Unsteady forces and moments acting on a cantilevered rectangular hydrofoil with tip clearance in cavitating conditions

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Abstract. It is known that the lift and drag forces of hydrofoil increase then decrease with the decrease of cavitation number, i.e. the development of cavitation, in many cases. In our previous study, the measurement of lift and drag forces of cavitating Clark Y-11.7% hydrofoil was conducted under the assumption of two-dimensional flow, which showed the similar tendency to above common knowledge. However, since there was a tip clearance, the bending moment should present to some content due to the flow asymmetry. In the present study, by using hydrofoil supported by a cantilever equipped with totally 8 strain gauges, the lift and drag forces and their moments are separately measured. It is found that the time-averaged moments around midspan due to lift and drag forces change with the decrease of cavitation number as well as the lift and drag forces change. This means that the working points of lift and drag forces move in the spanwise direction, indicating the importance of the three-dimensionality of cavitation development including that due to tip clearance flow. Unsteady lift and drag forces and their moments also show the significant fluctuations due to periodic behaviour of cavitation instabilities.

1. Introduction
Cavitation often occurs in high-speed liquid turbomachinery. The cavitation is an evaporation phenomenon which is known to occur locally in low-pressure area below saturated vapor pressure. In cases of hydrofoils, it is known that, at some angles of attack, the lift and drag forces of hydrofoil increase before their rapid decrease with the decrease of the ambient pressure, i.e., the development of cavitation (for example [1]). This increase of lift force has been said to be caused by the change of the deflection angle of the flow due to cavitation or the change of effective camber line due to the existence of cavitation zone. In our previous study [2], the measurement of the lift and drag forces of cavitating Clark Y-11.7% hydrofoil has been conducted under the assumption of two dimensional flow, i.e. uniform spanwise distribution of the blade loading. The similar slight increase of the lift force was observed. The unsteady lift and drag forces were also investigated and it was found that the lift and drag force fluctuations were highly related to the periodic behaviors of cavitation and vortical flow and that they seemed to affect the time-averaged lift and drag forces. It is also known that the cavitating flow
even in two-dimensional hydrofoils presents three-dimensionality due to the end-wall and tip-clearance effects and the others. Actually in our above-mentioned study, the test hydrofoil has a tip clearance in one side, showing the tip leakage vortex cavitation and the different shape of surface cavity in near-tip region from that in the main portion. Moreover, when comparing the results with those of numerical simulation with a homogeneous cavitation model conducted by ourselves [3], it was observed that the numerical prediction of lift force is apparently larger than the measurement even in non-cavitating condition while the surface pressure distribution at the mid-span well agrees with experiment. This fact indicates that the bending moment coming from the flow asymmetry due to the existence of tip clearance is in-negligible.

Many types of turbopumps have a tip clearance due to their structural restriction. Axial and mixed flow turbopumps are typical ones. In such machines, cavitation develops three-dimensionally, and the cavitation in near tip region is crucial for their suction performance [4] as well as for the occurrence of cavitation instabilities [5]. Therefore, the unsteady nature of cavitation under the presence of tip clearance effect deserves to be studied. The effect of the size of tip clearance on the characteristics of tip leakage vortex has been investigated using stereo PIV [6], and tip-leakage vortex cavitation has been well simulated by RANS simulation [7]. Moreover, with the objectives of preserving metal materials, favorable light weight design, passive control of cavitation development and the others, the composite material is considered to be applied for hydraulic turbomachinery such as marine propulsor [8] and marine hydro-turbine [9]. Many studies have been devoted to the fluid-structure interaction for simpler case, i.e. a single elastic hydrofoil as seen in [10] and [11] for examples. Since the structure responses against the fluid forces in such cases, it is thought to be still important to study the unsteady force and moment characteristics in cavitation conditions even for rigid hydrofoils to understand the exciting forces to the structure.

In the present study, the measurement system of the forces acting on the hydrofoil is upgraded to be capable of measuring the lift and drag moments in addition to the forces. Measurements are based on the bending moment distribution along the cantilever supporting the test hydrofoil. Employing eight strain gauges (two gauges per two direction and two longitudinal locations) to measure the local bending moments enables us to divide the forces and moments. The unsteady measurements are conducted along with the high speed observation of cavitating flow.

2. Experimental method

Experiments are carried out in a closed-loop cavitation tunnel in Kyushu University, consisting mainly of an upstream tank, a rectangular test section with the width of 200mm and the span of 81.5mm, and a circulating pump. The transparent acrylic windows are set on top and bottom walls for easy access for visual observations. In the present study, a two-dimensional Clark Y-11.7% hydrofoil with the chord length of C=100mm and the span of S=81.0mm (i.e. the tip clearance is 0.5 mm) as shown in Figure 1 is used as a test hydrofoil.

The lift and drag forces ($F_L$ and $F_D$) and their moments ($M_L$, $M_D$) are measured by the strain gauges attached to the rectangular cantilever supporting the test hydrofoil. As shown in Figure 2, the strain

![Figure 1. Clark Y-11.7% hydrofoil.](image1)

![Figure 2. Cantilever and strain gauge arrangement.](image2)
gauges are attached to the cantilever at the position of 70.5mm and 105.5mm distant from midspan of hydrofoil on all cantilever surfaces. The thickness of the cantilever is 20mm and 10mm respectively for the normal and tangential to the hydrofoil chord, which results in the different resonance frequencies of cantilever system of roughly 190 Hz and 70 Hz in bending modes of the corresponding directions. From each strain gauges, the local bending moments can be measured considering the cross-talk among each strain gauge outputs. They can be converted to the lift and drag forces \( F_L, F_D \) and their moments \( M_L, M_D \) around the midspan of the test hydrofoil. Please note that, in principle, the measured forces/moments include those working on the hydrofoil base in addition to those of the test hydrofoil. The forces and moments on the base might be in-negligible because of the short span length of the present test hydrofoil.

To obtain the time-averaged force characteristics, the sampling time is set to be 40 s with the sampling frequency of 1,000 Hz. In the high-speed observation of cavitation appearance, the top and the side views of the hydrofoil are recorded simultaneously using one high-speed camera with the aid of mirrors. The frame rate is set to be 8,000 fps with the total time of recording of 1s. The measurements of forces and moments are synchronously carried out with high-speed recording.

Figure 3 shows the dependence of boundary layer developing along the suction surface of test hydrofoil on the angle of attack \( \alpha \) in non-cavitating conditions, which has been specified from the measured surface pressures and the oil film visualizations. From this figure, we have selected \( \alpha=2.0, 8.0 \) and 20.0 degs. as the test conditions; at \( \alpha=2.0 \) degs., the laminar boundary layer smoothly transits to the turbulent one around the minimum pressure location. At \( \alpha=8.0 \) degs., the laminar separation bubble promoting the turbulence transition forms near the leading edge of hydrofoil. At \( \alpha=20.0 \) degs., the turbulent flow separation occurs near the leading edge. The flow velocity is set to approximately \( U=8.1\text{m/s} \) at \( \alpha=2.0 \) and 8.0 degrees, and \( U=5.8\text{m/s} \) at \( \alpha=20.0 \) degrees. The gas content in water is evaluated by the amount of dissolved oxygen (DO) which is measured before and after every experiment. We have also examined the effect of dissolved oxygen content, but in this paper we only focus on low DO cases less than 30% of saturated value.

![Figure 3](image_url)

**Figure 3.** Boundary layer characteristics of suction side of Clark Y-11.7 hydrofoil (Non-cavitation, \( Re=4.5\times10^5-1.0\times10^6 \)).

![Figure 4](image_url)

**Figure 4.** Directions of lift and drag moments around L-axis and D-axis.

The results are summarized in the non-dimensional forms using the cavitation number \( \sigma \), the lift and drag coefficients \( C_L \) and \( C_D \) and the lift and drag moment coefficients \( C_{ML}, C_{MD} \), which are defined by:

\[
\sigma = \frac{p_t - p_v}{0.5 \rho U^2}
\]
cal simulation \[3\]. The measurement seems to be
he
CS
2
CS
2
ML
D
D

\[ C_L = \frac{F_L}{0.5 \rho U^2 \text{CS}}, \quad C_D = \frac{F_D}{0.5 \rho U^2 \text{CS}} \]  \hspace{1cm} (2)

\[ C_{ML} = \frac{M_L}{0.5 \rho U^2 \text{CS}^2}, \quad C_{MD} = \frac{M_D}{0.5 \rho U^2 \text{CS}^2} \]  \hspace{1cm} (3)

where \( p_t \) is the test section pressure, \( p_v \) is the saturated vapor pressure, \( \rho \) is the water density, \( F_L \) and \( F_D \) are lift and drag forces, and \( M_L \) and \( M_D \) are lift and drag moments. Figure 4 illustrates the definition of the direction of the moment around L-axis and D-axis.

3. Result and Discussion

3.1. Time-averaged force and moment characteristics

3.1.1. Non-cavitating condition

Figure 5 shows the time-averaged lift and drag coefficients \( (C_L \) and \( C_D) \) versus the angles of attack \( \alpha \) in non-cavitating condition. Colour of the plots indicates the lift (blue) and drag (red) coefficients, and the closed and open symbols show the results of the present study (3-D measurement) and the previous two-dimensional (2-D) measurement. In the lift coefficient \( C_L \), the result of the present study is larger at the middle and large \( \alpha \) and is found to agree quantitatively with our past numerical simulation \[3\]. The difference between the present (3-D) and previous (2-D) measurements increases as \( \alpha \) is increased. It is thought that, with the increase of \( \alpha \), the tip leakage flow becomes more significant, resulting in more remarkable discrepancy between 3-D and 2-D measurements. Figure 6 shows the time-averaged moment coefficients of lift and drag \( (C_{ML} \) and \( C_{MD}) \) versus \( \alpha \). In this figure, the lift moment coefficient \( C_{ML} \) increases with the increase of \( \alpha \). It seems that the working point of lift force moves to the hydrofoil root, causing the under-estimation of the lift force \( C_L \) in the 2-D measurement. For large \( \alpha \), the flow separation occurs on the suction side of the blade, and the tip leakage flow is thought to become less sensitive to the change in \( \alpha \). This results in the moderate change in \( C_L \) and \( C_{ML} \).

In the drag coefficient \( C_D \), the result of the present 3-D measurement is smaller than the previous 2-D measurement at small angles of attack \( \alpha \), while larger at large \( \alpha \) as shown in Figure 5. In the range of small \( \alpha \), the drag moment coefficient \( C_{MD} \) gradually but negatively increases with the increase of \( \alpha \) and it takes the negative maximum around \( \alpha =12 \text{ degs.} \) as shown in Figure 6. Then, in the range of \( \alpha \) larger than around 15 degs., \( C_{MD} \) takes positive value and increases with the increase of \( \alpha \). The change of sign from positive to negative means the change of acting location of drag forces from the tip to the root sides. However, it should be noted that the accuracy of measurement seems to be insufficient for quantitative discussion because of the small drag force with the relatively large drag moment.

![Figure 5. Time-averaged lift and drag coefficients versus angle of attack in non-cavitating condition.](image1)

![Figure 6. Time-averaged lift and drag moments versus angle of attack in non-cavitating condition.](image2)
3.1.2. Cavitating conditions

Figure 7(a)-(c) shows the lift and drag coefficients ($C_L$ and $C_D$) and moment coefficients ($C_{ML}$ and $C_{MD}$) versus cavitation number $\sigma$ at angle of attack $\alpha=2.0$, 8.0 and 20.0 degs., respectively. The blue and red plots are $C_L$ (or $C_{ML}$) and $C_D$ (or $C_{MD}$), and the closed and open symbols show the results of the present (3-D) measurement and those of previous (2-D) measurement respectively. In the lift coefficient $C_L$, although the value of 3-D measurement is larger than that of 2-D measurement, the shape of the curve is similar; the breakdown point defined by the beginning of lift decrease against the decrease of $\sigma$ is slightly larger for $\alpha=2.0$ and 8.0 degs.. On the other hand, in the drag coefficient $C_D$, the increase against $\sigma$ is more significant in the 3-D measurement. It keeps large value at very low $\sigma$ with super-cavitation, although the lift force $C_L$ is significantly decreased.

Figure 7. Force and moment coefficients plotted against cavitation number.
In the lift moment coefficient $C_{ML}$, it can be seen that $C_{ML}$ negatively increases/decreases in accordance with the increase/decrease of $C_L$ and that it finally approaches to zero with the decrease of cavitation number $\sigma$. It seems that the working point of the lift force does not change significantly with the development of cavitation. On the other hand, in the drag moment coefficient $C_{MD}$, it can be seen that the magnitude of $C_{MD}$ decreases against the increase of $C_D$ and becomes finally positive in the cases with $\alpha$=2.0 and 8.0 degs. This indicates that with the development of cavitation, the working point of the drag force moves from the tip to the root side. In the case with $\alpha$=20.0 degs. $C_{MD}$ takes positive value even at the non-cavitating condition and it increases with the increase of $C_D$ due to the development of cavitation.

### 3.2. Unsteady forces and moments with cavitation

Figure 8 summarizes the FFT analysis of lift and drag forces ($C_L$ and $C_D$) and lift and drag moments ($C_{ML}$ and $C_{MD}$) from top to bottom. The vertical axis is Strouhal number $St=fC/U$ and the horizontal axis is cavitation number $\sigma$. The colour contour shows the amplitude of fluctuation.

![Figure 8](image_url)

**Figure 8.** Frequency characteristics of unsteady forces and moments against cavitation number.
From these figures, the distinct component with $St$ of around 0.1 can be seen in the all angle of attack cases, but its characteristic is not very similar. At $\alpha=2.0$ degs., the component can be recognized only in $C_L$ and the Strouhal number $St$ decreases with the decrease of $\sigma$. The weakness of this component in other three coefficients ($C_D$, $C_{ML}$ and $C_{MD}$) seems to simply come from the small magnitude of time-averaged value (see Figure 7(a)). Looking closely at the contour maps of three coefficients, this component can be slightly seen in $C_{ML}$ and $C_{MD}$. At $\alpha=8.0$ degs., this component can be recognized in all four coefficients, and $St$ decreases with the decrease of $\sigma$ as similar to $\alpha=2.0$ degs case. Figure 9 shows the example of cavitation behaviours and corresponding time histories of forces ($C_L$ and $C_D$) and moments ($C_{ML}$ and $C_{MD}$) in this condition ($\alpha=8.0$ degs. and $\sigma=1.05$). The cavity presents significant periodic behaviours between partial to super-cavitation with this frequency, which is known as the transitional cavity oscillation [12].

![Figure 9. Cavity patterns (left) and time histories of $C_L$ (blue) and $C_D$ (red) (right top) and $C_{ML}$ (blue) and $C_{MD}$ (red) (right bottom) at $\alpha=8.0$ degs. and $\sigma=1.05$.](image)

Returning to Figure 8 (c) with angle of attack of $\alpha=20.0$ degs., it can be seen that the Strouhal number $St$ of the distinct peak in the all force and moment coefficients apparently increases from around 0.1 to almost 0.2 with the decrease of cavitation number $\sigma$, which is totally different from the previous cases with $\alpha=2.0$ and 8.0 degs. Figure 10 shows cavitation behaviours and corresponding time histories of forces ($C_L$ and $C_D$) and moments ($C_{ML}$ and $C_{MD}$) in this condition ($\alpha=20.0$ degs. and $\sigma=2.51$). The periodic appearance of short leading edge cavitation with the convection of large cloud cavity can be clearly seen in the figure, which is again different from the previous cases. In this angle of attack, the turbulent flow separation occurs on the suction surface of the hydrofoil. The interaction of separation phenomenon and the formation of leading edge cavitation seems to play a dominant role in this instability, the detail of which should be discovered by the further investigation.

Although the clear fluctuations of moments can be observed in the above two examples, it is hard to recognize the three-dimensional behaviour of cavitation responsible for the generation of moment fluctuation. Further observation is needed to understand the mechanism of unsteady moment.
Figure 10. Cavity patterns (left) and time histories of $C_L$ (blue) and $C_D$ (red) (right top) and $C_{ML}$ (blue) and $C_{MD}$ (red) (right bottom) at $\alpha=20.0$ degs. and $\sigma=2.51$.

4. Conclusions
In the present study, unsteady force and moment measurements have been conducted for the single Clark Y-11.7% hydrofoil in cavitating conditions at the angles of attack of 2.0, 8.0 and 20.0 degrees.

From the comparison with the previous two-dimensional measurement, it is found that the three-dimensional measurement is necessary for the quantitative measurement. The working points of lift and drag forces are found to move spanwisely with the development of cavitation.

At the low and moderate angle of attack, the transitional cavity oscillation, well-known instability is observed at low cavitation numbers, and the force and moment fluctuations caused by this instability are observed. The mechanism of the unsteady moment is not yet understood by the present study.

On the other hand, at large angle of attack with which turbulent boundary separation occurs, the cavitation instability with different frequency characteristics is observed. The interaction of separation and the formation of leading edge cavitation seems to play a dominant role in this instability.

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