In Situ Health Monitoring of Piezoelectric Sensors

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ABSTRACT

The developed technology is an in-situ measurement system for monitoring the performance of piezoelectric sensors, particularly accelerometers. The technology's dynamic response can be used to evaluate the operating range, health, and as-mounted resonance frequency of a transducer, along with the transducer's mechanical coupling with a structure. Characteristics such as sensitivity, frequency response, cable status, connectivity, bonding and linear range are determined in an instant as installed. Sensors are tested in a very wide frequency range extending to over 200 MHz, and without specialized transducers or wiring. Beyond detecting transducer failure or detachment, the technology can also identify structural changes such as deformation and microfracturing within a test article. With this monitoring system, degraded sensor performance can be quickly and economically identified with hand held unit or integrated directly into test equipment.

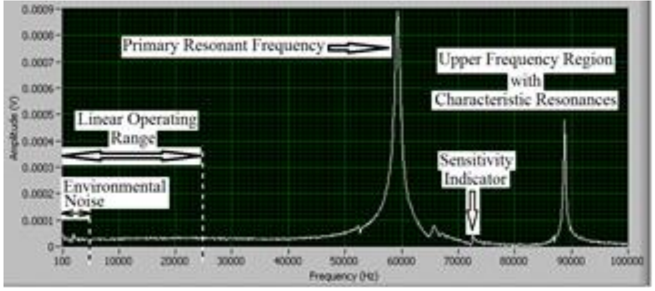
Keywords: in-situ, monitoring, health, resonance, as-mounted-resonance, sensitivity, frequency-response, cable-status, connectivity, linear-range, diagnostic

1 BACKGROUND

Commercial test equipment suitable for testing piezoelectric sensors is expensive and requires that the sensor be removed from the test article for evaluation. This innovative technology permits monitoring the health of piezoelectric sensors while installed on, or after thaving been removed from test articles. On several occasions with Stennis Space Center (SSC) rocket engine testing, anomalies appear in the accelerometer and dynamic pressure data recorded by the Low Speed and High Speed Data Acquisition Systems. An in-situ test system was necessarytoassess if the transducers were operating properly or if the transducers were in error. It is often unclear if anomalies in recorded signals are due to differences between the Low and High Speed Data Acquisitions Systems, differences between the transducers, a failed transducer, *or* if everything is working correctly and the systems were actually accurately recording real events. One particular data anomaly incident investigation led to conecption of this. A poor cable connection was energy to build up within an accelerometer cable due tovibrations induce from the ongoing propulsion test. Energy creation within a cable due to vibrational conditions is often known as a cable slap phenomenon. Periodically the poor connection would reconnect which dumped the cable's energy into the accelerometer. Due to the converse-piezoelectric effect, the accelerometer would vibrate in response to the stimulus; in turn, the vibrations were inducing a signal reading within other accelerometers mounted on a common tri-axial block. It was then that the idea that the converse-piezoelectric effect could be employed for introducing a stimulus energy into the structure under test while allowing the stimulus energy's response to be collected was conceived. The process possessed the potential to obtain valuable information about the sensor and the corresponding structure being tested. This is now known as the piezoelectric stimulus-response effect. The signals produced by the piezoelectric sensor under test yields an abundant amount of frequency spectrum information. The state of health of the sensor and structure can be determined by spectral analysis.

2 THE IN-SITU HEALTH MONITOR FUNCTIONALITY

The developed technology is an in-situ measurement system for monitoring the performance of piezoelectronic sensors, particularly accelerometers. With this technology, characteristics such as resonant frequency, response, cable status, connectivity, bonding and linear range, can be determined. Sensors can be tested in a very wide frequency range, extending to 200 MHz and beyond, without removing them from their mounted locations, and without requiring specially constructed transducers or special wiring. The dynamic response can be used to evaluate the operating range, health and as-mounted resonance frequency of the transducer, as well as the strength of a coupling between the transducer and a structure, and the health of the structure. The monitoring system provides the full frequency of the sensor, the linear operating range, and the resonant frequencies-both normal and as-mounted for different configuration types. The low frequency region captures the environmental noise identifying the noise levels one can expect during data collection similar to using a placebo transducer. The sensitivity indicator resonant amplitude precisely revealed the transducers sensitivity (see Figure 1). The system also provides the ability to



monitor piezoelectric transducers between propulsion tests to detect any trend indicative of transducer failure or detachment. Additionally, the system can be made portable, incorporating the unit in a battery powered sealed box, for testing in the field. Physical contact with the sensor is not necessary, therefore, monitoring can be done up to 250 feet, or even longer if certain provisions are made. With only slight modifications, this monitoring system can be used with all common transducer instrumentation. This monitoring system, can quickly and economically identify degraded sensor performance . Additionaly, installed piezoelectric sensors can be evaluated, without requiring physical contact or removing them from their mounted locations;tests are conducted through cabling. Because it is not necessary to remove the device, data that reflect the device's specific physical configuration (such as as-mounted resonant frequency) are retained, and devices that are physically inaccessible can still be tested. The testing system is not limited to identifying degraded performance in the sensor's piezoelectric elements; it can detect changes within the entire sensor, and sensor housing.

The in-situ piezoelectric test apparatus is far simpler and the system includes several enhancements and innovations over existing prior art. All of the transducer's resonant frequencies are monitored and quickly assessed, unlike other known apparatus that are only censored with the primary resonate frequency. The transducer's primary resonate frequency and sensitivity can be unknown prior to performing transducer tests. The developed test apparatus quickly performs a far more comprehensive test. It can detect changes in the transducer sensitivity, cabling, piezoelectric element, transducer housing, transducer attachment, and test article.

Some transducers have built in amplifiers that convert the generated electrical charges into voltage signals. The developed apparatus can be employed in these kinds of transducer systems. This type of transducer is widely employed and the fundamental components of previously known apparatus prevents their use in this type of transducer. This charge to voltage conversion inside of the transducer makes the signal less susceptible to changes in cable length. This is an important advantage to this class of piezoelectric devices. The developed in-situ piezoelectric test system used in conjunction with the charge converters significantly enhances the capability of piezoelectric devices.

3 THE IN-SITU HEALTH MONITOR TECHNOLOGY

Piezoelectric transducers generate electric charges in response to mechanical deformation of the materials from which they are made. Pierre and Jacques Curie discovered this phenomenon in the 1880s. The first application of the piezoelectric effect was the detection of submarines during World War 1. They also demonstrated the inverse piezoelectric effect in which an electric field applied across a piezoelectric material deforms mechanically. The research was performed at the SSC Data Acquisition and Control System Laboratory and provided a means to test piezoelectric transducers while they are installed in the field. The technology has been further refined into a portable field diagnostic tool, laboratory bench tester, and integrated system components. The hand held portable units, in a battery powered sealed box, for performing tests within the field, are known as the Piezo- Electric Transducer Testers (see Figure 2). The units have already aided in resolving questions concerning data anomalies. The patented technology has also been designed for integration within facility instrumentation systems.

Figure 2: PiezoElectric Transducer Tester Version 3.3 (PETT-3.3)

The fully functioning system consists primarily of an excitation device capable of delivering low voltage microsecond duration electrical pulses to the sensor, a high speed data acquisition device for collection data, a control circuit, and a computer with appropriate software. The in-situ health monitoring technology utilizes the primary components for executing the piezoelectric stimulus-response effect.

A simple control circuit performs a test sequence by first triggering the excitation device. The excitation device injects stimulus energy into the accelerometer under test, and the piezoelectric material inside the accelerometer physically deforms due to the converse piezoelectric effect. The piezoelectric material, commonly known as the element, inside of the accelerometer is forced to vibrate due to the deformation similar to ringing a bell (see Figure 3). The control circuit then drains residual electrical energy out of the piezoelectric element as the vibrational energy reverberates throughout the accelerometer and associated structures. The mechanical vibrations of the accelerometer correspondingly produces electrical signals due to the

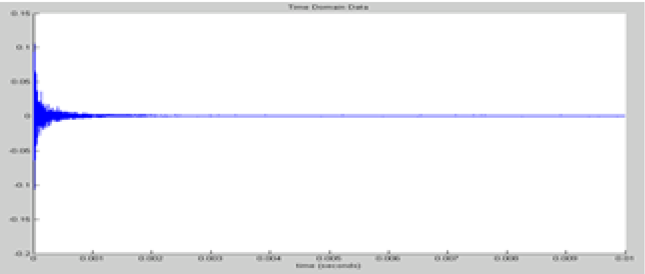


Figure 3: Time domain data of vibrational ringing response within an accelerometer from injected stimulus.

piezoelectric effect. The same piezoelectric element within the accelerometer can now be used to measure the structure's mechanical reverberating response. The data acquisition device is subsequently triggered for recording the responding signals (see Figure 4). The width of the applied pulse from the excitation device determined the frequencies contained in the pulse energy. A sharply shaped pulse contains a wide range of frequencies adequate for exciting a resonance ringing response in nearly all piezoelectric transducers even shock accelerometers and pressure transducers. One type of excitation device functions well for all kinds of transducers, and does not need exists for multiple execution configuration.

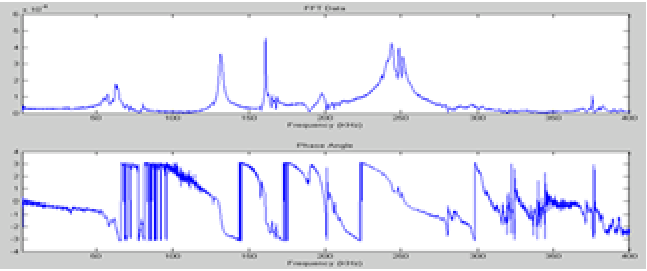


Figure 4: Frequency domain data of the vibrational ringing response within an accelerometer.

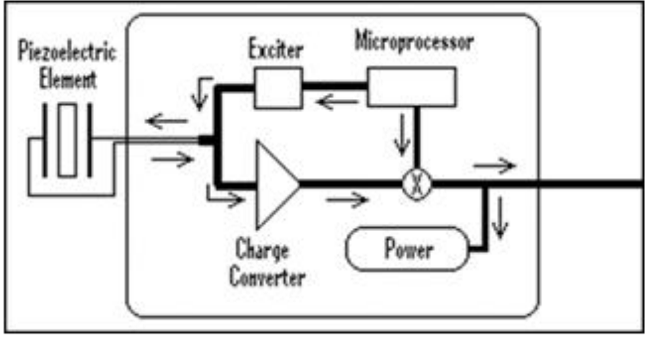


Figure 5: Generalized Test Cycle Flow Diagram

4 DATA REDUCTION AND ANALYSIS BY THE VECTOR EVALUATION

Sensor diagnoses are made by applying predefined limits to polar values that are linked to a specific structure and sensor type. The polar values are generated with a vector evaluation algorithm that transforms data sets into multidimensional vectors. The differences in the magnitudes and angles of the vectors are then computed, and results are displayed in a two dimensional polar plot with a single mean value. This process significantly reduces the massive amounts of multidimensional frequency data generated from the technology into a simplified two dimensional representation. Automated indication can also be implemented with the polar plot limits.

Multiple test cycles are consecutively perform with the sensor's response data being saved for each cycle. Each resulting data set is processed into Fast Fourier Transform (FFT) data (see Figure 6). Each value of a FFT data (each frequency bin) is represented as one dimension of the set multidimensional vector. If the data sets are identical, the vector evaluation algorithm will find no difference between the data sets and produce a point in the center of a polar plot. The greater the differences between the data sets, the larger the angle and amplitude will become. The multiple test cycles will accumulate into a cluster of values (see Figure 7). The resulting cluster should produce a linear pattern when the data sets are compared. The linear pattern indicates a good data collection was achieved, and a shotgun pattern indicates a poor data collection was performed with irregularities between data sets. This instantly validates any data reading. Fundamentally, the algorithm quickly condenses

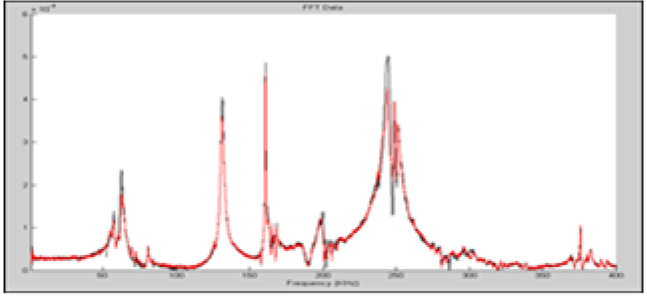


Figure 6: FFT data sets collected from multiple stimulus-response test cycles

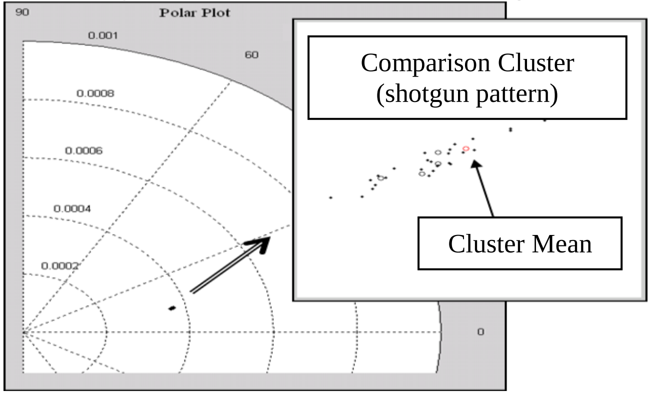


Figure 7: Vector evaluation polar plot of multipe test cycles with irregularities between data sets

large amounts of data into a polar plot capable of quantifying small changes between the large data sets.

Diagnosing a bad piezoelectric transducer is obviously identifiable with the vector evaluation algorithm. An example of diagnosing a broken accelerometer can be seen in Figure 8. The accelerometer experienced a shock during rocket testing that slightly damaged the piezoelectric element. The damage continued to progress with subsequent testing. Determining the coupling strength between the transducer and a structure is also obviously identifiable with the vector evaluation algorithm. An example of analyzing a properly mounted accelerometer can be seen in Figure 9. A significant difference is seen when the structure changes the accelerometer's characteristic frequencies by mechanically becoming coupled with structure. With the vector evaluation algorithm, determining the state of a piezoelectric transducer without any prior data or information is straight forward. Diagnoses can be performed by incrementally coupling the transducer to a block while performing stimulus-response tests. a notable change will occur when the transducer mechanically becomes coupled with the block. If a notable change does not occur, then the transducer is faulty (see Figure 10). The technology can also be utilized for revealing minuscule differences in a test article. The technology was successfully demonstrated for use as a smart glass monitor for solar collection mirrors. The difference between placing a dime, penny, and nickel at any location on a irregularly shaped four foot diameter mirror was reliably discernable (see Figure 11).

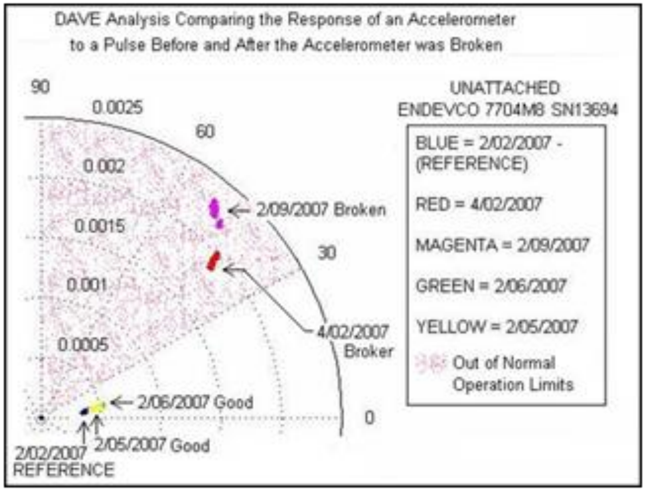


Figure 8: Example of diagnosing a broken accelerometer

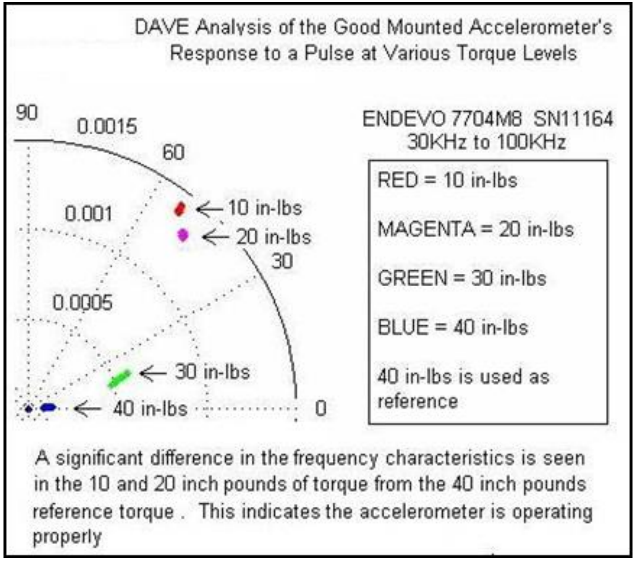


Figure 9: Example of analyzing a properly mounted accelerometer

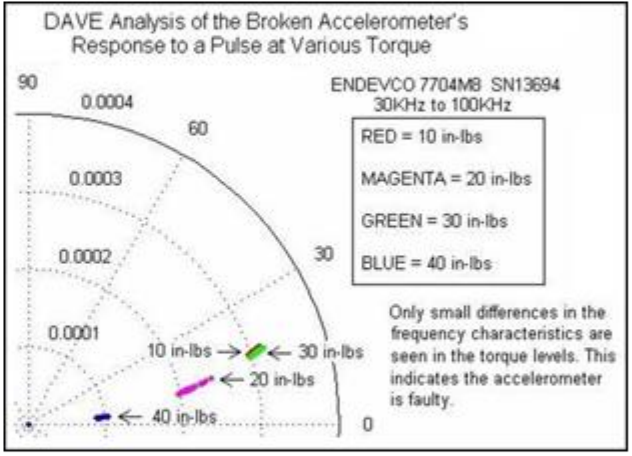


Figure 10: Example of diagnosing a broken accelerometer without any prior data or information

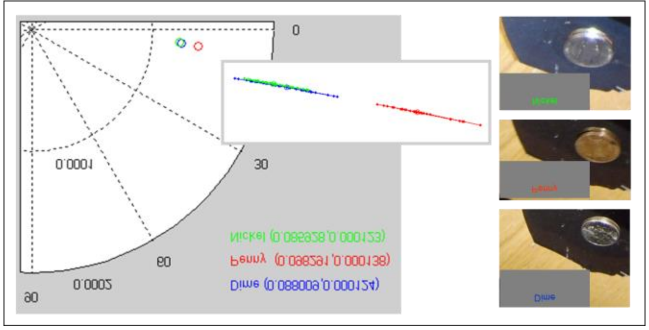


Figure 11: Example of discerning the difference between a dime, penny, and nickel on a mirror

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