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Development of vector hydrophone using thickness–shear mode piezoelectric single crystal accelerometer

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ABSTRACT

In this study, a vector hydrophone was developed for a towed array sonar system using a shear type accelerometer. In general, inertia type vector hydrophones using accelerometers have higher sensitivity than multimode vector hydrophones. However, the sensitivity still needs to be enhanced as much as possible for practical application. For the purpose, the effect of the structural parameters of a shear type accelerometer on the receiving voltage sensitivity (RVS) of the vector hydrophone was rigorously analyzed, and the structure of the vector hydrophone was optimized to maximize the RVS. The developed vector hydrophone has an external diameter of 23 mm and the minimum RVS over the given frequency range of -201.4 dB. It was also verified that the designed vector hydrophone exhibits the characteristic of a dipole mode beam pattern. Furthermore, a prototype of the vector hydrophone was fabricated with the optimal dimensions, and its acoustic characteristics were measured to verify the validity of the design. The vector hydrophone developed in this work has the highest feasible RVS over the desired frequency range in comparison with other types of vector hydrophone like the multimode hydrophone.

1. Introduction

Underwater acoustic detection equipment commonly used a towed array sonar system (TASS) to detect targets in the underwater. A TASS is a line array of omnidirectional cylindrical hydrophones, i.e. scalar hydrophones. The array consisting of scalar hydrophones is widely used due to the advantage of easy target detection but has difficulty in distinguishing the direction of the target [1–3]. Therefore, researches regarding a vector hydrophone need to be conducted to address this problem. The vector hydrophone not only measures the magnitude of a sound pressure and detects the direction of a source, but also has many advantages such as smaller size and simple structure [4–7]. A vector hydrophone generates a dipole mode beam pattern to detect the direction of a sound source [8]. The dipole mode beam pattern is combined with an omnidirectional mode beam pattern implemented with a scalar hydrophone to make a cardioid mode beam pattern. The generated cardioid beam pattern exhibits a large difference in sensitivity between a receiving direction and the opposite direction; therefore, the direction of the sound source can be conveniently detected. These vector hydrophones are mainly divided into multimode and inertia types.

The multimode vector hydrophone is generally of either a spherical or a cylindrical type [9–13]. These multimode vector hydrophones are relatively convenient to use because cylindrical and spherical hydrophone are already widely used in underwater acoustic detection devices. However, the size of the multimode hydrophone must be increased in inverse proportion to the operating frequency, and the receiving voltage sensitivity (RVS) is relatively low [1]. Meanwhile, the inertia type vector hydrophone using accelerometers exhibits a relatively high sensitivity in low frequencies [14]. Various studies regarding the vector hydrophones using the accelerometer have been conducted over the past several years [15–20]. The piezoelectric accelerometers for the hydrophone can be classified into two types, i.e., compressive and shear types. The compressive type accelerometer uses the longitudinal vibration mode of a piezoelectric element, and the poling direction of the piezoelectric element is parallel to the direction of output voltage. The output voltage of the compressive type accelerometer is determined by the piezoelectric constant d_{33}. The shear type accelerometer uses a shear vibration mode of a piezoelectric element, and the poling direction of the piezoelectric element is perpendicular to the direction of output voltage. Therefore, the output voltage of the shear type accelerometer is determined by the piezoelectric constant d_{15}. The sensitivity of the shear type

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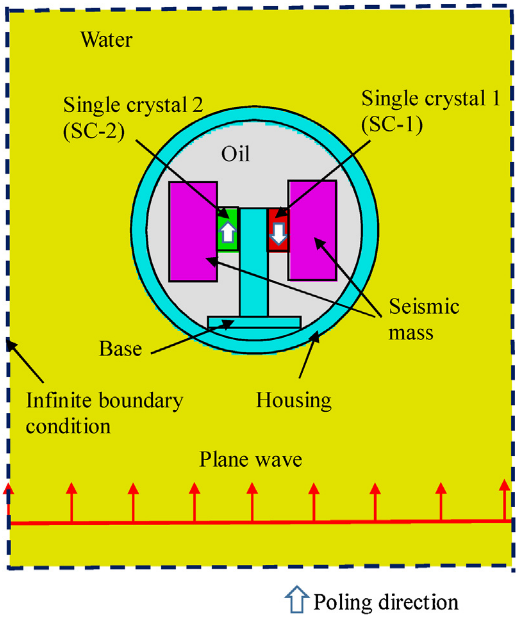

Fig. 1. Finite element model of the basic structure of vector hydrophone.

Table 1
Material properties of the PIN-PMN-PT single crystal of orthorhombic mm2 symmetry [21].

Elastic compliance constants ($10^{-12} m^2/N$)	s_{11}^E	18.27	Piezoelectric constants ($10^{-12} C/N$)	d_{15}	2203
	s_{12}^E	−29.36		d_{24}	114
	s_{13}^E	14.05		d_{31}	460
	s_{22}^E	69.97		d_{32}	−1156
	s_{23}^E	−40.37		d_{33}	782
	s_{33}^E	31.23	Dielectric constants	$\varepsilon_{11}^T/\varepsilon_0$	5000
	s_{44}^E	15.41		$\varepsilon_{22}^T/\varepsilon_0$	1030
	s_{55}^E	131.58		$\varepsilon_{33}^T/\varepsilon_0$	2920
	s_{66}^E	18.76	Density (kg/m^3)	ρ	8102

Table 2
Properties of the materials constituting the vector hydrophone.

Components	Seismic mass (Tungsten)	Circular housing (Aluminum)	Silicone oil
Density (kg/m^3)	19,400	2,700	1,020
Longitudinal velocity (m/s)	5,200	6,149	1,409
Shear velocity (m/s)	2,900	3,097	0

Table 3
Basic dimensions of the components constituting the vector hydrophone.

Components	VB_W	P_W	P_L	P_T	SM_W	SM_L	SM_T
Dimension (mm)	2.5	5.7	10.0	1.5	11.4	38.0	3.0

accelerometer is generally higher than that of the compressive type accelerometer because the d_{15} of a typical piezoelectric material is higher than d_{33}. Furthermore, in numerous applications, shear type accelerometers are preferred because the influence of environmental factors such as ambient temperature change can be conveniently compensated with the shear type accelerometer when compared with compressive type accelerometers.

The concept of vector hydrophone using this shear type piezoelectric single crystal accelerometer was rigorously analyzed in the precedent work of the authors [14]. However, it was on the design of a thickness-shear mode vibrator for the shear type accelerometer, not up to a practical underwater hydrophone. The present work utilizes the result in Ref. [14] to further develop the practical underwater vector hydrophone by employing the thickness-shear mode accelerometer from Ref. [14]. In order to develop a high performance vector hydrophone, it is necessary to derive the optimal structure of the hydrophone to achieve the highest feasible sensitivity over the desired frequency range. There have been no such studies.

In this study, to develop a practical vector hydrophone using the shear type accelerometer, we rigorously analyze the effect of individual structural parameters of the vector hydrophone on the performance using the finite element method (FEM). Based on the results, the structure of the vector hydrophone is optimized to maximize the RVS while presenting the dipole mode beam pattern. The vector hydrophone developed in this work is to have the highest feasible RVS over the desired frequency range in comparison with other types of vector hydrophone like the multimode hydrophone. The validity of the design is verified by fabricating a prototype of the vector hydrophone to exhibit the optimized structure and comparing its measured performance with the simulation results.

2. Finite element analysis of the vector hydrophone

To develop a high sensitivity vector hydrophone using the shear type accelerometer, a finite element (FE) model of the hydrophone was constructed and the RVS of the hydrophone was analyzed with the model. Fig. 1 shows the FE model constructed with the commercial software package PZFlex®. The shear type accelerometer is composed of dual seismic masses, dual piezoelectric elements, and a metallic base [20]. The accelerometer is mounted in a metallic cylinder by connecting the metallic base to the inner surface of the cylinder as shown in Fig. 1. The inner volume of the cylinder is filled with silicone oil. The two piezoelectric elements have opposite poling directions. The electrical output voltage from one of the piezoelectric elements is subtracted from that of the other piezoelectric element to double the response of the accelerometer to an external force while eliminating the effect of environmental factors such as ambient temperature change. The piezoelectric material comprises $Pb(In_{1/2}Nb_{1/2})O_3$-$Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PIN-PMN-PT) crystals with orthorhombic mm2 symmetry [20]. The piezoelectric constant d_{15} of PIN-PMN-PT crystals with the orthorhombic mm2 symmetry poled along $[011]_c$ is much larger than that of other crystals of different symmetries like the tetragonal symmetry poled along $[011]_c$, which is very beneficial for high sensitivity of the accelerometer. The crystals are from Ibule Photonics (Incheon, Korea) and their material properties are presented in Table 1 [21], where s, d, ε, and ρ denote elastic compliance, piezoelectric constant, permittivity, and density, respectively. The superscripts E and T indicate that the properties were measured at a constant electric field and constant stress, respectively. The term ε_0 denotes the permittivity of free space. The materials of the metallic base and the seismic masses are aluminum and tungsten, respectively, whose properties are presented in Table 2.

The structural parameters to design the vector hydrophone are illustrated in Fig. 2. *SP* is the space between the inner surface of the cylinder and the edge of the seismic mass, which was set to 1 mm for the convenience in fabrication. The symbol *VB* denotes the vertical base, *P* the piezoelectric single crystal, and *SM* the seismic mass, whereas the subscripts *W*, *L*, and *T* imply width, length, and thickness, respectively. The inner diameter (I_D) and thickness of the cylinder were set to 20 mm and 1.5 mm, respectively, and the total length of the hydrophone was set to 40 mm in order for the hydrophone to be mountable in an ordinary low frequency TASS. The other initial dimensions of the structural parameters were determined through preliminary FE analysis with the model in Fig. 1 for the hydrophone to operate over the frequency range of our interest.