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A DIFFERENTIAL PIEZOELECTRIC ACCELEROMETER CHARGE SYSTEM

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ABSTRACT

In certain vibration measurement situations, the differential system described in this paper has significant advantages over the traditional single-ended system. These advantages are most apparent in one application for which the differential piezoelectric technique was developed; that is, airborne monitoring systems employing piezoelectric accelerometers to measure jet engine vibration. As a system, the differential technique is relatively insensitive to extraneous electrical signals at the accelerometer mounting surface, along the length of the input cable, and at intervening connectors. In most applications ground loop and frame voltage problems can be eliminated without using traditional single-ended isolation techniques, such as insulated studs. The differential technique also allows the use of a single bulkhead connector for more than one accelerometer input. Triboelectric cable noise is reduced in the differential system to the point where an adequate signal-to-noise ratio can be obtained without noise-treating the input cable. A brief description of the differential piezoelectric accelerometer system is presented, and a comparison is made to the single-ended system.

INTRODUCTION

While traditional single-ended piezoelectric accelerometer systems have been successfully used for many years to measure vibration in a wide variety of applications, the continuous vibration monitoring of jet engines in airborne vibration monitoring systems has presented unique problems. As a practical solution to such problems as ground loops, multiple bulkheads, high magnetic fields, lock-wiring, cable noise, and established cabling and electronics packaging practices employed by the aircraft industry, a differential technique was developed.

THEORY OF OPERATION

As with any "differential" system, the differential piezoelectric accelerometer charge system is sensitive to the difference between the signals present on the input terminals. In the case of the differential piezoelectric accelerometer charge system, the output voltage of the differential charge converter (with respect to ground) is proportional to the differential charge signal developed by the accelerometer between the input leads. (See Figure 1)

CONSTRUCTION

The accelerometer is constructed with the piezoelectric crystal assembly electrcially floating with respect to the case. The accelerometer signal leads are connected to the pins of the connector. The case of the differential accelerometer is both mechanically and electrically connected to the shell of the connector. Figure 2 shows the differential accelerometer along with the equivalent single-ended construction. The interconnecting cable between the accelerometer and the charge amplifier is twisted-pair shielded cable for the differential system as compared to coaxial cable for the single-ended system. The shield is connected to the shell of cable connectors, while the twisted leads are attached to the connector pins. The differential charge amplifier consists of a differential operational amplifier with capacitive feedback that converts the differential charge signal developed by the accelerometer to a voltage signal referenced to ground. Figure 1 illustrates the block diagram representative of both the differential and single-ended systems.

OPERATION

It can be shown that the approximate transfer equation for the differential system is (Ref. Figure 1);

$$(1) \qquad \frac{e_o}{q_a} = \frac{1}{C_f} \left(1 + \frac{C_x}{C_y} \right)$$

where q_a is the accelerometer charge output, C_f is the feedback capacitance of the charge converter, and e_o is the output voltage with respect to ground. Provided the impedance from either input lead to ground (C_x & C_y) is the same, equation (1) is of the same nature as the transfer equation of the single-ended system;

$$(2) \qquad \frac{e_o}{q_a} = \frac{1}{C_f}$$

For the balanced condition, it can be seen that the differential system is equivalent to the single-ended system in terms of such typical characteristics as frequency response and temperature response.

ERROR ANALYSIS

The primary advantage of the differential system is in its inherent cancellation of extraneous signals. In the following paragraphs the nature of these signals and the relative response of the single-ended and differential systems are examined.

In an aircraft environment the most likely sources of extraneous signals common to piezoelectric accelerometer systems are frame voltages, ground loop potentials, electrostatic pickup, and cable noise. Frame voltages and ground loop potentials are closely related since they both represent potentials on the case of the accelerometer with respect to system ground.

Frame voltages common to commercial aircraft are the result of the practice of using the structure of the aircraft as the neutral power lead of the three phase power system. When an unbalanced load is placed on the generators, a current flows through the frame of the ship which develops a voltage drop across the small, but finite, resistance of the aircraft frame between the engine mounted generator and the reference ground buss in the electronic compartment.

Ground loop potentials, on the other hand, can exist when there is an absence of frame voltages. Figure 3 illustrates this effect. When the accelerometer is mounted to the engine, and through cable and electronics, is electrically connected to the ground buss, a loop is completed since the engine is also electrically connected to the ground buss. Thus, a potential is readily developed at the accelerometer due to the stray magnetic flux from the generator. It should be noted that a ground loop can be produced at any point from the mounting surface to electronics such as at intervening bulkheads.

Electrostatic pickup is produced by any voltage source such as signal or power leads in close proximity to the input so that a finite capacitance exists between the voltage source and the input.

Cable noise is generally due to what is called the "triboelectric" effect. The triboelectric effect refers to potentials developed between the shield and the outer surface of the dielectric due to shield separation resulting from vibration of the cable. This voltage develops a charge input to the system through the capacitance of the dielectric to the signal leads.

Single-ended error sensitivity - In order to best illustrate the relative performance of the differential system, a comparison to the response of the single-ended system to the various error sources is developed. For both ground loops and frame voltages the response of the single-ended accelerometer of the construction shown in Figure 2 will be approximately described by;

$$(3) \qquad \frac{e_o}{e_g} = \frac{C_a}{C_f}$$

where e_g is the frame voltage at the accelerometer. In general, C_a will range from 500 to 10,000 pF, while C_f is generally 1000 pF. Thus, for either frame voltage or ground loop potentials, the output voltage of the single-ended system described will be from 1/2 to 10 times the accelerometer case voltage. The above analysis is a simplification since the effects of distributed voltage throughout the length of the cable have been neglected.

Normally, the sensitivity of the single-ended system to frame voltage and ground loop potentials can be greatly reduced by electrically isolating the case and cable shield from the mounting surface and intervening frame structures. This technique eliminates the troublesome ground loop, and substantially reduces the frame voltage sensitivity as described by;

$$(4) \qquad \frac{e_o}{e_g} = \frac{C_g}{C_f} \left(\frac{s}{s + \frac{1}{R_c C_a}} \right)$$

where C_g is the capacitance of the insulation (normally 10 to 100 pF), R_c is the cable shield resistance and s is the Laplace notation equal to $j\omega$.

While the isolation technique would appear to solve the frame voltage and ground loop problem, for airborne engine vibration monitoring it is not considered practicable. The isolation technique would require isolation of each accelerometer and bulkhead connector from the engine and the aircraft frame. This isolation could not be allowed to deteriorate in the engine environment which includes fuel and oil spillage and, in some cases, temperatures in excess of 1000°F. In addition, complex lock-wiring techniques would have to be employed in order to avoid shorting out the insulators when lock-wiring the connectors and mounting hardware to the engine.

The approximate response of the single-ended system to electrostatic pickup is;

$$(5) \qquad \frac{e_o}{e_p} = \frac{C_p}{C_f}$$

where e_p is the electrostatic pickup voltage and

C_p is the capacitance between the pickup voltage source and the input. The single-ended system must have its input completely shielded including the cable, connectors, and within the electronics package, to eliminate electrostatic pickup. In terms of hardware this would mean that individual coaxial cables, bulkhead connectors, and coaxial connectors on the electronics package for each channel would be used. Again, this is not practicable for an airborne engine monitoring system since such cabling and connectors are non-standard and also relatively expensive (especially flame-proof firewall connectors).

The problem of cable noise is generally minimized for the single-ended system by "noise-treating" the coaxial cable. The "noise-treatment" consists of coating the outer surface of the dielectric with a conductive material such as silver paste or carbon, which shorts out the triboelectric voltage. But, again, the practicality of the solution is limited as such noise treatment will deteriorate with time, and in the engine environment the time to failure can be very short.

Figure 4 illustrates the equivalent error signal sources discussed above for the single-ended system.

Differential error sensitivity - By comparison, the differential system represents a practical solution to the problems stated. With respect to frame voltage, ground loop potentials, and electrostatic pickup, the differential system minimizes these effects by virtue of the characteristic of responding to only the difference in signal between its input leads. Thus, the error signals mentioned are regarded as common mode signals as they are equally impressed upon both leads. Provided there is a reasonable balance from each lead to the error source, a negligible difference in signal will exist between the input leads; hence, the output signal will be negligible. This characteristic is evident from the following approximate equation (See Figure 5);

$$(6) \qquad \frac{e_o}{e_e} = \frac{C_e}{C_f}$$

where e_e is the error voltage and C_e is the unbalanced capacitance from either lead to the error voltage source. For frame voltages and ground loop potentials C_e is equal to the difference between C_X and C_Y. In most practical situations C_e can be kept to less than 10 pF. Therefore, the differential system is, for all practical purposes, insensitive to frame voltages, ground loop potentials, and electrostatic pickup without employing the isolation and shielding required by the single-ended system.

In terms of cable noise, the sensitivity to triboelectric voltages is a function of the unbalance of capacitance between the source and either signal lead. It has been established in practice that tightly twisted signal leads of the twisted pair shielded cable significantly reduces cable noise due to the triboelectric effect. While such twisting is not as efficient as "noise treatment", the triboelectric noise can be reduced to a satisfactory level merely by being selective as to the type of twisted pair shielded cable employed. It should be noted that when "noise-treated" twisted pair cable is employed, the noise level is lower than the single-ended systems with "noise-treated" coaxial cable.

Summary - As can be summarized from the above discussion, the differential system essentially eliminates many of the problems associated with applying piezoelectric accelerometers for aircraft engine monitoring. Since the differential system is relatively insensitive to frame voltage and ground loops, the accelerometer can be mounted on the engine and the connectors can be attached to bulkheads without electrical isolation. Lock-wiring can be accomplished in the traditional method and the problems associated with maintaining isolation in the engine environment are eliminated. Again, due to the insensitivity to electrostatic pickup, provided a reasonable balance is maintained, continuous shielding is unnecessary. Hence, a number of accelerometer signals can be fed through a common multi-pin connector. In fact, with some precaution, other signals can be tolerated on the same connector. The connector on the electronics package can be of rack and panel type, and the electronics can be of standard package design. The differential system employs cabling of the standard type which has been proven to be reliable in the aircraft environment. For this application the differential piezoelectric accelerometer charge system is well suited, both in terms of performance and convenience.

CONCLUSIONS

The differential piezoelectric accelerometer charge system senses the difference in charge developed between the accelerometer signal leads. Neither terminal of the accelerometer crystal stack is electrically referenced. The signal is transmitted to the differential charge converter by means of a shielded, twisted-pair cable. The charge converter consists of a differential operational amplifier with capacitive feedback. The case of the accelerometer, connector shells, and cable shield are electrically connected to ground. The response of the differential system to vibration is equivalent to that of the traditional single-ended system.

Several error sources present significant problems to the single-ended system. Frame voltage and ground loop potentials require the use of isolation. Pickup and cable noise make individual bulkhead connectors, continuous shielding, and "noise treatment" coaxial cable a requirement for the single-ended system. These preventative techniques are of doubtful practical worth in this application.

By contrast, the differential system is relatively insensitive to these problems without using any unusual material or installation techniques. Frame voltage, ground loop potentials, and electrostatic pickup appear as common mode signals, and are rejected by the differential system as a function of the capacitive balance of the signal leads to the error source. Cable noise due to the triboelectric effect is significantly reduced by the same common mode rejection by the system. Thus, the differential piezoelectric accelerometer charge system is well suited to the application for which it was designed.

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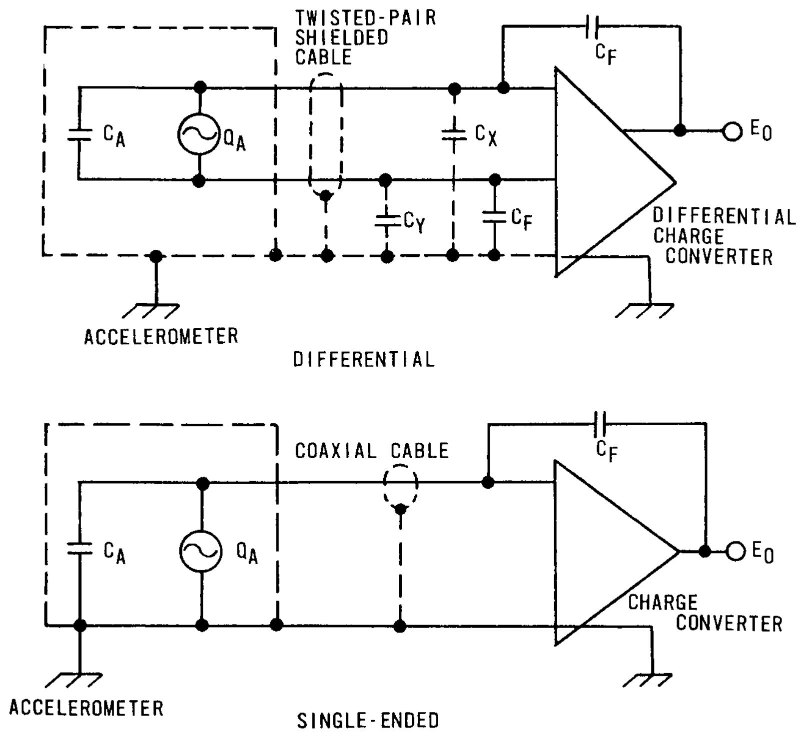
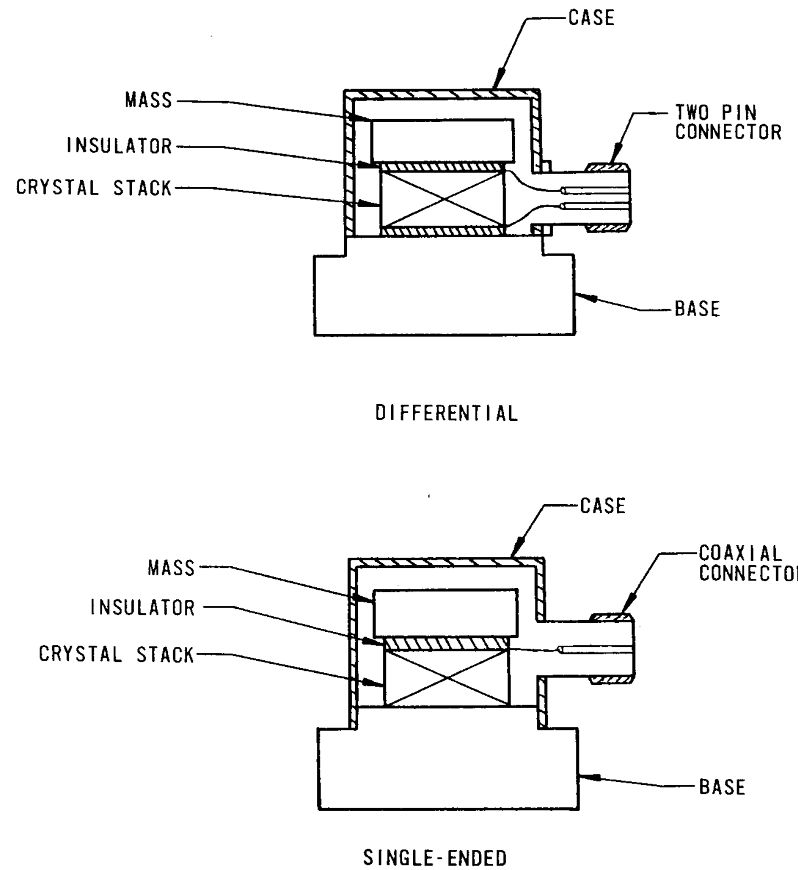


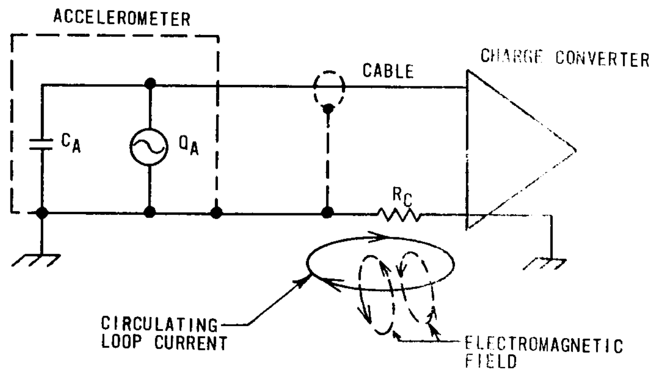
BLOCK DIAGRAMS

FIGURE 1



PIEZOELECTRIC ACCELEROMETER CONSTRUCTION

FIGURE 2

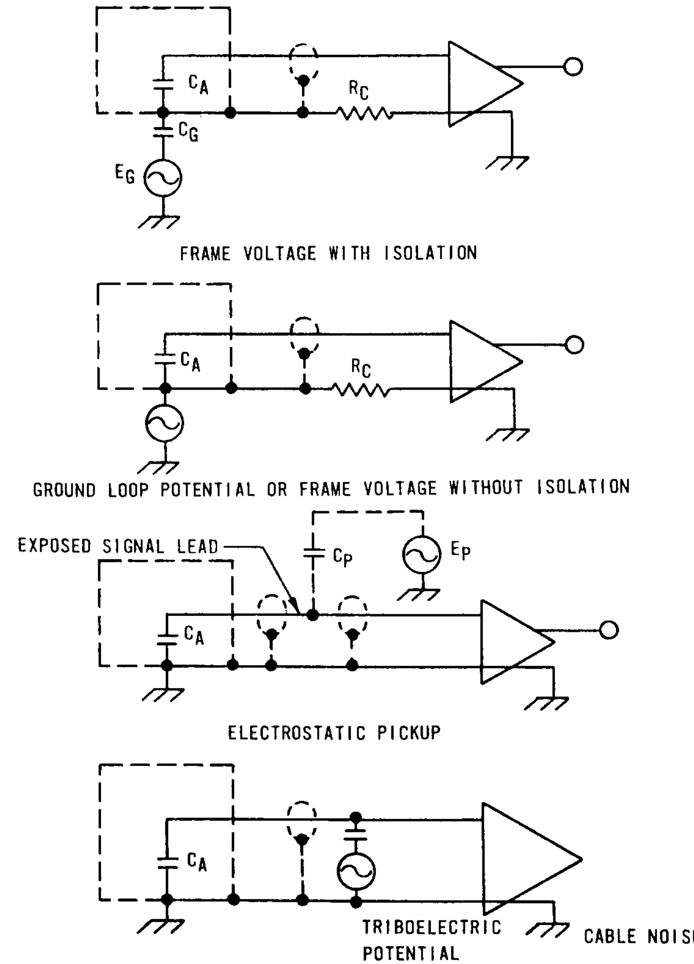


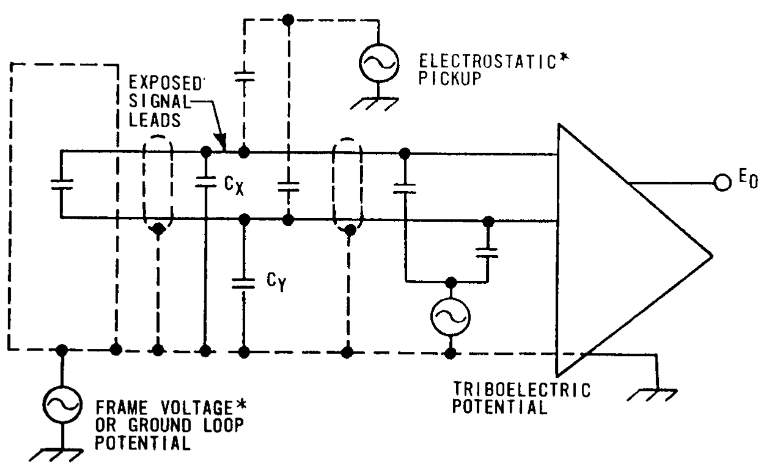
GROUND LOOP PATH

FIGURE 3

SINGLE-ENDED ERROR SIGNALS

FIGURE 4





* REFERRED TO IN TEXT AS E_E

DIFFERENTIAL ERROR SIGNALS

FIGURE 5