IMPACT LOCATION ESTIMATION IN ANISOTROPIC MEDIA

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ABSTRACT

Impact location estimation techniques are important components of Structural Health Monitoring systems. This paper considers impact location estimation in composite structures using acoustic emission signals arriving at a passive sensor array attached to the structure. Because composite structures are anisotropic, the wave propagation properties depend both on the direction of propagation and the location on the structures. As a result, this is a substantially more difficult problem than that of impact location estimation in isotropic media. The algorithm presented in this paper uses three sensor clusters and formulates the impact location estimation problem as one of minimizing a quadratic objective function. Unlike many published location estimation algorithms, the algorithm in this paper does not require the waveform velocity profile for the structure. Experimental results demonstrating the ability of the algorithm to accurately estimate the impact location using acoustic emission signals is included in the paper.

Index Terms— *Impact location estimation, anisotropic structures, passive system, structural health monitoring.*

1. INTRODUCTION

Structural Health Monitoring (SHM) is important for maintaining a variety of structures including civil structures such as bridges and aerospace structures such as aircraft and space vehicles. Detecting impacts and estimating the location of impacts accurately and quickly when they occur are among the most important aspects of an SHM system. Figure 1 shows the block diagram of a SHM system for estimating impact locations. The acoustic emission (AE) signals generated by the impact are acquired by the sensors attached to the structure. The impact is detected and located through analysis of the AE signals. Additional analysis to address damage characterization and the subsequent determination of repair strategies may follow. Damage may be produced in such composite structures due to impacting and impingement in addition to static and fatigue loading.

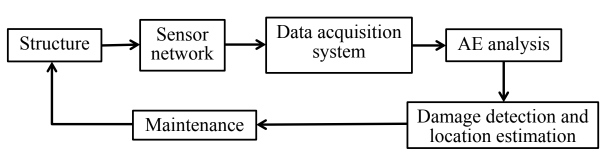

Fig. 1. A generic block diagram of an impact location estimation system.

Even though impact location estimation has received considerable attention, there remains many issues associated with composite structures that make impact location estimation more difficult. First, composite structures are in general anisotropic, and thus the wave velocities display directional dependence in such structures. Consequently, source location estimation methods designed for isotropic structures generally are not appropriate for use with composite structures. Second, wave propagation in structures includes multiple modes propagating at different velocities. Often these waveforms arrive at the sensors with the modes overlapped. Estimating the time-of-arrival (TOA) and the time-difference-of-arrival (TDOA) of the source signal at different sensors is particularly difficult when the sensors are well-separated from each other because variations in dispersion of the source signal along different directions result in differences in received signal shapes at sensor locations. Furthermore, it is difficult to precisely characterize the wave propagation properties in complex composite structures. Even when such characterizations are done, changes that occurs to the structure over time due to damage production and repair, as well as changes caused by environmental variations such as temperature and moisture absorption make it difficult to use the information in practice.

The goal of this paper is to develop a method for estimating the impact location on a composite structure using AE signals without such precise knowledge of the wave propagation properties of the structure.

Many methods to estimate the impact location in an anisotropic structure with a passive sensor array are available in the literature. Most of these methods require knowledge of the velocity characteristics of the anisotropic structure at all locations and in all directions for estimating the impact location [1]-[4]. In [1], the authors estimated impact locations using the classical triangulation method. A genetic algorithm-based optimization procedure was applied to estimate the impact location. In [2], the authors proposed an algorithm which can be applied to both isotropic and anisotropic structures. The method used three sensors and can be extend to more sensors. An objective function that was dependent on the impact location, sensor locations, wave velocities and the TDOA of the wave between sensors was defined and the impact location was estimated as the (x,y) coordinates values that minimized this objective function. The minimization was performed using a grid search. A modified version of this method was proposed in [3]. In [4], sensor clusters, which used sensors in a linear array, were considered. Wave velocities corresponding to different clusters were calculated and the velocity profiles were utilized to match the solved wave velocities to the direction of the arriving wave at all clusters. The intersections of the different directions of arrival formed the impact location estimates. While the methods [1]-[4] are applicable to anisotropic structures, it is not practical in general to precisely know the wave propagation properties of the structure. Only a few impact location estimation algorithms that do not require wave velocity information have been published to date. The authors of [5] used three sensor pairs that were assumed to be sufficiently far away from the impact location. An objective function which included impact location, wave velocities, sensor locations and TDOA between the first sensor and the remaining sensors was derived assuming that the wave velocity to each pair was the same. The Newton method and polynomial backtracking technique were applied to estimate the impact location as the first two components of the minimizer of the objective function. This method required the TDOA estimation for widely separated sensors. As described earlier, the direction-dependent dispersion due to the anisotropic propagation properties of the structures make TDOA estimation for sensors located at significant distances from each other unreliable, and such estimates may result in large location estimation errors. The authors of this paper presented a similar algorithm in [6]. Three-sensor clusters that formed right triangles and assumed to be far away from he impact were used in [7] and [8] to find the signals direction of arrival at one cluster. The solution depended only on the TDOA between sensors. The intersection of directions of arrival at two separate clusters was the impact location estimate. By following a similar derivation of the objective function in [2], an 18 sensors cluster which follows a "Theodorus Spiral" pattern was used in [9] to determine the probable area of impact. In [10] the impact locations were estimated based on the strain measured at different sensor locations. Maximum strains measured at two sensors and the corresponding sensor locations were used to estimate the impact location. The accuracy of the estimation procedure depended on the sensing region of the sensors and may have large estimation errors in situations where the sensor placement did not provide complete coverage of the structure. Other methods including the time-reversal approach [11], Multiple Signal Classification (MUSIC) algorithm [12] and eigen-analysis-based methods [13][14] have also been applied to estimate the impact location.

In this paper, composite structures that exhibit material anisotropy are considered. The location estimation algorithm employs a passive sensor array and does not require knowledge of the velocity profile in the structure. Experimental validation using a carbon/epoxy composite panel is presented to demonstrate the accuracy of the algorithm.

The rest of this paper is organized as follows: The theory of the proposed impact location estimation algorithm is introduced in Section 2. Experimental validation results on a quasi-isotropic carbon/epoxy panel are provided and analyzed in Section 3. Finally, some concluding remarks are given in Section 4.

2. DERIVATION OF THE IMPACT LOCATION ESTIMATION ALGORITHM

For simplicity of explanation, a 2-D anisotropic structure is considered. However, extension to many 3-D structures is not difficult. The impact location estimation algorithm is formulated as an unconstrained quadratic optimization problem.

2.1. Problem Setup

Let us consider an anisotropic plate with one impact at location $\mathbf{X}_S = (x_S, y_S)^T$ and three sensors $\mathbf{S}_i = (x_i, y_i)^T, i = 1, 2, 3$. The three sensors $\mathbf{S}_1$, $\mathbf{S}_2$ and $\mathbf{S}_3$ form one sensor cluster with the layout shown in Figure 2. The definitions of the variables used in the figure are provided in Table 1.

We assume that the sensors in a cluster are located very close to each other, and that the impact location is far away from the sensor clusters, i.e., the distance from the impact location to the cluster is much larger than the distance between the sensors in the cluster. Based on this assumption, we can approximate the signals arriving at the cluster to be a planar wave. We can also approximate the difference between the distances of the path $\overline{\mathbf{X}_S\mathbf{S}_1}$ and $\overline{\mathbf{X}_S\mathbf{S}_2}$ to be the length of the segment $\overline{\mathbf{AS}_2}$. Similarly, we will approximate the extra distance the signal travels from $\mathbf{X}_S$ to reach $\mathbf{S}_2$ over the distance travelled to reach $\mathbf{S}_3$ to be the length of the segment $\overline{\mathbf{BS}_2}$. In general, the clusters are widely separated on the structure, and at most one cluster may violate the above assumption. Assuming that we have three or more clusters, we can identify this cluster during the location estimation process and exclude it from further analysis.

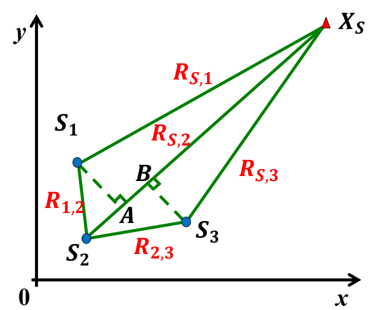

Fig. 2. Sensor locations and impact location. The circles $\mathbf{S}_1$, $\mathbf{S}_2$ and $\mathbf{S}_3$ denote sensor locations and the triangle $\mathbf{X}_S$ denotes the impact location. $\overline{\mathbf{S}_1\mathbf{A}} \perp \overline{\mathbf{X}_S\mathbf{S}_2}$ and $\overline{\mathbf{S}_3\mathbf{B}} \perp \overline{\mathbf{X}_S\mathbf{S}_2}$.

Table 1. Definition of Variables

$R_{S,i}$	Distance between the impact and the i-th sensor
$R_{i,j}$	Distance between the i-th and the j-th sensors
v_i	The average signal transmission velocity from the impact to the i-th sensor
t_i	The time-of-arrival (TOA) for the signal generated by the impact at the i-th sensor
$\tau_{i,j}$	The time-difference-of-arrival (TDOA) of the AE signal between the i-th and the j-th sensors; $\tau_{i,j} = t_i - t_j$

2.2. Mathematical Solution

As shown in Figure 2, $\overline{\mathbf{S}_1\mathbf{A}}$ is perpendicular to $\overline{\mathbf{X}_S\mathbf{S}_2}$ and $\overline{\mathbf{S}_3\mathbf{B}}$ is perpendicular to $\overline{\mathbf{X}_S\mathbf{S}_2}$. Now, consider the triangles with vertices $\mathbf{X}_S$, $\mathbf{S}_1$, $\mathbf{A}$ and with vertices $\mathbf{S}_1$, $\mathbf{S}_2$, $\mathbf{A}$. It is easy to see that

$$R_{S,1}^2 - \overline{\mathbf{X}_S\mathbf{A}}^2 = \overline{\mathbf{S}_1\mathbf{A}}^2 \quad (1)$$

and

$$R_{1,2}^2 - \overline{\mathbf{S}_2\mathbf{A}}^2 = \overline{\mathbf{S}_1\mathbf{A}}^2. \quad (2)$$

From (1) and (2), we get

$$R_{S,1}^2 - \overline{\mathbf{X}_S\mathbf{A}}^2 = R_{1,2}^2 - \overline{\mathbf{S}_2\mathbf{A}}^2. \quad (3)$$

Because of the assumptions described earlier, we can further assume that the signal propagation velocities from the impact to sensors $\mathbf{S}_1$, $\mathbf{S}_2$ and $\mathbf{S}_3$ are the same, i.e., $v_1 = v_2 = v_3$. Furthermore, this choice of sensor topology results in sensor signals in each cluster being very close to each other in shape, but with slight offsets corresponding to the extra distance travelled.

Based on the above assumptions and approximations, the distance $\overline{\mathbf{S}_2\mathbf{A}}$ can be written as

$$\overline{\mathbf{S}_2\mathbf{A}} = \tau_{2,1}v_1. \tag{4}$$

Consequently,

$$\overline{\mathbf{X}_S\mathbf{A}} = R_{S,2} - \tau_{2,1}v_1. \tag{5}$$

Substituting (4) and (5) into (3) and simplifying results in the following equation:

$$R_{S,1}^2 - R_{S,2}^2 + 2R_{S,2}\tau_{2,1}v_1 - R_{1,2}^2 = 0. \tag{6}$$

Similarly, analysis of triangles with vertices $\mathbf{X}_S$, $\mathbf{S}_3$, $\mathbf{B}$ and with vertices $\mathbf{S}_3$, $\mathbf{S}_2$, $\mathbf{B}$ gives

$$R_{S,1}^2 - R_{S,2}^2 + 2R_{S,2}\tau_{2,1}v_1 - R_{1,2}^2 = 0. \tag{7}$$

Solving for the velocity v_1 from (7) and substituting the result into (6) gives

$$R_{S,1}^2 + \left(\frac{\tau_{2,1}}{\tau_{2,3}} - 1\right) R_{S,2}^2 - \frac{\tau_{2,1}}{\tau_{2,3}} R_{S,3}^2 + \frac{\tau_{2,1}}{\tau_{2,3}} R_{2,3}^2 - R_{1,2}^2 = 0. \tag{8}$$

For simplicity, define

$$\alpha_1 = \frac{\tau_{2,1}}{\tau_{2,3}} - 1,$$

$$\beta_1 = -\frac{\tau_{2,1}}{\tau_{2,3}},$$

and

$$\rho_1 = \frac{\tau_{2,1}}{\tau_{2,3}} R_{2,3}^2 - R_{1,2}^2.$$

Then, (8) can be simplified as

$$R_{S,1}^2 + \alpha_1 R_{S,2}^2 + \beta_1 R_{S,3}^2 + \rho_1 = 0. \tag{9}$$

Since $R_{S,i}^2 = (x_S - x_i)^2 + (y_S - y_i)^2$, (9) can be expressed as:

$$\begin{aligned} &(1 + \alpha_1 + \beta_1)x_S^2 - 2(x_1 + \alpha_1 x_2 + \beta_1 x_3)x_S \\ &+(1 + \alpha_1 + \beta_1)y_S^2 - 2(y_1 + \alpha_1 y_2 + \beta_1 y_3)y_S \\ &+x_1^2 + y_1^2\alpha_1(x_2^2 + y_2^2) + \beta_1(x_3^2 + y_3^2) + \rho_1 = 0. \end{aligned} \tag{10}$$

The TOA t_i of the wave propagated from the impact location to the i-th sensor may be measurable from the sensor signal. We assume for now that t_1, t_2 and t_3 are available. The TDOA $\tau_{2,1}$ and $\tau_{2,3}$ can be estimated directly from these measurements. Since the sensor locations are known, α_1, β_1 and ρ_1 are also known. Thus, in (10), only the impact location $(x_S, y_S)^T$ is unknown. Thus, the use of one sensor cluster results in one equation with two unknown parameters associated with the impact location. Additional equations in the same unknown parameters can be derived for other sensor clusters located on the structure. If there are $N \geq 2$ sensor clusters, the impact location can be estimated from the N simultaneous quadratic equations in two unknown variables.

More formally, let $f_i = 0$ represent the quadratic equation in (10) for the i-th cluster. Define an objective function f as

$$f = \sum_{i=1}^{N} f_i^2. \tag{11}$$

The impact location is estimated by minimizing the objective function f over the unknown variables x_s and y_s.

To summarize, the procedure to estimate the impact location employing N sensor clusters is as follows: Assume that for each sensor cluster, the three sensors are indexed as 1,2 and 3. The order of the three sensors may be selected arbitrarily.

- For the first sensor cluster,
  - Measure the TOA t_1, t_2 and t_3;
  - Calculate the TDOA $\tau_{2,1}$ and $\tau_{2,3}$;
  - Calculate α_1, β_1, and ρ_1;
  - Construct f_1 as in (10).
- Repeat the above procedures for the remaining $N-1$ sensor clusters and obtain $f_i = 0$ for $i = 2, \cdots, N$;
- Construct the objective function $f = \sum_{i=1}^{N} f_i^2$;
- Find the location (x_s, y_s) that minimizes of the objective function in (11).

Since there are only two variables over which the minimization is derived, we perform a simple grid search to minimize the objective function.

2.3. TDOA Estimation

Recall that the system only requires the TDOA estimates for sensors within each cluster. This was performed as follows: First, a coarse estimate of the TOA of the signal at one of the sensors was estimated as the time at which a short-term variance of the signal (calculated via a sliding window processing) exceeded the produce of a pre-selected constant and the measurement noise power measured at a time when there was no impact on the structure. For our experiments, the constant multiplier was selected to be 100, and the noise power was calculated from a portion of the measurements acquired before the impact. Recall that at least at the time of arrival of the signal at the sensors belonging to the same cluster, we expect the signals to be similar with offsets corresponding to the TDOA. Thus, we perform the TDOA estimation by identifying a small segment of the first sensor signal and then estimating the time offsets of this segment for which the best match between the shifted segment and segments of the same length on the other two sensor signals are obtained. In our experiments, the amplitude peak that is immediately after the estimated TOA is found first. The segment of the first sensor signal starts at an amplitude peak immediately prior to the identified peak and ends at another amplitude peak immediately after the identified peak. It is necessary to use relatively small segments because even for closely located sensors, the dispersive nature of the structure results in somewhat different signal shapes at the three sensors as the length of the segment is increased.

3. EXPERIMENTAL VALIDATION

The experiments utilized carbon/epoxy composite panel with a $[0/45/90/-45]_{3s}$ quasi-isotropic layer stacking sequence of size 116.8 cm × 116.8 cm × 0.3 cm . Five clusters of Acellent Single Smart Layer piezoelectric sensors were attached to the panel. The sensor signals were acquired using a 16-channel NI system (PXIe-1073) and the data rate was set to 2×10^6 samples/s/channel and 14 bits/sample. Impacting was performed by dropping a steel ball

Table 2. Sensor coordinates (The origin is the lower left corner of the panel.)

Cluster number	1			2			3			4			5		
Sensor number	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
x (cm)	40.6	40.6	42.2	76.2	76.2	77.8	88.9	88.9	90.5	40.6	40.6	42.2	21.3	22.9	22.9
y (cm)	27.9	26.4	26.4	22.9	21.3	21.3	72.7	71.1	71.1	93.0	91.4	91.4	66.0	66.0	64.5

Table 3. Impact location estimation errors for different sensor cluster selection from five sensor clusters over 25 different impacts

Number of clusters selected	2	3	4	5
Mean error vector (cm)	(-1.5,-1.8)	(-1.4,-1.1)	(-1.3,-1.5)	(-1.2,-1.6)
RMS (cm)	17.3	9.9	6.6	5.0

(1.3 cm diameter) at 25 different pre-designed locations on the panel. Figure 3 shows the sensor locations and impact locations. The red circles denote sensors and the blue dots denote impacts. Since TDOA estimation in the presence of reflections that confound TOA estimation is not considered in this paper, we constrained the impact locations to be sufficient away from the panel boundaries. The coordinates of the sensor locations are listed in Table 2. The sensor signals acquired from the experiments were analyzed to estimate the impact locations.

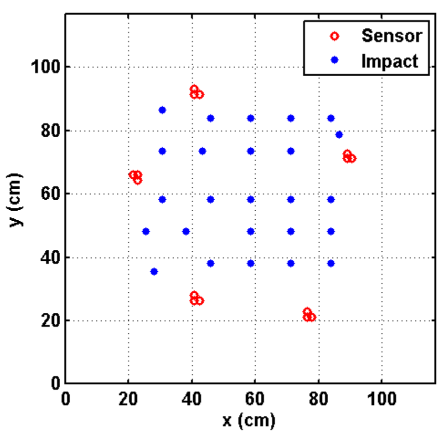

Fig. 3. Sensor distribution on the quasi-isotropic carbon/epoxy panel.

Table 3 shows the impact location estimation results. The mean value of the location estimation errors along the x and y-coordinate directions calculated over the 25 impacts as well as the root-mean-square (RMS) error value are tabulated in this table when the estimates employed 2 to 5 sensor clusters. When less than 5 clusters were employed, we considered all possible sensor cluster combinations, and the averages reported in Table III are based on all such estimates. We can see that the RMS error values decrease substantially with increasing number of sensor clusters. The trend shown indicates that adding more sensor clusters may further reduce the error; however, we were constrained to using no more than 16 sensors by the data acquisition system. The mean error values shows a small bias. We believe that this is probably due to the small sample size of the experiments. It is also possible that the nature of the anisotropy of the structure will introduce small amounts of bias in the location estimation process. Further analysis is required to fully characterize the performance of the algorithm.

We conducted a performance comparison of the algorithm of this paper with that in [7] using the same experimental data set and the same time-of-arrival estimates. The algorithm in [7] utilized a two clusters system. We estimated the 25 impact locations using each of the 10 possible combinations of two three-sensor clusters on the structure. The RMS value of the estimation error calculated from the 250 estimates so obtained was 81.6 cm. For comparison, the RMS value for the method of this paper when using only two clusters was 17.3 cm. The RMS values calculated for each pair of sensor clusters ranged from 8.7 cm to 234.4 cm for the method of [7] and from 8.5 cm to 24.6 cm for the method of this paper. We can see from these comparisons that the method of this paper performs substantially better than the approach of [7].

4. CONCLUSIONS

This paper presents an algorithm that utilizes two or more sensor clusters to estimate the impact locations in anisotropic structures using acoustic emission signals. The placement of sensors in a cluster is quite simple. The only requirements are that the sensors are located on the corners of a triangle and that they are sufficiently close to each other. The algorithm avoids the need for carefully calibrating the structure for wave propagation characteristics and environmental factors since it does not require wave propagation properties in the structures. Rather, the proposed algorithm utilizes only sensor locations and time-difference-of-arrival of acoustic emission signals at sensors in each cluster. Good location estimation accuracy of the algorithm was demonstrated using experiments with different numbers of sensor clusters. The algorithm is computationally easy to implement. Comparisons with competing method available in the literature and our own experiments have demonstrated the superior performance of our approach. Consequently, this method has the potential to become a key component in structural health monitoring systems for complex, composite structures typically found in aerospace applications. Additional research on refining the algorithm, especially in situations where signal reflection from boundaries complicates the time of arrival calculations as well as theoretical performance evaluation of the algorithm are currently underway.

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