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Experimental Study on the Vibration Transfer Function of a Small Autonomous Underwater Vehicle

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Abstract

This paper presents the experimental results about vibration characteristics of a small autonomous underwater vehicle (AUV) named OKPO 300. The autonomy of AUVs leads to the increased use of AUVs in scientific, military, and commercial areas because their autonomy makes it possible for AUVs to be utilized instead of humans in hazardous missions such as mine countermeasure missions (MCMs). It is impossible to use devices with electro-magnetic waves for gathering information in an underwater environment. Only sonar systems that use sound waves can be utilized underwater, and the performance of sonar can strongly affect the autonomy of AUVs. Since a thruster system that combines a motor and propeller in a single structure is widely used as the propulsion system of an AUV and is mounted on the outside of the AUV's stern, the vibration generated by the thruster system can be transferred throughout the shell of the AUV from the stern to the bow. The transferred vibration can affect the performance of various sonar systems that are installed in the AUV such as side-scan sonar or forward-looking sonar. Therefore, it is necessary to identify the effect of the transferred vibration of the AUV on the sonar systems. Even if various numerical methods were used to analyze the vibration problem of surface ships, it would be hard to apply numerical methods of the surface ships to identify the vibration phenomena of an AUV because of the underwater environment. In this work, an experimental study with OKPO 300 and an impact hammer was carried out to analyze vibration features of an actual small AUV in the air. Based on the experimental results, the frequency response function of vibration is presented. Based on the experimental results of this study, the natural frequency of OKPO 300 was confirmed, and the possibility of estimating the vibration characteristics of AUV using the transfer function method was shown.

Key words : Autonomous underwater vehicle, Underwater radiated noise, Frequency response function, Experimental analysis, Vibration transfer function

Ⅰ. Introduction

The autonomy of autonomous underwater vehicles (AUVs) leads to the increased use of AUVs in scientific, military, and commercial areas because the autonomy makes it possible for AUVs to be utilized instead of humans in hazardous missions such as mine countermeasure missions (MCMs). They require a high level of autonomy in order to gather information about the environment

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without human intervention. It is impossible to use devices with electro-magnetic waves for gathering information in an underwater environment. Only sonar systems that use sound waves can be utilized underwater. Self-radiated noise can affect the performance of sonar systems on an AUV. Therefore, it is necessary to reduce self-radiated noise of AUVs in order to increase their autonomy.

It is essential to identify the mechanism of self-radiated noise including its source and propagation path in order to reduce it. It is important to estimate and consider self-radiation noise in the initial design phase as reducing self-radiation noise after the construction of AUVs is very difficult. However, even though it is important to identify self-radiated noise of an AUV, there is little research about it. There are some studies that estimate self-radiated noise from a fixed vibration source based on numerical tools such as the finite element method (FEM) and the boundary element method (BEM) for a surface ship. Chen et al. (2003) carried out a nonlinear hydro-elastic analysis of a moored box-type floating in a body using linear and nonlinear three dimensional hydro-elastic equations. Ohkusu and Namba (2004) carried out a numerical analysis to predict the bending of a very large floating structure of thin and elongated rectangular-plate configurations such as a floating airport. Askari and Daneshmand (2009) proposed a finite element method using the Galerkin method to analyze the coupled vibration of a partially-fluid-filled cylindrical container with a cylindrical internal body. Sigrist and Garreau (2007) used the finite element method to carry out a coupled fluid-structure dynamic analysis with a pressure-based formulation, using the modal and spectral method. Ugurlu and Ergin (2008) investigated the effects of different end conditions on the response behavior of thin circular cylindrical shell structures fully in contact with flowing fluid, using the finite-element and boundary element methods.

Although numerical methods can be used to estimate self-radiated noise for surface ships, these methods require a long calculation time to analyze new cases when the conditions for self-radiated noise are changed such as the vibration frequency or the length of the structure. Since an AUV is usually slender, has a cross section similar to a circle and is surrounded with water, the self-radiated noise phenomena of an AUV will be different from that of a surface ship. Thus, it is quite difficult to apply numerical methods used for surface ships to the case of AUVs, and some research carried out experiments to identify the variation of an AUV. Min et al. (2011) carried out an experimental study on the hydro-elastic analysis of a circular cylindrical shell and found that the natural frequency of the cylindrical shell in the semi-submerged case is greater than that in the air for the same mode. However, since this experimental research only deals with a big AUV with an inner vibration source, it is not suitable to apply its results to a small AUV with a thruster.

One alternative to numerical methods for the estimation of self-radiated noise of an AUV is the transfer function method. In the transfer function method, the transfer function is defined as the relationship between a single source or propagation paths and the derived self-radiated noise level. Therefore, it is possible to simplify the generating mechanism of self-radiated noise by dividing the vibration source and the travelling paths, and the total self-radiated noise of the structure is finally calculated by the summation of a transfer function about various sources and propagation paths. If there is little difference between two structures, the transfer functions of the two structures can be similar, so the transfer function method could be an effective method for estimating self-radiated noise of an AUV at the initial design stage.

In this paper, several experiments were performed to identify the transfer function of vibration for a small AUV, which is named OKPO 300, and an impact hammer. And the experimental results are presented. The transfer function of vibration for a small AUV is defined based on the experiment results.

Ⅱ. Research method

The transfer function of vibration is usually defined as a mathematical representation of the relationship between the source of a vibration and the output of a system that can be described as a linear time-invariant system (Jefferys, Broome and Patel, 1984; Halevi and Wagner-Nachshoni, 2006), for example, the transferred vibration or the generated acoustical generation. The frequency response function is one of the transfer functions about vibration and describes the relationship between the source of a vibration and the output of a system in the frequency domain.

In an experiment with an impact hammer, the frequency response function can be described as a function of the relationship between the particular point that was hit by the impact hammer with a force gauge and another point on the structure that is attached to an accelerometer by measuring the excitation force and the response acceleration.

The resulting equilibrium of such a system for an experiment with an impact hammer can be represented by the following differential equation:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = y(t). \quad \cdots\cdots\cdots\cdots \quad (1)$$

where x(t) is the output of the system and y(t) is the excitation force in the time domain.

Through Laplace transformation, the second-order differential equation given in Eq. (1) can be represented by the following algebraic equation:

$$\{Ms^2 + Cs + K\}X(s) = Y(s). \quad \cdots\cdots\cdots\cdots \quad (2)$$

The transfer function of the system can be denoted by

$$H(s) = \frac{Y(s)}{X(s)}. \quad \cdots\cdots\cdots\cdots \quad (3)$$

In Eq. (3), $X(s)$ is the output of the system, and $Y(s)$ is the excitation force in the frequency domain.

Although the frequency response function can provide the relationship between the excitation force and the vibration acceleration and is widely used to analyze the vibration feature of structure, it needs to analysis the transfer function of acceleration because the acoustic wave can be mathematically described as acceleration. Thus transfer function for vibration and acceleration can be efficient to effect of the vibration on the sonar system of the AUV. In this paper, the transfer function which is described (4) was used to verify the effect of vibration on the sonar system.

$$TF = 20\log\left(\frac{a_f}{a_i}\right). \quad \cdots\cdots\cdots\cdots \quad (4)$$

In Eq. (4), is a measured acceleration for the target point and is a measured acceleration for the vibration source.

Ⅲ. Research results

1. Experimental condition

Experiments were performed to obtain the vibration transfer function of an AUV, OKPO 300, with an impact hammer. OKPO 300 in [Fig. 1] was developed and manufactured by Daewoo Shipbuilding and Marine Engineering (DSME) Co. Ltd. The length of the AUV is 1.8 m, and its diameter is 0.26 m. The detailed specifications are shown in Table 1.

Experiments on the vibration analysis of OKPO 300 were performed in the air, and OKPO 300 was hung by slings connected to two points on both ends.

A thruster system that combines a motor and propeller in a single structure is widely used as the propulsion system of an AUV and is mounted outside of the AUV's stern, so the impact hammer was determined to be the source of the vibration instead of the internally mounted exciter. The accelerometer for measuring the transferred vibration through OKPO 300 was also mounted outside of the AUV for the same reason. The excitation position by the impact hammer was chosen at the stern of the AUV, where the thruster system is connected, and 4 points were selected in the clockwise direction by 90 degrees intervals from the top of backward view. The transferred vibration acceleration measure point was at the head of the AUV, where forward-looking sonars or range sonars are usually mounted. [Fig. 2] describes the points of excitation for the experiments.

The DYTRAN 3148 was used as an accelerometer sensor, and this sensor has a capacity to measure up to 10 kHz. The PCB impact hammer was used as the vibration source. The Benston Fieldpaq II, a 24-bit, 4-channel dynamic signal acquisition board, was used for acquiring data and analyzing the vibration and acceleration signals.

[Fig. 1] Overview of OKPO 300.

[Fig 2] The location of excitation points by the impact hammer.

<Table 1> Specifications of OKPO 300

	Description
Vehicle Dimensions (L ×D)	1.8 ×0.26 m
Hull Material	Acrylic
Weight (in air)	55 kg
Maximum Operating Depth	300 m

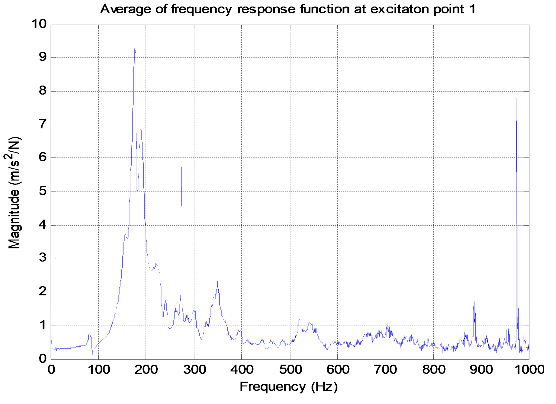
2. Experiment analysis

The experiments were performed with the impact hammer 10 times with respect to each point in order to determine the vibration transfer characteristics of OKPO 300. The frequency response function of each excitation point was calculated by the mean of 10 experiment results in the frequency domain. The calculated frequency response functions for each excitation point are shown in [Figs. 3, 4, 5, and 6]. The results described in [Figs. 3, 4, 5, and 6] show that the peaks in the response functions were observed near 200 Hz from all excitation points. From Excitation Points 1 and 2 in [Fig. 2], other peaks of the frequency response functions were observed over 900 Hz. Since it is necessary to clarify whether the frequency is the natural frequency of OKPO 300 in order to identify its vibration characteristics, an additional analysis was carried out regarding the experiments on excitation Points 1 and 2.

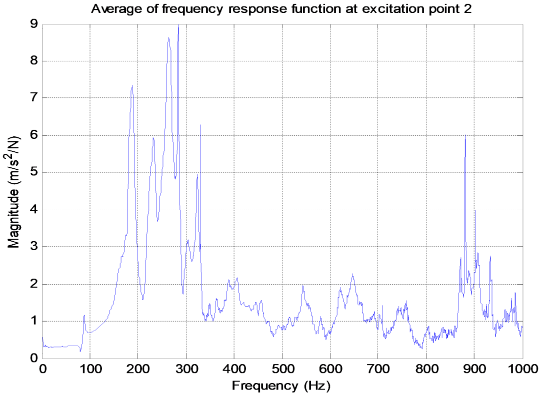
<Table 2> Measurement instruments

Type	Description
Impulse hammer	PCB 086C02
Accelerometer	DYTRAN 3148
Data acquisition hardware	Bensone Fieldpaq II
Software	Benstone Noviant

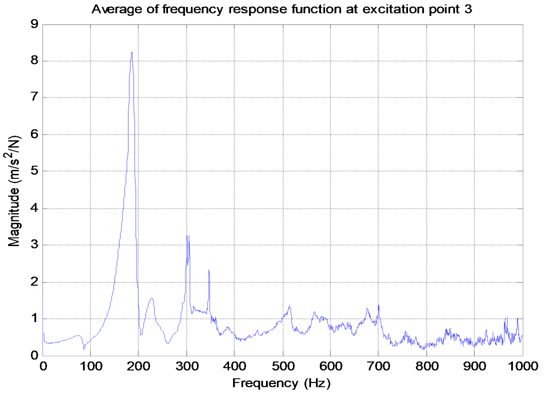
[Figs. 7 and 8] show the 4 cases of frequency response functions for the experiments on Points 1 and 2, respectively. From [Figs. 7 and 8], the peaks of the frequency response functions were observed near 200 Hz in all 4 cases of Excitation Points 1 and 2. Other peaks of the frequency response functions of Excitation Point 1 were



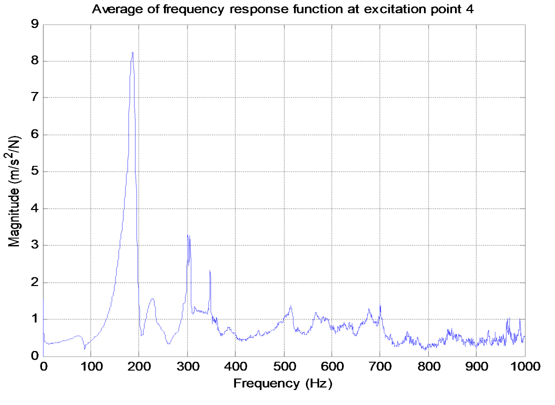
[Fig. 3] Frequency response function of Excitation Point 1.



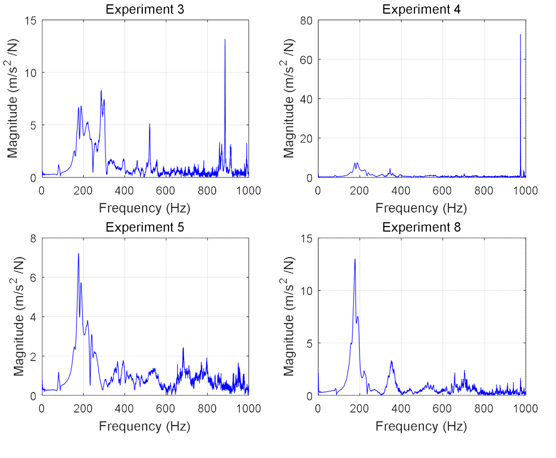
[Fig. 4] Frequency response function of Excitation Point 2.



[Fig. 5] Frequency response function of Excitation Point 3.

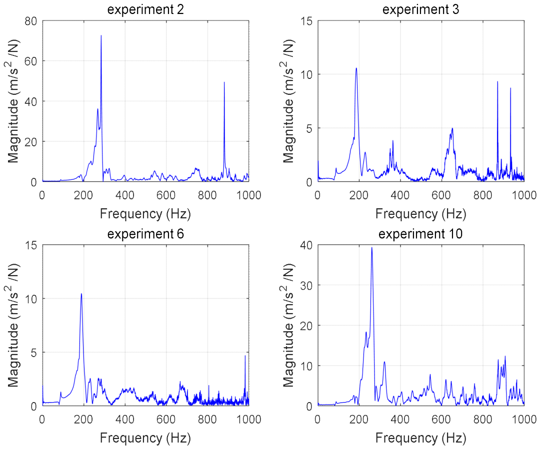


[Fig. 6] Frequency response function of Excitation Point 4.



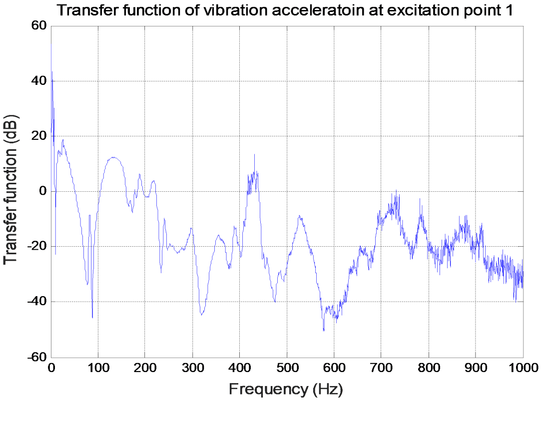
[Fig. 7] 4 Frequency response functions about experiment for Excitation Point 1.

observed over 900 Hz from 2 cases in [Fig. 7], and the peak close to 1000 Hz in Experiment 4 in [Fig. 7] showed a big value. Since the value of the peak near 900 Hz is almost 9 times the value of the peak near 200 Hz, the peak near 1000 Hz in [Fig. 3] could be considered as the effect of that big value by the mean of 10 experiment results of Excitation Point 1. The results in [Fig. 8] also show the other peak of frequency response function occurred near 1000 Hz, but the value of these peaks were not as big as the result in Experiment 4 in [Fig. 7].

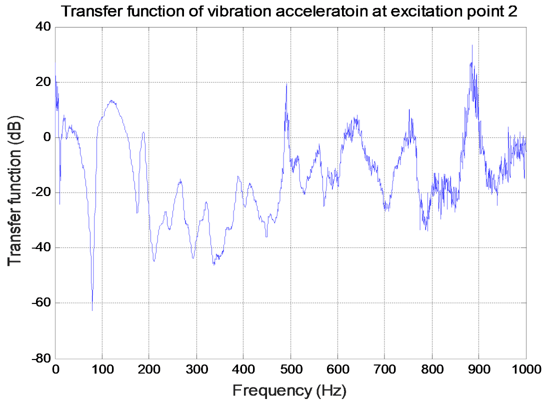


[Fig. 8] 4 Frequency response functions about experiment for Excitation Point 2.

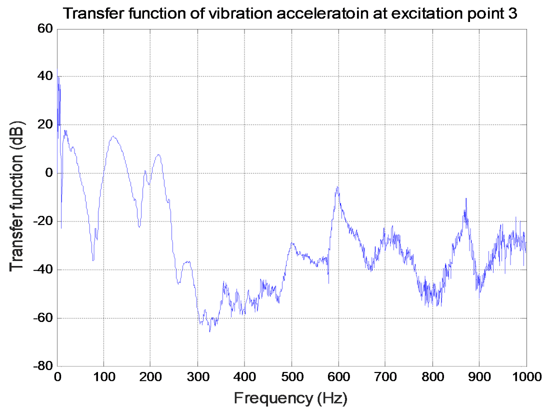
Since the low-frequency of a passive sonar system for an AUV is usually 100 - 1000 Hz, the vibration from the stern of the AUV can affect the performance of the passive sonar system and it is necessary to analyze the effects of transferred vibration acceleration. Thus, the transfer function based on Eq. (4) for each excitation point was depicted in [Figs 9, 10, 11, and 12]. From the [Figs 9, 10, 11, and 12] the vibration with freq-



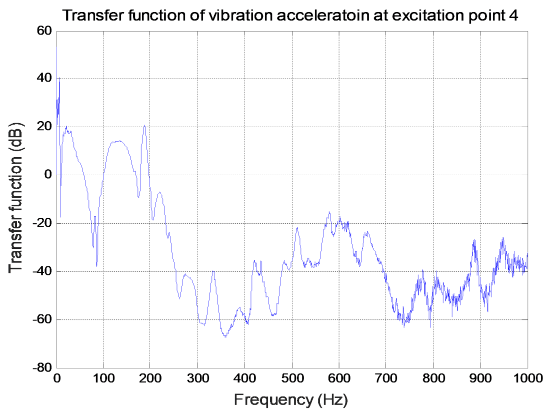
[Fig. 9] Transfer function of vibration acceleration at point 1.



[Fig. 10] Transfer function of vibration acceleration at point 2.

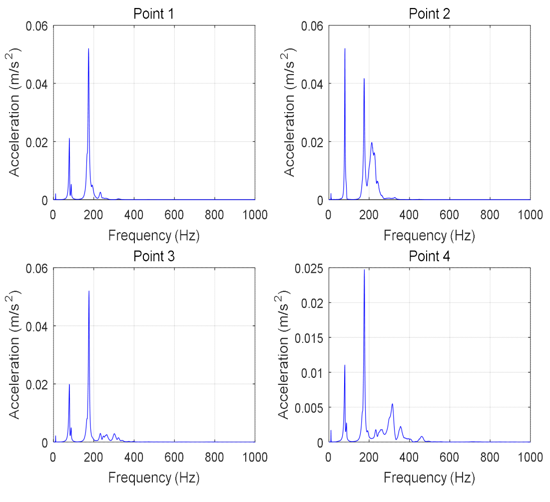


[Fig. 11] Transfer function of vibration acceleration at point 3.



[Fig. 12] Transfer function of vibration acceleration at point 4.

-uency near 200 Hz transferred with the lowest reduction with close 0 dB from all experiment and the vibration of which frequency were closed to 400 ~ 500 Hz was decreased by about 60 dB was transferred through 1.3 m length of OKPO 300. According to the analysis, the vibration acceleration measured at the nose of the OKPO 300 showed more accurate vibration characteristics of the OKPO 300. [Fig. 13] shows the average of vibration acceleration measured from the nose of OKPO 300 at each excitation point. From the [Fig. 13], the peak of acceleration was observed near 200 Hz from all excitation points, and there was no peak in acceleration near 900 Hz. [Fig. 13] also shows the fact that the acceleration measured at the excitation point 2 had a phenomenon different from other cases, and thus this different form of acceleration at the excitation point 2 leads to a different form of transfer function. Based on the results from several experiments, the natural frequency of OKPO 300 in vibration may be 200 Hz, and it could be interpreted that the vibration in



[Fig. 13] Average of vibration acceleration measurements at each point.

the 900 Hz frequency was transferred from the thruster to the nose of OKPO 300 throughout the shell under some specific vibration conditions. Since the low frequency of a passive sonar system for an AUV is usually 100 - 1000 Hz, the vibration from the stern of OKPO 300 can affect the performance of the passive sonar system, and it is necessary to analyze the effects of the transferred vibration acceleration.

Ⅳ. Conclusion

The autonomy of AUVs makes it possible for them to be utilized instead of humans in many areas and is strongly dependant on sonar systems that gather information about underwater environments. And self-generated noise of an underwater vehicle from a high-powered motor and propeller adversely affects sonar and the vehicle's performance. Thus, it is necessary to identify the effect of self-generated noise made by the AUV on the sonar system.

This study carried out several experiments to examine the vibration transfer function that can describe the vibration features of the AUV and analyzed the experimental results using an impact hammer in view of the vibration acceleration transfer function. The results of the experiments showed that the natural frequency of OKPO 300 in vibration may be 200 Hz, and that the vibration with 900 Hz frequency could have been transferred from the thruster to the nose of OKPO 300 throughout the shell under some specific vibration conditions. From the experimental results, it was confirmed that vibration noise needs to be considered in the initial design stage about AUV due to the fact that the natural frequency of vibration of OKPO 300 and the low frequency band of passive sonar used in AUVs are close. The results of this experiment can be used to verify the performance of the developed method when the numerical analysis method for vibration transfer of AUVs is developed in the future.

The experiment in this study was performed in the air as a basic study to apply the transfer function to an AUV and did not reflect the fact that AUVs navigate underwater, which is a limitation. For future study, it will be necessary to predict the vibration acceleration transfer function under the underwater condition based on the frequency response function derived from this study. Also, experiments need to be carried out with actual thrusters as the vibration source for the calculation of the real vibration transfer function of the AUV.

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