A NEW ACOUSTIC EMISSION TECHNIQUE FOR DETECTING AND LOCATING GROWING CRACKS IN COMPLEX STRUCTURES

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INTRODUCTION

BACKGROUND The first use of a periodic proof stress in conjunction with acoustic emission monitoring to detect crack growth was presented by Dunegan, Harris, and Tetelman at a symposium sponsored by the Southwest research institute in 1969. This report was later published in Reference 1. The first use of this technique for verification of the structural integrity of pressure vessels was published by Harris and Dunegan in 1972 (Reference 2). The use of this technique with a multiple channel AE system for predicting structural failure was published by Dunegan in 1974 (Reference 3). The first multiple channel AE system to utilize not only 2 dimensional location capabilities, but also the capability of measuring various signal parameters such as rise time, amplitude, pulse width etc. was produced by Dunegan/Endevco in 1974 (Reference 4). Over the past 25 years great improvements have been made in instrumentation and software for testing with these traditional methods. Most manufacturers produce fast digital systems and very sophisticated software in comparison to the original systems produced 25 years ago. Traditional methods utilizing state of the art electronics and software have worked well over the past 25 years for the testing of pressure boundary structures such as pressure vessels, piping, and valves. One of the reasons for the successful AE applications for these types of structures is that one can easily reproduce the working stresses by conducting a simple periodic proof pressure test to stresses above the values experienced under working conditions. One can easily locate sources of AE because of the simple plate like surface of these structures, with few attenuating boundaries. One of the important criteria used to locate and assess growing cracks is the acoustic emission occurring between the working pressure and proof pressure and during hold at the maximum pressure (Harris, Dunegan 1972-Dunegan 1974). Another way one can use AE to detect an old crack is to monitor a pressure vessel that has been in operation at the working load for a long period of time, and observe the AE present due to oxide crushing along the crack surface as the vessel is de-pressurized (Dunegan, 1977 reference 5). Another important factor leading to a successful test is the fact that one can conduct the proof pressure test with a minimum of extraneous noise from friction and impact. For some conditions small amounts of extraneous noise due to friction, attachments welded to the vessel, EMI and leaks are present. Measurement of the signal parameters in traditional systems and software analysis is usually sufficient for getting around such minor disturbances. Therefore if one is only interested in detecting and locating crack growth in pressure boundaries that can be easily taken to a proof pressure, the traditional methods are still applicable.

Over the past 25 years many attempts have been made to apply traditional AE technology for global monitoring of large complex structures such as bridges, offshore platforms, and aircraft, to detect crack growth. The results from such tests with the exception of a few directed toward determining if crack growth is occurring from a small preselected area have met with failure. The primary reason for the failure of AE for these applications has been the inability of traditional methods to identify the presence of crack produced AE signals in the presence of AE signals produced by noise sources such as impact and friction. The complexity of these large structures disallows the spatial filtering approach applied so successfully to simple structures such as pressure vessels and piping. The size and complexity also disallows a periodic proof stress approach for AE testing. The only alternative left for monitoring of such structures is continuous monitoring over a period long enough to detect the severity of any growing cracks with an AE system capable of determining the difference between signals from a growing crack and those from extraneous noise.

A NEW APPROACH

Dunegan Engineering Consultants Inc. (DECI) has designed and patented a Smart AE Sensor and Instrument that is capable of not only identifying crack produced AE signals in the presence of extraneous noise, but accomplishing this in real time. This is accomplished by modal analysis of the AE signal to determine what type of plate mode is present. Noise sources such as impact and friction are out-of-plane (OOP) sources and they produce a low frequency flexure wave, a high frequency shear wave, and a very weak extensional wave. Crack growth is an in-plane (IP) source which produces high frequency extensional and shear waves with very weak low frequency flexural wave components depending on the depth in the plate where the crack extension occurs. The patented SE9125-M transducer is constructed with partial mass loading of the piezoelectric crystal in the transducer. This design produces a sensor that is equally sensitive to the displacement produced by low frequency flexure waves and high frequency extensional waves. It will also detect both Sh and Sv shear waves in the plate. The patented AESMART 2000 instrument is designed to split the AE signal into a low frequency (LF) and high frequency (HF) channel. The signals in each channel are then peak detected and read with an A/D converter. The ratio of the high frequency (HF) channel to the low frequency channel (LF)-HF/LF is then calculated by the computer. Signals from the SE9125-M produce ratios of approximately 1 for OOP signals in plate thickness ranging from 0.125 in. (3.13 mm) to 0.750 in.(18.8 mm). IP signals produce ratios from approximately one to infinity, depending on the depth in the plate where the crack growth occurs. If crack growth occurs exactly at midthickness in the plate, no flexural wave component is produced and the ratio is infinity. The instrument defaults these readings to a value of 60.

NOISE REJECTION

Noise rejection in real time is accomplished by setting a ratio filter to approximately one. Only signals having ratios greater than the set ratio will be detected and stored by the instrument. Crack depth measurements are estimated by observing the absolute value of the calculated ratio for a crack-produced signal. Since all noise signals are rejected, only valid crack growth related signals are stored and therefore the storage requirements are minimal compared to the traditional approach.

MULTIPLE CHANNEL APPROACH

The growth of cracks due to fatigue, stress corrosion, and hydrogen embrittlement in bridge structures, aircraft, offshore platforms and other major large complex structures is a major concern. For welded structures , it is not uncommon for a crack to initiate in weld material or heat affected zone, propagate into more ductile parent material and arrest. When a crack initiates and grows due to local stresses, the region in the near vicinity of the crack becomes more compliant and stresses are transferred to adjacent members in redundant structures and the driving force for additional crack growth is relieved. Therefore the presence of a crack in a redundant structure is not necessarily of great concern. Whether or not the crack is growing and could lead to failure of a member is of great concern.

The growth of a crack is usually a slow process. It will act as a repeating source of AE signals for a long period of time. Therefore a statistical sampling technique from a sensor in the vicinity of a growing crack will give all the information needed to evaluate the progress of the crack growth. It is therefore unnecessary to have simultaneous measurements from all sensors connected to the structure.

DECI’s approach to multiple channel monitoring of a complex structure is to string all sensors on a single cable and statistically sample each sensor on a periodic basis. The major advantages to this approach is the cost savings produced by only having one instrumentation channel for monitoring up to 100 transducers or more, with only a single cable connecting all transducers required. The same ratio filtering techniques for eliminating extraneous noise signals can be utilized, as well as observing the ratios of valid signals to estimate crack depth of the growing crack. The LF-HF feature of the AESMART 2000 can be used to estimate the distance from the transducer to the crack site for later visual observation. If one wishes to monitor a known crack an additional trigger transducer can be utilized to allow for a trigger delta T filter to be used to assure that the signal is coming from the selected crack site.

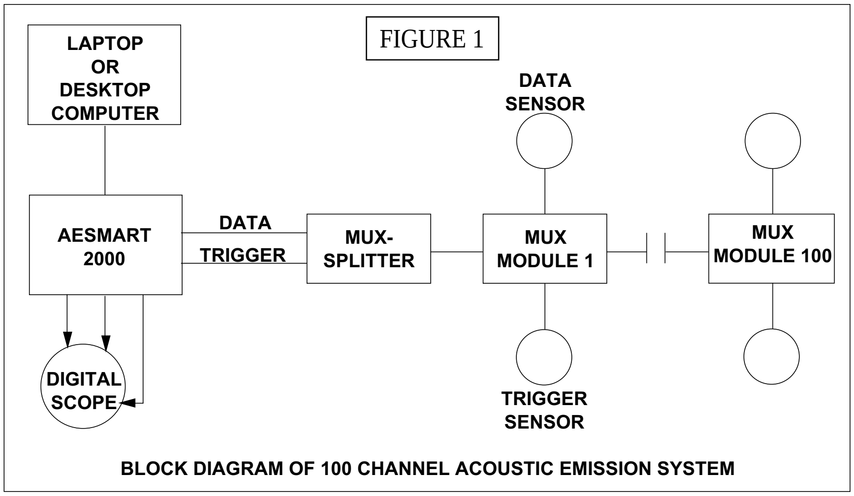
FIGURE 1

BLOCK DIAGRAM OF 100 CHANNEL ACOUSTIC EMISSION SYSTEM

Figure 1 shows a block diagram of a multiplexing 100 channel AESMART 2000 Acoustic Emission System. All channels are on a single twisted pair shielded coaxial cable with power and signal for a trigger and data transducer on the same cable. Any channel can be manually selected by the operator, or channels can be selected sequentially .on a periodic basis by the computer. Sample period can be changed on command. AE signals associated with crack growth are automatically transferred to an Excel spread sheet each time a new channel is selected. Summation of AE counts from the high frequency channel are accumulated for each sensor location. This data allows one to evaluate the amount of crack growth occurring and determine if a critical situation is being approached. Activity of all sensors can be viewed in near real time in an Excel bar graph chart. Summation of counts as a function of time or parameter can be viewed on command for any sensor showing high activity. A plot of HF/LF ratio vs time or parametric can also be viewed from any channel for estimating crack depth. Numerous other graphs can be created by the user by utilization of the information contained in the Excel spread sheet for each channel.

FIGURE 2

Each Mux Module (figure 2) has a unique address that can be selected on the AESMART 2000 virtual screen by the simple movement of a mouse. Only the address selected draws power from the main cable, and transfers data from the AE transducers. The Mux Module is connected to the trigger transducer via a BNC side connector and to the data sensor via a BNC connector at the other side of the mux module. Connection to the main cable is made via a BNC Twinax connector at one end and connection to other Mux modules is made via the same type of connector at the other end of the Mux module. All power for operation is supplied by the main coaxial cable. The Mux Module is constructed from 304 stainless steel and is designed to be insensitive to large temperature fluctuations.

The model SE9125-MI is the recommended data transducer, and the SE375-MI is the recommended trigger transducer. Both of these sensors contain an integral preamplifier, which is a requirement for operation with the MUX-MODULE. When field testing both sensors and Mux Module are held in place with a Mag-80 magnetic hold-down with 80 pounds of holding force. The transducers are constructed from 304 stainless steel. The proprietary material that completely fills the transducer case along with integral cable construction provides an excellent moisture barrier, shock resistance and high reliability. A pulser which takes its power from the trigger connector can be supplied to provide a periodic 1 per second pulse of either 150 or 400 volts to provide a calibration signal for any location on the structure.

FIGURE 3

Figure 3 shows a MUX-SPLITTER module which is used to transfer data from the twisted pair cable from the “data” and “trigger” transducer of the MUX-MODULE to the AESMART hardware. The cable from the MUX-MODULES connects to the center connector, and signals from the data and trigger transducers are input to the front panel of the hardware via coaxial cables from each end.

Figure 4 shows the virtual screen of the AESMART 2000 multiple channel system. The instrument is designed to be easily operated without referring to an operation manual. The function of the modules contained in the screen can be explained by selecting "help" and then moving the cursor with a mouse to each module. A popup window will then explain each feature.

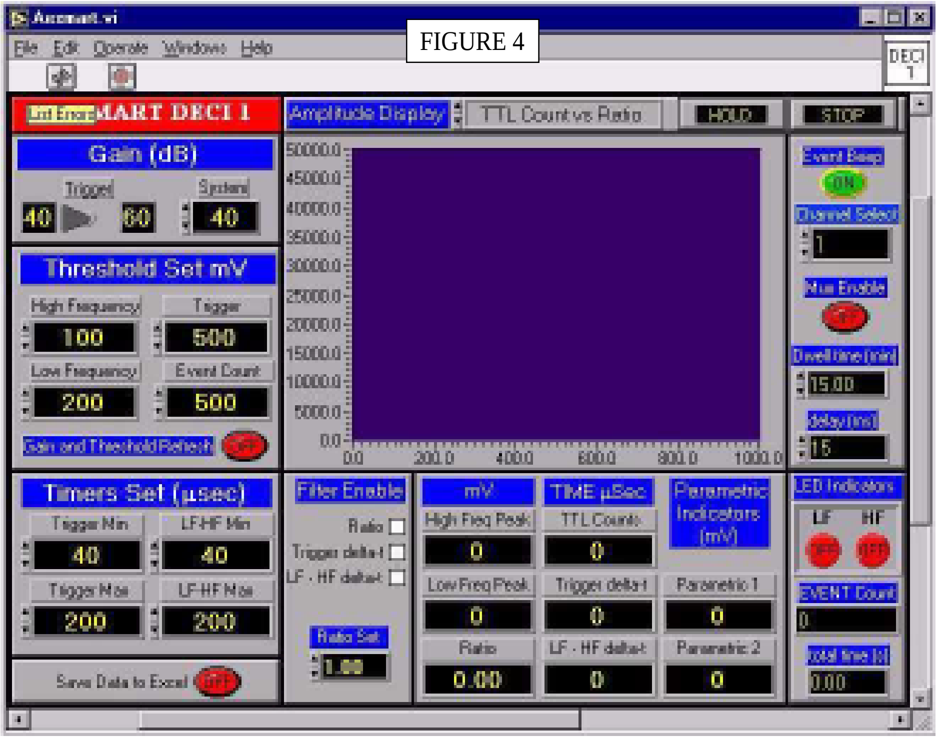
FIGURE 4

Aesmart.vi

Gain (dB)
Trigger 40 60
System 40

Threshold Set mV
High Frequency 100
Trigger 500
Low Frequency 200
Event Count 500
Gain and Threshold Refresh OFF

Timers Set (µsec)
Trigger Min 40
LF-HF Min 40
Trigger Max 200
LF-HF Max 200
Save Data to Excel OFF

Filter Enable
Ratio ☐
Trigger delta-t ☐
LF - HF delta-t ☐
Ratio Set 1.00

mV
High Freq Peak 0
Low Freq Peak 0
Ratio 0.00

TIME µSec
TTL Counts 0
Trigger delta-t 0
LF - HF delta-t 0

Parametric Indicators (mV)
Parametric 1 0
Parametric 2 0

Event Beep ON
Channel Select 1
Nux Enable OFF
Dwell time (min) 15.00
delay (ms) 15

LED Indicators
LF OFF
HF OFF
EVENT Count 0
total time (s) 0.00

OPERATION

It is recommended in order to become familiar with operation of the instrument that an aluminum or steel plate approximately 20 inches square by 0.100 to 0.500 thickness be utilized with the instrumentation configured as shown by figure 1. If a trigger transducer is placed at the center of one edge on top of the plate and the data transducer is placed in the center of the plate approximately 10 inches from the trigger transducer, one can experiment with in-plane (IP) and out-of-place (OOP) sources by breaking 0.3mm pentil pencil leads on the edge and top of the plate near the trigger transducer. Examples will be given of data taken from a 20X20 inch aluminum plate 0.190 inches thick.

Referring to the block diagram in figure 1. The high frequency (HF) and low frequency (LF) outputs from the instrument were input to a digital oscilloscope and the trigger SYNC signal was used as an external trigger to the oscilloscope. 0.3mm pencil lead breaks were made on top of the plate to create signals representative of noise (OOP sources), and on the edge of the plate to create signals representative of crack growth (IP) sources. Both of these lead breaks were made at the trigger sensor location near the edge of the plate.

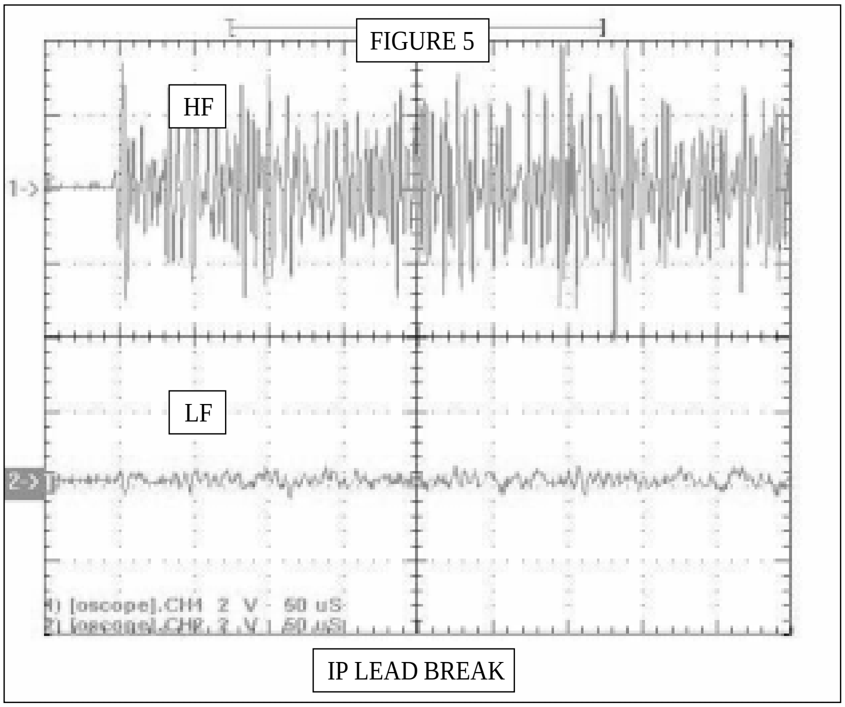
FIGURE 5

IP LEAD BREAK

The waveforms shown in Figure 5 resulted from an in-plane (IP) lead break on the edge of the plate at the trigger transducer location. Note the high amplitude signal occurring at 50 microseconds in the high frequency channel (HF). This is the arrival of the extensional wave created by this crack like source. The signal shown arriving at approximately 80 microseconds in the HF channel is a high frequency shear wave.

Note the low amplitude of the low frequency wave (LF) in the lower trace of figure 5. The pencil lead was broken at approximately half depth in the plate which results in very little of the low frequency dispersive flexure wave being produced. The large amplitude signal arriving at approximately 150 microseconds in the HF channel is a reflection from the back side of the plate. Note that the ratio of the HF /LF peak amplitude for this IP signal is much greater than 1.

In the next example (Figure 6) the pencil lead was broken on the top of the plate near the trigger transducer. This is an OOP source and simulates the type of sources due to impact and friction (noise sources). Note the very low amplitude of the signal arriving at 50 microseconds in the HF trace. This shows that very little extensional wave is produced by this OOP source. The shear wave arriving at 80 microseconds in the HF trace is well defined as well as the reflection from the back surface of the plate at approximately 150 microseconds.

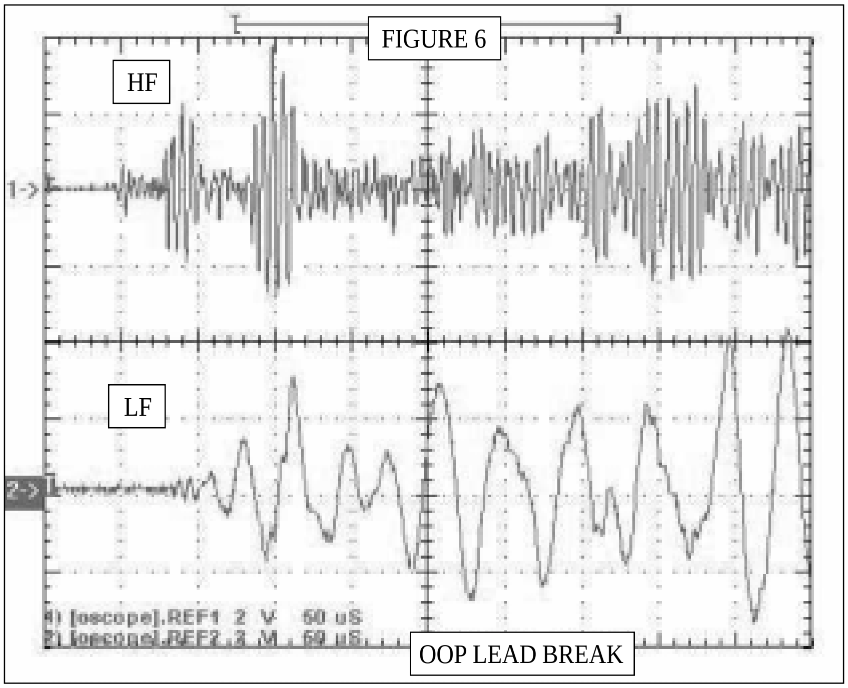
FIGURE 6

This OOP source produces a large amplitude low frequency flexure wave (LF) with arrival time of approximately 100 microseconds. (The small high frequency signals preceding 100usec. are components of the high frequency shear wave leaking through the 2 pole filter). Note that the HF/LF ratio of the peak amplitudes of the signals present from this OOP source is approximately 1. This is a design feature of the SE9125-MI transducer used as the data transducer in these examples. If an HF/LF ratio is set in the instrument to a value of 2, and the ratio filter activated, only the signals from the IP source would be accepted by the Instrument. This feature of extracting information from the signal of a single transducer to identify the source of the signal is the most powerful feature of the AESMART 2000 approach. More detailed information concerning this feature extraction can be found in Reference 6.

Note that both the IP (crack like) source and the OOP (noise) source generate a high frequency shear wave. Without the time reference provided by the trigger transducer , or the low frequency signal produced by the OOP source it would be difficult based on the HF signal characteristics alone to tell the difference between the extensional wave produced by the IP source in figure 5 and the shear wave produced by the OOP source in figure 6. The presence of a high frequency shear wave produced by **both** IP and OOP sources is the primary reason traditional methods have not been successful in the testing of complex structures. Signals from a single transducer cannot be used to tell the difference between a noise source and a crack growth source using traditional signal parameter measurements.

The lack of a time reference from other transducers in the array or guard transducers used by traditional methods prevents spatial filtering from being utilized.

EXCELL GRAPHICS

When changing channels either manually or automatically in the multiple channel system, data in the previous channel received is automatically transferred to an Excel spreadsheet template. Two graphics are provided with the multiple channel system. One, a histogram showing the summation of valid events for each channel (figure 7), two, summation of counts versus time for individual data sensors (figure 8). Both graphics can be observed in real time during a test when the mux button on the screen is enabled. Other graphics can be constructed by the user from the Excel spread sheet of the data.

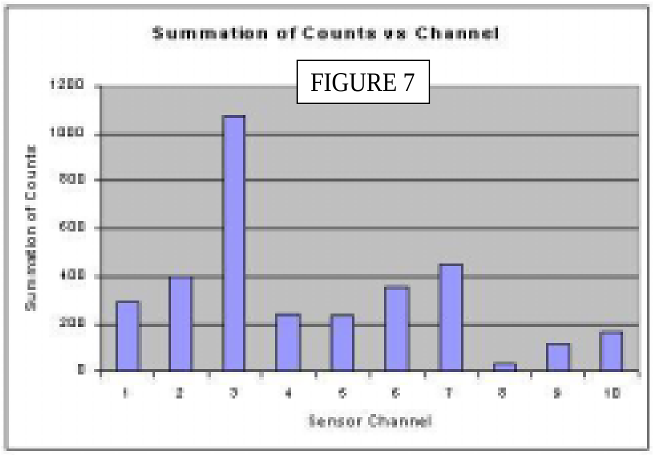

FIGURE 7

Figure 7 shows a histogram display from a 10 channel system showing cumulative counts activity from each channel. If it is observed that a lot of activity is present from a particular channel; that sensor channel can be selected and the summation of ounts as a function of time can be observed to determine the history of the recorded events from that particular sensor. An example of this graphic is shown in figure 8.

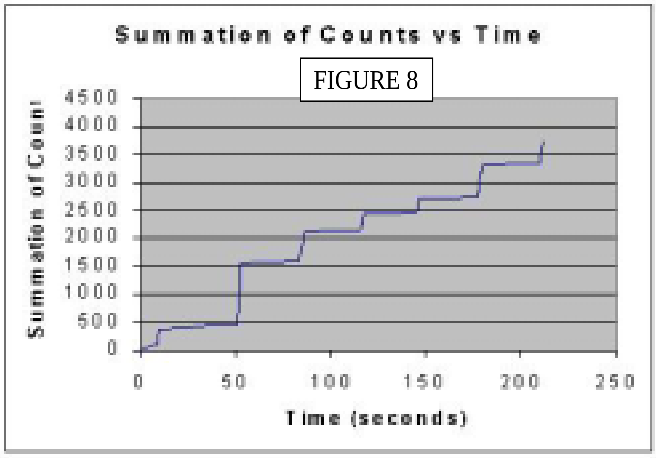

FIGURE 8

Figure 8 shows the historical data for seven scans from sensor 1 for a 10 channel system responding to simulated signals on an aluminum plate to which the transducer was attached. The dwell time selected was 0.05 minutes. Note that the flat regions of the graph where no data is recorded was the time spent on recording data from the other nine channels. Over a long period of time the “flat” regions would disappear and the summation of counts curve would appear more like it would for continuous monitoring of the sensor. This type of data can be curve fit and failure criterion models setup (reference 7) to provide an alarm if a critical crack size is being approached.

CONCLUSION

Historical reference has been given to the use of a periodic proof test for the testing of crack growth in pressure vessels, piping and valves using traditional acoustic emission methods developed by the author and associates over 25 years ago. Traditional AE methods are still a viable method to use for short term tests of pressure vessels utilizing periodic proof tests, and many codes and standards have been written for this application. Traditional AE methods have not worked well nor has the method been accepted as a viable test method for global testing of large complex structures such as aircraft, bridges, and offshore platforms. Pressure vessels can be easily proof tested with a minimum of extraneous noise and their simple outer surface allows for 2 dimensional location of AE sources to assist in isolating signals from crack growth from extraneous noise sources. Traditional methods cannot be used for testing of large complex structures for the following reasons: One, these complex structures cannot be easily subjected to a quite proof stress above their working stress, two, their structural complexity does not lend itself to the use of spatial filtering so successfully used for pressure vessel testing, three, signals from a single transducer cannot tell the difference between sources due to crack growth and the high frequency shear wave generated by noise sources. An additional disadvantage of traditional AE methods for testing of large complex structures is the high cost associated with fielding hundreds of channels of instrumentation with a separate cable required for each channel.

A new technique which utilizes a single cable to connect all transducers and a single channel instrumentation multiplexing system for continuous monitoring of large structures on a statistical sampling bases is described. This system which utilizes modal analysis of the AE signal from a single dual mode transducer has the ability to recognize the difference between AE sources due to crack growth and those produced by noise. If can also provide information regarding crack depth, and distance of the source from the data transducer. All data is transferred to an Excel spreadsheet which provides the user with the ability to do analysis and graphics that suits his or her particular purpose.

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