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DEVELOPMENT AND APPLICATION OF A 0.14 gm PIEZOELECTRIC ACCELEROMETER

Howard C. Epstein

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Development and Application of a 0.14 gm Piezoelectric Accelerometer *

HOWARD C. EPSTEIN †

Endevco-Dynamic Instrument Division
Pasadena, California

When does the mass and/or size of an accelerometer affect test results?

Ideally an accelerometer has zero size and zero mass, but in actuality the mass of the unit does load the test structure. Simply pushing on a test location with a finger can sometimes help "get a feel" of the structure's local compliance. This rough estimate of the compliance can be useful in assessing at what frequency test errors result from the weight of the accelerometer.

A piezoelectric accelerometer generates its signal by taking mechanical energy from the test specimen and converting some of that energy into an electrical output. In attempting to attain high sensitivity, high resonance frequency, and a low transducer mass—all desirable qualities—one is limited by the efficiency of the conversion of mechanical energy into electrical energy.

A commercial 0.14 g piezoelectric accelerometer has been developed with a resonance frequency of 54 kHz and a charge sensitivity of 0.5 pC/g. The transducer benefited from increased transduction efficiency at the cost of increased stress levels in the sensor.

INTRODUCTION: ACCELEROMETER WEIGHT WATCHING

Current applications for accelerometers include uses where the mass of the transducer causes test errors. Scale model testing, dynamic response analysis of small electromechanical devices, and vibration ruggedness evaluations of integrated circuits are typical of situations that require minimal weight accelerometers.

A B-1 Bomber Flutter Model is shown being tested in Figure 1. Its Subsonic Spoiler Panel, shown in Figure 2, is instrumented with a 0.14 g accelerometer. The dynamics engineer in charge of the test rejected using an available 0.5 g accelerometer because it would have affected the resonance frequency of the 1.5 g test specimen.[1]

A vibration test fixture used for environmental testing of integrated circuits is shown in Figure 3. The size of the accelerometer allows it to be potted adjacent to the microcomponents that are being evaluated. With a larger accelerometer the vibration could not be monitored at the real point of interest.

Electromechanical devices such as valves, relays, and traveling magnetic recording heads generally have response characteristics that are determined by spring-loaded masses. An accelerometer on such a "masslike" part will raise the device's response time unless the accelerometer weighs only a small fraction of that mass.

The effective mass at a test location on a panel, shell or other distributed structural member may not be readily known. At such a point the effective mass is a function of frequency and will diminish greatly if the location participates in a resonant motion.

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† Physicist.

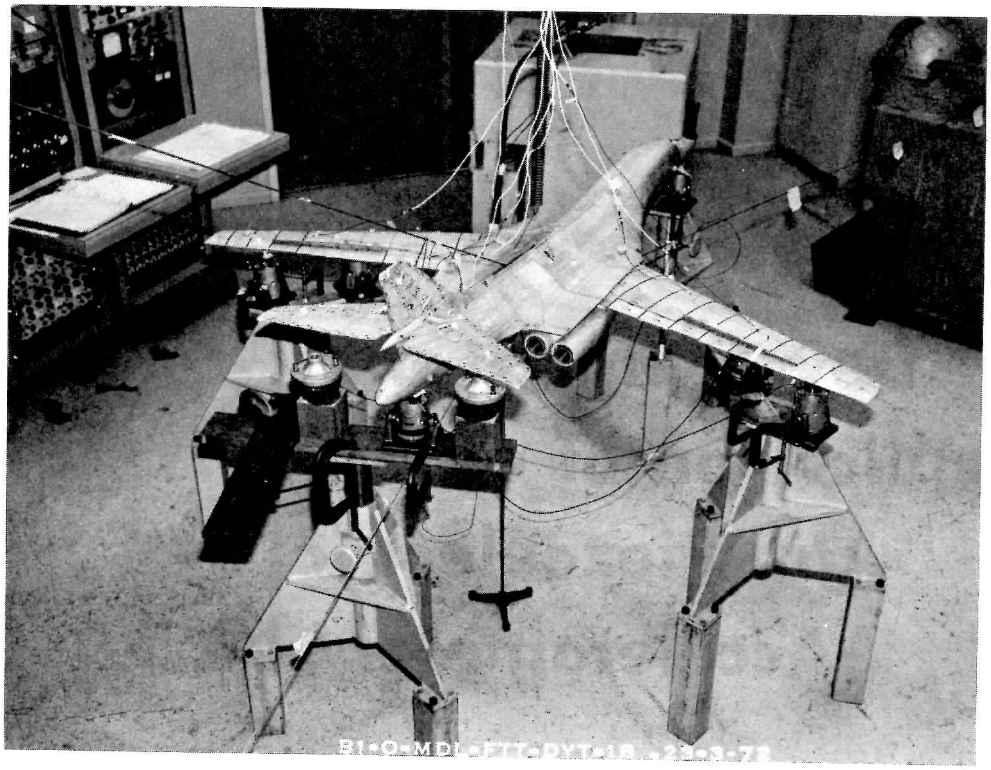


Figure 1. Testing of a B-1 Bomber flutter model, with mounted accelerometers monitoring resonances excited by acoustic drivers. (Photo courtesy of North American Aviation, Los Angeles Division.)

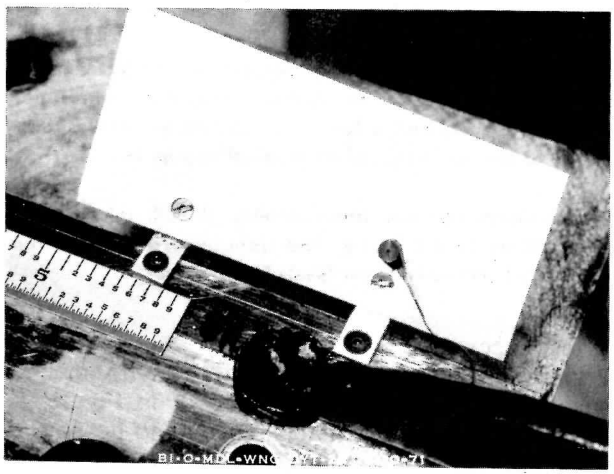
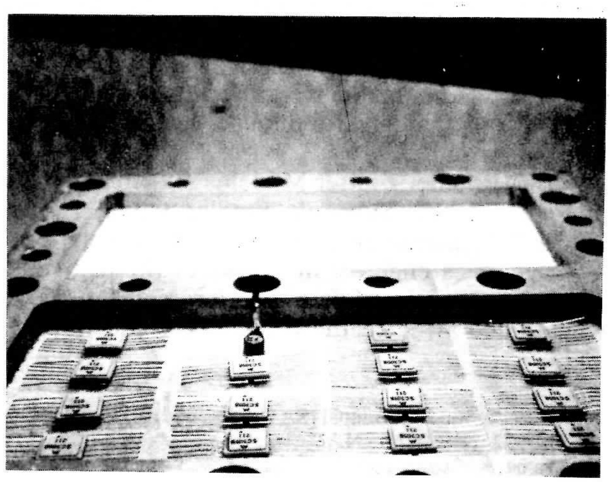


Figure 2. Subsonic spoiler panel from B-1 bomber flutter model instrumented with a 0.14 g accelerometer. A 0.5 g accelerometer would measurably change the resonance frequencies of the 1.5 g specimen. (Photo courtesy of North American Aviation, Los Angeles Division.)

Figure 3. Accelerometer shown fits in test cavity ensuring that vibration monitored is same as seen by integrated circuits being tested. (Photo courtesy of Motorola Semiconductor Inc., Phoenix.)



The added mass of an accelerometer on a resonant position can effect drastic changes in the magnitude of the motion and shift the frequency of the resonance. Also, the stiffness of an accelerometer may produce a node where there ought to be motion.

The compliance of a cantilevered member increases as the third power of its length. Because of this fact, the mass of an accelerometer often induces new bending resonances in a structure. These new resonances not only produce inaccurate information about the test location, but they also distort the motion of other areas.

In short, real accelerometers are not ideal, but rather, can measurably burden the motion of their hosts.

RULE OF THUMB—WHEN IS AN ACCELEROMETER TOO HEAVY?

On a complicated structure it is oftentimes more practical to rely on experience and intuition that on calculation to determine the effect of the added weight of an accelerometer. The rule of thumb outlined below may aid in getting a feel for such a test situation. The rule assumes that the presence of the accelerometer on the distributed structural compliance produces a new resonance.

For minimal effect, the frequency of this resonance should be more than 3 times the maximum frequency of interest. This new resonance frequency is determined by the relation $\omega = (1/mc)^{1/2}$, where ω is the resonance frequency (in radians/sec), m is the mass of the accelerometer, and c is the test structure's static compliance at the accelerometer mounting point. The test estimates the magnitude of the compliance by a push on the test location with a finger. The author's "calibrated index finger" is uncomfortable with a 10 second push of more than about 4 kg (9 lb). The same author can "feel" motions of 10^{-4} m (0.004 in.). Thus, if one pushes firmly on a test point and feels it barely move, then the compliance is at least

$$\frac{10^{-4}\text{ m}}{4\text{ ``kg-force''}} = 2.5 \times 10^{-6}\,\frac{\text{m}}{\text{N}}$$

The rule of thumb is:

To determine maximum accelerometer weight:
(1) Push firmly on the test location with the index finger.
(2) If you can just "feel" the structure move—then,

(3) The accelerometer should weigh less than:	If the maximum frequency of interest is:
10 g	330 Hz
1 g	1000 Hz
0.1 g	3300 Hz

If it is important to predict the frequency where measurement error results with an accuracy of better than ±1 octave, then it is recommended that the above rule be refined by making more accurate measurements of applied force and displacement.

DEMONSTRATIVE TEST

A demonstrative test was conducted which seemed to verify the validity of the above rule of thumb. An ENDEVCO Model 22 Accelerometer (0.2 g with connector plus cable) was mounted on a violin top plate. The plate was attached to the shaker of a frequency response console. The top trace of Figure 4 is a log plot of the response of the accelerometer on the violin plate as compared to a standard accelerometer in the shaker. Three different weight accelerometers were then mounted in turn adjacent to the original accelerometer. The outputs from the new accelerometers were not monitored, but were used to see how the response of the first accelerometer changed in their presence. The bottom three traces of Figure 4 show the responses under the influence of a neighboring 0.2 g accelerometer, of a 1 g accelerometer, and of a 3 g accelerometer. (The above weights include cables.) Figure 5 shows the violin plate with the 3 g accelerometer next to the original 0.2 g transducer.

Comparing Trace 1 of Figure 4 to Trace 2, one finds that the addition of the 0.2 g accelerometer did not change the response significantly. However, the blocked off sections of Figure 4 indicate there were very significant changes in the response above 1000 Hz when the 1 g accelerometer was present. There were large differences at frequencies higher than 500 Hz when the 3 g accelerometer was present.

By interpolation, our rule of thumb had predicted that the 3 g accelerometer would distort the response beyond 600 Hz, the 1 g accelerometer beyond 1000 Hz, and the 0.2 g accelerometer beyond 2300 Hz. The actual responses were within the ±1 octave accuracy range of the rule.

ENERGY LIMITED TRADEOFFS OF PIEZOELECTRIC ACCELEROMETERS

Why not make a lighter accelerometer by just taking a good accelerometer and making it smaller?

The reason is that fabricating diminutive parts is not the only barrier to producing a lightweight accelerometer. If an accelerometer is subjected to a scale size reduction, the sensitivity decreases as the third power of the reduction, while the resonance frequency increases linearly. The relationship between a piezoelectric accelerometer's resonance frequency, charge sensitivity, voltage sensitivity and mass revolves around the transducer's efficiency in converting mechanical energy to electrical energy.

The portion of mechanical potential energy in a piezoelectric material that's available as electrical energy is an intrinsic crystal property defined as k^2.

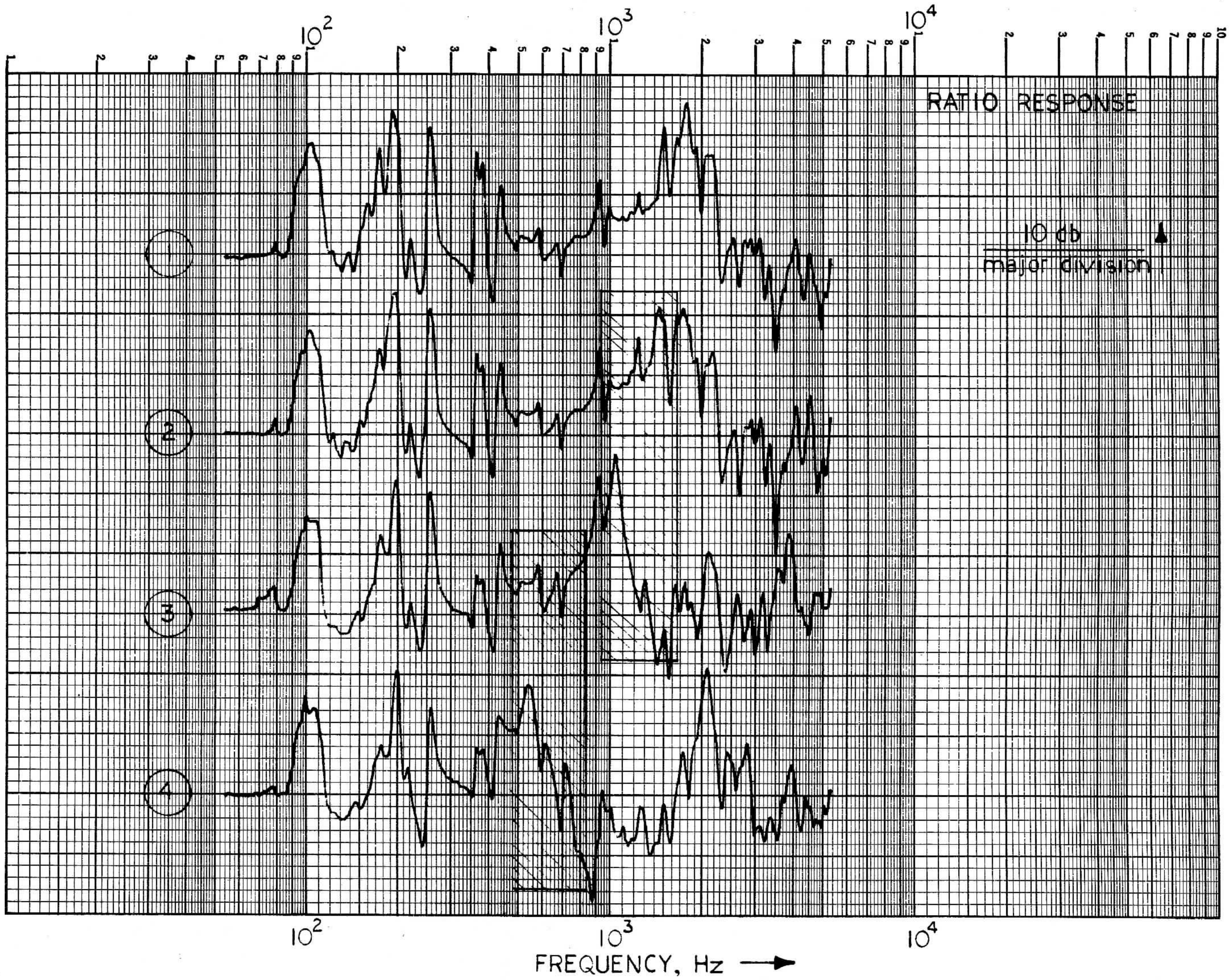


Figure 4. Effect of mass loading of accelerometers on motion of violin top plate shown in Figure 5. Trace 1 is log response (10 dB per major division) of 0.14 g (0.2 g with cable), accelerometers mounted on plate relative to standard in shaker; traces 2, 3 and 4 show respective responses of same 0.14 g unit under influence of neighboring 0.2 g, 1 g, and 3 g accelerometers. Boxed areas show onset of major differences between "true" motion of trace 1 and traces 3 and 4.

k is known as the "electromechanical coupling constant." The electrical energy E_e stored in this piezoelectric capacitor is the product of half the charge Q times the voltage V.

The potential energy E_m stored in a spring (our piezoelectric crystal) is $1/2\, F^2/y$, where y is the spring constant. $F = ma$ is the force. If we recognize y/m as the square of the resonance frequency (in radians/sec), we have

$$E_m = 1/2 \frac{m^2 a^2}{y} = 1/2 \frac{ma^2}{(2\pi F_n)^2}$$

where F_n is the resonance frequency in Hz. Not all of this energy actually gets to the crystal. Let G define the fraction of the transducer's mechanical energy that is in the crystal. The fraction E_e/GE_m is equal to k^2, the ratio of electrical energy to mechanical energy in the crystal.

Then,

$$Gk^2 = E_e/E_m = \frac{QV}{\frac{ma^2}{(2\pi F_n)^2}}$$

$$S_q = \frac{Q}{a} = \text{charge sensitivity}$$

$$S_v = \frac{V}{a} = \text{voltage sensitivity}$$

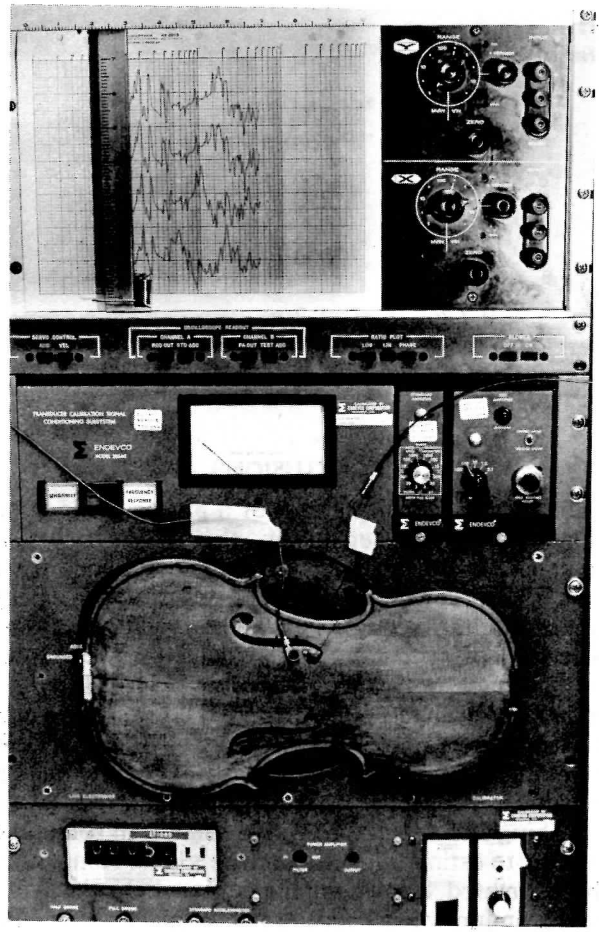


Figure 5. Shaker activated violin top plate, showing 3 g accelerometer (trace 4, Figure 4) mounted at left of test 0.14 accelerometer.

Hence,

$$\underbrace{G}_{\text{transducer efficiency}} \quad \underbrace{k^2}_{\text{crystal efficiency}} = \underbrace{\frac{S_q S_v (2\pi F_n)^2}{m}}_{\text{accelerometer performance desirables}} \qquad (1)$$

The right side of expression (1) is the mathematical product of desirable accelerometer performance parameters, namely, sensitivity, resonance frequency, and reciprocal mass (i.e., small mass). Given a crystal material and a transducer effiency, the desired parameters can only be increased at the expense of each other—hardly a surprising result. Since k^2 is fixed by nature, the transducer efficiency (always <1) is the only place to make an overall gain.

There are basically two drains on transducer efficiency. The first is due to the accelerometer having weighty components (connector, cover, base, etc). that do not contribute to signal output. The second is due to compliances other than the sensor being in mechanical series with the "working mass" and the mounting surface. The amount of energy stored in a spring that is subjected to a given force is proportional to its compliance. Hence, any compliance not in the sensor represents an energy loss. Generally, the greatest portion of the total compliance is not in the sensor, because the sensing crystal is stiff and it is purposely isolated from the mounting surface in order to diminish base strain sensitivity.

DESIGN APPROACH FOR 0.14 g ACCELEROMETER

The 0.14 g accelerometer mentioned in the test above resulted from a two-year program to make a threefold size reduction in accelerometers. In view of the basic tradeoffs we have just discussed, the program took the approach of increasing the energy efficiency.

We chose a crystal material with one of the highest known electromechanical coupling constants, ENDEVCO PIEZITE P-8, a modified Pb (Zr Ti) O_3 ceramic; $k^2 = 0.4$. Sixty percent of the transducer's mass was made into "working mass."

Typically, the portion of an accelerometer's mass that puts stress on the crystal is 30%. The gain in working mass was made largely by reducing the terminating area of the electrical cable. The crystal compliance was reduced relative to other compliances.

Below, we list the key performance parameters of the resultant transducer:

Total transducer mass	m	=	0.14 g
Resonance frequency	F_n	=	54 kHz
Charge sensitivity	S_q	=	0.5 pC/g
Voltage sensitivity	S_v	=	2.5 mV/g

From Equation (1),

$$\frac{S_q\, S_v\, (2\pi F_n)^2}{m} = Gk^2 = 0.01$$

$$k^2 = 0.4$$

so

G = energy coupling efficiency of transducer
= 2.5%

The accelerometer which was designed to have high energy efficiency transmits only 2.5% of the available energy to the sensor. Is this result shockingly low? No. We compare this value with the coupling efficiencies of other accelerometers that are widely used for low mass applications.

ENDEVCO Model 2222B (0.5 g): G = 1%

ENDEVCO Model 2226C (2.3 g): G = 0.3%

0.14 g accelerometer

(ENDEVCO Model 22 "Picomin"): G = 2.5%

Accelerometers (same crystal material)

Property	Model 2226C	Model 22 "Picomin"
Amplitude linearity (g level of 1% rise in sensitivity)	500 g	250 g
Zero shift (g level where 2% zero shift is probable)	4000 g	2000 g
Strain sensitivity (equivalent output at 250 microstrains per ISA RP 37.2 [1964])	0.7 g	2 g

The cost of the 0.14 g accelerometer's high efficiency can be surmised from the above table:

High efficiency was bought by increasing sensor stress levels. The consequence was a narrower dynamic range. The 0.14 g transducer has more direct coupling between the mounting surface and the sensor. The result was less isolation from base strains. The Model 22 is 8 times more efficient than the Model 2226C, but the latter has one-third the strain sensitivity, twice the amplitude linearity, and twice the zero shift free acceleration range.

The 0.14 g accelerometer required many new fabrication techniques. However, the key development was the cable. The "Picomin" accelerometer necessitated a low mass, compliant coaxial cable that was 100% shielded and free of triboelectric noise. The resultant cable achieves maximum strength in a small diameter by utilizing a solid corrosion resistant steel sheath and center conductor. The diameter is 0.4 mm (0.017 in.), including a TFE jacket. The cable terminates in a coaxial connector that threads into the accelerometer case.

The operational temperature range of the "Picomin" accelerometer is −73° C −100° F) to +204° C +400° F). In order to prevent ground loops, the case is electrically isolated from signal ground. The transducer can see 10 000 g acceleration without being damaged.

CONCLUSIONS

The mathematical product of a piezoelectric accelerometer's voltage sensitivity, charge sensitivity and the square of its resonance frequency divided by its mass is a direct measure of the transducer's energy conversion efficiency. The above relation outlines basic tradeoffs inherent in piezoelectric accelerometers. A high resonance frequency (54 kHz), wide temperature range (−73° C to 204° C), and low mass (0.14 g) accelerometer was successfully developed by achieving a more efficient energy conversion. The transducer's sensor uses relatively high stress levels.

Pushing a test structure with a finger can sometimes be an aid to estimating the structure's local compliance. The estimated local compliance can help determine the maximum weight accelerometer mass allowable.

ACKNOWLEDGMENT

G. E. Gilbertson played a key role in developing the ENDEVCO Model 22 accelerometer's connector features and fabrication techniques.

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1. E. H. Hooper. Personal correspondence. North American Aviation, Los Angeles Division, North American Rockwell.