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Design and Evaluation of Noise Suppressing Hydrophone

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ABSTRACT

This paper describes the design and evaluation of a noise suppressing hydrophone that is robust to external noise without sacrificing its performance as a receiver. To increase robustness of the receiver to the external noise, first, effects of location of the external noise on its performance are analyzed with the finite element method (FEM). Based on the results, geometrical variations are implemented on the structure with additional air pockets and damping layers that work as acoustic shields or scatterers of the noise, and fourteen trial models are developed for the noise suppressing hydrophone structures. The results show that the effect of the external noise is most significant when it is applied to near the mid-side surface of the hydrophone housing. The external noise is isolated most efficiently when two thin damping layers combined with five air pockets are inserted to the circumference of the hydrophone housing. Overall, of the fourteen structural variations of the hydrophone, the best one shows about 87 % reduction in the response of the original structure to external noise.

1. Introduction

Hydrophone for use in deep sea is an array of tonpilz-type piezoelectric transducers as shown in Fig. 1 [1-2]. The tonpilz transducer is composed of a piezoelectric driver that transmits and receives vibration to and from a head mass and a front face exposed to water. On the other end of the driver is a tail mass, which has large mechanical impedance and so permits maximum vibration of the head mass. The hydrophone is mounted in many applications on a vibrating surface and is expected to work as an underwater acoustic signal receiver without sensing external noise. Sources of the exterior noise are structural vibration in the host hull, propeller motion, acoustic cavitation in water stream, fluid flow around the surface of hydrophone, and so on[3]. Acoustic intensity of the external noise is usually high enough to shield an actual underwater acoustic signal, and the hydrophone performance is degraded by the interference of the noise. Hence, there has been deep interest in developing hydrophone structures that are sensitive to the acoustic signal only while robust to the interference, that is, noise suppressing hydrophones.

Prior to the present work, several types of the noise-suppressing hydrophone have been proposed that employ either electrical or mechanical means [1, 3-8]. In general, to design the noise insensitive hydrophone is, firstly, to make the transducer insensitive to noise, and secondly, to isolate the transducer from the noise propagation path. In general, the electrical means focuses on the first method while the mechanical means does on the second method. Representative electrical method is to combine the normal piezoelectric ceramic in the tonpilz transducer with another rather special ceramic so that the whole transducer gains higher robustness to external noise. Zain et al[7] employed "voided" piezoelectric ceramic for the special ceramic in the sense that it is insensitive to transverse noise. When outputs of the two piezoelectric ceramics are appropriately weighted, phase reversed, and combined, the transducer functions as a good hydrophone but a poor accelerometer. However, modification of the tonpilz transducer is a quite difficult job and it may also require modification of the whole electric circuits to process the signal. Hence, in comparison with the electrical means, the mechanical method is more readily acceptable because of its ease of practical implementation. The study in this paper is also on the mechanical method to achieve the noise-suppressing hydrophone structure.

Representative mechanical methods are to use a heavy housing and tail mass in the hydrophone, and to insert various acoustic walls into the housing to isolate the transducer from the noise path. P. Dufourcq[1] proposed air-compensated tonpilz transducer, in which the inner pressure inside the transducer housing is maintained to be the same as external pressure. If a static pressure is applied to the housing and on the head mass, the stress on the ceramic stack is amplified a lot due to the ratio of cross sections of the head mass and ceramic driver. The stress amplification causes noise related problems to the transducer. Dufourcq's method solves this problem by the pressure compensation technique instead of the heavy housing and tail mass. However, it needs complex process to manufacture the hydrophone, and the sensitivity of the hydrophone is decreased a lot in low sea. The second method is placement of air pockets at proper positions inside the hydrophone housing so that the sensing element can be isolated from the noise propagation path due to the impedance mismatch with the metallic housing. The third solution introduces a compliant layer between the head mass and the housing of the hydrophone. The function of the compliant layer is to dynamically decouple the head mass from the housing, and to support static pressure loads on the head face. The main advantages of this method are simplicity of the structure, good efficiency, and no deformation around the transducer, and thus there is no variation of baffling conditions for an array. In this case, selection of the compliant material is very important and the material having compliance longitudinally high and transversely low is known as the best for the layer. The last two methods are more versatile and, if properly designed and combined with each other, a lot of noise suppressing effects can be expected. However, so far, the mechanical methods described above have been applied to development of low noise hydrophone structures in rather separate manner. For effective development, more systematic studies need to be carried out considering all the possible means. Further, configuration of both the isolation and the compliant layers should be determined considering detailed hydrophone response to the various external noises. However, no such rigorous investigation has been performed so far, and this motivates the study in this paper.

In this paper, by means of the acoustic walls consisting of both the air pockets and the compliant layers, we design an effective self noise-suppressing hydrophone structure that shows good robustness to the external noise without sacrificing its receiving performance. The air pockets are expected to serve as acoustic isolation layers to separate the tonpilz transducer from the mounting surface, and the compliant layers as acoustic noise absorbers to attenuate the residual noise that passes through the isolation layers. Hence, the material inside the compliant layer is assumed to have sufficient damping properties to work as an acoustic absorber, and the compliant layer is called as a damping layer hereafter. The damping layers also serve as acoustic walls by providing impedance mismatch onto the noise propagation path. For development of the new structure, first, effects of the external noise on the performance of the hydrophone are investigated with the finite element method (FEM). Second, based on the results, geometrical variations are implemented on the original structure, and fourteen trial models are developed for the noise suppressing hydrophone structures. The structural variation is combination of the additional air pockets and damping layers of various shape. Results of the investigation reveal the best hydrophone structure among the fourteen models.

2. Finite Element Model

The hydrophone considered in this study consists of an array of several tonpilz transducers, a host and back-plate member, an acoustic window, and shielding layers. The hydrophone has the height of 10 cm and the diameter of 25 cm at its fixed boundary. The tonpilz transducer consists of a head mass (aluminum), two pieces of cylindrical piezoelectric ceramics (PZT4)[9], and a tail mass (SUS304). The ceramic elements are stacked with their polarization directions alternately reversed so that they may be connected electrically in parallel, while remaining mechanically in series. A metal rod through the center of the ceramic stack connects the tail mass to the head mass and provides a means for pre-stressing the ceramic stack. The tonpilz transducer is supported by a host structure and a back-plate member made of aluminum. The acoustic window made of polyurethane[10] is mounted against the front faces of the transducer elements and forms part of the water-proof housing of the hydrophone. The thin shielding layer made of onion skin paper[11] is inserted to between each of the transducer elements and the back-plate. Also thin layers made of Corprene DC-100[12] are inserted to between the head masses of the transducer. The thin shielding layers contribute to reducing mechanical or acoustical cross-coupling of the tonpilz transducers, and that leads to reduction of internal noise.

To analyze the hydrophone response to external noise, a three-dimensional finite element model has been constructed that includes all the details of the tonpilz transducer described above (Fig. 1). The modeling and analysis is carried out with a commercial finite element analysis package[13], ANSYS. Considering symmetry conditions, only a quarter of the whole sensor including an outside fluid medium is modeled. All the displacements are fixed at the upper part of the host structural member of the hydrophone that connects with the platform via bolts. To prevent reflection of an acoustic wave by the fluid medium, pressure relief conditions are applied to all the outside fluid boundaries. In this paper, we are not interested in the generation mechanism or source of the external noise, and its transfer characteristics in the fluid medium. Instead, we care about the effect of the noise that eventually reaches the hydrophone surface by any means. That is, we are concerned more about the propagation path of the noise inside the hydrophone, so that we can find the optimal position of the acoustic walls to be inserted. Further, the noise coming through the front window can not be distinguished from desired acoustic signals by structural means, and all the noises are assumed to come from the fixed boundary and side surface of the hydrophone. Hence, the external noise is arbitrarily divided into five representative load cases according to their locations of application to the hydrophone surface as shown in Fig. 1. Each load case describes linear pressure loading all around the circumference of the hydrophone surface. The load case 1 describes the external noise component originated from the host structural vibration, and is loaded on all around the fixed boundary of the housing at which the hydrophone is connected with the host structural member. The noise components applied on the outside surface of the hydrophone are described as from the load case 2 to the load case 5. These load cases describe the noise components transferred through the fluid medium, possibly originated from propeller motion, acoustic cavitation in water stream, fluid flow around the surface of the hydrophone, and so on[1]. The load case 2, in particular, describes the noise component positioned at the edge of the front acoustic window. The noise components at the side surface of the hydrophone are modeled as concentrated loads spaced at equal distance from each other, and are described as from the load case 3 to the load case 5. Actually the external noise is widely distributed over the hydrophone surface and is not concentrated on specific points as in this model. However, for the purpose of selecting most noise sensitive position of the hydrophone surface, this concentrated stress model is more efficient way of investigation. For the input noise signal, an impulsive pressure that is 1,000 Pa in magnitude and 0.01 sec. in duration is applied for each load case. The response of the hydrophone with the external noise locations is investigated with the finite element method through transient response analysis.

3. Influence of the External Noise Locations

Transient responses of the hydrophone detected by the three tonpilz transducers S1, S2, and S3 in Fig. 1 are shown in Figs. 2-4. These three transducers are selected as representative sensing elements because they can represent all the other transducers by means of structural symmetry of the hydrophone.

Considering the difference of their positions, the responses of the three transducers are quite similar. In magnitude of the responses, the transducer S3 located near the side surface of the hydrophone is most sensitive to the noise, while the transducer S3 is most robust to the noise. This is explained by the propagation path of the noise components. All the noises are injected through the metallic housing of the hydrophone. The transducer S3 is closest to the metallic housing, and most vulnerable to the noises. For the noises to reach the transducer S1, however, they have to go through the attenuative polymeric acoustic window and onion skin paper layers, and thus undergo too much attenuation to generate significant responses. Maximum response of the transducer S3 is about 0.013 mV for the load case 1, and 0.92 mV for the load case 4, respectively. Hence, in designing the low noise structure, more emphasis should be placed on protecting the transducer S3 from the external noise.

For the same magnitude of the external noises, the structure–borne noise, the load case 1, causes much smaller responses than the others. Of the five load cases, the load case 1 is different from the others in that the noise transfers to the hydrophone through the structural connection (fixed boundary), while for all the other cases through the water. Besides, its direction of propagation is vertical, i.e. parallel to the direction of the transducers. Hence, the noise component is very likely to keep propagating and being reflected back in the vertical path inside the metallic housing, and to have less chance to reach the transducers. Further, the noise responses to the load case 2 are also small compared with those to the load cases 3-5. As mentioned in section II, the load case 2 describes the vertical noise component positioned at the edge of the front acoustic window. Similarly to the load case 1, the noise mostly transfers to the stepped hydrophone housing, and the host structural member, in turn. The noise partially deviates from the vertical direction, and transfers to the tonpilz transducers, and thus not much influence. Pictorial description of the power flow of the noise inside the hydrophone, Fig. 5(a), clearly verifies this description. On the other hand, the noises applied to the curved side surface of the hydrophone are directed to the piezoelectric sensing elements from the beginning, and after passing through the relatively unattenuative metallic housing are very likely to have direct influence on the transducer responses. Of the load cases 3-5, the load case 4 generates the highest responses in all the transducers. As mentioned in the previous section, the load case 4 describes the external noise component applied to the middle of the side surface. As shown in Fig. 5(b), it has the shortest propagation path inside the housing, and has the most direct transfer direction to the piezoceramics. This result shows that placement of the air pockets and damping layers around the position of load case 4 will be more efficient than any other locations in blocking the propagation of the external noise to the sensing element. Hence, in the analysis of the effects of structural modification and damping layer properties in the following sections, application of the external noise follows the load case 4. However, considering the difference in its nature, we also check the noise reduction efficiency of our models for the load case 1, too, in the following analyses.

4. Influence of the Structural Modifications

The hydrophone structure is modified with the air pockets and the damping layers based on the above results. Additional air pockets and damping layers are inserted to side parts of the host structural member of the hydrophone as shown in Fig. 6. In the figure, five air pockets are denoted as A1, A2, A3, A4, and A5, and three damping layers as D1, D2, and D3. The damping layers have the material properties of onion skin paper, for the moment, that is Young's modulus of 0.8 Gpa, relative damping coefficient (α in Rayleigh damping for FEM analysis[14]) of 0.2, Poisson's ratio of 0.4, and density of 1,000 kg/m^3. The structure of the hydrophone housing is modified with various combinations of the air pockets and the damping layers, and fourteen different hydrophone structures have been devised as shown in Table 1. Before the dynamic transient response analysis, static failure analysis has been performed first for all the models in the Table 1 in order to check their structural stability. Within the test range of the hydrostatic pressure over the hydrophone surface up to 5×10^6 Pa corresponding to the underwater depth of about 500 m, no structural weakness has been observed for all the models, and that verifies stability of the models. In case of the modified structures, the transient analysis is carried out only for the load cases 1 and 4 following the conclusion of § 3. The best model of the hydrophone is selected among the fourteen trial structures based on the transient analysis results.

The results compared with the response of the original hydrophone are shown in Fig. 7 for the load case 1, and Fig. 8 for the load case 4, respectively. S1, S2, and S3 are the tonpilz transducers in Fig. 1. In case of the load case 1 that describes the host structural vibration in the hull, all the models show more than 70% reduction in response to the noise compared with that of the original hydrophone response. The models 1, 2, 5, and 8 that use the air pockets only have the reduction up to about 70% of the response of the original. On the other hand, the models 4, 7, 10, 11, 12, and 13 have the reduction as much as about 78% of the response of the original. These models use at least two air pockets and two damping layers in common. This result shows that the air pockets reflect most (70%) of the host structural vibration and the additional damping layers absorb and reflect the remained 8% of the residual noises, which verifies higher efficiency of the air pockets in reducing the noise level. However, it is more effective in isolating the transducer from the host structural vibration if the air pockets are combined with the damping layer than single use of either of them.

In case of the load case 4, all the models reveal the response decreased more than 60% of the original. Variation of the response over the models is somewhat similar to that in Fig. 6. S1, S2, and S3 transducer of the model 12 has the response about 25%, 25%, and 35% of that of the original, respectively. When the results for the load case 1 and load case 4 are considered together, the best model for the noise-suppressing hydrophone is the model 12 that has the modified structure with five air pockets and two damping layers.

5. Conclusion

This paper describes the design and evaluation of self-noise suppressing hydrophone structures that show good robustness to external noise without sacrificing its performance as a receiver. The analysis has been performed with the finite element analysis method. The results show that the effect of the external noise is most significant when it is applied to near the mid-side surface of the hydrophone. The noise transferred to this region from the surrounding fluid medium is isolated most effectively when five air pockets combined with two thin damping layers are inserted to the circumference of the hydrophone housing. The structure corresponds to the model No. 12 of the fourteen structural modifications tried in this paper. Overall, in the best structure, the noise level is reduced down to about thirteen percent of that of the original structure.

The results in this paper show that when the hydrophone structure is properly designed with various acoustic wall (air pockets and damping layers), a lot of noise level reduction can be achieved, and that amounts to 87 % in this paper. The noise suppressing hydrophone structure developed in this paper can reduce the burden of other parts of the whole underwater sensor system by providing much clearer acoustic signals, and make a lot of contribution to the improvement of the system performance. Further, the design procedure in this paper can be applied to other types of underwater transducers, too, like flextensional transducers, for development of low noise sensors.

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Table 1. Modified models of the hydrophones structure with insertion of either air pockets or damping layers. The damping layers have the material properties of onion skin paper[11].

Model no.	Air pockets					Damping layers		
	A1	A2	A3	A4	A5	D1	D2	D3
1	O	⊗	⊗	⊗	⊗	⊗	⊗	⊗
2	O	O	⊗	⊗	⊗	⊗	⊗	⊗
3	O	O	⊗	⊗	⊗	O	⊗	⊗
4	O	O	⊗	⊗	⊗	O	O	⊗
5	O	O	⊗	O	⊗	⊗	⊗	⊗
6	O	O	⊗	O	⊗	O	⊗	⊗
7	O	O	⊗	O	⊗	O	O	⊗
8	O	O	⊗	O	O	⊗	⊗	⊗
9	O	O	⊗	O	O	O	⊗	⊗
10	O	O	⊗	O	O	O	O	⊗
11	O	O	●	O	O	O	O	⊗
12	O	O	O	O	O	O	O	⊗
13	O	O	O	O	O	O	O	O
14	●	O	O	O	O	O	O	O

O : Insertion, ⊗ : No insertion

● : Insertion of the air pocket filled with the compliant material

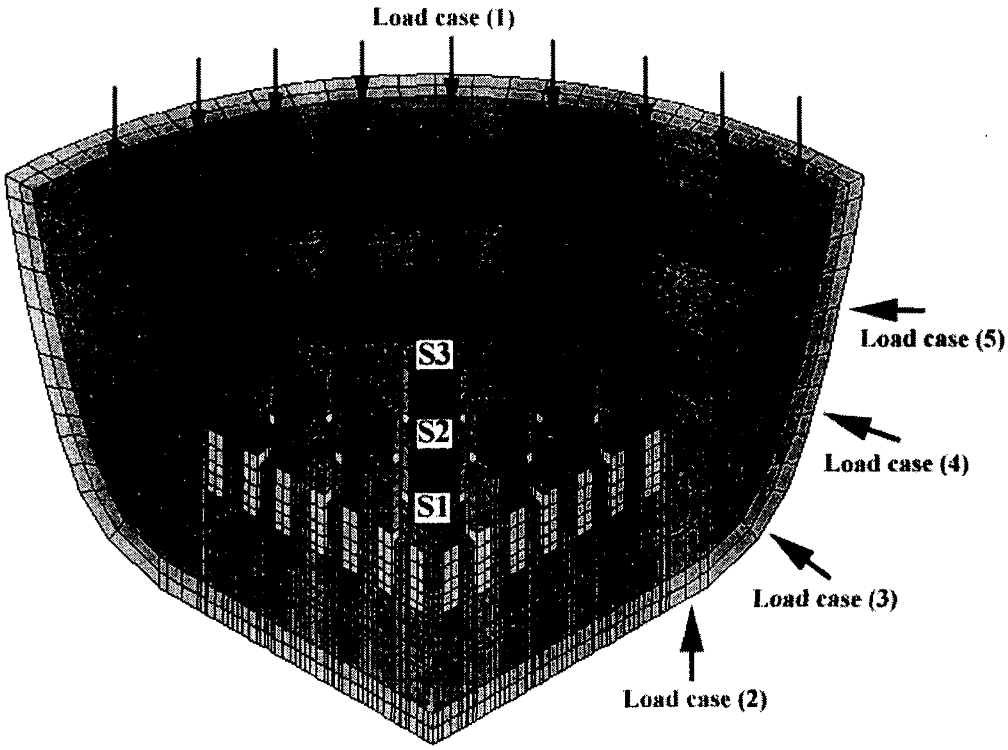


Fig. 1. Finite element model and applied load positions for the transient analysis of the hydrophone.

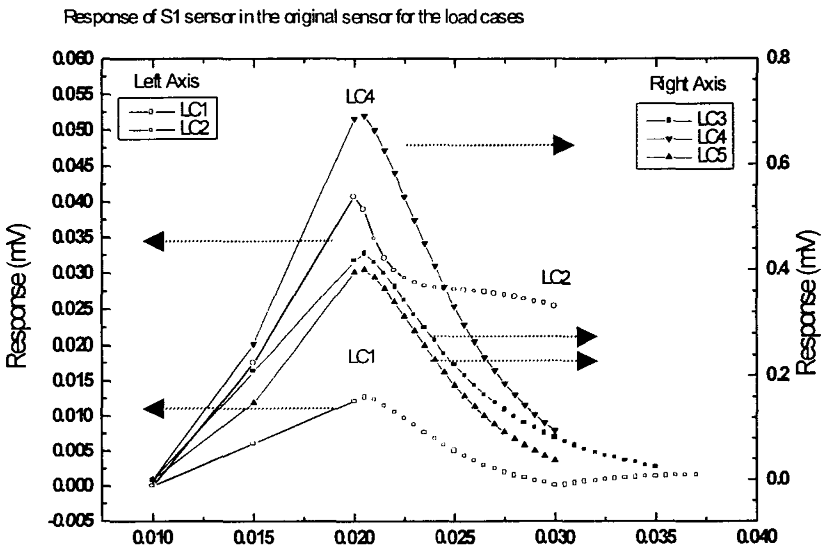


Fig. 2. Transient responses of the S1 sensor for the external noise applied on surface of the original hydrophone.

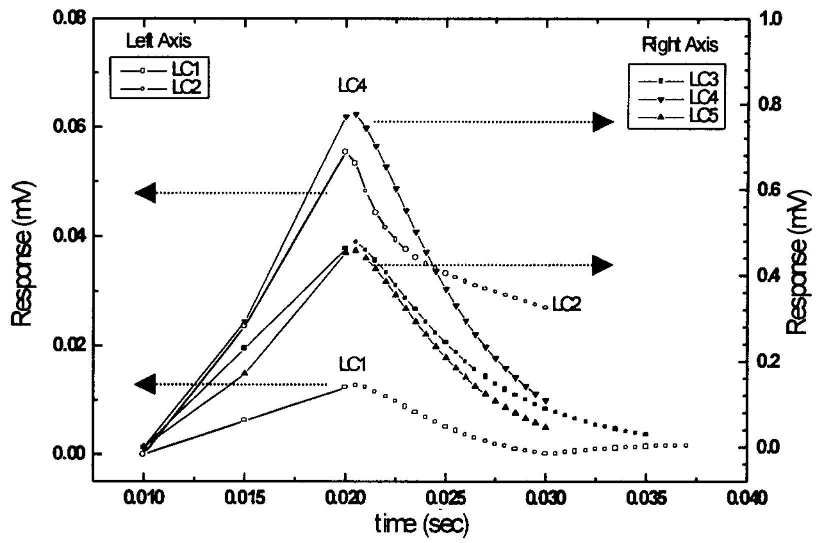


Fig. 3. Transient responses of the S2 sensor for the external noise applied on surface of the original hydrophone.

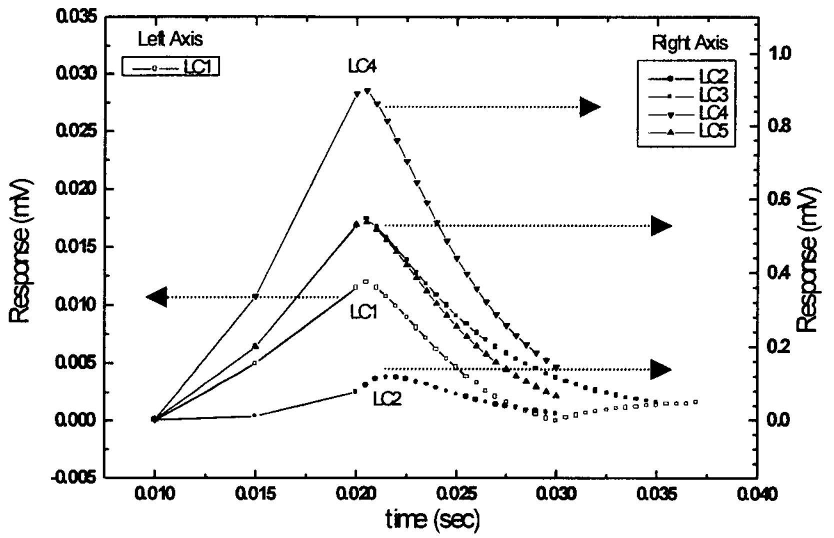
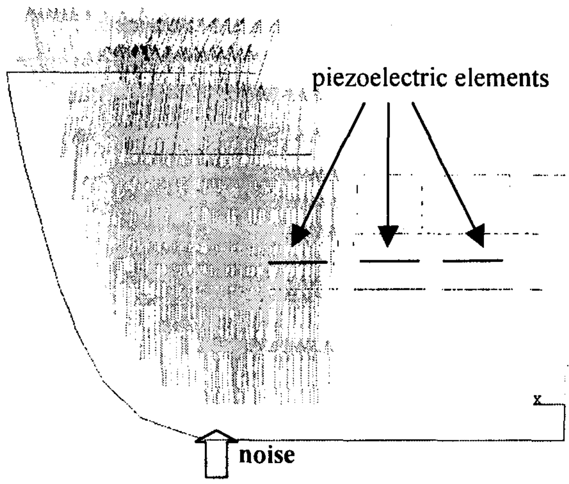
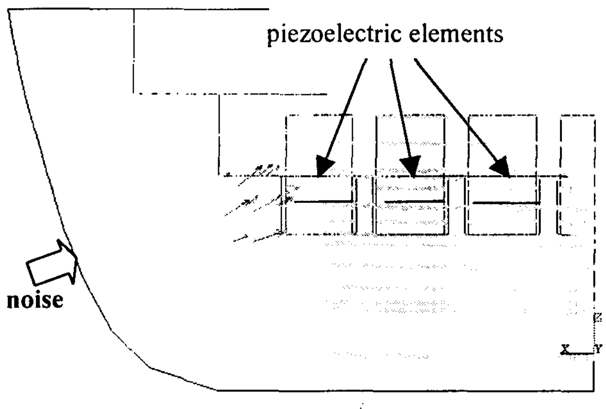


Fig. 4. Transient responses of the S3 sensor for the external noise applied on surface of the original hydrophone.

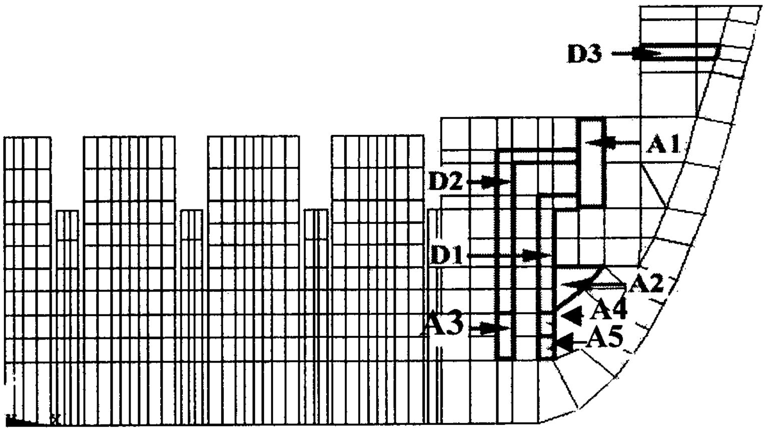


(a)



(b)

Fig. 5. Power flow of the stress wave inside the hydrophone for each load case (a) load case 2, (b) load case 4.



A1, A2, A3, A4, and A5 : Air Pockets
D1, D2, and D3 : Damping Layers

Fig. 6. Inserted positions of air pockets and damping layers for the modification of the hydrophone structure.

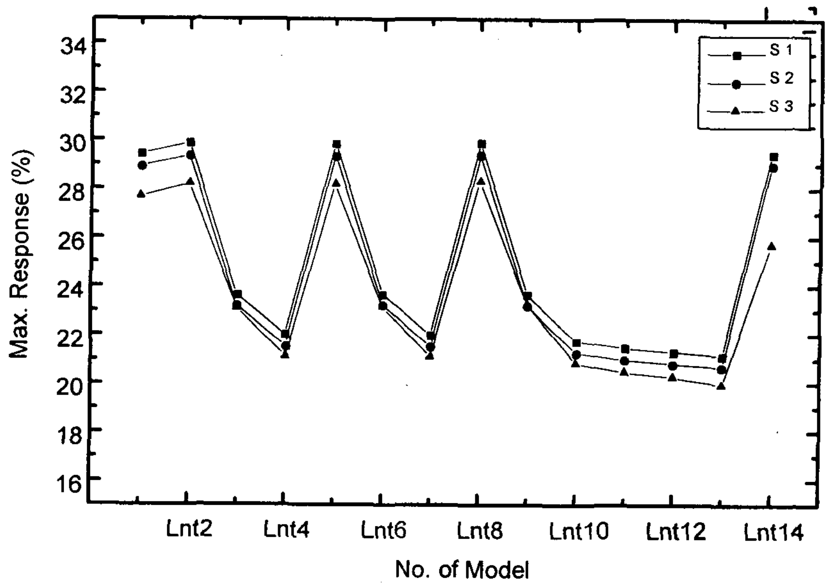


Fig. 7. Responses of the modified hydrophone structure for the load case (1). Vertical axis represents ratio of the maximum response of each model to that of the original structure.

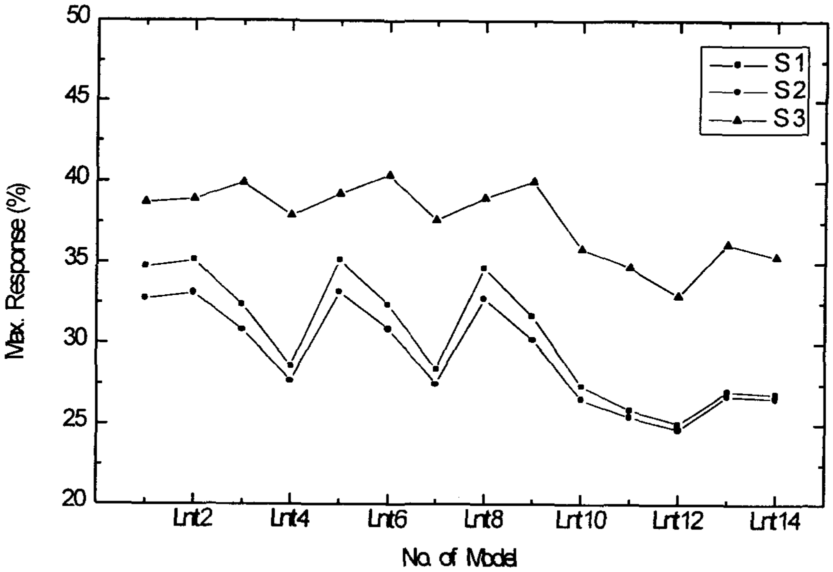


Fig. 8. Responses of the modified hydrophone structures for the load case (4). Vertical axis represents ratio of the maximum response of each model to that of the original structure.