Piezoelectric Transducer Calibration Simulation Method Using Series Voltage Insertion

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By James E. Rhodes

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It is often desirable to check a transducer system's calibration before, during, or after a test. A convenient method for doing so, now in wide use, involves insertion of a voltage source in series with an ungrounded transducer. The voltage simulates the self-generating output of the transducer.

The technique, useful in both laboratory and field tests, is applicable to practically every situation involving piezoelectric transducers.

Typical of the situations in which the technique is advantageous are:

¶Establishing the proper system gain calibrations when many elements are involved in a system. This applies, for example, to the adjustment of system gain in order to obtain the desired deflection of a recording galvanometer at a specified input level.

¶Checking a system for gross malfunction, i.e., shorts, opens and unintentional maladjustment. This may apply to laboratory testing as well as to flight tests.

¶Evaluating the electrical characteristics of preamplifiers, signal conditioning equipment, readout and data storage devices under conditions which closely simulate the final measuring situation.

How to Do It

The test method requires insulating the transducer case from instrument ground. With an accelerometer, the best way is to insulate the accelerometer from electrical contact with mounting surfaces. This is quite simple if the accelerometer is lying open upon a bench; if the accelerometer is attached to a test specimen the use of insulating mounting studs is recommended. Endevco's Type 2980B is such a stud. Electrical insulation is also inherent in certain adhesive mounting techniques.

Next the ground side of the signal output is broken and measures are taken to insert a voltage in series with the transducer on the ground side (Fig. 1).

The usual method assumes that there is no mechanical excitation of the transducer while the simulation of

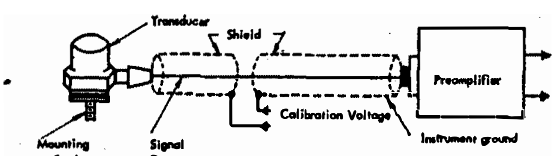

FIGURE 1
Inserting voltage in series.

calibration is being performed. Techniques whereby the simulation voltage could be applied in the midst of measurements would require some means of separating the calibration signal from the transducer output.

There are several techniques based on the set-up as diagrammed in Figure 1. Some of them, with some of their advantages or limitations, are:

(1) Breaking the shield of the coaxial cable and connecting a voltage source to the two sections of the shield. Satisfactory in the laboratory as an emergency measure, but reliable and workmanlike connections are difficult to make. A small portion of the signal lead may be left unshielded—a possible source of noise pick-up.

(2) Incorporating a "T" junction, fitted with connectors to match the associated cables, at which point a voltage source may be connected. With this configura-

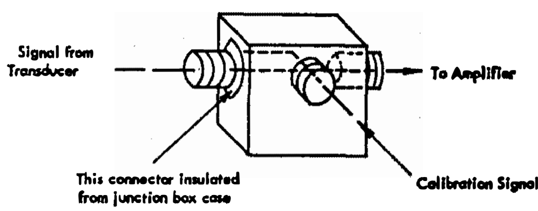

FIGURE 2
'T'-junction box.

tion the ground circuit is open within the junction box and must be closed externally (measurements cannot be made when the calibration input connector is left open). A shorting plug on the calibration signal connector can be used to short the calibration input during actual measurements.

The junction box should be insulated so that it will not ground out to a mounting surface when it is installed, a precaution that will prevent creation of a ground loop in the measuring system.

(3) Incorporating a "T" junction or "cable insert," similar to that outlined above, which contains, however, an internal resistor or potentiometer to close the ground circuit and permit measurements with external calibration circuitry connected or disconnected. In some cases, calibration simulation is based upon the current rather than the voltage from the calibration source. Current measurement is preferable if the lead resistance from the cable insert to the calibration source is appreciable in comparison with the internal resistor in the cable insert. When the basis of calibration simulation is the current through the calibration resistor, the simulation

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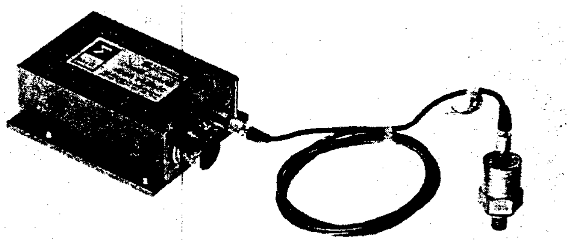

The Endevco® 28319A System includes a Model 2642M58 Amplifier and a Model 2272M15 Accelerometer. Several amplifiers in this series incorporate a fixed resistor or a potentiometer as a ground-side calibration resistance.

voltage is $E = IR$, where I is the calibration current and R is the resistance of the calibration resistor.

A commercial part incorporating a 100-ohm resistor is Endevco Part No. 2944.1. Its connectors mate with the standard connectors on Endevco coaxial cables.

(4) Providing a calibration resistance in the associated amplifier. Calibration voltage depends on the length of coaxial cable between the transducer and the amplifier.

(5) Providing an internal calibration resistance within the transducer being used. Two connectors and two coaxial cables are required—one for signal output and one for calibration input. Has the advantage that the level of calibration voltage is independent of any external capacitance in the system. With all techniques that use insertion of a calibration voltage at some point outside the transducer, the calibration voltage is dependent upon the external capacitance (primarily cable capacitance) between the transducer and the point of voltage insertion.

Circuit Theory Background

The usual simplified transducer equivalent circuit consists of a charge generator in parallel with the transducer capacitance. The amount of charge generated is proportional to the input excitation, as per Figure 3.

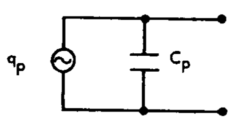

FIGURE 3

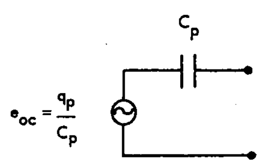

FIGURE 4

This transducer circuit is equivalent to a voltage generator and a series capacitance (Fig. 4):

$e_{oc} = \dfrac{q_p}{C_p}$ = open circuit voltage generated by the transducer.

An actual measuring circuit involves an external capacitance and a shunt resistance. The external capacitance C_1 is commonly cable capacitance plus input capacitance of the associated amplifier. The shunt resistance R_L is commonly the input resistance of the associated amplifier.

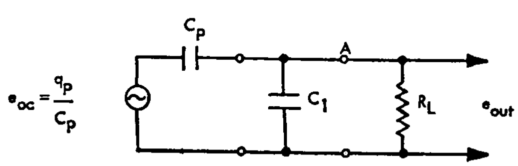

FIGURE 5

This circuit is, in turn, equivalent to:

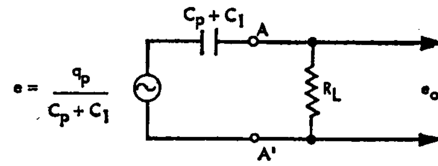

FIGURE 6

where $e = \dfrac{q_p}{C_p + C_1}$ = open circuit voltage at A — A'

The above system is subject to a low frequency roll-off which is dependent upon the time constant $R_L (C_p + C_1)$. In other words, for accurate measurements the resistance R_L should be large compared to the reactance of the capacitance $C_p + C_1$ at the lowest frequency of concern.

To obtain large values of the time constant $R_L (C_p + C_1)$, it is common practice to use an amplifier with a large input resistance ($R_L = 10^8$ to 10^9 ohms), to use a transducer with a large capacitance C_p, or to use a large external capacitance C_1.

When the time constant $R_L (C_p + C_1)$ is sufficiently large, the voltage e_{out} is dependent upon the charge at the transducer and the total system capacitance:

$$e_{out} = \frac{q_p}{C_p + C_1}$$

The addition of the external capacitance C_1 reduces the voltage at the amplifier input. When the source capacitance C_p is large, the decrease in output due to the addition of C_1 is minimized.

It should be noted that the presence of C_1 and R_L in the measuring circuit has no effect at any time on the high frequency response of the system, even though the low frequency response is determined by the time constant $R_L (C_p + C_1)$.

Measuring Circuit Including Calibration Resistor

When a voltage insertion resistor is included in the system, the equivalent measuring circuit with a voltage amplifier is as follows:

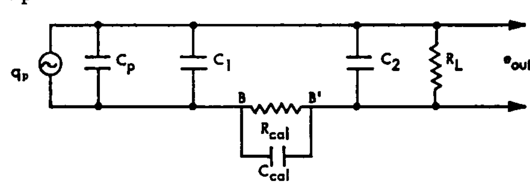

FIGURE 7

R_{cal} may be an actual series resistance inserted into the system, or may be the internal resistance of a voltage generating device connected to B - B' for calibration voltage insertion. C_1 is the external capacitance of the cable between the transducer and circuit point B where R_{cal} is inserted into the system. C_2 is generally cable capacitance and/or amplifier input capacitance. C_{cal} is the shunt capacitance of the calibration voltage source; in actual use R_{cal} will be small compared with Xc_{cal} and the presence of C_{cal} can be ignored.

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It is of interest to determine whether there are any limitations on the value of R_{cal} which can be used.

Ignoring C_{cal}, the above circuit is equivalent to:

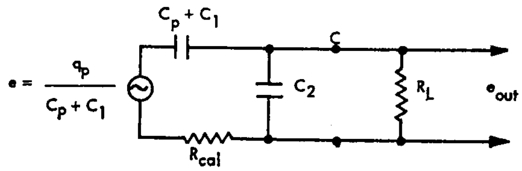


FIGURE 8

Consider the portion of the circuit excluding R_L:

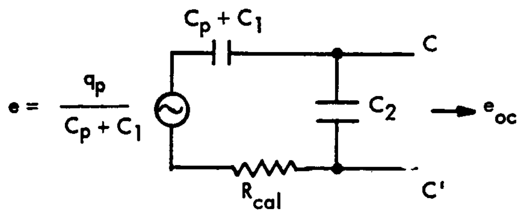


FIGURE 9

For this portion of the circuit, the open circuit output voltage at C - C' is:

$$e_{oc} = \frac{q_p}{C_p + C_1}\left[\frac{1}{\frac{C_p + C_1 + C_2}{C_p + C_1} + j \quad R_{cal} C_2}\right]$$

if $\omega R_{cal} C_2$ is small compared with $\frac{C_p + C_1 + C_2}{C_p + C_1}$, this reduces to:

$$e_{oc} = \frac{q_p}{C_p + C_1 + C_2}$$

and the equivalent circuit reduces to the normal equivalent previously discussed:

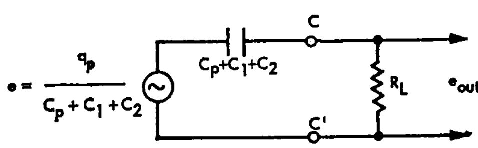


FIGURE 10

Therefore, in order for R_{cal} not to affect the circuit performance during measurement, it is essential that

$$\omega R_{cal}\, C_2 << \frac{C_p + C_1 + C_2}{C_p + C_1}$$

or $R_{cal} << \frac{C_p + C_1 + C_2}{\omega C_2\,(C_p + C_1)}$ at the highest frequency of interest.

In all practical situations encountered to date, a value of R_{cal} of the order of 100 ohms has proven to be more than satisfactory when a high impedance voltage amplifier is used with the system.

When a charge amplifier is used rather than a voltage amplifier, the above requirement reduces to:

$R_{cal} << \frac{1}{\omega\,(C_p + C_1)}$ at the highest frequency of interest.

For $R_{cal} = 100$ ohms and a maximum frequency of interest at 10 Kcps, it is satisfactory for $C_p + C_1$ to be as large as ten thousand picofarads or more. With the charge amplifier, less than 1 per cent fall-off in high frequency response will be encountered if

$10\, R_{cal} \overset{<}{=} \frac{1}{\omega\,(C_p + C_1)}$ at the highest frequency of interest.

Calibration Voltage Level

It is of interest to determine the calibration voltage that should be used. During calibration insertion the transducer acts as a passive capacitor. The equivalent circuit is:

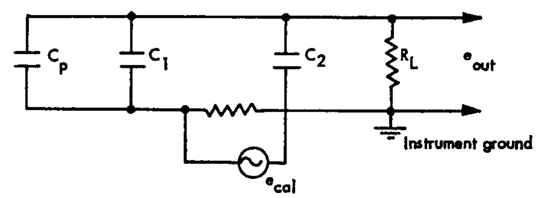


FIGURE 11

or, rearranging and combining elements:

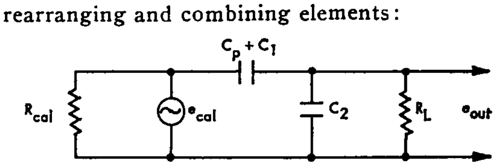


FIGURE 12

In order to simulate the transducer properly, the calibration voltage sensitivity must be

$$e_{cal} = \frac{q_p}{C_p + C_1}$$

For an accelerometer:

e_{cal} = calibration voltage sensitivity in peak volts/peak g
q_p = transducer charge sensitivity in pk pcmb/peak g
C_p = transducer capacitance in pf
C_1 = external capacitance in pf between the accelerometer and the point of calibration voltage insertion.

Laboratory calibrations of piezoelectric accelerometers are sometimes reported in terms of a known voltage sensitivity with a known external capacitance. In this case

$q_p = e_K\,(C_p + C_K)$, where
q_p = transducer charge sensitivity in pk pcmb/peak g
e_K = known voltage sensitivity in pk volts/pk g with an external capacitance C_K.
C_p = transducer capacitance in pf
C_K = external capacitance in pf for which e_K is known.

(cont. next page)

Calibration Simulation

Substituting in the previous relationship

$$e_{cal} = e_x \left(\frac{C_p + C_x}{C_p + C_1} \right)$$

In the above conclusion, e_{cal} and e_x can be either in volts/g or millivolts/g, as long as consistency is maintained. Voltages and g levels can likewise be peak, RMS, or peak-to-peak, as long as they are consistent.

The discussion concerning piezoelectric accelerometers is pertinent, too, to piezoelectric pressure pickups and force gages. Sensitivities are then expressed in electrical output per psi or electrical output per pound rather than electrical output per g. Electrical insulation of a pressure pickup or force gage from instrument ground may be difficult if not impractical in some situations.

With respect to the calibration circuit itself, there are three items worth mentioning when considering the following circuit approximation:

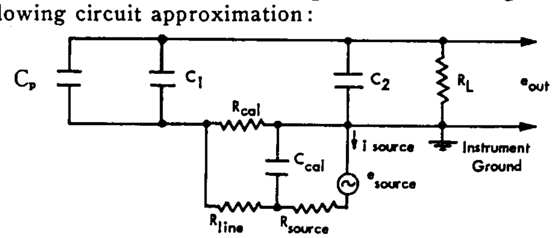


FIGURE 13

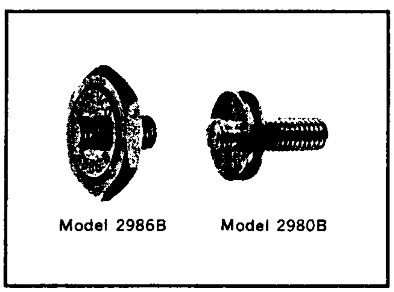
R_{source} = Output resistance of the calibration voltage source.

C_{cal} is primarily the cable capacitance of the cable from the insertion point to the calibration voltage source.

(1) The calibration voltage may not be the same as the voltage at the source being used to generate the calibration signal; it is usually desirable that the resistance R_{cal} be as small as is practical, and R_{source} plus R_{line} may then be appreciable in comparison with R_{cal}.

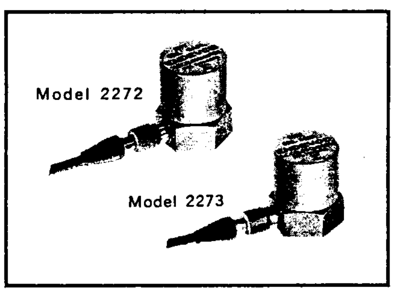
(2) The capacitive reactance Xc_{cal} will normally be very large compared with the resistances involved; however, it may be well to make certain that Xc_{cal} is at least 10 times $R_{cal} + R_{line}$ at the highest frequency to be used in the calibration simulation.

(3) It is desirable that the voltage e_{source} be isolated from any frame or power supply ground, such that the system instrument ground can be tied to earth ground at one point only. This may suggest transformer coupling of the voltage e_{source} into the calibration circuit. #



INSULATED MOUNTING STUDS

Troublesome ground loops in shock and vibration measuring systems can be prevented by using Endevco® Insulated Mounting Studs. Models 2980B and 2986B, shown above, provide 10 MΩ, minimum isolation from ground. This isolation is essential for calibration insertion. Detachable studs eliminate the expensive rebuilding required when integral studs are damaged. Most Endevco® Accelerometers accept detachable studs.

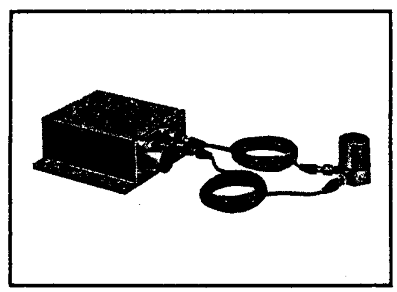


HIGH TEMPERATURE AND CRYOGENIC ACCELEROMETER

Model 2272 Accelerometer combines extremely high stability, high charge sensitivity, high capacitance, high resonant frequency, low transverse sensitivity, and reliable operation from −452 F to +500 F. It is capable of direct readout with a VTVM or oscilloscope. All these characteristics make it ideal for general purpose shock and vibration measurement.

ULTRA-HIGH TEMPERATURE AND CRYOGENIC ACCELEROMETER

Model 2273 Accelerometer exhibits extremely flat temperature response over the range of −452 F to +750 F with stability comparable to natural crystals. It not only gives ten times the charge sensitivity of accelerometers using quartz, but also eliminates the problem of twinning above +500 F. These features and an all-welded hermetic seal make this a true ultra-high temperature accelerometer.



TELEMETRY SIGNAL CONDITIONERS

Endevco® 2640 Series all transistorized one-package systems have variable features to meet the many requirements of telemetry systems. Filtering, biasing, limiting, extra power regulation, extra amplification, and calibration insertion are all available. Filters can be front-mounted on 2640 Charge Amplifiers.

Nomenclature

$a(t)$ = instantaneous acceleration input pulse.

a_a = acceleration indicated by accelerometer.

c = damping coefficient.

k_a = spring constant of accelerometer.

k_m = equivalent spring constant of mount.

m_a = mass of accelerometer.

m_m = equivalent mass of mount.

t = time.

x_a = displacement of accelerometer mass.

$\dot{x}_a$ = differential with respect to time of x_a.

$\ddot{x}_a$ = differential with respect to time of $\dot{x}_a$.

ΔV = velocity change of input pulse.

ξ = ratio of actual damping to critical $= C/2\sqrt{mk}$.

$\tau_i/_2$ = duration of input half-sine pulse.

ω = circular natural frequency.

ω_a = circular natural frequency of accelerometer.

ω_i = equivalent circular natural frequency of input pulse.

ω_m = circular natural frequency of mount.

y = input displacement.

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4. Carslaw, H. S. and Jaeger, J. E., "Operational Methods in Applied Mathematics," First Edition 1941, *Oxford University Press.*

Table 2

Case	a.1	a.2	b.1	b.2	c.1	c.2
ω_m equal to	$25\ \omega_i$	$25\ \omega_a$	$5\ \omega_i$	ω_m	ω_m	$5\ \omega_a$
ω_i equal to	ω_i	$5\ \omega_a$	ω_i	$5\ \omega_m$	$25\ \omega_m$	$25\ \omega_a$
ω_a equal to	$5\ \omega_i$	ω_a	$25\ \omega_i$	$25\ \omega_m$	$5\ \omega_m$	ω_a
Peak a_a	$1.08\ A$	$0.99\ \omega_a\Delta V$	$1.08\ A$	$0.99\ \omega_m\Delta V$	$1.06\ \omega_m\Delta V$	$1.06\ \omega_a\Delta V$
Peak a_a (from Table 1.)	A	$\omega_a\Delta V$	A	$\omega_m\Delta V$	$\omega_m\Delta V$	$\omega_a\Delta V$

Table 3

No.	Typical Impact Situation	Typical Values $\tau_i/_2$ Imp. Dur.	f_i equiv.	f_m	f_a	Remarks
1	a. Shock Wave phase of Water Entry b. Hard Target Impact of Bombs	20 μs	25,000 CPS	5,000 CPS nose plates	1000 CPS mechanical accelerometer	Case c.2—Accelerometer response greatly reduced; however, a measurement of velocity change can be obtained from the peak indication (Fig. 7 and Table 2).
2	a. Shock Wave phase of Water Entry b. Hard Target Impact of Bombs	20 μs	25,000 CPS	1000 CPS plate near ctr. of bomb	5,000 CPS Usable range of 25 KC crystal gage	Case c.1—Same remarks as No. 1.
3	a. Soft Target Impact of Bombs b. Water Entry of Streamlined Bombs c. Aircraft Ejection d. Torpedo-Submarine Impact e. Wooden Carrier Deck Impact	20 ms	25 CPS	725 CPS Medium Freq. Mount	125 CPS Low Freq. Mech. accel. used for high sensitivity	Case a.1—Accelerometer indicates acceleration with approx. an 8% error (Fig. 5 and Table 2).
4	Same as No. 3	20 ms	25 CPS	125 CPS Low Freq. Mount Char. of Aft sections	725 CPS mechanical accelerometer. Higher sensitivity than No. 1	Case b.1—Same remarks as No. 3.
5	a. Steel Carrier Deck Impact b. Some rough handling situation c. Medium Target Impacts	1/2 ms	1000 CPS	200 CPS Medium Frequency Cushioning System	5000 CPS High Freq comp. to be protected from shock	Case b.2—Shock sensed by component reduced by 60% (Fig. 6). If component is an accelerometer, accurate determination of velocity change can be obtained.
6	Same as No. 5	1/2 ms	1000 CPS	5000 CPS High Freq. Mount	200 CPS Low Freq. large components	Case a.2—Same remarks as No. 5.

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