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Dynamic Analysis of Piezoelectric Sonar Transducer

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Key Words: FEM, Piezoelectric Materials, Tonpilz Transducer, Flextensional Transducer

ABSTRACT

Piezoelectric underwater acoustic transducer is a kind of device for underwater detection working as not only an actuator but also a sensor. The technique that can predict acoustical characteristics of transducer is important for robust design of transducer in harsh underwater environment. This paper represents the dynamic analysis of piezoelectric acoustic transducers based on finite element method through USAP software. Two dimensional model of Tonpilz transducer and three dimensional model of Flextensional transducer are generated for the dynamic analysis and some results obtained by USAP are compared with those by ANSYS.

1. INTRODUCTION

Piezoelectric materials have been used for transducer application for a long time. Piezoelectric sonar transducers used for underwater detecting present good performance working as not only an actuator but also a sensor [1,2].

Finite element method (FEM) is a very powerful method for the characteristic analysis of transducer in different circumstances such as in air or in acoustic fluid [3]. Thus, two different finite element (FE) transducer models are generated: one is two dimensional Tonpilz transducer and another is three dimensional Flextensional transducer [4]. Through FEM, modal, harmonic and admittance analysis are conducted for Tonpilz FE model; harmonic and admittance analysis are conducted for Flextensional FE model.

The main tool for the dynamic analysis of these two FE transducer models is a developing software called USAP(Under Water Sensor Analysis Program) based on FEM. It is a very useful software for characteristic analysis of underwater transducers. After preparing needed input files and choosing analysis type, it will make corresponding analysis.

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2. THEORY

2.1 Working description of transducer under water

Fig.1 shows the working circumstance for the underwater transducer. The transducer can be represented by the combination of elastic material part and smart material part. Around the transducer, finite fluid, different kinds of boundary conditions and working conditions are considered and infinite fluid boundary is set for the outmost of it in order to make the working conditions more close to the real world. Finite element model will be generated for both structure and surrounding fluid with all kinds of given boundary conditions, then FEM will be applied to make dynamic analysis of transducers.

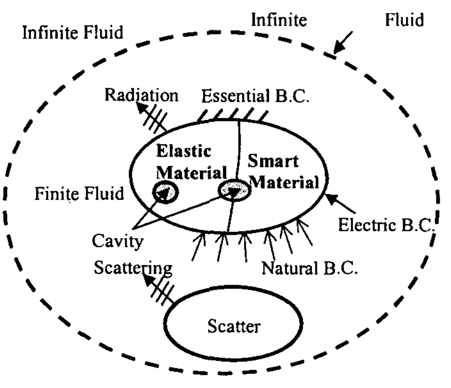

Fig.1 A Schematic Diagram of Underwater Acoustic Transducer

2.2 Analysis of fluid-structure coupled system using FEM

For harmonic analysis of structure in fluid, fluid-structure interaction problem must be considered. In this case, the governing equation of structure is:

$$M\ddot{u} + C\dot{u} + Ku = Qp + f_1 \tag{1}$$

The governing equations of compressible fluid are[5]:

$$\nabla^2 p - \frac{1}{c^2}\ddot{p} = 0 \tag{2}$$

$$\frac{\partial p}{\partial n} = -\rho \ddot{u}_n \tag{3}$$

$$E\ddot{p} + Hp = \rho Q^T \ddot{u} \tag{4}$$

where, ρ : fluid density

p : fluid pressure

c : sound velocity in fluid

u : displacement

In the finite element analysis, variables are all calculated on nodes, thus the following relations are obtained for the mechanical displacement and pressure calculation.

$$\hat{u} = \overline{\mathbf{N}}\mathbf{U} \qquad \hat{p} = \mathbf{NP} \tag{5}$$

where, $\overline{\mathbf{N}}$: elastic field shape function

$\mathbf{N}$: fluid field shape function

$\mathbf{U}$: nodal mechanical displacement

$\mathbf{P}$: nodal fluid pressure

So, from above equations, the coupled equation of fluid-structure interaction case for finite element analysis can be deduced as follows:

$$\begin{bmatrix} \mathbf{M} & 0 \\ \rho\mathbf{Q}^T & \mathbf{E} \end{bmatrix}\begin{bmatrix} \ddot{\mathbf{U}} \\ \ddot{\mathbf{P}} \end{bmatrix} + \begin{bmatrix} \mathbf{C} & 0 \\ 0 & \mathbf{A} \end{bmatrix}\begin{bmatrix} \dot{\mathbf{U}} \\ \dot{\mathbf{P}} \end{bmatrix} + \begin{bmatrix} \mathbf{K} & -\mathbf{Q} \\ 0 & \mathbf{H} \end{bmatrix}\begin{bmatrix} \mathbf{U} \\ \mathbf{P} \end{bmatrix} = \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{f}_2 \end{bmatrix} \tag{6}$$

After transformation, it can be written to the form as

$$\begin{bmatrix} -\omega^2\mathbf{M} + i\omega\mathbf{C} + \mathbf{K} & -\mathbf{Q} \\ -\rho\omega^2\mathbf{Q}^T & -\omega^2\mathbf{E} + i\omega\mathbf{A} + \mathbf{H} \end{bmatrix}\begin{bmatrix} \mathbf{U} \\ \mathbf{P} \end{bmatrix} = \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{f}_2 \end{bmatrix} \tag{7}$$

Meanwhile, if potential form of fluid is preferred, then from the relations:

$$\mathbf{u} = \nabla\phi \qquad p = -\rho\dot{\phi} \tag{8}$$

Another finite element equation for fluid-structure coupled case can be obtained:

$$\begin{bmatrix} \mathbf{M} & 0 \\ 0 & -\rho\mathbf{E} \end{bmatrix}\begin{bmatrix} \ddot{\mathbf{U}} \\ \ddot{\phi} \end{bmatrix} + \begin{bmatrix} \mathbf{C} & \rho\mathbf{Q} \\ \rho\mathbf{Q} & -\rho\mathbf{A} \end{bmatrix}\begin{bmatrix} \dot{\mathbf{U}} \\ \dot{\phi} \end{bmatrix} + \begin{bmatrix} \mathbf{K} & 0 \\ 0 & -\rho\mathbf{H} \end{bmatrix}\begin{bmatrix} \mathbf{U} \\ \phi \end{bmatrix} = \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{g}_2 \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} -\omega^2\mathbf{M} + i\omega\mathbf{C} + \mathbf{K} & i\omega\rho\mathbf{Q} \\ i\omega\rho\mathbf{Q}^T & \omega^2\rho\mathbf{E} - i\omega\rho\mathbf{A} - \rho\mathbf{H} \end{bmatrix}\begin{bmatrix} \mathbf{U} \\ \phi \end{bmatrix} = \begin{bmatrix} \mathbf{f}_1 \\ \mathbf{g}_2 \end{bmatrix} \tag{10}$$

where, $\mathbf{g}_2 = \int_0^t \mathbf{f}_2 dt$.

All system matrices from equation (1) to (10) are listed in Table.1.

Table.1 Matrices for Fluid-Structure Coupled System

Matrix	Description
$\mathbf{M} = \int_V \rho_s \overline{\mathbf{N}}^T\overline{\mathbf{N}}dV$	The Mass Matrix of Structure
$\mathbf{C} = \int_V k\overline{\mathbf{N}}^T\overline{\mathbf{N}}dV$	The Damping Matrix of Structure
$\mathbf{K} = \int_V \mathbf{B}^T\mathbf{C}\mathbf{B}dV$	The Stiffness Matrix of Structure
$\mathbf{Q} = \int_{\Gamma_I} \overline{\mathbf{N}}^T\mathbf{n}\mathbf{N}d\Gamma$	The Area Matrix Coupled Pressure with Structural Load
$\mathbf{E} = \frac{1}{c^2}\int_{\Omega_f} \mathbf{N}^T\mathbf{N}d\Omega$	The Fluid Inertia Matrix
$\mathbf{A} = \frac{\beta}{c}\int_{\Gamma_E} \mathbf{N}^T\mathbf{N}d\Gamma$	The Symmetric Matrix for the Fluid where, $\beta = \frac{\gamma}{\rho_0 c}$ γ : Characteristic Impedance of the material at the boundary.
$\mathbf{H} = \int_{\Omega_f} \nabla\mathbf{N}^T\nabla\mathbf{N}d\Omega$	The Fluid Stiffness Matrix
$\mathbf{f}_1 = \int_{\Gamma_I} \overline{\mathbf{N}}^T\mathbf{n}p_0 d\Gamma$	The Structural Force
$\mathbf{f}_2 = \int_{\Gamma_I} \mathbf{N}^T \frac{\partial p_0}{\partial \mathbf{n}} d\Gamma$	The Force due to an Initial Wave Force Field

2.3 Analysis of piezoelectric–structural coupled system using FEM

Piezoelectric materials are the main function component of transducers. So its working principle is of great importance. Its linear constitutive equations are as follows, which are based on the quasi-static assumption, that is, electric field should be balanced with elastic field.

$$\mathbf{T} = \mathbf{C}^E\mathbf{S} - \mathbf{h}^T\mathbf{E} \qquad \mathbf{D} = \mathbf{hS} + \mathbf{b}^S\mathbf{E} \tag{11}$$

where, $\mathbf{T}$: stress field

$\mathbf{D}$: electrical displacement

$\mathbf{S}$: strain field

$\mathbf{E}$: electric field

$\mathbf{h}$: piezoelectric coupling constant

$\mathbf{b}^S$: dielectric constant

$\mathbf{C}^E$: elastic stiffness for piezoelectric materials

$\mathbf{h}^T$: transpose of piezoelectric coupling constant

As we know, electric field E and electric potential has relation $\mathbf{E} = -\nabla\phi$. Then, in order to make finite element analysis, the following relations are obtained to calculate mechanical displacement and electric potential.

$$\hat{u} = \overline{\mathbf{N}}\mathbf{U}$$
$$\hat{\phi} = \mathbf{N}_\phi \mathbf{\Phi} \qquad (12)$$

where, $\overline{\mathbf{N}}$: elastic field shape function

$\mathbf{N}_\phi$:electric field shape function

$\mathbf{U}$: nodal mechanical displacement

$\mathbf{\Phi}$: nodal electric potential

From above, the finite element governing equation for piezoelectric materials can be obtained[6]:

$$\begin{bmatrix} \mathbf{M}_{uu} & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} \ddot{\mathbf{U}} \\ 0 \end{bmatrix} + \begin{bmatrix} \mathbf{K}_{uu} & \mathbf{K}_{u\phi} \\ \mathbf{K}_{u\phi}^T & \mathbf{K}_{\phi\phi} \end{bmatrix}\begin{bmatrix} \mathbf{U} \\ \mathbf{\Phi} \end{bmatrix} = \begin{bmatrix} \mathbf{F} \\ \mathbf{Q} \end{bmatrix} \qquad (13)$$

All system matrices from equation (11) to (13) are listed in Table.2.

Table.2 Matrices for Piezoelectric-Structure coupled system

Matrix	Description
$\mathbf{M}_{uu} = \int_V \rho \overline{\mathbf{N}}^T \mathbf{N} dV$	The Kinematically Constant Mass Matrix
$\mathbf{K}_{uu} = \int_V \overline{\mathbf{B}}^T \mathbf{C}^E \overline{\mathbf{B}} dV$	The Elastic Stiffness Matrix
$\mathbf{K}_{u\varphi} = \int_V \overline{\mathbf{B}}^T \mathbf{h}^T \mathbf{B}_\phi dV$	The Piezoelectric Coupling Matrix
$\mathbf{K}_{\phi\phi} = \int_V \mathbf{B}_\varphi^T \mathbf{b}^S \mathbf{B}_\phi dV$	The Dielectirc Stiffness Matrix
$\mathbf{F}$	The Point Force
$\mathbf{Q}$	The Point Charge

3. MODELING AND ANALYSIS

3.1 Modeling and analysis of Tonpilz transducer

3.1.1 FE Model of Tonpilz transducer

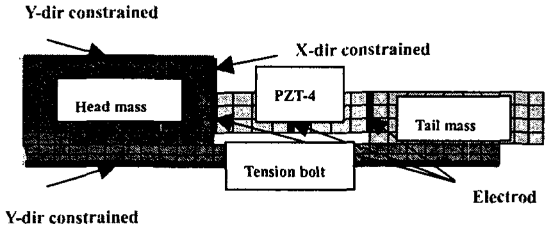

Fig.2 2-D axisymmetric FE model of Tonpilz

The Tonpilz two dimensional 1/2 axisymmetric FE model is shown in the Fig.2. It consists of four parts: head mass, tail mass, tension bolt and PZT-4 ceramics and it is a very typical structure of Tonpilz transducer. This FE model is made up of 4-node quadrilateral axisymmetric elements, which contains 193 elements and 240 nodes. From the boundary condition assigned on the model, one can find its forcing direction is x direction. Thus when it works, it will generate vibration in this direction.

3.1.2 Modal analysis of Tonpilz Transducer (short circuit)

Table.3 shows the modal analysis result for short circuit case of Tonpilz. The first five natural frequencies are listed and compared between USAP and ANSYS analysis results.

Table.3 Modal analysis result (short circuit)

Mode	USAP(Hz)	ANSYS(Hz)	Rel.Error(%)
1st	18833	18639	1.04
2nd	38050	36424	4.46
3rd	48739	48123	1.28
4th	59326	58602	1.23
5th	80681	77311	4.36

Fig.3 shows the first three mode shapes of short circuit case between USAP and ANSYS analysis results. From the comparison of each natural frequency and mode shape, one can find that USAP results have good correspondence with ANSYS results.

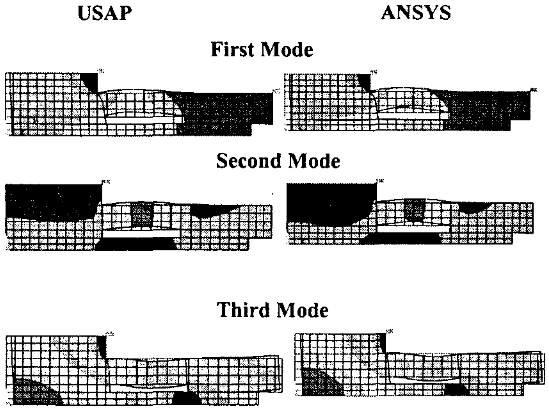

Fig.3 Mode shape comparison (short circuit)

3.1.3 Harmonic analysis of Tonpilz transducer in Fluid

Fig.4 shows 1/2 axisymmetric FE model of Tonpilz transducer in water, which is also made up of 4-node quadrilateral axisymmetric elements and contains 383 elements and 444 nodes. The detailed structure and boundary conditions of Tonpilz is the same as Fig.2 shows. From this figure, Tonpilz transducer is made on contact with water by one surface from head mass and tension bolt. Here, 1V voltage is given to the middle electrode and two side electrodes are grounded.

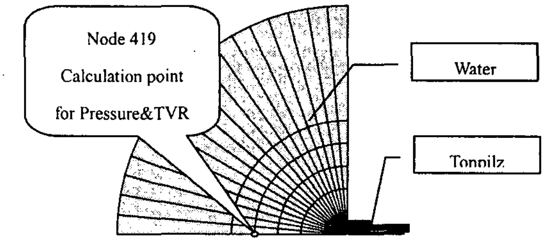

Fig.4 2-D axisymmetric FE model of Tonpilz in water

Through harmonic analysis, TVR (transmitting voltage response) and pressure results of Tonpilz in water at a reference point are obtained as shown in Fig.5. Node 419 is selected for the reference point as shown in Fig.4.

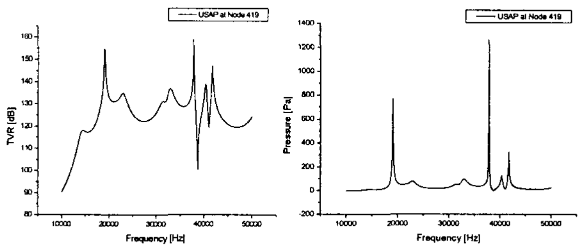

Fig.5 TVR and pressure result of Tonpilz in water

From analyzing Fig.5, the first natural frequency is obtained at around 19045 Hz. At this natural frequency, the pressure distribution in water and the deformed shape of Tonpilz transducer is also obtained as shown in Fig.6

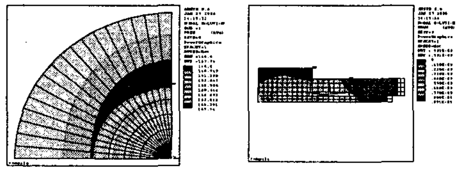

Fig.6 Pressure distribution(left) in water and deformed shape of Tonpilz(right) at first natural frequency

3.1.4 Admittance analysis of Tonpilz transducer in Fluid

Admittance or Impedance is also a very important characteristic for the analysis of transducer. For admittance Y , $Y = G + iB$, where G is conductance, B is susceptance. The analysis result of admittance is presented in Fig.7.

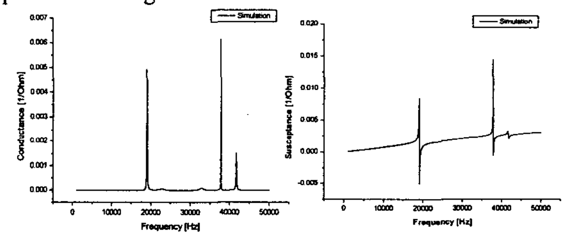

Fig.7 Conductance and susceptance result of Tonpilz

3.2 Modeling and analysis of Flextensional transducer

3.2.1 FE model of Flextensional transducer

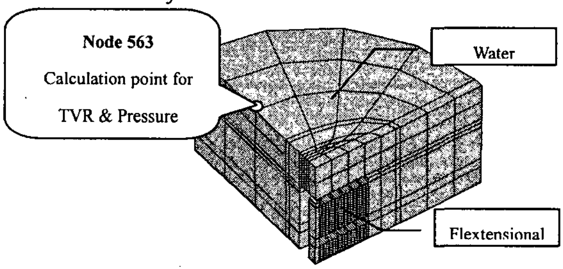

Fig.8 3-D axisymmetric FE model of Flextensional transducer in water

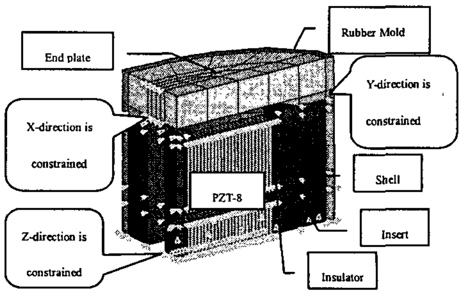

Fig.9 3-D axisymmetric FE model of Flextensional

Flextensional transducer is another type of underwater acoustic transducer. In this paper, certain analyses are also conducted to provide some useful dynamic characteristics of it. Fig.8 and Fig.9 shows 1/8 axisymmetric FE model for Flextensional transducer and Flextensional transducer in water. These two FE models are made up of 8-node brick axisymmetric elements and the former one contains 269 elements and 580 nodes, another one contains 138 elements and 400 nodes. Flextensional transducer consists of six parts: end plate, rubber mold, shell, insert, insulator and PZT-8 stacks.

3.2.2 Harmonic analysis of Flextensional transducer in fluid

Through harmonic analysis, TVR and pressure at a reference point are obtained, node 563 is selected for the reference point as shown in Fig.8. The results are showed in Fig.10.

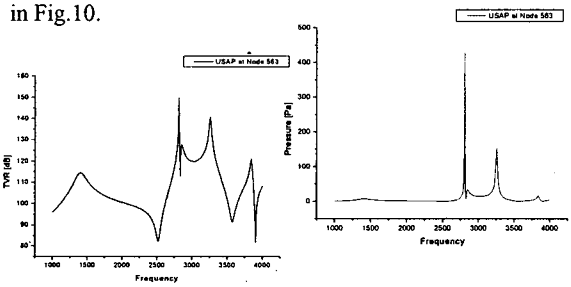

Fig.10 TVR and pressure result of Flextensional transducer in water

From the analysis of Fig.10, the first natural frequency of Flextensioal transducer in water is found at around 2811 Hz. Then based on this frequency, the pressure distribution and the deformed shape of transducer are obtained as shown in Fig.11.

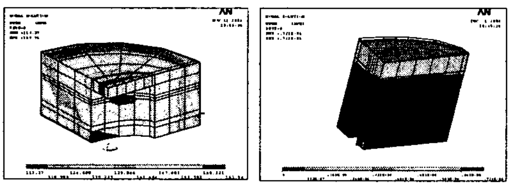

Fig.11 Pressure distribution in water(left) and deformed shape of Flextensional(right) at first natural frequency

3.2.3 Admittance analysis of Flextensional transducer in fluid

Through analysis, conductance and susceptance results are obtained as shown in Fig.12.

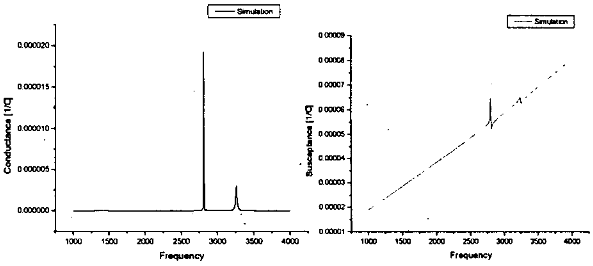

Fig.12 Conductance and susceptance result of Flextensional

4. CONCLUSION

FEM is a very effective method to analyze dynamic characteristics of underwater acoustic transducer. In this paper, axisymmetric FE model of Tonpilz type transducer and Flextensional type transducer are generated and dynamic analyses (harmonic analysis, modal analysis and etc.) are conducted by USAP. Results obtained by USAP reasonably describe the dynamic characteristics of these two types of acoustic transducers. However, there still exists some unsatisfying aspects, and more efforts should be paid to improve its performance.

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