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Numerical Analysis of Non-Cavitating Underwater Propeller Noise

Hanshin Seol, Byungsuk Jung and Soogab Lee
Underwater Acoustics Research Center (UARC)
School of Mechanical and Aerospace Engineering
Seoul National University, Seoul, 151-742, Korea

Abstract

The non-cavitation noise of underwater propeller is numerically investigated. The main purpose is to analyze non-cavitation noise from underwater propellers in various operating conditions with different configurations. The noise is predicted using time-domain Acoustic Analogy and Boundary Element Method. The flow field is analyzed with potential based panel method, and then the time-dependent pressure data are used as the input for Ffowcs-Williams Hawkings formulation to predict the far-field acoustics. Additionally boundary element method is also considered to investigate the effect of ducted propellers. With the BEM, sound deflection and scattering effect on the duct can be considered. Noise prediction results are presented for single propeller and ducted propeller in non-uniform inflow condition similar to real situation. Through this study, we can analyze dominant noise source of marine propeller and provide a basis for proper noise control strategies.

1. Introduction

Sound generated by a propeller is critical in underwater detection, and often related to the survivability of the vessels especially for military purpose. Cavitation of the marine propeller is the most prevalent source of underwater sound in oceans and often the dominant noise source of a single marine vehicle. However, submarine and torpedoes are usually operated under the deep sea enough to avoid cavitation [1]. Compared with the extensive amount of literatures concerning cavitation noise of propellers, the non-cavitation noise of propellers from underwater propellers has hardly been attempted to assess so far. The approach for the investigation of the non-cavitation noise is potential based panel method coupled with the acoustic analogy and boundary element method. There are various ways to evaluate Ffowcs Williams-Hawkings equation and the three types of noise source term (monopole, dipole, and quadrupole) have been proposed. Farrasat proposed a time-domain formulation that can predict noise from an arbitrarily shaped object in motion without the numerical differentiation of the observer time [2]. The implementation of this formulation is quite straightforward because contributions from each panel with different retarded times are added to form an acoustic wave. Blade surfaces are divided into rectangular panels radiating noise as sources at different retarded times. Besides, we predict sound deflection and scattering effect on the duct with the boundary element method.

2. Methodology

2.1 Time Domain Acoustic Analogy

Ffowcs Williams and Hawkings formulated the equation for the manifestation of acoustic analogy proposed by Lighthill [3].

The solution for the acoustic pressure can be obtained in the following form by using Green's function and coordinate transformations

$$4\pi p'(\vec{x},t) = \frac{1}{c_0}\frac{\partial}{\partial t}\int_{f=0}\left[\frac{\rho_0 c_0 v_n + l_r}{r(1-M_r)}\right]_{ret} dS + \int_{f=0}\left[\frac{l_r}{r^2(1-M_r)}\right]_{ret} dS$$

The subscript ret denotes that the integration is evaluated at the retarded time. The speed and accuracy of the numerical calculation is improved by eliminating the numerical differentiation. The final result is as follows.

$$p'(\vec{x},t) = p'_T(\vec{x},t) + p'_L(\vec{x},t)$$

where

$$4\pi p'_T(\vec{x},t) = \int_{f=0}\left[\frac{\rho_0 \dot{v}_n}{r(1-M_r)^2}\right]_{ret} dS + \int_{f=0}\left[\frac{\rho_0 v_n\left(r\dot{M}_i\hat{r}_i + c_0 M_r - c_0 M^2\right)}{r^2(1-M_r)^3}\right]_{ret} dS$$

and

$$4\pi p'_L(\vec{x},t) = \frac{1}{c_0}\int_{f=0}\left[\frac{\dot{l}_i\hat{r}_i}{r(1-M_r)^2}\right]_{ret} dS + \int_{f=0}\left[\frac{l_r - l_i M_i}{r^2(1-M_r)^2}\right]_{ret} dS + \frac{1}{c_0}\int_{f=0}\left[\frac{l_r\left(r\dot{M}_i\hat{r}_i + c_0 M_r - c_0 M^2\right)}{r^2(1-M_r)^3}\right]_{ret} dS$$

Here p'_T and p'_L respectively denote the acoustic pressure due to thickness and loading, corresponding to the monopole and the dipole terms. Near-field and far-field terms are seen explicitly as $1/r^2$ and $1/r$ terms in the integrals, respectively

2.2 Boundary Element Method

The BEM is based on the equations of linearized acoustics and predicts the sound scattered by a finite length cylindrical duct that has been irradiated by some simple source process. Simple acoustic sources are used to generate incident sound. We consider the scattering of sound by real duct configuration (JD-75). The duct is irradiated by incident sound produced by a collection of N point dipoles that generated by unsteady loading on propeller blades. In this research, we use integral equations are derived through the application of Green's second theorem and analyze noise directivity according to the characteristic wave number.

The total acoustic pressure in the sound field is split into known incident and unknown scattered parts.

$$p'_t(r,\psi,z,t) = p'_i(r,\psi,z,t) + p'_s(r,\psi,z,t)$$

In a frame of reference moving with the duct, the symmetry of the source process is such that all dependent acoustic variables can be expressed as linear superposition of time harmonic circumferential modes. Submarine and torpedoes do not use liner, so we use hardwall boundary condition for duct surface wall. In order to have unique solution, we must constrain the behavior of the acoustic pressure in the far-field and the duct edge. To ensure continuity of the trailing edge we impose the Kutta condition. For physically reasonable solution to exist we apply the Sommerfeld far-field radiation condition. Furthermore, common BEM method is singular at the characteristic wave number. So we use the improved direct formulation originated by Burton and Miller [4].

3. Results

The propeller models are shown in Figure 1. Acoustic analogy results of single propeller and ducted propeller have similar noise directivity tendency. These results are shown in Figure 2, the three dimensional noise directivity patterns of each source. Boundary element method results are shown in Figure 3 and Figure 4, which show acoustic pressure field and sound pressure level respect to helmholtz number. As shown in these figure, number of acoustic lobe is increased according to BPF order. The first BPF (ka=2) case, noise directivity pattern is similar to acoustic analogy result. But noise directivity pattern is more complex in higher order BPF due to sound deflection and scattering by the duct. In general the first BPF noise is dominant. Therefore on noise propagation, the effect of a duct is little because of a long fundamental wavelength under non-cavitating condition. Duct is used for propulsion efficiency and cavitation noise reduction, but we analyze this research non-cavitating propeller noise. So duct does not effect on acoustic performance of propeller at the far field under non-cavitation situation.

Conclusions

The non-cavitation noise generated by underwater propeller has been analyzed numerically in this study. Potential based panel method coupled with time-domain acoustic analogy is used to predict the noise generated by single and ducted propeller in non-uniform flow condition.

For the noise prediction, Ffowcs Williams-Hawkings equation is applied as Farrasat proposed. In non-uniform flow condition similar to real situation, the noise directivity pattern is a direct result of dipole dominating overall noise level.

Sound deflection and scattering effect due to duct is considered using boundary element method. Acoustic pressure and noise directivity are analyzed for wave numbers. The first BPF noise directivity is similar to single propeller result. But in high order BPF, wavelength is relatively short. Therefore, the noise is deflected and scattered by the duct, but its effect is so little since the first BPF noise is dominant for general cases. It is due to the fact that noise generated by a marine propeller under the non-cavitating condition has a long fundamental wavelength, and the effect of duct is not so important at the far field in the viewpoint of acoustic performance.

Acknowledgements

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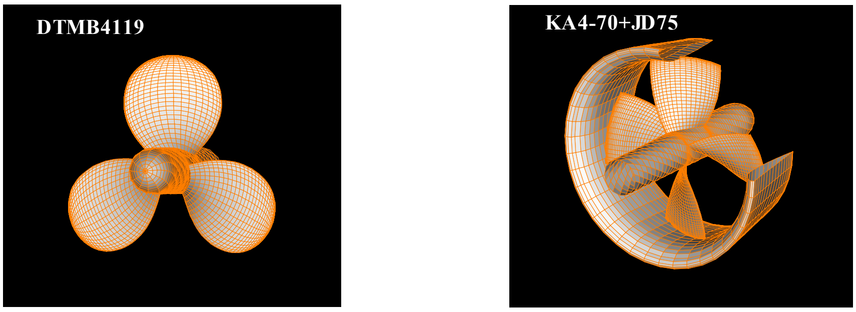
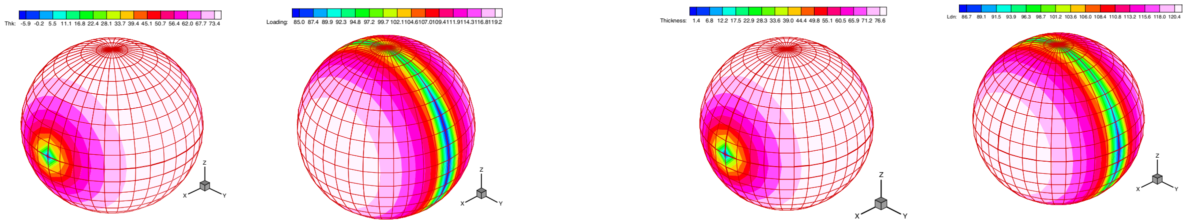


(a) (b)

Figure 1: Propeller Models and conditions.

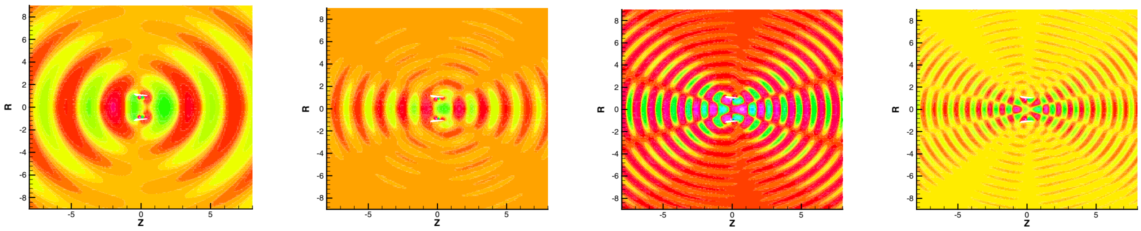
(a) DTMB 4119 with 3 blades, Rev : 120 rpm, Forward Speed : 1.6 m/s.
(b) KA4-70 with 4 blades + JD 75 Duct, Rev : 120 rpm, Forward Speed : 1.78 m/s.



(a) (b)

Figure 2 : Noise Directivity 3D Contour.

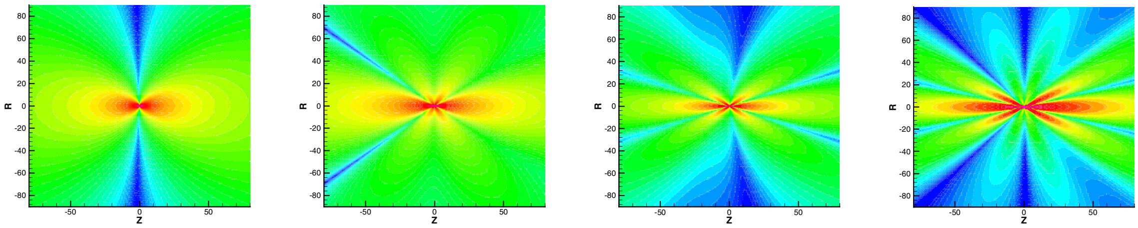
(a) Single Propeller, Thickness Noise and Loading Noise.
(b) Ducted Propeller, Thickness Noise and Loading Noise.



(a) (b) (c) (d)

Figure 3 : Acoustic Pressure Fields.

(a) ka=2, (b) ka=4, (c) ka=6, (d) ka=8



(a) (b) (c) (d)

Figure 4 : Sound Pressure Level.

(a) ka=2, (b) ka=4, (c) ka=6, (d) ka=8.