dynamic instrumentation

PIEZORESISTIVE STRAIN GAGE ACCELEROMETERS INCREASE SPECTRUM OF SHOCK AND VIBRATION MEASUREMENT CAPABILITY

TP 230

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ABSTRACT

The general acceptance of piezoresistive strain gage transducers, in particular accelerometers, suggests a look at the place of these accelerometers in the "period-of-interest" spectrum of shock and vibration measurement. This "period-of-interest" spectrum concerns the measurement of constant acceleration with superimposed high frequency vibration or long duration shock pulses. The spectrum is defined and used to compare three types of shock measuring transducers: wire wound strain gage, piezoelectric, and piezoresistive strain gage. A typical piezoresistive strain gage accelerometer is examined in detail for application, performance and user test results. A brief examination of possible future expansion of the spectrum concludes the presentation.

INTRODUCTION

A recent review of instrumentation handbooks revealed one volume on engineering measurements, vintage 1948[1], which, while revealing a wealth of information on the measurement of time, temperature, pressure, etc., was devoid of any reference to devices for the direct measurement of displacement, velocity or acceleration. While the development of the mathematical theory for analyzing shock pulses began to solidify in the early nineteen forties, it wasn't until after World War II that instrumentation to measure these shock effects began to appear. Some of these devices were developed for the transportation industry; for example, to monitor cargo shocks in trucks, railroad cars and aircraft. Most of the postwar development seems to have been brought on by the need for blast shock measurements on ships structures, aircraft buffeting and landing shocks, and other use or abuse loads to the new weapon systems. Each new requirement brought about a need for higher natural frequencies, greater sensitivities, and higher ranges.

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[1] H. Diederichs and W. C. Andrae, Experimental Mechanical Engineering Vol. I, Engineering Instruments, John Wiley & Sons.

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The most recent development in this line is the piezoresistive strain gage accelerometer. The advent of piezoresistive strain gages, with their inherently high gage factors (eighty to one - hundred times that of the conventional wire wound gages) has allowed the design of accelerometers with high sensitivities, high natural frequencies and low frequency response down to DC. Strain elements such as these have brought about a minor revolution in the measurement of pressure, force, acceleration, displacement and temperature.

Piezoresistive strain gage accelerometers have been under development since about 1960. The following presentation will examine one specific design, discuss its place in the "period-of-interest" spectrum and the future expansion of the spectrum through design improvements.

BRIEF HISTORY

The original need for inertial or displacement information was handled by the sensing elements available to the designer. The potentiometer, the linear variable differential transformer and the magnetic pickoff were all quite suitable for the steady state and low frequency test and control instruments specified at that time. The allowance for shock response in structures was usually handled by theoretical means such as proposed by Frankland[a] in the forties. As both the structures and their environments became more complex and severe, three major fields advanced along with the requirements. These were static and flight load determinations utilizing strain gages, environmental testing as a necessary requirement, and solid-state physics. The first brought about a vast understanding of strain measurement and strain gages, possibly due to the amazing number of test points per aircraft and number of aircraft tested. The second brought about the development of shaker type test equipment and the auxiliary monitoring equipment necessary to control and monitor them. These resulted in today's piezoelectric accelerometers and inductive velocity sensors. The third resulted in a spin-off, namely the definition of the piezoresistive effect present in many of the new electronic materials.

The first two devices to emerge were the wire wound strain gage accelerometer and the piezoelectric accelerometer. The first device had two of the essential elements, the ability to sense steady state conditions and infinite resolution. The second device was also capable of infinite resolution and, because of the nature of its construction, high natural frequencies and high signal levels. These devices had several weaknesses too. The wire wound strain gage devices, due to their relatively large displacements, had low natural frequencies and correspondingly low frequency response even with reasonable damping. The piezoelectric accelerometer, although capable of generating essentially steady state signals, were required to operate into signal conditioning equipment with low frequency rolloff to filter out extraneous thermal effects.

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[a] J. M. Frankland, "Effects of Impact on Simple Elastic Structures", Experimental Stress Analysis, 1947 (approximate).

The use of the semiconductor strain gage, with its gage factor one to two orders of magnitude greater than that of the wire or foil gages, allowed the design of an accelerometer combining the desirable features of both devices and eliminating many of the undesirable ones.

PERFORMANCE

Obviously, the solid-state strain gage accelerometer has not eliminated the need for all other accelerometers any more than the equivalent pressure transducer has affected the alternative designs of that discipline. Therefore, a means to examine the place of these instruments as tools in the measurement of transient acceleration, was needed.

The three parameters considered to be most important for such measurements were: (1) Sensitivity, (2) High Frequency Response, and (3) Low Frequency Response. The sensitivities of various devices can be looked at directly. No weighting of the sensitivity figure of any accelerometer is necessary, as few, if any, transducers in existence today are blessed with too much signal. High frequency response, although becoming increasingly harder to obtain, is also essentially a linear improvement. A unit which is "flat" to 2000 Hz is essentially twice as "good" as a device which is "flat" to 1000 Hz. Thus, no adjustment of this fiture is necessary either. The use of damping to extend the response of any of these devices is taken into account and the use of ±5% response error is used to define "flatness." (The use of a lower figure such as ±2% does not affect the relative merit of any one design to another.) The last parameter to be examined is the low frequency capability of these devices. The low frequency rolloff of all devices is also considered to be ±5%. This limit is taken for the signal conditioning equipment used with piezoelectrics, and is required to remove extraneous signals such as pyroelectric effects. As both strain gage accelerometer designs have low frequency response to zero Hz (steady state or direct current) the use of zero (frequency response) or infinity (period) would rapidly eliminate the utility of any comparison to the piezoelectric accelerometers. It was decided to use an algebraic expression which approached some finite limit asymptotically to compare low frequency response. The relation used is:

$$\text{L.F.R.} = \frac{T}{10 + T}$$

where: T = period (in seconds) of lowest frequency response and 10 a relatively weighted constant.

The limit of the expression is 1 when T approaches infinity.

Thus, the resulting figure of merit for measuring shock pulses becomes:

$$Fm = S \times (H.F.R.) \times (L.F.R.)$$

where: S = Full Scale Sensitivity

H.F.R. = Limit of high frequency response (±5% amplitude distortion)

L.F.R. = Adjusted figure for low frequency response

The advertised or catalog sheet performance of approximately sixty (60) accelerometers were examined as a typical sample. (A problem existed here of too much data rather than not enough, so a certain amount of selectivity exists.) The plotted curves represent the maximum performance of each type of transducer, lower figures of merit exist for each are due undoubtedly to the influence of some other design restraint. The figures of merit (Fm) are plotted against the full scale acceleration range noted by the manufacturer.

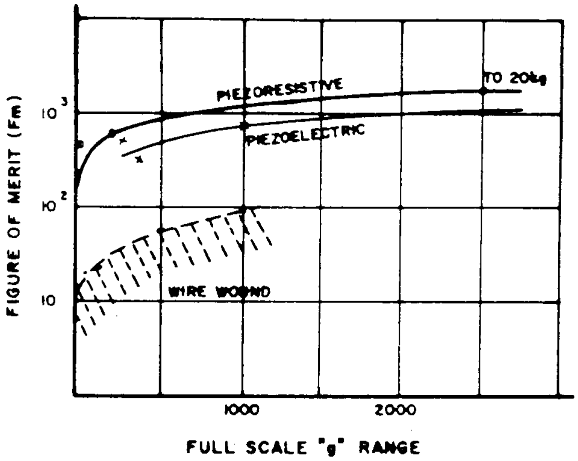

FIGURE 1.

PERIOD-OF-INTEREST, TYPICAL ACCELEROMETERS

The wire wound strain gage transducers can be seen to have excellent low acceleration utility along with their steady state capability. Two envelopes are noted. The maximum one being the result of optimum damping, the minimum one allowing for a maximum excursion in damping due to temperature effects. The piezoelectric and piezoresistive transducers being essentially undamped (less than 0.05 of critical damping) are not affected by viscosity changes.

The piezoresistive and piezoelectric transducers reflect approximately equal performance except in three areas: (1) Maximum accelerations, (2) Minimum acceleration, and (3) the ability to measure long duration shock pulses.

To indicate the restrictions necessary when examining accelerometer performance reference is made to an article by L. B. Wilner in The Review of Scientific Instruments, "Sensitivity Comparison of Transduction Mechanisms"[3] where, using the energy methods of Stein, comparison of the measurement of steady state harmonic input signals, it is deduced that the transition frequency from the most sensitive strain gages to the most sensitive piezoelectric is in the 1000 Hz range.

The piezoresistive strain gage accelerometer has a wide application and requires no new technology on the part of the using agency. The device utilizes the Wheatstone bridge requiring the selection of power supply and recording equipment only on the basis of the input parameters. These units are operating at reasonable strain levels (500 to 1000 microinches per inch) and can withstand overloads on the order of three times full scale. The use of sensing elements with gage factors on the order of 120 to 200, result in designs combining high sensitivities with high natural frequency.

A unit for use in long duration, high shock pulse measurement is ENDEVCO® Model 2261 shown in Figure 2.

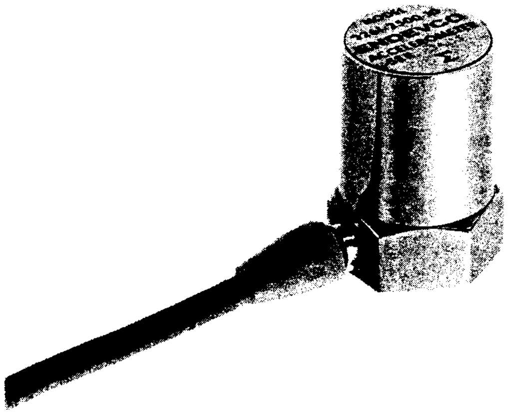

FIGURE 2.

PIEZORESISTIVE STRAIN GAGE ACCELEROMETER

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[3] L. B. Wilner, "Sensitivity Comparison of Transduction Mechanisms", The Review of Scientific Instruments, Vol. 36, No. 5, pp. 693-695, May 1965.

This unit has a specified range of 2500 g's and a full scale sensitivity of 250 millivolts (at 10 volts DC excitation) and a natural frequency of 30,000 Hz nominal allowing it to operate "flat" to above 6000 Hz.

To better indicate the performance of piezoresistive strain gage accelerometers, the following comparison is made. Consider two accelerometers, each having the same natural frequency, operating under reasonably severe thermal conditions. The following sketch shows the response of each to a long duration pulse with a steep front ramp.

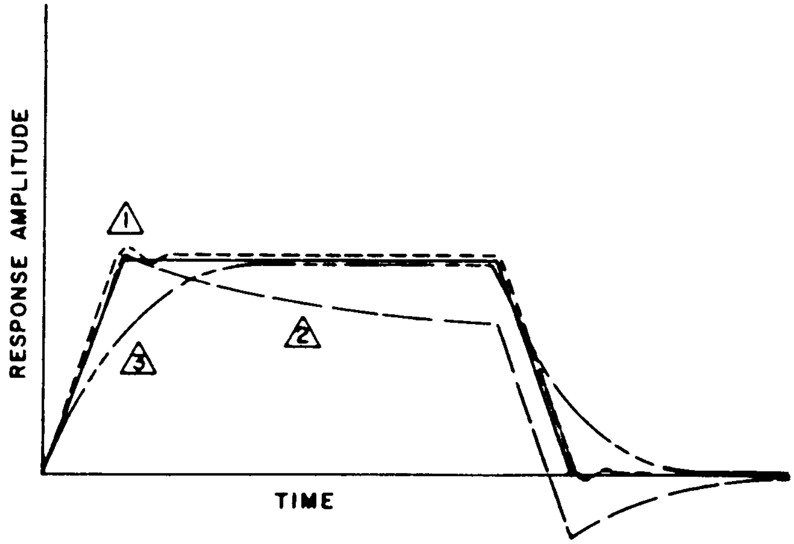

FIGURE 3.[4]

THEORETICAL RESPONSE, TYPICAL ACCELEROMETERS

Input: an idealized ramp function of long duration. Curve 1 depicts the theoretical response of a piezoresistive accelerometer with a high resonant frequency. Curve 2 shows the response of a high resonance, underdamped system with inadequate low frequency response. Curve 3 is typical for a 0.6 damped, low resonant frequency, wire wound strain gage accelerometer.

Note that for the initial period of the shock the performance of the instruments is essentially identical but as the long pulse continues the piezoelectric transducer exhibits characteristic droop, due to the low frequency rolloff of the signal conditioning equipment, again when the shock pulse ends, the characteristic undershoot due to the same phenomenon. Also noted is the response of an equivalent strain gage accelerometer with 0.64 of critical damping.

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[4] D. E. Lovelace, "Development and Applications of a Piezoresistive Strain Gage Accelerometer", Journal of Environmental Sciences, p. 16, April 1964.

TYPICAL APPLICATIONS

Recently the 2500 g range piezoresistive strain gage accelerometer has been used for some rather severe applications. Some of these are:

(1) To record the impact shock profile of a projectile in order to determine consistency of surface penetrated.

(2) Flight test data on high performance missiles having severe natural environments. Determination of boost separation shock loads superimposed on high, thrust induced, steady state accelerations.

(3) Extraction and impact shock data for airborne drop tests. The continuous recording of acceleration and shock phenomena on air-dropped or high speed ground extraction of pallet mounted cargoes.

(4) Ground test recording of shock and vibration on high performance rocket motors. (In one instance, this included the extraction of data from a spinning motor case through slip rings.)

(5) Monitoring test parameters on large hydraulic shakers, with low output impedance for use with computerized data analysis, at very low frequencies.

(6) Non-military applications such as collision shocks in automotive safety testing and design load verification for a jack-hammer.

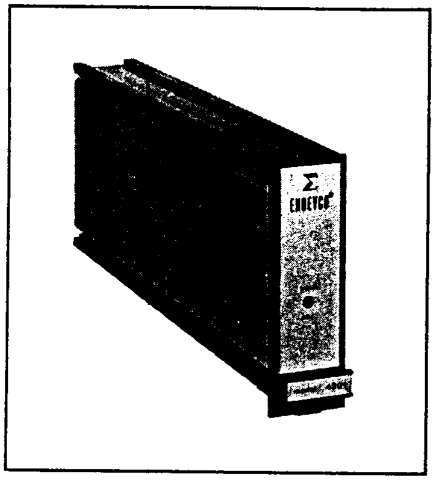
FUTURE EXPANSION

The available configurations of piezoresistive strain gage accelerometers are by no means complete. The spectrum of testing capability needs to be expanded further. There is a need for expansion of the ranges available. Low ranges are necessary for inertial data and higher ranges are available for external shock testing; for example, close in data on explosions. Eventually these units should be available, in approximately the same envelope with higher signal levels (0 - 5 volts perhaps) and capable of operating from relatively raw power supplies.

CONCLUSION

No new instrumentation concept has ever eliminated the need for already existing designs. Transducers utilizing piezoresistive strain gage sensing elements, in particular the accelerometers, have expanded and supplemented the envelope of available information. In the area of shock and vibration this appears to be a reasonable expansion of the envelope in the realm of long pulse duration. As the users' needs expand, so has the suppliers' ability to meet their requirements.

ENDEVCO® MODEL 4201 STRAIN GAGE POWER SUPPLY



Recommended for use with Model 2260 and Model 2261 Accelerometers as well as for other strain gage transducer applications.

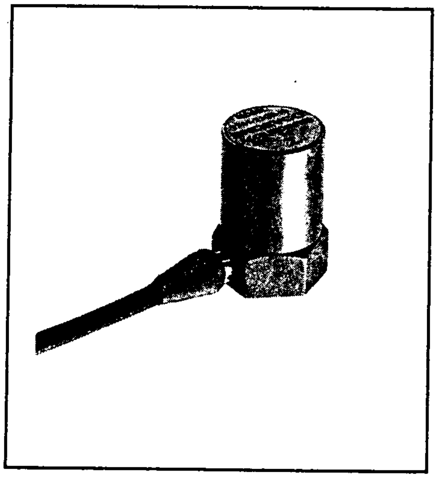
The Model 4201 is a reliable, rugged, all-silicon supply developed specifically for fixed and portable strain gage applications. It produces a 10 VDC output and has a provision for ±0.5 V adjustment. Regulation is specified at 0.25%, and its output impedance is less than 0.05 Ω. Guarded/shielded construction ensures excellent isolation from ground as well as channel to channel isolation. Noise to ground measured over a 10,000 Hz bandwidth with a 350 Ω grounded bridge is only 10 μV pk/pk. The 4201 is short circuit proof *with automatic recovery.* Ten of these units use only 5¼ inches of vertical space in a standard 19-inch rack.

Also available are:

Model 4202 — 30 VDC output with ±1 V adjustment.
Model 4203 — 1 to 15 VDC continuously adjustable.
Model 4204 — 1 to 30 VDC continuously adjustable.
Model 4251 — 200 μA to 25 mA constant current.

For more detailed information about these products write direct to Endevco Corporation.

ENDEVCO® MODEL 2260 & 2261 PIEZORESISTIVE ACCELEROMETERS



Ideal for such applications as:

Long Pulse Shock Studies
Simultaneous Static and Dynamic Acceleration Measurements
Ballistic Studies
Low Frequency Vibration Testing of Large Structures
Centrifuge Testing
Drop Testing

These accelerometers have full bridge sensing elements with four active arms. They are essentially undamped, and exhibit near-zero phase shift over their full rated ranges. Both accelerometers are low impedance devices and produce high-level outputs. This permits direct driving of sensitive galvanometers, low-level VCO's, etc. Endevco conducts 100% testing on these units at three-times full scale output to ensure reliability of operation. Small size and lightweight ensure minimum physical loading of test specimen.

Model 2260 is rated at ±250 g. Its resonant frequency is greater than 12,000 Hz which gives it flat response from 0 to 2000 Hz.

Model 2261 will operate to ±2500 g with response flat from 0 to 6000 Hz. Its resonant frequency is greater than 30,000 Hz.

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