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PARAMETRIC INVESTIGATION OF A TRANSDUCER FOR GUIDED WAVES APPLICATIONS

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Abstract

The use of dry-coupled thickness-shear piezoelectric transducers for the generation of ultrasonic guided waves in Non Destructive Testing is well established in industry. The control of guided waves can be supported by designing transducers that achieve a uniform excitation over frequency and contact area. It is necessary to control the wave modes generated such that only modes with characteristics useful for inspection are transmitted and received. Recent research has identified the need to improve the ultrasonic performance in terms of amplitude and signal-to-noise ratio of guided waves via the miniaturization of the transducers. The influence of the geometry of the transducer on the generation of guided waves needs to be investigated. It is well known that the geometry of the transducers influences the normal modes of the ultrasonic transducers, which in turn can influence their ability to excited ultrasonic guided waves. However, the influence of transducer geometry on ultrasonic performance is still not completely understood: mode coupling and the presence of satellite modes might be detrimental for the generation of guided waves. These requirements drive the testing of design changes in terms of geometry and shape of the electrodes to improve the ultrasonic performance of the aforementioned transducers. The transducer is analysed both numerically (by Finite Element Analysis) and experimentally (with Laser Vibrometry) to offer a characterisation of existing piezoelectric elements. It is shown that a change in the actuation area of the transducer leads to a significant difference in the ultrasonic output.

1. Introduction

The need to assess the structural integrity of pipelines, storage tanks and various other structures in industry has been of interest both to academic and industrial institutions for quite a long time. In the recent decades long range ultrasonic guided wave testing has been experiencing a growth both in theoretical studies and practical applications. The method is based on the generation of guided waves travelling along the boundary of the inspected structure: the reflected wave bouncing back to the emitting point can then be interpreted to assess whether a potential flaw exists in the structure (1).

There are a variety of methods to excite guided waves, the most common being piezoelectric transducers and electromagnetic acoustic transducer (2, 3). Alleyne and Cawley developed a system comprising dry-coupled thickness-shear piezoelectric transducers able to generate longitudinal modes in a pipe (3). Those transducers inserted in arrays were later proved to be capable of inspecting other structures (4). The authors also demonstrated that the ultrasonic output increases with the force applied to the transducers: Engineer further demonstrated that the frequency response can change with varying coupling force. (5). Marques studied array designs for plate inspection and demonstrated possible enhancements when the objective is to excite the first shear horizontal mode in a plate-like structure. Even though he demonstrated that successfully, he also predicted through modelling that a denser array built with smaller transducers than he had available could achieve better results (6).

Thus, a correlation of the geometry of the transducer to the ultrasonic output becomes crucial: to the best of the author's knowledge, only Lowe has correlated the influence of the geometry to the behaviour of the transducer when it is functioning in receiving wave modes (7). However, a quantitative indication of how mode proportionality changes with the geometry is missing. Some indications of this change in a plate are analysed both numerically and experimentally in this paper.

2. Thickness-shear transducers

2.1 Current design

The transducer studied in the paper comprises an assembly of three main components bonded together: a thickness-shear transducer, an alumina plate and a backing mass of stainless steel.

The piezoelectric element is a ceramic, PZT 5A. As a thickness-shear element, the imposition of an electric field normal to the polarization axis induces a shear stress to the specimen (8): the material is polarized along its length. The dimensions of the element are 13x3x0.5 mm. The alumina layer is used to prevent the mechanical failure of the material, given the forced dry contact between the transducer and the surface of the waveguide. The geometrical dimensions are the same as those of the piezoelectric transducer. As a third element, a block of stainless steel is used as a backing mass to increase the flexural stiffness of the material and to provide an appropriate distribution of pressure on the piezoelectric element.

The electrical contact to the piezoelectric element is provided through plated electrodes with one wrapped around from the bottom surface to the top (9): The transducer and its imported FEM assembly can be seen in Figure 1.

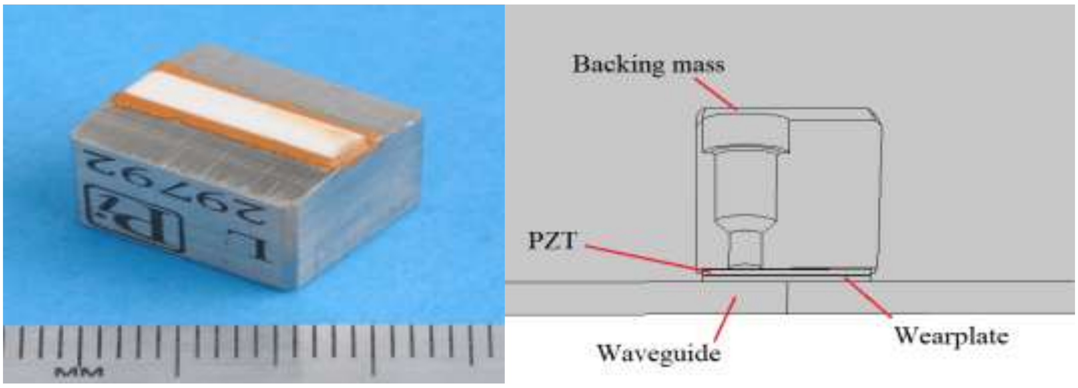

Figure 1 Picture of the backing mass with in evidence the layer of alumina (left) and of the imported design in COMSOL Multiphysics (right).

3. Numerical analysis

3.1 Introduction

The finite element method is one of the most powerful and developed ways to analyse the ultrasonic generation of guided waves when taking into account the specific geometry of the transducer, and has been shown to validate well against experimental results (6-7): the chosen software was the commercial software COMSOL Multiphysics (10).

3.2 Description of the model

A full 3D model was created with COMSOL to analyse both the generation of Lamb and shear horizontal waves in a circular steel plate. The transducer was placed on the centre of the plate and the receiving points were set at the edge of the plate. The transducer under consideration was the transducer with the wrapped around electrode.

The chosen study was a time domain transient study with the solid mechanics module, the excitation signal being a 5 cycles, Hann windowed burst with a centre frequency of 90 kHz. The excitation force was applied as a boundary load on the surface of the piezoelectric element. The plate was of 0.4 m radius and 3 mm thickness. Before starting the computational model, the software Disperse was used to understand which modes could be excited in the frequency of interest (11). The dispersion curve predicts which modes exist and at what velocity for a particular range of frequency-thickness products. The typical range of excitation of the transducers previously described is 20-120 kHz. In this 3mm plate over that frequency range, the only excitable modes are the fundamental symmetric and asymmetric modes (S0 and A0) Lamb modes and the fundamental shear horizontal mode (SH0).

It is well known that thickness-shear transducers generate Lamb waves along the axis of vibration, in this case the length, while the shear mode is generated on the perpendicular axis (7). For convention, the axis of excitation (along the longitude) is defined as the x axis of vibration. Due to the symmetry of the problem, only half of the waveguide was simulated numerically, by imposing a condition of symmetry longitudinally on the transducer and on the waveguide. For the mesh tetrahedral elements were used and the mesh was refined in order to achieve the recommended number of eight elements per wavelength, in order to sample properly the excited waves across the waveguide (12).

2.2 Numerical results

At the frequency of interest, 90 kHz, the fastest mode is S0, which is expected to arrive at 74 μs at a distance of 0.4 m, according to the calculations to obtain the time of arrival (14). The asymmetric mode A0 should then arrive at 153 μs while SH0 should arrive at 125 μs. An example of the wave propagation pattern can be seen in Figure 2 where the S0 and SH0 mode are clearly identified.

The numerical model appears to be able to predict the propagation of guided waves in a structure. As far as the symmetric and asymmetric modes are concerned, the results can be seen in Figure 3 where the data are normalized to the mode with the higher amplitude, i.e. S0.The receiving point is along the waveguide, parallel to the axis of the excitation. The normalization is obtained by dividing every component of displacement to the highest, which in this case the in-plane of the S0.

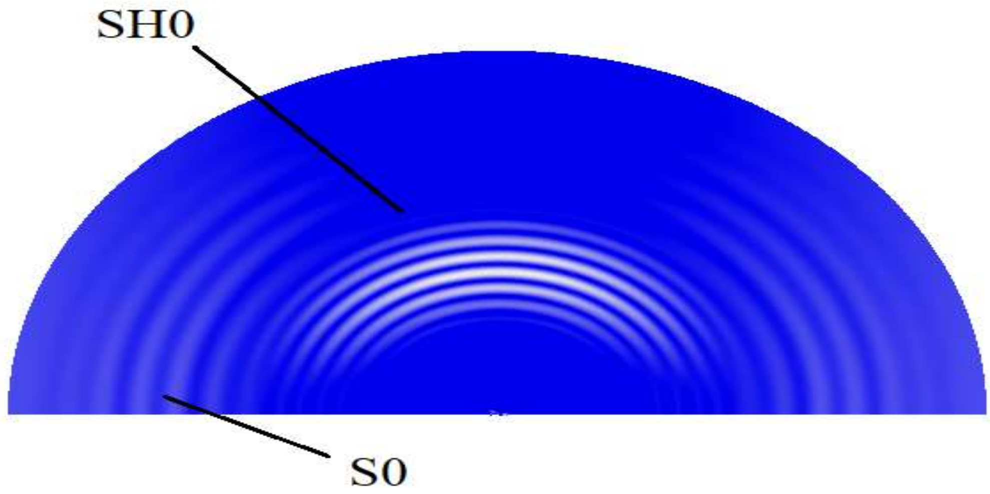

Figure 2 Wave propagation at 80 μs for half a waveguide: the colour scale represents the amplitude of displacement. The transducer is inserted in the centre of the plate. Note that S0 and SH0 are propagating on a direction parallel and perpendicular to the exciting transducer.

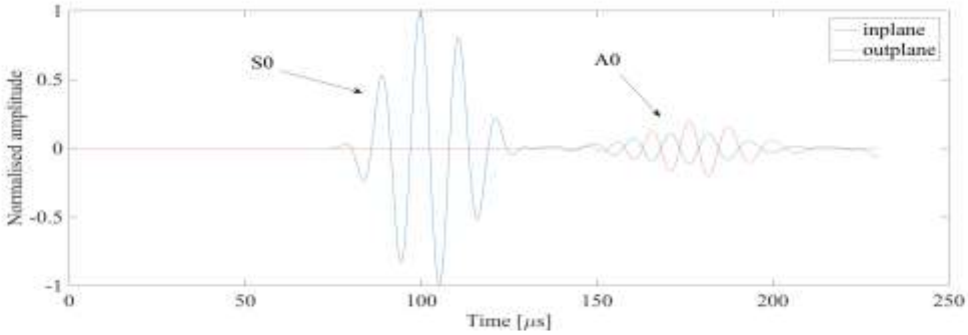

Figure3 Plot of computed normalized displacement on a point parallel to the axis of excitation of the standard transducer at the frequency of 90 kHz. In plane and out of plane are in blue and orange, respectively.

As expected, at this frequency, the displacement pattern for S0 is mainly in plane, while the A0 burst presents both in and out of plane components in antiphase: also, as the A0 is affected by dispersion, the mode appears as stretched. The capability obtained with the previous model was then extended to predict how changing the surface of excitation can change the ultrasonic response. A similar model to the one presented above was implemented by removing the configuration of the wraparound electrodes, so that a boundary load was inserted along the complete top face of the transducer. Thus the actuation area was completely covering the top surface of the transducer. The excitation signal, type of load and mesh were not changed.

The numerical results for this different model in regards to the propagation of Lamb modes on the same direction of propagation are shown in Figure 4. Again, data were normalized to the mode with higher amplitude, S0. It is clearly seen that in comparison to the previous result the proportionality between S0 and A0 is changed, because in comparison to the previous case the amplitude of S0 is reduced. As a reason for the diminution of S0, it is suggested that a larger actuation area increases the influence of the backing mass on the vibration pattern: the mass would then diminish the in-plane component of motion. By comparing the results of Figure 3 and 4 it is evident how a small change into the design leads to a considerable difference in the generation of guided waves.

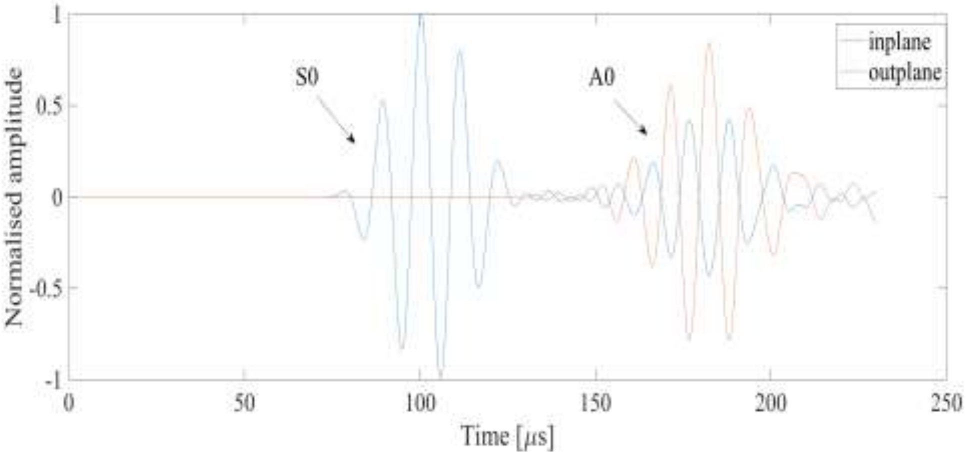

Figure 4 Plot of computational normalized displacement on a point parallel to the axis of excitation of the modified transducer. In plane and out of plane are in blue and orange, respectively.

3. Experimental analysis

3.1 Introduction

The numerical results shown in section two require experimental validation. Many authors have proven that good agreement is found between numerical and experimental findings when a vibrometer is used (13).

The Vibrometer emits a laser towards a target point on a surface and surface vibration at that point modulates the backscattered light, which in turn is detected by the vibrometer. The type of instrument used was a Polytec 3D Scanning Laser Vibrometer PSV-400-3D-M.

As a waveguide, a 2x2x0.003 m steel plate was chosen and the radius of the scanning area was 0.4 m around a transmission point, as was the case in the numerical analysis. The reason to employ such a large plate lies in the importance of avoiding any reflection of the guided waves coming from the edges of the plate. The waveguide is shown in Figure 5. The propagation of the waveguide was measured on 38 receiving points around the circumference: on these points thin adhesive retro-reflective film was applied to enhance the detection of the backscattered light by the vibrometer. As an excitation signal, a 5 cycles Hann windowed burst with a centre frequency of 90 kHz was used. As a function generator the commercially available system Teletest Focus+ was used (5). Due to the necessity to guarantee a force coupling between the waveguide and the transducer a loading device similar to (7) was deployed. The coupling force was 250 N.

3.2 Experimental results

In Figure 6, the experimental symmetric and asymmetric Lamb modes measured along the axis of vibration are presented. Both the in-plane and out-of-plane component of motion are presented: data are normalized to the maximum value of displacement to offer a valid comparison to the numerical results.

As far as the time of arrival is concerned, the inspection of experimental results shows that S0, the faster mode, arrives at 73 µs, while in the numerical results it arrives at 74 µs: on the other hand, A0 mode arrives at 151 µs in the experiment and at 153 µs in the simulations respectively. Thus, it is confirmed that the numerical model is able to predict with good approximation the time of arrival.

In regards to the proportionality between in-plane and out-of-plane motion in the experiment, some differences are notable. As a matter of fact the out-of-plane component of motion is remarkably stronger for the asymmetric mode in the experimental results, when compared to the numerical case with the standard electrodes.

It is suggested that the reason for this mismatch lie in the capability of the vibrometer, which is presents a higher signal to noise ratio for the out-of-plane motion. On the other hand, it is possible that the real behaviour of the transducer is not precise enough and further analysis is required, both in terms of the coupling force (and its distribution), which is neglected in the model and the form of excitation (mechanical boundary load).

Figure 4 Picture of the waveguide used for vibrometry studies, 2x2x0.003 m steel plate

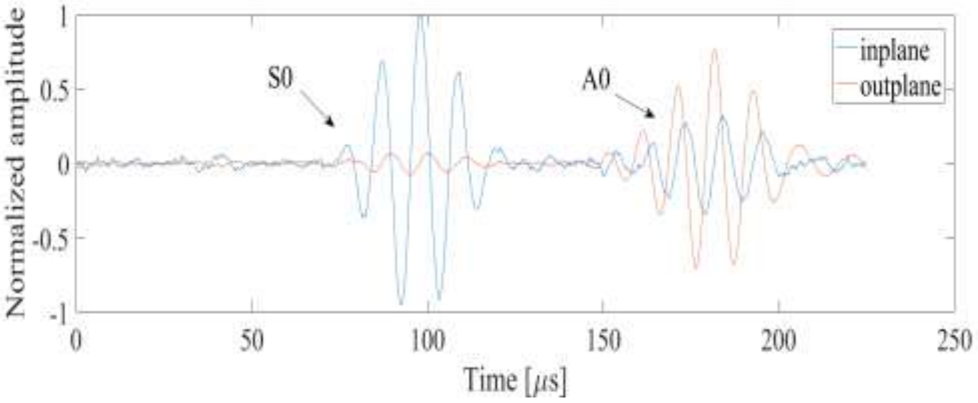

Figure 5 Plot of experimental normalized displacement on a point parallel to the axis of excitation of the modified transducer. In plane and out of plane are in blue and orange, respectively.

4. Conclusions

It has been shown that the complete assembly of a dry coupled thickness-shear transducer can be fully modelled and the time of arrival of Lamb modes match both numerically and experimentally. Some differences are found in the proportionality between the in plane and out of plane displacement in the experimental and the numerical case, which could be attributed to the limitations of the current equipment.

Furthermore, it was demonstrated that even a small design change in the actuation area of the transducer lead to a considerable change into the relative amplitudes of the excited guided waves. The sensitivity of the actuation area to the excitation of the symmetric mode was found. To the best of the authors' knowledge this result has not yet appeared in the literature for this specific transducer.

The model here explained will then be extended to a full electromechanical model inserting the voltage and a comparison with the ideal mechanical case will be carried out, to discuss whether any change arise and extended to various transducer design to predict their behaviour and offer practical recommendations for their manufacturing, in order to achieve greater mode control

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