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Testing an improved cymbal hydrophone

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Abstract: Cymbal hydrophones have small volume and high sensitivity, but their reception is not stable enough, and their reception is in too narrow a frequency band. In order to overcome these inadequacies, the structure of the cymbal hydrophone was improved. The single ceramic piezoelectric element was replaced with a double one, the radius of the ceramic piezoelectric element was reduced, and a parallel circuit was added. A static analysis of this new structure was developed, and then simulations were made of both the traditional and new hydrophone structure using finite element software. Tests were then conducted in a tank. The results showed that the improved hydrophone has reception in a wider frequency band, reception performance is stable within this frequency band, and sensitivity is still high.
Keywords: cymbal hydrophone; sensitivity; resonance frequency; parallel connection; frequency band
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1 Introduction

The cymbal transducer is a miniature Class V flextensional transducer developed at the Materials Research Laboratory, Penn State University and patented by Newnham and Dogan in 1998[1]. The design is an improvement on the commercially successful "moonie" transducer patented by Newnham et al[2]. The name cymbal comes from the crescent cavity shape created by the endcap and the shape of the cap. The cymbal transducer consists of a thick poled piezoelectric disk bonded to truncated conical metal endcaps[3].

Due to the reversibility of the piezoelectric effect, like the other piezoelectric devices, cymbal transducer can be exploited both as hydrophones and projectors. As hydrophones, the metal endcaps serve as mechanical transformers to convert and amplify the axially applied force into both axial and radial stressed inside of the ceramic disk[4]. Then, both d_{31} (=d_{32} for disk) and d_{33} coefficients of the ceramic contribute to the charge generation, resulting in a very high effective d_{33} value. Therefore, the cymbal hydrophones often have higher sensitivity. On the other hand, due to some limitations related to manufacture problems[5], the reception performance of the cymbal hydrophone is not stable enough, due to narrow receiving frequency band. In order to improve the inadequacy, in this study, a new way is presented. PZT (Lead Zirconate Titanite) ceramics were used to build up cymbal hydrophones and brass was chosen as the metal endcap material.

2 Static analysis of the cymbal hydrophone

A cross sectional view of the cymbal hydrophone is shown in Fig.1. It would be best that the height of the shallow cavity H is not too high. The shallow cavity allows deformation of the metal toward the ceramic disk by closing the cavity that reduces stress amplification in the ceramic and prevents breakdown during shockwaves or under very high hydrostatic pressure[6]. The concept of the stress transformation can be explained in a simple manner using the cross section in Fig.2 and the following equations.

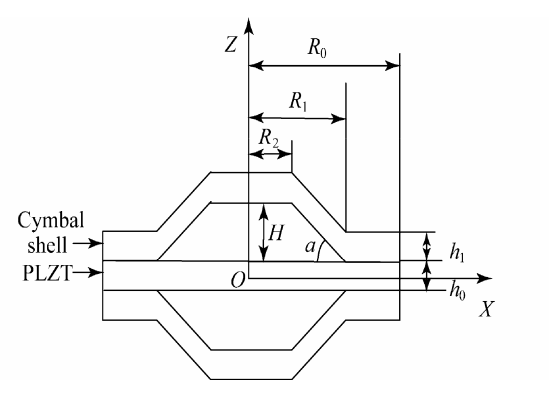

Fig.1 Geometry of the cymbal hydrophone

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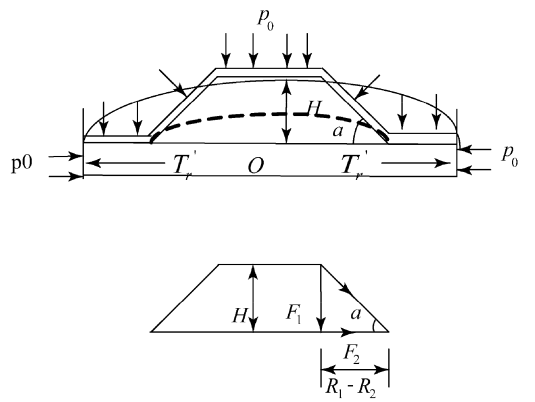

Fig.2 Simplified model for static analysis

$$\frac{F_1}{F_2}=\frac{H}{R1-R2}$$

$$F_1=\pi\cdot R_1^2/2\cdot p_0,$$

$$F_2=\pi(R_0^2-R_1^2)\cdot\frac{h_0}{2}/2\cdot T'_r$$

$$T'_r=-\frac{R_1^2\cdot(R_1-R_2)}{H\cdot(R_0^2-R_1^2)}\cdot\frac{P_0}{h_0/2}=$$

$$-k\frac{R_1^2}{h_0(R_0^2-R_1^2)}p_0$$

$$k=\frac{R_1-R_2}{H/2}\cong 2\frac{1}{\tan\alpha}$$

In addition, for the cylindrically symmetric structure, we can get[7]

$$\begin{cases} T_{r1}=p_0\dfrac{a^2b^2}{b^2-a^2}\left(\dfrac{1}{r^2}-\dfrac{1}{a^2}\right) \\ T_{\theta 1}=p_0\dfrac{a^2b^2}{b^2-a^2}\left(-\dfrac{1}{r^2}-\dfrac{1}{a^2}\right) \end{cases}$$

Let T_r be the r – direction stress and T_θ be the θ-direction stress, then

$$T_{r1}+T_{\theta 1}=-2p_0$$

$$T_r+T_\theta=-2p_0+T_r{}'=$$

$$p_0\left(k\frac{S_2}{h_0S_1}-2\right)$$

$$T_z=p_0\frac{S_1}{S_0}$$

Considering the resulting polarization equation as [6]

$$d_h=T_zd_{33}+T_rd_{31}+T_\theta d_{32}$$

Therefore,

$$(d_h)_{\max}\cong d_{33}\frac{S_1}{S_0}+d_{31}\left[\frac{kS_2}{h_0S_1}-2\right] \quad (1)$$

S_1 is the surface area of the metal-PZT bond and S_0 is the surface area of the PZT disk. S_2 denotes the bottom area of the middle shallow cavity.

Moreover,

$$Q=\int d_h\cdot\mathrm{d}s\ ;\ C\cong\frac{\varepsilon_rS_0}{h_0} \quad (2)$$

Q is the total charge and C the capacitance of the hydrophone. Thus, the voltage reception sensitivity M of the cymbal hydrophone is

$$M=\left|\frac{V}{p_0}\right|=\left|\frac{Q}{Cp_0}\right|$$

$$=\frac{h_0}{\varepsilon}\left[d_{33}\frac{S_1}{S_0}+d_{31}\left(k\frac{S_2}{h_0S_1}-2\right)\right] \quad (3)$$

3 Improvement of the cymbal hydrophone

In order to increase the stable property of the cymbal hydrophone, some changes were made, namely the single piezoelectric ceramic was changed to double one with parallel connection, the radius of the piezoelectric ceramic was reduced, and parallel circuit was used, as shown in Fig.3.

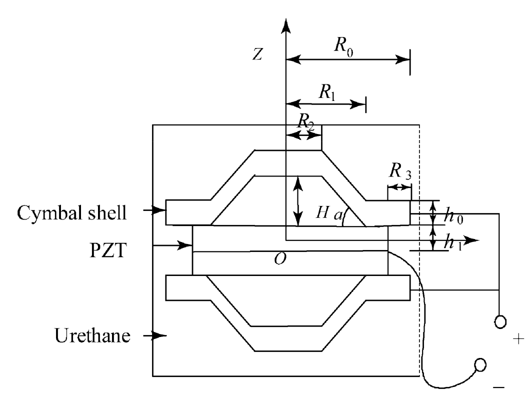

Fig.3 The improved hydrophone

4 Finite element analysis

The purpose of finite element analysis is to numerically solve complex partial differential equations so as to mathematically describe or predict the physical behavior of an actual engineering system under various loading conditions.

4.1The structure –fluid coupling principle

For common dynamic problems of structure, the finite element equation is as follows:

$$\boldsymbol{M}\{\ddot{U}\}+[\boldsymbol{C}]\{\dot{U}\}+\boldsymbol{K}\{U\}=\{F\}$$

M is mass matrix, ***C*** damp matrix, ***K*** rigidity matrix, and $\{U\}$ the displacement vector of node. These matrixes and vector have different states, which decide different types of analysis.

For special harmonic response, the finite element constraint equation turns to

$$\boldsymbol{M}\{\ddot{U}\}+[\boldsymbol{C}]\{\dot{U}\}+\boldsymbol{K}\{U\}=\{F^a\}$$

where $\{\boldsymbol{F}^a\}$ are loads exerting on structure, in general, $\boldsymbol{F}^a=f_0e^{jwt}$. Then the finite element constraint equations for fluids and structure would be

$$\begin{aligned}&\boldsymbol{M}_s\{\ddot{U}\}+\boldsymbol{K}_s\{U\}=\{F_s\}+\boldsymbol{R}\{P\}\\&\boldsymbol{M}_f\{\ddot{P}\}+\boldsymbol{K}_s\{P\}=\{F_f\}-\rho_0\boldsymbol{R}^{\mathrm{T}}\{\ddot{U}\}\end{aligned} \qquad (4)$$

R is coupling matrix, and Eq.(4) can be combined as

$$\begin{bmatrix}\boldsymbol{M}_s & 0\\ \rho_0\boldsymbol{R}^{\mathrm{T}} & \boldsymbol{M}_f\end{bmatrix}\begin{pmatrix}\ddot{U}\\ \ddot{P}\end{pmatrix}+\begin{bmatrix}\boldsymbol{K}_s & -\boldsymbol{R}\\ 0 & \boldsymbol{K}_f\end{bmatrix}\begin{pmatrix}U\\ P\end{pmatrix}=\begin{pmatrix}F_s\\ F_f\end{pmatrix}$$

4.2 The calculation of underwater receiving voltage sensitivity

According to the reciprocity theorem, the receiving voltage sensitivity *M* of the transducer can be calculated by its transmitting current response S_I when transducer is reciprocal. The changed form of the equation from Ref.[8] is

$$J_s=\frac{M}{S_I}=\frac{2}{\rho f}$$

where J_s is the reciprocal constant which is inversely proportional to density ρ and frequency *f*, thus the receiving voltage sensitivity of a hydrophone may be obtained from its transmitting current response (TCR). TCR is achieved at 1V of the current and the corresponding transmitted sound pressure at 1 m underwater, both of which are calculated by ANSYS software.

4.3 Finite element model

A theoretical analysis of the cymbal hydrophone was performed using the finite element analysis program ANSYS version 10.0. Because the cymbal transducer exhibits axial-symmetry about its central axis, it was modeled as a two-dimensional axial-symmetric body. A two-dimensional axial-symmetric model offers the advantage over the corresponding three-dimensional one in which the size of the model is smaller and consequently the calculation time is much less. The results reported in this paper are for brass-capped cymbal hydrophone with the dimensions given in the caption of Fig.4. The half axially-symmetric model in air (improved and original cymbal hydrophone) is shown in Fig.5. The values of the requisite material properties necessary for this analysis are listed in Table1. The admittance and the sensitivity of the cymbal hydrophones will be discussed further in details in the following sections.

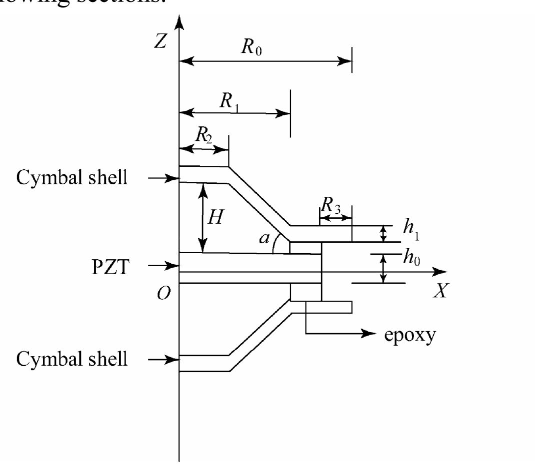

Fig.4 The geometry of the improved cymbal hydrophone with dimensions: h_0=1 mm, R_0=14 mm, R_1=6 mm, R_2=2 mm, R_3=4 mm, *H*=0.45 mm, h_1=0.3 mm

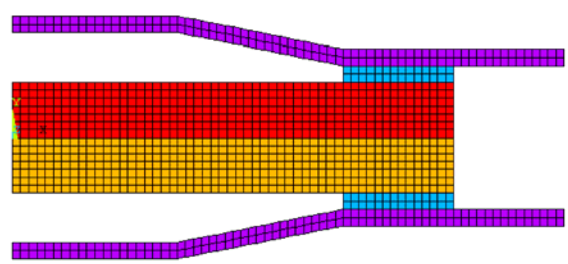

Fig.5 Half axially-symmetric finite element model in air (improved cymbal hydrophone)

Table 1 Values of the material's properties

cap material	ρ/ kg·m^{-2}	*E*/ GPa	σ
Brass	8550	100.6	0.35
Epoxy	1430	2.5	0.36
PZT	7500		

5 Experiment

The free-field sensitivity is measured in a testing water pool using impulsive technique by a comparison method. The prototype was positioned under water 1.5m deep, and 2m far away from the standard hydrophone, which was set at the same depth with the prototype. Admittance was measured using an Impedance Analyzer HP 4194A in the frequency range of 0-30kHz.

6 Result and discussion

Table 2 Calculated resonance frequencies Hz

Resonance frequency	First	Second	Third
Improved	24 670	52 250	130 060
Original	23 685	50 280	104 460

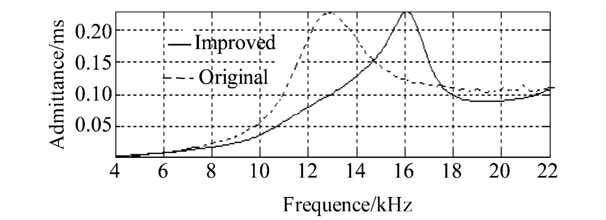

Fig.6 Measured admittance spectra in the neighborhood of the first resonance for the improved cymbal hydrophones and the originals in water

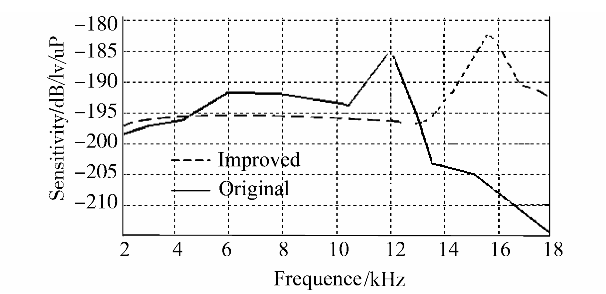

Fig.7 Measured sensitivity as a function of frequency for the improved cymbal hydrophones and the originals in water

Table 2 illustrates the calculated resonance frequencies in air by ANSYS modal analysis. From Table 2, it can found that the improved cymbal hydrophones exhibit higher resonance frequency, and a broader receiving frequency band is expected.

The measured admittance spectra and sensitivity spectra are shown in Fig.6 and Fig.7. The first resonance frequency of the improved cymbal hydrophone is about 12 kHz, and that of the original is about 16 kHz. When in water, the fundamental resonance shifts to a lower frequency due to mass loading. Fig.7 shows a flat sensitivity in the frequency range from 2~18 kHz for the improved cymbal hydrophone, and the original cymbal hydrophone shows a flat sensitivity only within the frequency range of 6~10kHz. It means the improved cymbal hydrophone can operate at wider frequency band and exhibit more stable reception property in comparison with the original cymbal hydrophones.

The improved cymbal hydrophone has parallel connection between the two ceramic disks. It is known that the parallel connection can enhance the capacitance, which has advantage in alleviating the cable shunting problem. Low capacitance for hydrophones is not desirable, because the output signals of the sensing elements are greatly reduced by the capacitance of the coaxial cables.

From Eq.(3), it is found that the sensitivity of the cymbal hydrophone is greatly affected by the dimensions of the cymbal hydrophone. Hence the sensitivity can still be higher by the improvement on the dimensions (see Fig.7).

7 Conclusion

By manipulating the dimensions of the cymbal hydrophones and adopting proper connection, the improved hydrophone has wider reception frequency band, the reception performance is stable within this frequency band, and the sensitivity is still high (about -195dB). Therefore, the improved hydrophones will be better than those originals.

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钹式水听器的改进和测试

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摘　要：钹式水听器体积小，灵敏度高，但其接收性能不够稳定，接收频带较窄. 为了克服这些弱点，对其结构进行改进. 运用双片陶瓷并联代替单片陶瓷，并缩小陶瓷半径. 再通过有限元仿真实验和水池实验，对改进前后的钹式水听器进行测试，结果表明，改进后的钹式水听器接收性能更加稳定，接收频带也明显增加，同时其灵敏度依然较高.

关键词：钹式水听器；灵敏度；频率响应；并联；频带