DAMAGE LOCATION IN COMPLEX STRUCTURES SUBJECTED TO MULTI-MODAL WAVE USING ELLIPTICAL ALGORITHM AND MODIFIED ACOUSTIC EMISSION TECHNIQUE

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Abstract

Acoustic emission (AE) propagation was studied for several decades and was proven difficult to understand as multiple modes occur in complex structures. The collected data may result in misleading interpretation due to limited understanding of the nature of acoustic emissions. The current paper deals with an algorithm that takes into account propagating multi-wave modes. The material property, dictates the wave amplitudes, in some cases resulting in different wave mode triggering the AE sensors. Since the first hit wave technique is generally used when dealing with acoustic emission, the corresponding time-of-flights may no more be related to a single wave mode, making the AE source location erroneous. The paper deals with this multi-mode related problem, allowing the user recovering the true AE source location.

1. INTRODUCTION

Acoustic emission (AE) technology has been used for many decades in various applications, such as oil and gas platform monitoring [1], civil engineering [2], space [3] and aeronautics [4]. Three research teams from Airbus, Ultra Electronics Ltd and Lloyd's Register EMEA, produced a comprehensive tool that uses acoustic emission for damage assessment in aeronautical structures. The system overcame several typical acoustic emission related problems such as large data streams, high speed asynchronous monitoring, wave propagation in anisotropic material found in aeronautics and accurate AE source location when time-of-flight and velocity data are inaccurate. The location algorithms, converting time-of-flight differences to x-y coordinates, are based on triangulation using techniques such as Tobias' analytical [5] or Barky's numerical [6] algorithms. The principle of triangulation is that, knowing the velocity of the wave propagation, we can determine the location of the acoustic emission through triangulation if we can measure the time elapsed between two hits of the sensors i.e *the time-of-flight difference*. The methods assumed that the velocity is identical in all directions since the material was metallic and therefore isotropic. Paget [7] has since developed an analytical algorithm for locating AE source location in anisotropic materials such as composite structures. The algorithm is based on elliptical wave front propagation, allowing location damage in most aeronautical structures with good accuracy. However, in all the above techniques, the major drawback results in locating damage whose AE sensors are hit by more than one Lamb wave mode. This is often caused by the propagation distance and its wave attenuation, as well as the complexity of the structure containing various attenuating features (such as stringers, sealants, joints). The authors have then created an analytical algorithm capable of locating AE source, where more than one mode has hit the sensors. Such an algorithm is known in this paper as Multi-Modal Compensation Algorithm (MCA). The present paper is divided in two parts. The first part is addressing the problem and the solution. The second part is evaluating the performance and limits of the proposed algorithm.

2. OUTLINE OF THE ALGORITHM

Previous work dealt with locating acoustic emission source in composite structures, using an analytical approach based on that the wave front propagates with an elliptical shape [7]. Such an analytical algorithm has the great advantage of providing a solution faster than numerical algorithms. However, this algorithm is applicable to single Lamb wave modes, that is, the same Lamb wave mode must hit the first three AE sensors in order to provide a solution with good accuracy.

In aeronautical structures, the mixture and Lamb wave attenuation of material as well as the complexity of structure often result in acoustic emission wave hitting the first sensors with more than one mode, as illustrated in Figure 1. This figure shows an example of attenuated Lamb wave modes propagating in a structure. At a propagation distance, $x_{threshold}$, the amplitude of the faster and more energetic mode (usually S_0 in most aeronautical applications) is becoming lower than a slower and less energetic mode (usually A_0 in most applications). It occurs usually when distance between sensors is large, or when the material type and thickness changes along the propagation path or in presence of the structural features. The structural features in aeronautical structures are typically stringers and joints. Therefore it is possible in many cases to have the AE sensors being triggered by Lamb wave from different modes.

The multi-modal algorithm triangulates using elliptical wave front principles, resulting in an eight-order polynomial equation to solve whereas the single-modal version has a forth-order polynomial equation. On the other hand, Tobias algorithm is based on second-order equation. The difference in the equation order is due to the number of different group velocities associated with the problem. The input parameters of the equations are the three hit sensor coordinates, the group velocities in the principal directions and the time-of-flight differences between the hit sensors, as indicated in Figure 2. For more details on the single modal algorithm see [4].

For that reason, the proposed multi-modal compensation algorithm (MCA) was developed to allow various combinations of Lamb wave modes triggering the first hit sensors in order to recover the AE location accuracy that is expected. The algorithm comprises of two main parts. The first part deals with the AE location based on elliptical Lamb wave front propagation, where the velocity on each AE sensor can be different. The second part determines what are the velocity combinations that can be physically possible, taking into account the given sensor coordinates and time-of-flight differences.

In this case, a minimum of four hit sensors is needed to determine the Lamb wave mode velocity and AE location combination.

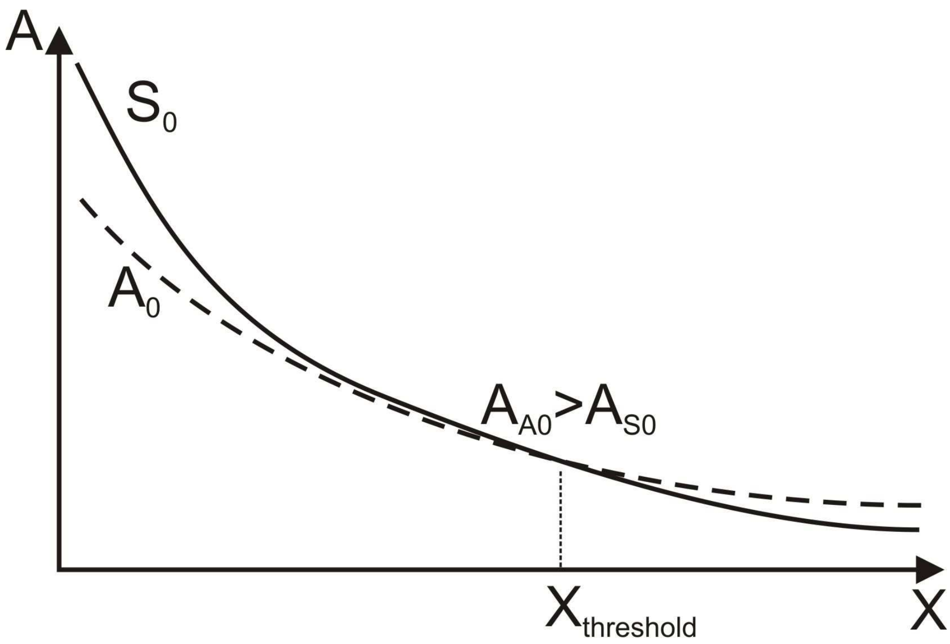

Figure 1: Amplitude attenuation curves of Lamb wave modes

Figure 2 shows an example of Lamb wave propagation following the elliptical approach used in [7]. In the figure, the AE position using MCA (AE_{MM}) and single-modal elliptical algorithm (AE_{SM}) is schematically shown. Further discussions are given in the next section.

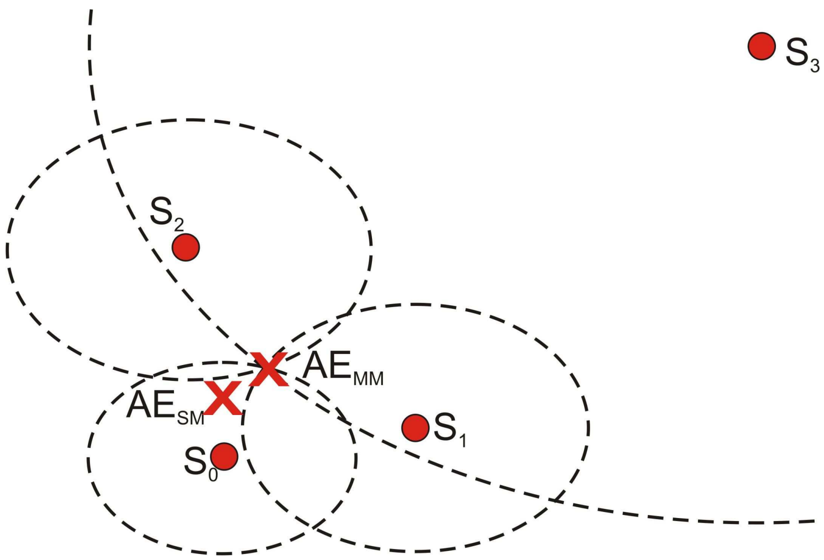

Figure 2: Multi-modal Elliptical setup

3. MCA EVALUATION

3.1 Comparative study

In the present paper, the performance of the algorithm is evaluated based on an analytical investigation, and focusing on specific examples to illustrate the results. Further in-depth theoretical and experimental study of this algorithm is expected in a later paper.

3.1.1 Setup data

The paper provides in the next sub-section some examples of AE location obtained by multi- and single-modal algorithm as comparison. Table 1 gives the data used in the calculation of the acoustic emission location using both the new multi-modal and the single-modal algorithms. The time-of-flight differences, ΔT, are determined using the predetermined AE location and the velocities of the multi-mode case only, as the comparison is to be made with this algorithm.

Algorithm	Group velocity (km/s)	Sensor coordinate (mm)
Multi-mode, Elliptical	$V0_0$=7, $V90_0$=5 $V0_1$=7, $V90_1$=5 $V0_2$=3, $V90_2$=2.1 $V0_3$=3, $V90_3$=2.1	S0=(10, 30) S1=(438, 94) S2=(-76, 498) S3=(1213, 948)
Single-mode, Elliptical	V0=3 V90=2.1	
Tobias	V=3	

Table 1: Algorithm input data

3.1.2 Comparative evaluation

This section is comparing the acoustic emission location using the Tobias algorithm, designed for metallic structures, the single-modal elliptical algorithm, designed for most aeronautical composites, and the multi-modal elliptical algorithm, for complex metallic and composite structures. Table 2 provides the acoustic emission location error obtained using the three algorithms aforementioned. The error was determined using the following relationship:

$$Location\ Error = \sqrt{\left(x_{Original} - x_{\mathrm{Alg}orithm}\right)^2 + \left(y_{Original} - y_{\mathrm{Alg}orithm}\right)^2} \quad (1)$$

where x and y are the coordinates for the AE origin and for those determined by the multi-modal algorithm.

				Location error (mm)		
AE location (mm)	ΔTs (μs)	ΔTs based on	MCA location (mm)	Multi-modal elliptical	Single-modal elliptical	Tobias
(110,230)	ΔT1=83.9 ΔT2=97.1 ΔT3=170.7	Multi-modal	(110,230)	0	119.8	113
(-30,750)	ΔT1=285.4 ΔT2=292.8 ΔT3=373.7	Multi-modal	(-30,750)	0	220.1	169.7
(250,405)	ΔT1=107.9 ΔT2=125.1 ΔT3=142.3	Multi-modal	(250,405)	0	322.8	580.7
(190, -70)	ΔT1=80.1 ΔT2=87.2 ΔT3=218.0	Multi-modal	(190, -70)	0	302.1	239.6

Table 2: AE location error (in mm)

In the shaded cells of Table 2, the results provided by the MCA are shown. In the short list of AE location evaluated in Table 2, and in the case the group velocity is not identical on all sensors monitoring composite material, the multi-modal elliptical algorithm has provided the exact result. However, such performance was expected since the data used with all AE location algorithms did not contain experimental uncertainties. The next section is devoted to the robustness of the MCA to re-enact the use of experimental data.

In the case where the velocity is identical on all sensors monitoring composite material, the single-modal elliptical algorithm is the algorithm expected to provide the best AE location results. Similarly, the Tobias algorithm is likely to be the best algorithm in metallic or quasi-isotropic composite materials when the velocity is the same on all AE sensors.

The MCA is in fact acting as a generic algorithm for all cases, multi- and single-modal cases in composite and metallic materials, meaning that it includes the multi- and single-modal elliptical algorithms as well as the Tobias algorithm. The MCA then verifies what is the possible solution utilising all velocity combinations and algorithms (both elliptical and Tobias). To illustrate this point, Table 3 shows the comparison between the MCA results and those from the three location algorithms. Here again, the MCA is capable of selecting the right velocity combination and its corresponding algorithm, as shown in Table 3, demonstrating how robust the MCA is as a triangulation tool of AE sources in both complex and simple metallic and composite structures. As indicated in the Table 3 the multi-modal algorithm did not work for the cases where the group velocity is identical on all sensors while the two single-modal algorithms, (the elliptical and the Tobias algorithms), generated location results. In these cases, the location error is dependent on the nature of the acoustic emission.

				Location error (mm)		
AE location (mm)	ΔTs (μs)	ΔTs based on	MCA location (mm)	Multi-modal elliptical	Single-modal elliptical	Tobias
(110, 230)	ΔT1=27.3 ΔT2=40.5 ΔT3=398.3	Single-modal	(110, 230)	-	0	38.7
(-30, 750)	ΔT1=255 ΔT2=183.2 ΔT3=334.2	Tobias	(-30, 750)	-	322.2	0
(250, 405)	ΔT1=41.1 ΔT2=75.4 ΔT3=291.9	Single-modal	(250, 405)	-	0	147.8
(190, -70)	ΔT1=80.1 ΔT2=87.2 ΔT3=218	Multi-modal	(190, -70)	0	302.1	239.6

Table 3: Automated algorithm and velocity selection by MCA

3.2 MCA Robustness

This section aims at emulating the experimental input to the multi-modal elliptical algorithm in order to ascertain its robustness.

The algorithm has for input the sensor positions, the Lamb wave velocity in the principal directions and the time-of-flight differences. The Lamb wave velocities are obtained using the theoretical dispersion curves and the sensor positions are determined by using geometry models, and therefore good accuracy of these data can be obtained. However, any AE systems would be providing the time-of-flight differences with a degree of uncertainty. The source to the uncertainties in experimental data is such as the effect of attenuation, background noise and signal threshold. Such an uncertainty is being recreated in this investigation in Figures 4 to 6. To compare the effect, the results are given in Figure 3 using the theoretical input. The data were estimated with points with a distance of 10mm apart.

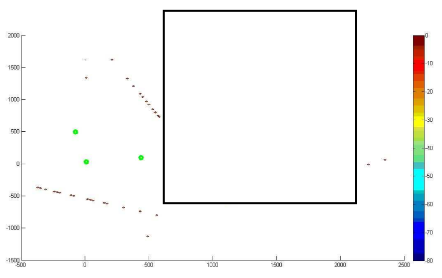

Figure 3: AE location plot with theoretical input to MCA

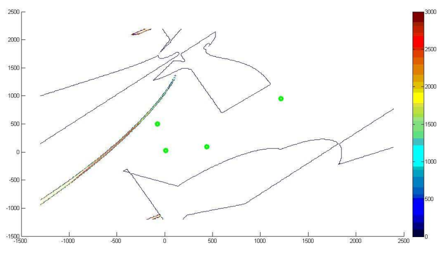

Figure 4: AE location plot with added random 4μs to MCA input

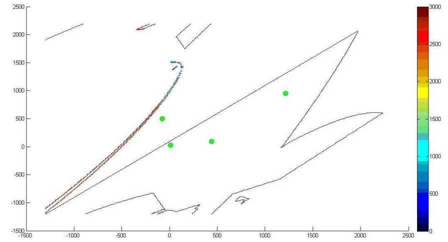

Figure 5: AE location plot with added constant 4μs to MCA input

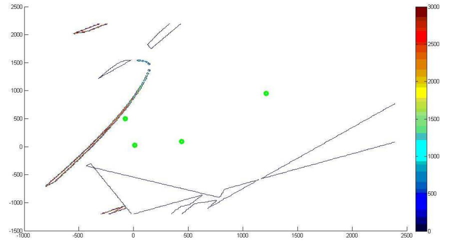

Figure 6: AE location plot with added random 8μs to MCA input

The thin black lines in the Fig 3-6 show the location where the algorithms did not generate any mathematical solution to the polynomial equations. The coloured lines represent various degree of error in the estimation of AE source whereas the white area corresponds to the locations where the error was zero.

The results in Fig 4-6 show that perfect fit between the calculated source locations and the original location was obtained also for cases with large uncertainties. In the cases where large error was obtained these only occurred in locations outside the sensor network. As shown in the figures the location of the acoustic emission source can be successfully identified with much improved performance even in the presence of significant measurement uncertainties. However, it is a few locations where no solution was obtained indicated by the black line. This is due to that no real solutions to the polynomial equations were determined. The current version of the MCA has not yet implemented a scheme to handle these cases.

The robustness of the single-modal elliptical and Tobias algorithms were already discussed in [8], and showed good behaviour of the algorithms, making such algorithms compatible with the current software of AE systems. Therefore the MCA, containing the multi-, single-modal elliptical and Tobias algorithms, is fit for use with AE system software, and is to be exclusively used with the VIGILANT acoustic emission equipment [9].

3.3 MCA Limitations

In order to be able to check all the various velocity combinations and algorithms, within the MCA, a fourth sensor is required. In other words, the distance between sensors must be so that at least four AE sensors are being hit by the acoustic emission wave.

The multi-modal elliptical algorithm includes an 8^{th} order polynomial equation, where all coefficients are zero if $V0_0=V0_1=V0_2$. In this case, the single-modal elliptical algorithm is used instead of the multi-modal algorithm.

The accuracy in the location is normally associated with how accurate we can measure the time elapsed between two hits of the sensors. As shown in Figures 3-6 the location accuracy was in most cases perfect indicating how powerful the algorithm is for determining the AE location.

CONCLUSIONS

In this research, we formulate a new generic algorithm to determine the AE location in complex structures. It was shown that a new multi-modal algorithm can take into account propagating multi-wave modes which frequently occur in aeronautical structure. It was also demonstrated that the proposed Multi-Modal Compensation Algorithm can effectively handle multi-modes cases. Using either the single modal or multi-modal algorithms, the source is accurate localized.

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REFERENCES

[1] L. M. Rogers, J. P. Hanson and J. J. C. Webborn, Application of Acoustic Emission Analysis to the Integrity Monitoring of Offshore Steel Production Platforms, Material Evaluation, Vol. 38, No. 8, 1980, pp. 39-45.

[2] C. U, Grosse, H.W. Reinhardt and F. Finck, Signal-Based Acoustic Emission Techniques in Civil Engineering, J. Mat. in Civil Engineering, Vol. 15, No. 3, 2003, 274-279

[3] D.A. Tiede, Acoustic Emission Inspection of Space Shuttle External Insulation, 23rd International Instrumentation Symposium, Las Vegas, Nev., May 1977, pp. 489-491

[4] C. A. Paget and K. J. Atherton, Damage Assessment in a Full-Scale Aircraft Wing by Modified Acoustic Emission, 2nd European Workshop on Structural Health Monitoring, Munich, Germany, July 2004, pp. 382-387.

[5] A. Tobias, Acoustic Emission Source Location in Two Dimensions by an Array of Three Transducers. Non-Destructive Testing, 1976, pp. 9-12.

[6] M. Barsky and N. N. Hsu, A Simple and Effective Acoustic Emission Source Location System, Material Evaluation, 1985, No. 1, pp. 108-110.

[7] C. A. Paget, K. J. Atherton, E. O'Brien, Triangulation Algorithm for Damage Location in Aeronautical Composite Structures, Int. Workshop on Structural Health Monitoring, Stanford, CA, September 2003, pp. 363-370.

[8] C. A. Paget, Limits of Single-Modal Elliptical Triangulation Algorithm for Structural Health and Usage Monitoring of Aeronautical Structures, *To be published at the CIMTEC conference*, Sicily, 2008

[9] Ultra Electronics Ltd, 417 Bridport Road, Greenford, Middlesex UB6 8UE, UK, (www.vigilant.co.uk), Damage monitoring system for all typical applications, including intrinsically safe and airborne.