Metal Cap Flexural Transducers for Air-Coupled Ultrasonics

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Abstract.

Ultrasonic generation in fluids is difficult due to the large difference in acoustic impedance between the piezoelectric element and the propagation medium, leading to large internal reflections and energy loss. One way of addressing the problem is to use a flexural transducer., which uses the bending modes in a thin plate or membrane. As the plate bends it displaces the medium in front of it, hence producing sound. A piezoelectric flexural transducer can generate large amplitude displacements in fluid media for relatively low excitation voltages.

Commercially available flexural transducers for air applications operate at 40 kHz, but there exists ultrasound applications that require significantly higher frequencies, e.g. flow measurements. Little work has been done to date to understand the underlying physics of the flexural transducer, and hence how to design it to have specific properties suitable for specific applications.

This paper investigates the potential of the flexural transducer and its operating principles. Two types of actuation methods are looked at: piezoelectric and electrodynamic. The piezoelectrically actuated transducer is more energy efficient and intrinsically safe, but the electrodynamic transducer has the advantage of being less sensitive to high temperature environments. The theory of vibrating plates is used to predict transducer frequency as well as front face amplitude to a reasonable degree of accuracy.

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INTRODUCTION

Flexural Cap Transducers

Flexural transducers use the bending modes of a plate or membrane to displace the propagation medium and hence produce sound [1]. Since the plate vibrations are mechanically coupled to the medium, there is no acoustic impedance mismatch. A relatively small amount of input energy can generate large amplitude vibrations in the plate.

There are many different designs of flexural transducers depending on their respective applications. Flexural transducers can be used as sensors [2] as well as for high power ultrasonics [3].

Fig. 1 shows a schematic diagram of the cross section of a metal cap piezoelectric flexural transducer. When an electric field is applied across the piezoelectric element it will try to expand, but because it is constrained at the boundary to the metal cap, it will cause the system to bend instead.

The active element in fig. 1 can be replaced by a pancake coil. The current in the coil induces a magnetic field $\overrightarrow{B}$ in the front plate of the metal cap, which generates a current density $\overrightarrow{j}$. The current in the cap interacts with the magnetic field to produce a Lorentz force $\overrightarrow{F} = \overrightarrow{j} \times \overrightarrow{B}$ [4], which sets the plate in vibration. The metal cap is therefore a necessary part for ultrasonic generation whilst also providing an integrated ruggedness, which is valuable for many industrial applications. The generation method is similar the one used for electromagnetic acoustic transducers (EMATS)[5], but without the static magnetic field. A static magnetic field can however be introduced, and is necessary for receiving ultrasound.

Large amplitude displacements can be achieved by driving the system at resonance frequency. The resonance frequencies, i.e. the modal frequencies, of the system depend on the geometry and material of the cap.

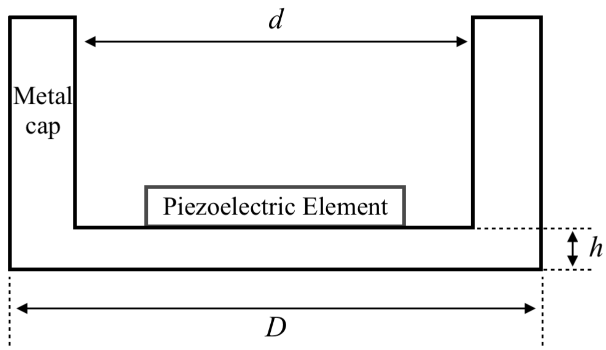

FIGURE 1. Schematic diagram of a cross section of a metal cap flexural transducer.

Theory of Vibrating Plates

The general equation describing the transverse displacement of a thin plate is [6]

$$D\nabla^4 w(\overrightarrow{x},t)+\rho h\frac{\partial^2 w(\overrightarrow{x},t)}{\partial t^2}=0, \tag{1}$$

where D is the rigidity of the plate, defined in (2), w is the transverse displacement, ρ is the volume density, and h is the plate thickness. The rigidity is given by

$$D=\frac{Eh^3}{12(1-\nu^2)}, \tag{2}$$

where E is Young's modulus and ν the Poisson ratio. For a full solution of (1) for an edge clamped circular plate see [6].

The frequencies of the normal modes are given by

$$f=\frac{1}{2\pi}\left(\frac{\lambda}{a}\right)^2\sqrt{\frac{D}{\rho h}}, \tag{3}$$

where $\lambda = ka$ is a root of the solution to (1). Remembering that D is proportional to the cube of the plate thickness, the frequency of any particular mode is inversely proportional to the radius squared and directly proportional to the thickness, for a given eigenvalue λ.

Solving (1) with the appropriate boundary conditions gives the shapes of the vibration modes. The modes are labeled (m,n), where m is the number of nodal radii and n the number of nodal diameters of the mode. The boundary conditions for an edge clamped plate are not strictly applicable to the flexural transducer illustrated in fig. 1. The edges of the cap will restrict the motion along the edge, but not completely stop it. However, the edge clamped plate is a good approximation, which gives useful insight into the behaviour of the flexural transducer.

METHODS

The finite element method (FEM) [7], was used to predict the properties and behaviour of the flexural transducer. The FEM software package PZFlex was used to simulate the metal cap flexural transducer, when excited by a piezoelectric element or by a time varying pressure load. By applying a broadband excitation pulse, the plate would vibrate at its natural frequencies, which could be found by Fourier transform. A particular mode could then be investigated by driving the transducer with a continuous signal at the resonance frequency of that mode.

A PolyTec laser vibrometer was used to measure the surface displacement of the radiating face of the transducers. The system was set up to scan the whole front face in steps of 0.3 mm, in order to determine both mode shape and frequency. A schematic diagram of the setup is shown in fig. 2.

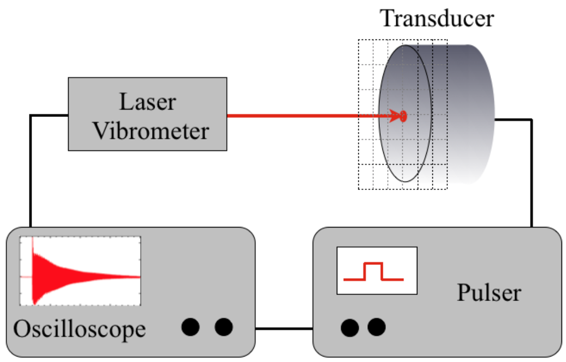

FIGURE 2. Schematic diagram of setup used to scan the front face of the transducer. When using a piezoelectric element to generate, an arbitrary function generator was used as pulser, and for electrodynamic generation an EMAT pulser was used

The dimensions of the cap in the FEM model and the prototypes were: Inner diameter $d = 9.0$ mm, outer diameter $D = 11.0$ mm, front face thickness $h = 0.5$ mm.

RESULTS

Flexural Transducer FEM Results

The frequency spectrum of the FEM modelled flexural transducer is presented in fig. 3. The spectrum was obtained by Fourier transform of the displacement signal from the front face of the metal cap, when excited by a broadband pulse. The displacement was measured at a point slightly off-centre, in order to capture the frequency peaks corresponding to non-axisymmetric modes, i.e. modes with one or more nodal diameters $(m, n > 0)$.

The first peak in the spectrum corresponds to the fundamental mode (0,0), and is located at 50 kHz. The calculated values from (3) for this mode are 42 kHz and 62 kHz, using the outer and the inner radius for a respectively. The second peak at 100 kHz corresponds to the first non-axisymmetric mode (0,1). The (1,0) mode is split into three peaks at 160 kHz, 180 kHz and 220 kHz. The peak at 390 kHz represents the third axisymmetric mode (2,0). The other peaks can similarly be associated with the theoretical vibration modes, by looking at the mode shape of the transducer at the location of the peak.

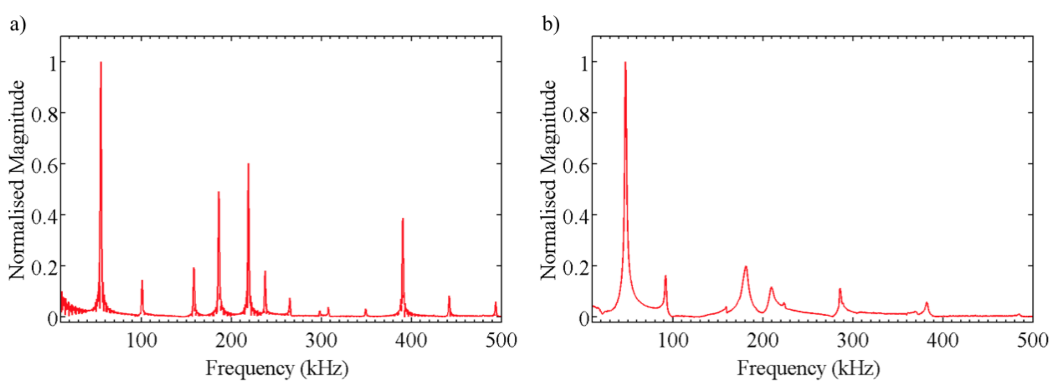

FIGURE 3. Normalised frequency spectra from a) FEM model and b) experimentally measured displacement signal from prototype electrodynamic flexural transducer

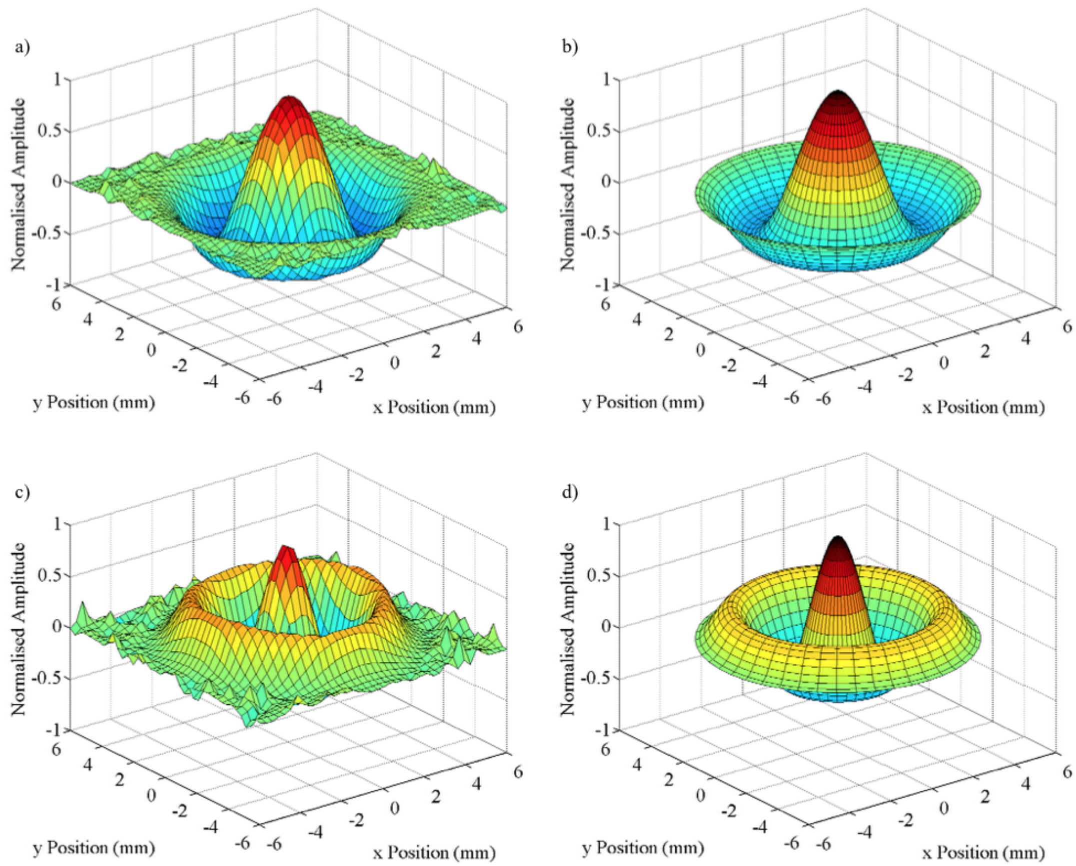

FIGURE 4. a) Experimental mode (1,0) at 180 kHz, b) theoretical shape of mode (1,0), c) experimental shape of mode (2,0) at 390 kHz, and d) theoretical shape of mode(2,0).

Results from Prototype Flexural Transducer

Fig. 3 shows the frequency spectra of a prototype transducer with the dimensions specified in §.

The locations of the mode frequencies are in good agreement with the FEM results, even though the relative amplitudes of the peaks do not agree. The amplitudes however depend on the specific generation method as well as the position on the front face of the transducer where the displacement signal was recorded. It is encouraging to see the three way splitting of the (1,0) mode, that was observed in the FEM model results.

Fig. 4 shows the measured (1,0) and (2,0) mode shapes and their theoretical counterparts. The measured frequencies of these modes are180 kHz and 390 kHz respectively. The other modes present in the frequency spectrum (see fig. 3) show similar correspondence between experimental and theoretical mode shapes. In general there is good agreement between the experimentally measured results and the theoretically calculated results.

CONCLUSION

The metal cap flexural transducers can be designed to operate at a specific frequency with a specific vibration mode. They show potential as an alternative ultrasound generation method in air and other low impedance media.

Metal cap flexural transducers show good agreement with the analytical theory of edge clamped circular plates. The theory can therefore be used to quickly predict the frequency and vibration mode shape of a transducer of known dimensions. The transducer has an inner and outer diameter values, which can both be used in the theory to give an upper and lower bound on any mode frequency. The frequency band between the bounds grows larger for higher modes, making them harder to predict accurately. For the fundamental mode a lower bound of 42 kHz and and upper bound of 62 kHz was calculated. The measured fundamental mode was found in between these values at 50 kHz.

The electrodynamic generation method requires higher excitation voltages than piezoelectric generation, but has other advantages including ease of manufacturing, the potential to work at high temperatures, and no problem with the active element debonding over time.

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REFERENCES

1. C. Germano, *"IEEE Trans. Audio Electroacoust."* **AU19**, 6–12 (1971), ISSN 0018-9278.
2. W. Manthey, N. Kroemer, and V. Magor, *Meas. Sci. Technol.* **3**, 249–261 (1992).
3. A. Barone, and J. Gallegoj, *J. Acoust. Soc. Am.* **51**, 953–959 (1972), ISSN 0001-4966.
4. J. Griffiths, *Introduction to Electrodynamics*, Prentice-Hall International, London, 1999, 3rd edn.
5. M. Hirao, and H. Ogi, *EMATS for Science and Industry: Noncontacting ultrasonic measurments*, Kluwer Academic Publishers, London, 2003.
6. A. Leissa, *Vibration of Plates*, U.S. Government Press, Washington, 1969.
7. W. Friedrich, H. Kaarmann, and R. Lerch, "Finite Element Modeling of Acoustic Radiation from Piezoelectric Phased Array Antennas," in *IEEE 1990 Ultrasonics Symposium : Proceedings, Vols 1-3*, IEEE, New York, 1990, vol. 2 of *Ultrasonics Symposium*, pp. 763–767.