Vibration Troubleshooting with Piezoelectric Strain Gages

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When a piece of equipment, component or structure fails due to fatigue from operational vibration, the troubleshooting tool of choice is a strain gage. Gages are mounted at or near the region of observed failure. Time waveform amplitude and frequency content are used to identify if strain is being enhanced by resonance or if system forcing functions are too high. Recent advances in piezoelectric technology have resulted in development of a new tool for troubleshooting use, a reusable ICP® powered strain gage that allows for quick setup without need for separate strain gage conditioners.*

Sound and Vibration magazine published an article in August 1989 by Chris D. Powell and Richard D. Sohaney titled "Modal Analysis and Strain Gage Testing of a Finned-Tube Heat Exchanger." Embedded within the article is a primer that describes advantages and pitfalls of strain gage testing titled "Strain Gages in a Nutshell." This article presents comparisons between traditional foil-based strain gages described in the primer and the new reusable piezoelectric gage. The resulting opinion is that piezoelectric gages have installation time-saving advantages, can be used to determine operational loads transmitted through mechanical members, can be installed in dirty environments, can be mounted during equipment operation, and can be used for a high percentage of troubleshooting projects.

The design goal for a piezoelectric strain gage is to have all base strain and no acceleration contamination. This is opposite from the goal in designing accelerometers to accurately measure acceleration while eliminating base strain contamination. Sensitivity of the piezoelectric gage due to acceleration is advertised to be an extremely low 0.001 $\mu\varepsilon$/g.

Physical Size of Gages

Figure 1 shows a new reusable piezoelectric strain gage along with a traditional foil strain gage. The piezoelectric gage is 0.6 inch long by 0.2 inch wide by 0.07 inch thick. The sensing element is quartz within a titanium housing. The lead wire is integral to the housing.

A foil gage is shown sitting on shim stock for photographic purposes. While the overall length of the foil gage is about the same as the piezoelectric gage, the actual "gage length," or length of strain sensing grid, is 0.250 inch. The two copper rectangles are solder tabs for attaching lead wires.

Gage physical size is a consideration when designing a test to meet project goals. Depending on the location of interest, it may be necessary to mount the gage on a curved surface or at a point where high strain gradient exists. Foil gages have an advantage of being very flexible to meet the former while being available in a wide variety of sizes for the latter. For example, if the region of interest is at a welded joint, a series of very small gages could be mounted on the weld and extend to points through the heat-affected zone. In this example, *small* could be a gage length of only 0.015 inch. Mounting a series of gages would reveal both peak strain and strain gradient profile for comparison to FEA results. Conversely, the piezoelectric gage is limited to mounting on a flat surface and, any strain gradient will be 'averaged' over its 0.6 inch length.

Structural Stiffness and Calibration

The material stiffness at the mounting location generally is not a consideration when using foil gages, but it is for the piezoelectric gage. Foil gages are very flexible relative to the structure to which they are attached. As such, a foil gage will precisely deform with the test object even if the object is a thin member.

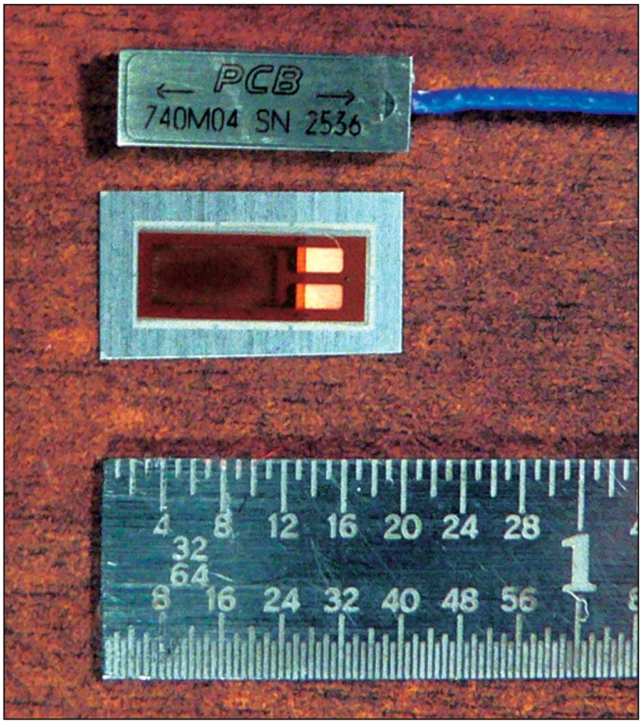

Figure 1. Foil gage versus piezoelectric gage.

Due to the piezoelectric gage's stiffness, consideration must be given as to the localized stiffness at the mounting point because the gage may effectively be a structural "hard spot." If the test object is relatively flexible compared to the gage, the measured strain will be much less than what is actually present. The best way to visualize such a phenomenon is a nonsensical example of mounting the gage on an inflated balloon. As the balloon gets bigger or smaller, the balloon deforms around the gage and the gage will essentially measure no change. To a much lesser degree, the same phenomenon occurs when a gage is mounted to any body. Factory-supplied calibration values are based on mounting the gage to steel. If the gage is mounted to a material other than steel, a different calibration value must be used to compensate for the relative differences in stiffness, which is a function of material modulus of elasticity. Similarly, if the gage is to be mounted on a thin shell or membrane, even if steel, a specific calibration value has to be developed for that thickness to compensate for differences in relative stiffness. On the other hand, if the goal is to identify point-to-point relative differences on the same membrane as presented later in a case history, use of an absolute calibration may not be necessary.

Piezoelectric strain gages come with a calibration certificate identifying the gage's sensitivity value in engineering units of mV/$\mu\varepsilon$. Calibration is based on a dynamic beam-bending test referenced to a pair of foil gages.

Foil gages must be balanced, or zeroed, to remove any DC component after installation. This assures that the full dynamic range of each strain gage condition is available. Resistance change of the active gage causes voltage unbalance of a 'wheatstone' bridge. *In situ* electrical calibration is accomplished by connecting a precision 'shunt' resistor in parallel with an active gage to cause a known resistance change. Channel gain is then adjusted to produce a voltage output for the desired calibration value; for example, 1,000 $\mu\varepsilon$/volt.

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*ICP is a registered trademark of PCB Group, Inc.

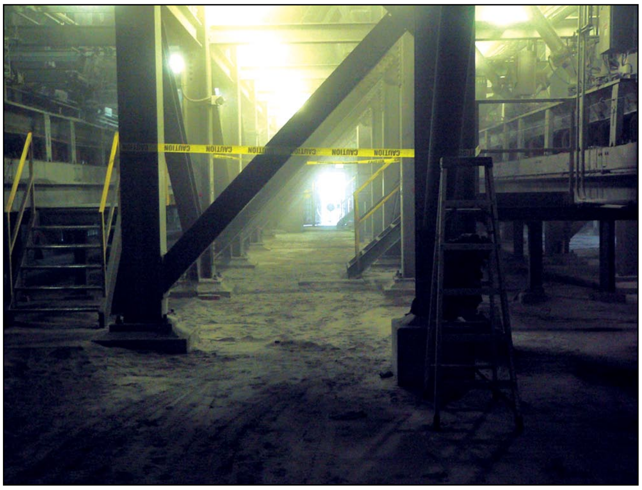

Figure 2. Test environment, columns to be instrumented.

Channel calibration has to be compensated for the manufactured "gage factor." Gage factor is a ratio of change in resistance divided by mechanical change in length. The factor varies from lot to lot and is supplied by the manufacturer.

Static Versus Dynamic Loading

For projects involving vibration troubleshooting, the only consideration is dynamic loading that can cause fatigue. Low-cycle fatigue can result from vibration if the loads are very high, but generally low-cycle damage results from repeated high-static loads or thermal cycles. Piezoelectric gages have an advertised frequency response of 0.5 Hz to 100,000 Hz. If project goals are to determine strain from statically applied loads, as in a dead load test, foil gages must be used.

Surface Preparation and Mounting

Surface preparation for foil gage mounting is a very rigorous series of exposing base metal, degreasing, cleaning, abrading, conditioning, and neutralizing. Abrading is done to produce a surface finish in the range 63 to 100 μin. If the bonding agent is cyanoacrylate (super glue), a catalyst must be applied to the gage and let to dry prior to putting glue on the test object. If any one step is substandard, the bond will be inferior and the gage may peel off when the positioning tape is removed. The single worst enemy of gage installation is airborne contamination. If foreign particles or dust fall onto the prepared location before positioning of the gage, or if dust attaches to the back of the gage, an inferior bond will result. An inferior bond will also occur if too much catalyst is used. Actually if there is a problem, it is good if the gage does peel off with the tape, because if it does not, acquired data will most certainly be in error. If a bonding problem exists, data may either be erroneously low or high. If contamination or air bubbles exists in the glue line, the gage can vibrate like a diaphragm and generate very high false strains.

Gage installation procedures should really be done in a laboratory environment, but that is rarely the case. As an example of real-life situations, photographs are presented in the following case histories that show such a high level of airborne contamination that the probability of successfully mounting foil gages would be essentially zero.

The average installation time for foil gages is 30 to 45 minutes each. This time includes soldering the lead wires and applying protective coatings. Protective coatings are necessary, not only to provide mechanical protection for the gage, but also to protect the solder joints so that electrical-conducting contamination does not cause resistance change between gage terminals. Installation and use of foil gages is a one-shot deal, the gage cannot be removed for reuse. The gage itself is inexpensive, but installation is labor intensive.

Surface preparation for mounting the piezoelectric gage is very simple when compared to foil gages. Base metal is exposed, degreased, and hand abraded with 400 grit abrasive paper to produce a recommended surface finish on the order of 63 μin. Bonding gel (supplied with the gage) is applied to the gage. The gage is pressed onto the object and held in place until the glue is cured. From my foil gage experience, I decided to take the additional step of applying a thin smear of catalyst onto the prepared mounting surface just prior to attaching the gage. I think that this gives a quicker and stiffer cure. Piezoelectric gages are reusable, and a well-designed gage removal tool is supplied with each gage. The lead wire is integral to the gage and only needs to be connected to an ICP power supply or analyzer input that has such a power supply. Total installation time is about 5 minutes per gage.

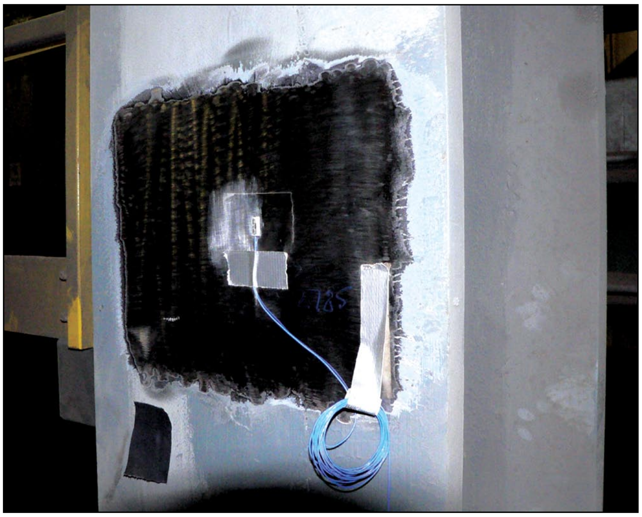

Figure 3. Piezoelectric gage mounted to building column flange at web centerline.

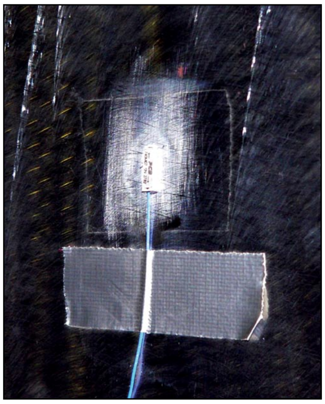

Figure 4. Piezoelectric gage mounted to a column.

Temperature Concerns

The temperature limit for most foil gages is 400° F, while the piezoelectric gage is good to 250° F. However, the limiting condition is the bonding agent. Cyanoacrylate glue is only good to about 200° F. If higher test temperatures will be encountered, epoxy advesive must be used.

Signal Conditioner Circuitry

The most common strain gage installation is called "quarter-bridge." This is a single gage oriented along a desired axis. If the stress state is indeed uniaxial, stress amplitude is 'essentially' equal to strain multiplied by modulus of elasticity ($\sigma = \varepsilon E$). I say 'essentially,' because gage transverse sensitivity and material Poisson's ratio have to be used to precisely calculate uniaxial stress from measured strain. If the stress state is unknown, three gages can be configured into a rosette and used to calculate the overall principal stress and direction. A three-gage configuration will require three data channels.

A half-bridge circuit uses two gages. This can separate bending effects from axial, or vice versa. A half-bridge bending circuit uses two gages but consumes only one data channel. A second half-bridge circuit can be used to measure only the axial component. Therefore, to separately measure bending and axial effects with foil gages requires mounting four foil gages, wiring two half-bridge circuits, and consumes two data channels. A full-bridge circuit use four gages to separately measure bending, axial or torsion while automatically compensating for the remaining two affects.

Measurement of bending and axial affects can be accomplished using two piezoelectric gages connected to a summing circuit for output of the axial effect while being T'd into a difference circuit

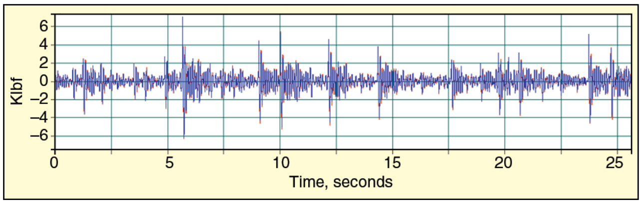

Figure 5. Strain time history at flanges of column.

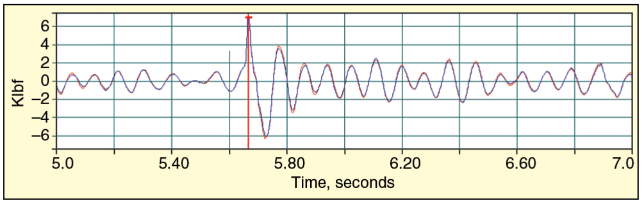

Figure 6. Strain time history at flanges of column showing pure axial loading.

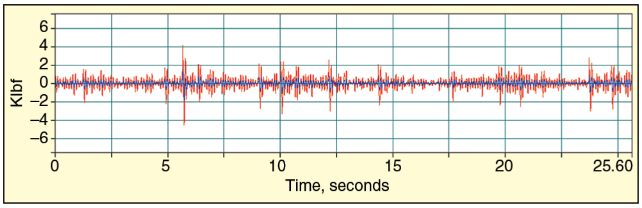

Figure 7. Strain time history at flanges of column.

for output of the bending effect. One data channel is used for each effect. Another approach for either foil or piezoelectric is analytical; that is, using raw time history data from two gages and calculate the separate bending and axial effects.

Transverse Sensitivity

In the world of foil gages, the project goal is usually to precisely determine the stress state at a point; therefore, calculational adjustment is required to compensate for each gage's transverse sensitivity, even though such sensitivity may only be 0.3%. From a pragmatic point of view and particularly for troubleshooting, using a single gage at a point is enough to determine time waveform and frequency content. If piezoelectric gages are used in a rosette configuration for calculating principal stress, transverse sensitivity should be taken into account. Transverse sensitivity is reported to be less than 5%.

Case History – Loading of Building Columns

A normal process causes intermittent dynamic loading of building structural steel members. The goal is to determine the force amplitude transmitted to the foundation and assess if bending exists in the columns. Given that this is dynamic loading of thick steel members, either foil or piezoelectric gages can be used. As seen in Figure 2, the level of airborne contamination makes it virtually impossible to install foil gages with any degree of confidence. Therefore, piezoelectric gages have a clear advantage. Additionally, since several locations are to be monitored, installation of piezoelectric gages provides substantial timesavings over foil gages.

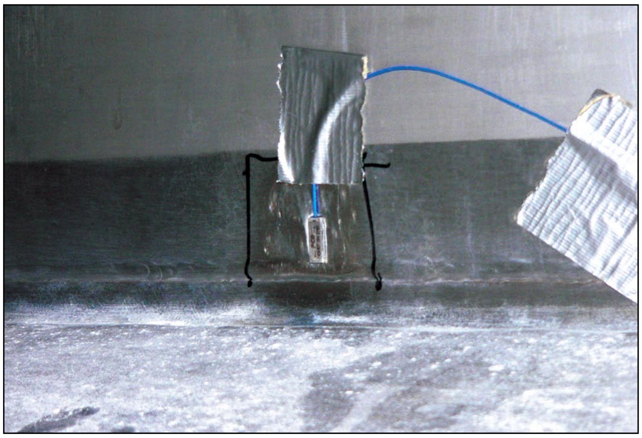

Figure 9. Piezoelectric gage mounted to nonfailed vessel.

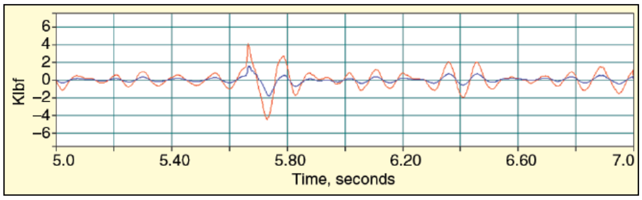

Figure 8. Strain time history at flanges of column showing axial plus bending.

Figure 3 shows one side of an instrumented column. (Note: plant personnel got a little carried away with their grinding.) Two piezoelectric gages were mounted to each column, one on each flange along the web centerline. Use of gages mounted on opposite flanges allows for determining both axial and bending loads. Figure 4 shows a closer view of a mounted piezoelectric gage.

Figure 5 shows time history strain data measured on the flanges of one of the columns. Figure 6 expands the data around 5.8 seconds to better show the waveforms. This figure clearly demonstrates that the column experiences pure axial loading (red and blue curves are identical in amplitude). Column geometry and material properties are used with gage sensitivity to calculate calibration values that produce engineering units in force pounds.

These data also demonstrate a sign convention difference between piezoelectric and foil gages. When a compressive load is applied to a foil gage, a negative voltage is output from the transducer signal conditioners. Conversely, a positive voltage is output when a compressive load is applied to the piezoelectric gage. Figures 7 and 8 show data for a column that has a combination of axial loading (red and blue curves are in-phase) plus bending (red and blue curves have different amplitude).

Case History – Vessel Failure Investigation

An industrial process contains two identical stainless steel vessels. One of the vessels has experienced repeated failures, while the second has not. The working environment is dusty, vessel temperature is nearly 200° F, and the process cannot be shut down for mounting strain gages. All things considered, it would be virtually impossible to install foil gages, making the choice to use Piezoelectric gages obvious. To associate strain with vessel motion, triaxial accelerometers were mounted to the top of each vessel.

Figure 9 shows a piezoelectric gage mounted adjacent to a weld that has not failed. Figure 10 shows a gage mounted to the region of weld repair on the second vessel. Gages were located at 0°, 90° and 180° to assess strain differences around each vessel. Figure 11 presents the strain time history at three locations around the vessel weld, showing that maximum strain occurs at the 90° location (blue curve). Figure 12 shows corresponding acceleration at the top of the vessel. There is visual correlation between the strain at 90° and vertical motion of the vessel in Figure 12 (red curve). Figures 13 and 14 present expanded views of Figures 11 and 12 at 4.5 seconds to better separate the time history data plots.

Frequency analysis of Figures 11 and 12 results in Figures 15 and 16 respectively. Vertical acceleration (red curve) in Figure 16 shows two dominant peaks at about 29 Hz and 31 Hz. Interestingly,

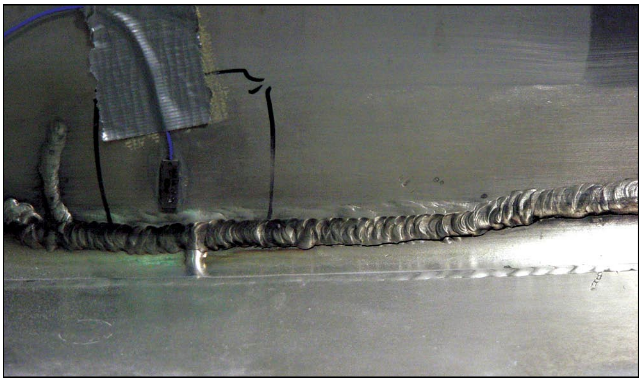

Figure 10. Piezoelectric gage mounted to failed vessel.

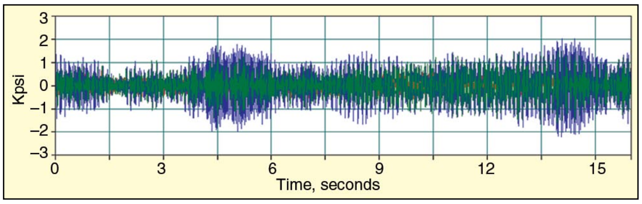

Figure 11. Strain time history at vessel weld.

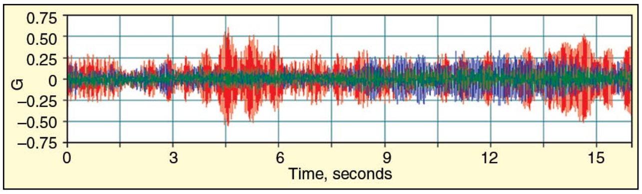

Figure 12. Acceleration time history of vessel.

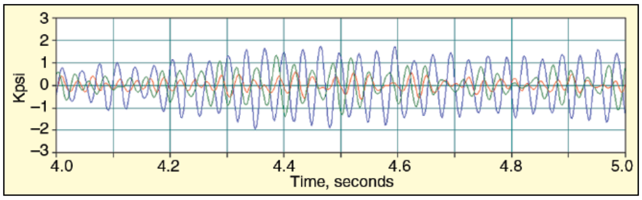

Figure 13. Expanded strain time history at vessel weld.

it is only the 31-Hz peak that is associated with the dominant peak in Figure 15 (strain at 90°, blue curve).

Summary

Piezoelectric strain gages were evaluated under hostile conditions that would render foil gage installation futile. In two case histories, piezoelectric gages were found to have distinct advantages of being quickly mounted in dirty environments. Installation of piezoelectric gages was achieved without shutting down process operation. It would have been virtually impossible to install foil gages onto a 200°F surface, unless using weldable gages, which is another topic. I think that piezoelectric gages are suitable for a high percentage of engineering studies, vibration troubleshooting projects, and failure investigations. The final benefit is that gages are reusable, allowing for greatly expanded studies with minimal setup time. SV

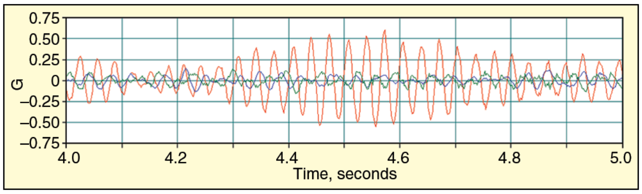

Figure 14. Expanded acceleration time history of vessel.

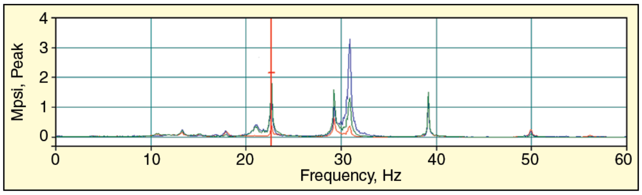

Figure 15. Strain time history at vessel weld.

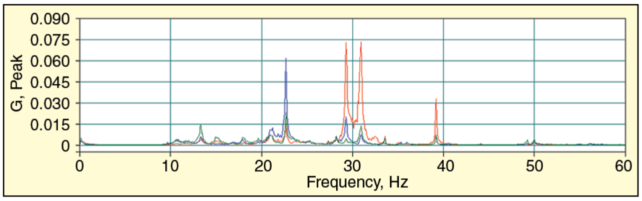

Figure 16. Acceleration time history at vessel weld.

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