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A CAPACITIVE ACCELEROMETER SUITABLE FOR TELEMETRY

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16. Abstract

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Although the present design of the capacitive accelerometer was optimized by using units of 0.635 cm diameter, construction of experimental accelerometers as small as 0.36 cm (0.14 in.) diameter has demonstrated the feasibility of further miniaturization.

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SUMMARY

This report presents the design and development of a miniature 0.635 cm (0.25 in.) diameter capacitive accelerometer for use in free-flight wind-tunnel telemetry. Instruments with full-scale ranges from ± 1 to ± 200 g were constructed, calibrated, and used in several wind-tunnel telemetry projects. Flat, high-frequency response from 0 to 1000 Hz or more was obtained by employing the inherent damping and stiffness in the air film surrounding the diaphragm-type spring that supports the inertial mass of the accelerometer. Design features to achieve minimum off-axis sensitivity and temperature stability are discussed, and the design requirements for use of the transducer with telemetry systems are derived. A transducer capacitance change of 0.16 pF full scale gave excellent resolution and provided a frequency deviation of 0.75 MHz for a 100 MHz FM oscillator.

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INTRODUCTION

The conventional method of determining the aerodynamic forces and moments acting on free-flying models is an indirect approach utilizing photography. The attitude and position of the body are determined as a function of time from each frame of film. The governing equations of motion are then used to infer the aerodynamic coefficients from these histories. Since this approach requires either assuming the form of the coefficients, or differentiating the data, the advantage of directly measuring the forces and moments is apparent. It was for this purpose that the Ames capacitive accelerometer was developed. Reference 1 describes tunnel tests on free-flight models containing accelerometers of this type, which provided four simultaneously recorded channels of data. Reference 2 contains a detailed analysis of the requirements for an accelerometer telemetry system when complete aerodynamic coefficients describing the flight are to be obtained.

ADVANTAGES OF CAPACITIVE TRANSDUCERS

Successful telemetry of pressure data from free-flight wind-tunnel models using Ames capacitive transducers had already been reported in references 3 and 4, and it was felt that a highly accurate capacitive accelerometer for free-flight telemetry application could be designed on the basis of experience gained from pressure cell design. However, other types of accelerometers were also carefully considered for proposed tunnel telemetry projects. Capacitive accelerometers were chosen because they appeared to have the following advantages over other transducers, especially for application to free-flight instruments: (1) Capacitive accelerometers respond to steady accelerations, whereas piezoelectric transducers will not operate below a certain minimum frequency. The accurate response at zero frequency of capacitive accelerometers simplifies the calibration procedure – a 2 g reference check against Earth's gravity can be made simply by taking output readings at 0° and 180° accelerometer positions. In some tunnel free-flight tests, very low frequency model oscillations were anticipated, and the uniform response of the capacitive accelerometer at very low frequencies improved the accuracy of the data. (2) A capacitive transducer may be used in the tank circuit of a high frequency L-C oscillator, whereas the use of the piezoelectric transducer for such an application requires a high-impedance input circuit with its associated noise pickup and humidity problems. (3) Capacitive accelerometers can serve the dual function of transducer and capacitive element in an L-C tank circuit of a telemetry oscillator. In this manner, the frequency modulation of the transmitted signal can be obtained without intermediate electronic stages and with few parts. Strain gages cannot function this way, and while inductance gages can, problems encountered with magnetic-core losses make them difficult to design for use at high telemetry frequencies (such as the standard FM band). (4) In the capacitive transducer, heat dissipation is not involved as it is with strain gages; thus the drain on the miniature battery used in the telemetry transmitter is minimized. (5) Experience with the hermetic seal-type capacitive pressure transducers had shown that high accuracy and temperature stability could be obtained with capacitive units without time-consuming temperature compensation procedures. (6) The capacitive transducers can be of simple, sturdy design. No glues, coils, fine wired, or easily fractured beams or parts are required.

ACCELEROMETER DESIGN AND CONSTRUCTION CONSIDERATIONS

Before the transducer shown in figure 1 is described, some of the requirements for high-performance accelerometers and how they were achieved will be discussed. (The performance characteristics of the accelerometer are listed in table 1.)

High repeatability and low hysteresis of the spring system are achieved by pretensioning and welding the diaphragm.

Low cross-axis sensitivity ($<$ 1 percent) and low rotational sensitivity are obtained by (a) supporting the mass on a circular diaphragm rather than on a cantilever beam, (b) supporting the mass symmetrically above and below the diaphragm, and (c) keeping the dimensions and resultant lever arms for rotational forces small through use of high density materials for the inertial mass.

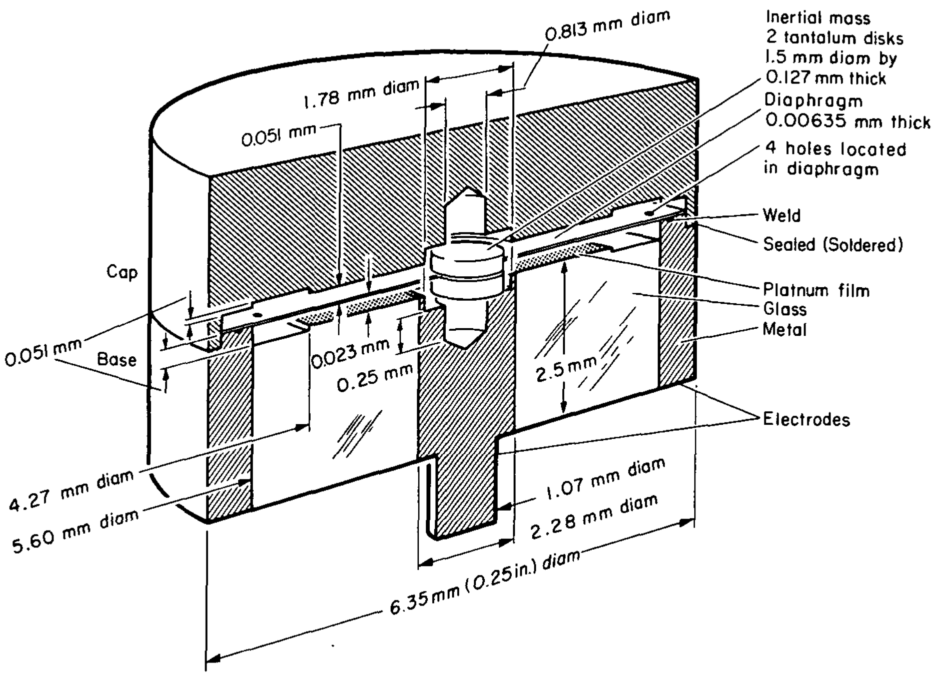

Figure 1. – Ames capacitive accelerometer.

The air damping and stiffness in the air film surrounding the diaphragm are employed to obtain a flat frequency response and will be discussed later.

Temperature stability is a major problem for most transducers, and capacitive transducers have had an unfavorable reputation in this respect. However, capacitive transducers can be designed with superior temperature characteristics. Two important principles for temperature stability design of transducers are that (1) whenever possible, all moving parts and their supports should be made from inorganic materials that have a low temperature coefficient of expansion, and (2) when two or more parts of a transducer requiring stability are to be assembled, they should be either welded, if metal, or fused if made of glass or ceramic and metal parts. These criteria are especially important when high frequency response, capacitive transducers are involved, since the maximum deflections to be measured are about 30μ in. (e.g., in 0.635 cm (0.25 in.) diameter instruments) and motions of 0.1μ in. are to be detected. Deflections much larger than these can be produced in poorly designed transducers by temperature and extraneous mechanical forces.

The temperature coefficients for the 0.635-cm. diameter instrument described here are conservatively rated at 0.02 percent and 0.05 percent full scale/°C for sensitivity change and zero shift, respectively. The temperature stability of the transducer is better than that of most transistor telemeters with which it has been used; however, full advantage of the transducer stability can be realized when the accelerometer is used with a hard-wire carrier current system. The stated temperature effects apply to an accelerometer in which full-scale diaphragm deflection is limited to 2 percent of the electrode spacing. The limitation in deflection is to achieve a low nonlinearity figure of 1 percent of full scale. If larger deflections for full scale are used and the resulting nonlinearity is electrically compensated, then temperature effects can be reduced even further – in proportion to the increased deflection used for full scale.

Accelerometer Construction

The accelerometer (fig. 1) has two major parts, (1) the base on which all of the working parts are secured, and (2) the cap, acting as an air-tight cover, which is sealed onto the base. Construction of the base is started using a commercially available (Hermetic Seal Corp., Rosemead, Calif.) glass-metal, single-terminal feedthrough or hermetic seal (figure 2). The fusion of the insulator and metal parts has already been performed by the hermetic seal manufacturer, and a minimum of machine work is required to make the instrument. The upper part of the center conductor is cut off. The glass and center conductor are machined to the shape shown in figure 1 and the central portion of the glass is painted with a platinum compound (Hanovia 05 Platinum Bright) which, after being fired at 1100° F, forms a firmly adhering coat of platinum making contact to the central conductor. The platinum film and central conductor constitute the stationary plate of the variable capacitor. The other plate of the capacitor, the variable one, is made as follows. A 0.000635 cm thick sheet of 48 percent NiFe foil (0.00025-in.) is clamped and stretched to a predetermined tension in a diaphragm stretcher (figure 3). (To determine the tension, a function of diaphragm resonant frequency, the foil in its stretcher is placed on the frustum of a cone above a radio-speaker driver which is excited by a variable frequency oscillator. A capacitive, or a magnetized-core inductive pickup measures vibration amplitude of the stretched diaphragm.)

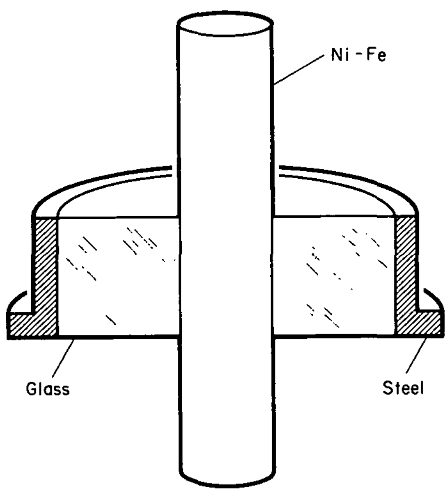

Figure 2. – Glass-metal seal.

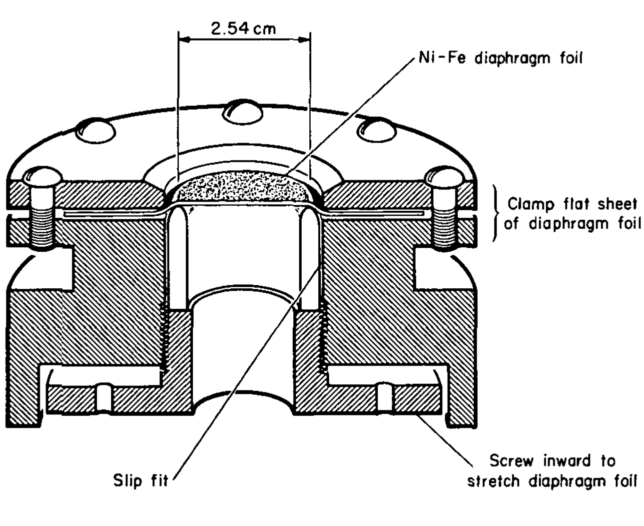

Figure 3. – Diaphragm tensioner.

A special jig is used to weld two tantalum disks (0.0127 cm (0.005 in.) thick by 0.1570 cm (0.062 in.) diam.) to opposite sides of the foil while it is in the stretcher. The foil is then placed over the base half of the transducer and welded to the outer rim of the hermetic seal by a series of overlapping spot-welds. The height of the welding rim above the platinum-coated glass is carefully machined before welding to give the desired sensitivity and air damping. The spacing is about 0.0025 cm (0.001 in.). The final operation is fitting and soldering the machined metal cap on to the base leaving a predetermined air space above the membrane and tantalum disk as described below. Air, at atmospheric pressure, is sealed into the transducer.

This construction provides, in a minimum of space, all the required components of an accelerometer. The high density tantalum disks act as the inertial mass. This inertial mass is supported by the stretched metal membrane which determines the spring constant for the system and provides the restoring force for a deflection produced by an acceleration force. The damping necessary to give a wide, flat frequency response to the accelerometer is provided by the viscosity of the air as it flows through the closely spaced plates into the sump cavities. The cavities are located in the center terminal and cap and in the glass and cap near the periphery of the diaphragm. (Four equally spaced, 0.016 cm (0.006-in.) diam holes punched into the diaphragm near its periphery assure equalization of pressure on the two sides of the diaphragm.) The change in electrical capacitance due to acceleration-produced motions of the mass-membrane with respect to the fixed platinum plate provides the electrical output of the accelerometer.

Several other design features, besides all operational parts being welded or fused together, contribute to the thermal stability of this transducer. The platinum film stationary plate and the diaphragm are supported close to the same place in the accelerometer. With this design, temperature has little effect in changing the spacing between plates compared with designs where the stationary plate is supported far from the diaphragm and where thermal gradients can act unevenly on the respective supports for the diaphragm and stationary plate. To maintain this design, the recess in the glass at its circumference which acts as an air sump, was purposely made shallow to keep the support for the glass close to the welding land for the membrane. This shallow air sump made additional air sumps necessary at the center of the instrument. The relation of air sump design to optimum damping will be discussed later. Another feature contributing to temperature stability is the metal film on the stationary plate. It is so thin that its differential expansion with temperature does not appreciably affect the plate spacing. The capacitance between the tantalum disk and the central electrode contributes to the output capacitance, but the change in thickness of the disk with temperature has been minimized by keeping it thin through the use of tantalum or tungsten, which possess higher densities than most metals. Tantalum was found to be much easier to fabricate and to weld to the diaphragm than tungsten. Finally, the change in sensitivity with temperature was minimized by selecting diaphragm material with a temperature expansion coefficient matching that of the rim of the seal to which the diaphragm was mounted. A diaphragm of nickel-iron alloy of 48 percent nickel matched the expansion of the rim very closely.

DESIGN REQUIREMENTS IMPOSED BY TELEMETRY SYSTEM

Certain specifications for the accelerometer were dictated by the need to match the telemetry system requirements.

1. The 0.635 cm (0.25 in.) size, the same as was used in the past for the telemetry pressure cells, was satisfactory since it is smaller than the largest component used in the telemetry transmitter (the silver-oxide batteries of 0.9525 cm (0.375 in.) diameter).

2. The at-rest electrical capacitance required to tune the oscillator circuit to the 108 MHz center frequency was 7.5 pF. (See figure 4.)

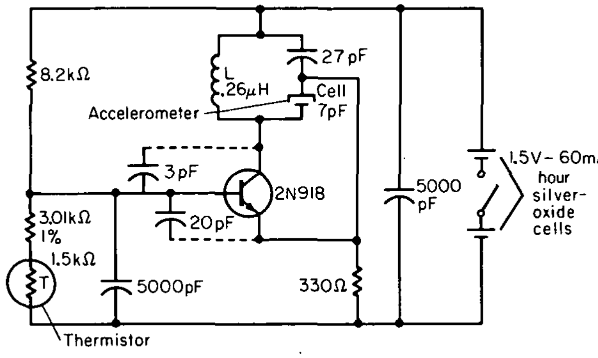

Figure 4. – Telemeter circuit.

3. The full-scale change in accelerometer capacitance required by the FM receiver was ± 0.16 pF. This capacity change produced a frequency variation in the receiver of ± 750 kHz, which was well within the 1 percent nonlinearity limits of the wideband receivers available. (The accelerometers used in reference 1 had full-scale ranges of 5, 20, 50, and 200 g.)

4. The accelerometer frequency response requested for the wind tunnel tests was flat to at least 300 cycles. However, the possibility of future use made it desirable to design the transducers for capabilities of higher frequency response.

With the design shown in figure 1 fixed as to size, only a few parameters were variable to meet the demands for full scale sensitivity as well as flat frequency response to a specific frequency. The spacing, d, between the capacitor plates had to accommodate the requirements for the initial capacitance, C, determining the center frequency of the FM transmitter, and the change in capacitance, ΔC, or frequency deviation for a given full-scale range as well as the damping coefficient, ρ, and air stiffness, k_a. Both ρ and k_a had to be of proper values to obtain flat frequency response, but they were also dependent on r, the radius to an air sump, and the plate spacing. (The area of the Pt film also could be varied over a small range to fix C and ΔC.) The other variable parameters were the mass, m, and the mechanical stiffness of the diaphragm, k_d. The latter could be varied by changing the initial tension or the thickness of the diaphragm.

STATIC DEFLECTION SENSITIVITY

An equation, useful for this accelerometer design, may be simply derived to express the zero and low-frequency sensitivity in terms of the change of deflection Δd, or change of capacitance ΔC, per unit acceleration a/g (or G). Assumptions are made that the spring is a true membrane under initial tension with no bending stress involved, and that the significant mass m is concentrated in the tantalum weight Ta (see figure 5). For a static deflection the restoring force F of the spring membrane equals the acceleration force producing the deflection Δd.

$$F = k\,\Delta d = ma = 2\pi R t\,\sigma \sin\theta$$

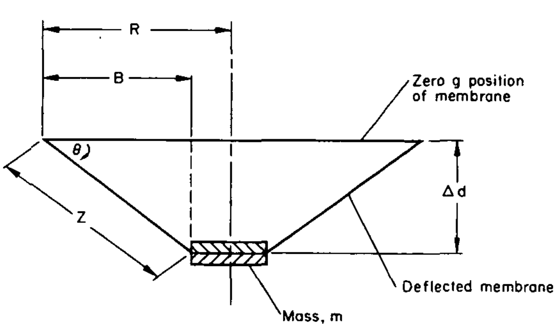

Figure 5. – Geometry of deflected membrane.

where k equals the spring constant, and, where σ equals the stress in the diaphragm of dimension Z and thickness t. In terms of modulus E and strain, where e_o = initial strain and e_d = strain due to Δd,

$$F = k\,\Delta d = ma = 2\pi R t\,E(e_o + e_d)\sin\theta \qquad (1)$$

From figure 5,

$$e_d = \frac{Z - B}{B} = \frac{[B^2 + (\Delta d)^2]^{1/2} - B}{B} \text{ cm/cm strain}$$

$$ma = 2\pi RtE \left(e_o + \frac{[B^2 + (\Delta d)^2]^{1/2} - B}{B} \right) \frac{\Delta d}{[B^2 + (\Delta d)^2]^{1/2}}$$

$(\Delta d)^2$ is neglected as insignificant,

$$ma = \frac{2\pi R}{B} Ee_o t\, \Delta d$$

Dividing by G and solving for $\Delta d/G$ yields

$$\frac{\Delta d}{G} = \frac{mgB}{2\pi REe_o t} \quad \left(\text{also } \frac{\Delta d}{G} = \frac{ma}{k(a/g)} = \frac{mg}{k}\right) \tag{2}$$

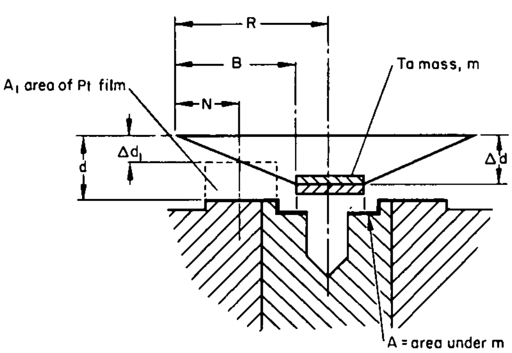

Figure 6 – Geometry of effective capacitive plate areas.

Now the object is to find $\Delta C/G$. The capacitance of membrane and tantalum mass with respect to the stationary plate is composed of two areas and can be expressed as

$$C = 0.0885 \left(\frac{A}{d} + \frac{A_1}{d}\right) pF$$

where, from figure 6, d is the initial spacing from the diaphragm to area A_1, and also the equal initial spacing between the tantalum mass and area A, underlying the tantalum.

The change in C due to Δd and Δd_1, neglecting the sign, is

$$\Delta C = 0.0885 \left(A \frac{\Delta d}{d^2} + A_1 \frac{\Delta d_1}{d^2}\right)$$

From figure 6, substituting $\Delta d\,(N/B)$ for Δd_1,

$$\Delta C = 0.0885 \frac{\Delta d}{d^2} \left(A + A_1 \frac{N}{B}\right) \tag{3}$$

Combining equations (2) and (3) gives

$$\frac{\Delta C}{G} = \frac{0.0885}{d^2}\left(A + A_1 \frac{N}{B}\right)\frac{mgB}{2\pi R E e_o t} \tag{4}$$

Equation (4) can be used directly in establishing the sensitivity of a transducer since e_o, the strain in the membrane tensioning jig, can be determined from the resonant frequency of the membrane in the jig. (There may be a slight change in tension in the membrane after it is welded to the accelerometer rim, depending on the welding technique.) It may be instructive to note from equations (1) and (2) that the static sensitivity $\Delta d/G$ is inversely proportional to the square of the undamped resonance frequency of the accelerometer.

$$\left(\frac{\Delta d}{G}\right) = \frac{ma}{k(a/g)} = \frac{mg}{k} = \frac{g}{4\pi^2 f_o^2} \tag{5}$$

where $f_o = 1/2\pi\sqrt{k/m}$

Ordinarily, in accelerometer design, an attempt is made to maintain this magnitude of sensitivity approximately constant over a frequency range, a fractional value of f_o, by the use of damping. In the Ames accelerometer, the properties of the air film between the diaphragm and backplate provided air stiffness, as well as air damping, which, when combined in the proper proportion, produce higher frequency response than can be obtained from damping alone.

FREQUENCY RESPONSE CONSIDERATIONS

The well-known linear, second-order differential equation describing the one-dimensional motion of a membrane having constant coefficients of m, p, and k, subjected to a driving force $F \cos \omega t$ is

$$m\ddot{x} + \rho\dot{x} + kx = F \cos \omega t \tag{6}$$

where $x = \Delta d$ the deflection. The frequency response for an undamped transducer, $\rho = 0$, is flat within ± 5 percent to only about 0.2 of the natural frequency. With optimum damping of about 0.6 of critical, the frequency response is flat, ± 5 percent, to about 0.8 of the undamped resonant frequency. However, linear optimum damping is difficult to achieve in practical devices.

Using the properties of thin air films makes it possible to manipulate both ρ and $k = k_a + k_d$ in the above equation to give much more control of frequency response (k_a is the air stiffness; k_d is the mechanical, diaphragm stiffness). In this case, ρ and k_a are not constant, but are frequency dependent.

As early as 1918, Crandall (ref. 5) showed how to improve the frequency response of air-damped instruments by incorporating frequency dependent stiffness and damping. Crandall derived the following Bessel equations for ρ and k_a for the case of radial air flow outward to a sump and radially inwardly when a moving member with piston motion compresses and expands the air film cyclically (see fig. 7).

$$\rho = \frac{2\pi r P}{\omega \alpha d}\left[\frac{\text{bei}\,\alpha r\,\text{bei}'\,\alpha r + \text{ber}\,\alpha r\,\text{ber}'\,\alpha r}{\text{ber}^2\,\alpha r + \text{bei}^2\,\alpha r}\right] \tag{7}$$

$$k_a = \frac{\pi r^2 P}{d}\left[1 - \frac{2}{\alpha r}\,\frac{\text{ber}\,\alpha r\,\text{bei}'\,\alpha r - \text{ber}'\,\alpha\,\text{bei}\,\alpha r}{\text{ber}^2\,\alpha r + \text{bei}^2\,\alpha r}\right] \tag{8}$$

where bei$'$ and ber$'$ are derivatives of the Bessel functions. The quantity αr = $(12\nu\omega/Pd^2)^{1/2}\,r$, where ν is the air viscosity, P is atmospheric pressure, d is the spacing of the damping plates, and r the radius of flow over these plates. An understanding of the mechanism of ρ, and k_a, can be gained by considering what happens as the moving member or piston is set in vibration. A downward motion of the piston squeezed air outward between the parallel surfaces and because of the viscosity of the air, resistance is developed. At low frequencies of vibration, the air has time to move into the sump on the compression part of the cycle – the damping resistance is high and the air stiffness is low. As the frequency is increased, the air compresses, having no time to move into the sump. Consequently, k_a, increases with frequency, and since the air motion is restricted, the air damping tends to decrease with frequency. The family of curves (Figs. 8 and 9) obtained with a digital computer show how ρ and k_a vary with frequency for different values of $H = r/d$ where r = radius of air flow and d = plate spacing.

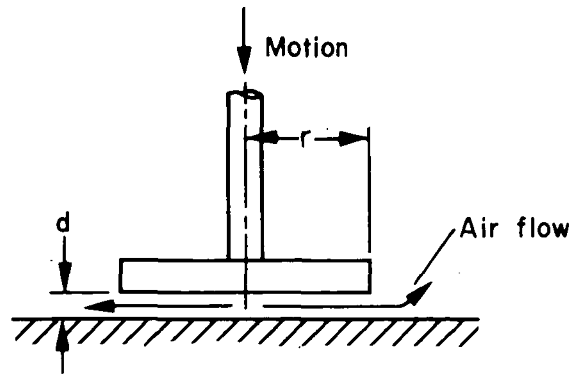

Figure 7. – Air flow beneath a moving piston.

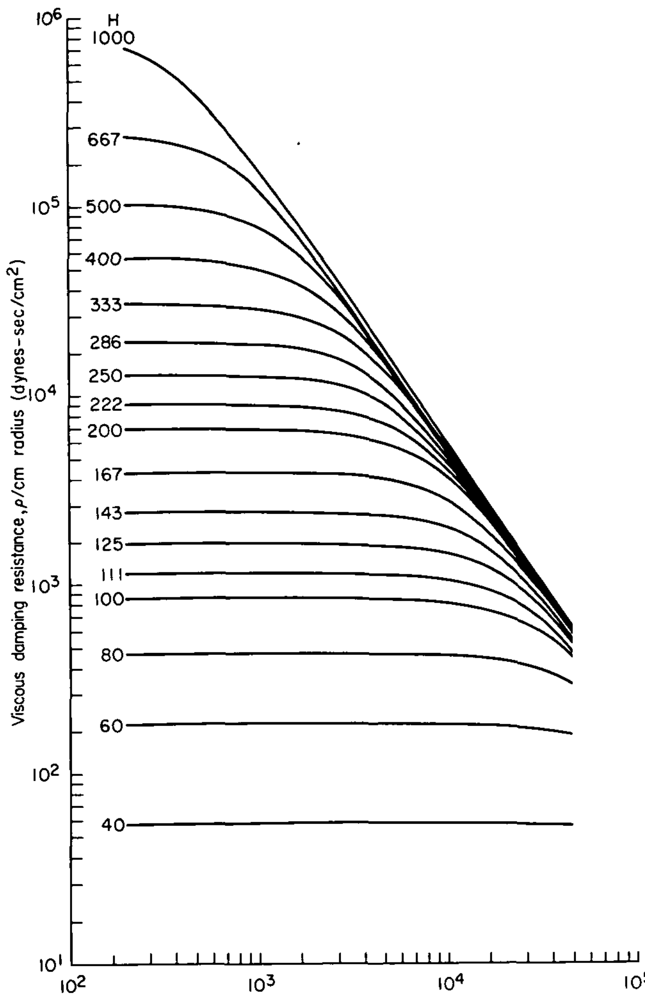

Figure 8. – Viscous damping resistance vs. frequency of vibrating piston for different ratios of air-flow radius to air-film thickness ($H = r/d$).

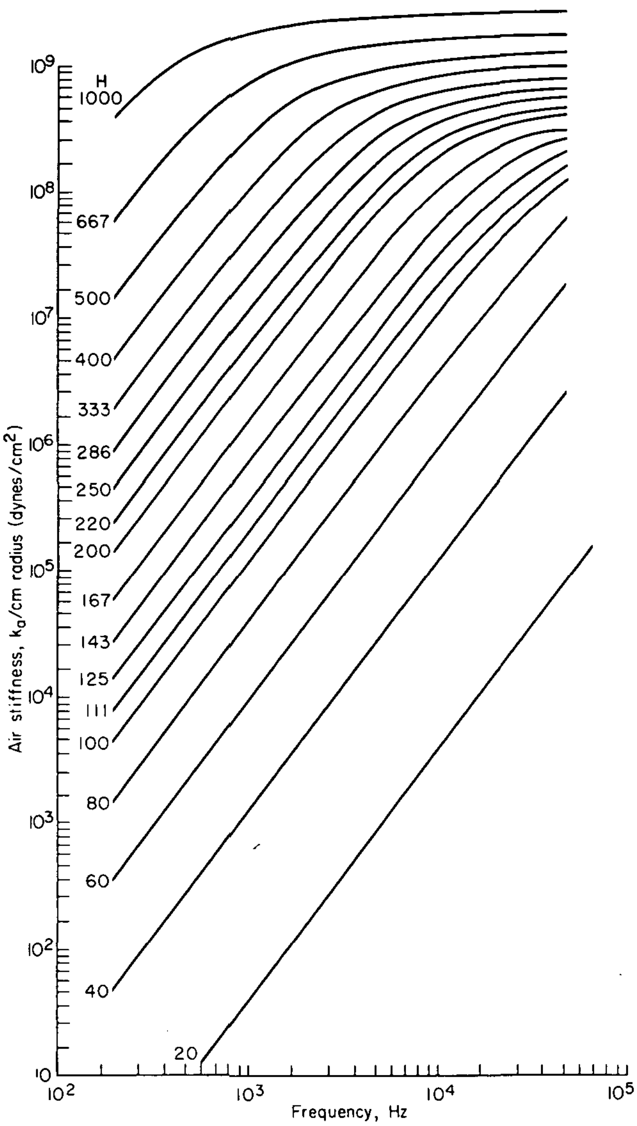

Figure 9. – Air stiffness vs. frequency of vibrating piston for different ratios of air-flow radius to air-flim thickness ($H = r/d$).

In two papers (refs. 6 and 7) Rule, Suellentrop and Perls arranged Crandall's Bessel functions to give an equation for μ the ratio of response relative to static sensitivity in terms of frequency with respect to resonant frequency.

$$|\mu| = \frac{x \text{ at } \omega}{x \text{ at } \omega = 0}$$

$$|\mu| = [(1 + \eta - \beta^2)^2 + 4\zeta^2\beta^2]^{-1/2} \quad (9)$$

where $\eta = k_a/k_d$, $\zeta = \rho/\rho_{cr} = \rho/2m\omega_o$, $\beta = \omega/\omega_o$, ρ_{cr} = critical damping, $k_d = m\omega_o{}^2$. This is a nonlinear, frequency-dependent equation analogous to the well-known linear equation giving the relative response of a second-order, linear vibrating system

$$|\mu| = [(1 - \beta^2)^2 + 4\zeta^2\beta^2]^{-1/2} \quad (10)$$

This last equation is derived from equation (6) and, here, ζ is a constant and $k_a = 0$.

Equation (9) is much more complex than equation (10) since η and ζ are frequency dependent. Rule et al. discovered they could simplify manipulation of this equation by imposing the condition that $H^2 f_o$ and $H^5 a/m$ are constants, thus making η and ζ functions of β only. They used a digital computer while employing different constants and plotted the resultant family of curves. One of the curves obtained, where $H^2 f_o = 2.59 \times 10^{-8}$ sec^{-1} and $H^5\ a/m = 2.21 \times 10^{12}$ cm/g, gave a theoretical and experimentally demonstrated flat frequency response within ±5 percent to 1.48 times the accelerometer undamped resonant frequency using the geometry shown in figure 10.

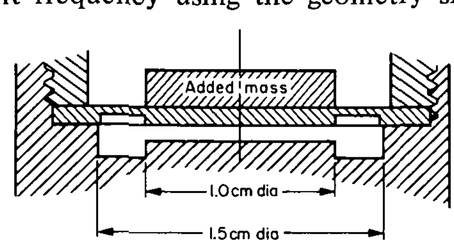

Figure 10. – Accelerometer of reference 5 and 6.

Comparing Rule's flat frequency response to that of an undamped transducer shows that $1.48\ f_o/0.2f_o = 7.4$; for equal response an undamped transducer would have to have 7.4 times the undamped resonant frequency of Rule et al. Since accelerometer sensitivity is inversely proportional to the square of the undamped resonant frequency f_o (see eq. (5)), Rule's system is over 50 times more sensitive than an undamped system providing the same frequency response. Computations also show that the nonlinear air damping and air stiffness used in the example above can provide 3.4 times higher sensitivity than an optimum damped unit that obeys the difficult-to-obtain theoretical linear equation of equation (6) or (10).

Obviously, it was desirable to use a similar type of frequency response control in the Ames accelerometer, but there the air flow pattern was considerably different from that in the Crandall and Rule design. Their design procedures could not be directly used. (The recess in the center of the Ames damping plate, which prevents the Crandall type radial air flow pattern, was necessary to accommodate the symetrically mounted mass on the diaphragm. The symmetry of the mass and the high density material used were features designed to minimize off-axis and rotational acceleration errors.) The plan for obtaining flat frequency response in the Ames geometry was to control the air stiffness and damping by adjusting the volume of the center sumps.

Experimental accelerometers were constructed in which movable central rods could be used to vary the sump volume (fig. 11). Alternate sump volume adjustments and frequency response calibrations with a mechanical shaker were made until the desired frequency response was obtained. This sump volume was then incorporated in the design of the production models for wind tunnel tests. The number of holes in the outer edge of the diaphragm also had an effect on the distribution of air flow and the frequency response.

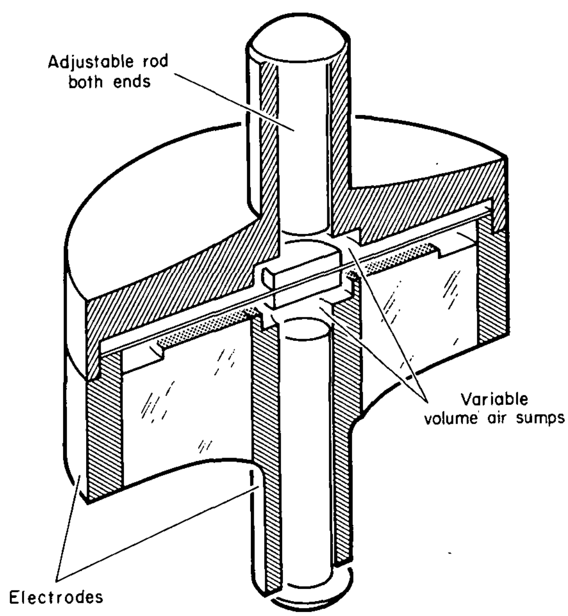

Figure 11. – Experimental accelerometer.

The papers of Crandall and Rule et al. and the curves of figures 8 and 9 derived from them were used extensively in the process of adjusting frequency response. The determination of the diaphragm resonant frequency in vacuum giving the diaphragm stiffness, $k_d = m\omega_o^2$, could be compared with the expected air stiffness k_a estimated, after making several assumptions, from the curves in figure 9. Likewise, something of the expected air damping for a given plate separation d and its variation with frequency could be determined from the curves of figure 8 and compared with the theoretical value for critical damping, $2\omega m_o$.

TYPICAL FREQUENCY RESPONSES

With the adjustable damping provided in the experimental units, it was possible to obtain a flat frequency response beyond the undamped, or vacuum, resonant frequency, but most of the accelerometers constructed for telemetry used had a cutoff at around f_o or below. Adjusting the

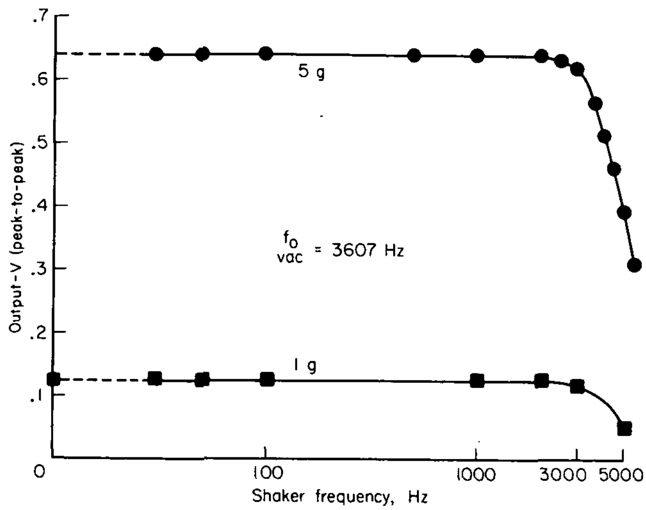

Figure 12. – Accelerometer frequency response.

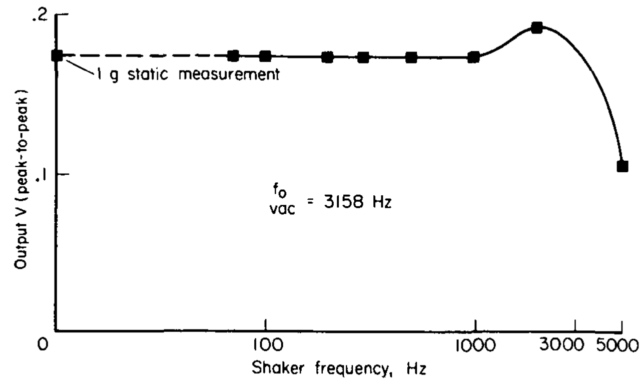

Figure 13. – Accelerometer frequency response.

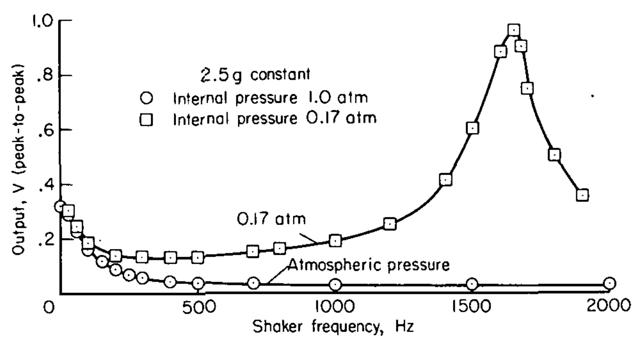

Figure 14. – Accelerometer frequency response, large k_a/k_d (air stiffness/diaphragm stiffness) ratio.

dimensions of the air sump so that the frequency response cutoff at the frequency lower than f_o, causes the response to deviate a smaller percentage from true flatness at the mid range frequencies. Some of the response curves cut off without any resonance (fig. 12) and some had a slight resonance (fig. 13). The lower curve in figure 14 shows how air stiffness can adversely affect the frequency response of sensitive accelerometers with a relatively large k_a/k_d ratio. This accelerometer is about eight times more sensitive than the two units of figures 12 and 13 and has no center air sump to relieve the air stiffness. The upper curve shows the effect of reducing the inside pressure from 1 to 0.17. The air stiffness is reduced, somewhat, improving the low frequency response, but the damping is reduced to such an extent that a large resonant peak occurs.

Figure 14, compared to figures 12 and 13, illustrates that careful attention to air damping and air stiffness is necessary to ensure flat frequency response in capacitive transducers.

AN ULTRAMINIATURE ACCELEROMETER

Obtaining free-flight acceleration data from small, thin conical models required accelerometers smaller than the 0.625 cm (0.25 in.) units. Two experimental accelerometers, 0.356 cm (0.14 in.) in diameter, were made and thoroughly tested. A calibration for the instrument is shown in figure 15. The output was linear ± 0.025 percent deviation from 0 to 60 g with a full-scale output of 1.4 V from the FM receiver. No special attempt was made to design for proper damping, but the response was flat to 800 cycles with a fourfold amplification peak at about 4000 Hz. It is believed that practical accelerometers for routine application can be made this small or even smaller.

CALIBRATIONS AND TESTING

Extensive calibration and testing were required for the three separate tunnel projects using the capacitive accelerometers. More than 30 transducers were calibrated for the project reported in reference 1. The calibration procedures and the optical calibration checks made on the Unholtz-Dickie Shaker are described in reference 2. A typical calibration of output vs G is shown in figure 16 for the 0.625 cm transducer. Each transducer was checked with the vibration calibrator for sensitivity and frequency response upon completion of construction and before being mounted on the telemeter oscillator board. This test was made with a capacitance bridge circuit employing a tri-axial cable for remote connection to the accelerometer.

An important piece of specially constructed test equipment was a small vacuum chamber, 6.25 cm diam, mounted on the Unholtz-Dickie Shaker. The metal chamber was cylindrical with the glass top cover sealed by an O-ring. A glass insulated coaxial connector provided a hermetic electrical connection to the instrument inside the chamber. This vacuum chamber was helpful in establishing frequency response design since knowledge of the transducer's undamped resonant frequency was required in design calculations. The accelerometer was placed inside the chamber with the cap only partly soldered on so that the inside of the cell could be evacuated. As the frequency of the Unholtz-Dickie Shaker was increased, a large output peak, as much as 15 times the low frequency output, indicated resonance. Finished cells with sealed in atmosphere were also tested in the vacuum chamber. The appearance of a resonance peak under vacuum, which disappeared on release of the vacuum, indicated a leak in the solder seal. This test was important, since the tunnel flights were made at pressures other than atmospheric.

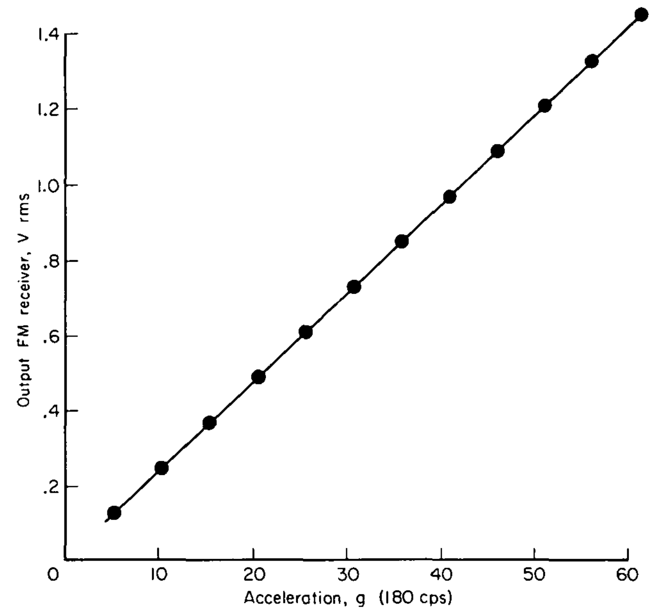

Figure 15. – Ultraminiature 0350 cm, 0.14 in. diameter, accelerometer calibration.

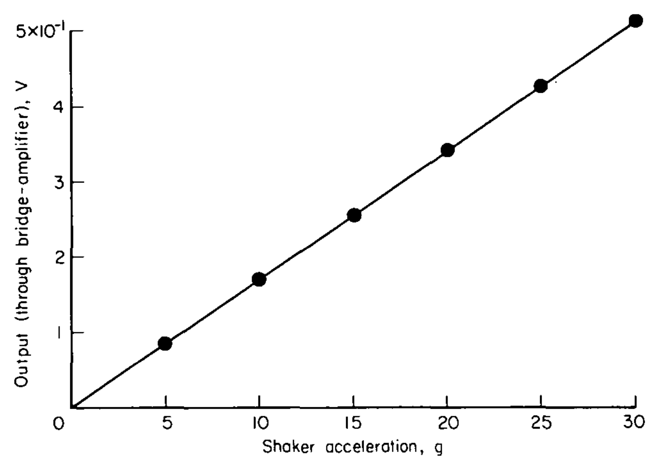

Figure 16. – Accelerometer 0.625 cm (0.25 in. diameter) calibration.

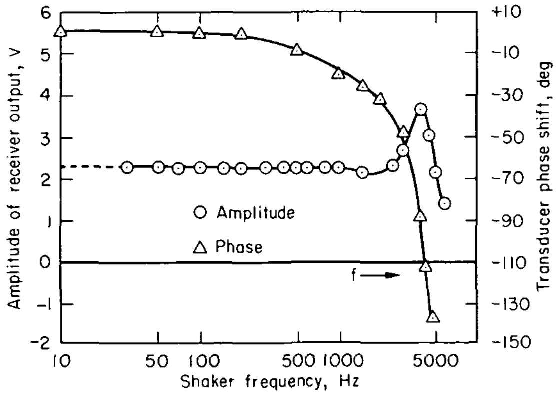

Figure 17. – Transducer amplitude and phase response referenced to piezoelectric accelerometer.

OSCILLOGRAPH TRACES OF TELEMETERED ACCELERATION DATA FOR 20° INITIAL PITCH ANGLE

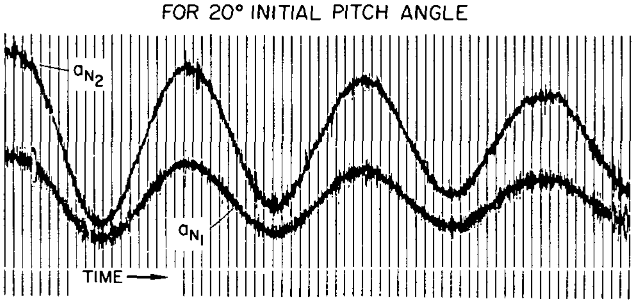

Figure 18. – Data from accelerometer mounted in free-flying model.

In addition to dynamic calibration and frequency response tests between 10 and 5000 Hz, steady acceleration tests at zero frequency were made using a rotating table. Off-axis tests at 90° showed off-axis sensitivity as low as one-sixth of 1 percent. No tests of the rotational sensitivity were performed, but the design ensures minimal errors because of this effect. Phase shift curves of the Ames transducers versus frequency were also made by comparing them with the shaker high frequency, piezoelectric calibration-accelerometer output. As the frequency was decreased below 20 Hz, excessive phase shift in the piezoelectric standard accelerometer occurred. At these lower frequencies, two fixed capacitive electrodes, secured near the oscillating shaker platform, were used in the capacitive bridge circuit for measuring amplitude and especially for comparing the acceleration phase of the shaker to that of the Ames transducer. As expected, the phase shift of the capacitive transducer approached zero in a straight line as the frequency approached zero. A logarithmic plot showing both phase shift relative to the piezoelectric transducer and frequency response over the entire frequency spectrum is shown in figure 17.

An example of tunnel data telemetered from on-board Ames' accelerometers to FM receivers, reproduced from reference 2, is shown in figure 18. The performance of these accelerometers was excellent during all calibration runs and wind tunnel experiments, the high stability and accuracy of the transducers being uncompromised by the small size.

CONCLUDING REMARKS

The Ames 0.635 cm (0.25 in.) diam capacitive accelerometer described here is an accurate and rugged instrument capable of measuring uniform, as well as rapidly varying, accelerations. It has been designed to minimize cross-axis and rotational sensitivity. Temperature effects can be made negligible and hysteresis minimized by use of a stretched and welded membrane. Equations derived for the static sensitivity are helpful in designing for a specified full-scale range.

The use of a capacitive transducer mounted directly in the tank circuit of an oscillator-telemeter has many advantages over other transducer-telemetry systems. (1) The telemetry transmitter can be of simple design requiring a minimum of parts. (2) A wideband, high resolution system can be used. (3) The use of a nondissipative transducer allows maximum life from the smallest available batteries where small telemetry transmitters are required. (4) Steady accelerations down to zero frequency can be measured in contrast to the limitation in this respect for commercially available, miniature, piezoelectric accelerometers.

The damping required in mass-spring type accelerometers for extending the static and low frequency response with equal amplitude to high frequencies is provided by the energy dissipation accompanying the air flow between the plates of the capacitor. Because the geometry of the transducer, chosen for other performance characteristics, produced unique air flow patterns, methods previously used for damping design were not wholly applicable. However, a method was developed for adjusting the frequency response to be flat to high frequencies, even in excess of its vacuum resonance frequency. Frequency dependent air stiffness, as well as air damping was employed to tailor the response to a wide range of specifications.

Several wind tunnel projects have shown the accelerometer to be well adapted to free-flight telemetry. Its small size (units 0.356 cm in diameter have been constructed) makes possible the telemetry from very small models. The Ames capacitive accelerometer should be found to have many other applications.

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National Aeronautics and Space Administration
Moffett Field, California 94305, May 31, 1972

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TABLE 1. – AMES CAPACITIVE ACCELEROMETER

Size	0.635 cm (0.25 in.) diameter by 0.5 cm (0.2 in.) long
Weight	0.75 grams
Accelerometer Range full scale (F.S.)	±1 to ± 200 g
Nonlinearity	< 2 percent F.S. (due to $C \sim 1/d$
Hysteresis	< 0.1 percent F.S.
Frequency response (50 g unit)	flat within ± 3 percent 0 - 1000 Hz
Circuitry	tuned circuit in telemeter oscillator or capacitance bridge
Relative sensitivity (50 g unit)	$(1/C)(\Delta C/\Delta g) = 0.2$ pF/7 pF · 50 g = 0.06%/g
Output – F.S. (from wide band FM receiver driven by 100 MC telemeter)	± 5 V p-p for ± 50 g
Cross axis sensitivity	< 1 percent F.S.
Zero shift with temperature	0.05 percent F.S./°C
Sensitivity change with temperature	0.03 percent F.S./°C

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