Numerical Study on Non-Cavitating Noise of Marine Propeller

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ABSTRACT

Blade Passing Frequency (BPF) noise of a fan or a propeller comprises of the thickness and loading noises. In general, the loading noise is regarded as the main noise source in non-cavitating condition because the thickness noise decreases rapidly with respect to distance from the noise source. In this study, underwater radiated noise for the model scaled propeller is calculated by the rotating dipole formulation coupled with acoustic finite element method which considers the loading noise with reflection surfaces in frequency domain. The CFD analysis is used to calculate blade surface pressures for obtaining the noise source. The wall effect is considered to carry out the noise analysis in the same condition as the water tunnel experiment. The noise predictions are conducted under without and with wake conditions to observe effects of inflow velocity and unsteady loading on the radiated noise, respectively. The both numerical results are in good agreements with experimental results. Based on these results, the prediction method can be used to design a low noise propeller and predict underwater radiated noise including the effect of acoustic reflection by a hull structure.

Keywords: Non-cavitating noise, Marine propeller, CFD, Finite element method

1. INTRODUCTION

Underwater radiated noise from ships becomes more important because it has negative effect on the marine environment. In recent years, the underwater noise regulation has been discussed in Marine Environmental Protection Committee of International Maritime Organization (MEPC-IMO), and shipbuilding companies and marine institutes began to research the underwater radiated noise and countermeasures to prepare for the regulation. Propeller noise is one of major noise sources for the underwater noise and can be predicted by a water tunnel test or a numerical method. The water tunnel test can obtain a noise level for a model propeller, but it is difficult to use for a low noise propeller design due to high experimental cost. There are also some issues such as a correction method for scale effect and an accuracy of the measurement system. Numerical methods are widely used for designs of a hull and a propeller by increasing computational capability. To develop a low noise propeller, numerical prediction for the propeller noise is required for reducing design cost.

A BPF noise is a major component for a propeller non-cavitating noise rather than a broadband noise. The prediction for the BPF noise is obtained from the blade loading calculated by using the CFD tool or the potential method. There are two methods to predict the BPF noise. Firstly, Ffowcs-Williams and Hawkings (FWH) equation considers monopole, dipole and quadrupole components of the noise radiated by a propeller. The BPF noise is related to the monopole and dipole which are thickness and loading noises, respectively. It is calculated in time domain. Secondly, Gutin equation was developed for predicting fan noise. The BPF noise in frequency domain is calculated by the rotating dipole model. Above methods are used in the free-field condition, and therefore acoustic boundary element method (BEM) or finite element method (FEM) is used to be coupled with them to solve the radiated noise field including structures near the propeller.

Numerical methods[1,2] for prediction of the propeller BPF noise have been developed by using Ffowcs-Williams and Hawkings (FWH) equation, Boundary Element Method (BEM), etc. The noises

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for model-scale propellers were investigated by considering noise sources and directivity. Surface pressures of the model-scale hull induced by propeller were also calculated and compared with experimental data. Recently, the noises for full-scale ships have been predicted by using CFD simulation for commercial ships and the acoustic analogy for underwater radiated noise[3,4], and it compared the broadband noise as well as the BPF noise with the field measurement data. There were differences between the prediction and the measurement, because it was difficult to exactly consider the environment for the field measurement into the numerical modeling.

In this paper the rotating dipole formulation coupled with the acoustic finite element method is used to calculate non-cavitating BPF noise for a model-scale propeller of a LNG carrier. The propeller loading is obtained from CFD calculation which result is validated with the test result for performance in the water tunnel. Underwater noise is calculated in various flow conditions and compared with the measured data.

2. METHODOLOGY

2.1 Flow Simulation

Unsteady surface pressures of blades for the loading noise analysis are calculated by using the commercial CFD software SC/Tetra[5], which uses the Reynolds-Averaged Navier-Stokes (RANS) equation with the turbulence model of SST k-ω. A CFD domain consists of two regions; a stationary region and a rotating region as shown in Figure 1. The size of the stationary region is same as that of the water tunnel in which the performance and noise measurements for the propeller were conducted. The propeller is in the rotating region with sliding interface and advances by 1° for each time step. The surface pressures of blades are storage at each time step to calculate the propeller noise. Thrust and torque values are also monitored for CFD validation.

In this study, flow simulations are performed for two conditions; without and with ship wake flow. The distribution of inflow velocity at the inlet of the stationary domain is uniform in the no-wake flow condition (open water condition), and the magnitude of velocity varies with the advance coefficient from 0.4 to 1.0. In the wake flow condition, the velocity distribution measured by towing tank test is applied to the inlet boundary condition for the CFD simulation.

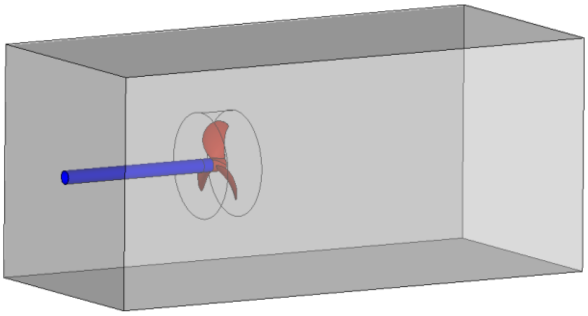


Figure 1 - CFD domain for flow analysis

2.2 CFD Validation

The accurate prediction of the blade surface pressures is directly related to that of the propeller noise. Therefore, the CFD result is validated with the experimental result in the no-wake flow condition. Figure 2 shows the comparison of thrust and torque of the propeller with respect to the advance coefficient J. The thrust coefficient K_T and the torque coefficient K_Q decrease when the advance coefficient increases, because the effective angle of attack for the blade is inversely proportional to the advance coefficient at the constant rotating speed. The numerical results for thrust and torque are in good agreement with the experiment results in the overall range of the advance coefficient.

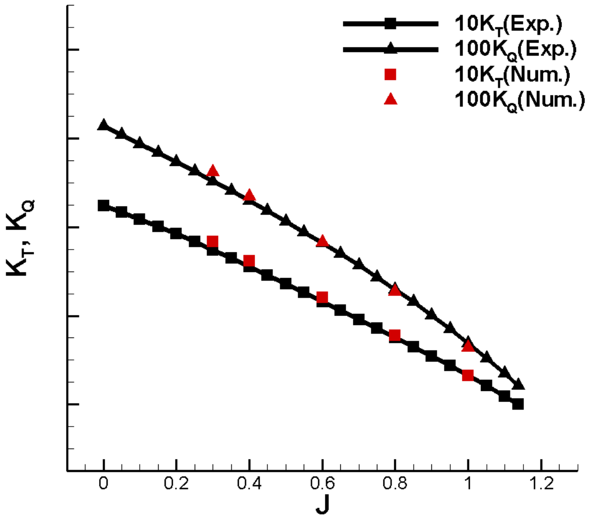


Figure 2 – Comparison of thrust and torque for propeller

2.3 Acoustic Simulation

The LMS software Virtual Lab.[6] is used to calculate the underwater radiated noise for the propeller. Unsteady blade loadings provided by CFD are imported in the fan source model of Virtual Lab. Acoustics, and the number of blades and rotational speed are defined. Rotating dipole sources are distributed along the spanwise direction of the blade as shown in Figure 3. FEM is used to investigate the acoustic reflection effect for walls of the water tunnel. The automatically matched layer (AML) property is a kind of non-reflecting boundary conditions, and is applied to a boundary condition for inflow and outflow regions in Figure 4. The AML or the rigid wall condition is applied to other regions for simulations in acoustic free-field and water tunnel conditions, respectively. Figure 5 represents the noise measurement system in the water tunnel. A hydrophone is located at the wall of port side and the distance between the hydrophone and the propeller hub is three times the length of radius of the propeller.

Figure 3 – Fan source model

Figure 4 – FEM grid

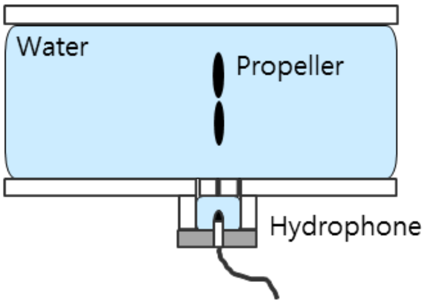
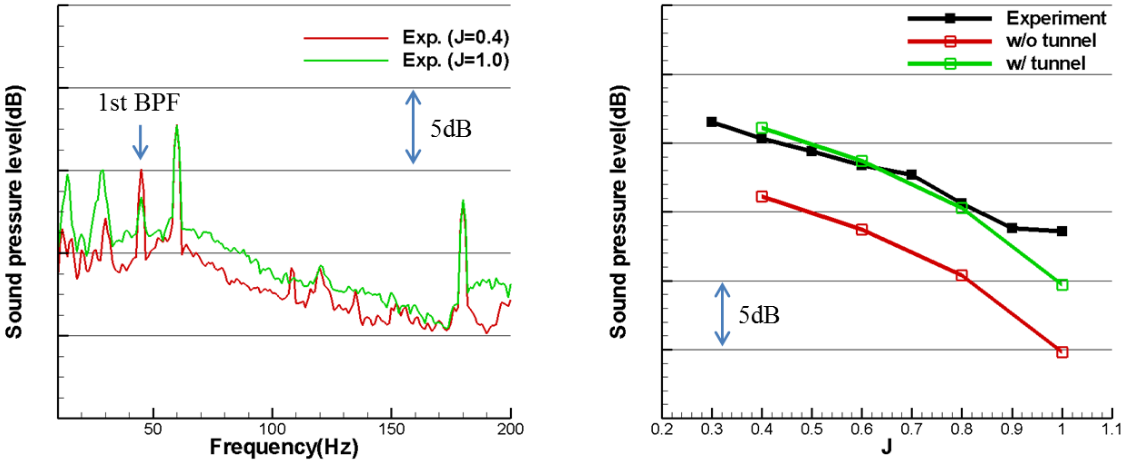


Figure 5 – Noise measurement system in the water tunnel (Top view)

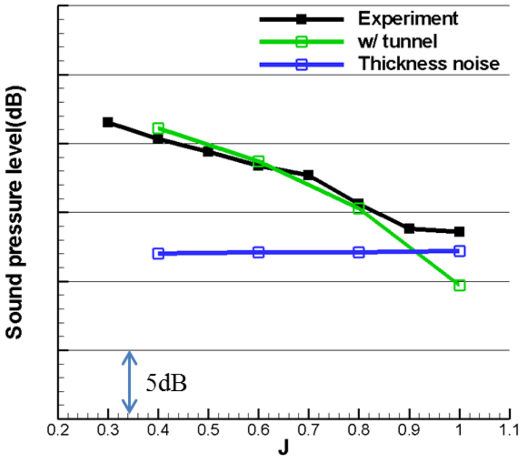
3. RESULTS AND DISCUSSION

3.1 Open Water Condition

Propeller noises were measured at various advance coefficients from 0.3 to 1.0. In figure 6(1), the 1st BPF noise is observed clearly at 45Hz when the advance coefficient is 0.4 and 1.0. Other tonal noises induced by the test equipment are also appeared, but they are distinguished from the BPF noise by frequency. The 2nd BPF noise cannot be found, and it seems to be less than background noise because the 2nd BPF level decreases dramatically for the steady loading condition. Figure 6(2) shows the variation of the 1st BPF noise level with respect to the advance coefficient. W/o tunnel means that the propeller noise is propagated in the acoustic free-field condition, and w/ tunnel means that acoustic reflection by the wall of water tunnel is considered in the simulation. The overall tendency for the BPF noise is similar to that for the thrust in Figure 2 because the non-cavitating BPF noise is dominated by the blade loading. The BPF noise increases by about 5dB for all advance coefficients due to the effect of acoustic reflection by the wall of water tunnel. The prediction result with the tunnel effect shows good agreement with the experimental data up to J = 0.8. The discrepancy between the prediction and the experimental results at the high advance coefficient is caused by the thickness noise. The experimental result includes the thickness and loading noises, but the present method considers only the loading noise.



(1) Noise spectrum of the experiment (2) Comparison with and without the tunnel effect



(3) Comparison of loading and thickness noises

Figure 6 – Sound pressure levels for the open water condition

Figure 6(3) shows the thickness noise calculated by using the term of thickness noise in the FWH equation[7] with various advance coefficient. The loading noise obtained by the rotating dipole model is dominant at the low advance coefficient, but the thickness noise becomes larger than the loading noise at the high advance coefficient because the loading noise decreases with respect to increasing the advance coefficient. It is noted that it considers the thickness noise as well as the loading noise to increase prediction accuracy up to the high advance coefficient. However, when the underwater radiated noise for the propeller is predicted in far field, the thickness noise is negligible compared to loading noise even though the advance coefficient is high. Therefore, it is enough that the loading noise is only considered for the prediction of propeller noise in the design stage.

3.2 Wake Field Condition

The ship wake field is carried out in towing tank test, and is applied to the water tunnel test and the CFD simulation. It generates the unsteady loading as shown in Figure 7, and tonal noises are observed up to 2nd BPF. The prediction result with the tunnel effect is compared with experimental data, and discrepancy between them is less than 5dB. The error for the wake field condition is larger than that for the open water condition, because the wake flow field of the experiment and the numerical simulation can be different. In the water tunnel test, field velocity of the wake is defined at a rotating surface of the propeller. However, in the CFD simulation, it is generally applied to the inlet surface of the CFD domain, and it may be dissipated by the grid size when the flow passes through the rotating surface of the propeller. Difference of the wake field at the rotating surface affects the unsteady surface pressure on the blade and the BPF noise, so it is more difficult to predict noise level accurately in the wake field condition rather than in the open water condition. Figure 8(b) shows the tunnel effect, and sound level increases by about 5dB, which is similar to the open water condition.

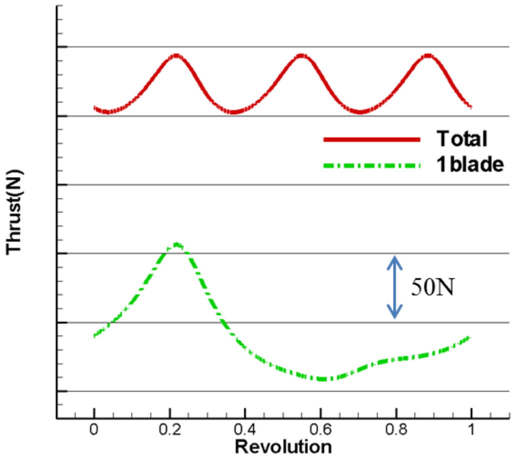
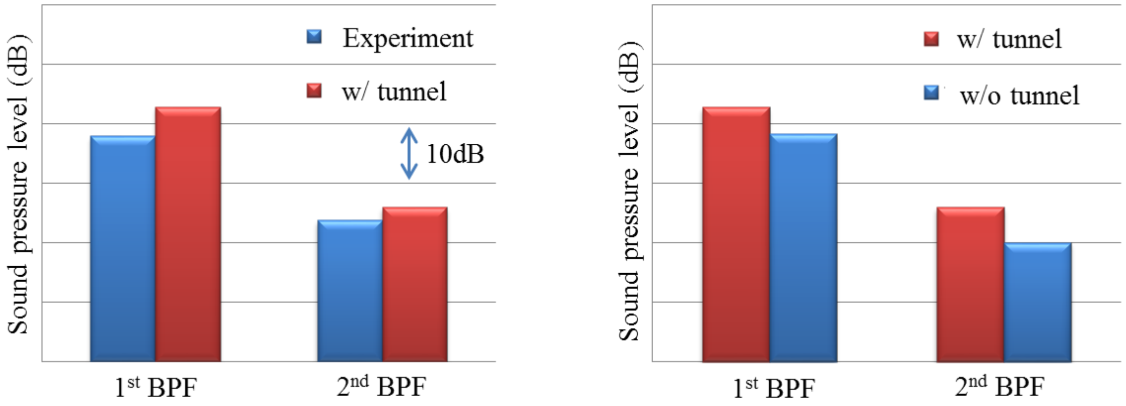


Figure 7 – Propeller unsteady thrust calculated by the CFD



(a) Comparison of experiment and prediction with tunnel effect

(b) Comparison with and without the tunnel effect

Figure 8 – Sound pressure levels for the wake field condition

4. CONCLUSIONS

The rotating dipole model is used to predict the underwater radiated noise of the propeller, and the acoustic FEM is coupled with that to consider the acoustic reflection effect for the rigid wall of the water tunnel. The prediction results including the wall effect for the open water and wake field conditions are reasonable agreement with experimental data. The thickness noise is considered additionally to increase the prediction accuracy in the high advance coefficient, but it is commonly known that the thickness noise is not important in far field.

In this study, the prediction method for the underwater radiated noise is validated for the water tunnel test, and it means that the noise for an isolated propeller is predicted with accuracy. Thus, it is anticipated that the noise analysis by using the method as well as a performance analysis for a propeller can be performed at a design stage to develop a low noise propeller. The method can also consider the effect of acoustic reflection by a hull structure and a surface of the water.

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