Study on Prediction of Underwater Radiated Noise from Propeller Tip Vortex Cavitation

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Abstract. The method to predict underwater radiated noise from tip vortex cavitation was studied. The growth of a single cavitation bubble in tip vortex was estimated by substituting the tip vortex to Rankine combined vortex. The ideal spectrum function for the sound pressure generated by a single cavitation bubble was used, also the empirical factor for the number of collapsed bubbles per unit time was introduced. The estimated noise data were compared with measured ship’s ones and it was found out that this method can estimate noise data within 3dB difference.

1. Introduction
Propeller cavitation is known as one of measure sources of vibration and noise of ships. Especially, it is important to reduce cavitation noise in designing propellers of the ships such as oceanographic research vessels because they use acoustic instruments and cavitation noise are harmful in using them. Therefore, it is indispensable to quantitative prediction of propeller cavitation noise. Among various types of propeller cavitation, it is very difficult to predict the noise of tip vortex cavitation, which occurs at a distance propeller blade, as well as to predict inception of tip vortex cavitation. In this study, the practical method in order to adapt at the design stage of propeller was investigated. The simple calculation model was combined with experimental data and the method to predict underwater radiated noise from propeller tip vortex cavitation was developed. Finally, this method was verified in comparison with measured ship’s noise data.

2. Prediction method
The prediction method is constructed, as follows.

2.1. Prediction of tip vortex cavitation
Analogous to McCormick’s assumptions [1], propeller tip vortex is substituted to a Rankine combined vortex, in which the pressure $P$ is shown in Eq.(1).

$$
P = P_0 + \frac{1}{2} \left( \frac{\Gamma r}{2 \pi a^2} \right)^2 - \left( \frac{\Gamma}{2 \pi} \right)^2 (r \leq a), P = P_0 - \frac{1}{2} \left( \frac{\Gamma}{2 \pi r} \right)^2 (r \geq a) \quad (1)
$$

It is necessary to know the strength of tip vortex and the radius of vortex core. The circulation of propeller at $r/R=0.95$ calculated by propeller lifting surface theory[2] was adopted as the strength of tip vortex. And also, it was assumed that the radius of vortex core is proportional to the displacement thickness of boundary layer on propeller blade surface at $r/R=0.95$ with using some empirical correction factor $K$ [3] as shown in Eq. (2).

$$
a = K (\delta^*_b + \delta^*_r) \quad (2)
$$
It was considered that the inception of a cavitation bubble occurred at center of a Rankine combined vortex. To calculate the growth of a cavitation bubble, Rayleigh-Pleset equation (3) was used.

\[
R \frac{d^2R}{dt^2} + \frac{3}{2} \left( \frac{dR}{dt} \right)^2 = \frac{P_c - P_\rho}{\rho}
\]  

(3)

At that time, it was assumed that the center of bubble placed at center of the vortex, so, the pressure at the bubble surface was equal to the pressure of the vortex at bubble radius. Finally, the maximum radius of bubble \(R_M\) and the pressure \(P_C\) at \(R_M\) were gotten.

2.2. Prediction of noise levels

A cavitation bubble with radius \(R_M\) collapsed under the pressure \(P_M\). Ideal spectrum function \(S_P(\omega)\) for the sound pressure generated by a single cavitation bubble was introduced as shown in Fig.1 [4]. In Fig.1, the angular frequency becomes non-dimensional by multiplying \(\tau_c\) as shown in Eq. (4).

\[
\tau_c = \frac{R_M \sqrt{\rho / P_c}}{\rho}
\]

(4)

In Fig.1, \(SP(\omega)\) is divided to 3 parts. Each part is expressed in Eq. (5), (6), (7).

Part 1

\[
\frac{S_P(\omega)}{R_M^4 \rho P_c} = \frac{\pi}{18} \left( \frac{\omega \tau_c}{(\pi/2)^2 - (\omega \tau_c)^2} \right)^4
\]

(5)

Part 2

\[
\frac{S_P(\omega)}{R_M^4 \rho P_c} = \frac{2.4}{9\pi} (\omega \tau_c)^{-0.4}
\]

(6)

Part 3

\[
\frac{S_P(\omega)}{R_M^4 \rho P_c} = \frac{2.4}{9\pi} (\omega \tau_c)^{-0.4} \left( \frac{\omega}{\omega_s} \right)^2, \omega_s = \frac{1}{9\tau_c} \left( \frac{\rho c_m}{P_c} \right)^{5/6}, c_m = \frac{c}{\sqrt{1 + \beta_s \rho c / \rho c_s}}
\]

(7)

And also, to consider the size of cavitation bubbles and noise level measured at sea, the numbers of collapsed bubbles per unit time were determined

![Fig.1 Ideal spectrum function for the sound pressure generated by a single cavitation bubble](image)

3. Results of prediction

The predicted noise data were compared with measured ones, as follows.

3.1. Subject ships

The prediction method was adapted to 3 ships as shown in Table 1. Ship A and B are oceanographic research vessels and Ship C is a training ship. Because the adopted case of the developed prediction method is limited to tip vortex cavitation noise, the ships and operating conditions which only tip vortex cavitation was observed in model tests were chosen.
The radiated noise from subject ships were measured by using a hydrophone which was suspended from measuring boat. The waters depth was about 1000m and subject ships were running at the point within 100m from measuring boat. So, noise propagation was assumed as spherical diffusion. The source level $L_S$ was calculated from the measured one $L_p$ using the distance $r$ between hydrophone and ship, considering of the sound reflection at sea surface, as follows,

$$L_S = L_p + 20\log(r) - 3 \tag{8}$$

| Table 1 Principal Particulars of Ship |
|-----------------------------------|
| Ship | A | B | C |
| Length (m) | 100.0 | 116.0 | 87.6 |
| Breadth (m) | 16.2 | 19.0 | 13.6 |
| Depth (m) | 8.9 | 13.2 | 8.8 |
| Displacement (ton) | 3991 | 8600 | 3515 |
| Engine Output (kW) | 5590 | 7355 | 3900 |
| Speed at Research (kn) | 16 | 16 | 8 |
| Propeller Diameter (m) | 3.7 | 4.1 | 3.3 |

3.2. Results of prediction
Predicted source levels are compared with measured ones as shown in Fig.2-4.

Fig.2 Comparison with Experiments for Ship A
Fig.3 Comparison with Experiments for Ship B
Fig.4 Comparison with Experiments for Ship C
Fig.5 Comparison with Experiments for Ship A
In the case of Ship A, measured noise levels were larger than those in prediction. At full-scale, measured noise data included not only propeller cavitation noise but also machinery ones. Therefore, it was considered that machinery noise were larger than those of cavitation with a range below 1 kHz. In the case of ship A, noise were measured at that the ship speed and propeller shaft speed were kept 0. The results are shown in Fig.5. It is clearly shown that the machinery noise is dominant with a range below 1 kHz. In the case of ship B and C, predicted data show good agreement with measured ones with a range above 100Hz. Calculated noise levels at 2, 5, and 10 kHz are compared with measured ones as shown in Fig.6. The difference of noise levels between calculation and experiment is less than 3dB. So, the developed prediction method can be evaluated that it is useful in design of propeller.

4. Conclusion
The method to predict the radiated noise from propeller tip vortex cavitation was developed. Tip vortex was substituted to Rankine combined vortex. The growth of a cavitation bubble was calculated by using Rayleigh-Pleset equation. Ideal spectrum function for the sound pressure generated by a single cavitation bubble was introduced. And also, to consider the size of cavitation bubbles and noise level measured at sea, the number of collapsed bubbles per unit time was determined. This method was verified in comparison with measured noise data at sea. The difference noise level between calculation and experiment was less than 3dB, so, it can be said that present method is useful at design stage of propeller.

At present, many researchers are working on the analysis of flow field near tip vortex by using CFD and detailed measurement. It can be expected that suitable model of phenomenon is developed and the accuracy of prediction increases. Furthermore, it is necessary to measure propeller noise at full-scale and to separate cavitation noise.

References
[1] McCormick, B.W., “On Cavitation Produced by a Vortex Trailing From Lifting Surface,” Journal of Basic Engineering Trans. ASME, Vol.84, No.3, 1962, pp369-379
[2] Hoshino, T., “Application of Quasi-Continuos Method to Unsteady Propeller Lifting Surface Problems,” Soc. of Naval Architects of Japan, Vol.158, 1985, pp51-71
[3] Oshima, A., “Study on Tip Vortex Cavitation Inception of Propeller,” The 2nd International Symposium on Cavitation, 1994, pp367-372
[4] Blake, W., Mechanics of Flow-Induced Sound and Vibration Volume I 6.4.1 Dependence of Sound on Stages of Bubble History, Accademic Press, 1986, pp404-413