Passive monitoring and location of impact events using in situ modal decomposition

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Abstract

A novel sensor based on Polyvinylidene Fluoride (PVDF) film and a linear periodic array of electrodes has been assessed for in situ passive monitoring of impact events. The sensor is coupled to a compact, low energy, high bandwidth, EMI hardened data-acquisition platform suitable for aircraft implementation. The sensor performance has been characterised for a range of distances from an impact on an isotropic plate. It is shown that two-dimensional fast Fourier transform (2D FFT) processing of the sensor data can provide a modal decomposition of the received signal which can be used to localise the impact. The performance of this source localisation strategy is compared to that of a triangulation scheme using three piezoceramic sensors. The results obtained by these two approaches for drop-weight impacts are compared and discussed from the viewpoints of localisation accuracy, ease of implementation and robustness.

1. Introduction

The amount of composite material used in primary aircraft structure has grown steadily over the years [1]. This is attributed to the higher specific stiffness, good radio-frequency compatibility, better fatigue properties and lower corrosivity of these materials, compared to metals [2]. A significant disadvantage is their susceptibility to impact damage. Common causes of impact damage include tool drop, bird strike and hailstones [3, 4]. These low energy impacts (10 - 30J) [5] can lead to the formation of Barely Visibly Impact Damage (BVID), which leaves little to no visual evidence on the surface, but can cause a significant decrease in flexural stiffness, posing a threat to structural integrity. The lack of a reliable tool for detection, localisation and characterisation of impact damage has forced manufacturers to over-engineer composite structures to accommodate the risk of low energy impact [6]. An ability to detect and accurately localise an impact is helpful in managing this risk. For example, by enabling accurate targeting of non-destructive inspection it can reduce maintenance time and labour costs. Additionally, the development of an effective tool for the detection and localisation of an impact may permit the use of less conservative design principles.

There has been a considerable amount of work within the Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM) communities on the development of impact detection and localisation methods. Most rely on the measurement of the
acoustic emission from an impact, which normally consists of a packet of Lamb waves. The propagation characteristics of these waves are dependent on the excitation frequency and material properties of the host medium [7].

Many different source-localisation techniques have been developed; however, the triangulation approach originally described in [8] remains one of the most popular. This method relies on obtaining the difference in wave time-of-arrival at a minimum of three sensor points. The general drawback of the triangulation method is that an exact time-of-arrival can be difficult to discern from a time signal if the wave propagation is dispersive, as is the case for the low frequency flexural wave which often dominates an impact response. Further issues arise in cases where multiple modes are excited as the signal then consists of different modal contributions that can be difficult to separate.

This paper compares the performance of a new source-localisation method based on modal decomposition against a conventional triangulation using three sensors. The modal decomposition method is implemented using a single multi-element Polyvinylidene Fluoride (PVDF) sensor in conjunction with a new interrogation device. In contrast to the triangulation method (where a minimum of three sensors are required), this approach is able to localise an impact from one sensing location.

This paper is organised as follows: Section 2 describes the new PVDF sensor array. Section 3 describes the experimental setup used for the impact localisation, and also details the impact localisation methodology using triangulation and the modal decomposition approach. The results of the experiments are described and discussed in Section 4. Conclusions and future directions for the work are outlined in Section 5.

2. Development of PVDF Sensor Array

The PVDF array is pictured in Figure 1. It is a flexible multi-element sensor array which is referred to by the acronym LAMDA, for Linear Array for Modal Decomposition and Analysis. A detailed description of the sensor is given in [9] so only a brief description is provided here. The sensor is ~0.15 mm thick and highly compliant, which makes it structurally far less intrusive than a piezoceramic sensor. The LAMDA contains 16 sensing elements, each 5 mm wide and 1 mm long with a pitch of 1.27 mm, as shown in Figure 1. The electrodes are connected to a high speed low-noise acquisition device termed the AUSAM+ which stands for Acousto-Ultrasonic Structural health monitoring Array Module [10]. This device has been specifically designed and developed for aircraft implementation which is reflected in its small size, low power consumption and ruggedness (both physical and to radio frequency interference). Despite its name, the device can be utilised for AE measurements as well, via circuitry and firmware that permits high-rate snap-shot sampling across multiple channels. Each AUSAM+ device has 4 input channels. However, multiple devices can be networked via an optical link to provide a theoretical maximum of 248 channels. A four device network was used in the present investigation to accommodate the 16 channel LAMDA. A measurement from this sensor/hardware system consists of 16 separate time records sampled at a 50 MHz rate. Following the approach described in [11] a two-dimensional fast Fourier transform (2D FFT) applied to such a measurement produces a set of wavenumber-frequency dispersion curves. The first demonstration of an in situ modal decomposition capability
suitable for SHM application was reported in [12], with a more recent demonstration described in [13]. However, unlike the capability described in the present study, neither of these prior implementations is capable of decomposing a spontaneous AE.

Figure 1: PVDF sensor array (LAMDA) developed to detect acoustic waves

3. Methodology

Figure 2 shows the experimental setup used for the impact localisation study. A rectangular 700 mm × 460 mm aluminium plate, 1.6 mm thick, was used as the test subject. Three piezoceramic circular disc sensors (A, B, C), 5 mm diameter and 0.5 mm thick, were affixed to the host medium using a 2 part conductive epoxy. The locations of the sensors are shown in Figure 3. The LAMDA was bonded to the aluminium plate using cyanoacrylate adhesive at position P in Figure 3. The technique used to bond the LAMDA is similar to that used for a conventional strain gauge [14].

A ball-bearing 10 mm in diameter and weighing 4 g was used as the impactor. The ball was held at a drop height of 1.2 m via a magnetic field generated by a solenoid which was de-energised to initiate the drop. Signal recordings were triggered by passage of the ball through a phototransistor unit resting on the plate with the centre of its aperture coinciding with the impact point. Drops were repeated 6 times for each of the impact positions shown in Figure 3. The response of the piezoceramic disc sensors was recorded using a high speed digital oscilloscope.
3.1 Source Location using Triangulation

The triangulation method applied in this study is described in [15, 16]. In its most basic form, triangulation relies on the difference in time-of-arrival of a wave at 3 different...
positions on a plate. Figure 4 depicts an impact event at position $U$ and the path lengths $s$ travelled by the resulting wave to three sensing locations $A$, $B$, and $C$. In an isotropic medium, the wave speed is identical in all directions. The time-of-arrival of the wave at each sensor will differ by an amount proportional to the difference in distance travelled.

In most practical situations, the exact time of impact is generally unknown, which means that the time taken for the wave to travel from the impact location to the sensor cannot be directly measured. However, to determine the location of the source, only the difference in time-of-arrival is required. For each of the three sensor pairs, one can write an equation of the following form,

$$s_t - s_j = c t_{ij}$$  \hspace{1cm} (1)

Here, $c$ is the wave speed in the medium and $t_{ij}$ refers to the difference in time-of-arrival between sensor $i$ and $j$. Three equations result and are solved for the three unknowns that determine the source location.

The speed of a Lamb wave is a function of frequency and is defined by the group velocity dispersion curves for the plate. In the present study, the relevant dispersion curves were calculated using published material properties which were not fully verified. As a consequence, some uncertainty in the velocity in Eq. 1 should be anticipated. In cases where the wave speed is unknown or known imprecisely, a more robust estimate for the source location can be obtained by using an optimisation procedure, as described in [15]. In this method, the impact position is determined by seeking the global minimum of the objective function,

$$E(x_t, y_t) = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \sum_{k=1}^{n-1} \sum_{l=k+1}^{n} [t_{ij} (s_k - s_l) - t_{kl} (s_t - s_j)]^2$$

$$s_t = \sqrt{(x_t - x_o)^2 + (y_t - y_o)^2}$$  \hspace{1cm} (2)

Here, $(x_t, y_t)$ refers to the Cartesian coordinates of the $n$ sensor positions and $(x_o, y_o)$ is the source position which is the variable that is to be optimised. The global minimum of this function occurs when $(x_t, y_t)$ coincides with the impact location $O$. In this study, the objective function is minimised using a grid-search approach.

![Figure 4: Schematic of a setup for source localisation using triangulation](image-url)
3.2 Source localisation using LAMDA

A detailed description of the source localisation procedure was given in [9] so only a brief outline is provided here. The first step in the procedure is to acquire time signals from the LAMDA, which is done simultaneously across the 16 sensing elements via the snap-shot sampling capability of the AUSAM+. Next, a 2D FFT is applied to decompose the signals into a set of wavenumber-frequency dispersion curves. Modes of interest are isolated using appropriate pass-band filters, as described previously in [17] and an inverse Fourier transform applied to generate the corresponding time signal. A Hilbert transform is then applied and the arrival-time determined from the peak in the time signal envelope.

Two distinct times of arrival are required to localise the source. These can be obtained from a single mode at two different frequencies or from two different modes. Assuming that two times-of-arrival are available, say \( t_{n1}, t_{n2} \), and the corresponding group velocities \( c_{g1}, c_{g2} \) are known, the time of impact \( t_o \) is obtained from the expression,

\[
t_o = \frac{c_{g1} t_{n1} - c_{g2} t_{n2}}{c_{g1} - c_{g2}}
\]  

The distance to the impact \( r \) relative to the centre of the LAMDA is calculated using Equation (4).

\[
r = \frac{c_{g1} c_{g2} dt}{c_{g1} - c_{g2}} \]  

In cases where the wave-vector is not aligned with the principal axis of the sensor, the modal signatures produced by the LAMDA will not coincide with the theoretical wavenumber-frequency dispersion curves. This mismatch provides the basis for determining the azimuthal angle of arrival \( \theta \), viz.

\[
\theta = \tan^{-1} \left( \frac{k^R(\omega)}{k(\omega)} \right)
\]

Here \( k^R(\omega) \) is the wavenumber at the centroid of the pass band region used to recover the time signal from which the distance is calculated, and \( k(\omega) \) is the obtained from the theoretical dispersion curve at the same frequency.

4. Results

4.1 Impact localisation using Triangulation

As detailed in Section 3.1 a three sensor triangulation approach was implemented in this study. Figure 5 shows representative voltage signals from the three piezoceramic sensors in Figure 3, for an impact at location ‘a’. Precise times-of-arrival are difficult to discern from these signals because the start in the wave-induced perturbation is indistinct. The thresholding technique described in [16] was used in the present study to determine wave arrival times. These arrival times were substituted into Equation (2) and
the impact position determined using a grid search in which the grid was successively
refined to localise the minimum. Figure 6 shows the topography of a representative
objective function $E(x, y)$. The presence of multiple local minima generally precludes
use of deterministic optimisation methods, and was the primary reason for employing a
grid-search approach in this study. Table 1 lists the experimentally estimated impact
positions and the corresponding error, for the 5 impact locations. The location error is
highest for impact position ‘c’.

![Figure 5: Piezoceramic sensor signals for an impact at location ‘a’](image)

**Figure 5: Piezoceramic sensor signals for an impact at location ‘a’**

![Cost function Result](image)

**Figure 6: Objective function $E(x, y)$ for an impact at location ‘a’**

### 4.2 Impact localisation using the LAMDA

Figure 7(a) shows the modal signature recorded for an impact at location ‘d’ which at a
distance of 122 mm from the centre of the LAMDA and at an angle of $26^\circ$ relative to its
principal axis. Due to this angle, the modal signature is shifted relative to the theoretical
dispersion curves for the plate which were obtained from DISPERSE [18]. At least four
modes have contributed to the impact modal signature: $A_0$, $S_0$, $A_1$ and $S_2$. Two pass-
band regions were chosen for the source localisation procedure, centred at 730 kHz for the \( S_0 \) and 1.48 MHz for the \( A_1 \), as shown in Figure 7. An inverse Fourier transform was applied to the filtered spectrum to generate the corresponding time signals which are shown in Figure 7(b). Finally, an arrival-time is determined from the envelope peak of a Hilbert transform applied to each time signal. Based on knowledge of the group velocity and using equations (3) and (4), the distance to the impact was estimated to be 130 mm, which represents a 6.6% error. Applying equation (5) to the \( S_0 \) signature produced an azimuthal angle estimate of 19.75°, and to the \( A_1 \) data 20.43°. The average of these two values is 20.09° which represents a 23% error. The analysis was repeated for all impact locations shown in Figure 3. The results were converted into Cartesian coordinates (see Figure 3) and are listed in Table 1 for direct comparison with the results from the triangulation method.

![Figure 7: Wavenumber spectrum (left) for an impact at location ‘d’, plotted against theoretical dispersion curves for a 1.6 mm thick aluminium plate. Solid line type denotes a symmetric mode and dashed type an antisymmetric mode. Modal order is shown in parenthesis. Dashed ellipses indicate pass bands from which time domain signals (right) corresponding to each mode are obtained.](image)

5. Comparison of LAMDA performance to triangulation

Table 1 compares the source localisation performance of the two methods. For impact locations ‘b’, ‘c’ and ‘d’, the localisation accuracy is comparable. For impact locations ‘a’ and ‘e’, the data furnished by the LAMDA was inconclusive. This is because as \( \theta \) approaches 90°, the apparent wavenumber approaches zero and the contributions of different modes become indistinguishable in the wavenumber-frequency spectrum. Another limitation of the LAMDA with respect to the estimation of the angle of arrival is that only the magnitude of this angle can be determined using the present implementation. Adding a second perpendicular arm to the LAMDA should overcome these limitations.

Notwithstanding these limitations the source localisation accuracy of the LAMDA is remarkably good, particularly in view of the economical use of the modal signature data. Specifically, the position estimates were obtained from only two of the four available modes and for a single frequency band. It is surmised that localisation
accuracy should improve as more modes and more frequency bands are incorporated into the analysis. This will be the subject of a future investigation.

**Table 1: Impact locations determined by using triangulation method versus using LAMDA.**

<table>
<thead>
<tr>
<th>Impact Location</th>
<th>Actual Position</th>
<th>TRIANGULATION</th>
<th>LAMDA</th>
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<tbody>
<tr>
<td></td>
<td>x&lt;sub&gt;actual&lt;/sub&gt;</td>
<td>y&lt;sub&gt;actual&lt;/sub&gt;</td>
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<td>a</td>
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<td>407</td>
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<tr>
<td>e</td>
<td>220</td>
<td>440</td>
<td>215</td>
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**6. Conclusion**

This paper has compared the impact localisation performance of a novel flexible multi-element piezoelectric sensor array to triangulation implemented using three monolithic piezoceramic sensors. The LAMDA was shown to produce results comparable to those obtained from the triangulation method for impacts within an angle of 30° from its principal axis, but with the benefit of requiring only a single sensor which is flexible and conformable to curved substrates. The primary shortcomings of the sensor, in its current form, are that: (1) it cannot locate a source perpendicular to its principal axis, and (2) it cannot determine the sign of the azimuthal angle of arrival. Future work will focus on the development of a second generation LAMDA with a second perpendicular sensing arm, which should overcome these limitations.

**References**