A novel high density piezoelectric sensing capability for in situ modal decomposition of acoustic emissions

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Abstract

An acoustic sensing system consisting of a flexible high-density linear piezoelectric sensor array coupled to a new modular, low-power, low-noise, high-bandwidth data-acquisition platform suitable for aircraft implementation is developed and applied to in situ modal decomposition of impact acoustic emissions. The performance of a 16 element array is assessed by spectrally decomposing acoustic emissions from ball-drop impacts made on aluminium and composite panels at various distances and orientations relative to the sensor. It is shown that with a priori knowledge of the dispersion characteristics of a panel the spectrally decomposed output from the array furnishes sufficient information to localise an acoustic source. The significance of this new capability to Modal Acoustic Emission (MAE) is discussed.

1. Introduction

Laser scanning vibrometry is widely considered to be a useful tool for guided plate wave measurement. This stems from its capacity, when coupled with a 2D FFT [1], to quantify the contribution of individual modes in a multi-modal wave-field. Single point sensing as traditionally applied in guided wave non-destructive testing e.g. [2], acousto-ultrasonics (AU) e.g. [3] and acoustic emission (AE) e.g. [4] is far more restrictive by comparison. The separation of individual modes in a time record is generally plausible at frequencies below the first cut-off, where only three modes exist and when the distance between the source and sensor is sufficient for separation to occur. However, restricting the frequency bandwidth and modal content will also restrict the diagnostic information contained in a signal.

Compared to a single point time-signal, a dispersion spectrum offers considerably more insight into the composition and properties of a wave-field. For example spectral-domain filtering can be used to isolate modes of interest [6-7], and remove boundary reflections [8] and other extraneous components including random noise. After isolating a mode, its time domain contribution can be retrieved via an inverse Fourier transform, which, as demonstrated in [9], allows for judicious selection of modes and frequency bands from which to compute arrival times for range estimation. At the most fundamental level however, the capacity to comprehensively decompose a wave-field into its constituent modes opens new opportunities in damage classification and quantification based on characteristic modal signatures or fingerprints, as briefly outlined in [9].
Such considerations were central to the development of the first in situ modal decomposition capability which was developed using a high-density fibre Bragg grating (FBG) array, as reported in [5]. The efficacy of this sensor as a structural health monitoring (SHM) capability was demonstrated experimentally by quantifying Lamb mode conversion at a structural inhomogeneity in an aluminium plate. More recently this sensor was used to successfully characterise the modal composition of guided waves travelling in an optical fibre [10]. Both cases involved an AU inspection as this capability is restricted to applications in which the acoustic source is controllable.

A logical next step is the development of in situ modal decomposition for acoustic emission (AE). However, this presents a much more difficult experimental problem. The central challenge is that AE events are spontaneous and isolated. To capture such events the sensing elements in an array must be sampled simultaneously. The existing FBG approach is not amenable. It relies on intensity based interrogation in which the wavelength of the interrogating laser must be tuned to the different operating wavelength of each FBG sensing element in succession [5]. This sequential scanning process limits the approach to situations in which the acoustic events are controlled and repeatable, e.g. AU. In the case of momentary and/or isolated acoustic events sequential interrogation is implausible.

This paper reports on the development of an alternative sensing approach that is capable of producing an in situ modal decomposition of spontaneous acoustic emissions. It consists of two key components: a new high density multi-element polyvinylidene fluoride (PVDF) sensor and new instrumentation capable of snapshot interrogation of a multi-element piezoelectric array [11]. After an outline of the salient features of both components a new source location strategy based on modal decomposition is introduced. Experimental demonstrations of in situ modal decomposition and source location are undertaken using isotropic and polymer composite test panels subject to non-damaging impact AE. The paper concludes with a discussion of the implications of this new capability for Modal Acoustic Emission (MAE).

2. A Linear Array for Modal Decomposition and Analysis

Figure 1 illustrates the two key elements of this new capability: a compact high-bandwidth low-noise interrogation module and a flexible PVDF based multi-element sensor array which is referred to by the acronym LAMDA, for Linear Array for Modal Decomposition and Analysis.

The LAMDA, shown in Fig. 1b, works on the same basic principle established in [5] but relies on piezoelectric rather than optical fibre sensing, for the reasons outlined previously. The construction of the LAMDA is similar to that of a sensor reported in [12] but with several key differences. The LAMDA is smaller in plan-wise dimension and is approximately half the thickness, consisting of two rather than three layers, as shown in Fig. 1b. The sensing elements are rectangular ~1 x 5 mm in size and spaced at a pitch of 1.27 mm leading to an overall footprint on the host (bonded area) of ~20 x 5 mm, dimensionally similar to an electrical resistance strain gauge. The sensor has a thickness of ~150 um and an overall mass of 290 mg; however this includes a 50 mm long section of un-bonded track (less than half of which is pictured in Fig. 1) so the
mass bonded to the structure is less than 50 mg. The small footprint, low mass and high compliance of the thin polymer construction minimises the inertial and structural impact of the sensor. The flexibility ensures excellent conformability which is an advantage for curved structural surfaces. It also facilitates the use of low-viscosity adhesives which foster thinner bond lines thereby minimising shear lag and acoustic attenuation effects.

The instrument pictured in Fig. 1a is termed the AUSAM+. A comprehensive description of this device was given in [11] so it suffices here to repeat only a few details that are relevant to the present work. The device has 4 variable-gain piezoelectric send/receive channels each with a 50 kHz - 5 MHz bandwidth and excellent low noise performance by virtue of its electronic design and EMI hardened packaging. Units can be used in isolation or connected via a synchronous optical link to create a sensing network of up to 248 independent channels. For the present study, a networked configuration consisting of 4 units was used to accommodate the 16 element LAMDA shown in Fig. 1b.

3. Theory of Operation

Figure 2 depicts schematically the AE from a localised source that is sufficiently distant from the LAMDA that a single mode component of the AE signal can be regarded as a plane wave with wave vector \( \mathbf{k} \). This plane wave strikes the \( N \) element LAMDA at angle \( \theta \) relative to the longitudinal axis of the array, the centre of which is at the origin. Assuming the sensor behaves ideally, i.e. with negligible inertial effect and a sensing area that is negligibly small in comparison to the wavelength, the disturbance sampled by the array has an apparent wavenumber

\[
k_s = k \cos \theta.
\]

Applying a 2D Fourier transform to the set of \( N \) simultaneously acquired time vectors, each consisting of \( M \) samples, yields a discrete wavenumber spectrum given by

\[
H_{k+1,f+1} = \sum_{n=1}^{N} \sum_{m=1}^{M} u_{n,m} e^{-2\pi i (n-1) k/N} e^{-2\pi i (m-1) f/M}.
\]
Here, $k$ and $f$ are wavenumber and frequency indices respectively and $u$ is the measured signal, which, for a PVDF sensor, is a voltage that is proportional to the strain rate. For a harmonic time-varying one-dimensional strain field, the relationship between voltage ($V$) and strain ($S$) is [24],

$$V(\omega) = \frac{1}{Y_e + (1 - \kappa^2_{31})Y_0} A \frac{d_{31}}{s_{11}} S_1,$$

$$Y_0 = i\omega\varepsilon_{33} \frac{A}{h}.$$

Here, $A$ is the sensor area, $Y_e$ is the external admittance, $d$ is the piezoelectric strain constant, $\kappa$ is the electromechanical coupling coefficient, $s$ is the mechanical compliance coefficient at zero electric field, $\omega$ is the circular frequency of the strain field oscillation and the numerical subscripts correspond to a coordinate system in which direction 1 is the principal axis of the PVDF sensor, which in the present study is aligned with the $x$ axis in Figure 2, 2 corresponds to the transverse in-plane direction and 3 is the through-thickness direction.

The wavenumber resolution and Nyquist limit of the array can be determined by sampling theory. These parameters are a function of only two sensor dimensions; the sensor pitch and the array length. For the dimensions given in Fig. 1, the relevant calculations yield a resolution and Nyquist limit of 331 and 2474 rad.m$^{-1}$ respectively.

![Figure 2. Plane wave with wave vector $k$ and amplitude $A(k)$ striking a linear array of $N$ sensor elements at an azimuthal angle $\theta$.](image)

3.1 Source Localisation

The localisation of a source using a linear sensing array of the type described in the previous section is demonstrated by example. Consider the hypothetical case of a 1.6 mm thick isotropic aluminium plate containing an acoustic disturbance consisting of the three Lamb waves in the frequency range bounded by the dashed vertical lines in Fig. 3. This range is deliberately centred at the point of modal confluence for the group velocity. At this confluence, neither time nor time frequency based methods are capable of separating the constituent modes and thus localisation of the source is challenging.
Synthetic strain response data was generated for this case using the analytical approach detailed in [13] with a 2 mm diameter circular shear traction centred at the origin acting as the source. The time modulation was a 7 cycle Hanning-windowed tone-burst with a centre frequency of 1220 kHz and a bandwidth of 500 kHz. Figure 4 shows the strain time-history $S_1(t)$ at a surface point located 125 mm away from the origin.

Consider next a linear array of sensors at this same location and arranged so that the sensing axis is aligned with the wave vector i.e. $\theta = 0^\circ$ in Fig. 2. A 2D FFT applied to a set of time signals spatially resolved at a 0.1 mm pitch over a length of 50 mm results in the wavenumber spectrum shown in Fig. 5. It will be noted that these dimensions differ from that of the actual sensor in Fig. 1 and will produce a higher-fidelity spectral decomposition. This is justified in the present context as the sole purpose of the case study is to describe the source localisation strategy, which can be done more effectively without the distracting artefacts caused by limited resolution. Such effects will be considered in a separate study.

Following the procedure described in [9] the individual time-domain contributions are separated by first isolating the required mode(s) in the frequency range(s) of interest via an appropriately shaped pass-band filter. An inverse Fourier transform is then applied to generate the corresponding time signal.
Figure 5. Wavenumber dispersion spectrum corresponding to strain response in Figure 4. Lines are dispersion curves obtained from Rayleigh-Lamb theory. Dashed ellipses indicate pass bands from which time domain signals corresponding to each mode are obtained.

Next, the source distance is determined from the measured time differences of arrival between modes and/or different frequency components of the same mode. Consider the case of two modes; $m_1$ and $m_2$, propagating at the respective frequencies $f_1$ and $f_2$. One can relate the arrival times of these two modes as follows,

$$v_{m_1,f_1}^{gr}(t_{m_1,f_1}^a - t_0) = v_{m_2,f_2}^{gr}(t_{m_2,f_2}^a - t_0) = r. \tag{4}$$

Here, $t_{m,f}^a$ is the measured arrival time for a mode with known group velocity $v_{m,f}^{gr}$ and $t_0$ is the origin of time which is obtained after rearranging Eq. 4, viz.

$$t_0 = \frac{v_{m_1,f_1}^{gr}t_{m_1,f_1}^a - v_{m_2,f_2}^{gr}t_{m_2,f_2}^a}{v_{m_1,f_1}^{gr} - v_{m_2,f_2}^{gr}}. \tag{5}$$

This leads to the following formula for the source-receiver distance,

$$r = \frac{v_{m_1,f_1}^{gr}v_{m_2,f_2}^{gr}\Delta t_{2,1}^a}{v_{m_1,f_1}^{gr} - v_{m_2,f_2}^{gr}}. \tag{6}$$

Here, $\Delta t_{2,1}^a = t_{m_2,f_2}^a - t_{m_1,f_1}^a$ is the time difference of arrival between modes $m_1$ and $m_2$.

To demonstrate the robustness of the source localisation capability furnished by the LAMDA, assume that a dominant component of the AE signal corresponds to a frequency near the confluence shown in Fig. 3. The mode-pair chosen is \{A$_0$, $f=1.05$ MHz; A$_1$, $f=1.1$ MHz\}. The required time signals are obtained by inverse Fourier transform of the wavenumber spectrum after nulling values outside the elliptical pass-band regions marked in Fig. 5 which correspond to the chosen mode-pair. Next, a Hilbert transform is applied to the time signals obtained and the arrival-time determined from the envelope peak. Substituting the required values in Eq. 6 yields a range estimate of 127 mm. This value is within 2% of the known distance. The source of this error is yet to be investigated however it is surmised to be mainly numerical in origin.
3.2 Azimuthal Angle of Arrival

The assumption that the wave vector is parallel to the sensor axis implies that the source direction is known which is unduly restrictive and unrealistic for many practical acoustic emission scenarios including accidental impact which is an important case for composite materials. An additional step is required to cater for an arbitrary angle of arrival.

It can be shown that an oblique sampling of a wave-field results in a vertical displacement of the modal signatures on wavenumber-frequency dispersion plots. Figure 7 illustrates this effect using the previous case study in which only the angle of incidence has been changed, specifically to 45°. Assuming that the thickness and elastic properties of the host are known, the angle can be recovered from Eq. 1, viz.

$$\theta = \cos^{-1} \frac{k_s}{k}$$

(7)

Here, $k_s$ is taken at the centroid of the pass band region used to recover the time signal from which the range estimate is derived, as indicated by the dashed red ellipses in Fig. 7, and $k$ from the theoretical dispersion curve at the same frequency. An estimate for the source distance is obtained as before. For the case at hand the relevant calculations yield angle and range estimates of 45.01° and 123.5 mm respectively.
Whilst the magnitude of the angle can be determined from Eq. 7, the sign cannot, which means the source could be in either one of two possible quadrants. This ambiguity can be resolved by adding another arm to the sensor, in the y-direction shown in Fig. 1, resulting in a cruciform or T patterned sensor array. Such an arrangement would also remove a blind-spot in the single arm design at $\theta = 90^\circ$, for which case Eq. 1 always yields an apparent wavenumber of zero, i.e. a featureless wavenumber spectrum.

4. Experimental Demonstration

The need for brevity allows only a few results to be reported. The cases selected are representative and focus exclusively on the source localisation performance of the LAMDA. The implications for source characterisation, i.e. the identification and quantification of the structural origins of an emission will be dealt with in a separate study.

The experimental setup is shown in Fig. 8. Two plate subjects were examined: (1) a regular aluminium panel, notionally isotropic, square in shape with a side dimension of 600 mm and 1.6 mm thick, and (2) a fibre composite panel also square in shape with a side dimension of 500 mm and 2.2 mm thick; manufactured from 16 layers of unidirectional carbon-bismaleimide pre-preg in a [90,-45,45,0,0,45,-45,90]s layup.

A LAMDA was attached to each panel using cyanoacrylate adhesive. For the composite panel the sensor was fixed in alignment with the 90° ply direction. As previously remarked four AUSAM units were networked to produce a 16 channel system. The acoustic source was generated by low-velocity ball-drop impact using a ball-bearing 10 mm in diameter and 4 g in mass. A drop height of 1.2 m was maintained throughout the testing. Impacts were made at a range of distances from and orientations to the sensor. The test panels were impacted sitting freely on a benchtop with a layer of bubble-wrap in between to acoustically isolate the panel from the benchtop.

4.1 Isotropic panel: impact at $r = 200$ mm, $\theta = 0^\circ$

Figure 9 shows the time signal at sensing element 8 which is adjacent to the centre of the array. The dominant signal feature is a frequency chirp which is characteristic of the
Ao mode at low frequency. The associated spectrum confirms a strong signature in the sub 200 kHz frequency range.

More interesting in the present context are the higher-frequency and higher-order modal contributions which dominate near the beginning of the time trace, i.e. between 25 and 50 $\mu$s in Fig. 9(a). This modal content is clearly revealed in the spectrum shown in Fig. 9(b). At least 4 modes are present in the frequency range above 600 kHz. These can be identified from the dispersion curves as $A_0$, $S_0$, $A_1$ and $S_2$. This abundance of modal information is significant for two reasons. Firstly, it illustrates that a simple impact can produce a complex modal signature which underscores the potential of this capability for source characterisation. Secondly, a relatively rich spectrum facilitates a robust estimate for the source position as is now demonstrated.

![Image]

Figure 9. Time signal (left) and spectrum (right) for an impact aligned with the sensor. Circled areas are pass bands corresponding to the mode pair: \{S$_0$, f=677 kHz, A$_1$, f=1.532 MHz\}.

An estimate for the source position is obtained from the mode pair \{S$_0$, f=677 kHz, A$_1$, f=1.532 MHz\}. This selection strikes a reasonable balance between minimising dispersion and maximising the difference in group velocity, as evident from Fig. 3. Following the steps outlined in the previous section, the time difference of arrival is calculated from time signals recovered from the pass bands corresponding to these modes, which are shown in Fig. 9(b). The relevant calculations are omitted but can be reprinted from the information just given. The resulting estimate is 205.73 mm. This represents an error of less than 3%. Given that only a fraction of the available spectrum was used in calculating the estimate, the magnitude of this error is not unreasonably large.

![Image]

Figure 10. Time signals corresponding to the pass bands circled in Figure 9.
4.2 Isotropic panel: impact at $r=200\,mm$, $\theta=30^\circ$

As expected from the discussion in Sec. 3, the angled sampling in this case has resulted in a skewed spectrum, as seen in Fig. 11. Whilst only one point on the modal signature is sufficient to recover the azimuthal angle, for this case points are taken on two separate modes corresponding to the centroids of the pass-band regions for the mode pair $\{S_0,f=732\,kHz, A_1,f=1.654\,MHz\}$. Calculations are again omitted for brevity. The estimate from the $S_0$ data point is $29.11^\circ$, and from the $A_0$ data point $37.14^\circ$. The average is $33.12^\circ$. The error is not insignificant, but it should be recognised that only a fraction of the available experimental data has been used. A relatively simple refinement of this estimation procedure that is expected to yield significantly improved estimates is outlined later in this paper.

![Figure 11. Measured wavenumber spectrum for an impact at an azimuthal angle of 30°. Circed areas are pass bands corresponding to the mode pair $\{S_0,f=732\,kHz, A_1,f=1.654\,MHz\}$.](image)

After correcting the spectrum using the average of the two angle estimates, the time signals for the mode pair are obtained from the spectrum as before. These signals are shown in Fig. 12. The resulting distance estimate is $194.6\,mm$, representing an error of $2.7\%$. In view of the noted error in the azimuthal correction the accuracy is remarkably good.

![Figure 12. Time signals corresponding to the mode pair in Figure 11 after azimuthal correction.](image)

4.2 Composite Panel: impact at $r=50\,mm$, $\theta=0^\circ$

A much shorter range was considered for the composite panel as acoustic damping rendered all but the $A_0$ at low frequency undetectable at ranges greater than $100\,mm$. 


Figure 13 shows a set of representative results corresponding to an impact aligned with the sensor. Only the $S_0$ and $A_0$ modes are visible in the spectrum. The relatively high centre frequency of the $S_0$ modal signature is consistent with the noted absence of this mode in measurements taken at longer ranges as attenuation in composite laminates increases exponentially as a function of frequency [14]. Whilst the frequency ranges for the two modes are well separated, both coincide with highly dispersive regimes for the respective modes, complicating the task of source localisation.

![Figure 13](image)

Figure 13. (a) Measured wavenumber signature for a non-damaging impact on a composite laminate (lines correspond to theory) and (b) theoretical group velocity dispersion curves.

The pass-bands for the source localisation in this case were chosen to correspond to the least dispersive part of the respective frequency ranges. Applying these filters followed by an inverse Fourier transform yields the time signals shown in Fig. 14. The resulting distance estimate is 48.87 mm. Considering that there is a noticeable discrepancy between the measured and theoretical wavenumber dispersion curves, this level of accuracy is remarkable. This discrepancy originates from uncertainties in the elastic properties used in calculating the dispersion curves. These properties were obtained from published sources and were not verified experimentally. Such verification (e.g. [15]) will be implemented in a sequel to the present study.

![Figure 14](image)

Figure 14. Modal time contributions corresponding to the circled pass bands in Figure 13.
5. Discussion and Conclusion

A new multi-element sensing capability for in situ modal decomposition of acoustic emissions has been developed, and its application for the accurate localisation of an acoustic source from its modal signature has been demonstrated experimentally. Modal decompositions were obtained for non-damaging impacts on isotropic and fibre composite panels. For both cases, the modal signatures obtained from the sensor were shown to contain sufficient information for the impact locations to be determined with remarkably good accuracy.

It should be noted that the localisation procedure outlined in this paper makes use of a minimal data set, i.e. only one mode pair for the range estimate and at most two points for the azimuthal angle. This was done solely to simplify elucidation of the approach. It is reasonable to expect that a locus of points should yield a much better estimate for the azimuthal angle and use of multiple mode-pairs a better range estimate. Alternative processing strategies are currently under evaluation.

This preliminary study has potentially significant implications for MAE. By providing a more complete and conclusive modal decomposition than can be obtained from existing time and time-frequency analysis methods, the LAMDA sensor combined with the AUSAM+ instrumentation offers a basis for improved identification and quantification of the structural origins of an acoustic source based on modal signatures. In conjunction with the proposed source localisation capability this constitutes a promising new sensing and analysis framework for MAE.

References