ABSTRACT

Although the acoustic emission (AE) technique has now aged for more than thirty years, the analysis techniques that are used in practical field testing are still very basic. The last decade has seen a growing awareness of the dangers involved in reducing an AE signal to its basic parameters and thus eliminating most of the information. This awareness has resulted in the development of practical AE analysis techniques that are based on the complete waveform rather than on the parameters. These techniques also make use of a growing insight into the theoretical principles of AE signal generation and propagation, which is evidenced by e.g. the use of the classical plate wave theory. This paper will lay out the principles of the classical plate wave theory and will demonstrate how this simple theory combined with a complete waveform acquisition can lead to a more reliable testing of composite materials.

INTRODUCTION

The acoustic emission technique (AE) has for many years been considered as the prime candidate for structural health and damage monitoring in loaded structures. It offers the user a number of inherent advantages, the main of which are its continuous and in situ monitoring capabilities and the possibility to examine the whole volume of a structure simultaneously with a limited number of sensors.

The increasing use of composite materials in loaded structures and their complex damage development has created a need for an efficient and reliable NDT technique that can be used during the service life of these materials. AE clearly has the potential to serve as a continuous damage detection technique for composites and during the past decades many studies have been undertaken to develop the technique to higher levels of performance. Three main types of data analysis have been extensively explored so far. That is, AE activity analysis (focusing on the amount of signals that are detected during a test), AE parameter analysis (studying evolutions in the basic signal parameters like amplitude, duration or energy) and AE frequency analysis (analyzing the frequency content of AE signals). Although many applications can be envisaged in all of the areas where composite materials are being used or could be used, it is surprising to see that the number of practical applications exploiting the AE technique has remained relatively limited. The main reasons for this are the limitations of the analysis techniques discussed above, which make it difficult to extend laboratory results to industrial structures. Commonly encountered problems are the large amounts of gathered data, the difficult separation of noise from real damage signals, the material anisotropy, the large wave propagation paths, etc. Summarizing these observations, one can state that AE has remained mainly a qualitative technique and that its further acceptance and practical use require a more quantitative approach based on theoretical concepts, which can reliably take into account source phenomena and wave propagation effects.

Another attempt at providing a better theoretical background for AE testing is now known as modal acoustic emission (MAE) or waveform based acoustic emission. MAE starts from the observation that AE waves are mechanical in nature and should therefore be treated as such. Following the general
theory of wave propagation in solids, AE waves should propagate through a structure in a variety of modes. The separation of these modes at the sensor could make it possible to extract information about the source event that produced the wave. Additionally, wave propagation theory offers theoretical tools to study the influence of attenuation and dispersion.

This paper will first provide a simple, yet practical, theoretical background for AE signal analysis. It will then be demonstrated how this theory can be used to make composite testing more reliable by demonstrating, on a laboratory scale, how signal recognition and discrimination, noise elimination and source location can be performed in a more consistent manner.

**PLATE WAVE THEORY**

A comprehensive overview of wave propagation theory as it applies to solid materials can be found in reference 1. Solutions to wave propagation problems in structures of arbitrary geometry can be obtained by using the three-dimensional equations of the elasticity theory. In the case of plate-like structures, however, a simpler theory can be used, i.e. classical plate wave theory. According to this theory, mechanical waves propagate through plate-like structures in three modes: the extensional mode (particle displacement in the plane of the plate and in the direction of wave propagation), the flexural mode (particle displacement perpendicular to the plane of the plate) and the shear mode (particle displacement in the plane of the plate and perpendicular to the direction of wave propagation). MAE has up to now made extensive use of the extensional and the flexural mode.

Based on the classical plate wave theory, the velocities of propagation of both modes can be calculated. Plate wave theory predicts a non-dispersion extensional mode: all frequency components of this mode propagate at the same velocity. Although practical results show that this is a reasonable approximation, it will not be satisfied completely. An analysis of the extensional mode based on higher order theories shows that the extensional mode exhibits limited dispersion behavior in which the velocity of propagation decreases with increasing frequency. For the flexural mode, plate wave theory predicts dispersion behavior in which the velocity increases with increasing frequency. A more detailed overview of classic plate wave theory and the way it has been applied in AE testing can be found in references 2-6.

**MATERIAL AND EXPERIMENTAL TECHNIQUES**

All tests performed in this study made use of a carbon/epoxy composite material, which was produced in three different 8 ply cross-ply lay-ups: [0, 903]s, [02, 902]s and [03, 90]s. Tensile samples were used having a length of 150 mm, a width of 12 mm and a thickness of 1 mm. Tensile tests were performed on the MTS 810 loading frame. All tests were monitored by attaching two broadband AE sensors (Digital Wave Corp., B1025) to the specimens. The AE signals captured by these sensors were fed into a Fracture Wave Detector (Digital Wave Corporation) system.

**RESULTS**

Wave mode recognition

Figure 1 shows a signal that was generated by transverse matrix cracking in a [0, 903]s laminate. The figure shows both the time and frequency domain of the signal. As is indicated on the time domain graph, the signal can generally be divided in two zones. The wave package that arrives first at the sensor shows a behavior in which the period of the subsequent cycles decreases with increasing time. The
frequency content of this mode increases with increasing time which also means that the lower frequency components arrived first at the sensor and propagated at the higher velocities. As was discussed before, this dispersion behavior is typical for the extensional mode. The wave package that arrives at approximately 40 µs exhibits a behavior, in which the period of the subsequent cycles increases with increasing time. The frequency content of this mode decreases with increasing time and thus the higher frequency components arrived first at the sensor and propagated at the higher velocities. This dispersion behavior is typical for the flexural mode.

Both plate wave modes can be recognized in this signal. Generally, the extensional mode propagates at a higher velocity than the flexural mode and exhibits a higher frequency content. As is indicated on the frequency domain graph, the range between 400 and 800 kHz corresponds to the extensional mode and the range between 0 and 200 kHz to the flexural mode.

![Wave package behavior](image)

Fig. 1: Matrix crack signal generated in a [0, 90]₃₅ sample: a) time domain, b) frequency domain (E: extensional mode, F: flexural mode)

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Discrimination between damage phenomena

The two main damage phenomena that are active during tensile testing of a cross-ply composite laminate are transverse matrix cracking at the early stages of testing and fiber fracture during the later stages of testing. An example of a matrix crack signal as it was generated in the [0, 90],₃s lay-up was given in Fig. 1. Further investigation of the matrix crack AE signals revealed that the frequency content of these signals increased as the 90-ply thickness decreased.

Figure 2 shows a signal that was attributed to fiber fracture, due to the load level at which it appeared. The signal exhibits a dominant extensional mode and its main feature is its higher frequency content as compared to the matrix crack signal. This is reflected in the frequency domain: the signal exhibits large frequency components above 1000 kHz. This is in contrast with the matrix crack signal (see Fig. 1) in which no significant content could be observed above 1000 kHz. It thus seems feasible to base discrimination between different damage phenomena on the properties of the plate wave modes.

Noise elimination

One of the main problems preventing the widespread use of AE in practical applications is the elimination of noise signals from the data set. Based on the classic parameter based analysis procedures, this elimination has proven to be very difficult. As will be shown here, noise signals can be eliminated in a more consistent manner based on the complete waveform and the modal properties. The main noise phenomena that are active during laboratory type tensile tests are EMI (electromagnetic interference) and grip noise. Figure 3 shows an example of an EMI signal, measured by two sensors. The
shape of these waves is quite different from the ones shown above. Both signals are detected at exactly the same time. Additionally, the signals are very high frequent in nature and do no exhibit plate wave characteristics or propagation effects. It should be noted here that a traditional AE analysis would have treated this signal as a signal with amplitude comparable to the one of the real damage signals, a short duration and a high number of counts. Reducing the wave to these parameters would have made it very difficult to eliminate this noise type.

Figure 4 shows an example of a grip noise signal. A clear signal was only observed at sensor 2. The signal appears not have propagated to sensor 1, which suggests that it originated outside the sensor region, at the sensor 2 side. The signal at sensor 2 does exhibit plate wave characteristics, but they are markedly different from the ones of the damage signals as the low frequency content is much higher. Both examples demonstrate how more consistent noise elimination should be based on the complete waveform and the modal properties of AE signals.

Source location

AE does not only offer the user the possibility to determine when damage occurs and what type of damage is active, but it also makes it possible to obtain information about the spatial location of the damage. Based on the arrival time of an AE wave at a limited number of sensors, a source location can be calculated, if the velocity of propagation in the material under study and the position of the different sensors are known. The key element in a good and accurate location procedure is the determination of the arrival times of the AE wave at the different sensors. Arrival times are traditionally determined by using a fixed threshold value: the arrival time of a wave is the point where it first crosses the threshold. This procedure is prone to an error as it does not take into account the modal nature of the AE wave. Using a fixed threshold, one can never be sure which part of the wave first reaches the threshold. A good location implies that the arrival times are determined on a part of the wave that has traveled with the same velocity to all of the sensors.

![Fig. 3: EMI noise signal: a) sensor 1, b) sensor 2.](image)
A detailed discussion of this problem can be found in reference 8. During the tests performed in this work, two sensors were used and a linear location procedure was applied. Some signals were observed that could pose problems to the classic AE location procedure as for some threshold values, the arrival times are determined on the extensional mode at one sensor and on the flexural mode at the other sensor. Using a fixed wave velocity, this led to location errors up to 35%. This demonstrates that for an accurate source location, the modal nature of AE waves should always be taken into account.

**CONCLUSION**

Waveform based AE analysis techniques use simple theoretical concepts as a theoretical background to study AE signals generated in composite plates. Here, it was demonstrated how plate wave modes can be recognized in real damage AE signals. Furthermore, a number of examples showed how the technique can discriminate between different damage phenomena, how it can be used to consistently eliminate noise signals from the data set and how it can improve on the location procedures as they are offered by traditional AE systems.

On a more general note, it is believed that more reliable techniques are needed if AE is to further improve into a generally accepted testing technique. Potential users of the technique are still put off by the empirical nature of the classic analysis techniques, which lack a theoretical basis and a general validity. It is believed that the evolution into an analysis of the complete waveform and its properties can be a big step into the right direction.
REFERENCES