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EXPERIMENTAL AND NUMERICAL ANALYSIS OF A TRANSDUCER FOR THE GENERATION OF GUIDED WAVES

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Abstract

Dry-coupled thickness-shear transducers represent one of the most common ways to excite guided waves for the inspection of tubular and plate-like structures. Although already established in industry, some features of these transducers need to be studied, i.e. the uniformity of vibration, the modes excitability and the transmission of ultrasonic energy into the inspected structure. In particular, due to the dispersive behaviour of guided waves and the mode coupling these transducers require a precise characterization to guarantee a uniform in-plane vibration. A numerical and experimental characterization of the assembly has been carried out to assess the influence of the elements of the assembly into the uniformity of vibration. The outcome of the results in terms of mode-shape, displacement pattern and resonance frequencies is discussed to predict useful design changes to enhance the ultrasonic performance of these transducers.

Keywords: Piezoelectric Transducers, Guided Waves, Laser Vibrometer, Finite Element Analysis, Modal Analysis

1. Introduction

The implementation of ultrasonic guided wave systems in the fields of non-destructive testing and structural health monitoring has been present in the industry for many decades. After various pioneering work in these fields [1-2], Alleyne and Cawley introduced dry-coupled piezoelectric transducers to excite guided waves for inspection in tubular structures [3], where the main advantages included the practical ability to mount them on pipelines and the capability to excite longitudinal modes. Liu et al. used this system to excite torsional modes in pipes [4].

The dry coupling requires the use of a mounting force to guarantee the effective transmission of the ultrasonic signal into the inspected structure. The influence of this force on the variation of the mechanical resonances has been investigated by Engineer [5]. Through Hertzian contact theory Engineer proved experimentally that when a force of 200 N is applied the first thickness shear resonance of the transducer shifts from 1.2 MHz to 21 kHz.

Marques focused his research on the characterization of an array of thickness-shear transducers for the generation of shear horizontal waves in plate-like structures. His main objectives were the directionality of this wave mode and the suppression of unwanted modes (Lamb waves) [6]. He proved how the capability of his array in terms of amplitude was limited by the size of the transducers. Thus, he stated the importance of an investigation into the possibility of miniaturizing the transducers.

The miniaturization of the transducers requires the understanding of their physical behaviour, in order to choose which geometrical parameters can be modified to improve the ultrasonic performance. This paper provides an insight into the identification of the mode-shapes, displacement patterns and resonances of all the components of the assembly.

Section 2 contains a background on piezoelectric transducers, while section 3 contains the numerical analysis, section 4 the experimental results and a discussion, section 5 the conclusions.

2. Piezoelectric transducers

2.1 Current transducer

The transducer under consideration is composed of an assembly of three elements, a thickness shear piezoelectric device, an alumina wear-plate and a backing mass of steel. PI Ceramics provides the first two components glued together (figure 1a).

Thickness shear transducers are defined as specimens where the application of an electric field normal to the axis of polarization causes a shear strain into the material [7, 8]. The class of the piezoelectric element is PZT 5 A. The geometrical dimensions are 13 x 3 x 0.5 mm. Longitude, width and thickness throughout the study are identified as the x, y and z axes.

The necessity to protect the mechanical failure of the piezo-element requires the presence of the alumina wear-plate in the actual applications: thus, in case of excitation of guided waves the dry-coupling happens to be between the wear-plate and the waveguide.

The backing mass of steel (figure 1b) is added to increase the flexural stiffness of the material. This motivation is different from conventional ultrasonics, where the backing mass is used to damp out vibrations [3]. The electrical contact to the transducers is obtained by a positive electrode on the upper surface and a negative electrode in the down surface wrapped around to the upper surface. A space of 1 mm is used to separate the two electrodes on the upper face.

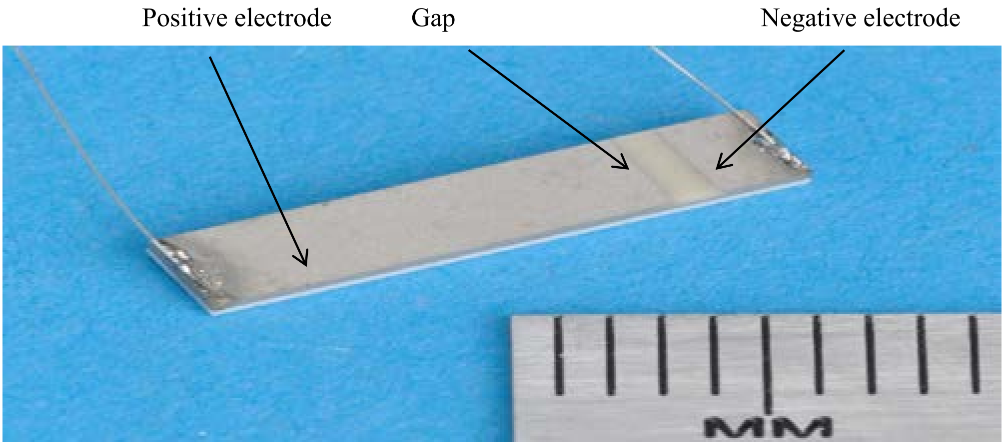

Figure 1: Picture of the piezoelectric element attached to the alumina wear-plate (Courtesy of TWI)

3. Numerical modelling

3.1 Methodology

The finite element analysis was obtained through the commercial software COMSOL, which contains a library for the piezoelectric analysis. In a previous study the finite element analysis with COMSOL was used to calculate the natural frequencies of the piezoelectric strip, with and without an alumina layer [9].

A further analysis has now been carried out by applying an electrical voltage as a boundary condition to calculate the mechanical displacement and the mode shape as an output of the model.

The study was conducted in the frequency domain: through this study it is possible to compute the effect of a model under a harmonic excitation. This excitation has been computed as a uniform load performed through a frequency sweep in the range 15-150 kHz. The frequency domain study was chosen for two reasons: first of all, it is computationally less expensive that a typical time-domain analysis; secondly it is readily seen how the eigenmodes interact with the applied voltage.

In this first analysis the response of a thickness-shear piezoelectric transducer to an applied voltage was computed. A voltage was applied on the positive electrode, to simulate the behaviour of the current transducer: the applied voltage was 15 V for all the frequencies in the sweep analysis, and the bottom surface and the wrapped around electrode were grounded. In terms of the mechanical boundary conditions, a free-free system was implemented.

Due to the geometry relatively simple of the system a free tetrahedral method was chosen: the total number of elements used was 15167.

As a second numerical step, the frequency response function of a piezoelectric strip attached to an alumina layer was analysed. The methodology followed was similar to the case presented in the previous section. However, in this case the number of elements of the mesh rises to 30514.

As far as the contact between the two surfaces is concerned, it is assumed that the materials are perfectly glued and the two materials are sharing the nodes of the mesh.

3.2.2 Numerical results

The numerical work indicates that in the range of applications no thickness-shear resonance can be found. Although this result can be expected from the theory, it is still important to quantify how the imposition of a voltage interacts with the eigenmodes of the structures. In particular potential undesired components of motion must be identified. In addition, when a preload is applied to the transducer, the very high frequencies will be reduced into the range of interest of this study.

The natural frequency analysis performed in [9] indicated the presence of flexural, torsional, shear horizontal and longitudinal modes: the experimental analysis proved that not all the modes are actually excited, due to the uniformity of the load along the longitudinal axis. These results are confirmed by the computational analysis here presented. Even though the mode shapes are constrained by the geometry of the piezoelectric element, the voltage drives the element to move along one axis. As an example the mode shape for 25 kHz is shown in figure: it can be clearly seen that there is a superimposition of thickness-shear motion on a flexural mode shape; moreover the presence of the wrapped around electrode changes dramatically the motion of the upper surface. Other results will be commented later in the sections of comparison with experimental results.

Figure 2: Picture of the numerical mode shape of piezoelement (left) and piezoelement with alumina (right) at 25 kHz. Colours indicate amplitude of displacements.

3. Experimental analysis

3.1 Methodology

The identification of natural frequencies and mode shapes obtained through numerical analysis requires experimental validation, especially because the computation is obtained with elements with free-free mechanical boundary conditions. One of the most widespread techniques for validation of numerical analysis in guided wave propagation and piezoelectric transducers is Laser Vibrometry [10]. As a matter of fact the necessity of not imposing constraints on the transducer drives the need of a non-contact measuring technique. A Polytec 3D Scanning Laser Vibrometer PSV-400-3D-M was used in this experiment [11]. This Laser Vibrometer is based on the emission of red laser from three heads to a specified moving surface: the backscattered energy is then compared to a reference signal to detect the velocity of the measured surface.

The three heads are used for the three components of velocity (see figure 3). The internal software offers the capability of defining a grid of points on the measured specimen to be scanned during the excitation of the element. The measurement is then repeated for every single point.

The form of excitation used was a chirp signal between 20-150 kHz. The chirp signal was used for two reasons: first of all it permits the frequency sweep in a specific range, secondly it is a signal often used in guided wave excitation. Thus, it can be used later for further comparisons when the waveguide will be introduced. As a function generator a Teletest Focus system was used: the voltage was 250 Vpp, spanning for 500 ms.

To increase the reflective power of the backscattered signal a bright sheet was used: although the application of the bright sheet considerably augmented the reflection, as a downsize some of the geometrical features were not clearly distinguishable. Therefore, the surface could not be completely measured. Moreover, as shown in figure 1, the ends of the transducers could not be measured due to the presence of the soldered cables.

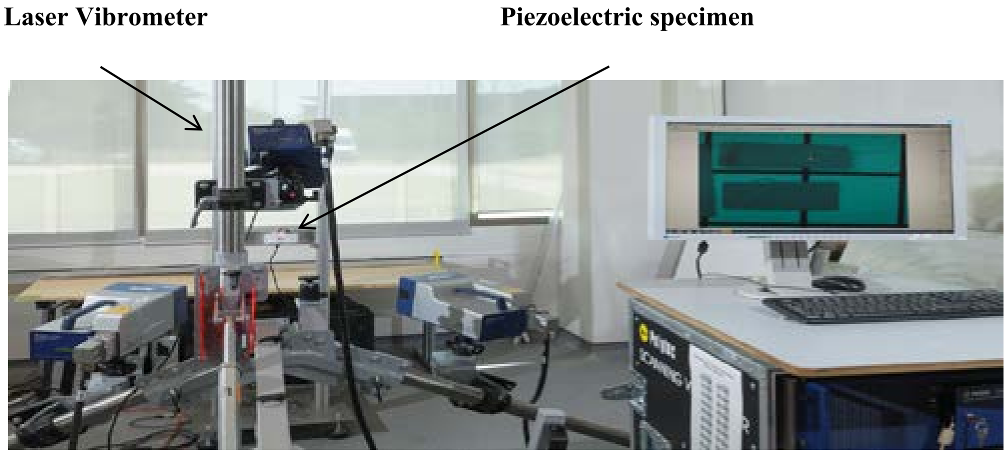

Figure 3: Picture of the 3D Laser Vibrometer (Courtesy of TWI)

3.2 Piezoelectric element

It can be readily found from analytical calculations [8] and experimental measurements [5] of the impedance that the first thickness-shear resonance of this analysed piezoelectric strip is around 1.7 MHz. Thus, one would expect that for a strip driven by a voltage in a range well below this threshold, the shape of vibration would be determined by the geometry. Flexural, torsional and extensional modes would then be expected.

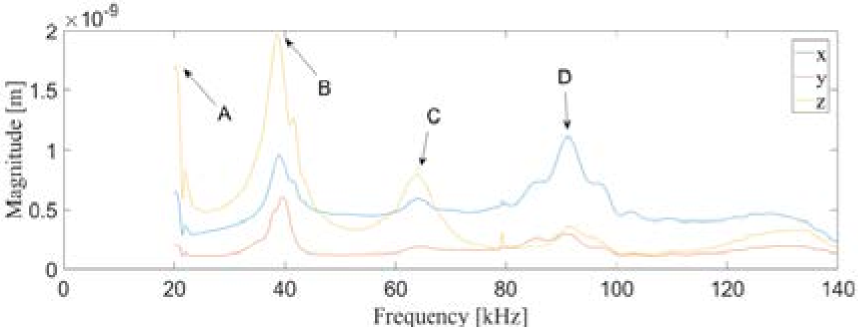

Figure 4: Average experimental spectrum of the piezo-element. Note that the resonance are labelled with letters

As an example of mode shape the magnitude of the displacement for resonance B and C are shown in figure 5. For resonances A, B and C a z component is higher than the other two components. Thus it is expected that those two components are actually flexural resonances.

The first resonance, A, at 20 kHz, is a flexural resonance of one complete cycle, although there is not a complete symmetry between the two cycles: as a matter of fact there is a larger area with an larger area with a downward deflection: the resonance C, at 64 kHz, is also a flexural type of resonance, with two complete cycles.

Resonance B, although not showing this peak of magnitude on the left, is showing how the left corner presents a different shape than the right corner. This area on the left corner was identified as the area surrounding the gap between the positive and negative electrodes. Also, resonance C on the left side presents a slight difference in the mode shape, i.e. a curvature of the end.

It is suggested that the discontinuity of electrodes is compromising the uniformity of excitation along the length, causing the rise of unwanted modes. Thus, almost one quarter of the piezoelectric element is actually not moving uniformly with the positive electrode. Therefore, this electrodes topology and its influence on the mode shape needs to be carefully investigated. In particular, a comparison with a topology with parallel electrodes or with different spacing of the negative electrodes needs to be investigated.

The investigation of the spacing of the electrodes would be useful for the generation of guided waves for two reasons: first of all the elimination of the current shape should help to generate a uniform guided wave signal. As a matter of fact an unwanted mode shape would lead to the excitation of not uniform wave-fronts, which results in a decrease of resolution and capability of detection of defects in plate-like and tubular structures. In addition, shortening the electrodes would be beneficial in terms of the miniaturization of the transducers.

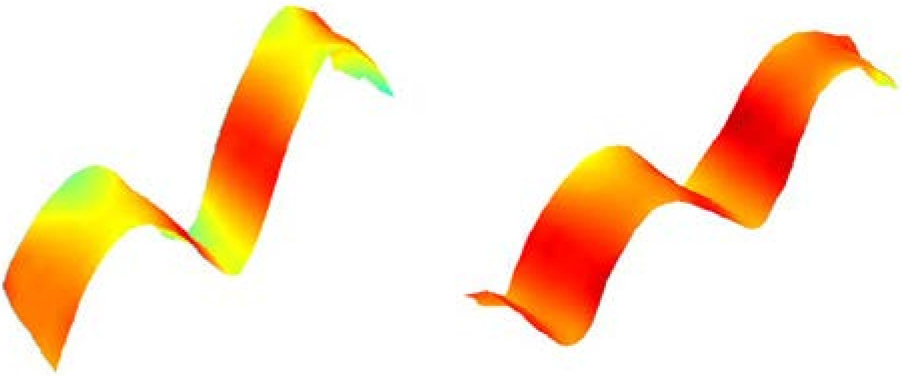

Figure 5 (a-b): Plot of the experimental mode shape for resonance B (a) and C (b)

3.3 *Piezoelectric element with alumina layer*

The addition of an alumina layer is expected to increase the natural frequencies, due to the increase of stiffness in the material. Moreover, adding a layer of material to the piezoelectric strip is likely to contribute to a decrease a displacement,

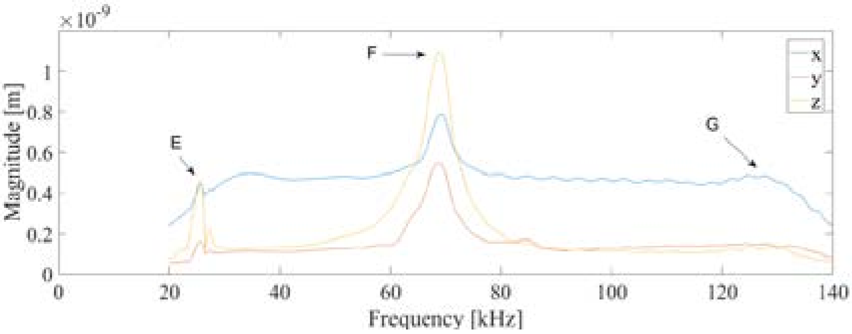

Figure 6: Plot of the average spectrum of the piezoelement attached to the alumina layer.

The piezoelectric-alumina layer was measured with the same technique used for the piezoelectric layer. The average spectrum is plotted in figure 6. In this case some important differences can be noted: first of all, it can be seen that there is a more uniform response othe displacement across the frequency. Secondly it should be noted that one of the resonances (the longitudinal resonance D) is not anymore present in this case. Thirdly, it is interesting to note that in both cases the longitudinal comparison (piezoelectric and piezoelectric plus alumina) is in the order of 600-500 pms, except for the resonances peaks.

In figure 7 the mode shape E of material joined together is presented. The comparison with the numerical results in figure 2 indicates a match in terms of shape, i.e. a flexural mode shape of the first order. Also in this case as for the piezoelectric element, it can be noted how in the left corner there is a remarkable difference in terms of displacement, due to the presence of the gap between positive and negative electrodes.

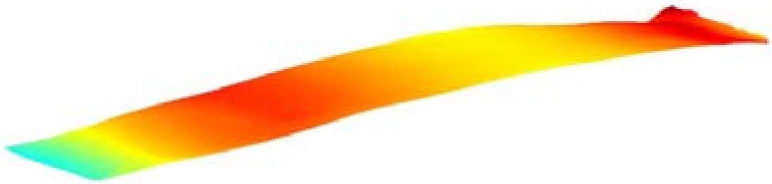

Figure 7: Plot of the experimental mode shape E

4.4 Comparison of results

The results presented in the previous section require a comparison method to understand physical trends and mismatches, where existing. In figure 8 the frequency response function of the piezoelectric element is presented both numerically and experimentally. Some details can be readily noted. First of all, the displacement pattern presents a similar response in the two cases: the out of plane vibration decreases dramatically for frequencies higher than 90 kHz, to become almost negligible: after this threshold the higher component is the longitudinal component. Secondly the response of the longitudinal component is flat across the frequencies except for the resonance around 90 kHz. Therefore one of the objectives for design changes would be to suppress the unwanted resonances in order to maintain only this component of motion.

On the other hand, there is a difference in magnitude between numerical and experimental results: one possible cause of explanation could be the difference of boundary conditions in the two cases. As a matter of fact in the experiment the cables of the transducers are fixed and there is also an interaction with the polystyrene foam: most likely these factors have contributed to decrease the amplitude.

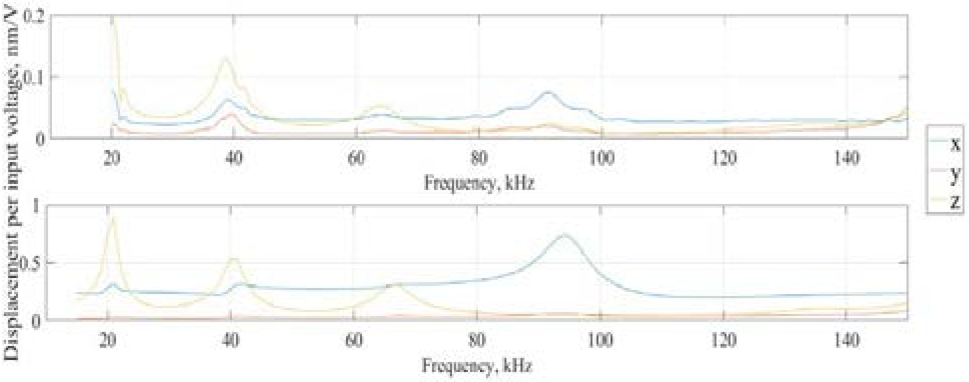

Figure 8: Comparison of experimental (up) and numerical results (down) for piezoelectric element

As far as the results with the alumina layer are concerned, it was expected that the presence of this component could flatten the resonances to obtain a more uniform response across the frequencies. In regards to the first resonance is concerned, it can be readily noted that it is shifted, as it would be expected by the increase in stiffness. On the hand the second resonance does not appear anymore. This fact can be explained by referring to the natural frequency analysis: no natural frequency appears in the range 25-60 kHz. As far as the general trend is concerned it can still be noted that the longitudinal component of motion is uniform.

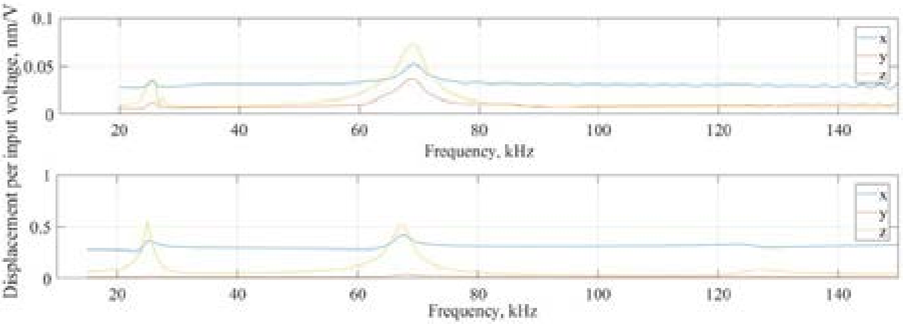

Figure 9: Comparison of experimental (up) and numerical results (down) for piezoelectric element and alumina

5. Conclusions and further work

The frequency response function of a piezoelectric transducer with and without an alumina layer has been obtained: numerical and experimental results have been described and compared. First of all, it has been shown that there is a match of resonance frequencies in the two cases; secondly the trend of displacement is quite similar. On the other hand, the magnitude of displacement presents some inconsistencies: the reasons have been discussed in the section of comparison, such as the importance of exactly replicating the boundary condition in the experiments. Moreover, the presence of the gap of the electrodes introduces modifications in the mode shapes that need to be investigated.

These results can now be used to define an objective function to indicate useful design changes for the increase of the ultrasonic performance: parameters such as frequency response across the frequency range, amplitude of displacement, ratio of components of displacement, geometric layout, represent core points to be analysed. However such an objective function needs to take into account not only the response of the piezoelectric transducer, but also the interaction with the waveguide.

Thus, a series of experiments and numerical analysis have to be carried out to test design changes of the piezoelectric transducers and compare them with the current design. Amplitude of the generated signal, sensitivity to defects and directionality of the modes will be assessed and compared to provide an insight for industrial applications of the generation of guided waves.

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