3-D FEM ANALYSIS OF LOW-FREQUENCY FLEXTENSIONAL BARREL-STAVE TRANSDUCERS WITH CONCAVE STRUCTURE

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1. INTRODUCTION

The flextensional transducer, as a low frequency projector with unique properties of broadband and high power[1][2], finds important applications in ocean acoustic tomography. In this paper, the performance of a flextensional barrel-stave transducer with concave structure is investigated by using a 3-dimensional finite element approach. This type of projector has the clear advantages of small size, light weight and inexpensiveness. In the frequency range of 300 - 500 Hz, more than 190 dB transmitting acoustic source level and a 100 Hz bandwidth can be achieved. The height of this projector is 0.52 m. In order to optimize the projector, transmitting voltage responses are calculated for different structure parameters. The vibration states are confirmed by the calculated deformed shapes. The in-air and in-water input electric impedance are also calculated.

2. DESIGN CONSIDERATIONS

In general, a flextensional transducer consists of two parts: the driving motor and the radiation shell. The driving motors are normally made from piezoceramic or magnetostrictive active materials. By applying electric power, the piezoceramic or magnetostrictive active materials yield a large mechanical force through piezoelectric or magnetostrictive effects.

The radiation shell should comprise three characteristics. First of all, the first flexural resonance frequency of the shell should be considerably lower than the fundamental piston resonance frequency of the motor (where the motor behaves as a $\lambda/2$ transmitter). Using the flexural vibration mode, the size of the flextensional transducer is significantly reduced being much smaller than a wavelength in water. The effective resonance frequency of the transducer will be modified slightly by the added stiffness of the motor. Thus, the flextensional transducer has an excellent ratio of power to size. Secondly, the radiation shell should have the capability of amplifying small vibration displacements which are produced in the connection area between the motor and the shell. This yields a large vibration displacement at other areas of the shell. The displacement amplifying characteristics of the shell requires a specially designed shape of the shell. Thirdly, using the flextensional transducer in a low frequency regime, the impedance of the acoustic radiation is small due to the small size of the transducer with respect to a wavelength in water (above 5 kHz, other types of transducers such as Tonpilz, free-flooded ring are more often used). The radiation shell should match the small acoustic radiation impedance and the high mechanical impedance of the motor. This property of the shell is similar to that of the cone shaped head-mass of a Tonpilz transducer. The impedance match consideration requires the optimization of the shape and thickness of the shell.

Compared to other types of flextensional transducers, the flextensional barrel-stave transducers are easier to prestress with a prestress bolt like the one used in a Tonpilz transducer. The radiation shell can be assembled after the driver is ready. The simplicity of manufacturing process makes the barrel-stave transducer practically attractive. There are mainly two types of flextensional barrel-stave transducers. One is flextensional barrel-stave transducers with concave structure. The other is flextensional barrel-stave transducers with convex structure.

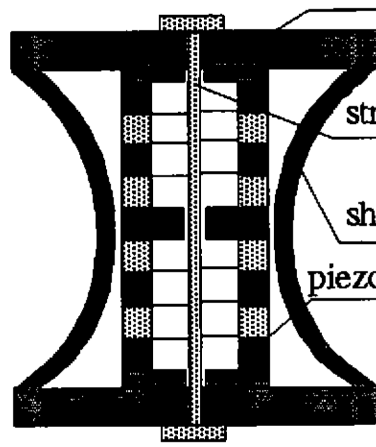

Fig.1. The schematic configuration of a flextensional barrel-stave transducer with concave structure

Fig.1 is the schematic configuration of a flextensional barrel-stave transducer with a concave structure considered in this paper. The shell consists of 12 curved staves. Between neighboring staves, a small slot is formed. This slot makes it possible to manufacture and assemble the staves one by one. The driver is made of 8 piezoceramic rings. The rings are axially poled and parallel connected. The prestress is applied to the ceramic stack by a central steel bolt.

There is no satisfactory solution, at present, for the pressure release problem in relation to water depth for this type of transducers[3][4]. Thus, an air backed configuration is often introduced by a rubber cover outside the shell. As the depth is increasing, the static pressure enhances the prestress of the piezoceramic stack by an inward pushing of the shell. This is an advantage of this concave structure over convex shell design with respect to depth capability.

3. FEM NUMERICAL APPROACH

The FEM code, Ansys, which is used in the calculations, has two important features. First, a fluid-structure interaction element based on the displacement continuity at the interface is used. In the solid structure domain, nodal displacements in three directions form 3 degrees of freedom. For a piezoceramic material, voltage is another degree of freedom. In the fluid domain, sound pressure is the only degree of freedom. At the structure-fluid interface, the displacements and the pressure constitute the degrees of freedom. Thus, farfield calculation can be carried out by eliminating displacement degrees of freedom in a large water regime. Second, since it is difficult to simulate an infinite fluid for a practical situation, a far-field boundary absorption coefficient is introduced. By setting a boundary absorption coefficient at the farfield, this FEM program calculates the farfield acoustic pressure in a realistic way. It is also proven that within one wavelength in water, at least 6 elements should be involved. The farfield distance to calculate the acoustic pressure has been shown to be more than 2 wavelength in water[5]. A mesh density of 12 elements per wavelength and 4 wavelength farfield distance are used in this paper.

4. BASIC DESIGN

According to the requirements of ocean tomography applications, the designed projector should have a transmitting source level larger than 190 dB and a bandwidth of 25% of the central frequency. The working frequency range is from 250 Hz to 500 Hz. Among various materials, aluminum forms a compromise proposal for the shell material aiming at high transmitting source level and broad bandwidth[6].

4.1 Geometry of the basic design

The maximum outside diameter and the height of the transducer are 34 cm and 52 cm, respectively. The radiation shell consists of 12 flat aluminum staves, which have a 58.4 cm radius of curvature and 1.4 cm thickness of the shell walls. The piezoceramic stack consists of 8 Navy type I piezoceramic rings. The outside diameters of the rings are 20 cm and the inner diameters are 12 cm. The thickness of the rings are 4 cm. The thickness is too thick for simplicity of the calculation and can be reduced by using more rings in order to match the power supply.

4.2 In-air analysis of the basic design

By using model analysis of the FEM code, different vibrational modes can be found. The first two modes are the first and the second flexural mode of the shell. The third mode is the longitudinal piston mode of the central driver. The natural resonance frequency of these three modes are 785 Hz, 2100 Hz and 2648 Hz, respectively. The displacement fields of these three modes are shown in Fig.2.

The in-air impedance plot as a function of frequency is shown in Fig.3. The three minimum points in this impedance plot correspond to the above mentioned three vibrational modes. It can be seen that the second mode is less efficient than the other two modes. In this calculation, the losses in the material and in the vibrational system are not included.

4.3 In-water analysis of the basic design

Fig.4 and Fig.5 are the in-water input electric resistance and reactance as functions of frequency of the projector. Fig.6 gives the transmitting voltage response (TVR) which is

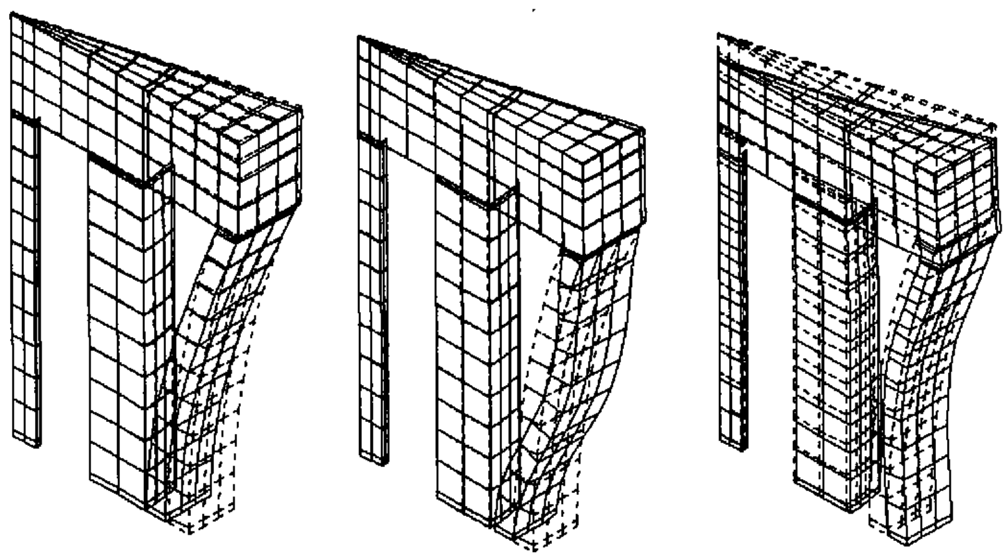

Fig.2. Deformed shape of the first three modes

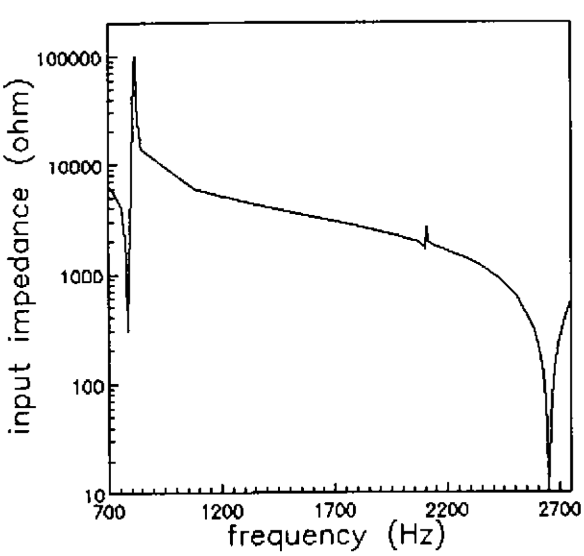

Fig.3. In-air input electrical impedance as a function of frequency of the projector

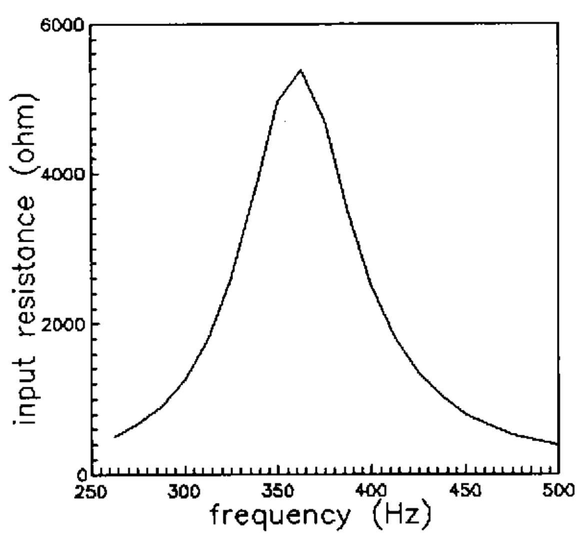

Fig.4. In-water input electrical resistance as a function of frequency of the projector

referenced to 1 μpa/V at 1 m. The reference value is also used in other TVR plots of this paper. The maximum value of TVR is 124 dB at 362 Hz. Based on a maximum electric field of 2000V/cm, a 202 dB maximum transmitting source level can be obtained at the in-water fundamental resonance frequency of 362 Hz for this projector. The Q factor is calculated to 3.9. Thus, a bandwidth of 25.6% of the central frequency can be achieved.

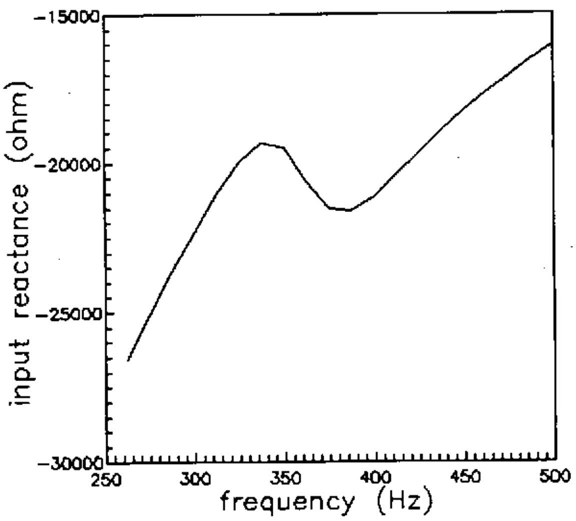

Fig.5. In-water input electrical reactance as a function of frequency of the projector

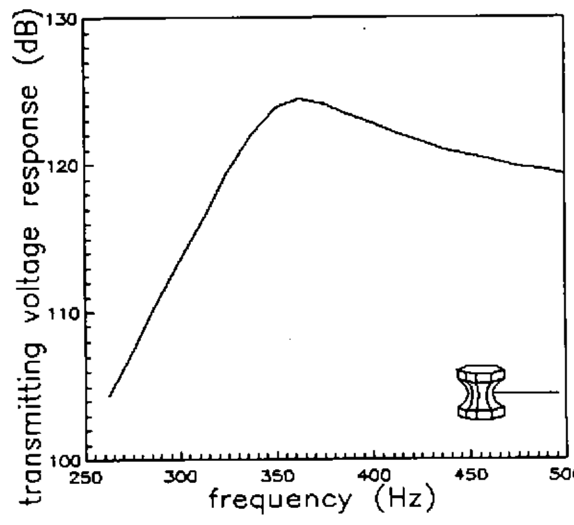

Fig.6. Transmitting voltage response

In water, the vibration displacement of the piezoceramic stave is amplified efficiently by the flexural vibration shell. A displacement of 7.1×10^{-10} m at the end of the piezoceramic stave is amplified to a maximum displacement 1.17×10^{-8} m in the center part of the shell by using a voltage of 1 V. This yields an amplification ratio of 16. At the first flexural vibrational mode in air, this ratio is 22.

5. OPTIMIZATION OF THE STRUCTURAL PARAMETERS

In order to understand the optimized design of the transducer, the transmitting voltage responses are calculated for various structural parameters.

5.1 Thickness of the shell

The shell thickness forms the most dominating parameter for this type of low-frequency flextensional projector. As mentioned above, there must be an optimized shell thickness. If it is too thin, the shell become very soft. Thus, the large force capability of the piezoceramic driver cannot be fully exploited. A too thick shell will be more stiff to drive. Fig.7 is the TVR plots for different thicknesses. The resonance frequency increases with increasing thickness as expected, while the bandwidth decreases. TVR obtains its maximum value for a 1.4 cm thickness shell. Low resonance frequency can be obtained by small shell thicknesses with the expenses of a decreasing maximum TVR.

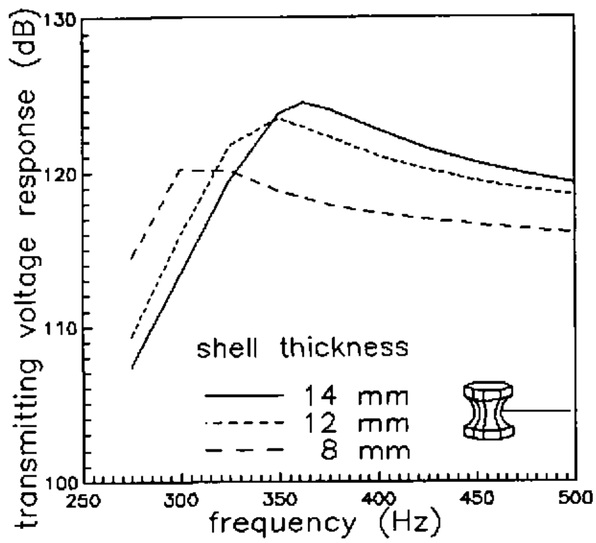

Fig.7. Transmitting voltage response versus thickness of the shell

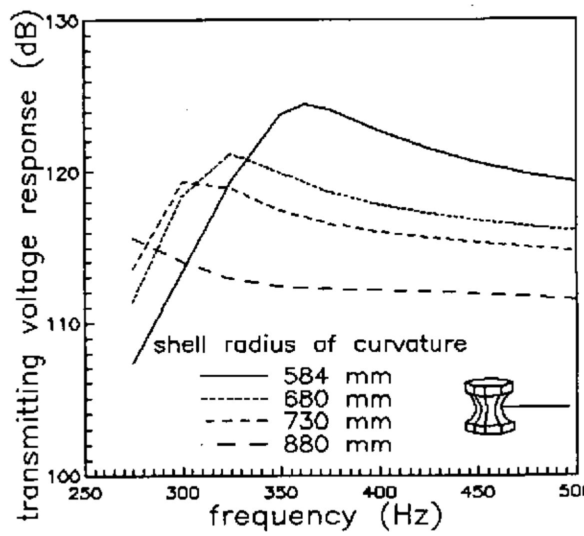

Fig.8. Transmitting voltage response versus radius of curvature of the shell

5.2 Stave curvature

Another parameter, namely the shell curvature plays an important role for obtaining a good volume velocity of flextensional brass-stave projectors. In the frequency range from 250 to 500 Hz, the resonance frequency and the TVR increase with decreasing of radius of curvature. However, this dependent relationship can only apply for low stiffness of the shell. It can be found from Fig.8 that the bandwidth decreases with the decreasing of radius of curvature. In order to avoid that the inner side of the shell is touching the ceramic stack, there is a limit to the minimum radius of curvature.

5.3 Thickness of end plate, outside radius of piezoceramic stack and the maximum outside radius of the transducer

Fig.9 and Fig.10 are TVR plots for different thicknesses of the end plate and the outside radius of the piezoceramic stack. Decreasing thickness of end plate or the outside radius of the PZT stack results in a change of the resonance of the flapping mode of the end plate. Thus, the end plate is not stiff enough to transfer the displacement of the ceramic stack to the shell. The size of the interaction area where the ceramic stave is mounted to the end plate is important for the vibration of the shell. If this area is situated close to the central axis of the transducer, the momentum for driving the shell becomes smaller and the transducer becomes inefficient. Fig.9 shows that the TVR increases with increasing of the thickness of the end plate. At the same time, the resonance frequency is obviously going up. Thus, a 60 mm thickness of the end plate is a suitable choice. It is shown from Fig.10 that the TVR is improved significantly by increasing the outside radius of the piezoceramic stack. But a physical limit exists for the maximum outside radius of the piezoceramic stack in order to avoid the inner side of the shell to touch the ceramic stack. The maximum value of the radius in this model is 100 mm. The maximum outside radius of the transducer also has the same

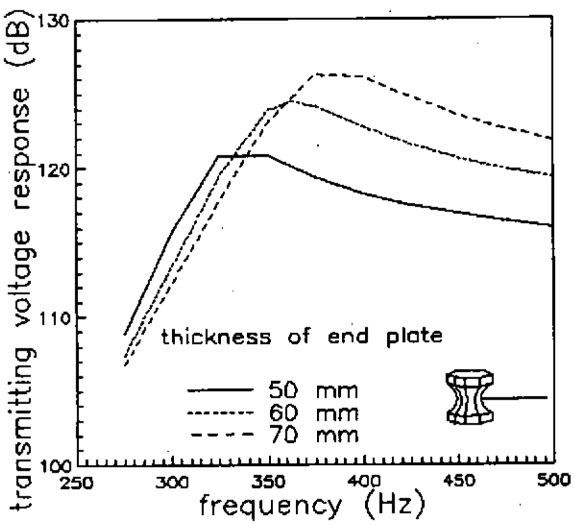

Fig.9. Transmitting voltage response versus thickness of the end plate

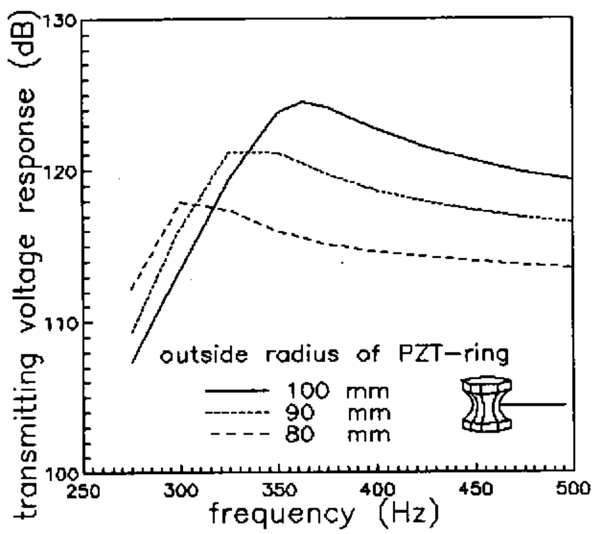

Fig.10. Transmitting voltage response versus outside radius of the piezoceramic stack

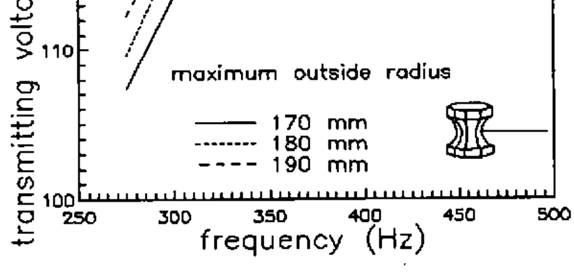

Fig.11. Transmitting voltage response versus maximum transducer outside radius

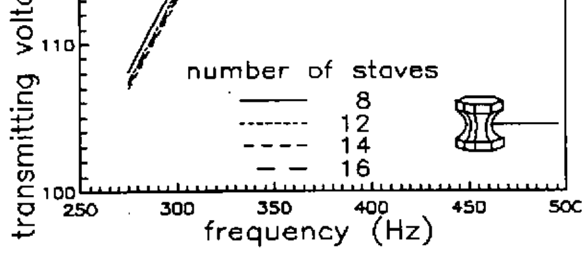

Fig.12. Transmitting voltage response versus number of staves

influences on the performance of the projector as mentioned above. Fig.11 shows the dependence of the TVR on the maximum outside radius of the transducer.

5.4 Number of staves

Because the shell is relatively thin compared with that of a high-frequency design in order to decrease the resonance frequency, it is soft enough to be driven. Thus, increasing the number of staves does not result in an improvement of the TVR. In the low-frequency regime, a smaller number of staves can be used for simplifying the manufacturing process. It may also be shown that even if the number of staves is reduced to 4, the fluctuation of the TVR in the horizontal plane at a certain distance in the farfield is less than 1 dB.

5. CONCLUSION

3-D FEM analysis provides detailed electrical and mechanical knowledge of flextensional barrel-stave transducers with a concave structure. The influences of various structure parameters on the performance of the transducer can be predicated.

Flextensional barrel-stave transducers with concave structure can provide more than 190 dB transmitting source level in the frequency range from 300 to 500 Hz. A maximum transmitting source level of 202 dB ref. 1 μpa/V @ 1 m can be obtained at the resonance frequency of 362 Hz. Corresponding to a calculated quality factor of 3.9, a bandwidth of 25.6% of the central frequency is also achieved.

6. REFERENCES

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