Advantage analysis of PMN–PT material for free-flooded ring transducers*

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The acoustic radiation characteristics of free-flooded ring transducers made of PZT4 and PMN–PT materials are calculated and compared. First, the theoretical formulae for free-flooded ring transducers are studied. The resonant frequencies of a transducer made of PZT4 and PMN–PT materials are calculated. Then, the transmitting voltage responses of the free-flooded ring transducers are calculated using the finite element method. Finally, the acoustic radiation characteristics of the free-flooded ring transducers are calculated using the boundary element method. The calculated results show that the resonant frequencies of the free-flooded ring transducer made of PMN–PT are greatly reduced compared with those made of PZT4 with the same size. The transmitting voltage response of the transducer made of PMN–PT is much higher than that of the transducer made of PZT4. The calculated 3-dB beamwidth of the acoustic radiated far-field directivity of the free-flooded ring transducer made of PZT4 at the resonant frequency 1900 Hz is 63.6° and that of the transducer made of PMN–PT at the resonant frequency 1000 Hz is 64.6°. The comparison results show that the free-flooded ring transducer made of PMN–PT material has many advantages over that made of PZT4. The PMN–PT is a promising material for improving the performance of free-flooded ring transducers.

Keywords: free-flooded ring transducer, PMN–PT, acoustic radiation

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1. Introduction

A free-flooded ring transducer is a horizontal unidirectional transducer. The coupling of cavity vibration and radial vibration is utilized, which leads to the low resonant frequency, wide bandwidth and high efficiency of the transducer. The transducer also has other features such as small volume and low weight, high power, good performance under deep-water, etc. In addition, it also has a simple structure and stable performance, which is why they are widely used in the underwater acoustic field.[1]

The earliest known analysis of free-flooded rings was given by Robey.[2,3] In 1964 McMahon[4] gave the theoretical formulae for the prediction of cavity resonant and radial resonant frequencies. The theory gave reasonable agreement with experiment both for long and short tubes. However, no other design parameters were calculated in McMahon's paper, such as impedance, transmitting voltage response (TVR), etc.

The calculations of the acoustic radiation characteristics of transducers have been widely noted and investigated.[5,6] The acoustic characteristics of free-flooded ring transducers can be calculated using the finite element method[7−10] in ANSYS software, including the vibration mode, resonant frequency, admittance curve, transmitting voltage response, acoustic radiated near-field characteristic, etc.

When the surface vibration displacement distribution of a free-flooded ring transducer is calculated using the finite element method, the result is then input into SYSNOISE software and the boundary element method[11−14] is used to calculate the acoustic radiated far-field characteristics, the radiation impedance, etc. As only the boundary of the structure needs to be meshed and calculated, the amount of calculation is largely reduced compared with the finite element method. It is suited for calculating the acoustic radiation far-field characteristics of transducers.

PMN–PT material, which holds many advantages over PZT material, has been recently studied.[15−18] It

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has been shown that PMN–PT has a larger electromechanical coupling factor, higher piezoelectric constant and lower Young's modulus, thereby potentially allowing sonar transducers with lower resonant frequencies and increased bandwidth as well as a higher transmitting voltage response.

In this paper, the theoretical formulae for free-flooded ring transducers are studied, the finite element model and the boundary element model of the transducers both made of PZT and PMN–PT materials are established and solved. The acoustic radiation characteristics of the free-flooded ring transducers are calculated and compared.

2. Comparison of the resonant frequency

2.1. Theoretical formulae of resonant frequency

Free-flooded ring transducers exhibit two fundamental resonant modes that can radiate acoustically into the water. They are the radial resonance of the shell and the cavity resonance of the enclosed water column. The coupling of these two resonant modes leads to the low resonant frequency and wide bandwidth of a free-flooded ring transducer.

Consider a free-flooded ring transducer with height h, mean radius a and thickness t. The ring geometry is shown in Fig. 1.

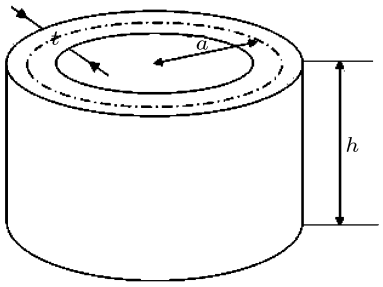


Fig. 1. Free-flooded ring transducer geometry.

The free-flooded ring transducer is made of PMN–PT or PZT4 material, which is radially polarized. For a free-flooded ring that has a short height ($h/a \ll \pi$), according to Ref. [4], the radial resonant angular frequency is

$$\omega_{\rm r} = \sqrt{\frac{Y_{11}}{\rho a^2}}, \tag{1}$$

where Y_{11} is the transverse Young's modulus of the ceramic in a constant electric field, ρ is the density of the ceramic in a constant electric field and a is the mean radius of the free-flooded ring.

While for the long height case ($h/a \gg \pi$), the radial resonant angular frequency is

$$\omega'_{\rm r} = \omega_{\rm r}\frac{1}{\sqrt{1-\sigma^2}} = \sqrt{\frac{Y_{11}}{\rho a^2}}\cdot\frac{1}{\sqrt{1-\sigma^2}}, \tag{2}$$

where σ is the Poisson's ratio in a constant electric field.

Radial vibration of a free-flooded ring shell can excite the cavity resonant mode in the enclosed water column. As for the calculation of the cavity resonant frequency, the cavity resonant angular frequency of the n-th mode is given by

$$\omega_{\rm c}^{(n)} = \frac{(2n-1)\pi c_0}{h+2\alpha a_1}, \tag{3}$$

where c_0 is the velocity of sound in the water column, $a_1 = a - t/2$ is the inner radius and α is an end correction.

Considering only the first cavity mode ($n = 1$), we will have

$$\omega_{\rm c} = \frac{\pi c_0}{h+2\alpha a_1}. \tag{4}$$

Define a dimensionless frequency parameter Ω as

$$\Omega = \frac{\omega_{\rm c} a_1}{c_0}. \tag{5}$$

When Ω is between 0.33 and 3.3, α can be expressed approximately as

$$\alpha = 0.633 - 0.106\Omega, \tag{6}$$

which, combined with Eqs. (4) and (5), leads to the frequency equation

$$\Omega\left[\frac{h}{2a_1} + 0.633\right] - 0.106\Omega^2 = \pi/2. \tag{7}$$

The velocity of sound c_0 within the tube is effectively less than c in open water because of the finite stiffness of the tube walls. Their relation is as follows:

$$c_0 = \frac{c}{\sqrt{1+2Ba_1/Y_{11}t}}, \tag{8}$$

where B is the bulk modulus of water.

From Eqs. (5) and (8), we have the expression of cavity resonant angular frequency

$$\omega_{\rm c} = \frac{\Omega\dfrac{c}{\sqrt{1+2Ba_1/Y_{11}t}}}{a_1}, \tag{9}$$

where Ω is determined by Eq. (7).

2.2. Calculation of resonant frequency

The free-flooded ring transducer is made of PMN–PT or PZT4 material, which is radially polarized. The structural parameter of the free-flooded ring transducer are as follows: the inner radius is $a_1 = 0.1$ m, the thickness is $t = 0.01$ m, the mean radius is $a = 0.105$ m and the height is $h = 0.2$ m. The sound velocity in open water is $c = 1480$ m/s and the bulk modulus of water is $B = 2.2 \times 10^9$ N $\cdot$ m^2.

The transverse Young's modulus of PZT4 material is $Y_{11} = 74 \times 10^9$ N/m^2 and its density is $\rho = 7600$ kg/m^3. The transverse Young's modulus of PMN–PT material is $Y_{11} = 15.3 \times 10^9$ N/m^2 and its density is $\rho = 8000$ kg/m^3. The radial resonant frequency of a free-flooded ring transducer made of the two materials can be calculated using Eq. (1). The cavity resonant frequency can be calculated using Eqs. (7) and (9). The calculated results are shown in Table 1.

Table 1. Calculated radial and cavity resonant frequencies.

	PZT4	PMN–PT
Transverse Young's modulus Y_{11}/N $\cdot$ m^{-2}	74×10^9	15.3×10^9
Radial resonant frequency/Hz	4730	2096
Cavity resonant frequency/Hz	1923	1233

As can be seen from Table 1, the resonant frequencies of the free-flooded ring transducer made of PMN–PT are greatly reduced compared with those of the transducer made of PZT4. The radial resonant frequency and the cavity resonant frequency are reduced by 2634 Hz and 690 Hz, respectively. This is because the Young's modulus of PMN–PT material is much lower than that of PZT4 material.

3. Comparison of the transmitting voltage response

Because the free-flooded ring transducer is axially symmetric and symmetric up and down. The two-dimensional (2D) axisymmetric finite element model can be used to calculate the transmitting characteristics of a free-flooded ring transducer. The size of the transducer is the same as that in Subsection 2.2. The ring transducer is made of PMN–PT or PZT4 material and is radially polarized. The size parameters of the free-flooded ring transducer are as follows: the inner radius is $a_1 = 0.1$ m, the thickness is $t = 0.01$ m, the mean radius is $a = 0.105$ m and the height is $h = 0.2$ m. The 2D axisymmetric finite element model of the free-flooded ring transducer is established and meshed in ANSYS software. Figure 2 shows the axisymmetric finite element model of the top half of the free-flooded ring transducer. The water area is modeled as the fluid element. The fluid area includes three parts: the first is the fluid at the interface between the structure and the water, which is used for analysing the fluid-structure coupling; the second is the outer area fluid, which is used for calculating the acoustic radiated field characteristics of the transducer underwater; the third is the fluid at the boundary of the far-field water area, which is used for simulating the infinite far-field radiation effect by the use of infinite elements as absorbing boundary. For the fluid analysis of transducer, it is difficult to establish an infinite area of fluid in ANSYS software. Therefore, it is simulated by the finite fluid area with infinite absorbing elements on the boundary. The radius of the finite fluid area should satisfy the far-field condition and be selected to be as large as possible in order to achieve a high accuracy of calculation. The condition which should usually be satisfied when the fluid area is modeled in ANSYS is

$$R > \frac{D}{2} + 0.2\lambda, \tag{10}$$

where R is the distance of the transducer centre to the outer boundary of fluid area, D is the maximum size of the transducer structure and λ is the sound wavelength when the harmonic response analysis is conducted.

Figure 3 shows the axisymmetric finite element model and meshes of the top half of the free-flooded ring transducer and fluid area.



Fig. 2. Axisymmetric finite element model of the top half of the free-flooded ring transducer.

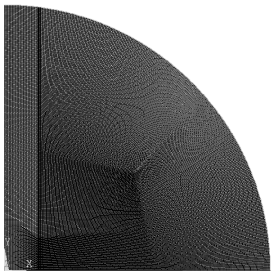


Fig. 3. Axisymmetric finite element model and meshes of the top half of the free-flooded ring transducer and fluid area.

The acoustic radiation characteristics of free-flooded ring transducer underwater can be calculated by harmonic response analysis in ANSYS based on the axisymmetric finite element model established above. The transmitting voltage response (TVR) of the free-flooded ring transducer can be calculated using the finite element model. First, the material attribution and the element type are set in the finite element model. The symmetric boundary condition is imposed on the model. The driving voltage of 1 V is exerted across the inner and the outer sides of the ring. Then, the radiated sound pressure on the circle at a certain distance in the acoustic far-field is calculated by harmonic response analysis at a given frequency. The sound pressure of the radiated farfield along the sound axis direction, which is the same as the radial direction of the free-flooded ring, is extracted. Finally, the TVR of the transducer is calculated by converting the radiated farfield sound pressure into the sound pressure level at a distance of 1 m away from the acoustic centre at different frequencies. Figure 4 shows the TVR of free-flooded ring transducer made of PMN–PT and PZT4 materials in water calculated by the finite element method. The solid line represents the TVR of the transducer made of PMN–PT and the dotted line represents the TVR of the transducer made of PZT4. It can be seen that the first resonant frequency of the transducer made of PMN–PT is reduced compared with that of the transducer made of PZT4. The transmitting bandwidth of the free-flooded ring transducer is very wide, because of the coupling of radial and cavity resonant vibrations. It is also shown that the transmitting voltage response of the transducer made of PMN–PT is much larger than that of the transducer made of PZT4. This is because the electromechanical coupling factor and the piezoelectric constant of PMN–PT are much higher than those of PZT4. The largest TVR achieved by the free-flooded ring transducer made of PMN–PT is 148.4 dB at a frequency of 4100 Hz. While for the PZT4 case, the largest TVR is 137.5 dB at a frequency of 4950 Hz. The largest TVR of the transducer made of PMN–PT is 10.9 dB higher than that of the transducer made of PZT4.

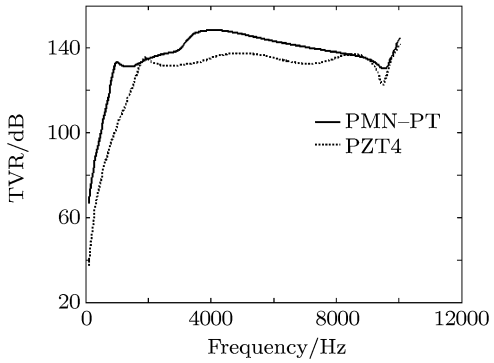


Fig. 4. Transmitting voltage response of free-flooded ring transducers made of PMN–PT and PZT4 materials.

4. Comparison of the acoustic radiation field

The boundary element method together with the finite element method is used to calculate the acoustic radiation characteristics of the free-flooded ring transducers made of PZT4 and PMN–PT materials. The 2D axisymmetric boundary element model of the top half of the free-flooded ring transducer, which is the axisymmetric model of the surface of the transducer, is established. The size parameters of the transducer are the same as those in Subsection 2.2. First, the harmonic response analysis of the free-flooded ring transducer is conducted using the finite element method in ANSYS at a resonant frequency. The surface vibration displacement distribution when the transducer vibrates underwater is obtained. The result is input into the SYSNOISE software applied to the boundary element model of the transducer. The surface vibration velocity distribution of the transducer is obtained. Then, the fluid density and the sound velocity are set in the boundary element model. The symmetric boundary condition is imposed on the model. The acoustic radiated field points are established, including both near-field points and far-field points. Further, the boundary element method is used to calculate the acoustic radiation characteristics of the transducer. When the free-flooded ring transducer is made of PZT4, the acoustic radiation characteristics are calculated at a resonant frequency of 1900 Hz and the driving voltage is 1000 V. When the free-flooded ring transducer is made of PMN–PT, the calculation

method is the same, while the material parameters and analysis frequencies are different. The calculation frequency for the PMN–PT case is 1000 Hz and the driving voltage is also 1000 V. The calculated results are output and processed in the Matlab software. Figure 5 shows the radiated sound pressure level of the free-flooded ring transducer made of PZT4 on the circle of 0.5-m radius from the centre of the transducer in the vertical plane at the resonant frequency of 1900 Hz, in which the results calculated by the boundary element method (BEM) and finite element method (FEM) are compared with each other. The solid line represents the calculated result by the BEM method and the dotted line denotes the calculated result by the FEM method in Section 3. Because the free-flooded ring transducer is axially symmetric and symmetric up and down, only the sound pressure in a range from 0° to 90° directions in the vertical plane is calculated. The radial direction is at 0° and the vertical direction is at 90°. The origin point is the centre of the free-flooded ring. The range of the sound pressure level calculated by the FEM is from 201.76 dB to 195.49 dB, while that calculated by the BEM is from 201.87 dB to 195.63 dB. It is seen that the results calculated by the BEM and FEM are very consistent with each other. The largest difference between them is 0.14 dB, which is caused by the modeling error. Figure 6 shows the radiated sound pressure level of the free-flooded ring transducer made of PMN–PT on the circle of 0.5-m radius from the centre of the transducer in the vertical plane at the resonant frequency of 1000 Hz, in which the results calculated by the BEM and FEM are compared with each other. The solid and dotted lines represent the same meanings as those in Fig. 5. The range of the sound pressure level calculated by the FEM is from 201.3 dB to 196.6 dB, while that calculated by the BEM is from 201.45 dB to 197.01 dB. It is seen that the results calculated by the BEM and FEM are also very consistent with each other for the PMN–PT case. The largest difference between them is 0.41 dB, which is also caused by the modeling error.

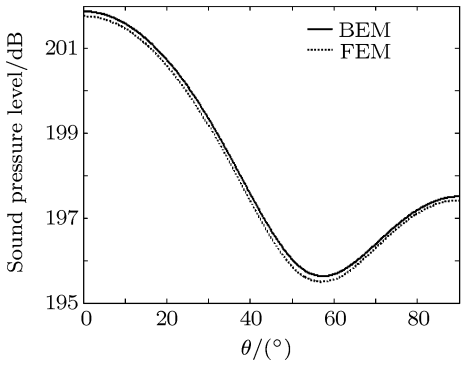


Fig. 5. Radiated sound pressure level of the free-flooded ring transducer made of PZT4 on the circle of 0.5-m radius in a vertical plane at the resonant frequency of 1900 Hz and comparison between the results calculated by the FEM and BEM.

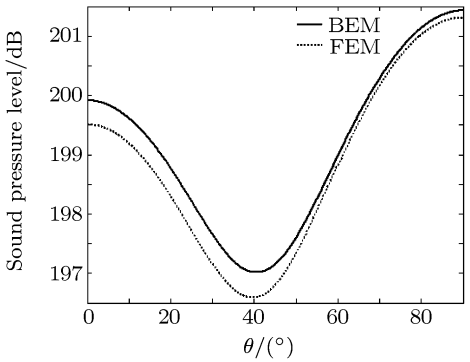


Fig. 6. Radiated sound pressure level of the free-flooded ring transducer made of PMN–PT on the circle of radius 0.5 m in the vertical plane at the resonant frequency of 1000 Hz and comparison between the results calculated by the FEM and the BEM.

Figure 7 shows the radiated sound near-field distribution of the free-flooded ring transducer made of PZT4 at the resonant frequency of 1900 Hz in the vertical plane, calculated by the BEM. Figure 8 shows the radiated sound near-field distribution of the free-flooded ring transducer made of PMN–PT at a resonant frequency of 1000 Hz in the vertical plane, calculated by the BEM. It is shown that the sound pressure is maximum in the fluid cavity of the transducer and decreases gradually in the outside fluid area. It decreases more rapidly in the vertical direction and more slowly in the radial direction.

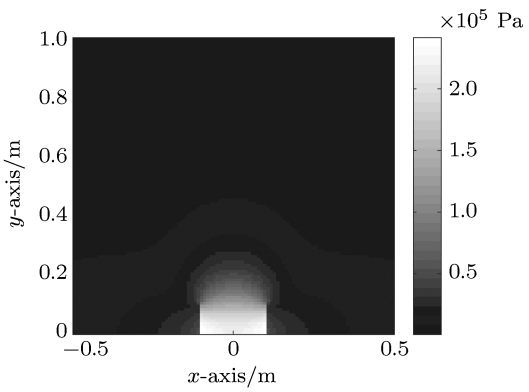


Fig. 7. Radiated sound near-field distribution of the free-flooded ring transducer made of PZT4 at the resonant frequency of 1900 Hz in the vertical plane, calculated by the BEM.

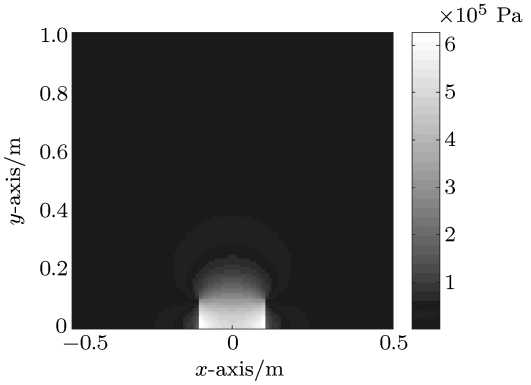


Fig. 8. Radiated sound near-field distribution of the free-flooded ring transducer made of PMN–PT at the resonant frequency of 1000 Hz in the vertical plane, calculated by the BEM.

Using SYSNOISE software, the acoustic radiation far-field directivity of the free-flooded ring transducer in the vertical plane can be calculated using the boundary element method. Figure 9 shows the radiated sound pressure level of the free-flooded ring transducer made of PZT4 on the circle of 1-m radius, converted by the spherical wave law from the far-field sound pressure on the circle of 10-m radius from the centre of the transducer in the vertical plane at the resonant frequency 1900 Hz, in which the results are calculated by the boundary element method and the driving voltage on the transducer is 1000 V. The radial direction is at 0° and the vertical direction is at 90°, the same as before. Figure 10 shows the acoustic radiation far-field directivity of the free-flooded ring transducer made of PZT4 in the vertical plane on the circle of 360° at the resonant frequency 1900 Hz. It is calculated by the boundary element method through utilizing the sound pressure on the circle of 10-m radius from the centre of the transducer. It can be seen from Figs. 9 and 10 that the far-field directivity of the free-flooded ring transducer is greatly different from the near-field directivity. For the near-field case, the sound pressure level in the radial direction is comparable to that in the vertical direction, while for the far-field case, the sound pressure level in the radial direction is much higher than that in the vertical direction. Therefore, the directivity in the vertical plane of the free-flooded ring transducer is formed in the far-field. The sound pressure is maximum in the sound axis direction, which is the same as that in the radial direction of the ring. The sound pressure level in the radial direction, i.e., in the 0° direction, is 196.2 dB and that in the vertical direction, i.e., in the 90° direction, is 175.5 dB. The 3-dB beamwidth of the free-flooded ring transducer made of PZT4 at the resonant frequency 1900 Hz can also be calculated through the results in Figs. 9 and 10, which is 63.6°. Figure 11 shows the radiated sound pressure level of the free-flooded ring transducer made of PMN–PT on the circle of 1-m radius, converted by the spherical wave law from the far-field sound pressure on the circle of radius 10 m from the centre of the transducer in the vertical plane at the resonant frequency 1000 Hz, in which the results are also calculated by the boundary element method and the driving voltage on the transducer is also 1000 V. Figure 12 is the acoustic radiation far-field directivity of the free-flooded ring transducer made of PMN–PT in the vertical plane on the circle of 360° at the resonant frequency 1000 Hz. It is also calculated by the boundary element method through utilizing the sound pressure on the circle of 10-m radius from the centre of the transducer. What is concluded from Figs. 11 and 12 is the same as that for the PZT4 case. The directivity in the vertical plane of the free-flooded ring transducer is formed in the far-field. The sound pressure is maximum in the radial direction. The sound pressure level in the radial direction, i.e., in the 0° direction, is 194.8 dB and that in the vertical direction, i.e., in the 90° direction, is 170.8 dB. The 3-dB beamwidth of the free-flooded ring transducer made of PMN–PT at the resonant frequency 1000 Hz can also be calculated, which is 64.6°. The sound source level of the transducer made of PMN–PT is a little lower and the 3-dB beamwidth is a little wider than that of the transducer made of PZT4 because the resonant frequency of the transducer made of PMN–PT is much lower than that of the transducer made of PZT4.

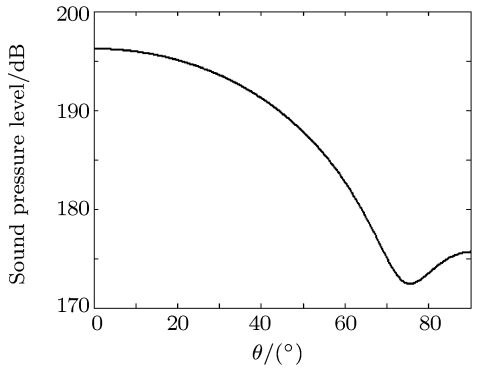


Fig. 9. Radiated sound pressure level of the free-flooded ring transducer made of PZT4 on the circle of 1-m radius converted from the far-field sound pressure in the vertical plane at the resonant frequency of 1900 Hz.

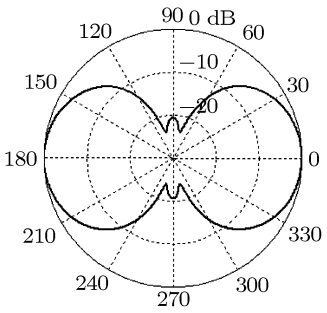


Fig. 10. Acoustic radiation far-field directivity of the free-flooded ring transducer made of PZT4 in the vertical plane at the resonant frequency 1900 Hz.

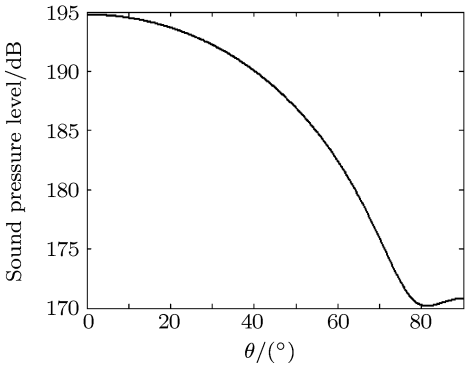


Fig. 11. Radiated sound pressure level of the free-flooded ring transducer made of PMN–PT on the circle of 1-m radius converted from the far-field sound pressure in the vertical plane at the resonant frequency of 1000 Hz.

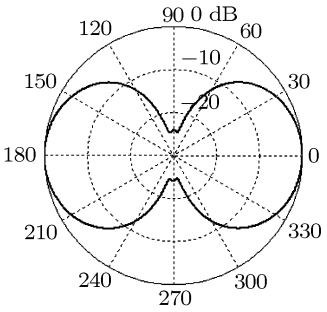


Fig. 12. Acoustic radiation far-field directivity of the free-flooded ring transducer made of PMN–PT in the vertical plane at the resonant frequency 1000 Hz.

5. Conclusions

In this paper, the performances of free-flooded ring transducers made of PZT4 and PMN–PT materials are calculated and compared. First, the approximate calculation formulae of the radial and cavity resonant frequencies of the free-flooded ring transducers are studied. The resonant frequencies of the transducers made of PZT4 and PMN–PT materials are calculated. The results show that the resonant frequency of the free-flooded ring transducer made of PMN–PT is greatly reduced compared with that of the transducer made of PZT4 with the same size in structure. Then, the 2D axisymmetric finite element model of the free-flooded ring transducer is established. The transmitting voltage response of the free-flooded ring transducer underwater is calculated using the finite element method It is shown that the transmitting voltage response of the transducer made of PMN–PT is much larger than that of the transducer made of PZT4. Finally, the 2D axisymmetric boundary element model of the free-flooded ring transducer is established. The acoustic radiation characteristics of the free-flooded ring transducer are calculated using the boundary element method. The calculated results show that the free-flooded ring transducer has a vertical directivity. The 3-dB beamwidth of the free-flooded ring transducer made of PZT4 at the resonant frequency 1900 Hz is 63.6°. That of the transducer made of PMN–PT at the resonant frequency 1000 Hz is 64.6°. The comparison results show that the PMN–PT is a promising material for improving the performance of free-flooded ring transducer. Free-flooded ring transducer made of PMN–PT is well suited for sonar applications which require low frequency, small size and high power.

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