Flow field and cavitation characteristics of hydrofoils coated with hydrophilic and hydrophobic polymers

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Abstract. Tidal power turbines take advantage of tidal energy to generate renewable hydropower. Since the tidal turbines are fixed in the ocean, it is common to paint the blade and the structure of tidal energy generator with antifouling coating to prevent marine organisms from attaching to them. In this research, hydrophilic and hydrophobic coatings which are thought to be useful as countermeasures to prevent marine organisms’ adhesion are studied. We focused on the influence of the (hydrophilic and hydrophobic) coatings on the cavitation and flow field characteristics. The hydrophilic coated foil restrained the cavitation inception and growth compared to the hydrophobic coated foil from our experiment. And then, FFT was carried out on the pressure fluctuation measured in each coating foil, and the absolute value of the pressure fluctuation amount and the difference in the fluctuation period were clarified. And as another characteristic of the coated foils, the flow field near the coating surface was investigated. The velocity distribution near the foil’s surface was measured using Laser Doppler Velocimetry (LDV). In this experiment, a flat plate with or without the hydrophilic and hydrophobic coatings were used. As a result, differences in the boundary layer thickness and the velocity near the wall were revealed.

Keywords: Coating, Hydrophilic, Hydrophobic, Cavitation characteristic, Flow field, Velocity distribution, Laser doppler velocimetry, Boundary layer thickness, Wall friction.

1. Introduction

These days, renewable energy has attracted attention as one of countermeasures against global warming [1]. Tidal power generation which relies on energy from tidal current is one of them. Marine equipment installed in the ocean are subject to nature, marine organisms and dirt can easily adhere to the turbine blades and floating structures [2]. This may cause fouling of the rotating blades and devices. As one of the common methods to prevent marine organisms from attaching themselves to the blades and the structure, antifouling coatings are used. For example, Katsuyama et al. [3] reported experimentally that it is effective to apply coatings to model turbine. They compared how the marine organisms attached to the model turbines which were fixed in the ocean for more than 6 months. Also, Onishi et al. [4] examined the fluid performance of hydrophilic and hydrophobic coated hydrofoils and described the cavitation characteristics of the coating. Therefore, it is important to predict the influence of the paintings to the turbine’s fluid performance. In this research, hydrophilic and
hydrophobic coatings which are thought to be useful as countermeasures to prevent marine organisms’ adhesion are studied. We focused on the influence of the (hydrophilic and hydrophobic) coatings on the cavitation and flow field characteristics. Fialova et al. [5] described the effect of hydrophilic coating and hydrophobic coating on fluid performance. When applying hydrophobic treatment in the experiment concerning circular disc friction, the wall friction speed has changed, and Fialova et al. report that the slip on the wall significantly affects the vortex structure of the flow. The disc friction loss of the pump and Francis turbine can use this hydrophobic technology, this technology reduced loss by 20%. And they compare the hydrophilic surface and the hydrophobic surface of the Francis turbine and report that the fluid efficiency in the turbine on hydrophobic surface has increased by 0.5%. But, these mechanisms have not been elucidated.

In this study, for the purpose of grasping the cavitation characteristics of the coating foil, the difference in cavitation inception, the difference in the pressure fluctuation of the foil trailing flow, and the difference in the cavitation fluctuation period were evaluated. In order to investigate another characteristic of the coated foils, the velocity distribution near the foil’s surface was measured using Laser Doppler Velocimetry (LDV). From the velocity distribution, it is possible to calculate the difference in friction stress of the wall at that point. And finally, the wall friction speed was calculated from wall friction stress.

2. Experimental setup

2.1. Characteristics of hydrophilic and hydrophobic coatings
First, on the difference of chemical characteristics of hydrophilic coating and hydrophobic coating, the hydrophilic coating is networked polymer with surface segregated amphoteric ions. The hydrophobic coating is composed of fluorine polymer. And the thickness of the coatings is about 3~4μm. Next, to evaluate the wettability of the coating using a contact angle goniometer, bubbles were placed on the surface of the film in a state sunk in pure water and those images are shown in figure 1. The contact angle of the bubble was about 20±5 ° for the hydrophilic coating and about 95±5 ° for the hydrophobic coating. Then the surface roughness of each coating surface was measured using an atomic force microscope (AFM). The enlarged image and the surface roughness of each surface are shown in figure 2. It can be seen that the surface roughness is reduced by applying the coating (it became smooth).

![Figure 1. Bubble contact angle in water.](a) Hydrophilic coating. (b) non-coated. (c) Hydrophobic coating.)
2.2. Cavitation tunnel

The experimental investigation was carried out using the closed-loop water circuit tunnel described in figure 3 shows a cavitation tunnel test section. The loop also contains two pumps and tanks upstream and downstream of the test section. The flow rate can be changed with a pump and the pressure can be changed by a vacuum pump connected to the downstream tank. The test section has a 100 mm × 100 mm cross section and is made of acrylic to visualize cavitation by high speed video camera. Test hydrofoil is shown in figure 4. The maximum chord length is 40 mm and the span length is 60 mm that cross section is shown in figure 5.

As shown in figure 3, pressure is measured upstream and downstream of the hydrofoil. The cavitation number is expressed by the following equation (1) using the upstream pressure $p_1$.

$$\sigma = \frac{2(p_1 - p_v)}{\rho U^2_\infty}$$

where $p_v$ is the saturated vapor pressure, $\rho$ is the density of water and $U_\infty$ is mean water velocity.
2.3. LDV measuring instrument
The LDV (Laser Doppler Velocimetry) measuring instrument and test section are shown in figure 6. As shown in figure 6, laser radiation probe is set in 3-axis traverser. A flat plate foil (shown in figure 7) was used as the test hydrofoil. The laser was irradiated perpendicular to the flow direction and the flow direction velocity was measured. The laser was moved from the foil surface to main flow part. Also, the velocity distribution near the foil was measured at center of cord length. The minimum and maximum measuring distances were from 10μm to 100μm, and the moving distance was decreased as approaching the foil surface.

3. Pressure fluctuation and cavitation fluctuation periods of each hydrofoils
In our previous study, experiments with coated and uncoated foils of NACA16021 were conducted. Figure 8. shows that the differences of cavitation inception in hydrophilic (H-PHI), hydrophobic (H-PHO), and no coating (N-C). TVC. is tip vortex cavitation, SC. is sheet cavitation, CC. is cloud cavitation.
To investigate this cause, this research was done. The left side of figure-9, 10, 11 shows a cavitation image of hydrophilic, hydrophobic coating and non-coated foil recorded by a high-speed video camera (mean velocity: 5 m/s, attack angle: 14°). It can be seen from these that the cavity length where cloud cavitation occurs and collapses, the size of cavitation area was different. As shown in figure 3, the downstream pressure fluctuation was measured simultaneously with the measurement of the high-speed video camera. In the right side of figure-9, 10, 11 FFT was carried out on the downstream pressure fluctuation. For example, it can be seen from the right side of Figure 11 that the frequency peak is at 19 Hz. The cavitation fluctuation period in the left side of figure 11 was approximately 21 Hz, almost coinciding with the frequency peak value. And then from figure 9, 10, 11, it is clarified that the magnitude of pressure fluctuation was larger in the order of H-PHO, N-C, H-PHI. It is thought that this is proportional to the volume of the cavitation fluctuation. From these, when the pressure fluctuation was rearranged by the frequency peak of the FFT, the change in the fluctuation period can be easily understood. Figure 12 shows changes in frequency peak according to the cavitation number at attack angle of 10° and 14°. From figure 12 (10°), it is found that H-PHO and N-C are almost the same cavitation number when they are compared with the same frequency peak (the same cavitation fluctuation period), but the cavitation number of H-PHI is low. In other words, cavitation is suppressed. From figure 12 (14°), the difference of characteristics in the cavitation number of H-PHO, N-C and H-PHI is clear. In figure 13, the pressure fluctuation of frequency peak was plotted on the vertical axis. The pressure fluctuation of P-PHI appears low, but relationship between H-PHO and N-C depend on attack angle. At angle of attack 10°, it is seen that N-C is larger than H-PHO, but at angle of attack 14°, H-PHO is always greater than N-C.

**Figure 9.** Hydrophilic $\sigma = 1.15$. 

**Figure 8.** Cavitation inception.
**Figure 10.** Non-coated $\sigma = 1.18$.

**Figure 11.** Hydrophobic $\sigma = 1.13$.

**Figure 12.** Frequency peak. (downstream pressure fluctuation)
4. Flow field of hydrofoils coated with hydrophilic and hydrophobic

In order to investigate another characteristic of the coated foils, the velocity field around the foil was measured. The velocity distribution was measured from point of the surface to the main flow. That point of the surface is the center of the span direction and flow direction of the surface where the trailing edge is cut in figure 7. Figure 14 show the results of measuring the velocity distribution around the flat plate using LDV (Laser Doppler velocimetry). In these results, please note that the point near the wall is not the 0mm distance from the wall. Since the minimum measuring distance was 10μm, it is thought that there are 10μm wall judgment errors as well. The vertical axis is the distance from the foil surface, and the horizontal axis is the flow velocity of each point divided by the mean velocity. From the figure 14, it is clarified that the boundary layer thickness varies with H-PHI, N-C and H-PHO. Also, because the wall friction speed was different, it can be estimated that the friction on the wall surface is different depending on the coating. This is an important thing that leads to flow fields and losses.

5. Discussion of flow fields data

In order to make $Y^+$ represented by the following equation (2) as the horizontal axis and $U^+$ represented by the following equation (3) as the vertical axis, it is necessary to calculate an appropriate wall friction speed. Here, $y$ is the distance from the wall surface, $U^+$ the wall friction speed, $ν$ the kinematic viscosity coefficient, and $u$ the flow velocity.
\[ Y^+ = \frac{yU^*}{v} \]  

(2)

\[ U^+ = \frac{u}{U^*} \]  

(3)

This time, the wall friction stress \( \tau_w \) was calculated by the equation (4) derived from the experiment of Blasius equation, and the wall friction speed is derived in the equation (5). Here, \( \delta \) is the boundary layer thickness, and \( \delta \) is the distance from the wall surface 99% of the average flow velocity.

- From Blasius law of friction

\[ \tau_w = 0.0227\rho U^2 \left( \frac{v}{U_\infty \delta} \right)^{\frac{1}{4}} \]  

(4)

\[ U^* = \sqrt{\frac{\tau_w}{\rho}} \]  

(5)

Figure 15 shows the results of arranging right side data\( (U_\infty : 7\text{m/s}) \) of figure 14. Also, the boundary layer thickness, wall friction stress from equation (4), and wall friction speed from equation (5) are shown in Table 1. From figure 15, the slope of the region starting from \( Y^+ \) 30 to 40 is different. These regions are called turbulent flow layers.

![Figure 15. Law of the wall. \((U_\infty : 7\text{m/s})\)](image)

| \( \delta \) mm | \( \tau_w \) Pa | \( U^* \) m/s |
|-----------------|----------|-------------|
| H-PHI           | 1.22     | 131         | 0.363       |
| N-C             | 1.35     | 130         | 0.362       |
| H-PHO           | 1.92     | 125         | 0.354       |
Here, the effect of surface roughness considered as one of the causes of wall friction loss is mentioned. If it satisfies the following equation (6), it can be said that it is hydrodynamically smoothly.

\[
\frac{U^* k_s}{\nu} < 5
\]  

(6)

Where \( k_s \) is the root mean square height, \( \nu \) is the kinematic viscosity coefficient. And then from figure 2 and table 1 it can be said that the surface of H-PHI/N-C/H-PHO is hydrodynamically smooth. Therefore, this time, it is judged that the surface roughness is not an important factor for the difference of wall friction of each coating. It is considered that the difference of the flow field caused by the properties of the coating and the difference of the wall friction speed are important factors.

6. Conclusion
(1) The downstream pressure fluctuation of H-PHI was suppressed compared to the case H-PHO and N-C with the same cavitation number.

(2) It was found that the boundary layer of H-PHI (cavitation inception number is low) was thin compared with the non-coated. In contrast, the boundary layer thickness of the H-PHO was thicker than N-C.

(3) Wall friction speed was changed by coating. It is found that the wall friction of H-PHO was the smallest in our test.

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