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A Numerical Study on the Source Mechanism of the Pressure Fluctuation Induced by Propeller Cavitation

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Abstract

This paper deals with the pressure fluctuation induced by propeller cavitation. The main objective of this study is to analyze the source mechanism of the pressure fluctuation induced by propeller cavitation. To analyze the source mechanism of the pressure fluctuation, modern acoustic theory is applied. The governing equation of the pressure fluctuation induced by propeller is derived using Ffowcs Williams-Hawkings proposed time domain acoustic method. The physical mechanism of pressure fluctuation at the blade rate frequency is analyzed using numerically generated cavitation volume variation. Finally the characteristics of the pressure fluctuation induced by a propeller are presented.
Keywords: pressure fluctuation, cavitation, propeller, source mechanism, acoustic method

1 Introduction

Recently, the load on a propeller is increasing due to the need of big size and high speed ship. Thus, the volume of propeller cavitation is increasing, and the resulting pressure fluctuation is becoming an important issue. In addition, the diameter of a propeller is becoming bigger, so the distance between propeller and hull is becoming closer. The limitation of tip clearance and an increase in high order pressure fluctuation can cause severe ship vibration and noise problem. Thus, the technique enabling to predict and control the pressure fluctuation induced by the propeller cavitation is needed at the design stage (Lee et al 1992).

There have been many studies about the pressure fluctuation caused by the propeller cavitation. (ITTC 2002) (Kinns and Bloor 2003) (Kim et al 1993) Most studies are investigated into correlation between prediction, model test, and ship measurement.

This study was designed to find a physical significance of propeller cavitation and pressure fluctuation through theoretical and numerical approaches.

Pressure fluctuation induced by a propeller is classified into mainly three parts: changes in the blade loading, rotation of blade thickness, and volume change of propeller cavitation. Since pressure fluctuation due to changes in blade loading and blade thickness are very small compared with that caused by cavitation. Various propeller cavitations affecting hull pressure fluctuation such as sheet cavitation, tip vortex cavitation, and bubble cavitation.

Pressure fluctuation measured peak value in a discrete form at the blade rate frequency, which is known due to the unsteady sheet cavitation.

To predict the pressure fluctuation induced by propeller sheet cavitation, modern acoustic method is applied. The existing prediction methods are difficult to intuitively understand the governing equation since they are taken in a form of solving boundary value problems based on a potential. They are also difficult to represent relative motion of source, near field effect and retarded time for the measurement point.

The pressure fluctuation induced by propeller cavitation is generally known to be proportional to the second time derivatives of cavitation volume variation and inversely proportional to the distance from sources, as shown equation (1).

$$p'(r,t) = \frac{\rho_0 \ddot{Q}(t - r/c)}{4\pi r} = \frac{\rho_0 (R^2 \ddot{R} + 2R\dot{R}^2)}{r} \tag{1}$$

However, equation (1) is valid only where pressure fluctuation sources keep still, and the observer is far away from the sources (r>>R). But the distance between rotating propeller and hull is small compared with the length of the pressure waves induced by propeller sheet cavitation. Because pressure fluctuation can be greatly affected depending on sheet cavitation motion and near field effect, equation (1) is cannot be applied. However, it was difficult to find studies and literatures discussing these problems. (Bark 1988)

Thus, this study applied the Ffowcs Williams-Hawkings proposed acoustic theory to the pressure fluctuation caused by the volume variation of propeller sheet cavitation, which has the dominant effect on pressure fluctuation and tried theoretical and physical approaches considering the source motion effect and near field effect due to the rotation of sheet cavitation. The findings will be a much help in studying hull pressure fluctuation in the future.

2 Discussion

2.1 Investigation of Governing equation

As mentioned above, the pressure fluctuation induced by propeller sheet cavitation is closely related to the cavitation volume variation and requires the consideration of cavity motion and near field effect for an elaborate prediction.

The governing equation is derived applying acoustic method developed by Ffowcs Williams-Hawkings. The pressure fluctuation due to a volume change of sheet cavity is proportional to the mass acceleration effect, which can be represented as shown in equation (2).

$$p'(\vec{x},t) = \frac{1}{c_0^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p = \frac{\partial}{\partial t}\left[\rho_0 \dot{Q}(\tau^*)\right] \tag{2}$$

where, p' is pressure fluctuation, ρ_0 and c_0 are the density and sound speed of undisturbed medium. Q is the volume of sheet cavitation, whose first and second derivatives were represented as $\dot{Q}$, $\ddot{Q}$, respectively.

From the relation of pressure fluctuation source term and observation point, the following expression can be derived.

$$g(\tau^*) = \tau^* - t + \frac{c_0}{r} \qquad (3)$$
$$r = c(t - \tau^*) = |\vec{x} - \vec{x}_s|$$

τ^*, t are source time and observer time, and $\vec{x}, \vec{x}_s$ are location of observer and source position.

Pressure fluctuation field whose source strength is $q(\vec{x}_s, t)$ can be expressed as follows.

$$p'(\vec{x},t) = \int \frac{q(\vec{x}_s, \tau^*)}{4\pi|\vec{x} - \vec{x}_s|} d^3y \qquad (4)$$

If cavitation volume changes and observation point is far away from the source while cavitation is still, the solution can be obtained as shown in equation (1) in accordance with Green's function theorem for wave equation.

However, since sheet cavitation rotate with blades as volume changes, source term of equation (2) can be expressed as shown in equation (5), considering relative velocity for observer:

$$p'(\vec{x},t) = \frac{\partial}{\partial t}\left[\frac{\rho_0 \dot{Q}(\tau^*)}{4\pi r(1 - M_r)}\right] \qquad (5)$$

Here, a few relational expressions will be introduced for physical phenomena. A relative velocity (v_r) can be obtained by differentiating distance from source time.

$$\frac{\partial r}{\partial \tau^*} = -v_r \qquad (6)$$
$$M_r = \vec{v} \cdot \bar{\bar{r}} / c_0$$

Equation (5) is finally developed into the following equation.

$$4\pi p'(\vec{x},t) = \frac{\rho_0 \ddot{Q}(\tau^*)}{r(1 - M_r)^2} + \frac{\rho_0 \dot{Q}(\tau^*) \dot{M}_i \hat{r}_i}{r(1 - M_r)^3} + \frac{\rho_0 \dot{Q}(\tau^*) c_0 (M_r - M^2)}{r^2 (1 - M^3{}_r)} \qquad (7)$$

Equation (7) represents pressure fluctuation at the observer time t and position $\vec{x}$. Pressure fluctuation source radiates pressure pulse at source time τ^* and position $\vec{x}_s$. As source is in motion, several terms affects pressure fluctuation, as shown in equation (7). In each term $(1-M_r)^{-1}$ is caused by the source movement. As sheet cavitation moves with blades, pressure fluctuation is stronger when it gets closer to observer $(M_r > 0)$ than when it go away from the observer $(M_r < 0)$ even though observer point is at the same distance from the source point.

The first two terms in equation (7) is far field term proportional to $1/r$, and the last term is near field term proportional to $1/r^2$.

Pressure fluctuation at the blade rate frequency is calculated through the Fourier transform and a total pressure fluctuation was calculated by equation (8), which is recommended by ITTC.

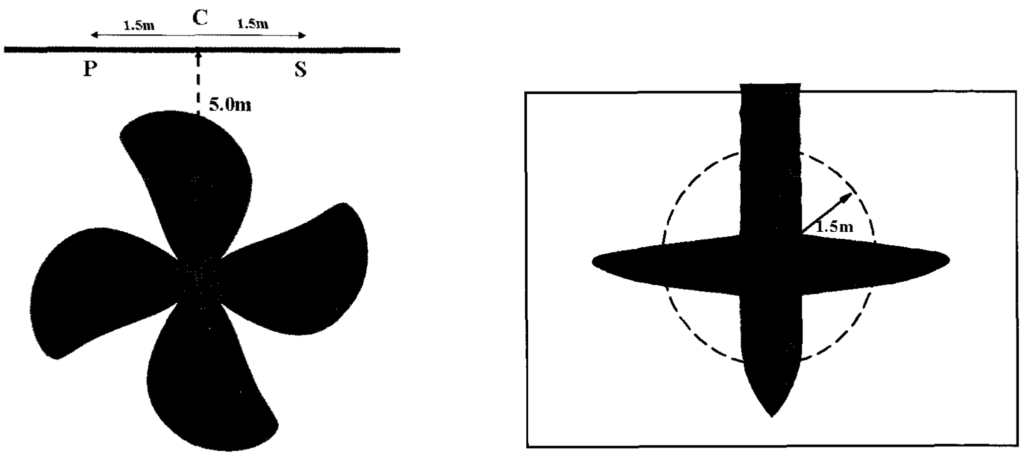
$$\widetilde{P} = \sqrt{P_1^2 + 2P_2^2 + 3P_3^2 + 4P_4^2 + \cdots} \tag{8}$$

2.2 Numerical Simulation

Using the governing equation in section 2.1 to make a physical analysis of the pressure fluctuation on the wall induced by propeller sheet cavitation, a propeller model, operation conditions, and volume variation of sheet cavitation is assumed. Because various factors may affect pressure fluctuation, these factors are simulated and analyzed.

Table 1: Propeller data & operating condition

Propeller Diameter	6.0 m
Hub-diameter ratio	0.18
Number of blades	4
Propeller rotational speed	120 rpm
Tip Clearance	2.0 m



(a) view from stern (b) view from upper side

Figure 1: Calculation Model and observer position

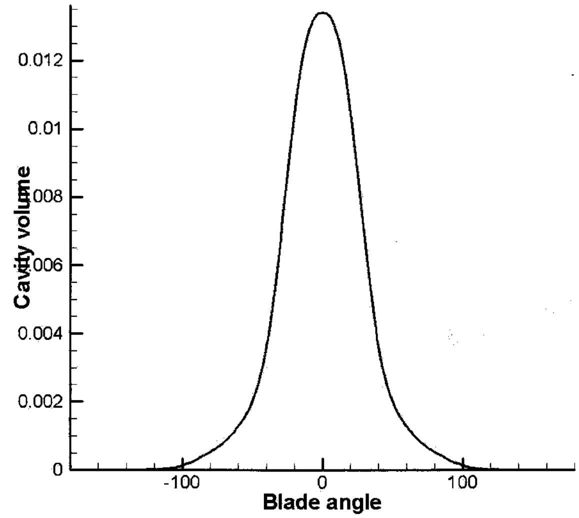


Figure 2: Volume variation of sheet cavitation

To find the formation mechanism of pressure fluctuation, the pressure fluctuation induced by the sheet cavitation of each blade was calculated. Figure 3 shows the pressure fluctuation induced by the sheet cavity of each blade at the center point of rigid wall (above the propeller plane), and the resultant pressure fluctuation.

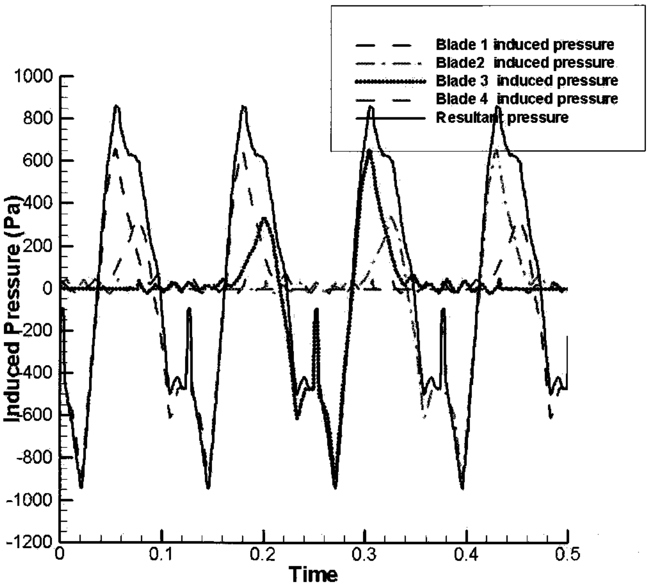


Figure 3: Pressure fluctuation induced by each blade

Because the first blade moved in the direction form blade angle from 0°to 90°, and the fourth blade moved 270° to 0°, they induced relatively large pressure fluctuation. But the second and third blades induced small pressure fluctuation because they produced little cavitation. Thus, resultant pressure fluctuation is represented by the summation of each blade induced pressure fluctuation, which has phase differences.

The pressure fluctuation induced by sheet cavitation was the sum of near field term and far field term. We studied how much each term affects the total pressure fluctuation. Figure 4 shows the pressure fluctuation of near field and far field terms induced at the center point.

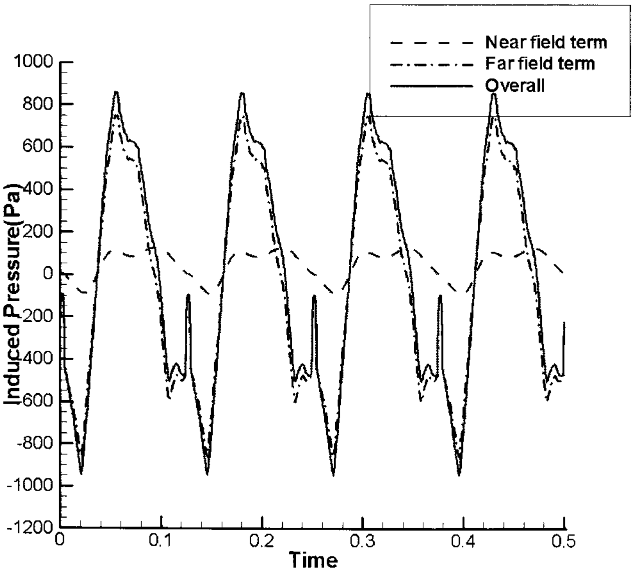


Figure 4: Near field term and Far field term at the center position

To find an attenuation effect of each term according to the distance, near field and far field terms were calculated at the propeller plane upward distance of 0.5, 1.0, 3.0, 10.0, and 20.0 times the radius of propeller. Figure 5 shows the result of computation.

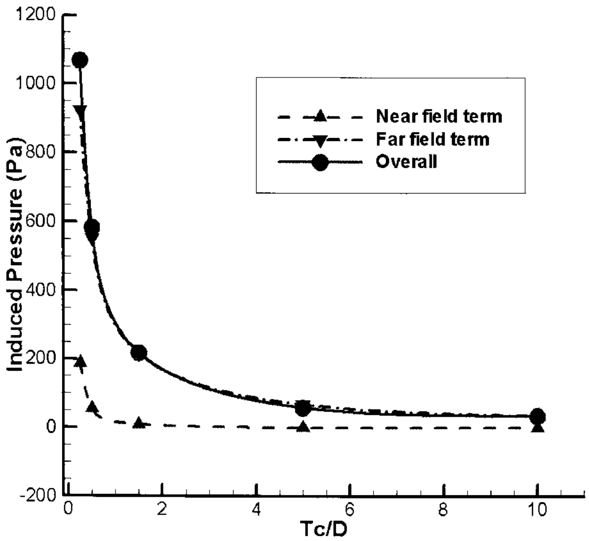


Figure 5: Near field term and Far field term according to the observer distance

Since near field term is proportional to $1/r^2$, and far field term is to $1/r$. Near field term is sharply reduced as it keeps away from the source, while far field term is dominant at a distance. Generally the tip clearance between the hull and propeller is less than 1.0, so near field term cannot be ignored as shown in Figure 5.

The derived governing equation (7) contains a relative velocity term, which is caused by the moving sources.

To find the influence of such effect, results for the consideration and not consideration of source relative motion were calculated at the center point. Table 2 shows the results.

Table 2: Effect of source movement

	w/ relative velocity	w/o relative velocity
Near field term	109.99 Pa	6.38 Pa
Far field term	752.10 Pa	732.73 Pa
Overall	862.09 Pa	739.11 Pa

As shown in the result, there was a slightly difference in results between consideration and no consideration of source relative motion according to observer point. As specified above, if a relative velocity is not considered, the same pressure fluctuation values are expected at the same distance between source and observer point. However, if the relative velocity of source is considered, results are somewhat different. Even though observer point is same distance from the source, induced pressure fluctuation results are stronger when source gets closer than when it gets away from the observer. These results are well shown in Figure 6.

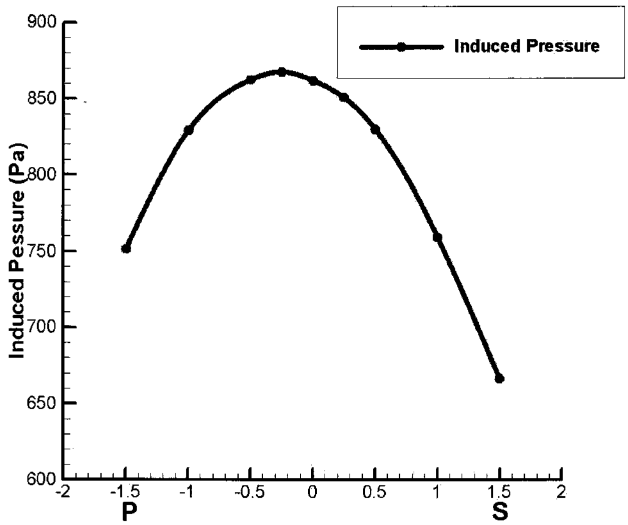


Figure 6: Pressure fluctuation from P to S (see. Figure 1. (a))
– Effect of source relative velocity

Finally, calculated pressure fluctuation results at the 5 point (see Figure 1. (b)) are presented in the Table 3 and Figure 7.

Table 3: Pressure fluctuation magnitude

P_{si} (kPa)	Port	Center	Starboard	Forward	After
P_{s1}	0.654	0.688	0.548	0.567	0.602
P_{s2}	0.149	0.240	0.216	0.192	0.182
P_{s3}	0.161	0.179	0.123	0.139	0.145
P_{s4}	0.059	0.050	0.036	0.044	0.045

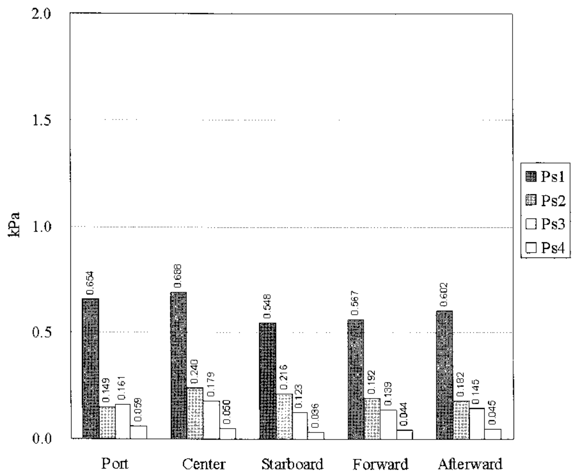


Figure 7: Pressure fluctuation magnitude

3 Conclusions

In this study, we made a theoretical and numerical investigation into factors for the pressure fluctuation induced by cavitation. Modern acoustic theory is applied to the source modeling of pressure fluctuation. Governing equation of sheet cavitation induced pressure fluctuation is derived using a physical and mathematical approach. Various factors affecting pressure fluctuation are analyzed based on the governing equation.

The pressure fluctuation induced by propeller sheet cavitation is not simply proportional to the second derivative of cavitation volume variation, and inversely proportional to distance. As shown in the derived governing equation (7), it is related to the first and second derivatives and it is represented by combined results of the far field term and near field term. Various simulations showed that an elaborate prediction of the pressure fluctuation induced by propeller sheet cavitation requires an overall consideration of near field effect, source motion effect, and retarded time.

The developed equation and findings can be used as a useful material for developing prediction tool for the pressure fluctuation induced by propeller, and studying pressure fluctuation in the future. Furthermore, they will be used as useful sources for predicting the hull pressure fluctuation induced by propeller at the design stage, and developing control technique.

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