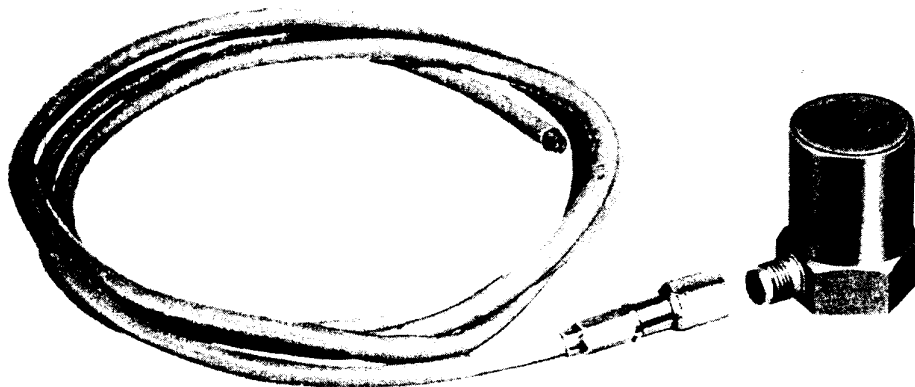


FIGURE 6.  
THE ENDEVCO<sup>®</sup> MODEL 2262 PIEZORESISTIVE STRAIN GAGE ACCELEROMETER

## CONCLUSIONS

The range of piezoresistive strain gage accelerometers can be usefully extended lower as well as higher. The major problems of low range, such as vulnerability to shock and relatively low natural frequency, can be overcome with certain configurations. These devices, of all usable ranges, can provide measurement of steady state acceleration with higher frequency shock or vibration environments superimposed. In some cases they can be provided with damping and all are available without damping when phase shift or time domain relationships are critical.

## NOMENCLATURE

A	steady state amplitude, inches
f	frequency, Hertz
f <sub>n</sub>	resonant frequency, Hertz
g	gravitational constant, inches/second <sup>2</sup>
γ	damping ratio, ratio of damping present to critical damping, unitless
t	time, seconds
ω	radial speed, radians per second
x <sub>0</sub>	steady state displacement, inches
x	instantaneous displacement, inches
ẋ	dx/dt, velocity, inches per second