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AN INVESTIGATION OF ULTRASONIC TRANSDUCER LOADING ON A WORKPIECE

Marco Zennaro
Loughborough University
Loughborough,
LE11 3TU, United Kingdom

Alex Haig
Eddyfi,
Granta Park
Cambridge,
CB21 6AL, United Kingdom

Dan J. O'Boy
Department of Aeronautical and Automotive Engineering
Loughborough University
Loughborough,
LE11 3TU,
United Kingdom

Stephen J. Walsh
Department of Aeronautical and Automotive Engineering,
Loughborough University
Loughborough,
LE11 3TU,
United Kingdom

ABSTRACT

Arrays of dry-coupled thickness-shear transducers are often employed in the guided wave sector to inspect pipelines and plate-like structure. The dry coupling permits to dismiss any coupling material between the transducer and the waveguide, but as a drawback a preload must be applied on the transducers to guarantee an effective coupling between the two surfaces. Although the influence of the preload on the natural frequencies is studied in the literature, the frequency response function of a transducer relating the input voltage to the displacement output is not present in the literature. Moreover, the distribution of force on the backing mass and the effect of the preload on the uniformity of vibration of the transducers are still missing. A natural frequency analysis and a forced analysis are then computed numerically with finite element analysis to quantify the influence of the preload on a thickness-shear transducer. Furthermore, these results are compared with experimental results obtained with a Laser Vibrometer. It is then shown how the geometrical layout of the transducer coupled with the preload influences the vibration of the transducer.

INTRODUCTION

The inspection of specimens such as pipelines and tanks for their structural integrity is one of the key challenges for safety, in particular in terms of reliability and practicability. In regards to these two requirements, one of the most used methods is the generation of guided waves, defined as waves travelling along the boundary of the structure (1), to be reflected from boundaries and detected. Guided waves can be generated in a variety of modes, the most common being piezoelectric transducers. Thus, the efficiency of the inspection is strictly correlated to the excitation of the piezoelectric transducers and to its consequent mechanical output generating the requested guided wave.

Alleyne and Cawley (2) successfully tested an array of thickness-shear transducers mounted on a pipe: the ultrasonic response was coherent with the longitudinal mode they aimed to generate. However, since they were also interested in generating shear modes, they preferred to have the transducer in dry coupling condition (solid-to-solid interface), instead of using a coupling liquid. The introduction of the dry-coupling permitted also to enhance the practicability of the system. However the dry-coupling required the use of a coupling force to enhance the amplitude of the signal output.

Engineer (3) then studied the mechanical and resonant behaviour of dry-coupled transducers: he found out that the dry-contact of the transducer and the waveguide follows the Hertzian contact law up to a threshold of 300 N. Moreover, he found out that the surface velocity of the transducer changes with the varying force. The influence of the preload on the ultrasonic output of the transducer was also confirmed by Lowe et al (4).

To the best of the authors' knowledge no other studies are available concerning how the coupling force influences the structural response of the transducer: in particular, the frequency response function of the transducer when the voltage is applied is missing; moreover, the distribution of force on the backing mass has not yet been computed. Only the natural frequencies of the transducer were computed by Engineer and compared to the experimental response of a transducer measured with a Laser Vibrometer. In the following paper the natural frequencies of a 'free air' (no mechanical boundary conditions) transducer will be computed and an experiment with the Laser Vibrometer will be performed to validate the results: moreover, the model will be extended to present the effect of a preload.

TRANSDUCER DESIGN

Assembly of the transducer

The transducer is composed of three elements, a piezoelectric transducer, an alumina wear-plate and a backing mass of steel.

The piezoelectric element is of the thickness-shear type, pertaining to the piezo-ceramic class PZT 5 A. For a thickness shear element, the interaction of an electric field normal to the polarization axis induces a shear motion in the specimen. In this particular case, the transducer is polarized along the length. The dimensions are approximately 13 x 3 x 0.5 mm. Since the piezoelectric element is a very brittle ceramic, an alumina layer is glued to the element to be directly in contact with the waveguide. The geometrical dimensions of the alumina layer correspond to the dimensions of the piezo-element. The piezoelectric element presents a particular electrode layout: to facilitate the electrical contact the negative electrode is wrapped around on the upper surface (5). Thus, the active area of the positive electrode is actually reduced from 13 to 10 mm. A cuboid of steel is then used as a backing mass to protect the piezo when the coupling force is applied and to make sure that the force is correctly distributed. The geometrical dimensions of the cuboid of steel are approximately 14 x 14 x 13.5 mm. The complete assembly of the transducer is shown in figure 1.

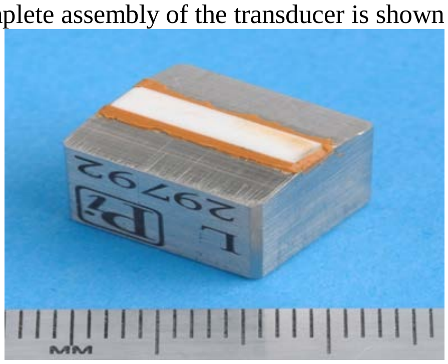


Fig. 1 – Picture of the full assembly of the piezoelectric transducer

NUMERICAL MODEL

Description of the model

The first model consists of the assembly of the transducer imported in the commercial finite element software Comsol Multiphysics with the Import Cad Module. Comsol was chosen for the capabilities in analyzing piezoelectric transducers (6). The two coupled physics were solid mechanics and electrostatics. At first the transducer was considered as not constrained mechanically to any surface: such case is referred as 'free air' transducer. The first study was a natural frequency analysis in the range 20-100 kHz, followed by a frequency domain analysis with an excitation of 15 V within the same range: the excitation was inserted on the upper surface of the piezoelectric element, where the positive electrode of the wrap around is present. The negative electrode of the piezoelectric element was considered as grounded.

In the case of the transducer connected with the waveguide, the presence of the waveguide was simplified for reasons of computation by reducing it to a plate of steel of 20 x 20 x 3.0 mm. To represent the presence of the waveguide, on the external surface of the plate a symmetry boundary condition was imposed. In this second case, before the two studies, a preload was inserted on the upper surface of the block to calculate the displacement and stress distribution due to the coupling. The results of the preload were defined as initial conditions for the natural frequency and frequency domain analysis.

In regards to the transducer with the waveguide, two cases were analyzed: a case where no upper force is applied and a case where a force of 250 N was applied. The first case was computed to understand the influence of the constraint of the block and the second to understand how the response function changes when the load is applied.

Results

The results of the frequency response function for the free air transducer will be presented in the experimental section, where the results will be compared to the experimental results. In this section the natural frequency of the first case will be discussed and compared to the second and third case: moreover, the frequency response function of the second and third case will be analyzed.

In Table 1 the natural frequencies in the range 20-100 kHz are shown. It is readily seen that when the transducer is not mechanically fixed, the first natural frequency is at 76.338 kHz. The presence of the plate considerably shifts the frequency. On the other hand the presence of the preload does not influence considerably the natural frequencies and minimal variations are found. This shows that the boundary condition created by including the waveguide is essential to consider when designing the transducer assembly.

As the backing mass isn't a uniform block due to the presence of an electrical cable, the force distribution is also not uniform over the wear plate. It would be expected that an uneven distribution of pressure would arise: such a phenomenon most likely will cause the ultrasonic output not to be consistent across the area of the ultrasonic transducer.

The out-of-plane component of displacement is plotted in figure 2: it is readily seen that the higher displacement is concentrated on the area of the body distant from the hole, while the other extreme of the body seems almost fixed. Thus, one would expect a moment of force to arise from such a displacement: moreover, the higher load would be experienced by the negative electrode area, which is not directly excited with a voltage.

Table 1 – Table of the natural frequencies of the transducer.

Eigenvalue case [1] [kHz]	Eigenvalue case [2] [kHz]	Eigenvalue case [3] [kHz]
	20.446	20.444
	27.501	27.5
	47.908	47.906
	54.668	54.666
	58.635	58.363
76.338	78.665	78.664
96.77	98.68	98.679

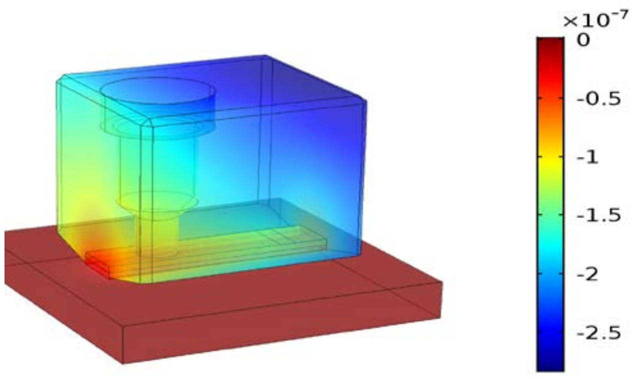


Fig. 2 – Out-of-plane (vertical in the picture) displacement originated by the application of a preload. The displacement in the bar is in m.

As far as the frequency response function is concerned, at first a lateral surface plot at the frequency of 30 kHz is plotted in figure 3 and 4, when no force is applied on the upper surface of the block.

In the first picture, it is readily seen that the lower part of the backing block is dragged by the motion of the piezoelectric transducer, while the upper part is moving in the opposite direction: clearly the negative motion is much stronger close to the piezoelectric transducer. But it must also be noted that the part of the piezoelectric element where the hole is inserted in represents the actuation area of the piezoelectric element. In regards to the second figure, it is noted how the out-of-plane movement is not symmetric and it tends to be much extended in the negative area, most likely for the presence of the block. This shows how the manufacturing considerations can lead to subtle changes in the desired output of the transducer. Indeed, if a purely in-plane or out of plane motion is required, then knowledge and control of how the force is applied is required to be known in advance.

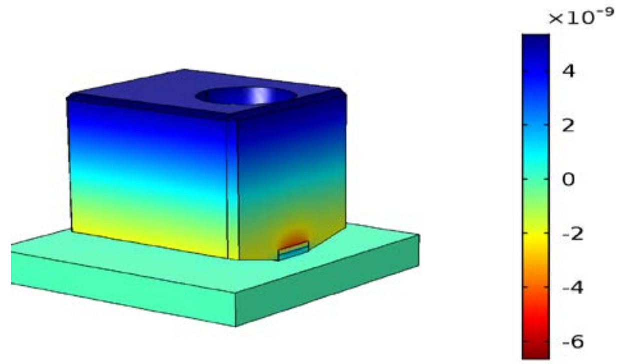


Fig. 3 – In-plane displacement calculated with the frequency response function at 30 kHz. The displacement in the bar is in m.

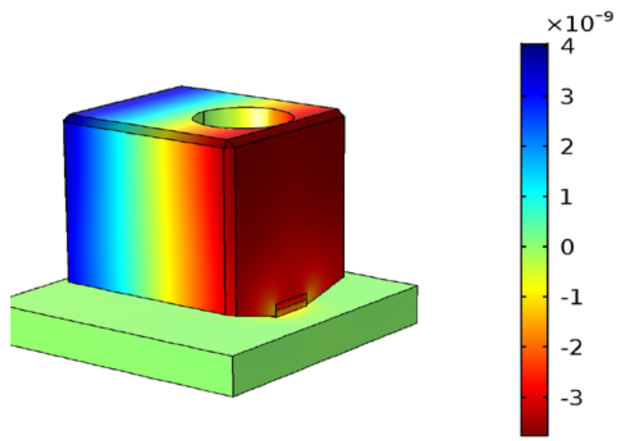


Fig. 4 – Out-of-plane displacement calculated with the frequency response function at 30 kHz. The displacement in the bar is in m.

The next step was then to analyze the same displacement plot when the preload on the upper surface is inserted. In figure 5 it is plotted the in-plane component of motion. It is readily noted that the displacement distribution on the backing mass is completed changed on the block and the interaction between the shear motion of the transducer of the preload brings all the body to move almost in one direction and only a small part (face of the transducer not shown in the picture) is moving in the opposite direction. Interestingly, the output of displacement in the pre-loaded case is higher than the previous case: hence, as the deformation is higher, the ultrasonic output will increase as indicated previously by Engineer (3).

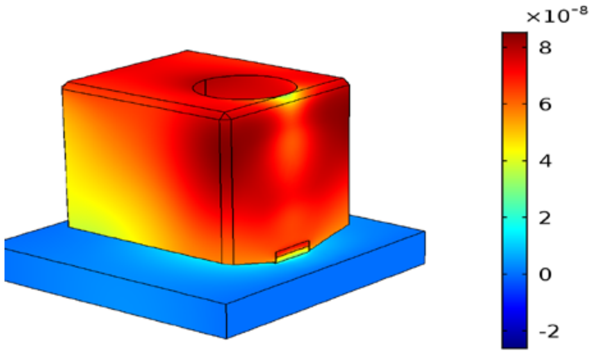


Fig. 5 – In-plane displacement calculated with the frequency response function at 30 kHz, in case of preload. The displacement in the bar is in m.

On the other hand the pattern of displacement in the out-of-plane case in figure 6 changes even more dramatically: as a matter of fact the backing block is experiencing a uniform movement in the negative direction and only when looking close to the transducer does it appear that the downward displacement is diminished, since it is counterbalanced by the thickness-shear movement at the edge. In comparison to the static case shown at the beginning of the section, the displacement is increased due to the movement of the transducer.

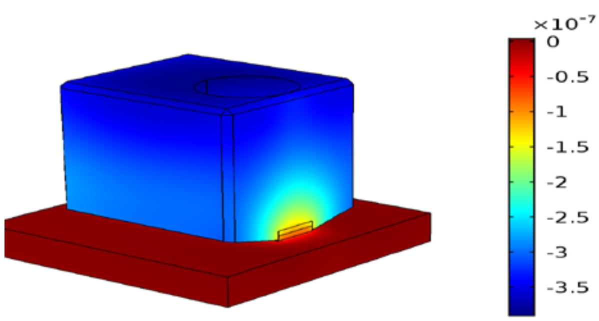


Fig. 6 – Out-of-plane displacement calculated with the frequency response function at 30 kHz, in case of preload. The displacement in the bar is in m.

Thus, it has been shown that the application of the force on the upper surface of the transducer can vary the displacement pattern generated. Even though experimental confirmation of the phenomenon is required, some interesting features of the ultrasonic transducer, such as the geometrical layout of the block can be further analyzed in terms of ultrasonic performance.

EXPERIMENTAL ANALYSIS

Experimental Method

An experimental validation of the first numerical modelling ('free air case') was conducted, since no analytical solution is possible for a free-free plate with the specific geometry and manufacturing considerations. One of the most effective methods to measure vibrations and wave propagation is Laser Vibrometry. A Polytec 3D Scanning Laser Vibrometer PSV-400-3D-M was used (figure 7). The three heads of the laser are used to measure the displacement of a moving surface (the transducer in this case).

The transducer was excited with a chirp signal in the range 20-120 kHz: the main reason to use the chirp signal was its capability to excite all the frequencies in the frequency range. As a function generator a Teletest Focus was used: the voltage was 250 Vpp, spanning for 500 ms. The excited signal captured with an oscilloscope is shown in figure 8.

As far as the surface of the transducer is concerned, it was chosen to measure the lateral face, since in a further measurement in contact with waveguide the bottom face would not be visible. The transducer block was attached on a surface without force or constraint.

Fig. 7 – Picture of the Laser Vibrometer.

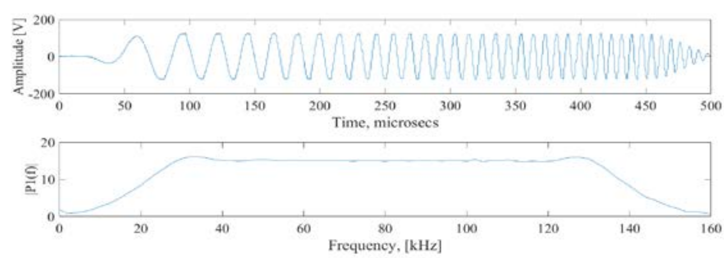


Fig. 8 – Plot of the chirp signal captured with an oscilloscope (top) and its frequency response function (lower).

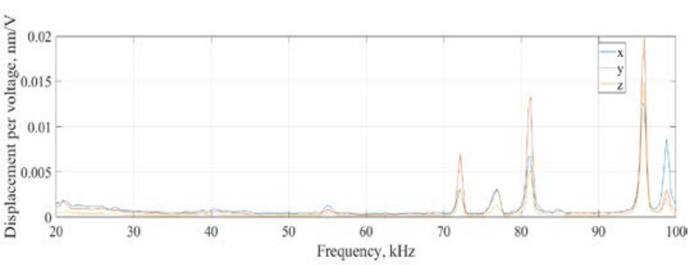
Experimental results

The natural frequency analysis indicated that only four dominant frequencies are present in the range of excitation, and two of them are due to non-standard geometry. Due to the size of the mass and to the results previously reported in the displacement output is expected to be even lower. Therefore experimental error and uncertainties could appear, since the limit of the Vibrometer is 2 nm.

The average displacement is shown in figure 9. In the range of excitation various resonances are found, some not coincident to the numerical calculation of the free air transducer: however the fact that more resonance appeared in the numerically constrained case indicate that even a small coupling influences the transducers, creating more resonances.

However it must be noted that the output is extremely low, therefore it becomes difficult to compare the numerical and experimental magnitude: therefore, only the numerical and experimental displacement pattern on the lateral surface is shown. As an example the out-of-plane displacement for the experimental resonances at 81 kHz and 95 kHz is compared with the two numerical resonances for the free air shown in table 1. The two shapes show clearly the influence of the hole in creating additional resonances to the transducer. Previous work conducted by Engineer (3) has shown the presence of a resonance due to the electrical access hole, while according to the numerical and experimental results in this paper, two resonances due to this peculiar geometry are present.

Thus, following the comparison of numerical and experimental results it can be concluded that a model has been produced capable of predicting the resonance frequencies and the displacement pattern of the transducer in an acceptable range. It has been shown that the geometry of the backing mass is influencing the frequency response function, and spurious modes are likely to be introduced in the guided wave generation.



.*Fig. 9 – Plot of the experimental frequency response function*

The eigenfrequencies found in the numerical analysis do not exactly match with the experimental results, however, they are close and may reflect exact inaccuracies in the boundary conditions or loading. However, they are sufficiently close to allow trends to be investigated.

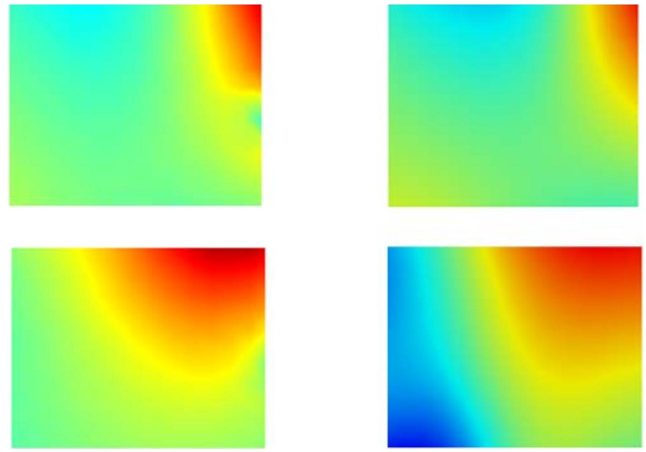


Fig. 10 – Experimental (left) and numerical (right) plot of the out-of-plane displacement for the two resonances at 81 and 95 kHz

CONCLUSION

A natural frequency analysis and a frequency response function for a transducer in three different numerical cases has been carried out. A free-air transducer, a constrained transducer and a constrained transducer with a static pre-load were analyzed. It has been shown that when the transducer is constrained to a block, many more resonances frequencies appear which were not present previously in the frequency range of interest. Moreover, it has also been shown that the frequency response function considerably changes the displacement generated, and the movement of the block tends to overcome the displacement driven by the piezoelectric element.

The experimental analysis has confirmed the validity of the free air transducer analysis, and the peculiar geometry of the transducer was shown to influence the resonance frequencies. However, the experimental analysis has shown that more experimental resonances appear than calculated in the numerical case. Therefore, further investigation is needed.

The results here presented can now be used to quantify how the propagation of guided wave changes when the preload is applied on the transducer. Moreover, the geometry of the block requires further study to understand how to overcome the pressure distribution. Thus, either some work on the position of the hole could be tackled, or a parametric study on the geometrical parameters can be performed. Potentially this could include a variation of impedance with position along the wear plate.

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