Characterisation of the vibration of an ultrasonic transducer for guided wave applications

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Abstract. Dry-coupled thickness-shear piezoelectric transducers are typically used to excite guided waves in plate-like or tubular structures in the frequency range of 20-150 kHz. The dispersive behaviour of guided waves and the excitation of unwanted wave modes require a precise tuning of the excitation frequency to facilitate effective inspection. A natural frequency analysis of a typical piezoelectric transducer has been performed to identify the shape of vibration in the frequency range indicated. Moreover, an experimental analysis of the vibration of the piezoelectric element through a scanning laser Doppler Vibrometer has been conducted. The numerical and experimental results agree in indicating no longitudinal mode is present up to 94 kHz. Experiments also has shown that the higher the frequency the higher the longitudinal component of displacement.

Keywords: Piezoelectric Transducers, Guided Waves, Laser Vibrometer, Natural Frequency Analysis

1 Introduction

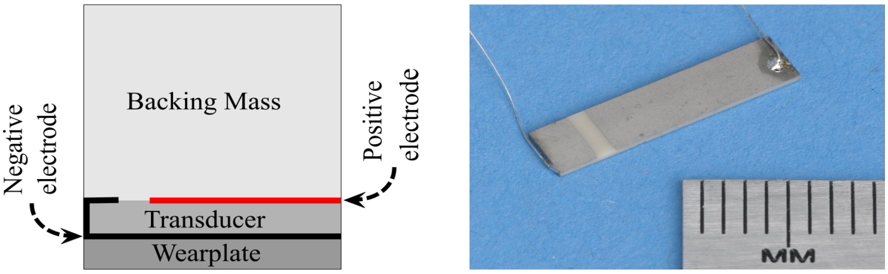
1.1 Industrial motivation of the project

In the last twenty years, a method known as ultrasonic guided wave testing has found its area of application within the field of non-destructive testing [1], i.e. the transmission of ultrasonic guided waves over relatively long distances (often tens of meters) in objects whose geometry forms a waveguide. The ultrasonic guided waves travel along a fixed boundary (such as the wall of a pipe). Therefore the wavelength of the guided wave must be comparable to the thickness of the structure. It is typical to make use of frequencies in the range of 20 to 150 kHz, where the generation of guided waves is most commonly obtained through piezoelectric coupling. In this study the focus will be on the piezoelectric transducer and its characterisation in terms of vibration, a first step towards a long term goal, which is the miniaturisation of the transducers. Section 1.2 has a brief background, the numerical results of a finite element prediction are provided in section 2, with corresponding experiment measurements from a laser vibrometer in section 3.

1.2 Guided waves and piezoelectric transducers

Alleyne and Cawley were the first to use dry-coupled thickness-shear transducers to generate guided waves [1]. The mechanical resonance of these dry-coupled transducers for guided wave applications was later studied by Engineer [2], who proved experimentally how changing the clamping force on the dry-coupled transducers shifts the resonance of the transducers.

Subsequently, Marques used thickness-shear transducers in plate-like structures. He showed that optimal ultrasonic output indicated by his simulations could not be obtained experimentally due to the relatively large size of the transducers limiting the array layout [3]. Thus, a miniaturization of the transducer is highly desirable. A miniaturization requires as a first step the complete characterization of the transducer as an electromechanical device. The numerical and experiment results presented in this publication regard just the piezoelectric material, shown in Fig 1 (b).



(a) Cross section of the assembly (b) Piezoelectric transducer

Fig. 1: Cross section of the assembly (left) and picture of the piezoelectric transducer (right)

2 Numerical Modelling

2.1 Methodology

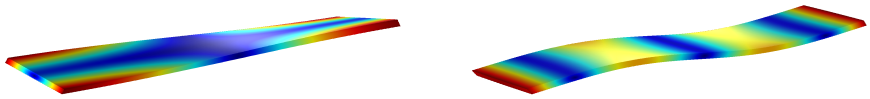
The use of finite element analysis (FEA) to solve thickness-shear transducer problems is well documented in the literature [4]. In this study, the natural frequencies and mode shapes of a piezoelectric transducer are predicted to understand in which frequency region the transducer should be tuned; since it is desired that the thickness-shear transducer should only create in-plane motion, the frequency must be tuned where the out-of-plane component is low.

The FEA software COMSOL was employed to mode both the natural frequencies of the piezoelectric element and the piezoelectric attached to a wearplate, consisting of 15167 elements and 30514 of free tetrahedral type respectively, with free-free boundary conditions. The analysis in COMSOL produces eigenvalues and eigenvectors showing the natural frequencies and corresponding mode shapes in the frequency range 20-150kHz. Note that the material is polarized along the longitudinal axis [4]. The material properties of the thickness-shear transducer and the wearplate are provided by the manufacturer, PI Ceramic.

2.2 Numerical Results

It is well known that various eigenmodes can arise in the calculation of the eigenfrequencies of a structure. Although not all of them will be significantly excited in a forced excitation, the natural frequency analysis is a first step to identify the potential natural motion of the structure. For example, for an element polarized along the horizontal axis, the application of an alternating voltage would lead to a symmetric stress pattern along that axis, hence the torsional mode would be unlikely to be excited at high amplitude.

Fig. 2 shows the mode shapes corresponding to the first two natural frequencies. The analytical indication [5] and the numerical calculation show that no thickness-shear resonance is to be found in the range of operation. However, as suggested by [2] and by the comparison of natural frequencies of Table 1 a shift of natural frequencies is likely to happen when the whole assembly is considered.



(a) First torsional mode, n = 1 (b) First flexural mode, n = 2

Fig. 2: First two eigenshapes of the piezoelectric element calculated with Comsol

Table 1: Table of first four natural frequencies

Frequency order	Frequency of piezo element [Hz]	Wearplate added [Hz]
n = 1	20375, first torsional	25224, first flexural
n = 2	20619, first flexural	62964, first torsional
n = 3	38987, first shear horizontal	67897, second flexural
n = 4	40242, second flexural	84111, first shear horizontal

3 Experimental analysis

In order to have confidence in the finite element predictions, and the subsequent response shapes, an experimental validation test was performed, to obtain the response frequencies and amplitudes of a PZT strip when an alternating voltage is applied.

3.1 Methodology

Measuring the velocity of the active surface of a transducer often requires the use of a non-contact technique to avoid any interaction between the measuring equipment and the transducer, especially for small, lightweight structures such as this PZT element. One of the most successfully applied techniques is laser Doppler vibrometry (LDV), which is capable of detecting the Doppler frequency shift of an infrared light back scattered from the surface of a specimen in motion.

The Laser Vibrometer PSV-400-3D-M used in this experiment is composed of three scanning heads each capable of measuring one component of surface velocity. The velocity is measured over a grid of points defined on the upper surface of the piezoelectric element. The measurement over the grid is covered by repeated measurements where the excitation was performed for the measurement of each point separately. A Teletest Focus system was used as a waveform generator to drive the transducer into vibration and to trigger reception by the vibrometry measurement [6].

To cover a relatively wide excitation bandwidth, a chirp signal was used as the input signal for the transducer, which consists of a sinusoidal signal with a linear increase in frequency over time (between 20-150 kHz). The amplitude of the voltage was 250 Vpp, spanning for 500 ms. It is well known that in the real application there is no transducer in free air, that is every transducer must be attached to the surface of the object being inspected. However, since it is well known that any mechanical coupling changes the response of the ultrasonic transducer [2], the transducer was attached to a polystyrene foam.

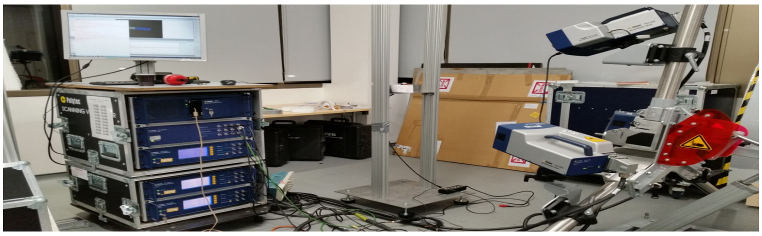
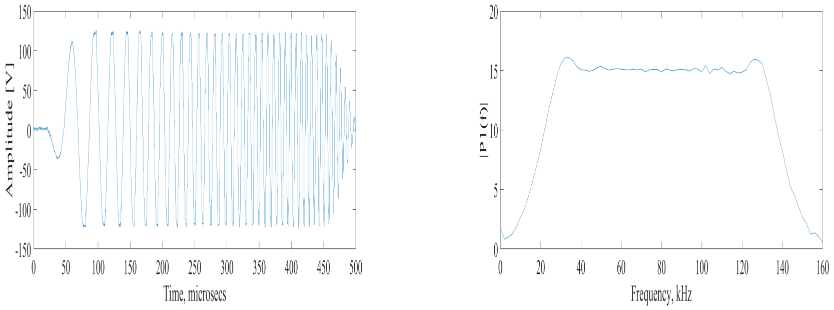


Fig. 3: Picture of the experimental setup.

3.2 Experimental results

The surface displacement plotted against excitation frequency is shown in fig 5. Interestingly, it is shown that in regards to frequencies up to 60 kHz the higher component of motion is the z-component, which is the undesired out-of-plane component. For the higher frequencies the longitudinal component (the x-component) becomes higher. However this component is still undesirable because the excitation of the surface results is not uniform.



(a) Amplitude of the signal (b) Fast Fourier Transform

Fig. 4: Plot of the chirp signal and its Fast Fourier Transform

This trend of frequencies is confirmed by the natural frequencies analysis: as a matter of fact the first longitudinal resonance does not appear until 91 kHz. Thus, the modes actually excited in the range of applications represent modes which need to be avoided. As far as the mode shape is concerned, in Fig. 6 it is shown as an example the shapes at the resonance frequency for 22 kHz and 39 kHz. The first excited resonance is the first flexural resonance and the second one corresponds to the second flexural resonance. These results confirm the validity of the numerical calculations.

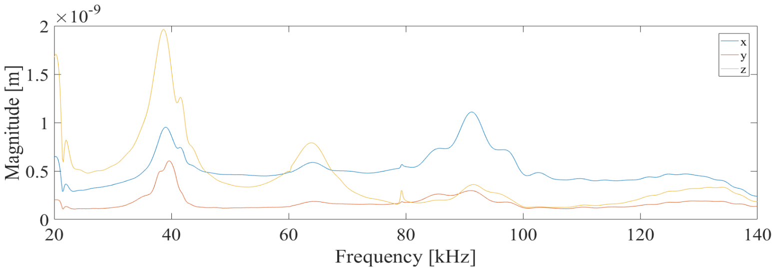


Fig. 5: Plot of the three components of displacement as a function of frequency.

4 Conclusion

It has been shown that a natural frequency analysis can be used to predict the resonance of a piezoelectric material. This prediction has been confirmed experimentally by the analysis with the PSV-400-3D-M laser scanning vibrometer. Moreover, the presence of the wearplate shifts the position of the natural frequencies. Not all the modes calculated numerically appear in the experiments.

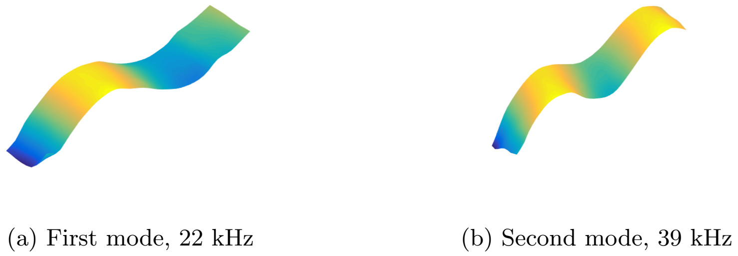

(a) First mode, 22 kHz
(b) Second mode, 39 kHz

Fig. 6: Plot of the experimental shape of the upper surface

Therefore there is a matter of mode excitability which needs to be carefully investigated. Since the electrical load is uniform across the width, it is expected that no torsional and shear horizontal modes are excited. In the next step of research the experimental analysis will be compared with a numerically computed forced excitation model. Moreover, both the forced numerical and experimental interaction of the piezoelectric element and its alumina wearplate will be analysed.

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References

1. Lowe, M. J. S., Alleyne, D., N., Cawley, P.: The excitation of Lamb waves in pipes using dry-coupled piezoelectric transducers. J. NONDESTRUCT. EVAL. 5.1, 11–20 (1996)
2. Engineer, B.A.: The mechanical and resonant behaviour of a dry coupled thickness-shear PZT transducer used for guided wave testing in pipe line. Diss. Brunel University, 2013.
3. Marques, H., R.: Omnidirectional and Unidirectional SH0 Mode Transducer Arrays for Guided Wave Evaluation of Plate-Like Structures. Diss. Brunel University, 2016.
4. Benjeddou A., Trindade M. A., Ohayon R. A unified beam finite element model for extension and shear piezoelectric actuation mechanisms. J. INTEL. MAT. SYST. STR. 8.12, 1012–1025 (1997)
5. Aurelle, N., Roche, D., Richard, C., Gonnard, P. Sample aspect ratio influence on the shear coefficients measurements of a piezoelectric bar. In: Applications of Ferroelectrics, 1994. ISAF'94., Proceedings of the Ninth IEEE International Symposium on pp. (162–165) (1991)
6. Mudge, P. J. "Field application of the Teletest long-range ultrasonic testing technique." Insight (2001).