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**Noise suppression and prevention in
piezoelectric transducer systems**

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A common problem in shock and vibration measuring systems is noise generated by ground loops and by pickup from electrostatic and electromagnetic fields. This article reviews the mechanisms of noise generation and suggests how such noise can be prevented or suppressed.

Introduction

Capacitively Coupled Noise. Presence of a varying electrostatic field (difference in potential) between two conductors coupled electrically by some stray capacitance is a prominent source of noise in piezoelectric transducer systems. For example, two pins in a connector act as plates of a capacitor and the mounting insulator is the dielectric. The pins are susceptible to noise pickup if they are not properly shielded.

Magnetically Coupled Noise. A varying magnetic field in the vicinity of a signal path is a source of noise in almost all measurement systems. If one of the pins above is conducting an ac current, there exists a magnetic field around it which can induce noise into the signal being carried on the other pin.

Current Coupled Noise. Installations where the signal current and other currents use a common path are also a prominent noise source. Any impedance in this path causes non-signal currents to induce noise into the signal currents. For example, if a conductor were used as both the "low" side of the signal path from a transducer and the "low" side of the ac exitation for another device, the common resistance would develop a component of the ac that would appear with the signal

.

Shielding for Capacitive Coupling. Charge amplifiers are widely used in vibration measurement systems because they offer so many advantages. But they are susceptible to electrostatic coupling because they respond directly to charge input. Consider the circuit in Figure 1 showing the schematic of a typical piezoelectric vibration measuring system. Assume that the transducer has a sensitivity of 10 pC/g and that the vibration level to be measured is approximately 1 g. Assume also an ac electrostatic voltage (e_1) present of 100 V (this can be typical). The charge amplifier measures the total charge appearing at its input, which in this example would be:

$$Q_1 = Q_a \times g + e_1 \times C_1$$
$$= 10 \ pC/g \times 1 \ g + 100 \ V \times C_1$$
$$= 10 \ pC + 100 \times C_1 \ pC$$

where C_1 is the capacitance, in pF, between the interference source and the charge amplifier input. This equation indicates that a coupling capacitance of only 0.01 pF will produce an error of 10% in the measurement. To ensure rejection of the electrostatic voltage, the signal lead must be shielded at all times, with the shield connected to the input common of the amplifier.

Shielding for Magnetic Coupling. It is generally more difficult to magnetically shield than to electrostatically shield. The instrumentation engineer must take precautions to ensure that instruments and cables are not located in the vicinity of power transformers, solenoids or motors; and that signal cables are not located in cable troughs with current carrying conductors. To understand the problem, refer to Figure 2. Circuit (a) illustrates a conductor carrying a current i, lying beside the input signal lines. The flux produces voltages e_1 and e_2 which have the polarities shown (at one particular instant). The magnitudes are:

$$e_1 = d/dt \ (N_1 \varnothing_1) \qquad\qquad e_2 = d/dt \ (N_2 \varnothing_2)$$

d/dt = rate of change with respect to time
N = number of turns being coupled (essentially one unless there is an excess of signal lead that has been neatly coiled!)
$\varnothing$ = number of lines of flux coupling the conductors (a function of the magnitude of i, how close the conductors are located over how great a length, and the effect of magnetic shielding).

If e_1 and e_2 were exactly equal, there would be no effective error signal. But this is seldom the case. A difference voltage usually exists, and it is induced into the measurement signal. Note that induced voltage will be larger at higher frequencies, due to the faster rate of change. Pickup can be suppressed by more direct cable runs through problem environments and by eliminating loops and turns.

A large improvement is achieved when the current-carrying conductor is tightly twisted with its return conductor. This results from the cancellation effect of having essentially equal and opposite electromagnetic fields in close proximity, with the resultant reduction of Ø. Similarly, the magnitude of the induced voltage can be reduced by locating a remote charge converter near the transducer and using twisted-pair cables between it and the amplifier. The amplified output also reduces the net effect of induced voltage. Remote converters are also beneficial because their lower output impedance reduces electrostatic coupling problems, but they may reduce signal-to-noise ratio because of their limited maximum signal input.

Isolation for Current Coupling. Current coupled noise occurs when a current other than the vibration signal is introduced into the measurement system. Referring to Figure 3, there would be no current flow in R_c if there were no potential difference between grounds 1 and 2. But grounding is never perfect, and it is usually less than desirable. In instrumentation "jargon," the path from ground 1 through R_c to ground 2 and back to ground 1 through e_g and R_g is called a ground loop. Such a ground loop can occur when a transducer is grounded directly through a test specimen, as well as indirectly through the coaxial cable shield to the amplifier which is grounded to the instrument rack and to the power system ground. When this is allowed to happen, the current flowing in the ground loop will couple a noise signal into the high side of the signal line to the amplifier.

The ground loop path can be suppressed by breaking the circuit at A, B or C so that the system is grounded at only one point. A break at A is achieved by using an insulating stud or washer. A break at B is obtained by using an accelerometer in which the low side of the transducer element and the cable shield are insulated from the transducer case. A break at C is accomplished by amplifier techniques rather than by simple insulation. A study of system grounding techniques and the relative achievements of each is provided in later sections.
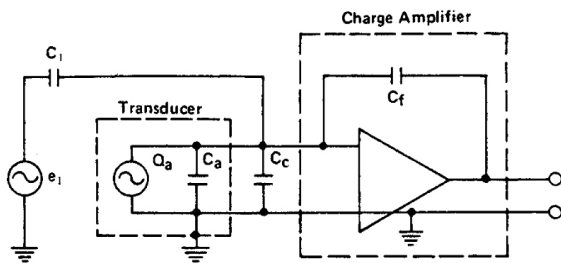

Figure 1: Electrostatic noise is generated by stray capacitance C_1 which couples electrostatical voltage, e_1 into the measurement system.
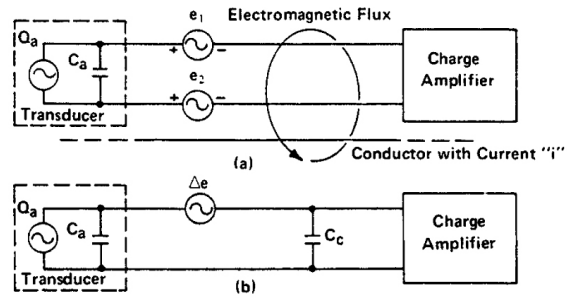

Figure 2: Electrostatic noise is generated by stray capacitance C_1 which couples electrostatical voltage, e_1 into the measurement system.
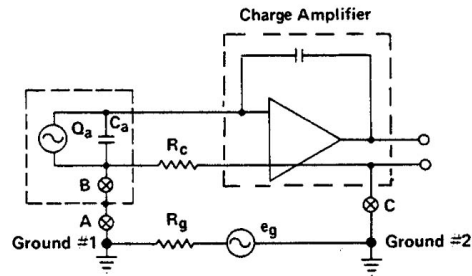

Figure 3: Electrostatic noise is generated by stray capacitance C_1 which couples electrostatical voltage, e_1 into the measurement system.

Amplifier Configurations. Amplifiers may be identified by the manner in which they handle the grounding of transducer signals. Single-ended amplifiers are most widely used. They have a common path for one side of the signal source, the amplifier input and amplifier output. This may be referred to as the low, common or ground side. Referring to Figure 4(a), the low side of the amplifier is "grounded" and in 4(b) "floating"

A single-ended grounded input should be used when the transducer low signal is connected to its case and the transducer is insulated from the specimen. Insulation can be accomplished by the use of an insulting mounting stud. This system provides excellent protection against noise pickup. When the transducer low signal is grounded to its case, which is in turn grounded through the test specimen, the system should not be grounded again at the amplifier. A single-ended floating amplifier eliminates the amplifier grounding, but a large capacitance to ground may still exist. Therefore, there may be poor protection against ground loops. The amplifier in 4(c) is better solution because the isolation amplifier opens the path from the transducer/ amplifier common. This not only breaks the dc path, but it also minimizes the ac (capacitive) path. Floating amplifiers do not provide as good isolation as single-ended grounded amplifiers, yet they are sometimes the only practical way to provide isolation.

If the transducer, cabling and charge amplifier are properly designed and correctly grounded, the system usually has a good signal-to-noise ratio. But these precautions may be inadequate for low level measurements in the presence of excessively high electromagnetic noise or when using very long cables. In these situations, remote charge converters are available for location near the sensor so that the majority of the line is driven from a low impedance source. Remote charge converters, like the circuits in integral electronic accelerometers, have limited dynamic range and limited slew rate as well as temperature limitations. In applications where these factors are critical to performance of the system, a so called differential charge amplifier may be required.

Charge Amplifier

Single-ended, Grounded

(a)

Charge Amplifier

Single-ended, Floating

(b)

Charge Amplifier

Isolation Amplifier

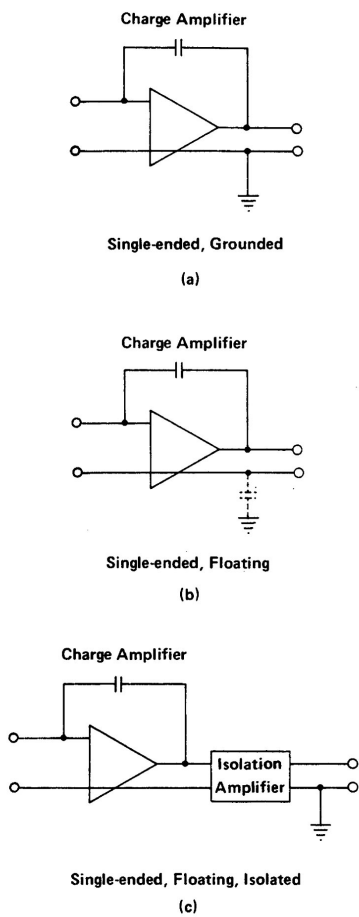**Single-ended, Floating, Isolated**

(c)

Figure 4: single-ended amplifiers are available with the input common path either grounded or floating.

Differential amplifiers reject common mode signals; i.e. non-data signals present on both conductors of a signal line. Unlike single-ended amplifiers which amplify the total signal between their input terminals, differential amplifiers amplify only the difference signal. Traditional differential amplifiers shown in Figure 5(a) and (b) use symmetrical capacitive feedback circuits, but the symmetry

is easily disrupted by a change in gain or change of cable or transducer. And they require use of specially-balanced differential accelerometers.

Figure 5(c) illustrates the differential charge amplifier. It overcomes symmetry problems and has proven to be highly satisfactory. Unlike common laboratory differential amplifiers, differential charge amplifiers do not reject the common mode signal. They equally amplify the two individual signals with respect to ground and differentially sum the resultants. The first amplifier (charge converter) is floating and is shielded with respect to the output ground. It provides a stable high level source for the second amplifier, which is a "differential in, single-ended out" voltage amplifier.

Charge Amplifier

Differential in Single-ended Out (Semi-Differential)

(a)

Charge Amplifier

Differential in, Differential Out (True Differential)

(b)

Charge Amplifier   **Voltage Amplifier**

Single-ended Floating Charge Converter to Differential In, Single-ended Out Amplifier
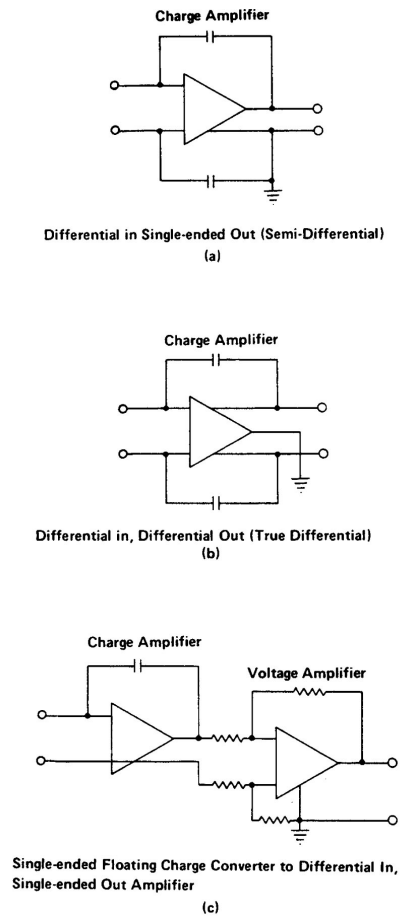
(c)

Figure 5: Differential amplifiers provide common mode rejection. The design shown in (c) is best suited to industrial applications

Because the two amplifiers are integrally assembled, symmetrical configuration is maintained, and the higher operating level allows lower impedance circuitry so that lack of symmetry due to reactive effects is greatly reduced. Therefore, a high degree of common mode suppression is achieved with much less difficulty than with conventional

differential amplifier systems. This is the design used in Meggitt's charge amplifiers, such as the 2735 and 6633. These amplifiers can also be operated in the single-ended grounded input mode.

A study of grounding configurations

Case-grounded transducer/Insulated mounting/Single-ended grounded amplifier. Generally, a case-grounded accelerometer with insulated mounting gives the best protection against pickup induced by ground-loop currents. The system should terminate with a single-ended grounded amplifier. The electrical equivalent of this system is shown in Figure 6.
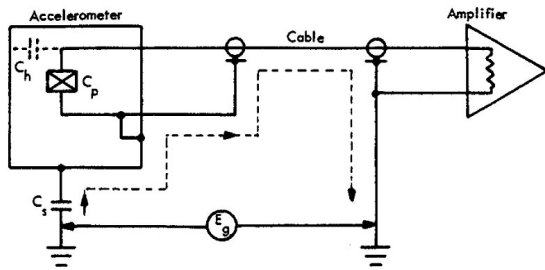

Figure 6: Case-grounded accelerometer with insulated mounting stud and single-ended grounded amplifier provides excellent protection against pickup induced by ground loops and capacitive coupling.

The accelerometer has an inherent capacitance C_h between the case and the signal side of the crystal (actually the crystal capacitance). It would normally be susceptible to electrostatic pickup, but the insulated mounting restricts ground loop currents to small values and to a path through signal ground as illustrated. The error introduced is negligible, typically less then 0.0001 g (equivalent)/V for 60 and 400 Hz power line frequencies.

Manufacturers offer a variety of insulated mounting studs and washers as well as cementing studs which may be attached to the specimen with an insulating adhesive. Some case grounded accelerometers have an integral insulating stud or washer. Because insulating studs lower the mounting resonance frequency and therefore the upper frequency limit by 15 to 30% compared to that available with grounded studs, it is sometimes necessary to use a grounded stud. Or, high temperatures may prevent the use of insulating adhesives.

Case-Isolated transducer / Grounded mounting / Single-ended grounded amplifier. Accelerometers with their electrical connectors insulated from the case may be more susceptible to noise pickup than case-grounded accelerometers. The electrical schematic of such a system is shown in Figure 7. There is no significant effect from coupling E_g through C_{in}. But the possibility of capacitance C_h from the case to the signal side of the crystal makes the circuit highly susceptible to pickup induced by E_g. This requires careful design of the accelerometer to minimize C_h.
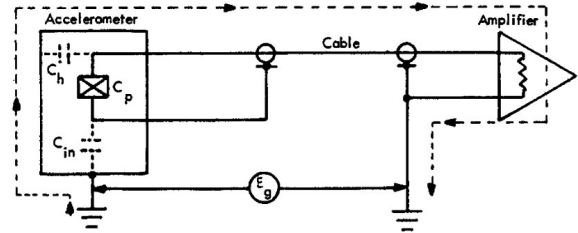

Figure 7: Case-isolated accelerometer with grounded mounting and single-ended grounded amplifier is susceptible to noise pickup through internal stray capacitance.

Case-grounded transducer / Grounded mounting / Single-ended grounded amplifier. This system shown in Figure 8 has two grounds and is, therefore, highly susceptible to ground loops. It is the most noise prone method of installing and connecting accelerometers. If a potential E_g exists between the two grounds, and it probably does, there is no alternative except to break the ground loop circuit.
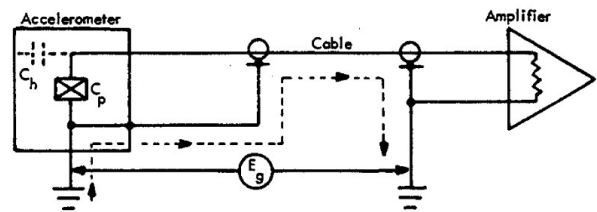

Figure 8: Measuring systems grounded at the transducer and at the amplifier are highly susceptible to noise induced by ground loops.

Case-grounded transducer / Grounding mounting / Floating amplifier. If a case-grounded transducer must be grounded through the test specimen, a floating amplifier should be used to ensure a single system ground, see Figure 9. The system may still be susceptible to ground loops because of imperfect grounding at the amplifier output unless an isolation amplifier is used, as in Figure 4(c). This feature is incorporated in the 2735 charge amplifier, whose differential amplifier conifguration shown in Figure 5(c) also protects against common mode noise. This is the best alternative to the system consisting of case-grounded transducer, insulated mounting and single-ended ground amplifier.
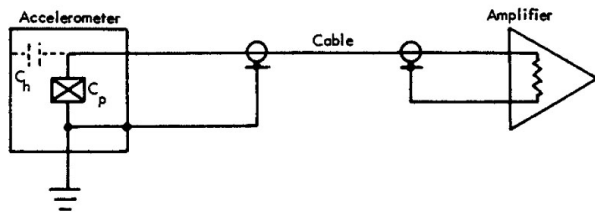
Case-grounded transducer / Insulated mounting / Floating amplifier. This system has no ground and is the logical recipient of spurious noise and ground loops from instruments, motors and other elctrical equipment on the same power line.

Case-grounded transducer / Insulated mounting / Floating amplifier. This system also lacks a ground connection and is susceptible to pickup from other equipment on the same power line.

A quantitative evaluation of noise suppression

Various instrument systems and ground configurations have been discussed qualitatively. Here, let us preform a quantitative comparison. Consider a system consisting of transducer, a coaxial connecting cable and a charge amplifier which exhibit the following parameters:

Transducer capacitance	1000 pF
Cable capacitance	15,000 pf
Cable resistance	8 ohms
Resistance between ground points	10 ohms
Insulating stud leakage resistance	100 megohms
Capacitance	70 pF
Floating transducer coupling capacitance to common	5 pF
Coupling capacitance to signal lead	5 pF
Coupling capacitance unbalance	0.5 pF
Floating charge amplifier resistance between grounds	50 megohms
Capacitance between grounds	200 pF

Assume a 50 Hz interface voltage and a voltage difference between grounding points of 1 V. A comparison of the current coupled noise magnitude for various system configurations is given in the Table below. This is a typical set of values. The magnitude will differ significantly for other test conditions, but the relative magnitudes serve to rank order the effectiveness of the various systems in protecting against noise pickup.

The Table indicates that a case-grounded transducer with an insulating stud and a single-ended ground amplifier

provides excellent protection. It is the simplest system available for laboratory and field use. If insulated stud mounting is not practical, use a case-grounded transducer with grounded mounting and a differential charge amplifier. With either system, a remote charge converter will significantly improve signal-to-noise ratio.

System	Case-Grounded Transducer	Case-Isolated Transducer
Grounded mounting, single-ended, grounded charge amplifier	3600 pC	5pC
Grounded mounting, single-ended, charge amplifier with remote charge converter (Endevco 2735 and 2731B)	134 pC	5 pC
Insulating stud, single-ended, grounded charge amplifier (Endevco 2735)	1.8×10^{-3} pC	5 pC
Insulating stud, single-ended charge amplifier with remote charge converter (Endevco 2735 and 2731B)	6.8×10^{-5} pC	5 pC
Grounded mounting, true differential charge amplifier	500 pC	0.5 pC
Grounded mounting, semi-differential charge amplifier	2.4×10^{-2} pC	0.5 pC
Grounded mounting, differential charge amplifier (Endevco 2735)	1.0×10^{-2} pC	0.5 pC
Grounded mounting, differential charge amplifier with remote charge converter (Endevco 2735 and 2731B)	1.8×10^{-4} pC	5 pC

Summary

A few simple rules will help minimize noise pickup in most vibration measurement systems.

1. Use high quality coaxial cable and coaxial connectors at each electrical connection.
2. Ground the system at a single point. Preferably, choose a point where the ground can be controlled and positive.
3. Avoid placement of cables in cable troughs or harnesses that contain power or high current conductors.
4. Avoid running cables close to large electromagnetic sources, and avoid long cable runs in difficult environments.
5. Use a remote charge converter if the susceptibility to noise pickup is high.
6. Last, choose a high sensitivity accelerometer to reduce the effect of noise pickup on signal-to-noise ratio.