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Cavity Shape Measurement Using Combination-Line CCD Camera Measurement Method

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ABSTRACT

Improving the theoretical prediction of propeller cavitation requires an investigation of unsteady propeller blade cavitation. We recently developed a new combination-line charge-coupled device camera-based method for measuring three-dimensional shapes that is faster and more accurate than conventional methods. To verify the system's effectiveness, model experiments were conducted in the National Maritime Research Institute's large cavitation tunnel using the highly skewed propeller of a training ship "Seiun-Maru-I". In this paper, we discuss the measurement results obtained for a model propeller blade and cavity shapes and show the effectiveness of the developed measurement system.

Keywords

Propeller cavitation, Combination-line charge-coupled device camera method, measuring cavity shape

1 INTRODUCTION

Cavitation generated by a propeller operating in a ship's wake can cause hull vibration, thrust reduction, and erosion. To address these problems, developing theoretical and numerical calculation methods for estimating cavitation with high accuracy at the design stage is necessary. Numerous cavitation tests have obtained measurement data on, e.g., propeller open water characteristics, cavitation patterns, and pressure fluctuation. Estimating cavitation with high precision requires measurements of cavity volume, as this has a strong correlation with pressure fluctuation. However, at present, there is no 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 2009a; Luca et al 2009b; Stefan et al 2012).

In this paper, we present a system for measuring cavity shape on model propeller blades using a combination of line charge-coupled device (CCD) cameras. To verify the effectiveness of the proposed system, model experiments on the highly skewed propeller (HSP) of a training ship, the "Seiun-Maru-I," were conducted in the large cavitation tunnel at the National Maritime Research Institute. Here, we discuss the measurement results obtained for a model propeller blade and cavity shapes and show the effectiveness of the developed measurement system.

2 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 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. In the figure, $P(X_0, Y_0, Z_0)$ is the measurement point and A and B are the installation positions of the left- and right-line CCD cameras, respectively. Using the principle of triangulation, the three-dimensional coordinates of the laser spot light can be calculated from the following equations:

$$X_0 = d \cdot X_L / (X_L - X_R) = X_L \cdot Z_0 / f \tag{1}$$

$$Y_0 = d \cdot Y_C / (X_L - X_R) = Y_C \cdot Z_0 / f \tag{2}$$

$$Z_0 = d \cdot f / (X_L - X_R) \tag{3}$$

where X_L, X_R, Y_C are the coordinates of the peak position of the laser on the captured image of each camera, $(X_L - X_R)$ is the parallax between the left and right cameras, d is the distance between points A and B, and f is the focal length of each camera.

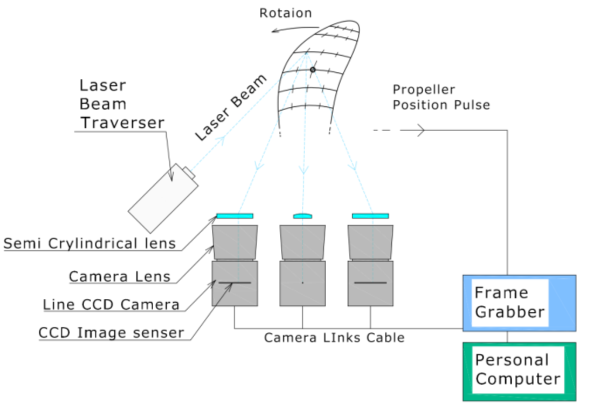

Figure 1 Schematic of measurement system

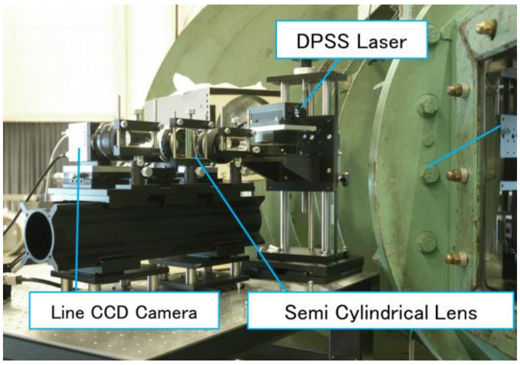

Figure 2 Photo of measurement system

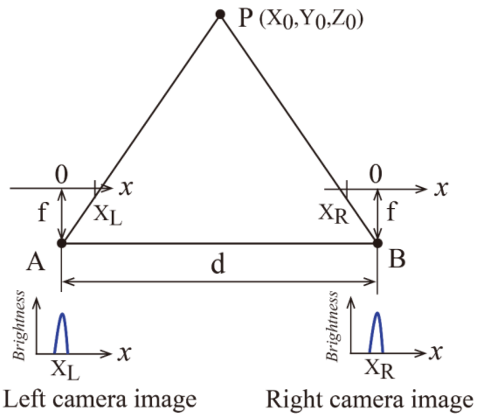

Figure 3 Illustration of the use of triangulation in the combination-line CCD camera method

3 EXPERIMENTS

3.1 EXPERIMENTAL SETTING

A propeller model was used to conduct the experiments (Figure 4). One of the five propeller blades was painted white to enhance reflection, while three other blades were painted black to prevent reflection. The principal parameters of the propeller are provided in Table 1. The cavity shape was measured from a non-uniform flow generated by a wire mesh screen; the axial wake distribution from this screen is shown in Figure 5. Measurements in the experiments were made using an O-XYZ spatial coordinate system (Figure 6).

Figure 4 Photo of model propeller

Table. 1 Principal parameters of model propeller

Diameter [m]	0.220
Pitch Ratio at 0.7 R	0.944
Expanded Area Ratio	0.700
Boss Ratio	0.1972
Number of Blade	5
Skew Angle [°]	45.0

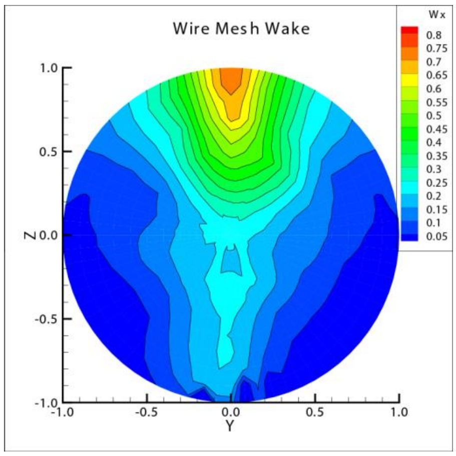

Figure 5 Axial wake velocity distribution in the cavitation tunnel

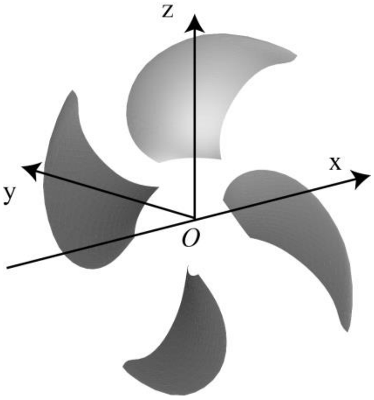

Figure 6 Propeller coordinate system

3.2 MODEL PROPELLER SHAPE MEASUREMENT

Model propeller shape measurement was performed under the non-cavitation condition. Prior to measurement of the three-dimensional shape of the Seiun-Maru-I's HSP, camera calibration was performed using the calibration board shown in Figure 7 over a range including the front and back of the model propeller. In the figure, the spacing between points is 15 mm.

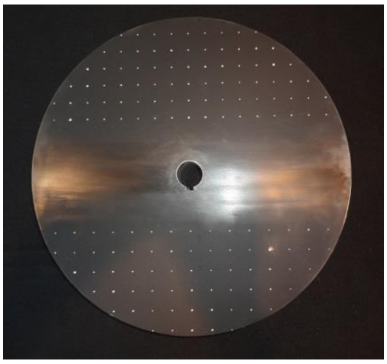

Figure 7 Photo of calibration board.

The shape of the propeller blades was measured at a propeller phase angle of 0° with a positive counterclockwise rotation of 15.0 revolutions per second (rps). Figure 8 shows the cavitation tunnel with the experimental system in place.

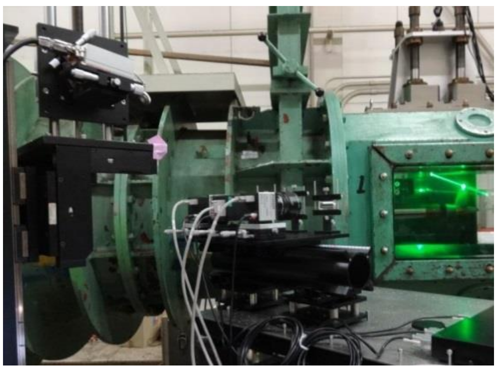

Figure 8 Photo of experimental arrangement

Figure 9 shows the layout of the system, with the three line CCD cameras and the green laser emitter located outside of the cavitation tunnel.

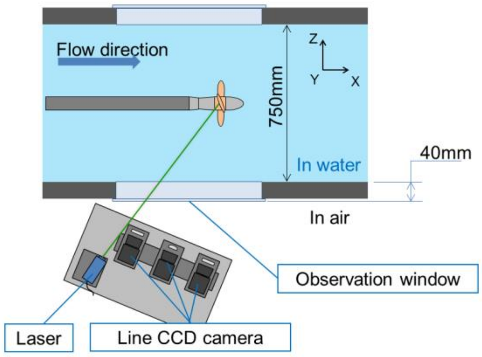

Figure 9 Top view of measurement system layout at cavitation tunnel

The obtained shape measurement results are shown in Figure 10 wherein the propeller blade surface shape is indicated by a wire frame and the red dots represent measurement points from which the measured blade shape is obtained through triangular interpolation. The contours show the errors between the measurement results and the actual propeller blade offset surface. Overall, the error was determined to be less than 0.8 mm, which lies within a robust measurement accuracy of 0.45 mm.

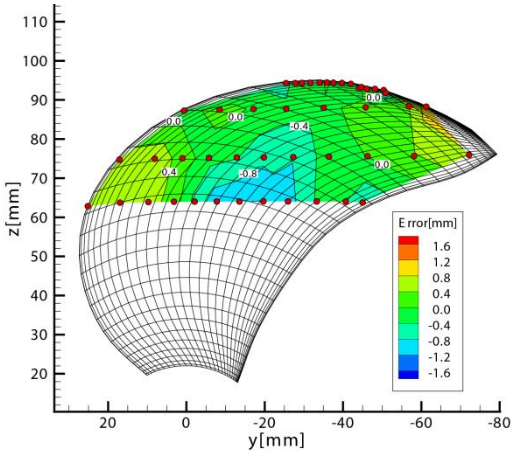

Figure 10 Shape measurement results obtained from the model propeller (HSP)

4 CAVITY SHAPE MEASUREMENT ON MODEL PROPELLER

Cavity shape measurement was then performed under the cavitation condition on the Seiun-Maru-I's HSP. A propeller dynamometer was used to measure the propeller revolution rate n_p (rps) and propeller thrust T (N). The non-dimensional propeller thrust K_T was defined using equation (4) wherein ρ (kg/m^3) is the water density and D_p (m) is the propeller diameter. The cavitation number σ_n is defined by equation (5) wherein P_0 (Pa) is the static pressure at the propeller position and P_v (Pa) is the vapor pressure. The experimental conditions were $K_T = 0.201$, $n_p = 30$ (rps), and $\sigma_n = 2.99$.

$$K_T = \frac{T}{\rho n^2 D_p^4} \tag{4}$$

$$\sigma_n = \frac{P_0 - P_v}{\frac{1}{2}\rho n^2 D_p^2} \tag{5}$$

Cavity shape measurement was performed at five propeller phase angles: 20.0°, 30.0°, 40.0°, 50.0°, and 60.0°. Figures 11–15 show the respective cavitation patterns imaged by a steel camera (left) and measured using the proposed system (right). 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. The region near 0.9 R at which the cavity volume increases is also captured. The figure sequence demonstrates the thickness of the cavity increasing and the cavitation growing toward the trailing edge. From Figure 11, it is seen that the system can measure thin cavitation around the leading edge at 0.8 R. The shape of the cavity can also be measured around 0.95 R, which was not possible in previous experiments. These results confirm that the cavity shape measurement range is expanded through the introduction the proposed system. In Figure 15, the red points around the blade tip indicates the surface of tip vortex cavitation. In this results showed that the developed method can measure the positions and shapes of the tip vortex cavitation.

5 CONCLUSION

In this study, we developed a three-dimensional cavity shape measurement system based on the use of a combination-line CCD camera method. To verify the accuracy of the proposed system, three-dimensional shape measurement of a model propeller was performed, with the results proving that the system can measure the model propeller shape to an accuracy of 0.5 mm. Further three-dimensional cavity shape measurements were performed on the unsteady cavity produced by the propeller blades, demonstrating the system's ability to measure the shape of the cavity in regions of the blade tip that had previously been unmeasurable. The results also confirmed an expanded measurement range

In a future study, we will calculate the cavity volume from the measured cavity shape, conduct comparisons with pressure fluctuation measured by a pressure sensor, and verify the correlation between the cavity volume and the pressure fluctuation.

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DISCUSSION

Question from Ding Yongle

1. Is the last model in your case study made of isotropic material?

2. How can you distinguish the experimented error from the measurement results?

Author's closure

1. Yes, it is. We used the model propeller made of carbon-filled nylon with isotropic.

2. When we measured the amount of deformation, the same points were measured under different experiment conditions. The deformations were calculated from the quantity of the measured point. Since errors included in both points are canceled, the errors can be removed from the measurement results.

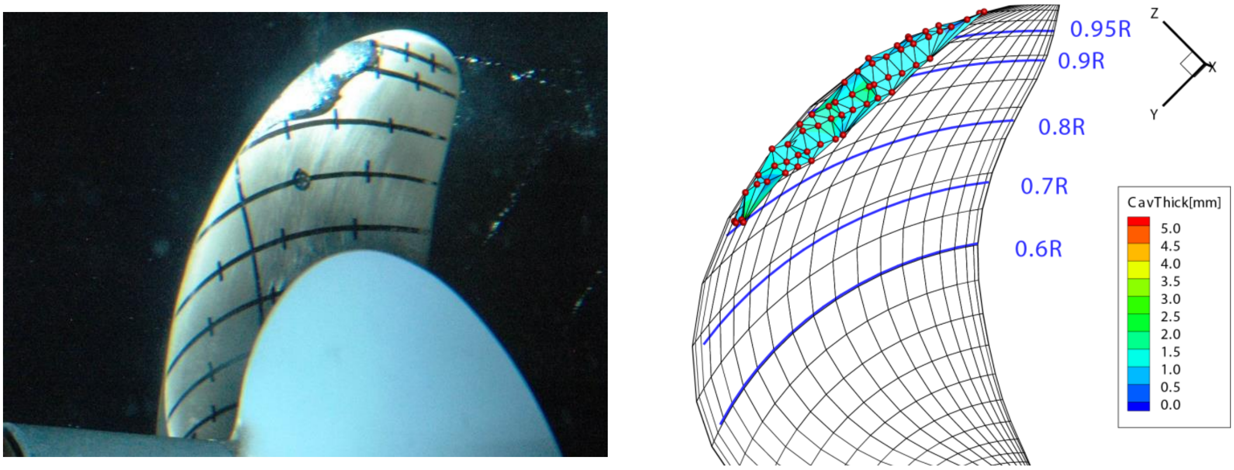

Figure 11 Image of cavitation patterns and measured cavity shapes on model propeller (Phase Angle = 20.0°)

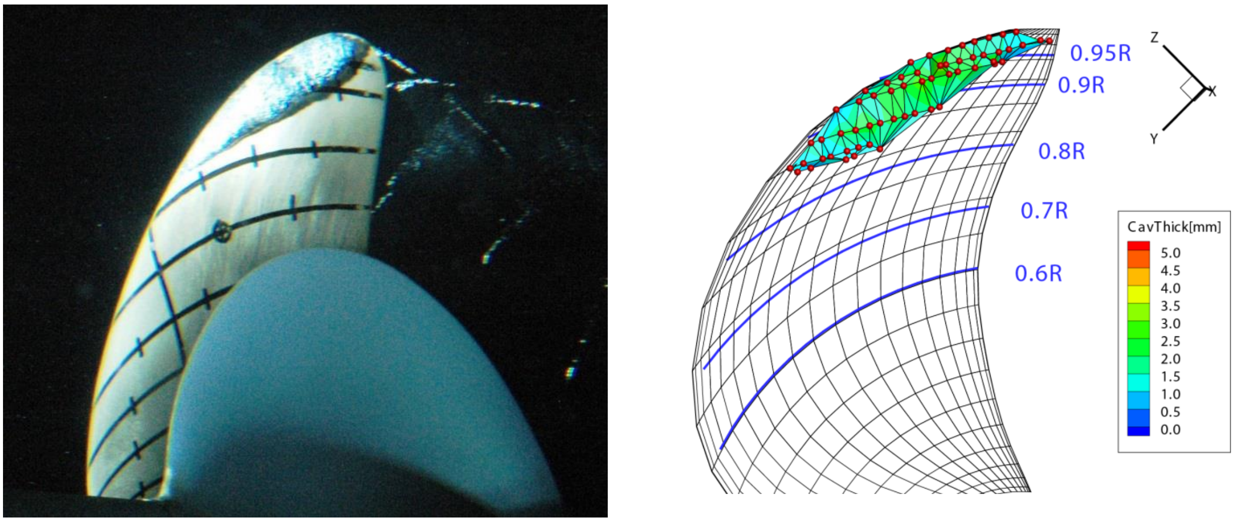

Figure 12 Image of cavitation patterns and measured cavity shapes on model propeller (Phase Angle = 30.0°)

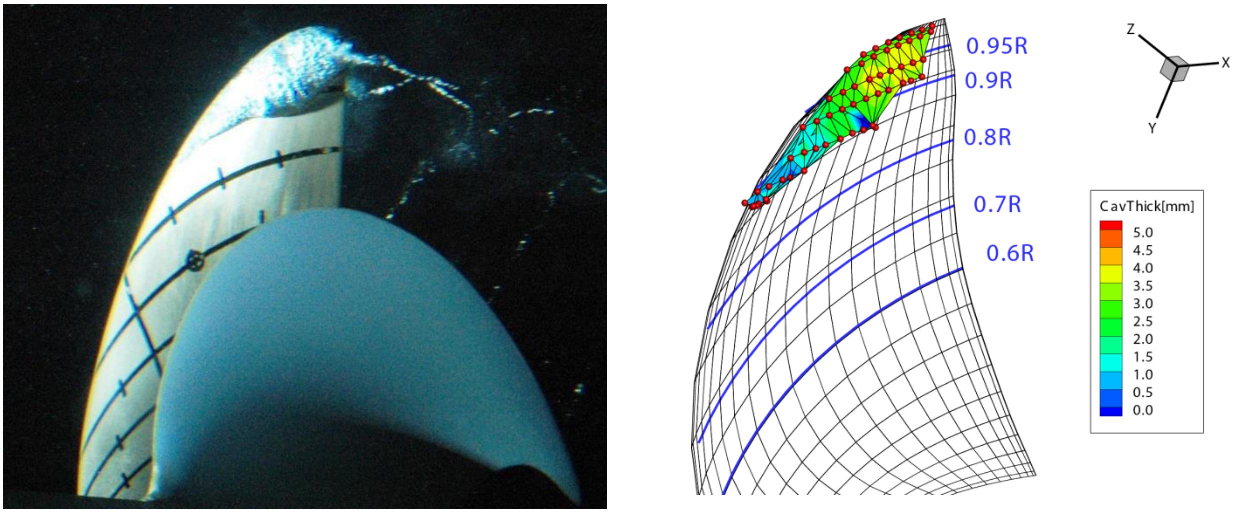

Figure 13 Image of cavitation patterns and measured cavity shapes on model propeller (Phase Angle = 40.0°)

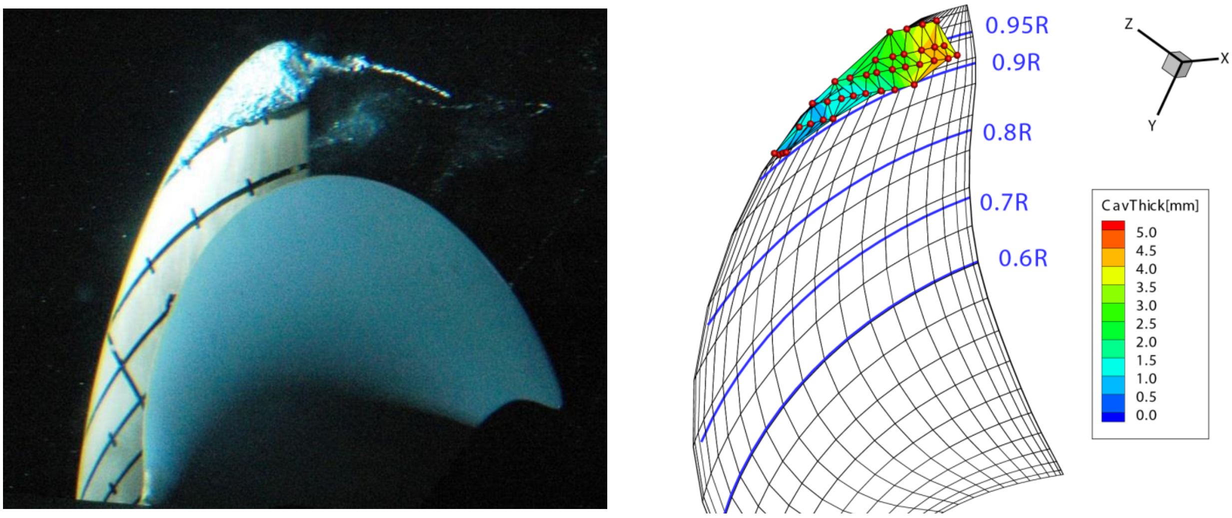

Figure 14 Image of cavitation patterns and measured cavity shapes on model propeller (Phase Angle = 50.0°)

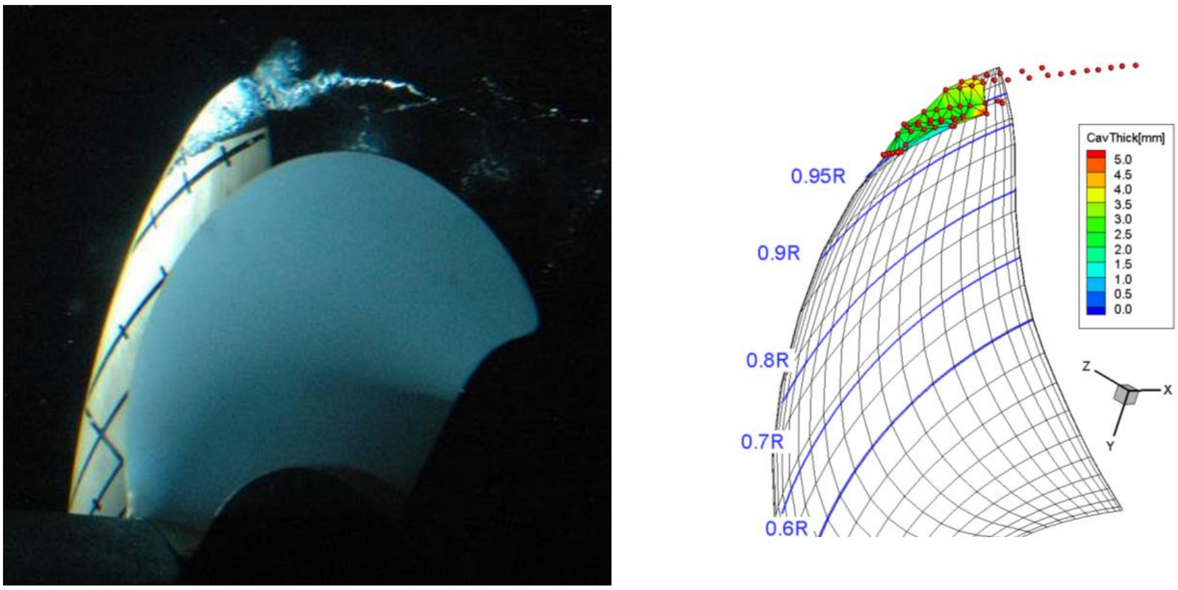

Figure 15 Image of cavitation patterns and measured cavity shapes on model propeller (Phase Angle = 60.0°)