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Structural damage localisation by acoustic emission technique: A state of the art review

Abstract

Structural damages are often associated with under- performance of an engineering system. Hence localisation of such damages, followed by remedial measures, is the key to ensure proper functioning of the structures during their design lives. Acoustic emission (AE) technique is one of the effective non destructive evaluation (NDE) techniques for damage localisation. The present study makes an effort to review the existing literature on this technique under a few broad categories and discuss chronological advancements in each such category. The advantages and drawbacks of each method are deliberated and further scopes of research are pointed out.

Keywords

Structural damage; source localization; acoustic emission; non destructive evaluation.

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1 INTRODUCTION

Management of any costly infrastructure is an area of growing interest in contemporary research. Up keeping of such infrastructural facilities in general and physical infrastructures in particular is extremely important from techno-economic point of view of a nation. Any sort of deviation in their normal functioning is a major concern to the engineering/scientific community. Such deviations/ malfunctioning are often caused by structural damage which arise due to faulty design/construction, overburden load, ageing effect and natural calamity. If a structure needs to survive through its design life such structural damages require proper remedial measures. However, such measures depend entirely on localisation of the damage and assessment of its extent. In this context, many structural damage localisation techniques are available in literature; out of them acoustic emission (AE) technique is an important one which has good potential for effective use in structural health monitoring (SHM) applications.

Acoustic emission (AE) is the generation of transient elastic waves due to sudden redistribution of stress in material. AE technique involves the recording of such waves, known as “AE waves”, by means of sensors, called as “AE sensors”, placed at different locations on the surface of the material and analyzing the recorded data for information about the source.

In engineering structures, it is found, that defects like generation of cracks, yielding, failure of bonds, fibre failure etc. generate AE waves. Therefore, AE technique, as a non-destructive technique (NDT), has the potential to be utilized for extracting the details, such as location, type and extent of such structural defects.

Data recorded from the AE sensors, as above, may be useful in localizing the defect/damage as the damage itself may be treated as the source of AE. Hence localizing the defects/damages in a given structure becomes a case of identifying the AE source from the data recorded by the sensors deployed at specific locations of the structure.

In this context, it is worth mentioning that all the other NDTs for structural investigation requires external excitations while the sensors record the relevant data with regard to the response. The AE technique does not require any external excitation for recording sensor data; instead the energy arising from the generation of the defect within a structure, in real time, is utilized.

Localisation of the damage which is the source of AE is one of the most important criteria for detection of damage and their classification. Various studies have been carried out by the researches in relation to AE source localisation and are available in literature. A close look into them indicates that such localisation techniques may be classified under a few broad categories. In this paper an effort has been made to review the state of the art for AE source localisation by going through the investigations done by different researchers; conclusion is drawn thereof for setting the future scope of work in regard to real type applications of AE technique in health monitoring of civil infrastructures.

2 SOURCE LOCALISATION METHODS

Using AE technique different source localisation methods are available in the literature. The localisations methods are broadly classified under five categories and their relevant developments have been discussed.

2.1 Source localisation by analytical modelling

Ono and Ohtsu (1984) have provided a generalized theory of Acoustic Emission (AE) based on the theory of elastodynamics and dislocation models. They have proposed that in the theory of AE, it is preferable to deal with dislocation models that describe displacement discontinuities over time and space. The reciprocity theorem of elastodynamics has been applied to a domain containing dislocation so that the displacement fields due to the AE source function components are expressed by two integrals. Green's functions of second kind in a half space are numerically evaluated to analyze realistic condition of AE detection. It has been observed that Poisson's ratio has a considerable effect on Green's function. Several representative cases are investigated including Mode I and Mode III crack. The experimentally detected AE waveforms compared favourably with the simulated AE waveforms.

Improving upon the generalized theory on AE, Ohtsu and Ono (1986) presented the relationship between the AE source representation and the moment tensor. The modelling of a crack in the generalized theory is correlated to the moment tensor representation, indicating that the principal vectors of a moment tensor represent the crack orientation and the principal values represent the principal axes of the radiation pattern emanating from the crack. In the tensile crack, the principal vector corresponding to the maximum principal value indicates the direction of crack opening and the remaining vectors define the crack plane. In the shear crack, the principal vectors point midway between the direction of shear motion and a unit normal to the crack surface. The authors also observed that the waveform due to a shear crack has the P and S wave components in the same polarity. This is in contrast to a tensile crack, where the two components have different signs. Such a difference in the waveforms can easily be employed in distinguishing a shear crack from a tensile crack.

In the generalized theory of AE it is found that information about AE sources can be extracted from the waveforms. Impulse response functions or Green's functions for different geometries were calculated theoretically and used to eliminate the geometrical effects from the waveforms. The resulting waveforms were then interpreted in terms of moment tensor analysis. However, in calculating impulse response functions for even the known simple geometries there are severe complexity. This complexity becomes more in case of complicated geometries like composite materials. In these materials the ability of the AE technique to distinguish between matrix cracking and fibre breakage has been the subject of considerable discussion in the literature for years. Gorman and Prosser (1990) proposed an approach for interpretation of AE signals in terms of extensional and flexural mode of plate waves which may be useful in determining AE source orientation. They have carried out experiment in rectangular aluminium plates by producing AE signals using pencil lead breaks (Hsu Neilsen sources) at different angles to the plane of the plate. They observed that with the increase of angle of application of AE signal there is an increase of flexural mode and decrease of extensional mode. They indicated in their studies that for better estimation of damage and source localisation measurements of the amplitudes of the different plate modes can be used effectively.

One of the main advantages of the AE technique is that it makes it possible to calculate a spatial source location based on the arrival times of an AE signal at a number of sensors positioned at different locations on the structure. Using two sensors makes it possible to calculate the source location along a line between the two sensors if the distance between the sensors and the velocity of wave propagation are known. This technique is called linear localisation. Ziola and Gorman (1991) in their studies used one mode and two sensors for linear location. They pointed out that accurate linear location can only be performed if the modal nature of AE signals is taken into account and the arrival times are determined on the same wave mode at both sensors. They proposed a method for AE source location by cross-correlating the transducer outputs with a single frequency cosine wave modulated by a Gaussian pulse. They have shown that for wave propagation in dispersive media, the accuracy of source location can be improved by locating corresponding phase points on the transducer outputs to determine the difference in arrival times.

Surgeon and Wevers (1999) proposed an alternative linear location approach which uses two modes and one sensor. According to them, any damage phenomenon will generally generate an AE signal which contains the two basic plate wave modes. Since both modes are produced at the same location, but propagate at different velocities, they will arrive at a sensor at different times. Using the arrival time difference between the extensional and the flexural mode and knowing the propagation velocity of both modes it is possible to back calculate the source location. This concept is helpful as it reduces the number of sensors needed for source location and thus making this technique cost effective. The feasibility of this concept was validated by carrying out the tensile and bending test on crossply and unidirectional carbon fibre reinforced polymer (CFRP) laminates.

Gorman and Ziola (1991) has demonstrated the AE resulting into extensional and flexural plate waves while transverse matrix cracks were induced in cross-ply laminate graphite/epoxy coupons by tensile loading. The extensional mode contained higher frequency components of larger amplitude than the flexural mode. The location accuracy of the conventional AE analyser was shown to be improved by filtering out the flexural mode.

Prosser et al. (1995) used waveform based AE system to study the initiation of transverse matrix cracking in cross-ply graphite/epoxy composites. Six different specimen thickness were tested under stroke controlled, quasi-static tensile loading and to analyze the data plate wave propagation analysis was used. It is observed that for thicker specimens, there was an exact, one to one correspondence between AE crack signals and observed cracks. The length of the cracks in these specimens extended the full specimen width. However, for the thin specimens it was very difficult to detect the crack as they generate significantly smaller amplitude AE signals. Thus in transverse matrix cracking, an identical source mechanism can produce a wide range of AE signal amplitudes.

In any engineering problem, classical/analytical modeling requires the problem to be simple and necessitates relevant mathematical skills. And in real life problems, which almost invariably are complex in nature, it becomes almost infeasible to implement this procedure. Perhaps this is the reason why, as the available literature reveals, the analytical technique for damage localisation has not attracted the attention of too many researchers, although there remains vast scope of studies on damage related problems. However, such analytical techniques for damage studies, as found in literature, include some extremely important aspects like crack type, nature of damage etc. in addition to localisation of such damage. In this context, it is important to note that analytical solutions are useful in validating the results for simple problems obtained by other techniques like finite element analysis (FEA).

2.2 Source localisation by signal processing

Due to the rapid development of microelectronics over last few decades, source localisation by signal processing became a popular area of research. In a signal-based approach the waveforms recorded by the sensors need to be analyzed. The first step in the analysis is usually the 3D localisation of rupture. The biggest advantage of signal-based AE technique is its capability of discriminating signal-to-noise ratio based on the waveforms. The quantitative relationship between the waveforms and source mechanisms is possible by transforming the signal to the frequency domain and calculating their coherence function as mentioned by Grosse and Linzer (2008).

Suzuki et al. (1996) first used the wavelet transform (WT) in the field of AE. They have shown that the WT is useful in analyzing the frequency components of an AE signal as a function of time and in separating valid signals from noise. AE signals from a longitudinal glass-fibre reinforced composite sample under tensile loading has been studied and WT was performed on the AE signals. In their study they have used the Gabor wavelet based on the Gaussian function. It has been observed that the characteristic features of waveforms are best revealed by the WT contour maps and by the bird's-eye view of wavelet coefficients. From the analysis of the test result four signal types classified by the WT were correlated to Mode-I fibre fracture, Mode-I matrix crack and Mode-II disbonding.

Takemoto et al. (2000) introduced application of WT to AE signal analysis for fracture type classification in fibre reinforced polymers (FRP). They have also introduced the concept of denoising the noisy signals by discrete WT and inverse WT. Jeong and Jang (2000) applied WT for analysis of dispersive plate waves using the Gabor wavelet. They indicated that dispersion of flexural mode can be well predicted by their proposed method even for anisotropic plate.

Hamstad et al. (2002a) using a finite element modelling code prepared an extensive database of modelled Lamb Wave AE signals. The AE signals that comprised the analyzed database were all calculated by the NIST-Boulder finite-element modelling (FEM) code. Since the exact source type and all its characteristics are known for each signal, the features of the AE signals can be unequivocally associated with particular source types. They have examined the possibilities of extracting meaningful source identification features by the use of a WT. The WTs were calculated with AGU-Vallen Wavelet, a freeware software program. The WT based magnitude ratio for A0/S0 (zero order anti-symmetric Lamb modes/zero order symmetric Lamb modes) was found to distinguish different source types when the sources were all centred at the same depth below the plate surface and with the same propagation distance. In their further studies Hamstad et al. (2002b) has shown that source location in large plates can be significantly enhanced by use of WT results. Further to this they have added electronic noise to the calculated FEM signals and studied the WT-based determination of arrival times. The study was carried out as a function of the signal-to-noise (S/N) ratio.

Jiao et al. (2004) applied the theory of the wavelet transform and modal acoustic emission to analyse the propagation of elastic waves in thin plates. Experimentally they have shown that by using Gabor Wavelet, the WT can be applied to the AE signal and using the peak of the magnitude of the wavelet transform, the arrival times of the different modes can be determined. Using the arrival time difference for the A0 and S0 modes the one sensor location can be determined.

Mostafapour et al. (2014) used the wavelet transform and cross time frequency spectrum (CTFS) to locate AE source with frequency varying wave velocity in plate type structure. A combination of wavelet packet decomposition and cross time frequency spectrum with frequency-varying wave velocity is used in this algorithm to calculate the time delay and location of AE source. By wavelet decomposition, a specified range of frequency is considered and by taking short time Fourier transform of cross correlation for selected frequency ranges the CTFS, time delay and corresponding frequency-dependent wave velocity are obtained. Maillet and Morscher (2015) proposed a new waveform based procedure for localisation of AE source based on the Akaike information criterion (AIC) which is actually driven by signal energy of the wave. The energy-based approach also offers a potential for damage monitoring that could be used to improve the description of AE sources. It has been demonstrated that the AIC-based AE event location determination can outperform the so-called first-threshold- crossing technique, being less dependent on the quality of material/sensor coupling.

Inspection of a structure for its health may be done by processing of recorded structural signals. It is a useful technique where good quality signals containing structural information are available. Literature reveals that quite a good number of researchers have used this technique for AE signals. One of the major limitations of signal based AE technique is that it is not possible to record all the AE signals because of dissipation and geometrical spreading effects that absorb many of the weak signals before they reach the surface of the structure. Moreover, a large number of signals have to be stored for smaller number of events which causes problem for even modern computer based equipments. It restricts the use of signal-based techniques to monitor large structures. Such limitations of signal based AE technique can be overcome by reducing the amount of data not related to the material failure by applying sophisticated trigger algorithms. The main disadvantage of this approach for diagnosis of damage is that the obtained signals contain, in addition to the relevant structural information, unwanted disturbance (noise) also. Extraction of structural parameters from noisy signal using filtering technique is a tedious process and expertise in this regard is not normally available in civil engineering community. Signal based methods being a relatively young field of research, where a very large number of AE signals must be processed automatically; till date there are lack of available algorithms and software. So to make this process effective in damage studies, one has to undergo rigorous training in signal processing.

2.3 Source localisation by application of artificial neural network

Venkatesh and Houghton (1996) developed a method utilizing arrival time differences, from a minimum of three sensors, to train a back-propagation network (BPN) for locating AE sources in 2-dimensions. AE source location accuracy using the BPN approach yielded a significant improvement over the traditional AE arrival time difference method, in both continuous aluminium plate and across a bolted aluminium channel structure. Experiments utilizing the BPN approach showed that with the right network parameters the network was able to locate sources far more accurately than the arrival-time difference method. However, further improvement in source location accuracy, utilizing the BPN approach, would require additional network input factors that describe certain wave propagation characteristics including frequency, velocity, amplitude and arrival time of each mode arriving at each of the three sensors, as BPN input parameters.

Grabec et al. (1998) has provided a theory of source localisation of continuous AE sources using sensory neural networks. An AE phenomenon is physically described by a relationship between the force density $f\left(r,t\right)$ and the displacement field $u\left(r,t\right)$, which represent the source and the emitted sound, respectively. The fundamental problem of acoustic emission analysis is to estimate the source field $f\left(r,t\right)$ from the acoustic signals detected at various positions $\left\{rd;\ d-1...D\right\}$ on a specimen. This inverse problem is ill conditioned because the signals from a finite set of points do not describe the complete displacement field. Empirical treatment of corresponding inverse problems has been explained and applied to location of sources which generate continuous AE signals. A continuous AE phenomenon is treated as a stochastic process which is represented by the source coordinates and the correlation function of the emitted sound. The empirical model of AE phenomenon is formed based on a set of samples. The model includes a network of AE sensors and a neural network (NN). In the model formation stage the AE signals are generated by typical known sources positioned on a specimen. The recorded signals are transmitted to the NN together with the source co-ordinates. The first layer of NN determines the cross-correlation functions of signals and source coordinates. In the second layer a set of prototype vectors is formed from the data vectors by a self-organized learning. After learning, the network is capable to locate the source based on detected sound. The sensors provide AE signals from the detected sound and NN determines the corresponding correlation function and associates to it the source coordinates. The association is performed by a non-parametric regression which is implemented in the third layer of NN.

To avoid the complexities and likely non-linearities involved in applying the classical approaches to AE detection in a complex system Spall et al. (1998) proposed the use of an artificial Neural Network to represent the relationships between the sensor data and the AE events instead of more direct deconvolution based methods. The authors have tested the NN based procedure on 150 cm steel I- beam pulsing it with laser induced AE signals at various locations and seeing whether a trained NN could accurately recover the location of the AE signal. The NN used was a simple feed forward network with one hidden layer. For the NN training MATLAB Neural Networks Toolbox was used and standard back propagation (gradient descent) algorithm was used for the training as given in the LEARNBP routine within the Toolbox. The actual locations of AE sources are compared with the predicted sources by trained NN and found to be almost similar.

In the structures of complex geometry small cracks and damage are difficult to detect because they have a small effect on the propagating waves as compared to the effects the complex geometry itself which causes dispersion and reflection of waves. Kirikera et al. (2007) proposed the use of passive structural neural system (SNS) for damage detection in such structures. It provides architecture to connect ‘n’ sensor nodes in series to form neurons, and the neurons in turn interact and pass signals similar to how the biological neural system functions. The SNS uses electronic logic circuits to mimic the signal processing in the biological neural system. In a simulated AE source (a pencil lead break) on riveted aluminium joint and on a composite plate they have tested a two-neuron prototype of the SNS to validate their analytical result. Laboratory testing showed that the SNS can detect and locate simulated AEs generated on aluminium and composite panels.

Study of the available literature reveals that a few researchers have attempted to address the issue of damage localisation using soft computing technique namely ANN. It is true that such a soft computing technique has huge scope of application in complicated engineering problems where exact cause-effect relationship among the relevant variables cannot be established with conventional mathematical tools. However, ANN requires plenty of useful data for predicting/studying engineering behaviour of a structure. In the context of sensor based damage study, availability of such huge data requires large number of sensors to be placed in the structure; which is techno-economically infeasible for big civil engineering structures. The existing literature does not throw much light on this aspect.

2.4 Source localisation by geometric methods

Based on the triangulation technique the location of acoustic sources has been reported over the last three decades. Using the analysis of the arrival times of the acoustic waves at three arbitrarily positioned AE sensors Tobias (1976) reported a methodology to locate the acoustic source in two dimensional workspace (i.e. plane surface). Based on the path differences for the 1st , 2nd and 1st ,3rd sensors that were calculated by multiplying the differences in arrival times to the sensors and the wave velocity, the location of the acoustic source was determined analytically using the polar coordinates relative to a reference sensor.

Asty (1978) proposed an arrangement of three sensors on a spherical surface and derived the formulae to identify the location of the acoustic source on the spherical surface by using the difference in arrival times of the acoustic signal between the sensors. However, this method can be extended to identify the source location on a plane surface by increasing the radius of the sphere to infinity; this results in Tobias's solution. A similar approach as used by Asty has been used by Barat et al. (1993) to locate the acoustic source on a cylindrical surface by mounting three AE sensors on a cylindrical structure.

Axinte et al. (2005) presented a methodology to locate AE sources into three/two dimensional workspace, by intersecting three spheres, with the AE sensors as their centres.

Kosel et al. (2005) demonstrated the applicability of independent component analysis (ICA) to separate and locate two independent simultaneously active AE sources on an aluminium band specimen. They have shown that estimation of time delay between AE signals by the cross-correlation function (CCF) is only applicable for one active AE source. If there are several simultaneously active AE sources, blind source separation (BSS) by ICA should be used.

The conventional triangulation technique for detecting AE source assumes that the wave speed is independent of the direction of propagation. This is not true in case of anisotropic plate as well as in case of isotropic plates with some impact point. Castagnede et al. (1989) proposed that based on the quasi-longitudinal bulk wave speeds AE sources can be located. Their method works well for thick structures but fails for thin plates when sensors are placed far away from the impact point.

Kundu et al. (2007) proposed an approach based on an optimization technique by minimization of a non-linear objective function or error function to locate the point of impact in isotropic and anisotropic plates. It has been observed that for impact point loading the optimization method is better than triangulation technique for predicting AE sources.

Kundu et al. (2008) modified the definition of the objective function they predicted earlier to overcome the problem of multiple singularities. Expression of the objective function for multiple sensors is also redefined to maximize the efficiency of detecting the impact point. Using this modified objective function the impact point in an anisotropic but homogeneous graphite epoxy composite plate is correctly predicted. Kundu et al. (2009) further applied this technique for predicting the point of impact in an inhomogeneous plate where the stiffeners make the structure inhomogeneous and found that this technique works well for the same. Hajzargerbashi et al. (2011) modified the objective function proposed by Kundu et al. (2009) and introduced a new algorithm for accurately predicting the impact point on an anisotropic and non homogeneous plate and verified experimentally. The modified objective function was found to be more computationally effective and the prediction accuracy has been significantly improved by the use of four sensors instead of three.

Kundu et al. (2012) used six sensors to localize the source in isotropic as well as anisotropic plates without knowing the wave velocity in the plate. In their formulation clusters of three sensors are placed at two different locations in a plate. From the difference in arrival time at the sensors in each of the clusters the angular direction of a particular sensor of a cluster with horizontal referential axis can be known. From the angles of two sensors in the clusters two straight lines can be plotted and such lines will intersect at a point; which will give the location of the source. The source localisation is found to be more accurate if instead of six sensors nine sensors are used by arranging them into three clusters.

Aljets et al. (2010) proposed an algorithm for locating AE sources by determining the direction from which the wave is approaching the array of sensors using the time of arrival and the distance the wave has travelled using the wave mode separation. Tests were conducted on a composite (CFRP) plate with anisotropic lay-up with a novel configuration of three sensors which are closely arranged in a triangular array with the sensors just a few centimeters apart. The main benefit of a closely arranged sensor array is the possibility to install all sensors in one housing such that mounting and wiring up of the AE system becomes simplified. Since the sensors are installed very close to each other, the signal of an event should look fairly similar at all sensors. This makes it easier to identify exactly the same wave feature in all three sensor signals. The accuracy of the source location in this method decreases with distance of the sensor array from the source.

Giridhara et al. (2010) developed a methodology for damage detection based on symmetry of neighbourhood sensor path and similarity of signal patterns with respect to radial paths in a circular array of sensors. Through this method it has been shown that with the use of information regarding Lamb wave propagation along with triangulation scheme the rapid location of damage is possible without using all of the sensor data. This methodology has been validated experimentally by studying hole and corrosion type damages.

Salamone et al. (2011) proposed an approach based on an array of macro-fibre composite (MFC) transducers arranged as rosettes using its directivity properties. Using three such sensors arranged as rosettes the principal strain directions were obtained. With minimum of two rosettes i.e. six MFC sensors the location of the AE source can be determined by intersection of the wave directions. The advantage of this approach is that it does not require knowledge of the wave speed in the material and can be applied for isotropic material. However, there are difficulties in applying this technique for an anisotropic plate since the wave propagation direction does not coincide with the principal strain direction for the anisotropic plate. Kundu et al. (2012) proposed another method through which the acoustic source in an anisotropic plate can be localized with only six or nine sensors without knowing the velocity profile in the plate. The proposed technique does not rely on the constraint condition that the principal strain direction must coincide with the wave propagation direction and is an improvement over the proposed approach by Salamone et al. (2011).

McLaskey et al. (2010) applied Beamforming technique as proposed by Grosse (2009) for acoustic source localisation using a small array of (four to eight) sensors. The basic principle of beamforming technique is based on the delay-and-sum algorithm. They have applied this technique for large plates and it also requires the knowledge of the wave velocity. He et al. (2012) followed the beamforming technique for source localisation in a thin steel plate. The original beamforming method proposed by McLaskey et al. (2010) and used by He et al. (2012) assumes constant wave speed in all directions and therefore works in isotropic medium only. Nakatani et al. (2012) extended the beamforming technique to anisotropic structures.

Xiao et al. (2014) proposed a novel AE source localisation approach particularly suited for plate like structures based on beamforming with two uniform linear arrays distributed in the x-axis direction and y-axis direction without knowing the accurate velocity of wave propagation. The accurate x and y coordinates of AE source are determined by the two arrays respectively. It has been shown that even if the velocity error is large, the AE source location can still be localized accurately. They have validated their approach with analysis using finite elements and experiments with generating AE source using pencil-lead-break.

Localisation of AE sources by Triangulation technique based on time of arrival (TOA) and single sensor modal analysis location (SSMAL), are based on assumptions derived from a simplistic structure. In complex geometry structures such assumptions may not be valid. To improve upon these Baxter et al. (2007) proposed a method called 'Delta T' source localisation. This method does not require knowledge of the sensor location or wave speed. It uses an artificial source namely the Hsu-Neilsen source or H-N source which provides an easy, repeatable, consistent, broadband AE source. The differences in times of arrival (ΔT) from a number of locations are recorded. This allows a map to be constructed displaying contour lines of equal ΔT for each sensor pair. Using this information, any previous, current or future AE data received from within the mapped area can then be overlaid on the ΔT maps, and its location can be identified. This method does not require information about sensor location or time of occurrence of source. The source location is defined with regards to a user defined grid, rather than sensor location. However, they suggested that ΔT source location should be used to monitor key areas in more detail, not for monitor the source AE source location in a global structure.

Hensman et al. (2010) extended the work of Baxter et al. (2007), and offered a number of improvements. They proposed one artificial source instead of ten artificial sources and thus the requirement of training data is reduced. It is proposed to directly learn the relationship corresponding to the inverse ΔT map instead of learning the ΔT map.

Eaton et al. (2012) extended the theory of ΔT mapping from complex metallic structures and geometries to anisotropic composite materials. They performed a thorough assessment to check the performance and the robustness of the "Delta T Mapping" approach and compared them with traditional techniques. The experiments were conducted on two carbon fibre composite specimens and a wide tensile specimen with a circular cut out to assess the performance of "Delta T Mapping" technique using both artificial H–N sources and real fatigue test data. It was found that AE source location using "Delta T Mapping" is be very good in all cases. An improvement in location accuracy over the traditional TOA approach was observed in nearly all cases.

Ernst and Dual (2014) proposed a method which allows the detection and localisation of multiple acoustic emission source with only a single, one point, unidirectional measurement using the time reversal principle and dispersive behavior of the flexural wave mode. The difficulties of distortion of elastic wave due to phase dispersion while using the TOA method are overcome by this method. In this method the dispersive behaviour of the guided wave is used to locate the origin of the acoustic emission event. Therefore, the localisation of source depends solely on the measured wave form and not on arrival time estimation. This method can successfully localise the source on anisotropic structures as well as structures having geometrical complexities like notches.

Kundu (2014) classified different source localisation techniques using geometric method and specified their advantages and limitations. Broadly the source localisation can be classified into three categories: Source localisation in isotropic plates, Source localisation in anisotropic plates and localisation in complex and three dimensional structures. For isotropic and homogeneous structures; if the speed of propagation of the wave is known then triangulation technique can be used effectively. By solving a set of nonlinear equations source localisation can be done in isotropic homogeneous structures even if the wave speed is not known. However, solution of the nonlinear equations makes this method less attractive. To overcome this, three unknowns i.e. the x coordinate, y coordinate location of the source and wave speed can be determined using optimization technique by defining an error or objective function and minimisation of the same with trial and error method by assuming x and y coordinate values. Major shortcoming of this method is that sometimes the objective function becomes infinite and special care needs to be taken to avoid such singularities. Beamforming array technique can be used effectively for isotropic plate which is based on the delay-and-sum algorithm. The advantage of this method is that it does not require the exact time of arrival of a specific wave mode and thus can handle noisy signals. For isotropic plate with unknown wave speed, strain rossette technique using Micro-Fiber-Composite sensors is another one technique which can provide good result for localisation of source. Using modal analysis of the propagation of the elastic waves and calculating the time difference between the extensional and flexural plate wave modes at a sensor the acoustic source in isotropic plate can also be localised. Advantages of this technique are that the acoustic source can be localised with fewer sensors and characteristics of the source can be predicted. However, the limitation of this approach is that the plate properties must be known for the theoretical analysis; which is very difficult to get accurately for anisotropic plates. For anisotropic plates beamforming array technique and the optimization technique can be used. However, both these techniques require direction dependent velocity profile in the anisotropic plate. Kundu et al. (2012) proposed a method where an acoustic source could be localised in an anisotropic plate without knowing the direction dependent velocity profile in the plate i.e. without knowing the material properties. For monitoring a critical region for any crack formation hit by a foreign object in anisotropic plate, without knowing its materials properties, Poynting vector technique is useful. However, exact location of acoustic source cannot be predicted by this technique. In complex three dimensional or two dimensional structures straight line propagation of the generated wave from the acoustic source to the sensor is not possible. In such situations alternate techniques such as Artificial Neural Network (ANN) or time reversal technique based on impulse response function (IRF) or placing of densely distributed acoustic sensors on structure can be used. However, since these methods are either labour intensive or require a large number of sensors, these techniques should be followed when all other methods fail. The uncertainties in source localisation arising from the wrong recording of the arrival time during different experimental techniques can be filtered out by the extended Kalman filter in case of isotropic plates as proposed by Niri and Salamone (2012) and Non-linear Kalman Filter in case of anisotropic plate as proposed by Niri et al. (2014).

From the available literature as above, it is found that geometric methods are mostly used for damage localisation only in plates of regular shape. However, effectiveness of such methods for plates of irregular shape and other type of structures like shells and frames are yet to be investigated. Besides, the sensitivity of geometric methods to minute deficiencies of the structure at the elementary level needs further investigation. Moreover, validation of such methods against field data is rare in literature. On the other hand, data recorded in the sensors contain structural information and it is only logical that such data be used directly to obtain the damage related information. However in geometrical method, the sensor data are processed through purely geometrical procedure which is not related to performance of the structure. Hence, this process seems to be practically cumbersome and technically undesirable especially for large and complex structures.

2.5 Source localisation by finite element analysis

In recent years researchers have tried to apply the Finite Element Analysis for damage localisation using AE technique. Gary and Hamstad (1994) proposed a two dimensional cylindrical symmetric dynamic finite element method (DFEM) for thin plate specimens to model AE source in a more general way than the Pencil-lead-break. The pencil-lead break is a valuable source for simulation of AE source experimentally. However, the limitations for this source are that it can be only applied to outer surface as out-of-plane source and the range of the source rise times and source dimensions are limited. To overcome these limitations, in the proposed model the source force versus time characteristics are varied and the time dependent displacement fields for the far-filed are captured. The AE source is simulated in the DFEM with a normal stress function after Breckenridge et al. (1990). Most of the numerical experiments are carried out for an aluminium plate of 0.6 m radius and 3.05 mm thickness. The numerical method was followed as described by Blake and Bond (1990). The element sizes were varied across the plate depth from 0.60 mm to 0.023 mm. The out of plane displacement responses were captured at a distance of 0.254 m from the source for 150 μs with a maximum time step of 0.082 μs and minimum time step of 0.0033 μs which satisfies Courant-Friedrichs-Lewy (CFL) stability condition (1987). The numerical simulated results for displacement response were found to be in good agreement with the experimental result carried out with pencil-lead-break. The input source function for AE has been varied for different rise times and the time dependent displacement responses were found. The rise time were taken as 1 μs, 10 μs, 40 μs and 100 μs. It was observed that with the increase in the rise time there is loss of amplitude, however the spectral shapes are roughly same. To simulate the AE source in more relevant way a force of constant intensity applied to a circular region with increasing radius. The applied force was kept constant across the source and dropped to zero at its edge for different diameters (0.3 mm, 0.46 mm, 0.91 mm, and 3.66 mm) of the source. The time dependent vertical displacements at 0.254 m indicated that there is some variation in the amplitude, but little variation in the shape of the output. The use of the DFEM helped to find out the vertical (out-of-plane) as well as radial (in-plane) displacement response easily. From the study it has been observed that the meshing needs to be denser in the neighbourhood of the source to launch the wave properly and intensity of the applied force than the source size is of considerable interest for AE studies of source effects on resulting AE signals.

Hamstad et al. (1996) extended the two dimensional DFEM approach in developing a three dimensional DFEM for predicting far-filed AE emission displacement fields generated by general AE sources. The material modelled in this case was steel in all cases. The 2-D model used a circular plate with thickness $d = 25.4$ mm and radius of $40d$. The source was considered at the centre and the time response of vertical displacements is captured at $8d$ from the source. The 3-D model used a square plate with thickness $d = 25.4$ mm and each side with $32d$. The out-of plane source was located on top surface at $x = 12d$ and $y = 16d$ from plate corner and the time response of vertical displacements is captured at $x = 20d$ and $y = 16d$. However for edge sources the source was located along the various depth of the plate along z direction at $x = 0d$ and $y = 16d$. The AE source is simulated in the DFEM with a normal stress function after Breckenridge et al. (1990). Comparisons between the out-of-plane displacement outputs for the 2-D and 3-D model are found to be in good agreement. The 3-D model vertical displacement time response is found to be in good agreement when it was compared with the laboratory experiment data for a 1.32 m x 0.78 m x 0.254 m plate with in-plane and out-of-plane surface pencil lead break except for two small regions due to the arrival of the sharp Rayleigh waves. The study indicated that to properly represent the Rayleigh wave the mesh density away from the source needs to be increased. To model AE sources that generate Rayleigh wave frequencies, the source size must be less than 3 mm diameter having a rise time of less than 1 ms and the element sizes of about 0.13 mm to 0.27 mm. The study on the dependence on the plate edge source position with 3-D model indicated that below the mid-plane, the out-of-plane top surface displacement waveforms vary significantly; however at the mid-plane of the plate the low amplitude flexural part of the observed waveform disappeared and the sources above the mid-plane the waveforms are almost same as the mid-plane source.

In the 2-D and 3-D DFEM used by Gary and Hamstad (1994) and Hamstad et al. (1996) a short-rise-time surface force was used as the AE source to accomplish experimental validations. However, a real AE source in general is a buried source. Hamstad et al. (1999) extended 2-D axisymmetric DFEM method to consider more complicated AE source as a buried transient dipole. To model a buried dipole, two closely spaced body forces were applied simultaneously along opposite directions. The applied body forces were step-like in nature and considered to be a cosine bell curve. The dipole was equivalent to two small but finite, simultaneous monopole sources in close proximity. The dipole strength was determined by multiplying the force of each of the equal (and opposite) monopoles by the small distance (dipole spacing) between the centres of the two monopoles. In the modeling they have considered that the minimum wave length must be bigger than the source size i.e. minimum wavelength to source size ratio should be always greater than 1. They have checked for convergence with respect to the ratio of the minimum wavelength to source size of the dipole and found that a ratio of 2.2 is satisfactory for a steel plate of 25 mm thickness. The study also suggested that for ratio of the minimum wavelength to element size more than 15 the convergence is well achieved. Their observation indicated that the dipole can be of minimum size of 3 cells, 1 each for the monopoles with 1 cell space between. The time dependent displacements obtained using the proposed model were compared with the other previously published analytical results and they are found to be in good agreement with the results obtained by the proposed model.

DFEM can provide time dependent displacements at selected times after the operation of the AE source. The DFEM method differs from the other alternate analytical approaches particularly from the fact that with DFEM the edge reflections can be modeled. Prosser et al. (1999a) validated the 3-D DFEM method experimentally for both normal and oblique edge reflections. They have studied the lead breaks on the surface and edge of the thin aluminium plate and found that the surface lead breaks generate A0 (zero order anti-symmetric Lamb mode) while the edge lead breaks generate S0 (zero order symmetric Lamb mode). The edge lead break source also generates Rayleigh wave and propagates along the plate edge. All these experimental observations were also validated by theoretical DFEM analysis. Their theoretical studies indicated that the Rayleigh wave generated interacts at the plate corner to produce a mode converted S0 wave. The Rayleigh waves were mode converted at the sides of the plate upon reflection to longitudinal waves, which then propagated through the thin plate as the S0 mode. The experimental studies found to be in good agreement with the theoretical studies.

Prosser et al. (1999b) used Mindlin Plate Theory (MPT) for predicting flexural plate mode acoustic emission waveforms in thin plates and compared the results with DFEM. Due to the approximate nature of the MPT some discrepancies are found in the waveforms while compared with DFEM. However, they identified that this method can be used effectively if the flexural mode is present only.

Sause and Horn (2010a) used finite element simulation approach for investigating the acoustic emission waveforms resulting from failure due to matrix cracking, fibre breakage and fibre matrix interface failure during mechanical loading of carbon fibre reinforced plastic (CFRP) specimens. They have used a new emission source model based on principle of virtual work and D'Alembert principle and used the Structural Mechanics Module of Comsol Multiphysics software for finite element modelling and simulation.

Sause and Horn (2010b) investigated the influence of microscopic elastic properties and the geometry of the AE source by finite element simulation. Through their model they have compared between the Lamb wave formation of the anisotropic, homogeneous model specimen and those of an anisotropic, microscopically inhomogeneous model and demonstrated that microscopic conditions close to the source influence the excitation of distinct Lamb wave modes significantly. This can help in distinguishing different modes of fracture in fibre reinforced materials.

Sause (2013) extended the studies done by Sause and Horn (2010b) on CFRP to CFRP with internal damage. The interpretation of dominant Lamb wave propagation modes for thin plate becomes more challenging in case of composite specimen with discontinuity. Their investigation pointed out that the AE source localisation is largely impacted by internal damage as these damages significantly alters the emitted wave fields of the original source and affects the initial arrival time of different wave modes.

Study of literature on AE techniques in damage analysis reveals that there is an ample opportunity for making the technique practically implementable. In the response based damage investigation it is well understood that response recorded at a proper location can produce useful information on the behaviour of structure. Hence, placing the sensors at such critical locations is crucial for damage identification by AE technique. Some researchers have tried to simulate the procedure of damage detection using sensor data by using FEM. This technique is useful as a researcher can perform parametric study on various types of structures by introducing artificial wave functions simulating AE wave at varied locations. Subsequently, the response recorded at each location can be analysed for finding out the critical locations of sensors. Using FEM as above many researchers, in the recent past, have tried to study damage on simple structures like plates using simplified sources of AE. However, further investigation is required to make it implementable in real life structures.

3 CONCLUDING REMARKS

Structural damage localisation by AE technique is an active area of research interest in structural engineering worldwide. The technique has evolved through the last few decades and researchers have tried quite a few different methods of AE for damage localisation. The present study makes an effort to review such methods of AE under five broad categories and discuss chronological advancements in each such category along with its pros and cons. Subsequently, the following general conclusions are drawn:

(1) Classical/analytical technique of damage localisation is difficult to apply in case of real life structures which are complex in nature. However analytical techniques can provide damage localisation details and type of damage for simple geometry which can be effectively used to validate the results obtained by other numerical analysis technique like FEA.

(2) By analysing the good quality recorded AE signals structural information can be available which helps in localisation of damage. However, damage localisation by signal processing requires expertise in signal processing. In absence of such expertise included noise in the AE signals may be wrongly interpreted as the original signal which may result in incorrect localisation of damage.

(3) Damage localisation by soft computing technique like ANN has got tremendous potential for detecting an AE source. However, the huge amount of data required for ANN requires a large number of sensors which is not feasible for big civil engineering structures. Techno-economical feasibility study has a potential amount of research scope in this regard.

(4) Damage localisation by geometric technique has been studied for regular geometric plate structures. However, the effectiveness of the damage localisation by geometric techniques for plates of irregular shape and other type of structures like shells and frames are yet to be investigated. Moreover, this localization method does not throw any light on the more detailed investigation (e.g. quantification and extent) of damage. Thus, there is scope for more rigorous studies on the geometric technique to address the above issues.

(5) Structural damage localisation using AE technique by FEM is a major area of research in recent past. Parametric studies have been carried out on simple plate structures by the researchers by introducing artificial AE wave function as AE source. More detailed investigations are required for the FEM to make it implementable for real life structures.

(6) The use of AE Technique is an attractive option and is increasing in use for SHM of structures such as steel and concrete bridges. Among the various NDTs, acoustic emission (AE) monitoring is arguably based on the simplest physical concepts (AE in the form of popping and cracking noises from materials under stress). High sensitivity to crack growth, ability to locate source, passive nature (no need to supply energy from outside; but energy from damage source itself is utilised) and possibility to perform real time monitoring (detecting crack as it occurs or grow) are some attractive features of AE. However, it is one of the most difficult techniques to practically implement due to the challenges in the area of analysis of recorded data. For effective SHM the need is for effective data analysis linked with three main aims of monitoring; accurately locating the source of damage, identifying and discriminating signals from the sources of AE and quantifying the level of damage of AE source for severity assessment. The study of the effectiveness of AE in the quantification of damage, severity assessment and predicting the remaining capacity of a structure still remains the

critical area of research. The sensitivity to scaling, geometry, material properties, degradation state, and AE sensor layout for SHM requires more detailed investigations to make this implementable for real life structures. Moreover, under critical dynamic loading condition like earthquake the SHM using AE techniques is very challenging as AE wave signal frequencies due to any damage during such events are to be separated out from the dynamic load frequencies which is very complex and have quite high potential for further research.

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