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RN-TM-0170

25 February 1965

FEASIBILITY REPORT FOR
A HIGH OUTPUT STRAIN GAGE
ACCELEROMETER

Written by
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Feasibility Report for a High
Output Strain Gage Accelerometer

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I. INTRODUCTION

One of the necessary requirements during the developmental phase of the NERVA engine is the measurement of vibration levels and vibration frequencies under operating conditions. The anticipated acceleration ranges are 25 and 50 g with a frequency range of 0 to 1000 cycles per second. Accelerometers used for these measurements, in addition to satisfying the acceleration and frequency range requirements, must be radiation hardened, have a high output for a good signal-to-noise ratio, and be compatible with the high gamma heating rates of the NERVA engine.

II. SUMMARY

A high output, bondable strain gage accelerometer is required for use in the NERVA environment. It is proposed that the Rokide bonding process be used for the development of such an accelerometer. The purpose of this feasibility study is to:

- A. Investigate the use of Rokide bonded strain gages.
- B. Determine the transducer operating characteristics and limitations.
- C. Determine the transducer environmental limitations in the NERVA environment.

III. CONCLUSIONS AND RECOMMENDATIONS

The use of Rokide bonded strain gages in the development of a high output accelerometer seems feasible, however, there are certain limitations. The accelerometer can be designed for good response up to 1000 cps. The study indicates that the optimum transducer acceleration range is above

100 g, while ranges of 25 and 50 g are desirable for use in the NERVA program. Since the output of the transducer depends on the excitation voltage and transducer range, with high excitation voltages a 100 g accelerometer could be used for the 25 and 50 g, and such outputs in the order of 250 mv to 100 vdc full-scale.

In non-radiation environments titanium material offers the highest output as long as size and weight are not a problem. In the NERVA radiation environment aluminum, with its excellent thermal conductivity, appears to be the only useable material; however, its heat dissipation characteristics depend largely on the design and method of mounting.

In case of one limit of the gage is high output strain gage, it is recommended that the gage be fully characterized as to its characteristics and limits of use as a strain gage.

It is also recommended that the gage be fully characterized and tested to optimize the design.

IV. TECHNICAL DISCUSSION

A. GENERAL

The proposed accelerometer is a cantilever beam type with Rokide bonded strain gages on both sides of the beam as depicted in Figure 1. Accelerometers of the cantilever beam type are not new innovations; they have been used in applications where ruggedness and simplicity are the prime factors, not size and weight. The use of this type of instrument is limited by the following inherent characteristics: (1) low output, (2) low frequencies, (3) high accelerations, and (4) large size and weight.

The underlying factor of these characteristics is the unfavorable ratio of strain energy stored in the spring compared to the minute quantity used in stretching the strain wires.

In transducers of this type the only damping present is solid or hysteresis damping within the beam, which is proportional to the maximum stresses developed and the velocity of the beam. Figure 2 illustrates the amplitude and phase angle relationships of various damping factors for a steady-state, forced-vibration system. In general, the damping forces in the transducer under consideration are quite small, i.e., damping ratio < 0.2 , so that the beam can be considered an undamped vibration system. The resonant frequency of the system is proportional to the acceleration range and inversely proportional to the weight. The weight, in turn, decreases with increasing range. At lower acceleration ranges the transducer is larger with a low resonant frequency. Damping ratios of 0.6 to 0.7 are required for satisfactory operation at lower frequencies (Figure 2). The addition of viscous damping devices such as vanes for oil or air damping results in a bulky instrument with seriously limited operating characteristics.

The full-scale output of the transducer is determined by the maximum allowable design stresses and would be the same by design for all acceleration ranges. However, the sensitivity of the instrument in mv/g will decrease with increasing accelerations to the point where resolution and accuracy are seriously affected.

One solution to this problem is to increase the sensitivity of the transducer to take full advantage of the more desirable operating characteristics at higher acceleration ranges with a corresponding increase in

resonant frequency and decrease in mass. The output of the transducer is a function of the maximum strain and excitation voltage. Maximum strain is fixed by design and is determined by the fatigue limit of the selected material. The selection of the best material, based on the design consideration, may not have the highest maximum strain. Another solution is to increase the excitation voltage. Recent developmental work (Reference 1) on Rokide bonded strain gages indicates that outputs of 1 vdc full-scale can be obtained by using higher input voltages.

The applications for this type of transducer are numerous where ruggedness and simplicity are desired. The all-metal-ceramic construction would have excellent radiation resistance. Use of this type of transducer in the NERVA radiation environment may be restricted because of the large weights encountered.

B. STRAIN GAGES

1. Types

Two major types of strain gages are available in the strippable form for use with the Rokide process (Types A and C). Type A is preferred when maximum stability must be maintained over long periods of time, or in installations where the zero cannot be rechecked conveniently. Type A gages are characterized by excellent inherent temperature stability and lower gage factors. Type C gages are better suited for low strains because of their higher gage factor although their response to temperature change is 100 times greater than that of Type A.

2. Selection

The selection of the proper strain gage is a major determining factor in the design and performance of a high output accelerometer. Type A strain gages are well suited for measuring dynamic strains but their

response is about one-half that of the Type C. The Type C gages are preferable for dynamic applications involving low strains because of their higher gage factor only if the strain fluctuations are much more rapid than the temperature fluctuations.

Developmental work performed on high output strain gages was of a limited experimental nature. However, the results indicated that Type C strain gages attached with the Rokide bonding process could be operated with input voltages from 10 to 300 vdc and attain outputs greater than 1 vdc. The developmental work involved single element gages. For the accelerometer, a four active arm Wheatstone bridge configuration is preferred to take advantage of the temperature compensation characteristics and the fact that the bridge output is four times that of a single element gage.

3. Requirements

Higher excitation voltages require that the gages have sufficiently good insulation from the beam material to preclude electrical breakdown or excessive leakage currents. Typical Rokide bonded strain gages installed on test beams have sustained "hi-pot" testing up to 300 vdc. The effect of high radiation levels on the electrical breakdown of the gages would have to be determined by radiation effect tests.

Higher excitation voltages also require that the gages be capable of carrying larger currents, be unaffected by self-heating, and be able to dissipate the heat generated. High output strain gage test results indicated that the characteristics of the gage were unaffected (other than zero shift) although the temperature increased considerably. The test

results also indicated that the Rokide material was conducive to heat dissipation from the strain wires. The range of power dissipation of a nominal 1000 ohm strain gage with input voltages (V) from 10 to 300 vdc is:

$$P = \frac{V^2}{1000} = 0.1 \text{ to } 90 \text{ watts} \quad (1)$$

The high output strain gage experiment reported in Reference (1) used special gages 1-in. long by 3/4-in. wide. Gages 1/2-in. long by 9/32-in. wide are now available in strippable form for use with the Rokide bonding process. The smaller gages are more desirable for minimizing the size of the transducer. Little is known about the heat transfer characteristics of the various size gages and the effect of varying the thickness of the Rokide material. Additional testing is required to better define the operating characteristics of the high output gages.

C. THEORY

The basic design theory of the cantilever beam accelerometer as depicted in Figure 1 is presented in the following equations (Reference 2):

$$f_0 = \frac{6.1}{L} \sqrt{\frac{n h}{\epsilon}} \quad (2)$$

$$W = \frac{\epsilon E b h^2}{6 n L} \quad (3)$$

$$\frac{f_0}{W} = \frac{36.1}{b E} \left(\frac{n}{\epsilon h} \right)^{3/2} \quad (4)$$

where:

- f_0 = natural resonant frequency
- b = width of beam
- h = thickness of beam
- L = length of beam
- n = range of transducer in units of g

E = Young's modulus of elasticity

W = weight of mass

ϵ = strain at root for full scale acceleration

The ratio f_0/W should be as large as possible, i.e., a high natural frequency and low values of weight are desirable. The ratio increases with increasing range, indicating better performance at higher ranges. The modulus of elasticity of the cantilever material should be as low as possible. The strain should also be as low as possible, but because the output E_0 is proportional to strain, the maximum value of ϵ must be used sacrificing performance to some degree. The thickness and width of the beam should also be low, with the thickness being slightly more important than the width.

D. MATERIALS

Materials considered for this study are aluminum, titanium, and stainless steel. All are being used in the NERVA program and the material properties of each have been thoroughly investigated in a radiation environment. The material properties for aluminum, titanium, and stainless steel, as given in Reference (3), are listed in Table I:

TABLE I
MATERIAL PROPERTIES

<u>Material</u>	<u>Density</u> <u>lb/in³</u>	<u>Mod of Elast.</u> <u>E psi</u>	<u>Fatigue Limit</u> <u>10⁷ Cycles</u> <u>psi</u>	<u>Max Oper</u> <u>Temp °F</u>	<u>Therm Cond</u> <u>BTU/hr</u> <u>ft²/°F/ft</u>
Aluminum	0.10	10.6×10^6	20,000 (Max)	400	70 - 100
Titanium	0.16	16.0×10^6	55,000 to 95,000	800	4.1 - 9.8
Stainless Steel	0.29	29.0×10^6	34,000 to 55,000	800	14.4

Very few aluminum alloys are available that are satisfactory for transducer applications and nearly all are temperature limited to 400°F operation. However, aluminum offers the advantage of the lowest density and modulus of elasticity, and the highest thermal conductivity. Several titanium alloys are available that offer good weight-to-strength ratios with satisfactory operation to 800°F. The thermal conduction is the poorest of the three materials considered, and the fatigue limit is the highest of the three.

Several types of 400 series stainless steels are also available for satisfactory operation to 800°F. The stainless steels are the heaviest of the materials considered with a large modulus of elasticity. The thermal conduction of steel is approximately twice that of titanium.

For design considerations the maximum strains (neglecting lateral stresses) are:

$$\text{Al} \quad \epsilon = \frac{S}{E} = 1900 \text{ } \mu \text{ strain} \quad (5)$$

$$\text{Ti} \quad \epsilon = \frac{S}{E} = 3400 \text{ to } 6000 \text{ } \mu \text{ strain} \quad (6)$$

$$\text{S.S.} \quad \epsilon = \frac{S}{E} = 1050 \text{ to } 1900 \text{ } \mu \text{ strain} \quad (7)$$

It is interesting to note that there is no advantage in using steel instead of aluminum to obtain higher outputs. The selection of the cantilever beam material will be dependent upon the operating temperature requirements within the desired design limits. The three materials noted are by no means the only ones available. They were selected for this analysis because the various properties represent the low, mid-point, and high values of density, modulus of elasticity, thermal conductivity, and strain.

E. RESONANT FREQUENCY

The virtual absence of damping in this type of accelerometer requires that the transducer be designed with a relatively high natural frequency to obtain higher operational frequencies. For an accelerometer with a frequency range of 1000 cycles the natural resonant frequency will be fixed by design to be a minimum of five times greater or 5000 cycles. As shown in Figure 2, with the ratio of $\dot{x}/f_0 = 0.2$, the accelerometer will have a relatively flat response to 1000 cycles with little phase-lag and will be similar in operation to an undamped crystal accelerometer operating well below the resonant frequency.

DESIGN CONSIDERATIONS

The actual design of the transducer requires that a judicious choice be made in the selection of values for b , L , h , and n based on the physical limitations of the system. Since the transducer size, weight, acceleration range, sensitivity, and gamma heating are all dependent on these values, it would be desirable to optimize the values for the various conditions.

1. Width

The minimum width of the beam depends on the space requirements of the strain gage. A one-inch minimum will be considered for this study. As noted in equation 2 the weight of the transducer is directly proportional to the width, therefore minimizing the width would be advantageous.

2. Weight

The determination of the weight of the mass depends on the variables n , h , and L . As noted previously, the ratio f_0/W should be as large as possible but with the value of f_0 set by design; increasing the ratio can only be accomplished by minimizing the weight. The weight required can be expressed by the approximation:

$$W \approx \frac{W_0}{4} + W_1 \quad (8)$$

where:

W_0 = weight of the beam

W_1 = weight concentrated on end of beam

The weight required decreases as the acceleration range and length increase. The weight of the beam increases with increasing length. The minimum value of W occurs when $W_1 = 0$ and $\frac{W_0}{4} = W$. Rewriting equations (1) and (2) and solving for n as a function of h and L for the minimum weight condition, the following expressions are obtained:

$$n = \frac{f_0^2}{(6.2)} \epsilon^2 \cdot \frac{1}{\beta} \quad (9)$$

$$n = \frac{2 \epsilon E}{3 \rho} \beta$$

where:

$$\beta = \frac{h}{L^2} \quad (10)$$

ρ = density

Figure 3 shows the minimum weight relationship of the acceleration range and the ratio β for each of the materials under consideration. It also shows the relationship of the acceleration range and the

ratio for the design resonant frequency of 5000 cps. The optimum ratio occurs at $\beta = 0.005$, however, the acceleration ranges are fairly high, ranging from 380 g for stainless steel to 2000 g for titanium.

3. Acceleration Range and Sensitivity

Determination of the acceleration range of the instrument depends on the minimum transducer sensitivity that is desired or that can be tolerated. As noted previously, the output of the strain gages is determined by the maximum strain and the excitation voltage.

A strain gage with a gage factor of 3.6, operating at the maximum strain for each of the materials, would have an incremental resistance change ratio of:

$$\frac{\Delta R}{R} = G.F. \epsilon \quad (11)$$

The output E_o of a four active arm Wheatstone bridge is given by:

$$E_o = V \cdot \frac{R_1 R_2}{(R_1 + R_2)^2} \cdot 4 \cdot \frac{\Delta R}{R} \quad (12)$$

The sensitivity of the transducer is:

$$\text{Sens} = \frac{E_o}{n} \quad (13)$$

Combining equations (11), (12), and (13) the sensitivity of the transducer, expressed as a function of the acceleration range and excitation voltage, is:

$$\text{Sens} = 4 \text{ G.F. } \frac{R_1 R_2}{(R_1 + R_2)^2} \epsilon \frac{V}{n} \quad (14)$$

Figure 4 shows the relationship of transducer sensitivity and acceleration range for various excitation voltages. The curve for a 10 volt excitation represents the nominal sensitivities presently available in strain gage transducers and is shown to demonstrate the advantages of using

higher excitation voltages. The solid curves are the sensitivities obtained for the three materials for a micro strain of 1900. The dash curves for titanium are for a micro strain of 6000. The curves indicate that relatively high sensitivities can be obtained at higher acceleration ranges and that titanium, with higher allowable working stress, appears to be better than both aluminum and steel.

4. Length

The analysis so far has indicated that it is desirable to operate the transducer at higher acceleration ranges to obtain the best physical dimensions of the transducers. However, selection of the length of the transducer must be determined by the desired operating strain. The strain considered in this analysis is the maximum strain occurring at the root of the transducer. The strain decreases along the length of the beam so that a strain gage placed on the beam will read an average strain less than the maximum as shown in Figure 5a. The average strain is approximately

$$\epsilon_{avg} \approx \frac{\epsilon_{des} + \epsilon_{min}}{2}$$

and increases as the length of the beam increases. Figure 5b shows the relationship of the ratios of the average strain and design strain versus the gage length and length of the beam. For an operating strain of 90% or more of the design strain, the length of the beam should be greater than five times the gage length.

G. THERMAL ANALYSIS

Using a transducer of this type involves consideration of the heat generated by the high excitation voltages and gamma heating in a radiation environment.

1. Self Heating

As noted previously, the power generated is directly proportional to the square of the excitation voltage:

$$P = \frac{V^2}{R_g}$$

Calculations show that the temperature gradient across the Rokide layer is small compared to the gradient across the length of the beam since the insulation thickness is very small compared to the beam dimensions. Neglecting the Rokide temperature gradient, and assuming that the total heat generated by the strain gages is conducted uniformly over the total surface area of the gage through the Rokide layer to the beam, the resulting temperature of the gages is given by the approximation

$$T_s \approx \frac{3.41 V^2 x}{R_g b h k} + T_0$$

where:

T_s = temperature of strain gages

T_0 = temperature by heat sink

V = excitation voltage

R_g = strain gage resistance

x = distance of strain gage from heat sink

b = width of beam

h = thickness of beam

k = thermal conductivity of beam material

The resulting temperature of the strain gages is dependent on the excitation voltage, the material, and the thickness of the beam. Figure 6 shows the expected temperature ranges for the three materials

under consideration for the value of h from 0.1- to 1-in. and the various excitation voltages. Operating temperatures below the maximum allowed material temperatures can be expected for all three types of transducer beam materials. Heat losses through convection and radiation are negligible because the surface area of the strain gage is small and the resulting temperatures are low.

2. Gamma Heating

Use of the transducer in the NERVA program necessitates that gamma heating be considered in the design. Assuming that all of the weight is concentrated in the end of the beam and the beam itself is weightless, the total heat generated in a gamma field of H watts/gm would be:

$$Q = HW$$

where

H = heating rate (watts/gm)

The weight required on the end of the beam for the imposed design conditions is:

$$W = \frac{C E b h^2}{6 n L}$$

The total heat generated is dissipated by conduction through the beam and by radiation and convection to the surrounding media. The heat conducted through the beam is:

$$q_b = \frac{k b h (T_w - T_o)}{L}$$

where:

T_w = temperature of the weight.

Using Newton's law of cooling, the heat lost by radiation and convection can be approximated by the linear relationship:

$$q \approx R A (T_w - T_o)$$

where:

$R = 0.27$ = convection coefficient for vertical surfaces in air

A = total surface area of weight

The heat balance equation is:

$$\frac{H C E b h^2}{6 n l} \approx \frac{k b h (T_w - T_o)}{L} + R A (T_w - T_o)$$

The temperature of the weight is:

$$T_w = \frac{H C E b h^2}{6 n l} \left(\frac{1}{k b h} + \frac{1}{R A} \right) + T_o$$

The temperature decreases with increasing acceleration range, but for a given acceleration range and material the temperature can be decreased further by increasing the surface area of the weight. Calculated temperatures for aluminum, neglecting radiation and convection losses, are in excess of 600°F for a heating rate of 1 watt/gm. Since the temperature varies inversely to the surface area of the weight, a substantial decrease in temperature can be made by replacing the weight with an equivalent weight in the form of radiating fins and increasing the cross-sectional area of the beam. Calculated temperatures for both steel and titanium, with low thermal conductivities, are far in excess of 10,000°F for a heating rate of 1 watt/gm. However, since both materials have higher operating temperatures than aluminum, it may be possible to decrease the operating temperature by the use of radiating fins and hydrogen cooling to acceptable limits.

V.

REFERENCES

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2. INSTRUMENT TRANSDUCERS, H. K. P. Neubert, 1963.
3. METALS HANDBOOK, Volume I, 8th Edition, American Society for Metals.

FIGURE 1
CANTILEVER BEAM ACCELEROMETER

FIGURE 2

AMPLITUDE AND PHASE ANGLE FOR A STEADY-STATE FORCED VIBRATION

FIGURE 3

ACCELERATION RANGE VS. B FOR MINIMUM WEIGHT

ACCELERATION RANGE VS. B FOR $f_0 = 5000 \text{ CPS}$

FIGURE 4

TRANSducer SENSITIVITY VS ACCELERATION RANGE

STRAIN VS LENGTH

(a)

STRAIN RATIO VS LENGTH RATIO

$\frac{GL}{2L}$

(b)

FIGURE 5

FIGURE 6

STRAIN GAGE TEMPERATURE RANGES FOR VARIOUS
EXCITATION VOLTAGES AND BEAM THICKNESS h .