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Novel scaling law for estimating propeller tip vortex cavitation noise from model experiment *

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Abstract: The tip vortex cavitation (TVC) noise of marine propellers is of interest due to the environmental impacts from commercial ships as well as for the survivability of naval ships. Due to complicated flow and noise field around a marine propeller, a theoretical approach to the estimation of TVC noise is practically unrealizable. Thus, estimation of prototype TVC noise level is realized through extrapolation of the model TVC noise level measured in a cavitation tunnel. In this study, for the prediction of prototype TVC noise level from a model test, a novel scaling law reflecting the physical basis of TVC is derived from the Rayleigh-Plesset equation, the Rankine vortex model, the lifting surface theory, and other physical assumptions. Model and prototype noise data were provided by Samsung Heavy Industries (SHI) for verification. In applying the novel scaling law, similitude of the spectra of nuclei is applied to assume the same nuclei distribution in the tip vortex line of the model and the prototype. It was found that the prototype TVC noise level predicted by the novel scaling law has better agreement with the prototype TVC noise measurement than the prototype TVC noise level predicted by the modified ITTC noise estimation rule.

Key words: Tip vortex cavitation, underwater radiated noise, scaling law

Introduction

Since tip vortex cavitation (TVC), usually the earliest type of cavitation to appear on a marine propeller, is related to cavitation inception speed (CIS) and underwater radiated noise (URN), the physical understanding of TVC is critically important in designing a propeller. In terms of URN, TVC noise is considered to be the most significant source of marine propeller noise because it occurs the earliest among other types of cavitation and significantly influences the noise spectrum over a broad frequency range[1].

Because of the complex flow and noise field around a marine propeller, a theoretical approach to TVC noise estimation is practically unrealizable. Thus, estimation of prototype noise level is realized through extrapolation of the model-scale measurement made in a cavitation tunnel. For this purpose, some scaling laws on cavitation noise have been suggested, which have been applied in many studies.

Levkovskii[2] initially proposed the cavitation noise scaling law, assuming cavitation as a single bubble. The derivation of the cavitation noise scaling law started from the fact that the ratio of radiated acoustic power to potential power of a single bubble is constant, which was based on experimental results. However, this scaling law could not be applied to the cavitation noise generated by a 3-D lifting surface since propeller parameters and boundary layer effect are not taken into account. For the cavitation attached to a propeller blade surface, such as sheet cavitation, the scaling law for propeller cavitation noise is well established by the ITTC noise estimation rule[3]. This scaling law has been applied to predict propeller cavitation noise from model tests in two studies[4,5]. In these studies, it was shown that the ITTC noise estimation rule had good agreement with the measured prototype cavitation noise level in the case of sheet cavitation developed on the blade surface.

It is known that TVC development is significantly affected by the boundary layer and propeller loading[6]. However, since the ITTC noise estimation rule does not include these effects properly, it would be inadequate to apply the ITTC noise estimation rule to cavitation occurring continuously at a distance from

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the propeller such as TVC. Latorre[7] measured the fully developed TVC noise of scaled hydrofoils and applied the cavitation noise scaling method of Bojorheden and Astrom[8] and the Levkovskii method[2]. Oshima[9] modified the ITTC noise estimation rule to incorporate the boundary layer effect using the Reynolds number, which significantly affects TVC occurrence. Prototype power spectral density (PSD) estimated with the modified ITTC noise estimation rule was compared with measured prototype PSD for verification. In this study, the scaling exponent determined from model and prototype experiments was 0.150, quite different from other experimental results (summarized in Shen et al.[10]). More importantly, the estimated prototype PSD did not match well with the measured data in the high frequency range above 6 kHz-7 kHz. From these analyses, it is ambiguous as to whether the model or prototype experiments are incorrect or the modified ITTC noise estimation rule gives incorrect estimation result. Since model and prototype experiments were conducted based on the visual inspection of TVC using an observation window (the method considered accurate), it could be considered that the experiments were performed correctly. Thus, it would be reasonable to re-examine the modified ITTC noise estimation rule that reflects only the boundary layer effect and suggest that such a treatment may be inadequate and incomplete.

To overcome this limitation of considering the boundary layer effect in applying the ITTC noise estimation rule for TVC noise, the scaling law for TVC noise is newly derived using the Rayleigh-Plesset equation, the Rankine vortex model, the lifting surface theory, and extra assumptions based on the physics of TVC, which will be detailed in Section 2. This will provide the broadband noise scaling law considering the hydro-acoustic basis of TVC. In Section 3, model-scale data are extrapolated with the modified ITTC noise estimation rule as well as the novel scaling law deduced in Section 2, and these two sets of extrapolated results are compared with the prototype measurements for verification. The causes of errors are also analyzed. Finally, the conclusions are provided in Section 4.

1. Derivation of the scaling law for TVC noise

TVC is a small bubble flume generated in the vortex core center and noise is emitted from the bubble growth, elongation, and collapse. Since it is impossible to consider the noise of each bubble when deriving the scaling law, derivation of the scaling law for TVC starts with consideration of the total power of the bubble flume as a whole. In addition, TVC results from nuclei that enter into a vortex trailing from the tip caused by crossover of fluid from the high pressure side to the low pressure side of the propeller. Therefore, to study this physical phenomenon it is necessary to bring all factors into play that underlying the physical basis of TVC, such as the bubble dynamics (Rayleigh-Plesset equation), vortex model (Rankine vortex model), the lifting surface theory, and the number of bubbles generated per unit time when deriving the scaling law for TVC noise. Since the novel scaling law derived in this study is generally based on Rayleigh-Plesset equation and the formulation for elongation of TVC is the same as that for initial radial growth of TVC (which can be identified in Arndt[11]), it can be normally applied to TVC noise estimation regardless of TVC development stage except for very long TVC.

1.1 *Rayleigh-Plesset equation*

The Rayleigh-Plesset equation, commonly used to describe the growth and collapse history of a bubble, is given for the bubble radius R in relation to time[12] as follows

$$\rho\left(R\ddot{R}+\frac{3}{2}\dot{R}^2\right)=p_v-p_\infty(t)+p_{g0}\left(\frac{R_0}{R}\right)^{3\gamma}-\frac{2A}{R}-4\mu\frac{\dot{R}}{R} \tag{1}$$

where ρ denotes the density of fresh water, R radial displacement of bubble, $\dot{R}$ radial velocity of bubble, $\ddot{R}$ radial acceleration of bubble, p_v vapor pressure, p_∞ ambient pressure at infinity, p_{g0} partial pressure of gas at the initial state, γ the ratio of the specific heat at constant pressure to that at constant volume, R_0 equilibrium radius, A surface tension force of bubble wall, and μ dynamic viscosity. As secondary terms such as gas pressure, surface tension, and viscosity can be ignored, the Rayleigh-Plesset equation can be simplified as follows

$$\frac{1}{2R^2\dot{R}}\frac{\mathrm{d}}{\mathrm{d}t}(\rho\dot{R}^2R^3)=p_v-p_\infty \tag{2}$$

The above equation is integrated from initial time $t=0$ to arbitrary time t and bubble wall velocity is expressed as

$$\dot{R}(t)=\sqrt{\frac{2}{3}\frac{p_v-p_\infty}{\rho}\left\{1-\left[\frac{R(0)}{R(t)}\right]\right\}} \tag{3}$$

In the growth stage of a bubble, $R(0)/R(t)$ is assumed to be zero except at the initial instant $(t=0)$. Thus, the bubble growth velocity becomes constant after the initial stage, that is

$$\dot{R}\approx\sqrt{\frac{2}{3}\frac{p_v-p_\infty}{\rho}} \tag{4}$$