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REON TECHNICAL MEMORANDUM

MASTER

FEASIBILITY REPORT FOR A METHOD OF
PIEZOELECTRIC ACCELEROMETER TEMPERATURE COMPENSATION

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I. INTRODUCTION

The charge sensitivity of lead zirconate - lead titanate piezoelectric transducers varies considerably with temperature. Figure 1 shows this variation and also shows the change in ceramic element capacitance with temperature. Data recorded in testing several samples indicate that these characteristics are repeatable with a given unit and are consistent among units of similar design and fabrication.

The possibility of using a ceramic element capacitance measurement as an indication of the relative change in charge sensitivity due to temperature variations was investigated. This type of measurement would enable data users to correct for temperature effects, thereby increasing the overall system accuracy.

II. CONCLUSIONS AND RECOMMENDATIONS

An alternating current bridge operating at 1 KHz with a 1 volt rms excitation voltage can be used to measure changes in transducer capacitance as a function of temperature when used with a long (250 foot) cable. The bridge excitation will introduce a 2% full-scale error in the recorded vibration data. The effects of the bridge elements on the vibration measurement system sensitivity and frequency response are negligible below 500 Hz.

The effect of the transducer output on the bridge is difficult to determine. In a simplified case, the voltage developed across the bridge ratio arm resistance when the transducer is operating at full-scale (25 g) represents a significant source of error and appears to be the worst problem in this application.

Several means of minimizing this error are available:

- A. The bridge can be operated at a higher frequency, such as 10 KHz.
- B. A filter circuit can be used on the output of the bridge to reject the lower vibration frequencies.
- C. The bridge can be operated on a different range which would reduce the ratio arm resistance from 10 K to 1 K ohms, therefore reducing the ratio arm error voltage at balance.

The effects of temperature changes and radiation on the cables were not considered in this study. Tests conducted over limited temperature ranges indicated that the cable capacitance changes were minor. Testing in a radiation environment indicates that cumulative effects are minor up to 10^{16} nvt but testing at dose rates comparable to NERVA has not been accomplished.

III. TECHNICAL DISCUSSION

The engine vibration measurement transducers which will undergo the largest change in operating temperature during NRX-EST testing are the nozzle flange units, H200R and H201T. These accelerometers will be operating at cryogenic temperatures in the early stages of the power run test and will reach temperatures as high as +300°F after steady-state full-power is established.

The Measurement Requirements List defines the frequency band of interest for these parameters as 0-500 Hz and the amplitude range as $\pm 25g$. Since frequencies above 500 Hz are of no interest to data users and since the wide band system electronics attenuates higher frequencies quite well, it is possible to excite the transducer ceramic element with a 1 KHz or higher signal and not disturb the vibration data.

A system which employs ac excitation at 1 KHz or higher, and which provides indication of relative capacitance changes in the transducer, would permit the recording of operating capacitance (and indirectly, operating temperatures). Such a system could be an ac bridge with a variable frequency oscillator power supply. The remainder of this technical memorandum will discuss a particular bridge operating at a particular frequency and its application and limitations when used as discussed above.

The bridge to be discussed is a General Radio Type 1650-A Impedance Bridge. A simplified schematic of the bridge element arrangement which applies to capacitance measurements is shown in Figure 2.

The manner in which the transducer is connected to the bridge is shown in Figure 3. It will be noted that the capacitance "seen" by the bridge is actually composed of a series-parallel combination consisting of the amplifier input capacitance C_A , the cable capacitance C_L , and the transducer capacitance C_S . The total capacitance C_B can be expressed as:

$$C_B = \frac{C_A (C_L + C_S)}{C_A + C_L + C_S}$$

The amplifier input capacitance is very large in comparison to $C_L + C_S$ so that $C_B \approx C_L + C_S$.

The questions that arise now are: (1) What are the magnitudes of C_L and C_S ? and (2) Will the bridge be sensitive enough to detect changes in C_S while it is operating in parallel with C_L ?

C_S , the transducer capacitance, normally falls in the range of 1300 to 1650 picofarads. A nominal figure of 1500 picofarads is used in this analysis. The cable capacitance is approximately 40 picofarads per foot and cable lengths are 250 ft. (from the charge amplifier to the transducer), resulting in a total cable capacitance of about 10,000 picofarads.

Referring to Figure 1, it can be seen that a 1500 picofarad accelerometer undergoes a capacitance change from about 600 picofarads to about 2400 picofarads in the temperature range from -300°F to $+300^{\circ}\text{F}$. The total capacitance C_B therefore varies from 10,600 picofarads to 12,400 picofarads.

The bridge output voltages which result from capacitance variations of this magnitude can be calculated as follows:

$$\frac{E_o}{E_i} = \frac{R_x + \frac{1}{j\omega C_x} - \left(\frac{R_A R_T}{R_N} + \frac{R_A}{j\omega C_T R_N} \right)}{\left(1 + \frac{R_A}{R_N} \right) \left[\left(R_T + \frac{1}{j\omega C_T} \right) + \left(R_x + \frac{1}{j\omega C_x} \right) \right]} \quad E_g (1)$$

where E_o = the bridge output; E_i = the bridge excitation; R_x = cable conductor resistance; $C_x = C_B$, the unknown capacitance; and R_A , R_N , R_T , C_T are the bridge elements shown in Figure 2.

It will be assumed that the bridge is balanced at room temperature when the unknown capacitance $C_x = C_L + C_S = 11,500$ pf. When the bridge is balanced $E_o = 0$ so that the numerator of Eq (1) must be zero and

$$R_x = \frac{R_A R_T}{R_N} \quad C_x = C_T \frac{R_N}{R_A}$$

From Figure 2, $C_T = 100,000$ pf and $C_x = 11,500$ pf so the ratio $R_A/R_N = 8.7$ and $R_T = \frac{R_x}{8.7}$. R_x is approximately 70 ohms for a 250 ft. cable, therefore $R_T = 8$ ohms.

R_A can be determined from the manufacturer's instruction manual which says that for a measurement range of 0-111,000 pf, the ratio arm resistance R_A is 10 K ohms. Consequently, $R_N = R_A \cdot C_x/C_T = 1150$ ohms.

With all bridge elements determined (for balance at $C_x = 11,500$ pf) it is possible to determine the bridge outputs at various values of the unknown capacitance being measured by plugging the known element values and the unknown element variations into Eq (1) and computing the results. Table I is a summary of the results of a series

of such computations and Figure 4 shows a plot of the same data.

TABLE I

C_X (pf)	$\left \frac{E_o}{E_i} \right 10^3$	Phase Angle
10,600	7.89	0
10,800	6.16	0
11,000	4.37	0
11,200	2.62	0
11,400	0.84	0
11,600	0.93	π
11,800	2.76	π
12,000	4.52	π
12,200	6.20	π
12,400	8.07	π
12,600	9.73	π
12,800	11.59	π
13,000	13.34	π

It can be seen that the bridge output will give adequate indication of capacitance changes in the transducer. All that is required is that the bridge output be connected through a phase-sensitive demodulator to the data recording system.

It has now been determined that it is possible to measure the capacitance of a ceramic element accelerometer while it is connected to a charge amplifier by a long (250 ft) cable. However, before such a system can be used, it must be determined what effect the charge generation of the transducer will have on the bridge and what effects the bridge excitation and bridge elements will have on the recorded vibration data.

The voltage across the unknown (the voltage impressed in series with the vibration transducer signal by the bridge) is easily calculated for bridge balance and for the two extremes of unbalance. Referring to Figure 5 it can be seen that

$$E_x = E_i \frac{Z_x}{Z_x + R_A}$$

and for the bridge elements as evaluated previously the voltage E_x is equal to 0.83 E_i , 0.81 E_i , and 0.79 E_i for minimum, normal, and maximum transducer capacitance, respectively.

If a 1 volt rms bridge excitation at 1 KHz is employed, the voltage across the unknown represents approximately 47.1 g at the charge amplifier input. However, since the NFO bandpass is such that sensitivity is down 39 db at the bridge frequency, recorded data would show only approximately 0.5 g or 2% of full-scale for the 25 g range.

The effect of the bridge elements on the vibration measurement system sensitivity and frequency response can also be calculated. Referring to Figure 5, the Thevenin voltage and impedance at the amplifier input terminals are:

$$E_{TH} = \frac{C_s}{C_s + C_L} E_s = 0.129 E_s \quad Z_{TH} = 10K - j 13.8 \left(\frac{10^6}{f} \right)$$

The effects of R_T , R_N , and C_T are neglected because they are shunted by the low impedance bridge excitation source. The Thevenin voltage and impedance without the bridge circuit in series are:

$$E_{TH} = 0.129 E_s \quad Z_{TH} = -j 13.8 \left(\frac{10^6}{f} \right)$$

The addition of the bridge circuit therefore reduces the sensitivity by a factor which is a function of frequency. The ratio of sensitivity with the bridge added S_W and without the bridge added S_{WO} is:

$$\frac{S_W}{S_{WO}} = \frac{-j 13.8 \left(\frac{10^6}{f} \right)}{10^4 - j 13.8 \left(\frac{10^6}{f} \right)}$$

Figure 6 shows a plot of this ratio and the corresponding phase shift experienced. From this plot it can be seen that no serious effects are experienced at frequencies below 500 Hz.

The effect of the transducer output on the bridge is more difficult to determine. The transducer not only generates a charge proportional to acceleration, it changes capacitance when the ceramic element is subjected to stresses. The average capacitance, however, should remain constant at constant temperature when the transducer is subjected to vibrations. The detector portion of the bridge assembly is equipped with a 1 K Hz twin-T RC filter which will tend to reduce all transducer outputs other than those at 1 KHz.

Assuming that the transducer is ranged properly, the highest "g" level which will be experienced will be $\pm 25g$. This is equivalent to about 475 MV rms output from the accelerometer assuming a sinusoidal vibration. A very small portion of the output will be reflected across the "unknown" terminals of the bridge due to the shunting effect of the bridge source. However, the bridge ratio arm resistance R_A will experience much larger percentages as can be seen in Figure 5. The voltage E_A across R_A due to the voltage E_s generated by the transducer will be $E_s \cdot \frac{10^4}{10^4 - j13.8(10^4)}$. This represents a significant source of measurement error and appears to be the worst problem area in this application. Several means of minimizing this error are available. The bridge can be operated at high frequency such as 10K Hz and a filter circuit on the output could be used to reject lower frequency signals. This would have the added benefit of further separating the vibrational data from the bridge excitation at the charge amplifier output. The bridge could be operated on a different range, 0-1.11 micofarad, which would reduce the ratio arm resistance from 10K to 1K ohms and therefore reduce the ratio arm error voltage at balance. A bridge tailored to meet the requirements of this application could be constructed. This approach would take more time and effort but would probably result in a superior system.

IV. ADDITIONAL PROBLEM AREAS

It is recognized that in an actual installation, the temperature of at least a small portion of the connecting cable would undergo changes proportional to those in the accelerometer and that cable capacitance would be affected. However, cables currently in use have been tested over a limited temperature range and the capacitance changes were minor. Other significant unknowns in the above scheme are the changes in transducer and cable capacitance and dissipation factors due to radiation (both cumulative and rate effects). Some testing has been accomplished at relatively low dose rates (GTR) which indicates that cumulative effects are minor up to 10^{16} nvt but testing beyond this point and at dose rates comparable with those experienced on NERVA engines has not been accomplished.

FIG. 1

GENERAL RADIO TYPE 1650-A IMPEDANCE BRIDGE

FIG. 2

IMPEDANCE BRIDGE CONNECTIONS TO
ACCELEROMETER CIRCUIT

FIG. 3

ELECTRICAL SCHEMATIC — TRANSDUCER CAPACITANCE MEASUREMENT SYSTEM

FIG. 5

SENSITIVITY & PHASE ANGLE OF VIBRATION
MEASUREMENTS WITH IMPEDANCE BRIDGE IN
CIRCUIT

FIG. 6