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결합형 유한요소-경계요소 기법에 의한 FFR 형태의 고출력 심해저용 쏘나 변환기 설계

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Design of a FFR-typed High Power Deep-water Sonar Transducer using a Coupled FE-BEM

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Abstract

A high power deep-water sonar transducer of FFR (Free Flooded Ring) type has been designed using a coupled FE-BEM. The present sonar transducer is composed of rectangular piezoelectric ceramics and pie-shaped steels for the advantage of simple fabrication. The dynamics of the sonar transducer is modelled in three dimensions and is analyzed with external electrical excitation conditions. Different results are available such as steady-state frequency response for TX and RX displacement modes, directivity patterns, back-scattering patterns, bandwidths, transmitting voltage responses and receiving sensitivity responses. The TV response shows a very high acoustic pressure of 150 dB/1V (ref 1 μPa at 1m) at 1900 Hz. This ultra high power response of the sonar transducer indicates a new possibility of the sonar transducer development.

1. Introduction

The most recent trend of the sonar transducer development is to design a sonar transducer of wide bandwidth, high power, low frequency. The FFR (Free Flooded Ring) typed sonar transducer is considered to fulfill such designing requirements. The deep-water FFR sonar transducer recently developed by Thomson Marconi Co. shows that 216 dB source level (ref 1 μPa at 1m) with bandwidth of 950~2250 Hz [1]. Their FFR sonar transducer is composed of piezoelectric ceramics which have to be poled in circumferential direction. This skim of materialistic polling is not easy in practice. This paper suggests a new design for a FFR sonar transducer. The aim of the paper is to simulate a FFR sonar transducer using a coupled FE-BEM. The result of the newly designed FFR sonar transducer shows very high acoustic power radiated in the deep water.

Last 20 years have been spent for the development of other FEM and BEM software design tools like ATILA [2,3], ANSYS [4] and PHOEBE [5], PAFEC [6] for sonar transducer design. ATILA and ANSYS use only finite elements instead of boundary elements for radiation conditions in the fluid. PHOEBE and PAFEC use boundary elements for the radiation condition but its calculation is done in single precision. The present coupled FE-BEM uses both boundary elements for radiation conditions in the fluid and double precisions for more correct computational results.

2. Numerical Method

2.1. Coupled FE-BE Method

The following equation (1) is the integral formulation of the piezoelectric equations modelling of a sonar transducer submerged into the water [7]:

$$\begin{aligned}\{F\} &+ [L](A^{\oplus})^{-1}\Psi^{\oplus}_{inc} \\ &= [K_{uu}]\{a\} + [\rho_f\,\omega^2[L](A^{\oplus})^{-1}B^{\oplus}]\{a\} \\ &\quad - \omega^2[M]\{a\} + j\omega[R]\{a\} + [K_{u\Phi}]\{\Phi\} \\ -\{Q\} &= [K_{\Phi u}]\{a\} + [K_{\Phi\Phi}]\{\Phi\} \end{aligned} \tag{1}$$

where

$\{F\}$ Applied Mechanical Force

$\{Q\}$	External Electrical Charge
$\{a\}$	Elastic Displacement
$\{\Phi\}$	Electric Potential
$\Psi^{\oplus}_{inc}$	Incident Pressure
$[K_{uu}]$	Elastic Stiffness Matrix
$[K_{u\Phi}]$	Piezoelectric Stiffness Matrix
$[K_{\Phi u}]=[K_{u\Phi}]^T$	
$[K_{\Phi\Phi}]$	Permittivity Matrix
$[M]$	Mass Matrix
$[R]$	Dissipation Matrix
j	$\sqrt{-1}$
$[L]$	Coupling Matrix at the Fluid-Structure Interface
$A^{\oplus}$	Fluid BEM Matrix [A]
$B^{\oplus}$	Fluid BEM Matrix [B]
ω	Angular Frequency
ρ_f	Fluid Density

Incident pressure of the equation (1) is zero in case of the present sonar transmitter. The isoparametric formulation for 3 dimensional structural elements is well documented by Allik H. et. al. [8]. Each 3 dimensional finite element is composed of 20 quadratic isoparametric nodes and each node has nodal displacement (ax, ay, az) and electric potential (Φ) variables. Table 1 and Table 2 show property values of the materials used for the FFR sonar transducer.

Table1. Piezoelectric Material Properties of PZT4 (Axially Polarized Properties)

Para-meter	Value	Unit	Para-meter	Value	Unit
ρ	7500	Kg/m^3	C^{xy}_{xy}	3.06E+10	N/m^2
C^x_x	1.39E+11	N/m^2	$e^x_{p,z}$	-5.2	N/Vm
C^x_y	7.78E+10	N/m^2	$e^y_{p,z}$	-5.2	N/Vm
C^x_z	7.43E+10	N/m^2	$e^z_{p,z}$	15.1	N/Vm
C^y_y	1.39E+11	N/m^2	$e^{yz}_{p,z}$	12.7	N/Vm
C^y_z	7.43E+10	N/m^2	$e^{zx}_{p,z}$	12.7	N/Vm
C^z_z	1.15E+11	N/m^2	ε^x_x	6.46E-9	F/m
C^{yz}_{yz}	2.56E+10	N/m^2	ε^y_y	6.46E-9	F/m
C^{zx}_{zx}	2.56E+10	N/m^2	ε^z_z	5.62E-9	F/m
K_{33}	0.69	-	K_{15}	0.70	-

Table 2. Properties of other materials used for the FFR sonar transducer

Property / Material	Density ρ $[Kg/m^3]$	Young's Modulus Y $[N/m^2]$	Poison's Ratio γ
Air	1.22	1.411E5	-
Water	1000	0.222E10	-
Steel	7850	207.0E9	029

2.2. Modelling of a FFR typed piezoelectric sonar transducer

In previous designs for FFR sonar transducers, only piezoelectric ceramics are used as driving materials. And their polling direction for each piece of ceramics is circumferential which is not easy to produce in practice. In the present study a new design for the FFR sonar transducer is suggested. Rectangular piezoelectric ceramics are put in series with pie-shaped steel parts to form a circumferential ring structure in whole (Fig. 1). The steel parts are used to connect rectangular ceramics in series. In this design, it becomes easier to fabricate the FFR sonar transducer because rectangular piezoelectric ceramics can be easily produced in regular polling direction. The ceramics are polled in thickness mode.

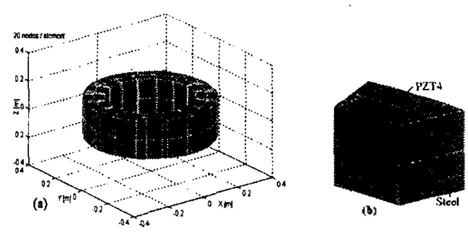

Fig. 1. Three dimensional view of the FFR sonar transducer within the fluid domain (a) and the materialistic composure of the modelled sonar transducer (b).

The piezoelectric FFR sonar transducer has been totally divided into 192 elements with 1440 nodes. The solid-fluid interfacing surface elements are 384 with 1152 nodes. Only one fourth of the total elements are used for formulation of the global coefficient matrix because of the symmetricity of the ring structure. The resulted size of the global coefficient matrix is 1524 by 1524. One important point for loading of electric charges on piezoelectric ceramics is that the typical ratio between the charges on the vertex node and on the mid-side node is -1:4 for the present parabolic shape function of the Serendipity family [7]. The principle of the superposition is applied to common nodes on adjacent elements. Table 3 indicates the dimensions of the FFR transducer.

Table 3. Dimensions of the FFR transducer

Type	[mm]
Inner Radius	213.5
Outer Radius	313.5
Height	271.0

3. Results and Discussions

The coupled FE-BE method has been programmed with Fortran language running at a SUN workstation. Calculation is done with double precision and the program is made for three dimensional structures. It is a common practice to have the size of the largest element to be less than $\lambda/3$. In this paper the interest frequency of the acoustic radiation is less than 2500 Hz, so that $\lambda/3$ is about 0.2 m. Fig. 2 shows the displacement modes of the one fourth of the total structure at 1900 Hz which is the resonance frequency of the present sonar transmitter. The figures are plotted with hidden lines in series for 1/10 intervals of one cycle, so that the change of the structural displacement can be viewed in different phases.

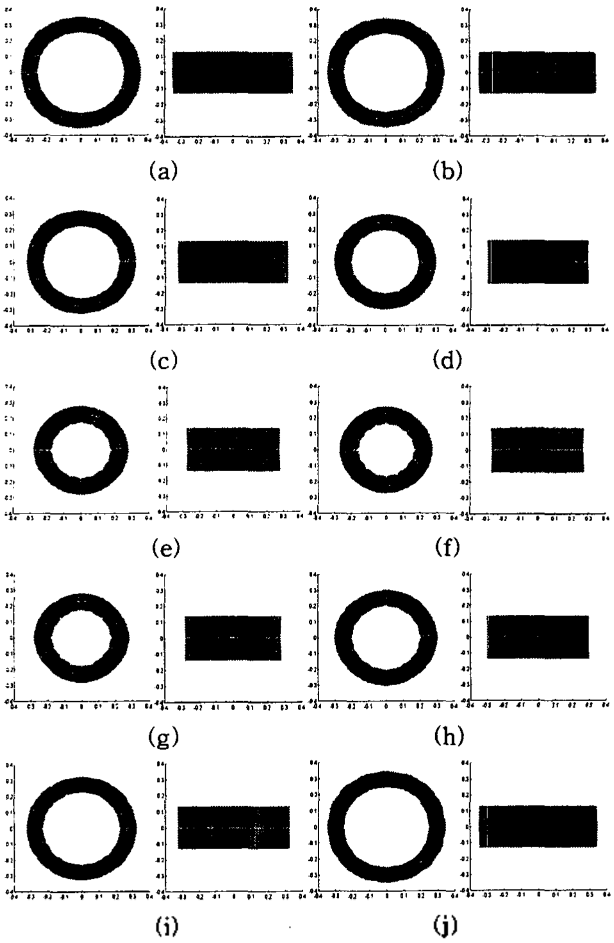

Fig. 2 Displacement modes of the one fourth piezoelectric FFR transducer at 1900 Hz with different phases

Fig. 3 shows beam patterns of the FFR piezoelectric sonar transducer at 100 Hz (a),(c) and at 1000 Hz (b),(d) in polar form. Fig. 3(a) and Fig. 3(b) are for far field (100m) beam patterns and Fig. 3(c) and Fig. 3(d) are for near field (1m) beam patterns. These figures are beam patterns of the modelled transducer as a power sonar projector. And Fig. 4 shows beam patterns of the FFR piezoelectric sonar transducer at 1900 Hz in linear scale in polar form (Fig. 4a), in rectangular form (Fig. 4b), in three dimension (Fig. 4c). Also Fig. 5 shows the same beam patterns as Fig. 4 but in dB scale which is often more desired in expression.

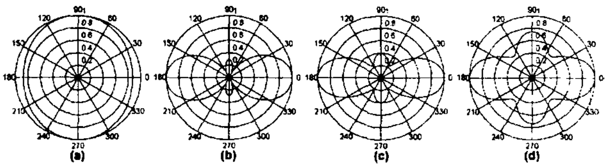

Fig. 3 Beam patterns of the FFR piezoelectric sonar transducer at 100 Hz (a),(c) and at 1000 Hz (b),(d) in polar form. (a) and (b) are for far field (100m) and (c) and (d) are for near field (1m).

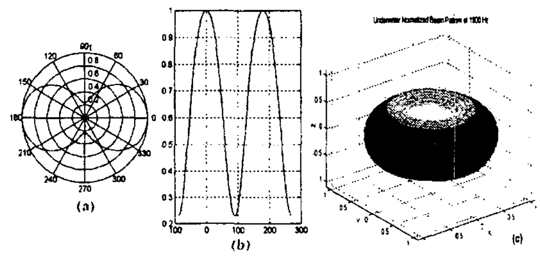

Fig. 4 Beam patterns of the FFR piezo-electric sonar transducer at 1900 Hz in three dimension (c) in linear scale.

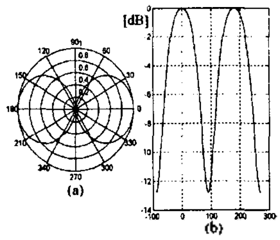

Fig. 5 Beam patterns of the FFR piezoelectric sonar transducer at 1900 Hz in dB scale.

Fig. 6 shows the transmitting voltage (TV) responses of the PZT4 FFT submerged transducer. The TV responses are calculated at 1m from the source origin. The resonance frequency of the present FFR transducer model is about 1900 Hz. And the acoustic power at the resonance is about 150 dB/V (ref 1 μPa at 1m) at both X and Z axes. Fig.

7 shows acoustic radiation impedance (Ri + j Xi) as a function of frequency.

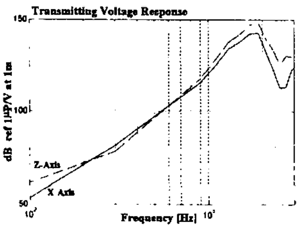

Fig. 6 Transmitting voltage response of PZT4 FFR submerged transducer.

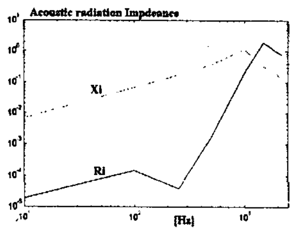

Fig.7 Acoustic radiation impedance (Ri + j Xi) as a function of frequency.

Fig. 8 and Fig. 9 show radial expressions of back-scattered pressures with the Z-axial (Fig. 8) and the X-axial (Fig. 9) incident pressure loadings respectively.

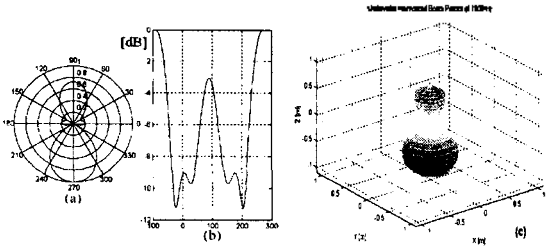

Fig. 8 Radial expressions of back-scattered pressures with the Z-axial incident pressure loading. RS = -1.045 nV/Pa at 1900 Hz

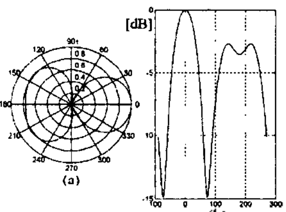

Fig. 9 Radial expressions of back-scattered pressures with the X-axial incident pressure loading. RS = -0.356 mV/Pa at 1900 Hz

4. Conclusion

The dynamics of the FFR sonar transducer of the piezoelectric material had been simulated using a coupled FE-BEM. The displacement mode was temporally figured to show the mode in different phases. In conclusion, this presented coupled FE-BEM code can be used for the design and the analysis of sonar transducers in many different aspects in material and in structure.

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References

[1] S.Debost and M.Edouard, "High power free-flooded ring transducer", Proc. of Institute of Acoustics, Vol. 21, Pt. 1, PP:96-102, 1999.

[2] ATILA Finite-Element Code for Piezoelectric and Magnetostrictive Transducer Modeling Vesion 5.03 User's Manual, Edited by Acoustics Laboratory, Institut Sup'erieur d'Electronique du Nord, Published by MAGSOFT Co., Sep. 1993.

[3] B.Hamonic, "Application of the finite element method to the design of power piezoelectric sonar transducers", Proceedings of the International Workshop on Power Sonic and Ultrasonics Transducers Design, Edited by Hamonic B.F., Decarpigny J.N., Published by Springer-Verlag, PP:143-159. 1988.

[4] D.F.Ostergaard, "A coupled field finite element for magnetostructural analysis", J. Appl. Phys., Vol. 63, No. 8, PP:3185-3187, 1988.

[5] A.Di Meglio, D.T.I.Francis and R.F.W.Coates, "PHOEBE: a 3D transducer modelling environment", Proc. Third European Conf. Underwater Acoustics, Vol. 1, 1996.

[6] S.Morgan, J.Oswin, D.J.W.Hardie, P.C.Macey, "FE/BE modelling of transducer interaction", Proc. of Institute of Acoustics, Vol. 21, Pt. 1, PP:194-201, 1999.

[7] S.S.Jarng, "PZT5 spherical hydrophone simulation using a coupled FE-BE method", J. of the Korean Sensors Society, Vol. 7, No. 6, pp:377-385, 1988.

[8] H.Allik and T.J.R.Hughes, "Finite element method for piezoelectric vibration", Int. J. Numer. Method Eng., Vol. 2, PP:151-157, 1970.