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Finite element three-dimensional analysis of the vibrational behaviour of the Langevin-type transducer

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Abstract

The vibrational behaviour of the Langevin transducer is usually analysed using 1D Mason model which is valid when the lateral dimensions of the transducer are smaller than a quarter wavelength at the fundamental longitudinal resonance. In this work a 3D finite element analysis of the Langevin transducer's behaviour operating in the underwater sonar range of frequencies (30–140 kHz) is presented. Several samples with total length greater, comparable to, and smaller than the diameter of the transducer are analysed. For each sample, the resonance frequencies in the observed frequency range are computed and compared with those obtained experimentally from the measurements carried out using several in-house built prototypes. For the most important aspect ratios the resonance displacement distributions are presented and discussed. The results obtained permit to gain insight into the coupling phenomenon between thickness-extensional and radial modes and suggest that in practical applications transducers with diameters comparable to or greater than total length of the active stack can also be used. The trade-off between the efficiency and power handling ability for different designs is also discussed.

Keywords: Langevin transducer; FE analysis

1. Introduction

The Langevin transducer is widely used in a large variety of underwater and industrial applications [1–4] because of its relatively high low frequency efficiency. It has been largely analysed with the classical 1D theory [5–7]; however, this approach is able to describe only the thickness-extensional modes and therefore does not take into account the unavoidable lateral vibrations of both the ceramic and the loading masses. This theory is sufficiently accurate only when the lateral dimensions are less than a quarter of the longitudinal wavelength. However, geometrical dimensions of many practical transducers often demand a 3D description. For example, in ultrasonic metal and plastic welding, where high power generation is required, lateral dimensions are usually larger than a quarter of longitudinal wavelength and the influence of radial modes on the fundamental thickness-extensional mode cannot be neglected. On the other hand, if needed, bandwidth enlargements can be achieved by exploiting the coupling between thickness-extensional and radial modes [8,9].

In the present work a finite element 3D analysis of the vibrational behaviour of the Langevin-type transducer is presented. A commercial FE package is implemented for calculations. The analysed structure is composed of a piezoceramic disk, with diameter 20 mm and thickness 2 mm, and two identical cylinder-shaped steel masses with the same diameter as that of the disk. The frequency spectrum, i.e., the map of the resonance frequencies, is computed varying the lengths of the cylinder-shaped masses between 1 and 32.5 mm. The analysis of the spectrum permits to identify the regions where coupling between thickness-extensional and radial modes exists. FEM's results are compared with measurements carried out on a series of manufactured prototypes. The discrepancies between simulations and experiments, due to the different continuity conditions at the interfaces between piezoceramic and masses, are highlighted and discussed.

Finally, the effect of the coupling between two modes, that occurs when their corresponding resonance

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frequencies come closer, is analysed by the observation of the modal shapes at the main resonance frequencies.

2. FE analysis

Fig. 1 shows the analysed Langevin transducer configuration; it is composed of a piezoceramic disk (PZT-5A by Morgan–Matroc [10]) with radius $a = 10$ mm and thickness $t = 2$ mm, which is poled along thickness and electroded on its flat surfaces, and of two identical steel-made cylinder-shaped masses (mass density $\rho = 7797\ \mathrm{kg/m^3}$, Young modulus $E = 20.15 \times 10^{10}\ \mathrm{N/m^2}$, Poisson ratio $\sigma = 0.3$), which have radius identical to that of the disk.

FE analysis was performed by using the commercial code ANSYS.

As the analysed transducer configuration was axially symmetric, a 3D analysis was performed by using 2D quadratic elements. The 2D axial symmetric model was validated by comparing its results with those obtained with a 3D model which uses hexahedral quadratic elements. Due to the excellent agreement, the 2D model was employed because computations are at least 2.5 times faster.

The structure was modelled by imposing the continuity of the displacements both in radial and in axial directions at the interfaces between piezoceramic disk and loading masses.

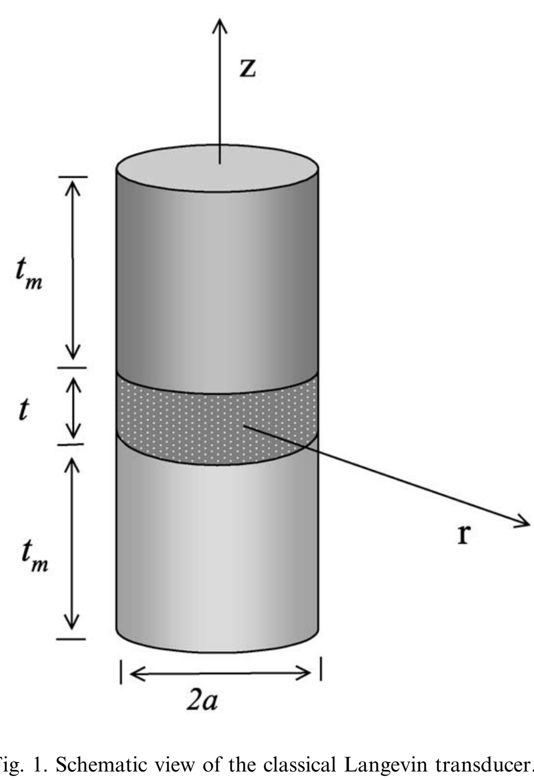

Fig. 1. Schematic view of the classical Langevin transducer.

In order to characterize the behaviour of the Langevin transducer for any aspect ratio, i.e., when the total length is greater, comparable to, or smaller than the diameter, simulations of structures with masses thickness varying from 32.5 mm down to 1 mm were carried out. For each sample, a dynamic analysis was performed and the resonance and antiresonance frequencies as well as axial and radial displacement amplitude distributions were computed for the first three resonance modes. In particular, the coupling regions were carefully analysed in order to investigate the influence of close modes on displacement amplitude distributions.

3. Experimental validation

Fig. 2 shows the frequency spectrum, i.e., the map of the resonance frequencies of the transducer, computed with ANSYS (black dots) up to 140 kHz. For comparison, the frequency spectra computed with the 1D thickness-extensional mode model [7] (solid curves T_1, T_2), as well as that obtained by experimental measurements (hollow circles) are also shown in the figure. The experimental results were obtained by measuring the electrical input admittance of 13 in-house built prototypes, which had the same piezoceramic and mass material and dimensions as those described in the previous section and mass lengths ranging from 2.5 to 32.5 mm, with step of 2.5 mm.

In the experimentally obtained spectrum, the diameter of the circles is proportional to the effective electromechanical coupling factor (k_{eff}), which is defined as [6]:

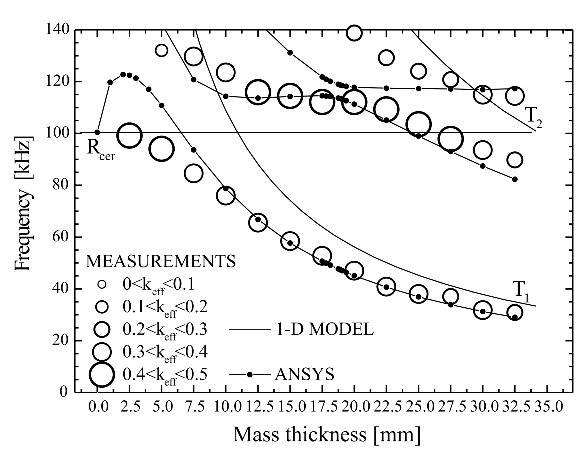

Fig. 2. The frequency spectrum versus the thickness of the loading masses. For the experimental data, the diameter of the circles is proportional to k_{eff}. T_1 and T_2 are the first two 1D thickness-extensional mode resonance frequencies, R_{cer} is the resonance frequency of the radial mode of the unloaded piezoceramic disk.

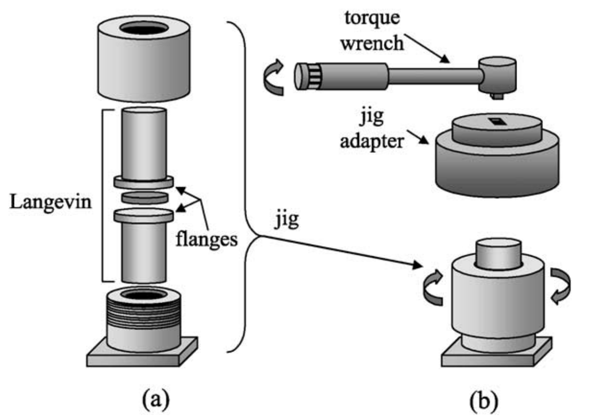

Fig. 3. (a) Exploded view of the transducer and of the jig; (b) the assembled structure, the accessory torque wrench and its jig adapter.

$$k_{\mathrm{eff}} = \sqrt{\frac{f_{\mathrm{p}}^2 - f_{\mathrm{s}}^2}{f_{\mathrm{p}}^2}}, \tag{1}$$

where f_{s} and f_{p} can be assumed to be the frequencies of maximum and minimum admittance, respectively.

The experimental results reported in Fig. 2 were obtained by applying to the manufactured samples a light pre-stress, just sufficient to ensure the mechanical contact between the piezoceramic and the masses. The pre-stress was accomplished with the jig shown in Fig. 3. The Langevin structure, whose masses are provided with flanges, was placed into the jig, composed of two threaded elements. By means of a jig adapter, a torque wrench was used to tighten the ceramic disk between the two masses, obtaining a good control of the pre-stress, which was applied only to the piezoceramic element. In order to minimize shear stresses during wrenching operations, a thin layer of grease was laid at the interfaces between piezoceramic and masses.

As can be seen from Fig. 2, the 1D model is able to predict resonance frequencies of the fundamental thickness mode T_1 only when the length of the transducer is much greater that its diameter.

As far as FE results are concerned, for mass thicknesses from 32.5 down to about 20 mm, the first two resonance frequencies increase when the mass thickness decrease, while the third mode resonance frequencies are nearly constant. Therefore, the first and second modes can be identified with the fundamental thickness mode and its first harmonic, respectively, while the third mode can be recognized as a radial mode. It should be noted that the resonance frequencies for this last mode are slightly higher than that of the pure radial mode of the unloaded piezoceramic disk, represented in the figure by the straight line R_{cer}.

For mass thicknesses from about 20 mm down to about 17.5 mm, the resonance frequencies of the second and third modes become very close and coupling between these two modes occurs.

For mass thicknesses from about 17.5 mm down to about 10 mm, the second mode may be recognized as a radial mode, while the resonance frequencies of the third mode rapidly increase beyond the range of the highest computed and measured frequency.

The first mode can be clearly identified with the fundamental thickness-extensional mode whenever mass thicknesses are greater than 10 mm. For further mass thickness reductions, the first mode couples with the second one and for mass thicknesses smaller than 5 mm, it may be considered a radial mode; its resonance frequency reaches a maximum value (at about the resonance frequency of the radial mode of the transducer) and successively decreases and tends to the radial resonance frequency of the sole piezoceramic.

From the comparison between numerical and experimental results, we observe a good agreement wherever the resonance frequencies of each mode are sufficiently far from those of other modes. On the contrary, in the regions where coupling between two modes occurs, experimental and numerical results follow different behaviours: numerical frequencies come closer than experimental ones. The reason for this disagreement can be attributed to the difference between the interface conditions imposed in the simulations and those achieved in the experiments. In fact, as aforementioned, the measurements were carried out by applying to each sample a very light pre-stress, and, furthermore, a thin layer of grease was laid at the interfaces between piezoceramic and masses. Consequently, this could lead to some lateral sliding, that is discontinuity of radial displacement at these interfaces, while in FE analysis the continuity of radial displacements was imposed.

4. Study of the vibrational behaviour

In order to investigate the evolution of the vibrational behaviour of the transducer, as well as the effect of coupling between modes, the modal shapes for several aspect ratios (total length greater, comparable to, or smaller than the diameter) were computed and plotted.

Fig. 4 shows the modal shapes computed at the first three resonance frequencies for the transducer with identical 32.5 mm loading masses (for comparison, see also Fig. 2). The lowest frequency mode (at 29 kHz) presents a clear piston-like motion and one nodal plane for the axial displacement. Therefore, it can be easily recognized as the fundamental thickness-extensional mode. The second mode (at 82.3 kHz) can be recognized as the first harmonic of the fundamental thickness mode because it clearly shows three nodal planes along z direction, and because the axial displacement is almost

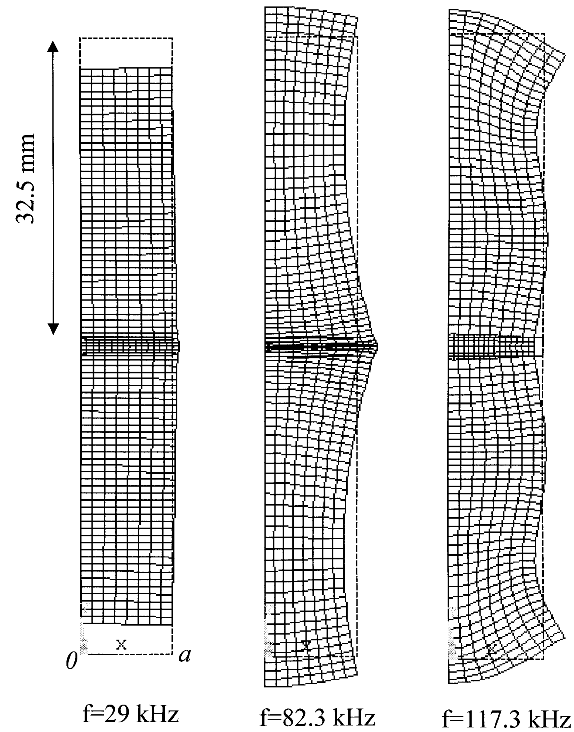

Fig. 4. Modal shapes of the first three modes for the transducer with loading masses of 32.5 mm.

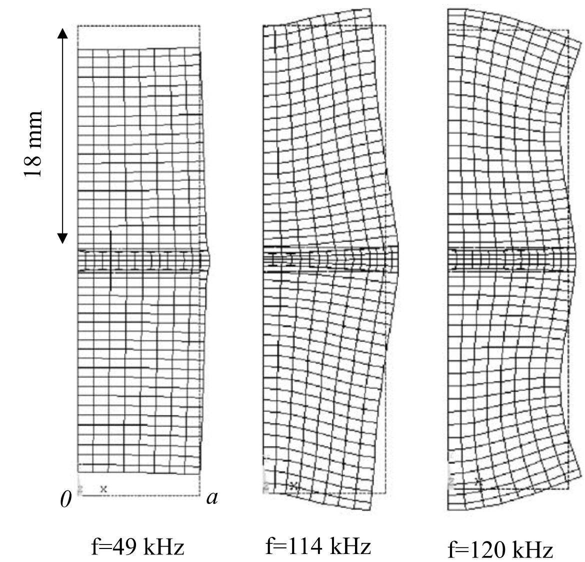

Fig. 5. Modal shapes of the first modes for the transducer with loading masses of 18 mm.

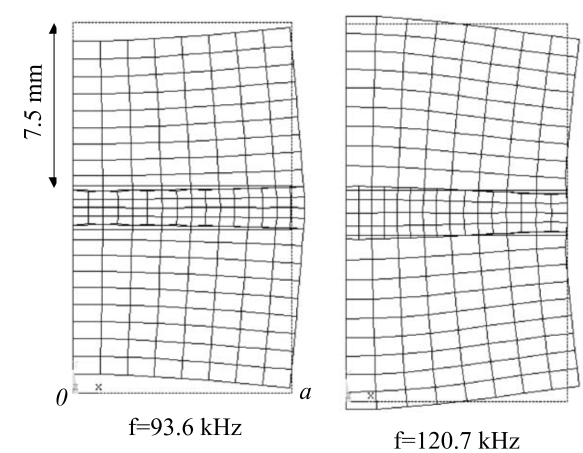

Fig. 6. Modal shapes of the first two modes for the transducer with loading masses of 7.5 mm.

flat at the end surfaces. As mentioned in the previous section, the third mode (117.3 kHz) is identified as a radial mode because its resonance frequency essentially depends on the radial dimension of the piezoceramic. It is higher than that of the pure radial mode because the loading masses constrain the radial motion of the piezoceramic and increase its stiffness. For this aspect ratio, this mode shows a node in the axial displacement at the end surfaces, and, therefore, it is unsuitable for practical applications.

Fig. 5 shows the modal shapes computed at the first three resonance frequencies for the transducer with loading masses of 18 mm in thickness. Also for this transducer the first resonance frequency (at 49 kHz) corresponds to the fundamental thickness-extensional mode. As can be seen from Fig. 2 the other two modes have very close resonance frequencies and are coupled. The third mode (at 120 kHz) has a modal shape similar to that of the third mode of Fig. 4, and therefore can be recognized as a radial mode, while the second mode (at 114 kHz), as a consequence of the coupling, presents a modal shape considerably different from that of an harmonic of the fundamental thickness mode.

The modal shapes of the first two modes of the transducer with loading masses of 7.5 mm are shown in Fig. 6. For this transducer the total thickness and the diameter are comparable and, consequently, the first mode (at 93.6 kHz) presents a modal shape that is a mixture between a thickness-extensional and a radial mode. Furthermore, the maximum axial displacement is comparable with the maximum radial displacement, which is achieved on the piezoceramic. Also for this aspect ratio, the axial displacement of the second mode (at 120.7 kHz) presents a node at the end surfaces.

Finally, Fig. 7 shows the modal shape of the sole mode (at 122.4 kHz) present in the observed frequency range for the transducer with loading masses of 2.5 mm in thickness. It is very similar to that of a pure radial mode. However, unlike the modal shapes of the other radial modes presented above, for this aspect ratio the axial displacement at the end surfaces has no nodes, and its maximum value is comparable with the maximum radial displacement.

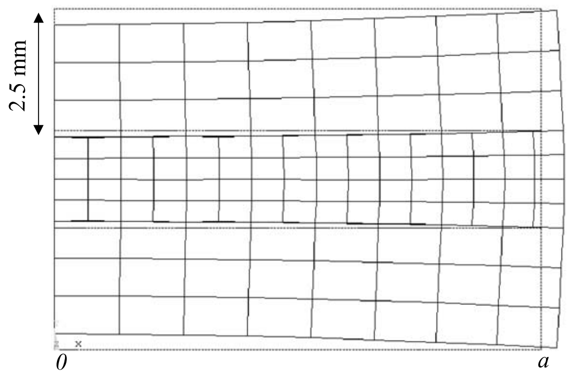

Fig. 7. Modal shapes of the first mode for the transducer with loading masses of 2.5 mm.

5. Conclusions

In this work, the vibrational behaviour of the Langevin transducer has been investigated by means of a FE analysis. The frequency evolution of first three resonance modes obtained by FE simulations for a wide series of aspect ratios has been compared with that achieved by experiments. A general good agreement, to within 5%, is observed except for the regions where coupling between two orthogonal modes exists. In these regions, due to the difference between the interface conditions imposed in simulations and those achieved in experiments, the resonance frequencies of two coupled modes are closer in simulations than in experimental results. The analysis of the modal shapes permits to identify the nature of the mode (thickness-extensional or radial) corresponding to each resonance frequency except in regions where two modes are coupled, where the shapes are mixed. For the analysed Langevin configuration, the radial mode can be easily identified because its resonance frequencies are constant and independent on aspect ratios. When the total length of the transducer is greater than or comparable to its diameter, the axial displacement of the radial mode presents a node at the end surfaces and therefore the transducer is unsuitable for practical applications. On the other hand, when the total length is smaller than the diameter and the radial mode corresponds to the first resonance frequency of the transducer, the axial displacement at the end surfaces has no nodes.

The present analysis has shown that, in principle, Langevin transducers with any aspect ratios can be exploited in applications, also when the diameter is comparable to or greater than the total length. In these last configurations, the high power capacity could compensate for the reduced efficiency with respect to a Langevin transducer with a high total length to diameter ratio at the same frequency.

References

[1] R.F.W. Coates, Underwater acoustic communication, Sea Tech. 35 (1994) 41.
[2] S.W. Or, H.L.W. Chan, V.C. Lo, C.W. Yuen, Dynamics of ultrasonics transducers used for wire bondings, IEEE Trans. Ultrason., Ferroelect., Freq. Contr. 45 (1) (1998) 453.
[3] J.A. Gallego, G. Rodriguez, E. Riera, C. Campos, F. Vazquez, V.M. Acosta, A macrosonic system for industrial processing, Ultrasonics 38 (2000) 331.
[4] J.A. Gallego, Power ultrasonic technologies for industrial applications, Proceedings of the World Congress on Ultrasonics (1997) 416.
[5] W.P. Mason, Electromechanical Transducers and Wave Filters, 2nd ed., Van Nostrand, New York, 1948, pp. 195, 399.
[6] D.A. Berlincourt, D.R. Curran, H. Jaffe, Piezoelectric and piezomagnetic materials and their function in transducers, in: W.P. Mason (Ed.), Phys. Acoustic, Academic, New York, 1964.
[7] E.A. Neppiras, The pre-stressed piezoelectric sandwich transducer, Ultrasonics International 1973 Conference Proceedings (1973) 295.
[8] D.W. Hawkins, P.T. Gough, Multiresonance design of a Tonpilz transducer using the finite element method, IEEE Trans. Ultrason., Ferroelect., Freq. Contr. 43 (1998) 782.
[9] Q. Yao, L. Bjorno, Broadband Tonpilz Underwater acoustic transducers based on multimode optimization, IEEE Trans. Ultrason., Ferroelect., Freq. Contr. 44 (1997) 1060.
[10] Vernitron Bulletin, Five Modern Piezoelectric Ceramics, January 1972. n. 66011/E.