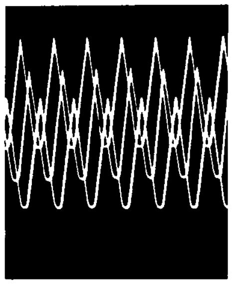
ENDEVCO TECH PAPER



TP 235

PIEZOELECTRIC TRANSDUCER FAILURE MODES AND EFFECTS

By Robert T. Reeds

SUMMARY

An investigation of the potential failure modes of piezoelectric transducers together with analysis of actual field use failure probabilities indicates preventative measures and provides the basis for direction of design activity toward reduction of existing failure modes. Discussion and recommendations for each mode are included, based upon analysis of units returned to the manufacturer after various lengths and applications of service, and based upon controlled experiments of transducer capabilities. The results are tabulated to include relative probabilities of failure, precautions to be observed to avoid failure causes, and failure effect significance. This analysis is also useful to the instrumentation and systems engineer in developing exacting reliability models.

Key Words (for information retrieval)

Accelerometer
Failure Modes, Mechanisms, and Effects
Piezoelectric
Reliability
Transducers

INTRODUCTION

This report describes the results and conclusions of observations and tests of more than one thousand transducers made over a two-year period. During this time, each transducer returned to Endevco after field service for either recalibration or repair has been tested for performance and stability, and in the case of repair units, analyzed for failure mechanism. About one hundred transducers, or ten per cent of the total, were analyzed for degradation or failure causes. All failure modes which actually occurred during the preparation of the report are included, plus modes which, although rare, are either significant to the use intended, or which in engineering judgment have more than an insignificant chance of occurring.

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INTRODUCTION (continued)

All probabilities calculated for this analysis are relative; that is, if a failure is assumed to occur, the stated probabilities are that it will fail in the given manner. These may be related to observed failure rates as required. Highly conservative estimates of field reliability have been assessed from repair and recalibration records. Data by transducer type are shown in Table 1. These data exclude a large number of transducers in active service which have never been returned for calibration. It is estimated that the times listed in Table 1 would be at least doubled if the entire population could be included.

It has been established that the majority of piezoelectric transducer failures are secondary failures caused by physical damage to the unit. These induced failures may take a variety of forms and are, therefore, treated under the over-all failure effect analysis. Discussion is included of preventative action, relative probabilities, and failure indicators. Since failure effects are of primary concern to the user, the tables in this report are so arranged, with cross tabulation by cause.

DESCRIPTION OF PIEZOELECTRIC TRANSDUCERS

The principal transducer types investigated are the single-ended compression, and shear piezoelectric accelerometers, which are shown pictorially in Figure 1. Basically, an SEC unit has a piezoelectric element mounted with a mass, under compression. The accelerating force to be measured further compresses or relaxes the preload, resulting in an electrical charge due to the piezoelectric effect in the crystal. This is picked off by means of electrodes at surfaces of the crystal, which are wired to an external connector. Shear versions of piezoelectric accelerometers behave analogously, but using the shear mode.

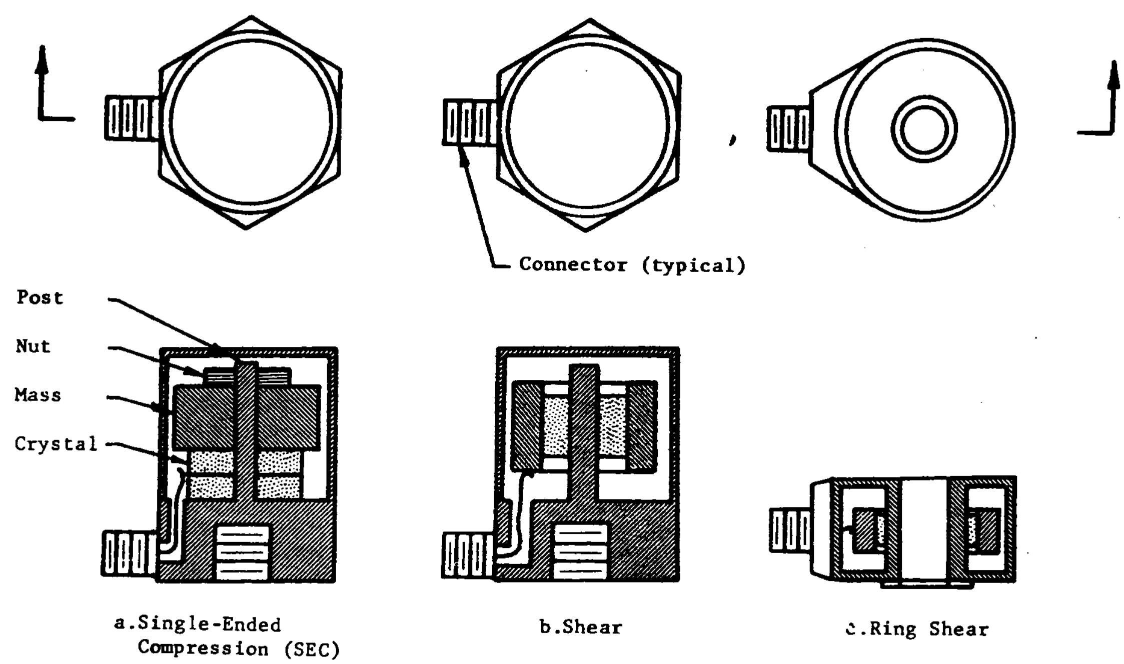

FIGURE 1.

PIEZOELECTRIC ACCELEROMETERS

DESCRIPTION OF PIEZOELECTRIC TRANSDUCERS (continued)

Omission of the seismic mass and a change of the structure so as to transmit external forces directly to the crystal results in a transducer sensitive to pressure (Figure 2) or force (Figure 3.) These examples do not exhaust the possibilities, but are representative.

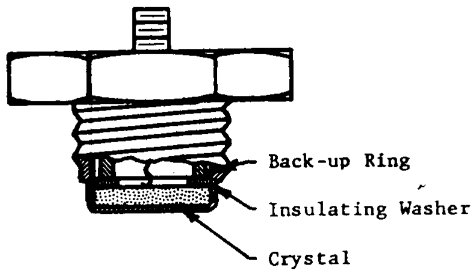

FIGURE 2.

PIEZOELECTRIC PRESSURE TRANSDUCER

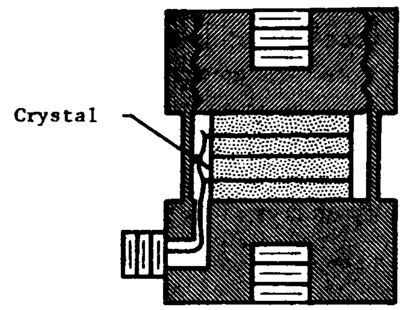

FIGURE 3.

PIEZOELECTRIC FORCE GAGE

ANALYSIS METHOD

Each transducer to be analyzed was first inspected and tested to operating performance specifications. Analysis methods were selected to suit each individual case, usually consisting of removal of the protective cover, and microscopic inspection of the piezoelectric element and structure. Occasionally, other means such as X-Ray of intact units were undertaken. The most probable cause was then determined from observed condition and tested performance. Where more than one probable cause existed, analysis was continued either until these were reduced to one, or until the preponderance of evidence indicated a most probable cause. Each failure mode was also duplicated by laboratory simulation.

FAILURE MODES

Seven effects account for ninety-seven per cent of the failures of piezoelectric accelerometers. These are: Transverse Axis Sensitivity (cross talk); Electrically Open; Shorted; Sensitivity Change; Capacitance Change; Poor Frequency Response; and Low Resistance. Sundry effects which account for the only significant modes in the remaining three per cent of experienced failures include Amplitude Non-Linearity, Loss of Identification, and Reversed Polarity.

TRANSVERSE AXIS SENSITIVITY (Cross Talk)

Relative Probability:	SEC	.23
	Shear	.17
	Ring	.03
	Miniature	.01

Piezoelectric accelerometers are so designed that for most applications the level of cross talk may be ignored in comparison with measurement errors in the test equipment. However, for the purposes of conservative analysis, any cross talk in excess of specification limits is considered a failure. Electrical non-homogeneity of the piezoelectric material is the principal source of cross talk in accelerometers as sold, with electrical non-perpendicularity of crystal to base caused by mechanical tolerances a minor source.

Causes

1. Deformed or gouged base, most frequently the result of either irregularities in the surface to which the accelerometer has been mounted, or dirt, sand, or metal particles not cleaned from that mounting surface. This problem can be aggravated by field attempts to resurface the accelerometer mounting end, which most frequently further degrades cross talk rather than improving it. This condition can usually be corrected by factory repair, unless the surface is severely damaged or the internal structure has been damaged. Preventative action is to inspect the mounting surface before each usage.

2. Occasionally caused by excess transverse shock, great enough to affect the internal alignment, and/or cause internal breakage. The prevention is by selection of transducers having shock limits greater than will be experienced, and care in handling.

OPEN ELECTRICALLY

Relative Probability:	SEC	.16
	Shear	.04
	Ring	.46
	Miniature	.10

The electrical path in an accelerometer is from the connector, through an internal lead wire to electrode(s) at the crystal surfaces, next the source crystals, and grounded either through contact with the case and thus to the outer portion of the connector or in insulated versions through a path similar to the positive path. Theoretically, an open circuit can occur in any of these elemental parts or interfaces. In practice, damage to the crystal element(s) is almost invariably the source of an open circuit.

OPEN ELECTRICALLY (continued)

Causes

1. Crystal damage due to excess shock. The degree of this damage can vary from complete disintegration of the crystal (extreme and sustained shock) to chips and cracks. Damage less than complete disintegration will usually be observed as a reduction of sensitivity and/or capacitance rather than a completely open circuit.

2. Internal lead fracture, also usually caused by excess shock. Could be caused by defective weld of connector to lead or lead to electrode if such defective units were allowed into the field. Lead material fatigue is another theoretical possibility; however, it should not be experienced with a properly designed transducer. Typical lead wire stresses for knowledgeable designs under maximum rated vibration are less than one per cent of the material endurance limit.

3. Connector damage, usually obvious, caused by dropping or by careless use of wrenches in mounting or demounting the accelerometer. Plastic socket wrenches which are available to fit all ENDEVCO® Accelerometers are recommended, but ordinary mechanics' open-end wrenches can be used with care.

SHORTED

Relative Probability:	SEC	.16
	Shear	.15
	Ring	.06
	Miniature	.29

Except for electrically isolated models, the entire case is at ground potential; therefore, any contact between the case and that portion of the device which is electrically on the positive side of the crystal element will cause a short.

Causes

1. Excess shock is the overwhelmingly prevalent cause of shorted transducers. This can cause either the preload to relax, or the coulomb friction of the crystal elements to be exceeded, allowing the electrodes to slide or rotate about the post and short the lead wire to the case.

2. Observed in the past as being caused by an extruded burr formed in assembly of the cover to base. Fortunately uncommon, but requires knowledgeable design to positively prevent.

3. Internal distortion or rupture caused by the use of too long a mounting stud. See discussion under Induced Failure commentary. Do not bottom studs in the accelerometer recess!

SHORTED/Causes (continued)

4. Intermittent shorting caused by foreign particles such as weld splatter created by excessive current in the cover weld operation. Since the only positive detection method is by destructive disassembly, this cause is most easily avoided by refusing to accept accelerometers with welds of poor workmanship, for the prevention is a controlled welding process.

SENSITIVITY CHANGE
CAPACITANCE CHANGE

Relative Probability:		
	SEC	.19
	Shear	.43
	Ring	.31
	Miniature	.41

These failure modes are treated together not because they necessarily occur together, but because the causes of change are by and large the same. The capacitance of a piezoelectric transducer is a function of the dielectric constant of the crystal material, and the geometry of its construction. The very minor effect of internal lead wire and connector may be entirely ignored. Sensitivity, on the other hand, is a function also of the crystal material's properties and geometry, but in addition is a function of the seismic mass and to a very small extent the preload. Thus, any change in the crystal geometry will affect both capacitance and sensitivity. Changes in the preload will affect sensitivity but not capacitance.

Causes

1. Crystal damage due to excess axial shock. See "Open Electrically" for complete description.

2. Relaxed preload due to stretched center post, caused by excess transverse shock.

3. Case strain due to over-torquing when mounting or other overstress.

4. Degradation due to instability of crystal material or surface. Except for a very few natural piezoelectric materials, less popular today because of performance limitations, the crystal material of which an accelerometer is constructed must be polarized to create a crystal domain conducive to the piezoelectric effect. If the crystal material is marginally unstable, depolarization may occur over a period of time or with temperature cycling, resulting in a corresponding deterioration of sensitivity. Similarly, stresses induced under vibration or temperature cycling can affect the sensitivity of natural crystal materials. These cause a slight change in the assembly preload but more significantly appear to cause a change in the effective area of the crystal to electrode interface, resulting in changes of both sensitivity and capacitance.

FREQUENCY RESPONSE

Relative Probability:		
	SEC	.20
	Shear	.19
	Ring	.12
	Miniature	.13

The operating limit of vibration frequency is governed by the resonant frequency of the transducer. Typically, measurements above one-fifth the resonant frequency are subject to increasingly significant error. This inherent limitation is normally sufficiently high in frequency as to pose no problem in instrumentation. However, if something causes low frequency resonances to develop, measurement error can occur over operating frequencies.

Causes

1. Reduction in resonant frequency as a result of crystal damage due to excess shock. See "Open Electrically" for complete description.

2. Base damage which prevents proper seating on the mounting surface. Since the operating characteristics of an accelerometer are as much a function of the coupling of transducer to mounting surface as of the transducer itself, any loss of coupling in operation such as by distortion or damage to the mounting surface can have the effect of lowering the transducer's resonant frequency.

3. Base deformation or crystal fracture caused by the use of too long a mounting stud. See "Induced Failure" commentary for complete discussion.

4. Local resonances of constituant parts, such as internal lead wire. This is either a design oversight or manufacturing error, prevented by knowledgeable design and manufacturing controls. External cable or cable connector resonances may also produce significant errors in the output at certain frequencies.

RESISTANCE

Relative Probability:		
	SEC	.05
	Shear	0
	Ring	.03
	Miniature	.04

The energy output of piezoelectric materials is extremely small. Yet, it is a useful level because very high input impedance devices are driven. If that input impedance is significantly lowered, whether internally in the transducer or externally by low resistance paths, the energy output is shorted to the low resistance path. In terms of usual piezoelectric materials outputs, a low resistance path is anything less than about 500 megohms shunting the intended load. Typical element resistance is greater than 20 gigohms at room temperature.

RESISTANCE (continued)

Causes

1. Failure to seal connector when operating in a high humidity or otherwise conductive atmosphere. While hermetically sealed transducers are available and are recommended for operation in conditions of high humidity, provisions for external sealing of the cables from the transducer must be made at the time of installation. Certain transducers with integral cables remove this problem from the immediate vicinity of the transducer; this changes the location of the needed sealing but does not obviate it.

2. Cracked insulating glass or ceramic on insulated models. Even a surface crack can cause a low resistance path. These may be caused by handling damage or excess temperature.

3. Leaking hermetic seal (rare). An imperfect seal of the transducer body - either the case weld or the connector seal - may allow moisture to enter the transducer and cause a low resistance failure. The best correction in this case is prevention. Good manufacturing process dictates 100% leak testing during the production cycle.

SUNDRY EFFECTS

A very small percentage of transducer failures are not included in those listed above. These can take a huge variety of forms, none of which represents more than a fraction of one per cent of experienced failures.

Amplitude Linearity is controlled by design and construction to very small deviations from linearity over the rated "g" range of the transducer. Fortunately, any change in linearity is almost always accompanied by aberrations in one or more of the other parameters discussed in detail above. Causes: Same as those listed under "Frequency Response" above.

Identification may involve either the loss of an engraved "lid" from the accelerometer, or damage which makes the engraving illegible. Although not usually of any consequence, it can become serious if two or more similar units become unidentifiable at the same time. Identification usually can be made with sensitivity calibration and a simple capacitance measurement and comparison of the results with the original calibration certificate. If both identification and calibration certificate are lost, then only a factory recalibration (at which time the transducer's base number can be traced to the serial number) will provide the solution to the problem.

Reversed Polarity is a rare defect, rather than a failure, caused by error in manufacture. Whereas an accelerometer is normally specified and produced to generate a positive electrical signal for acceleration in a positive direction (acceleration directed from mounting surface toward top being defined as positive direction), it is possible for the element

Reversed Polarity (continued)

assembly to be reversed or wired in reverse so that this polarity is wrong. Fortunately, this fault is both rare and usually of no consequence. It can be of significance when the transducer is being used for non-periodic or shock measurements. Ready detection of polarity reversal is done either by comparing the transducer with any other known transducer, or by comparing the output to a known vibration input. Phase reversal across other test equipment such as amplifiers must, of course, be taken into account.

INDUCED FAILURE MODES

Three types of abuse routinely cause damage to piezoelectric transducers: Dropping, Wrench Impact and Unknown Shock Levels in test. Since the damage caused by such treatment may not be externally evident, the effect may first become known through performance aberrations.

Dropping

Very large g forces are generated by dropping a transducer. For example, test data indicates that dropping an accelerometer three feet to a vinyl tile floor generates shock forces greater than 5000 g. Similar forces are to be expected by abrupt contact with hard workbench or desk surfaces. Frequently, obvious case damage indicates a problem. At other times, opens, shorts, excessive changes in sensitivity, capacitance, or cross talk, or poor frequency response can all be present with no external evidence of damage.

Wrench Impact

Piezoelectric transducers are frequently mounted by being cemented in place. This is a recommended practice; however, subsequent demounting by hitting the transducer with a wrench or screwdriver is distinctly not recommended.

Unknown Shock Levels in Test

While ENDEVCO® Accelerometers are very conservatively rated with respect to actual shock damage limits, they can and are damaged by impact grossly above ratings. Where doubt exists, it is usually worth the effort to first run the test with an accelerometer designed for use in shock motion measurements.

Improper Stud Mounting

The use of a mounting stud with too long a threaded portion for the accelerometer mounting hole will deform the surface of the base in the hole. Since this surface is directly opposite the piezoelectric element, all of the failure modes listed under Excess Shock Damage can also be caused by too long a mounting stud. With a properly designed mounting stud, the achievement of a satisfactory union between the accelerometer and

Improper Stud Mounting (continued)

mounting surface is assured primarily by the tension in the stud, and not by the length of thread engagement. It is good practice to use only mounting studs recommended by the manufacturer.

Crossthreading or Excess Torque

Both the connector and base can be damaged in this manner, and frequently are. Excess torque can be avoided with respect to the base by the use of a torque wrench, or can be minimized by the use of a short wrench. Crossthreading can only be prevented by careful handling.

Excess Heat (rare)

Although the temperature limitations imposed by "twinning" of natural quartz material and by low Curie temperature of some piezoelectric ceramics has been all but completely overcome by the development of superior manufactured piezoelectric materials, temperature limits still exist. Temperature hardened units are available to as high as 750° F.

Deliberate Field Modifications

Occasional units are received back for repair which have had holes drilled through the case, or have had the bases machined in some manner for a special application. Since the g forces involved in such rework can easily exceed the shock limits of the transducer, and because the transducer's performance is directly dependent upon mechanical integrity, such attempted rework invariably causes performance degradation or complete failure. Special mounting provisions, etc., are available from the manufacturers. These should be specified at the time of purchase rather than attempting rework after purchase.

CONCLUSIONS

Piezoelectric transducers have very high inherent reliability. Very conservative estimates of Mean-Time-Before-Failure for the various construction types range from about two to ten years. The failure modes experienced in actual field use include many causes; for which indicators and preventative action are recommended. Under normal operating care and use, visual examination combined with periodic calibration checks will detect degradation or failure of piezoelectric transducers. For maximum reliability, manufacturers' environmental ratings should be followed, and test equipment personnel should be made familiar with the transducers' operating characteristics.

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INDICATED FIELD RELIABILITY
PIEZOELECTRIC ACCELEROMETERS

Accelerometer Type (See Figure 1)	Field Reliability, Months	
	Best Estimate	Lower 90% Confidence Limit
SEC, Shear, Ring	79	65
Miniature (2gm) Ring	27	21
Miniature (3gm) Shear	37	32
Shock-design Shear	145	110
Very High Sens. Comp.	46	34

Table 1

PIEZOELECTRIC ACCELEROMETERS
FAILURE MODE AND EFFECT SUMMARY
Table 2

FAILURE MODE	RELATIVE PROBABILITY SEC	SHEAR	RING	MINIATURE	CAUSE	INDICATORS	PREVENTION
Crosstalk	.23	.17	.03	.01	Deformed base	Visual	Clean mtg. surfaces
					Excess Shock	External damage (visual) or factory recalibration	Handling care
Open Electrically	.16	.04	.46	.10	Excess shock	Capacitance check	Handling care
					Defective weld or leads	Factory recalibration	Factory controls
					Connector damage	Visual	Handling care
Shorted	.16	.15	.06	.29	Excess shock	Capacitance check	Handling care
					Too long stud	Resistance check Factory recalibration	Use recommended stud
					Foreign particle	Intermittent Destructive analysis	Design and factory controls
Sensitivity change Capacitance change	.19	.43	.31	.41	Excess axial shock	Capacitance check Factory recalibration	Handling care
					Excess transverse shock		
					Case strain, Excess torque		
					Crystal instability		Proven piezoelectric materials
Frequency Response	.20	.19	.12	.13	Excess shock	Capacitance check	Handling care
					Too long stud	Factory recalibration	Use recommended studs
					Base damage	Visual Factory recalibration	Care in mounting
					Part resonance	Factory recalibration	Design & fabrication control
Resistance	.05	0	.03	.04	Unsealed connector	Resistance test	Seal entire exposed system
					Cracked insulator glass	Visual Resistance check	Care in handling Observe Temp. range
					Leaking case seal	Leak test / Resis. Test Factory check	Factory controls
Amplitude Linearity	negligible				See Frequency Response		
Identification	negligible				Lost Lid Engraving damage	Capacitance check Factory recalibration	Factory controls Maintenance of calibration records
Polarity	negligible				Factory error	Comparison with std or known polarity vibration Factory recalibration	Factory controls