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Experimental estimation for pressure fluctuation on ship stern induced by cavitating propeller using cavity shape measurements

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Abstract

Authors have recently developed a combination-line charge-coupled device camera-based method for measuring three-dimensional shapes that is faster and more accurate than conventional methods. Furthermore, the developed system can measure cavity shapes on a model propeller through the experiments in the large cavitation tunnel of NMRI. However, it is necessary to verify how much accuracy the system has in the cavity shape measurement. In this paper, we verify the accuracy through a comparison of the pressure fluctuation estimated by the cavity volume and measured by the pressure sensor. In the estimation, since the unsteady cavity is replaced by a spherical bubble moving with varying radius, the pressure fluctuation induced by the sphere is calculated. The pressure fluctuation is estimated by applying the proposed method to experimental data of the cavity shape. The pressure fluctuation estimated by the proposed method is in good agreement with the pressure fluctuation measured by pressure sensors. This result also showed that the cavity shape measurement system developed by the authors has sufficient accuracy.

Keywords: Cavity volume, 3D shape measurement, Combination line CCD camera method, Pressure fluctuation induced by cavitating propeller.

1. Introduction

Cavitation generated by a propeller operating in a ship's wake can cause hull vibration, thrust reduction, and erosion. To solve these problems, developing theoretical and numerical calculation methods for estimating cavitation with high accuracy at the design stage is necessary. Estimating cavitation with high precision requires measurements of cavity volume which has a strong correlation with pressure fluctuation. At present, there is a few method for measuring cavity shape with high accuracy. To fill this knowledge gap, various methods of measuring cavity shape have been proposed, including the use of stereo photography and laser beam scattering (Ukon et al 1991; Luca et al 2009; Stefan et al 2012). Recently, we have developed a three-dimensional cavity shape measurement system based on the use of a combination-line CCD camera method (Shiraishi et al 2017). However, we haven't verified the accuracy of the developed system of cavity shape measurement. In order to verify the precision of the system, we investigate the relationship of cavity volume and pressure fluctuation induced by an unsteady cavitation on propeller blades. For estimation of pressure fluctuation by cavity volume, unsteady cavitation is replaced by a spherical bubble moving with varying radius. Then the pressure fluctuation induced by the sphere is calculated by applying the potential theory.

2. Cavity Shape Measurement

2.1 Combination-line CCD camera measurement method

We used a combination of line CCD cameras to measure cavity shapes on the model propeller (Hoshino et al 2004). In this method, a laser beam is irradiated onto a measurement object and light scattered from its surface is photographed using three line CCD cameras. Based on the resulting image data, the three-dimensional surface of the object is reconstructed via triangulation. In line CCD cameras, the image-receiving elements are arranged in a row. Such cameras have the advantage of much higher scan rates and resolution than area CCD cameras. The configuration and a photo of the camera system used in this study for three-dimensional shape measuring are shown in Figures 1 and 2, respectively. We used a green laser (532 nm), a wavelength with high penetration ability in water. The specific measurement method used by the proposed system is outlined as follows. First, the laser beam is used to irradiate the position to be measured, with laser light scattered from the surface of the measurement object passed through a semi-cylindrical lens and focused onto the line CCD elements for imaging. Triangulation is then used to extract the three-dimensional coordinates of the laser light spot position from the peak coordinates of the luminance distributions of

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the images captured by the cameras. Figure 3 shows the measurement principle applied by the combined-line CCD method as seen from the depth direction.

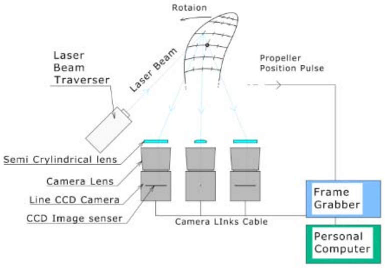

Figure 1 Schematic of measurement system

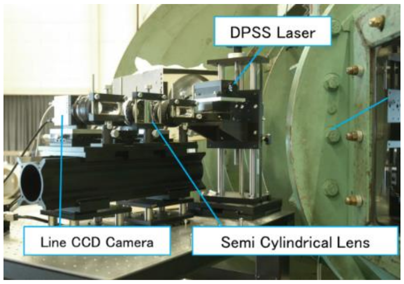

Figure 2 Photo of measurement system

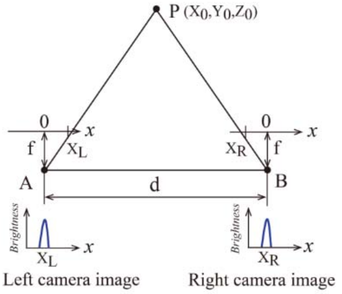

Figure 3 Illustration of the use of triangulation in the combination-line CCD camera method

2.2 Measurement results of the cavity shape

Cavity shape measurement was then performed under the cavitation condition on the Seiun-Maru-I's HSP (Shiraishi et al 2017). The detail of the calculation conditions and definitions are same to the paper. Cavity shape measurement was performed at six propeller phase angles: 15.0°, 20.0°, 30.0°, 40.0°, 50.0° and 60.0°. Figures 6–9 show the respective cavitation patterns imaged by a steel camera (left) and measured using the proposed system (right) at six propeller phase angles: 30.0°, 40.0°, 50.0° and 60.0°. It is seen from these comparisons that the proposed method can be used to measure the cavity shape over a wide range of phase angles.

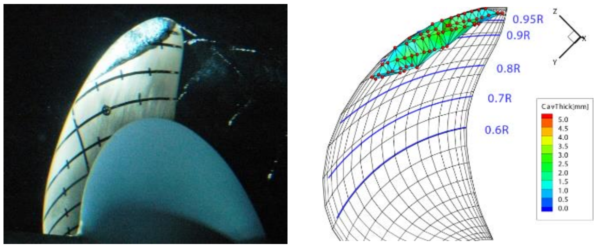

Figure 6 Image of cavitation patterns and measured cavity shapes on model propeller (Phase Angle = 30.0°)

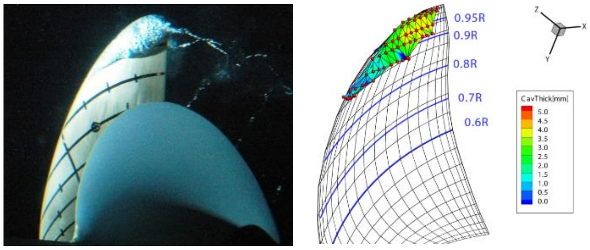

Figure 7 Image of cavitation patterns and measured cavity shapes on model propeller (Phase Angle = 40.0°)

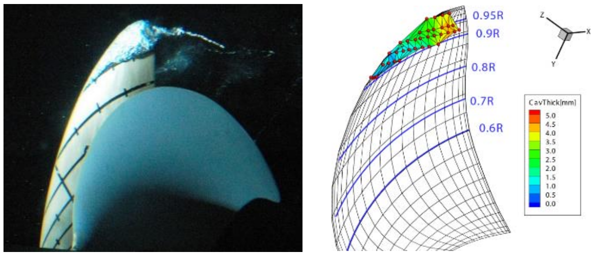

Figure 8 Image of cavitation patterns and measured cavity shapes on model propeller (Phase Angle = 50.0°)

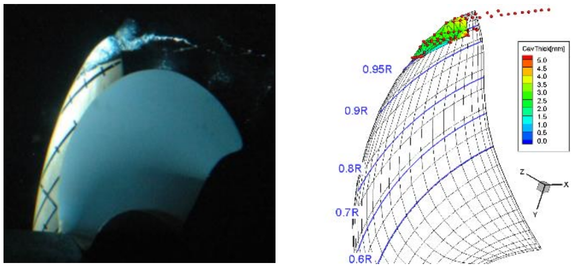

Figure 9 Image of cavitation patterns and measured cavity shapes on model propeller (Phase Angle = 60.0°)

3. Estimation for pressure fluctuations using measured cavity volume

3.1 Approximation of cavity volume with a spherical bubble

In this study, the pressure fluctuation is estimated from the cavity volume using the method of Hoshino (Hoshino, 1979). Firstly, the cavity volume is replaced with a moving spherical bubble. Then, the fluctuation of the cavity volume is considered as fluctuation of the spherical bubble. When this pressure fluctuation is calculated based on the potential theory, the fluctuating pressure is expressed by the following equation.

$$C_p = \frac{a^3}{r^3}\left(3\cos^2\theta - 1\right) + 5\frac{a^2}{r^2 U}\frac{da}{dt}\cos\theta - \frac{1}{4}\frac{a^6}{r^6}\left(3\cos^2\theta + 1\right)$$
$$+ 2\frac{a}{rU}\left\{2\left(\frac{da}{dt}\right)^2 + a\frac{d^2a}{d^2t}\right\} - \frac{a^4}{r^4U^2}\left(\frac{da}{dt}\right) - 2\frac{a^5}{r^5U}\frac{da}{dt}\cos\theta \qquad (1)$$

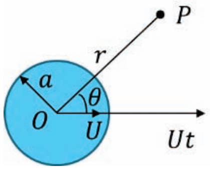

Figure The coordinate system of a moving sphere bubble

By triangulating the measurement points of the cavity shape, the surface of the cavitation is generated by a triangular panel. Then, the region surrounded by the propeller blades and the cavitation surface is assumed to be cavity volume. By approximating the obtained cavity volume as a single spherical bubble, the radius of the spherical bubble is calculated. In this study, we call this radius the equivalent spherical bubble radius. This process is executed for each propeller phase angle at which the propeller shape measurement is performed, and the data is subjected to spline interpolation to calculate time series data of the equivalent spherical bubble radius. Substituting this time series data into the equations (1), the fluctuating pressure is calculated. In this study, in order to consider the boundary effect of the flat plate, the pressure coefficient is multiplied by the boundary coefficient of 2.0.

3.2 Comparison with experiments

We apply this estimation method to the cavity measurement result of SeiunMaru I in the aquarium test and estimate the fluctuating pressure. Then, the estimated fluctuating pressure is compared with the fluctuating pressure measured by the pressure sensor, and the effectiveness of the constructed estimation method is shown. First, the results of calculating the cavity area and the cavity volume from the cavity shape measurement shown in Chapter 2 are shown in Figure 10 and Figure 11, respectively. It can be seen from these figures that the decreasing tendency of cavity area increase and the tendency of increasing cavity volume are different. It can be confirmed that the cavity volume sharply decreases as compared with the cavity area. From this, it can be seen that the cavitation characteristics cannot be sufficiently grasped only by the cavity area.

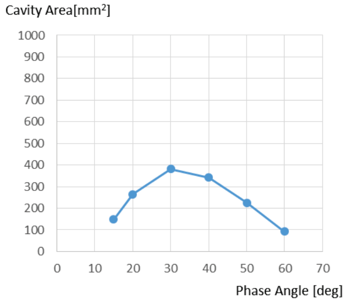

Figure 10 Measurement results of the cavity area

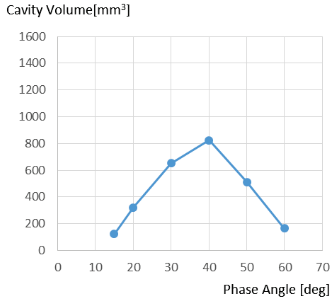

Figure 11 Measurement results of the cavity volume

Next, the equivalent spherical radius is calculated from the calculated cavity volume, and the result is interpolated with a spline. Figures 12 (a), (b), and (c) show the first derivative and the second derivative of the equivalent spherical radius. Substituting these values into the equation(1), the pressure coefficient C_p of the fluctuating pressure generated by the cavitation is calculated. The result is shown in Figure 12 (d). From these results, it was confirmed that a smooth pressure waveform is obtained without significant undulation by spline interpolation.

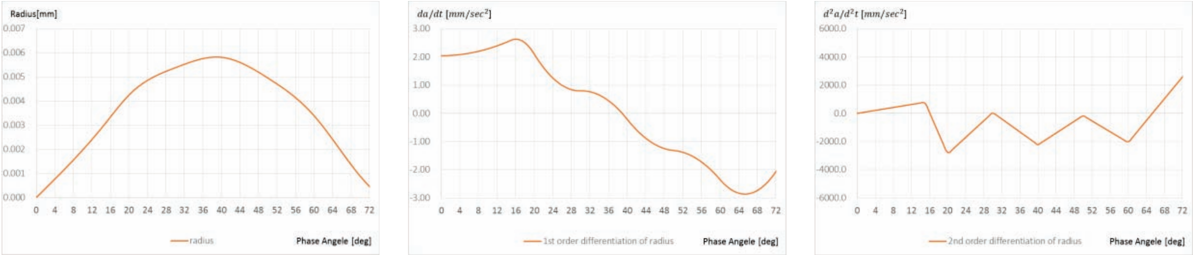

Figure 12 (a) Equivalent bubble diameter: a, (b) its first derivative value: da/dt, (c) its second derivative value: d^2a/dt^2.

Next, we compare the fluctuating pressure estimated from the cavity volume with the fluctuating pressure measured by the pressure sensor. Since the fluctuating pressure calculated above is only the component due to cavitation, the component of Non cavitation is added to this component. In this research, as a non-cavitation component, the measurement result obtained by separately measuring with a pressure sensor is used. The time series of the fluctuating pressure of both are shown in Figure 13. The blue line shows the measurement result of the pressure sensor, and the orange line shows the estimated value from the cavity volume. From this figure, it can be confirmed that the estimated value and the measured value coincide very well. In the estimated value, high-frequency components do not appear because it is not possible to consider Tip vortex cavitation. From the above, it was confirmed that the cavity shape measurement method developed by the authors has sufficient accuracy.

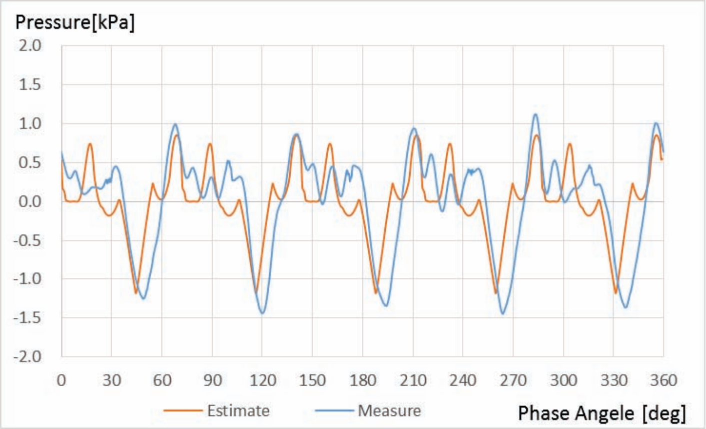

Figure 13 Time series comparison of pressure fluctuation of pressure sensor and estimation.

Conclusion

In this study, the method to estimate fluctuating pressure induced by cavitating propeller using the cavity volume measurement was proposed. The pressure fluctuation was estimated by the cavity volume measurement result of the Seiun-Maru I's HSP using the proposed method. The pressure fluctuation measured by the pressure sensors was compared with the estimated results. As a result, it was confirmed that the estimated and the measurement result coincide very well. We also showed that the cavity shape measurement method developed has sufficient accuracy.

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