Modal AE: A New Understanding of Acoustic Emission

Michael R. Gorman

Abstract

Modal AE provides increased understanding of acoustic emission through analysis of guided waves in plates, rods and shells. Modal AE technology means wideband detection of the elastic displacements, theoretical calculations of velocities and wave shapes, and signal processing of wave mode details in order to establish a definite and physical correspondence with AE source mechanisms. The fundamental assumptions upon which Modal AE technology is based are stated and discussed in this paper. Some relationships between sources and waves in various materials and geometries are presented. In this paper the basic assumptions behind AE parameter analysis are reviewed, and it is shown that these assumptions are in direct opposition to the true nature of wave modes in finite media. Further, it is explained why the AE parameters are highly correlated - they are in effect dependent variables. It is concluded that future research should be focused on wave detection and analysis in conjunction with materials science and mechanics. This paper is based on a talk given by the author at the Ringberg Workshop, Teegernsee, Germany, October 1996.

Introduction

A new direction for AE testing of materials is Modal AE. Modal AE is the study of the ultrasonic wave modes produced by acoustic emission sources in plates, rods, shells and other thin-walled materials. Modal AE brings to the field what it has long lacked - technology based on physical fundamentals of the ultrasonic wave modes produced by AE sources in plates and other guided wave geometries. Plate waves have been mentioned before in the literature, but true understanding of the importance of their interpretation has come only recently. Even more recent is the technological innovation which makes the measurement and analysis of plate waves practical and easy to use in the laboratory.

In engineering materials laboratories, testing of thin-walled specimens is, in the main, the dominant procedure, whether the specimens be unidirectional coupons, biaxial plates and shells, rods, or even pressure vessels. In terms of waves, a specimen is thin if its characteristic di-

mension (e.g., thickness of a plate) is less than a wavelength of the appropriate AE waves, which is the case that holds in many, if not most, of the standard tests. This is the domain of Modal AE, and it is a practical one as well in the context of NDE (nondestructive evaluation) since many engineering structures are built of plate sections.

Modal AE has been around long enough now to have made some real progress in proving its capabilities for definitively detecting and locating crack sources in certain materials, especially in the presence of extraneous noise. However, future research directions need to be defined and explored, especially within the context of the AE literature. In past attempts to analyze AE signals, many good ideas were offered, but the “noise” created by deformation could only be explored by RMS (root mean square voltage, sometimes called mean amplitude in the literature of the 1970s) and counts (aka threshold crossings). Now with Modal AE the individual waves can be examined and the wave propagation details studied. This is very important when developing correlations with the deformation and fracture behavior of materials. The now commonly understood relationship between source orientation and the type of mode produced is a good example. (Gorman and Prosser 1990)

In some ways Modal AE is very similar to the early efforts to relate AE “seismic” sources with bulk wave characteristics (Proctor et al., 1983; Kim and Sachse, 1986; Ohtsu and Ono, 1986). However, it is important to recognize the effect which specimen geometry has on AE waves. Guided wave modes are profoundly different from the bulk wave modes that have long dominated AE discussion. It is a little known fact that the bulk waves (P, S and R) simply do not manifest themselves in thin laboratory specimens.

After reviewing about a hundred papers in the literature on AE, it became evident to this author that instead of the acoustic emission technique being used to study materials, more often materials were used to study AE. Counts and RMS voltage were studied and countless correlations with material behavior were cited in the literature, but AE did not become a commonly used technique for metallurgical investigation. Recent Modal AE results on crack detection in aircraft components (Martin et al., 1995; Searle et al., 1995) show that the promise of AE can still be realized with increased understanding of the measurement.

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Every measurement technique has its limits. It is particularly relevant here to examine the assumptions of the resonant sensor parameter (RSP) technology which has so long dominated the field. The main problem with RSP technology is the lack of scientific basis. This has been pointed out before by Pao (1978) during the push in the late 1970s and early 1980s to codify correlations so that they would be accepted for use in certain industries. Astonishingly, nowhere in the literature does a critical analysis of the basic tenets of RSP measurements appear. Thus, a detailed examination seems pertinent before turning to Modal AE technology.

Resonant Sensor Parameter (RSP) Technology

It is important to realize that there are limitations which apply to any measurement and that any measurement is interpreted and the instrument which makes the measurement is designed according to some hypothesis or theory which is derived from some basic assumptions. To be unaware of the limitations of a measurement or to ignore them can be compared to using a standard mercury barometer on the moon; you might get a reading but what would it mean? We can "listen" to any material with a resonant transducer, but what are we measuring?

For the past thirty years or so, acoustic emission in engineering materials has been measured with resonant transducers, 150 kHz being the generic frequency. Analysis of the sensor signal consisted of correlating counts, amplitude, risetime, duration and energy, the so-called AE parameters, with whatever was known about the material being studied.

The foundations of RSP technology boil down to two fundamental assumptions. 1) an acoustic emission is a damped sine wave and 2) the wave propagates at a single (i.e., constant) velocity. The measurement data, the AE parameters risetime, peak amplitude, duration, energy and counts, describe a damped sine wave as shown in Figure 1. Given that an AE signal is as shown in Figure 1 (a damped sine wave), an AE instrument was designed to measure and record the parameters which describe that wave. This is logical, for if the signal were not a damped sine wave, then the parameter definitions (not to mention all the circuits) would have to be changed to suit another shape.

In reality, an AE wave is not a damped sine wave, as can be demonstrated by a simple lead break on a plate. In any plate, including the widely used laboratory coupon, AE is not a single propagating disturbance but multiple wave modes with many frequencies in each mode, all propagating at different velocities as shown in Figure 2.

Figure 2. Waveform Produced by a Lead Break on a Plate

Turning to the propagation characteristics, in RSP technology the assumptions imply that the propagating signal must not change its shape, except for simple attenuation. Otherwise, the signal parameter definitions would lose their meaning, depending on where the signal was measured. The unchanging shape and the assumption of constant velocity, are important for source positioning since arrival times and location are determined by threshold crossing and an assumed single velocity. Again this assumption violates the experimental evidence that the modes change shape dramatically as they propagate. It can be argued that the resonant transducer and narrowband filter produce a signal that fits the damped sine model of AE waves. This is true enough, but then one must conclude that it is mainly the characteristics of the sensor and filter that are being measured. Of course, only one wave is implied in all of this discussion because with multiple modes, one would have to ask which mode was used to trigger the arrival time clocks. Which mode produced the parameter values?
generated by in-plane and out-of-plane lead breaks on a plate. The in-plane lead break gives rise to an E wave and the out-of-plane lead break results in an F wave. These modes also exist in rods and shells.

![Lead Break Signals](image)

**Figure 3.** Extensional and flexural modes from lead break sources in a plate

It is important here to make two observations: (1) The fundamental modes carry most of the energy, and (2) the plate wave mode excitation is strongly dependent on the orientation of the source.

To fully appreciate the difference between Modal AE and Resonant Sensor Parameter (RSP) AE, one should understand the basic assumptions of each method.

In RSP AE, two basic assumptions are made:
1. AE is a damped sine wave, and
2. the wave travels at a constant velocity.

AE parameters measure the damped sine wave. Therefore, we should design an AE instrument to measure parameters. The instrument is characterized by narrowband, resonant sensors hooked up to AE “analyzer” circuits that record the parameters of interest.

In Modal AE, it is observed that the basic assumptions of parameter AE are incorrect. In fact:
1. AE consists of more than one wave mode, each with a wide spectrum of frequencies, and
2. each frequency in each mode propagates at a different velocity.

True AE waveforms are captured with high-fidelity, wideband sensors. Therefore, we should design a Modal AE instrument to capture and record the actual waveforms so that they can be studied with wave propagation theory (elastodynamics). The Modal AE instrument is characterized by high-fidelity, wideband sensors which capture the actual physical variables of the waveforms.

This reasoning can be expressed as shown in Table 1.

<table>
<thead>
<tr>
<th><strong>Modal AE Analysis</strong></th>
<th><strong>RSP AE Analysis</strong></th>
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<tr>
<td>Sources create ultrasonic energy</td>
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</tr>
<tr>
<td>The energy propagates as wideband wave modes in thin-walled structures (guided wave geometries).</td>
<td>The energy propagates as a (narrowband) damped sine wave. No modal behavior is accounted for.</td>
</tr>
<tr>
<td>The wave modes should be detected as physical variables, i.e. displacement, velocity or acceleration. Wideband, high fidelity, displacement or velocity sensitive sensors used.</td>
<td>Resonant sensors used measure no physically meaningful quantity.</td>
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<tr>
<td>Based on Newtonian Physics, analysis is deterministic - there is a definite relationship between wave mode characteristics and source characteristics. These characteristics can be modeled theoretically and do not change if the instrument settings are changed, e.g. the amplifier gain is decreased.</td>
<td>Analysis is based on empirical correlations between features of the detected signal and whatever is known about the AE sources for specific test conditions.</td>
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**Table 1.** Theoretical Foundations of AE Methods

**Modal AE Instrumentation**

The process of capturing waveforms for Modal AE is more difficult than storing resonant sensor parameters. The front end of the waveform (the direct wave) must be captured for further inspection and analysis, the wave must not be distorted, and flash A/D conversion is required. These conditions have resulted in some very specific requirements for the Modal AE measurement process (Gorman, 1994).

The technology required to properly capture and analyze these waves differs substantially from the old technology, even though it looks very much the same.
First and foremost, a flat (with frequency), wideband sensor is used for the detection of waves. The high-fidelity response of the sensors is required so that comparisons with theory can be made.

Secondly, the signal conditioning electronics must not distort the waveform before it is digitized. Signal filtering is performed using Bessel filters. Bessel filters are used rather than Butterworth filters due to their “nice” time domain characteristics, i.e., they do not distort the waveform. Instead of the maximally flat amplitude associated with Butterworth filters, Bessel filters have a maximally flat time delay. Butterworth filters have a sharper roll-off, but they shift the phase non-linearly with frequency, thus distorting the waveform.

For Modal AE purposes, digitization speed and resolutions tradeoffs are mostly a matter of budget for off-the-shelf components. For good shape information, the digitizer sampling frequency should be at least five times and preferably ten times the highest frequency component being captured. There are two important points to be made about the digitizer. (1) A/Ds are readily available as plug-in boards for PCs. However, extreme care must be exercised when using an A/D board due to the digital roar inside a PC. (2) The more bits an A/D has, the greater the vertical resolution. However, noise can easily eliminate the least significant bits negating any advantages of the higher resolution. For most purposes, an 8-bit digitizer like in most digital oscilloscopes is perfectly adequate, especially since theory guides the analysis and the modes are readily distinguishable.

Waveform throughput is very important for a Modal AE instrument. AE events are not only transient, but they occur randomly. Waveforms must be captured and stored at high throughput rates. This requires sophisticated software programming techniques. Throughput speeds above two million bits per second directly to the hard drive have been achieved on a PC. Higher rates can be expected in the future, however, a focus on event rate should not be at the expense of event quality. A waveform digitizer with high throughput rate combined with capturing just the right part of the wave are two things that distinguish an AE instrument from the many commercially available laboratory transient recorders and digital oscilloscopes.

Modal AE Analysis

Modal AE analysis methods range from basic visual recognition of the wave modes to advanced computational wave propagation, signal processing and source location techniques. Basic relationships between AE sources and wave mode excitation have been established.

Source identification begins with the greatly enhanced ability to separate signals from noise. Waveforms from different source mechanisms in 7075 aluminum are identified and described by Carpenter and Gorman (1994). In Figure 4 crack growth waveforms from a single event detected by three different sensors are presented. The upper two waveforms were detected with wideband sensors which have a non-resonant, flat response and a working range from 50 kHz to 3MHz. The extensional mode can be seen at the front of the first (top) waveform. A noticeable time lag to the start of the second (middle) waveform indicates that sensor was farther from the source than the first sensor. The extensional mode travels faster than the flexural mode and a slightly greater separation can be observed between the two modes in the second (middle) waveform. The distortions in the waveform are caused by reflections from the edges of the specimen. The third (bottom) waveform was detected with a resonant AE sensor. Very little detail about the wave modes is evident in this waveform. This sensor was closest to the notch (crack source) and triggered the system.

![Waveform Diagram](image)

Figure 4. Waveforms due to crack extension in aluminum. Top two waveforms detected by wideband sensors, bottom waveform detected by resonant sensor (after Carpenter and Gorman, 1994).

Various types of noise, ever present in the real world, can be distinguished by examining the wave propagation characteristics of measured signals and comparing with theory. Figure 5 shows the type of waveforms produced by grip noise. While the waveform captured by a wideband sensor looks markedly different from the crack waveforms in Figure 4, the resonant sensor waveform looks essentially the same. Again the RSP method problem goes back to the fact that the signals are heavily filtered by the resonant sensor which tends to make all signals look the same.
The above examples demonstrate that determining the shapes of the modes and their frequency content is a main analysis objective of Modal AE. Just as vibrational modes have definite shapes, traveling modes also have definite shapes. In Modal AE, this information is used to decide whether a signal is due to material fracture or is just noise.

Structural vibrations can be quite complex and consist of many frequencies. Likewise, a wave mode can be quite complex. Also, the signal pattern (shape of the mode) changes as the mode propagates due to a phenomenon known as dispersion (see Figure 6). Dispersion means that each frequency of the mode travels at a different velocity. Each of the different frequencies interferes constructively or destructively, depending on its relative phase and thus, the mode shape changes. The shape is a function of both position and time.

For the extensional wave, the velocity given by classical plate theory is

\[ C_f = \sqrt{\frac{E}{\rho (1 - v^2)}} \]

This can be used to very easily check AE measurements of lead breaks and other sources. Although frequency is not in this equation, there is dispersion in this mode according to higher order plate theory. What this means is twofold. A theory can have limits, so the assumptions must be understood when applying it, and the effect of dispersion is smaller at very low frequencies, i.e. the mode is almost nondispersive at low frequencies. For the flexural wave, the velocity given by classical plate theory is

\[ C_f = \left[ \frac{D}{\rho h} \right]^{1/4} \frac{1}{\sqrt{\omega}} \]

where \( \omega = 2\pi f \), \( f \) is the frequency, \( h \) is the plate thickness, and \( D = Eh^3/12(1 - v^2) \) where \( E \) is Young's modulus and \( v \) is Poisson's ratio. As can be seen, the frequency is a variable in this equation and thus the mode is dispersive, even in classical theory. This means that an AE pulse made of these waves will change shape dramatically as it propagates. This violates the usual assumption of constant velocity pulses used by RSP AE analyzers to trigger source location clocks. The largest displacement component of this mode is perpendicular to the plate of the plate (Carp 1993). Higher order theory explains the dispersion in both modes. For composite materials, Mindlin plate theory accurately predicts velocities and wave shapes in the flexural mode, and Mindlin-Medick theory accurately predicts velocities and wave shapes in the extensional mode.

Traditionally, first threshold crossing techniques have been used for source location. The difficulty with these methods derives from the fact that the acoustic emission pulse changes shape due to dispersion, introducing considerable error as the distance to the sensors increases. This means that the timing clocks are not triggered at the same phase point of the waveforms. Modal AE source location is based on a given mode and mode frequency, the velocity of which is computed based on material data. Planar source location requires the placement of at least three sensors. We may look at either the flexural or extensional mode in a given test. One method of determining \( \Delta t \)'s is to choose a frequency which appears in the waveforms received at each sensor, and cross-correlate with a single frequency wave. The peak of the resulting signal is chosen and, from this, the difference in arrival times (\( \Delta t \)'s) at each sensor pair can be calculated. The location of the event is determined by triangulation algorithms using the computed group velocity. Source location using cross-correlation methods can be performed independent of gain or voltage threshold selection (Ziola and Gorman, 1991).
Ask yourself if you know which mode is triggering your AE system. Remember lead breaks on the surface of your specimen produce a larger flexural mode, but the crack you want to measure produces a larger extensional mode.

Considerations for Modal AE Testing

In Modal AE, I usually start by considering what type of source I would like to measure or, to put it another way, what is the important source in the test. Generally, this involves the type of material, its condition, and the type of load to be applied. Next I consider the geometry of the specimen and the geometry of the source. I then predict what I expect to measure in terms of the wave modes. This has a twofold advantage. If I don’t get what I expect, then I ask why. This is important in advancing knowledge. If I do get what I expect, then the theory and technique are supported further, and I can provide both definite and useful information to material analysis efforts.

What if there are multiple sources? I ask if they can be isolated somehow, either by the load or loading arrangement. If several types of sources are expected to emit simultaneously, then the question becomes, “Can they be separated somehow through creating different wave modes?” If two sources create the same mode, are they much different in frequency or energy? If there is no way to distinguish between the various sources of emission, then the purpose of measuring acoustic emission in the test is reduced to one of activity alone and you should ask if that is sufficiently useful.

Next, I ask myself about noise. Are there sources of noise? Note that when noise is transferred into a specimen, it will propagate as modes too. Can the modal characteristics created by noise be distinguished from the modal characteristics created by the desired source(s)?

Before attaching any sensors, I consider the best positioning for measuring the expected (predicted) waves. Most desirable is a sensor near a source and one further away so that the modes can separate and the details of the wave propagation verified against theory. For example, given a notched coupon tensile specimen with a four-inch gage length, I would put one sensor at one inch from the notch and the other two inches away from the notch on the other side of the notch (Figure 7). I try not to have notches at the center of the gage length. That way I can place the second sensor a bit further away. For longer length specimens and for specimens where I don’t know the source position in advance, I like to use at least three sensors, one in the middle and the others at the two opposite ends. This helps to identify grip noise, enhances location, and allows me to see the higher frequencies which damp so rapidly, especially in composites.

![Figure 7. Typical sensor placement for Modal AE testing](image)

I do not like to place sensors on grips because the wave is so distorted. On the other hand, parts with abrupt bends may be used to advantage to isolate sources in a certain section of a structure. For example, for cracking in the flange of a beam, put the sensor on the flange not the web, because very little sound energy is transferred from the flange to the web.

Wave guides are necessary in some cases. Assuming that the wave guide is a prismatic rod, the wave modes in the plate section, which could represent a portion of a large diameter pipe, do convert to E wave modes in the rod. The rod modes should be studied carefully. The plate extensional mode does not convert as well as the plate flexural mode. The wavelength of the E wave is long and the out-of-plane displacement component is small. The detection of the E wave can be enhanced by increasing the contact area of the rod, but this may not be practical.

![Figure 8. Direct wave and reflection](image)

It is simply not possible to convey all of the facets of this subject in one talk, so I will discuss what in my experience is a very common point of confusion in looking at Modal AE waveforms. There are big differences in the appearance of the modes in different materials and geo-
metrics. I can give here only a few general principles to follow when looking at the modes. In the first place, find the direct wave (Figure 8).

In small coupon specimens, reflections arrive at the sensor almost as soon as the direct wave. Reflections distort the direct wave, and the modes may be almost unrecognizable. The superposed reflections often produce a higher peak amplitude than the direct wave (Figure 9) complicating the use of any type of amplitude and risetimes analysis. (The main other complication is dispersion, see Figure 7.) Sometimes I can see only the first two cycles of the extensional mode in small specimens. How to extract source information in this case is an area of current study.

![Reflections](image)

Figure 9. Superposed reflection shows higher amplitude than direct wave

Increasing plate thickness for a given material will begin to suppress the flexural mode. A thick plate simply cannot bend as easily as a thin one, especially at the higher frequencies. In a very thin plate, the extensional mode is almost dispersionless out to one megahertz but, as the plate thickness is increased, the frequency point at which significant dispersion begins is lower. For example, with aluminum at 1.588 mm (1/16") the frequency is about 1 MHz, at 3.1/8 mm (1/8") the frequency is about 900 kHz and at 6.35 (1/4") the frequency is about 300 kHz. With increasing thickness, higher modes become possible, although I have not seen any excited by real AE sources with energy anywhere comparable to the two fundamental modes. The velocity of the first part of the E mode is constant. This makes it easy to verify the plate mode nature of the wave. Note that in aluminum the E mode velocity is about 5200 m/s while the bulk longitudinal wave (aka P or L wave) travels at 6300 m/s. A list of practical tips which makes use of bulk wave velocities for performing Modal AE tests is given later on.

As I have said, this subject goes on and on, and all of the general understanding of waves has a bearing on Modal AE including not only topics like reflection and refraction as for bulk waves, but also guided wave dispersion, a somewhat more difficult topic. Since this is supposed to be a workshop, I feel that philosophical points are fair game, so here goes. A question I am often asked is where are the longitudinal, shear and Rayleigh waves in my coupon specimens or in my structure built of plate sections? The answer, as far as I am concerned, is that they simply aren't there. P, S, and R waves exist in principle even in thin plates but, for all practical purposes you can ignore them unless you are studying a bulk medium or very high frequency emission (much higher than the ones we typically measure in acoustic emission). The fact is, the velocities we measure are plate velocities, and therefore we are observing plate and not bulk modes. Consider a 3.175 mm (1/8") thick specimen, a somewhat thick coupon depending on one's point of view. For a distinct bulk wave to propagate its wavelength should be not much more than 10% of the thickness. Noting that λf = c, where λ is the wavelength, f is the frequency and c the phase velocity (6,300 m/sec.), in aluminum this means a frequency of 16.8 MHz. Even in 1/4" (6.35 mm) aluminum the frequency is still 8.4 MHz. For composites the velocity is usually much higher in the fiber direction, which is the direction the waves preferentially propagate. For those wondering about the whole subject of stress waves, recall that the stress waves Kolsky measured were excited in a large diameter cylinder (Kolsky, 1963). Stress waves in a Hopkinson bar are nothing more than the extensional and flexural modes.

**EXAMPLES OF MODAL AE TESTING**

1. **Transverse Matrix Cracking**

Predicting the result of the test before I run it is a much different philosophy towards AE testing. It used to be I would attach sensors to a specimen, check that the AE system (sensor plus analyzer) was active by doing a few lead breaks, and then run the test. As the test progressed I would look at the various parameter plots on the computer screen and try to discern any patterns. Of course, I would already have an idea of the failure mechanisms possible and at what loads I might expect them to appear. Then after the test was finished, I would examine various plots of the parameters, examine the specimen, and look for indications as to the meaning of all of the events. However, many nagging questions were always in the back of my mind. Could I say anything definite about the emission? Since I mainly studied composites like graphite/epoxy, the typical questions were: is this matrix cracking, delamination or fiber breakage? What about fiber pull-out as some researchers were studying at the time? What about interfacial failure? As the load increased the amplitudes would increase. Was this a direct correlation? The event rate would usually increase with increasing load. What did this mean? I finally concluded there were just too many variables.
Other workers, as well as myself, were trying or had tried to isolate a single failure mode in a composite, some with unidirectional specimens and neat resin (Averbuch, 1986; Valentin, et. al., 1983), and some with model composites containing a single fiber. The AECM conferences in the 1980s documented these attempts. The efforts in composites were not unlike the work done with metal alloys in the 1970s. Attempts to isolate mechanisms were considered to be extremely important as well. I do not have time to go into this here but the reader is advised to review the literature and see the many parallels.

I spent a great deal of time studying transverse matrix cracking in composites. According to composite mechanicians, transverse matrix cracking is the first failure mode to occur in crossply materials, and it occurs at low load levels like 30% of ultimate, whereas significant fiber breakage doesn’t begin until 95% of ultimate. After studying cracking for years and then, specifically TMC, I concluded that the AE parameters were well distributed over a wide range of values even from a single source. The parameters were really telling me nothing more than the fact that cracking produced a wide range of amplitudes, energies, etc. As I pondered the fundamental parameter definitions, I realized that, in fact, they were not independent variables. If I have one, then I essentially have them all. This has been discussed above. It means that if amplitude could not be used to distinguish matrix cracking, then none of the other parameters could either. It could be argued, and was argued, that cracking was not the only possible AE source in my experiments. Fine, I would say to myself, then we have true sophistry at work - I can’t say that I have only TMC because there is the possibility of a very few fiber breaks and other mechanisms. Therefore, I can’t say that amplitude distributions do not sort out failure mechanisms. Of course, this subtle reasoning meant AE was telling nothing to product engineers and analysts, and AE was rejected as a test technique by most engineers and managers at my company as well as those in the composites world in general. Personally, not being able to prove that I was measuring something definite was very unsatisfying. Recently, I have written a review of AE measurements of TMC, which describes the success of Modal AE in making definitive measurements of TMC (Gorman, 1997).

2. Example of Modal AE Testing in an Aircraft Application

An example of the use of Modal AE technology used in a practical application was the testing performed at the Northrop Corporation, Aircraft Division by myself and others in 1993. Fatigue crack growth in military aircraft results from aging aircraft, environmental conditions, and extreme loading. There is great need to develop methods to remotely detect crack growth. A study was designed to monitor a representative stiffened wing skin panel during constant amplitude and spectrum fatigue loading. This work has been reported at many meetings. Later studies along the same lines have been published (Martin et. al., 1995.)

The specimen was a simulated F-5 wing skin made of 0.125” thick, 7075-T6 aluminum, 24” x 18”. A 2” diameter access hole was cut in the specimen, and a notch was machined into the panel at the access hole to create a stress concentration, which resulted in crack growth during the loading. T-shaped stiffeners were attached with aircraft fasteners. For several of the tests, a 0.25 inch steel plate patch was bolted onto the panel over the access hole to simulate a repair (Figure 10).

A Digital Wave Corporation F4000 Fracture Wave Detector was used to perform the tests. Four DWC B1000 wideband sensors were mounted on the specimen with vacuum grease, and the signals from the sensors were amplified 40 dB using DWC PA2040 preamplifiers. The signals from the preamplifiers were input into the signal conditioning modules of the Fracture Wave Detector which are capable of independent gain and bandpass filtering on the trigger settings and the acquisition signal.

Figure 10. Diagram of Simulated F-5 Wing Skin Specimen

settings. The gain on the acquisition signals was 27 dB with a 50 kHz to 1.5 MHz bandpass. The gain on the trigger signals was 24 dB with a 500 kHz to 750 kHz bandpass. The signals were digitized, stored on the hard drive of the computer, and displayed on the monitor. A series of 17 tests were conducted, initially without the steel patch, and later with the patch in place. Spectrum fatigue loading cycles were used. Crack growth was monitored with a video microscope to verify the results of Modal AE analysis.

A large portion of the data consisted of noise from fastener, stiffener or patch fretting, crack face rubbing, or EMI. Representative waveforms from the tests are shown in Figure 11.
Only 1 in 10 events out of every 1000 recorded were positively identified as crack growth events. These events were correlated to load, the video, and source location. During the testing, AE from fatigue crack growth

Figure 11. Representative Waveforms of EMI, Fretting, Crack Fretting and Crack Growth

from both constant amplitude and spectrum fatigue loading was detected and captured. The results were:

1. Crack growth was detected with AE and confirmed, both with parametric and video coverage.

Figure 12. Location of Crack Events. Test numbers are in chronological order.

2. The direction of the crack growth from the notch could be tracked and crack length measured to roughly 0.25 inches, even though sensor placement was varied throughout the testing. Higher accuracy could have been obtained with better measurement of sensor location, better measurement of propagation velocity, and smaller sensor diameters (Figure 12).

3. Wideband AE could differentiate between crack growth events, crack face rubbing events and noise signals due to fretting and EMI.

Practical Tips for Modal AE Testing

Reproduced here are some practical tips to bear in mind when performing Modal AE tests. In thin plates only two types of waves are excited with any appreciable energy, those being the extensional plate wave and the flexural plate wave described above. The modes can be verified by comparing the measured velocities to those predicted by classical plate theory. Since many of the structures monitored are of a plate shape, AE measurements can be based on theoretical foundations, which, in turn, will yield greater understanding of the detected signals (CARP, 1993).

The following general points should be kept in mind when performing Modal AE tests to obtain the best data for analysis:

1. For any AE test, consider the geometry. Then try to decide the types of waves which are allowed to propagate. For plate waves, the thickness must be smaller than the wavelength(s) being measured.

2. Compute the wavelength from \((\text{wavelength}) = (\text{velocity})/(\text{frequency})\). When velocity is in \(\text{m/s}\) and frequency is in \(\text{Hz}\), the length will be in meters. Since the shortest wavelength should be greater than the plate thickness, the bulk shear velocity for the medium divided by the highest frequency will provide a reasonable approximation of the wavelength.

3. The extensional wave travels at approximately 0.21"/\(\mu\text{s}\) or 5.4 mm/\(\mu\text{s}\) in aluminum. This velocity is about twice as fast as the highest velocity usually seen in the flexural wave. An extensional wave in graphite/epoxy can travel at 9.2 mm/\(\mu\text{s}\) or faster depending on the material.

4. Near the source the extensional wave and the flexural wave are mixed together. Far from the source, say 20 times the plate thickness, they are usually well separated.

5. The flexural mode changes shape rapidly as it moves. The high frequencies can reach the edge of a plate and reflect back and interfere with the lower frequencies of the same wave before the slower moving low frequencies even reach the boundary.

6. Sensor spacing should be based on the wave mode to be measured. In general, due to attenuation, lower frequencies propagate further than higher ones.
7. The mode to be measured depends on several factors: the directionality of the source motion, the attenuation with frequency of the material, the type of source or failure mode under study, geometrical factors of source and medium, the intent of the test, etc.

8. To study typical waveforms in a test sample, try to simulate the dominant source motion as closely as possible to the actual source motion.

Conclusions

Cracking in materials is being measured with Modal AE. One example of initial study is transverse matrix cracking. Another is monitoring crack growth in aluminum. Other materials like ceramics and metal matrix composites also present the extensional and flexural modes for study as they fracture. It is clear that AE has a new direction that will enable much new research in materials, and the AE literature contains many studies and approaches that could be revisited in light of Modal AE. Modal AE can be studied both experimentally and theoretically, and the importance of theory cannot be emphasized enough. Modal AE technology is logically compatible with previous fundamental studies on AE propagating as bulk waves.

References


