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Piezo-electric Thick Films for Sensing

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Abstract

Monolithic piezoelectric sensors commonly used for acoustic emission and ultrasonic inspection are non-conforming, bulky, costly and heavy. This means they do not fit well to complex geometries, they can be susceptible to damage, and on larger structures their cost and weight can be prohibitive. An alternative to this is the use of piezo-electric thick films, which comprise of piezo-electric particles suspended in a matrix material. Such materials could provi*de "paint on" or "printable" sensors and sensor networks that are low profile, easy to* mount and very cheap. In this work we explore the potential of piezo-electric thick films to sense and actuate for Acoustic Emission and ultrasonic applications. Sensors were produced by dispersing PZT 5a particles within water based acrylic and epoxy matrix materials with up to 70% fill by weight. The PZT films were applied to steel and their responses to artificial AE sources (Hsu-Nielson) were assessed and three-dimensional laser vibrometry was used to study the frequency response and mode shapes of the sensors under excitation. The results showed that although less sensitive than monolithic piezoelectric transducers, the thick film sensors can excite and detect ultrasonic waves for SHM applications and there is great potential for the development of a low cost, printed sensor network for SHM.

1 INTRODUCTION

The use of wave based inspection techniques is very common in both non-destructive testing (NDT) and structural health monitoring (SHM) applications. Both passive and active wave based inspection approaches are utilized. Acoustic emission (AE) is a passive technique that requires the detection of propagating elastic stress waves released by the growth of damage; akin to seismology the occurrence of damage, its magnitude and its location can be determined. Active methods such as ultrasonic testing (UT) and acousto-ultrasonics (AU) require the excitation and acquisition of elastic stress waves within a structure and can be used to detect and locate the presence of damage.

Both active and passive approaches to wave based inspection require the conversion of mechanical displacements (wave motion) into a transient voltage trace, or vice versa. This is most commonly achieved using monolithic piezoelectric materials, and a wide range of commercially available transducers exist that use this technology. However, commercially available transducers are often bulky, heavy and costly; this can be prohibitive for the SHM of large structures where the required number of sensors is high and weight and cost are a concern. In addition, monolithic piezoelectric materials are very brittle and do not conform well to curved surfaces that are becoming more common as the use of optimized complex geometry structures increases. For this reason there is much interest in the development of low profile, flexible, transducers for such applications.

A variety of approaches to the development of film-like transducers for wave based SHM have been investigated and the following is a brief review of the most relevant. A range of techniques have been used to pre-prepare film transducers that require adhesion to structures of interest. Pickwell et al [1] used a sol gel approach to produce a composite PZT film on a Kovar substrate. Spin coating was used to produce uniform thicknesses and multiple layers were built up to form a ~18μm thick film. The produced PZT transducers were compared to commercially available AE sensors and demonstrated similar frequency response but lower sensitivity. Others have explored the use of Polyvinylidene fluoride (PVDF), which is a polymer that exhibits piezoelectric behavior. It is relatively cheap and readily available but has quite a low piezoelectric coefficient (<10pC/N). Some researchers have demonstrated improved sensitivity through the use of interdigitated electrodes on PVDF transducers for the excitation and acquisition of elastic stress waves [2]. Macro-fibre composite (MFC) transducers are formed from aligned piezoelectric fibres in a polymer matrix and have a much higher piezoelectric coefficient than PVDF (~170pC/N). They have been shown to work effectively as actuators and sensors for elastic stress waves [3, 4], but they do exhibit significant directional sensitivity due to their fibrous configuration and have limited flexibility. Prefabricated films of this nature are often costly due to manufacturing processes required, they require bonding/coupling to a structure of interest and, although flexible, in practice can only be conformed to single curve surfaces.

An alternative approach to the development of film-like sensors is the use of ‘paint on’ or ‘print on’ ferroelectric composites that can be applied directly to a structure of any geometry and in any shape required. Li and Zhang [5] developed and analytical model to predict the performance of piezoelectric paints based on PZT 5a powder dispersed in an epoxy resin. They postulated that a 70% weight fraction of PZT 5a would result in a piezoelectric coefficient (d33) of 81.4pC/N. In practice they were only able to produce paints with a 42% weight fraction of PZT 5a. Pre-fabricated and bonded to a substrate of interest they demonstrated a 12pC/N piezoelectric coefficient (d33), which compared well to their predictions. Others [6, 7] successfully developed a water-based acrylic PZT paint with up to 70% weight fraction of PZT 5a for use in strain sensing applications. In this work the use of these acrylic PZT 5a paint on films for excitation and detection of elastic stress waves is investigated. A Hsu-Nielsen [8] artificial AE source is used to assess detection sensitivity and 3D scanning laser vibrometry is used to characterize excitation potential.

2 SENSOR PREPARATION

The piezoelectric paint is formed by the addition of an active material, in this case a piezoelectric powder, in to a passive matrix material to form a 0-3 ferroelectric composite. This is one of the most common types of piezoelectric composites, whereby the active component has no electrical connectivity in any direction and the passive component has connectivity in all three directions. This indicates that the individual elements of the active component are isolated from one another in a continuous matrix [9]. The piezoelectric material used in this study is PZT 5a (lead zirconate titanate) ceramic powder provided by Piezo Kinetics Inc. (Bellefonte, USA) with the name of PKI-502. The polymer matrix is a commercial acrylic paint base provided by Rohm and Hass (Frankfurt, Germany) with various additives (coalescent, plasticizer, surfactant, etc.) required for a viable paint. The piezoelectric paint was applied to a 150x16x0.6mm steel substrate using k hand coater supplied by RK PrintCoat Instruments Ltd. (Royston, UK). The k hand coater uses precision drawn stainless steel wires wound on to a stainless steel bar. The spacing between the wires can be adjusted to precisely control film thickness. In this application a film thickness of 80μm was used.

Following curing of the piezoelectric paint an electrode was applied to the upper surface (substrate provides lower electrode) with dimensions of 70x10mm. The electrodes were produced using the same acrylic paint base supporting a “filler” of conducting pigment to make a conductive-paint electrode compatible with the piezoelectric paint. The electrode was applied by brush and following curing further conductive paint was used to attach a wire to the electrode. After fabrication the sensor was poled at 250V which equates to ~3kV/mm. An image of the completed sensor is shown below in Figure 1.

Figure 1: Piezoelectric paint sensor

3 WAVE ACTUATION

The ability of the piezoelectric paint film to excite elastic stress waves was investigated using 3D scanning laser vibrometry. A Polytec Ltd. PSV 3D500-M vibrometer system was utilized to measure the thick film sensor displacement. Laser vibrometry uses the Doppler effect to measure vibrational velocity based on the wave length of backscattered laser light. By using three lasers focused on the same position on the sample, the three dimensional vibration in x, y and z directions can be resolved. This provides an in depth analysis of the characteristics of the thick film sensor in a non-contact broadband fashion. The thick film sensor was excited using a ±150V swept sine wave from 1-500kHz over 1ms, using a Mistras Group Ltd. Arbitrary Waveform Generator. The area of the sensor was monitored by 1598 vibrometry measurement points with approximately 21 across the width and 76 along the length (numbers vary slightly based on the perspective effect on sample geometry in the video image). Vibrometry data were recorded at a sample rate of 1.28MHz and a frequency range of 0.6-500kHz was analyzed.

A Fast Fourier Transform (FFT) power spectrum that represents the average of the data from all 1598 measurement points is presented in Figure 2 for all three orientations (x,y,z). It is clear that there are a number of frequencies at which resonant behavior is observed. These correspond to frequencies of 11.3kHz, 59.4kHz, 141.3kHz and 153.8kHz; with the greatest energy content observed at 11.3kHz and 153.8kHz. The 3D laser vibrometery data allows the visualization of the sensor displacement, or rather the velocity at which it displaces, across the area of the sensor. Figures 3-5 present the resonant behavior of the sensor at 11.3kHz, 141.3kHz and 153.8kHz frequencies.

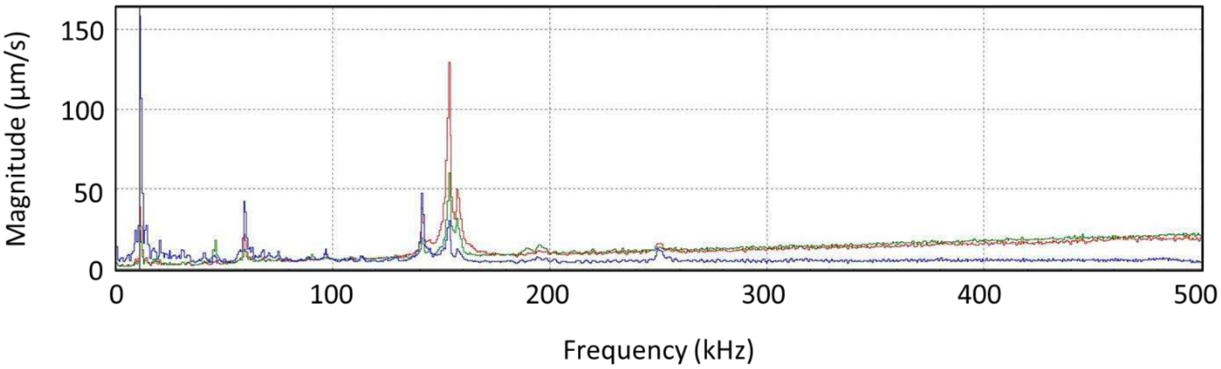


Figure 2: Power spectrum (FFT) of averaged vibrometry measurements. Red, green and blue are x, y and z directions respectively.

Figure 3 shows the resonant mode shape for the sensor at an excitation frequency of 11.3kHz, it can be seen that a global displacement behavior is occurring, with the majority of the actuation displacement in the out-of-plane (z) direction. The peak velocity recorded at this frequency is 500µm/s. The resonant mode shape at an excitation frequency of 141.3kHz is shown in Figure 4, where again the majority of the displacement is in the out-of-plane (z) direction. However the peak actuation velocity is seen to be significantly less at only 150µm/s. In this case the mode shape is more complex forming three peaks (ridges) and two troughs that run along the length of the sensor area. A similar mode shape was observed at 59.4kHz (although not presented here) with two peaks and one trough.

The observed out-of-plane actuation of the piezoelectric film at 11.3kHz, 59.4kHz and 141.3kHz excitation frequencies is to be expected due to the through thickness poling induced in the material. This behavior is corroborated in the spectrum in Figure 2, where the peaks observed at these frequencies are greatest for the blue z direction (out-of-plane) curve. However the large peak observed at an excitation frequency of 153.8kHz, is dominated by the red x direction (in-plane) curve. Figure 5 shows that the resonant mode shape at this excitation frequency is an in-plane expansion and contraction across the width of the sensor area. A relatively high peak actuation velocity of 350µm/s is also seen for this mode.

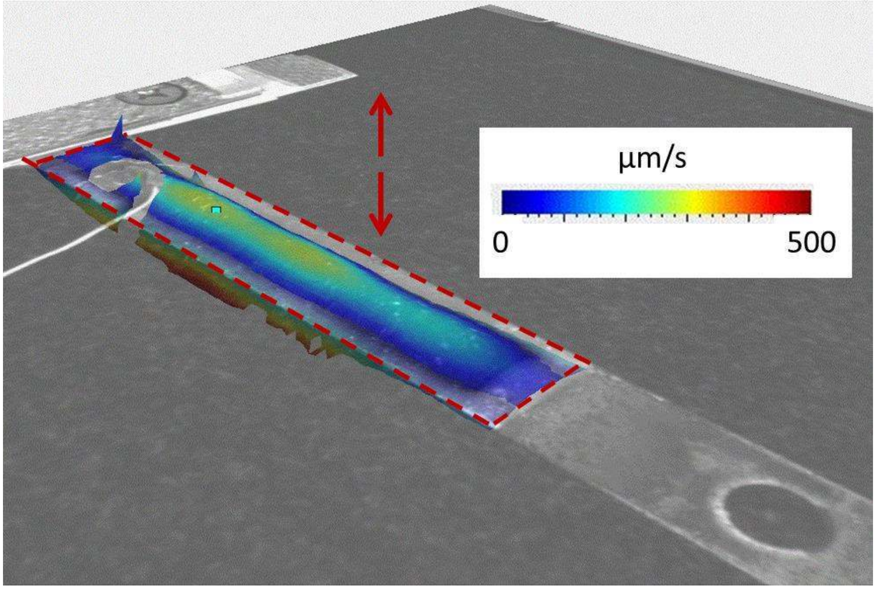


Figure 3: Thick film sensor behavior at 11.3kHz excitation frequency (red arrows indicate z direction and red dashed area indicates sensor area).

The 3D laser vibrometry results show that the developed piezoelectric film can be used to excite elastic stress waves at a range of frequencies suitable for structural health monitoring applications. The results also highlight the potential to control the excitation mode (in-plane versus out-of-plane) based on excitation frequency. There is also potential to further control the film sensor characteristics by controlling the shape and thickness of the applied film.

In order to explore this further a commercially available piezoelectric sensor (Pancom Pico-Z) was mounted to the substrate adjacent to the film sensor, using a cyanoacrylate adhesive, such that elastic stress waves excited by the film sensor could be recorded (Figure 6). The piezoelectric film was excited with a sine windowed ten cycle sine wave, using a Mistras Group Ltd. Arbitrary Waveform Generator, at the four identified resonant frequencies: 11.3kHz, 59.4kHz, 141.3kHz and 153.8kHz. The output of the commercial sensor was recorded using a Keysight DSO1052B digital oscilloscope, without any pre-amplification.

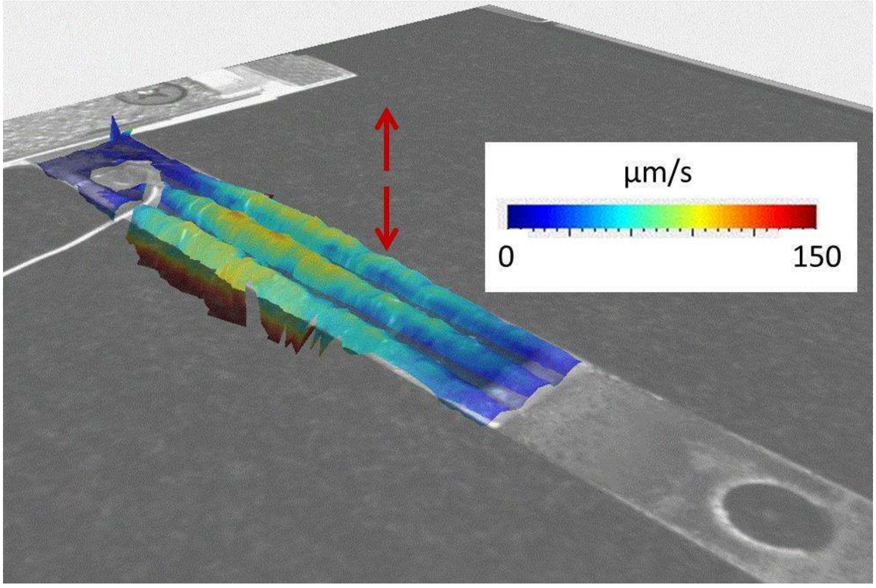


Figure 4: Thick film sensor behavior at 141.3kHz excitation frequency (red arrows indicate z direction)

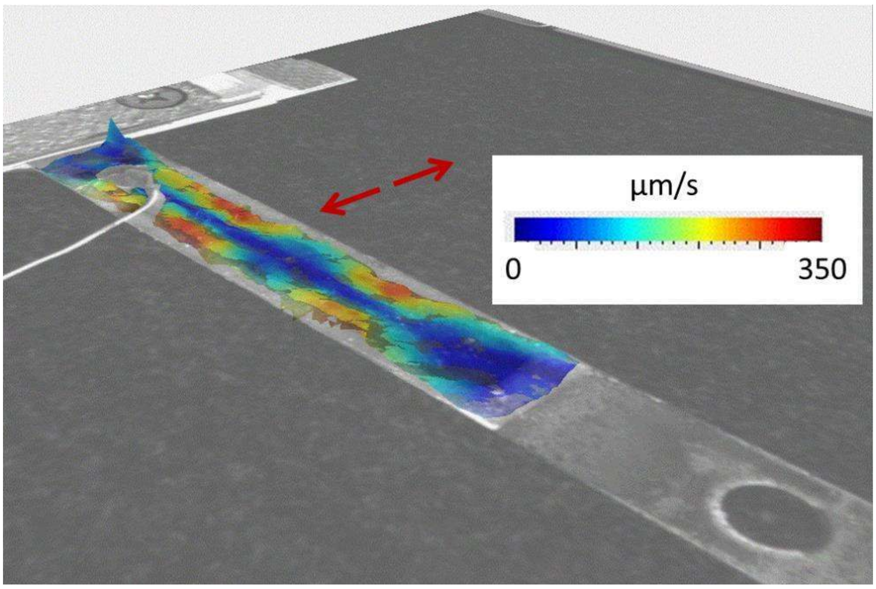


Figure 5: Thick film sensor behavior at 153.8kHz excitation frequency (red arrows indicate x direction)

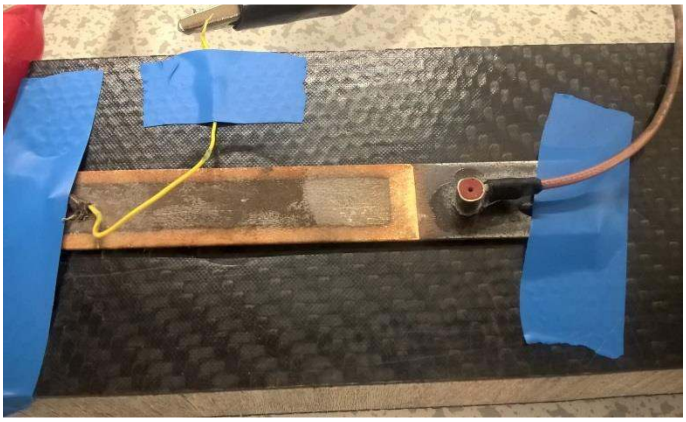
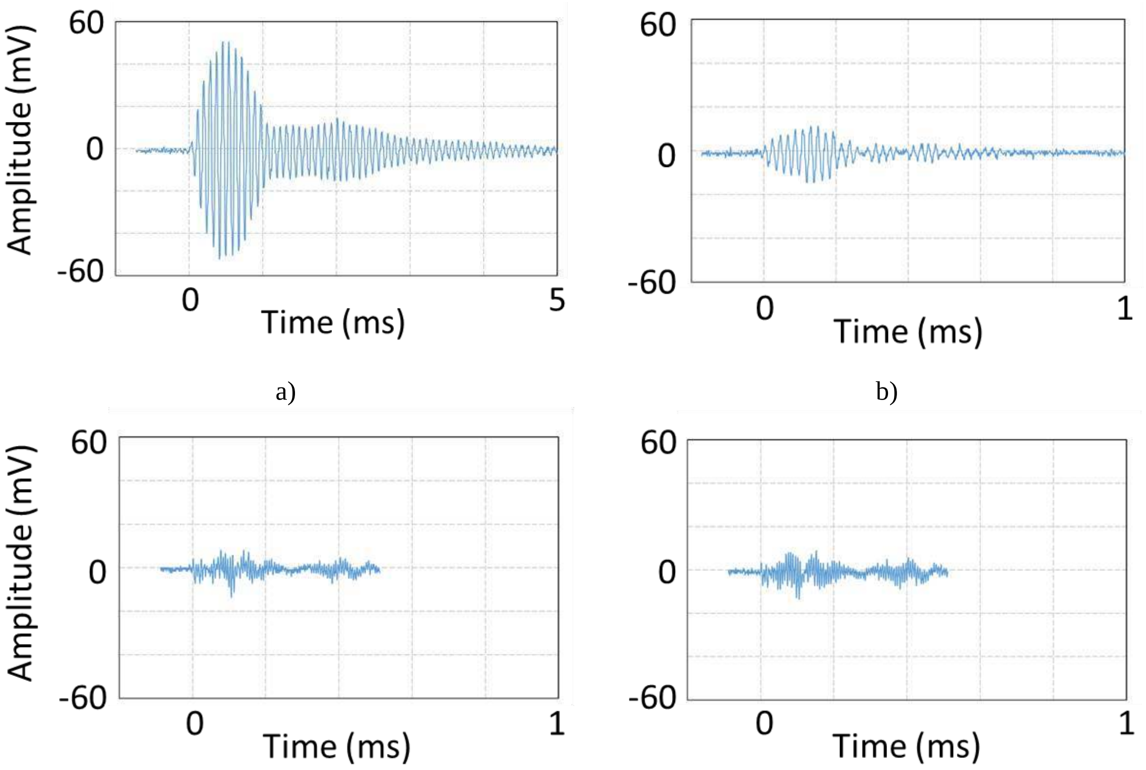


Figure 6: Pulse-receive experimental setup

Figure 7 a-d present the waveforms recorded by the commercial sensor following excitation of the film sensor at 11.3kHz, 59.4kHz, 141.3kHz and 153.8kHz, respectively. The three lower frequencies represent out-of-plane excitation modes with reducing peak excitation velocities (Figures 3 and 4) and a corresponding drop in amplitude in the waveforms recorded by the commercial sensor is seen. This demonstrates that selection of the correct excitation can generate readily detectable elastic stress waves. Surprisingly, despite the high actuation velocity observed at 153.8kHz, the amplitude recorded by the commercial sensor remains very low. It is anticipated that this results from the in-plane action of the film at this frequency that does not match the out-of-plane sensitivity of the commercial sensor.



a) b)

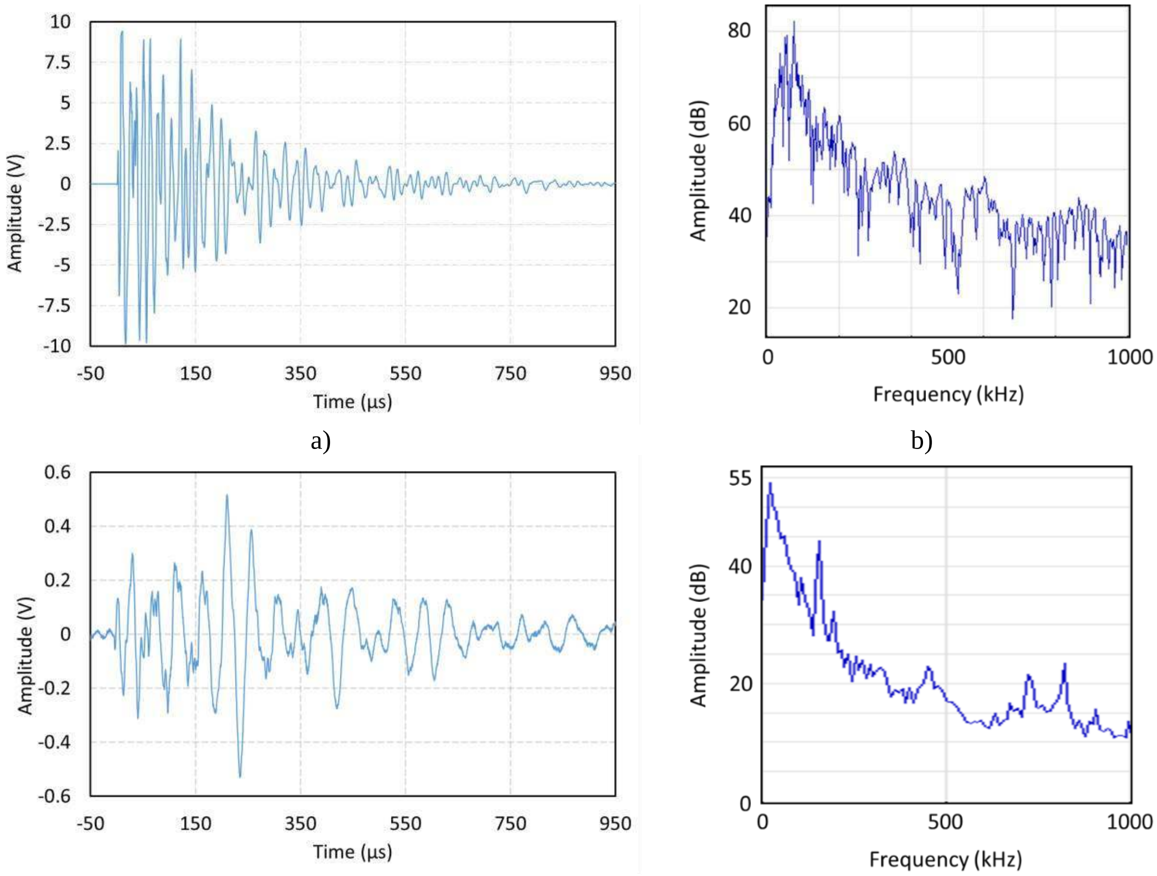
c) d)

Figure 7: Recorded signals following excitation by piezoelectric film a) 11.3kHz, b) 59.4kHz, c) 141.3kHz and d) 153.8kHz

4 WAVE DETECTION

The ability of the piezoelectric film sensor to detect elastic stress waves was assessed using the standard Hsu-Nielsen (H-N) source. The H-N source is a standard approach that uses a pencil lead fracture to assess the operation and coupling arrangement of acoustic emission sensors, as outlined by ASTM E976. The outputs of both the film and commercial sensors were amplified by 40dB using a Mistras Group Ltd. 2/4/6 pre-amplified and monitored using a Mistras Group Ltd. PCI-Express 8 acquisition system. H-N sources were conducted on the steel substrate surface between the film and commercial sensors.

As would be expected the commercial sensor recorded an average amplitude of 99dB_{AE} in response to the H-N source, whereas the film sensor recorded an average amplitude of 75dB_{AE}. The dB_{AE} scale is a log scale and therefore the sensor output voltage for the film sensor is significantly lower than that of the commercial sensor, as seen in Figure 8 a) and c), which present the recorded waveforms for the commercial and film sensors, respectively. The peak amplitude of the film sensor output is approximately one twentieth of that of the commercial sensor. Greater background noise is also present in the film sensor waveform (even if the difference in graph scale is accounted for) because, unlike the commercial sensor, the whole active area is unshielded and is expected to capture electromagnetic noise. However a good signal to noise ratio is still achieved with a clear signal observed above the noise level. The structure of the signals is slightly different, however, the frequency spectrum of the waveforms (Figure 8b and d) shows much greater similarity, with much of the energy at lower frequencies. The commercial sensor has a peak frequency content at ~75kHz and the film sensor is slightly lower at ~30kHz. The piezoelectric film sensors has therefore demonstrated the ability to detect elastic stress waves, albeit with a reduced sensitivity.



a) b)

c) d)

Figure 8: Comparison of piezoelectric film and commercial sensor (Pico-z). Waveforms, a) commercial and c) film. FFTs, b) commercial and d) film.

5 CONCLUSIONS

A trial piezoelectric paint tick film sensors has been manufactured with a 70% PZT powder weight fraction and assessed as an ultrasonic transducer for the excitation and detection of elastic stress waves. A methodology based on 3D scanning laser vibrometry and H-N sources was developed and demonstrated for the assessment of the sensing capabilities of piezoelectric films. The 3D scanning laser vibrometry proved particularly informative in the characterization of the frequency response and displacement modes of the piezoelectric film.

The potential of the piezoelectric film to both excite and receive elastic stress waves was successfully demonstrated. Four resonant frequencies were identified up to 153.8kHz and the lowest three resonances were shown to result from an out-of-plane displacement, whereas the higher frequency resonance demonstrated an in-plane excitation. The lowest frequency resonance, at 11.3kHz, was shown to produce the greatest peak excitation velocity (500µm/s) and, correspondingly, to transmit the most energy. The range of resonances and differing excitation modes identified is of great interest and demonstrates the potential to control sensor behavior and controlling the excitation mode can be used to excite waves with differing propagation modes. In addition to this there is great potential to explore changes in sensor shape and thickness, to further control and tune the sensor characteristics, which is easily achievable in the fabrication process of these sensors.

The presented piezoelectric thick film sensors have demonstrated the potential to develop ‘paint on’ sensor networks, whereby sensors with specific characteristics can be easily applied to complex geometry structures providing cheap and effective wave base SHM.

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