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Acoustic emission source location in composite materials using Delta T Mapping

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ABSTRACT

The location capability of the acoustic emission (AE) technique is often considered its most powerful attribute. However, assumptions made in the calculation of location by current algorithms can be limiting in complex geometries and materials. This work forms a detailed study into the use of a novel mapping technique for AE source location in fibre reinforced composite materials. Both the performance and the robustness of the approach are assessed using artificial and real AE sources. Furthermore a large fatigue specimen was used to demonstrate detection and location of damage onset and development, where findings were validated using a thermo-elastic stress analysis (TSA) system. Substantial improvements in location accuracy were observed and early detection of damage onset was seen to outperform TSA.

1. Introduction

The use of large-scale and safety critical fibre reinforced composite structures for infrastructure and transport is continuing to rise at a rapid rate. A prime example of this rise is seen in current commercial aircraft, with Airbus and Boeing stating a usage of approximately 15% composite by airframe weight in their A380 and 777 aircraft, respectively. Both manufacturers claim this value will increase to around 50% with their next generation of aircraft (A350 xwb and 787, respectively) with composite materials being used extensively in the wings, tail section and even the fuselage. Another example of the expanding use of large-scale fibre reinforced composite structures is the wind power industry. Driven by the rapidly expanding off-shore wind sector, turbine manufacturers are continually aiming to upscale the capacity and therefore the size their turbines, with manufacturers such as Vestas proposing the production of turbines with rotor diameters in excess of 160 m. This increasing use of composite materials brings with it a need to establish inspection and/or monitoring regimes to ensure safe operation and structural integrity throughout service life. This can make the cost of ownership high, with down time being an important issue. Any structural health monitoring (SHM) methodologies that could increase the inspection intervals for a structure and indicate damage before costly failures occur would be very advantageous.

The acoustic emission (AE) technique has great potential for use in the structural health monitoring (SHM) of large-scale fibre reinforced composite structures. The continuous monitoring of such structures can increase safety and also reduce the amount of required inspections, thus reducing their operating and ownership costs. The AE technique is a passive NDT technique that uses piezoelectric transducers to detect elastic stress waves emitted during damage growth, allowing continuous and global monitoring of a structure. The most useful feature of AE monitoring is the ability to globally locate the source of a detected signal and hence the damage itself. This process is well-established for homogeneous structures and materials, however in complex geometries and materials such as fibre reinforced composites the current established methodologies become less effective.

In this paper a novel AE source location methodology known as "Delta T Mapping" is applied to composite materials. Originally developed for use in complex metallic structures and geometries, the methodology has many features that make it suitable for use with anisotropic composite materials. A thorough assessment is conducted to assess the performance and the robustness of the "Delta T Mapping" approach and comparison is made with traditional techniques. In addition the findings are validated using a thermoelastic stress analysis (TSA) system.

2. Background

The laminate nature of fibre reinforced composite materials means that structures can be readily approximated to plate-like structures. Therefore only location methodologies applicable to two-dimensional plate-like structures are considered within this paper. As such it can be assumed that AE signals under consideration will be propagating as Lamb waves adding a further level of complexity.

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The most common approach to locating AE sources in a structure, which is readily available commercially, is known as the time of arrival or TOA technique. The TOA methodology is discussed in detail in the NDT handbook [1] and by Rindorf [2], where user-defined inputs of sensor positions and a propagation velocity are required. Source location is then resolved using the difference in arrival times (delta t, Δt) of a given signal at different sensor pairs. The calculation assumes that wave speed is constant in all directions and that the signal path from source to sensor is uninterrupted. Deviation from these assumptions will introduce errors in the accuracy of the calculated location. Due to the nature of composites, it is common that their material properties, and therefore the propagation velocity, are dependent on material direction, with higher velocities observed along the fibre directions than those observed in off-fibre directions. Furthermore many real world structures will have geometric features such as holes, stiffeners and thickness changes that will interrupt the path of the signal and can result in mode conversion and variation in velocity. This can lead to poor performance of the TOA algorithm resulting in poor location accuracy and therefore limiting the capability of AE monitoring in large-scale composite structures. A further source of location error discussed in the NDT handbook [1] comes from the signal arrival time estimation, although important this topic is not directly addressed in this paper, however a reduced threshold level is utilised to aid arrival time estimation.

A number of authors have attempted to address the problem of AE source location in composite materials. Paget et al. [3] used analytical solutions, based on the assumption of an elliptical wave front, to find a closed form solution of the source location based on the Δts from a triangular sensor array. There are however a number of limitations with such an approach, firstly the wave front in composite materials can often be more complex than an ellipse. Secondly the accuracy of arrival time measurements, specified velocities and sensor positions are rarely good enough to ensure stability when calculating a source location with a closed form solution in this way. Aljets et al. [4] developed a novel two-stage approach, in which a closely spaced triangular sensor array is used to predict source locations within a large plate. Firstly, the angle of incidence of a signal upon the triangular array is ascertained using the difference in arrival times of the A_0 mode at each of the three sensors. Secondly, the distance from the source to the sensor array is calculated using the temporal separation of the S_0 and A_0 wave modes and their respective velocities for the propagation direction predicted, as performed in single sensor modal analysis location (SSMAL) [5,6]. Ciampa and Meo [7] utilised a specific layout of sensors to show good location accuracy of impact events in anisotropic materials. A triangular array of three closely placed pairs of sensors (six sensors in total) allows the source location to be described using a simplified set of six non-linear equations, with six unknowns (x position of source, y position of source, travel time to first hit sensor and three propagation velocities). Since no prior knowledge is required of the relationship between wave velocity and propagation direction, the approach is well suited to use in anisotropic materials. The solution of the non-linear equations is found using an iterative Newton method, in which an objective function representing the six equations is minimised. Although effective the algorithm is very demanding, requiring $\sim$2 s to resolve one location, when in industrial AE tests 100,000s of signals can be recorded per day. Additionally implementation requires twice as many sensors as traditional arrangements and propagation velocity is assumed to be constant for a given direction which may not be the case in complex geometries.

An alternative approach to the AE source location problem is the concept of mapping, whereby a relationship between the signal arrival time differences (Δt) and a spatial coordinate system is formed and used to aid source location. Mapping a structure in this way allows compensation for variation in propagation velocity and the effects of geometry, seen to reduce accuracy when utilising the TOA method of location calculation. Scholey et al. [8,9] describe the best-matched point search method that compares measured Δts with those analytically calculated for an array of points on an anisotropic composite panel. The point at which the difference is minimised is deemed to be the location. The accuracy is affected by the resolution of the mapping array, so small spacing's of 1–2 mm are used, and it is also important that accurate wave velocities are known for a given material. The approach is also not well suited to dealing with complex structures, in which the calculation of arrival times is far from trivial. Baxter et al. [10], Pullin et al. [11] and Hensman et al. [12] instead used artificial AE sources to determine Δts from known grid positions, to aid location in complex metallic structures. Baxter et al. [10] and Pullin et al. [11] generated contour maps of constant Δt for each sensor pair, linearly interpolating between grid points to improve resolution. Contours corresponding to measured Δts from real AE test data can then be selected for each sensor pair and overlaid to find a crossing point and hence a prediction of source location. Hensman et al. [12] followed a similar methodology, but chose instead to represent the relationship between the Δts and the spatial grid using Gaussian processes. Both mapping approaches were shown to improve source location in metallic structures with complex geometries and inherently compensate for variations in wave speed and any obstructions in wave propagation.

The inherent attributes of a mapping approach to AE source location makes it ideally suited for use in composite materials and structures with complex geometries and lay ups. In this paper the “Delta T Mapping” approach proposed by Baxter et al. [10] is used to investigate source location in composite materials. A thorough investigation was conducted to assess the performance and robustness of the “Delta T Mapping” approach for locating both artificial AE sources and real AE sources from a fatigue specimen. In addition damage onset detection and location accuracy were validated using a thermoelastic stress analysis (TSA) system.

3. Delta T Mapping

The “Delta T Mapping” methodology discussed above [10,11] has five associated steps, which are outlined briefly below:

Determine area of interest: Delta-T source location can provide complete coverage of a part or structure, or it can be employed as a tool to improve source location around specific areas of expected fracture, which could potentially be identified via finite element modelling.

Construct a map system: A grid is placed over the area of interest within which AE events will be located. It should be noted that sources are located with reference to the grid and not the sensors and it is not required that sensors be placed within the grid.

Obtain time of arrival data from an artificial source: An artificial source (nominally a H–N source [13,14]) is generated at the nodes of the grid to provide AE data for each sensor. An average result of several sources is used for each node. Missing data points can be interpolated from surrounding nodes.

Calculate Delta T map: Each artificial source results in a difference in arrival time or Delta T for each sensor pair (an array of four sensors has six sensor pairs). The average Delta T at each node is stored in a map for each sensor pair. The resulting maps can be visualised as contours of constant Delta T.

Locating real AE data: The Delta T values from a real AE event are calculated for each sensor pair. A line of constant Delta T equivalent to that of the real AE event can then be identified on the map of each sensor pair. By overlaying the resulting contours, a convergence point can be found that indicates the source