Unsteady Lift and Drag Characteristics of Cavitating
Clark Y-11.7% Hydrofoil

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Abstract. Unsteady cavitating flow and lift/drag characteristics of a two-dimensional Clark Y-11.7% hydrofoil are experimentally investigated in order to clarify the relation between the lift drop mechanism and the unsteady cavity behavior. Unsteady lift and drag forces are measured by strain gauges attached on the cantilever supporting the hydrofoil, assuming the negligible bending moment. In combination with the above force measurements, the cavitating flow is filmed from both top and side simultaneously using two high speed video cameras. It is clearly observed that, in larger attack angle conditions (4-10 degrees), the time-averaged lift coefficient slightly increases from that in the non-cavitating condition. After the slight increase, the lift gradually decreases then its steep decrease starts to occur. On the other hand, in a small attack angle case (2 degrees), little increase of the lift is observed, and just after that the sudden lift drop occurs. From the instantaneous frequency spectra of the lift, the followings are found; during the slight increase of the lift, the cavity is being a partial cavity in almost steady state, but during the subsequent gradual lift decrease, the partial cavity oscillates with cloud cavity shedding, in other word, the partial cavity oscillation occurs, whose frequency decreases with the growth of the cavity. During the sudden lift drop, the low frequency transitional cavity oscillation occurs, in which the cavity dramatically changes between partial and super cavities. The typical events of cavity behavior during the cavitation instabilities are found to be able to be related with the behavior of instantaneous lift force and pressure.

1. Introduction
The recent rapid progress of computer science including hardware as well as numerical simulation technology has enabled us to simulate the cavitating flow and achieve the qualitative, and in some extent, the quantitative agreements with real flows from basic ones such as cavitating hydrofoils and to practical ones such as cavitating pumps and hydroturbines. However, in some cases, CFD (Computational Fluid Dynamics) simulation still often fails to predict the cavitation performance. For example, the industry-university collaborative research project on cavitation CFD organized by Turbomachinery Society of Japan has carried out benchmark tests with several CFD codes for the cavitating flow around two types of hydrofoils, NACA0015 and Clark Y-11.7% (see Kato [1]). It was shown that none of the cavitation models can correctly predict the sudden breakdown of the lift coefficient as observed in experiments; with the development of cavitation, the lift force slightly increases just before the sudden decrease especially for high lift conditions in experiments [2]-[4].
while the lift force gradually decreases in numerical simulations. This discrepancy is considered to be mainly due to the under-prediction of the development of cavity in the current numerical simulations, but the reproduction of the unsteady behavior of cavitating flow might be also an important factor as described in [5].

Cavitation is well known as a highly unsteady phenomenon, and as for the cavitating flow around isolated two-dimensional hydrofoils, it is also well known that the attached cavity developing on the suction surface becomes unstable and causes a strong vibration when the cavity length exceeds about 75% of the chord length (Wade and Acosta [6], Kawanami et al. [7] and etc.). This type of oscillation is called transitional cavity oscillation. Under the oscillation, the cavity dramatically changes between partial and super cavity with low frequency, and it often accompanies the large cloud cavity shedding and the re-entrant-jet. There is another cavitation instability, called partial cavity oscillation, which has been recognized through careful visual observation and unsteady pressure measurements by several researchers (Le et al. [8], Arndt et al. [9] and etc.). Under this oscillation, it is often observed that the small (in more developed cases, large) cloud cavities are continuously shed from the cavity trailing edge. The frequency of this oscillation decreases as the cavity becomes longer, keeping the Strouhal number based on the cavity length almost constant. The cavitation instabilities of two-dimensional hydrofoil seem to be classified mainly into above two oscillations. Their frequency characteristics have been well simulated by theoretical analysis (Watanabe et al. [10]).

In the present study, in order to understand the flow physics behind the lift/drag characteristics of hydrofoil, the unsteady lift and drag forces of cavitating Clark Y-11.7% hydrofoils are directly measured for the different angles of attack. In combination with the high-speed camera observation, the relation between the instantaneous lift/drag forces and the unsteady cavity behavior is discussed.

2. Experimental apparatus

Present experiments are done using a cavitation tunnel in Kyushu University (Watanabe et al. [5]). This tunnel has a rectangular test section with the width (height) of 200mm and the span of 81.5mm. Test obstacles can be set horizontally at the center on one of the side walls with arbitrary angle of attack. In the present study, a two-dimensional Clark Y-11.7% hydrofoil with the chord length of $C=100$ mm and the span of $B=81.0$ mm as shown in Fig. 1 is tested. The tunnel height to the chord length ratio is $200 \text{mm}/100 \text{mm} =2.0$, indicating a substantial blockage effect of tunnel walls. The top, bottom and one of side walls of the test section consist of transparent windows made with acrylic resin for visual observations. The cavitating flows are filmed from the top and the side simultaneously using two high-speed video cameras (Vision Research, Phantom V310 and V4.3) as shown in Fig. 2(a). The frame rate is set to be 8,000 frame/s, and the spatial resolution was 704*256 and 512*128 pixels respectively for the top and the side views, roughly covering the region from the leading edge to the one chord downstream of hydrofoil.

In the present study, to understand the relation between the lift/drag forces and the unsteady cavity behavior around the hydrofoil, the instantaneous lift and drag forces are measured by strain gages attached on the cantilever supporting the test hydrofoil as shown in Fig. 2(b). The flow around the hydrofoil is considered to be asymmetric in the spanwise direction due to the existence of tip clearance only at one edge of the hydrofoil. However, in this study, we neglect the resultant bending moment due to the flow asymmetry, and measure the lift and drag forces under the assumption of 2-D like flow. For the measurement, we apply so-called two-gage method for each force component in the directions tangential and perpendicular to the chord, and convert them to the lift and drag forces using the pre-tuned matrix obtained through the validation of the measurement system. For the unsteady measurement, the eigen-frequencies of the bending mode of the cantilever with the test hydrofoil are important, which have been found by hammering test carried out under the water to be 180Hz and 70Hz respectively for the force components tangential and perpendicular to the chord. In addition to the unsteady lift/drag force measurements, unsteady wall pressure measurements are carried at two locations approximately 20mm upstream and downstream of the test hydrofoil. Strain-gage type
pressure transducers (Kyowa Electronic Instruments Co., Ltd, PGMC-A-200KP) are used, which are flush-mounted to draw out their frequency response characteristics.

The measurements are done with the main velocity of $U=8.3\text{m/s}$ (then the Reynolds number based on the chord length is roughly $8\times10^5$) and the attack angle of $\alpha=2, 4, 6, 8$ and $10^\circ$. The cavitation number used here is defined as

$$\sigma = \frac{p_{ref} - p_v}{\rho U^2 / 2},$$

where $p_v$ and $p_{ref}$ denote the vapor pressure and pressure at the reference location (200 mm upstream from the mid-chord), $\rho$ the density of water. In every experiment, the amount of dissolved oxygen is checked to be less than 2 ppm before and after the experiments to keep the similar conditions in terms of water quality.

3. Results and discussions

3.1. Time averaged lift/drag characteristics

To obtain the cavitation characteristics of time-averaged lift and drag coefficients, we gradually decrease the mainstream pressure, i.e. cavitation number, from non-cavitating to super cavitating conditions. The time duration of the pressure reduction is more than 30 minutes, during which we acquire the force components with the sampling frequency of 1,000Hz. Short-time averaged data for 40 seconds are used to represent the time averaged lift and drag characteristics.

Figure 3 shows the time averaged lift and drag coefficients, $C_L = L/(BC\rho U^2 / 2)$ and $C_D = D/(BC\rho U^2 / 2)$, plotted against cavitation number $\sigma$ for various angles of attack $\alpha$. Cavitation is well known as a highly unsteady phenomenon, and it is also known that the cavitating flow around an isolated hydrofoil often reveals the global flow instabilities, partial and transitional cavity oscillations [10]. The cavity behavior observed during the experiment is depicted by capital Roman numbers I-V in the figure.

From fig. 3, we can firstly see that, with the sufficient decrease of cavitation number $\sigma$, the lift coefficient $C_L$ suddenly decreases for the all angle of attack cases $\alpha$. However, the cavity behavior is different between small and large numbers of $\alpha$. For larger angle of attack with $\alpha \geq 4^\circ$, we firstly observe the stable partial cavitation after the cavitation inception (region II). During the development of stable partial cavitation, $C_L$ gradually increases, showing the added lift force due to cavitation. After that, the partial cavity becomes unstable and the cavity length oscillates often with the cloud cavities shed from its trailing edge (region III: partial cavity oscillation). At the same time, $C_L$ starts to
gradually decrease, and for with $\alpha \geq 8^\circ$, it takes the local minimum and then increases again. After the further decrease of $\sigma$, the cavity begins to strongly oscillate with rather low frequency (IV: transitional cavity oscillation), and $C_L$ steeply decreases. On the other hand, in the case with smaller angle of attack, namely $\alpha = 2^\circ$, we do not observe the stable partial cavitation, due to the fact that the minimum pressure locates not near the leading edge but a little downstream [11]. In this angle of attack, $C_L$ starts to decrease just after the occurrence of cavitation instabilities without showing the added lift due to cavitation.

From the time averaged drag coefficient $C_D$, we can see that $C_D$ increases monotonously with the development of cavitation from the cavitation inception to the onset of transitional cavity oscillation (IV) for all the examined angle of attack $\alpha$. $C_D$ takes the maximum value during the transitional cavity oscillation, then decreases with the decrease of cavitation number.

Figure 4 shows a typical example of the time history of the lift coefficient $C_L$ and its short time frequency analysis (STFA). The angle of attack is set to be $\alpha = 8^\circ$, where we clearly see the local minimum of $C_L$ after the added lift due to cavitation as can be again presented in fig. 5. From those figures, we can discuss the relation between the time averaged lift coefficient $C_L$ and its instantaneous values as well as the occurrence of cavitation instabilities.

At the time between ① and ② in figs. 4 and 5, where steady partial cavitation is observed, we rarely observe the lift force fluctuation and the time averaged lift coefficient $C_L$ slightly increases with the decrease of cavitation number $\sigma$. After the time ②, the lift fluctuation apparently increases, which is caused by the partial cavity oscillation, whose frequency gradually decreases from about 70Hz as can be recognized in fig. 4(b). Until the time ③, where we have the local minimum in the $C_L$ curve as shown in fig. 5, the minimum lift during one cycle of partial cavitation gradually decreases, resulting in the gradual decrease of the time averaged lift coefficient $C_L$. However, after the time ③, the decrease of the minimum lift during one cycle stops, whereas the maximum lift during one cycle continues to increase, resulting in the increase of the time averaged lift coefficient $C_L$. After the time ④, the amplitude of lift force fluctuation again begins to increase due to the transition from the partial cavity oscillation to the transitional cavity oscillation. At the time ⑤, the transition completely finishes, after

**Figure 3.** Time averaged lift and drag characteristics of cavitating Clark Y-11.7% hydrofoil for various angles of attack. Observed cavity behavior is indicated by I-V.
that the strong transitional cavity oscillation is clearly observed, whose frequency is around 10Hz. At this stage, the time averaged lift steeply decreases.

3.2. Lift/drag force fluctuation during cavitation instabilities

In order to understand the relation between the instantaneous lift coefficient and the unsteady cavity behavior during the cavitation instabilities, the high-speed video observation coupled with the lift/drag

\[ \text{Figure 4. Unsteady lift characteristics of cavitating Clark Y-11.7\% hydrofoil at } \alpha=8^\circ \]

\[ \text{Figure 5. Detailed relation between lift/drag characteristics and cavitation instabilities } (\alpha=8^\circ) \]
force measurements are carried out with the frame rate (sampling frequency) of 8,000Hz at constant cavitation numbers.

Figure 6 shows the snapshots of the sheet and cloud cavitation during the one cycle of the partial cavity oscillation observed at the cavitation number of $\sigma=1.45$ and the attack angle of $\alpha=8^\circ$. The corresponding time histories of the instantaneous lift and drag coefficients are also shown in the figure. Since the lift and drag forces show the similar trend during the one cycle of oscillation, we herein concentrate on the relation between the instantaneous lift coefficient and the cavity behavior.

After the time $\circ\ A$ and $\circ\ B$, during which the cloud cavity generated in the previous cycle passes near the trailing edge of the hydrofoil, the sheet cavity starts to develop, and the lift coefficient recovers from the minimum value. At the time $\circ\ C$, the lift coefficient takes its maximum value and turns into the gradual decrease with the new large cloud cavity generated from the trailing edge of the sheet cavity. During the time $\circ\ D$ to $\circ\ E$, the lift coefficient keeps almost the similar value, while the sheet cavity is developing and the cloud cavity is being convected on the suction surface of the hydrofoil. At the time between $\circ\ F$ and $\circ\ G$, the lift coefficient decreases again until it takes the minimum value, during which the cloud cavity passes near the trailing edge of the hydrofoil. Since the cloud cavity has a strong vortical structure, the low pressure region in its center pulls the flow leaving from the pressure side of the hydrofoil toward itself when it passes the trailing edge of the hydrofoil. As a result, the flow turning by the hydrofoil decreases, which is probably the reason why the instantaneous lift coefficient decreases at this moment. The similar discussion has been made by the two-dimensional numerical simulation done by Qin et al. [12], but the present study is perhaps the first report to experimentally confirm this phenomenon as far as we notice.

Figure 7 shows the time histories of the pressure measured upstream and downstream as well as lift and drag force fluctuations under the occurrence of the transitional cavity oscillation. The cavitation number and the angle of attack is $\sigma=1.45$ and $\alpha=8^\circ$ respectively. From the time histories of pressure and lift force, we can clearly confirm the low frequency fluctuations, whose frequency is about 8Hz.
Besides the low frequency mode, pulse like fluctuation is observed only in the downstream pressure during the increase stage of the lift force.

Figure 7. Time histories of pressure (top) and lift and drag forces (bottom) during transitional cavity oscillation ($\alpha=8^\circ$, $\sigma=0.90$)

Figure 8. Detailed relation between lift/drag characteristics and transitional cavity oscillation ($\alpha=8^\circ$, $\sigma=0.90$)

Besides the low frequency mode, pulse like fluctuation is observed only in the downstream pressure during the increase stage of the lift force.

Figure 8 shows the snapshots of the cavity behavior during one cycle of the transitional cavity oscillation. At the time A, the sheet cavity is the longest during this cycle and is longer than the chord
of the hydrofoil (super cavitation), and the lift coefficient takes the smaller value. At the time \( C \), a
large cloud cavity is being generated, at which we observe the small pressure spike downstream. Near
the time \( D \), the sheet cavity dramatically shrinks and just after that the strong pressure spike is
observed. The cloud cavity generated at \( C \) is convected downstream, and at the time \( E \) where the
cloud cavity just passes the trailing edge of the hydrofoil, the lift coefficient temporally decreases due
to the same mechanism observed in the case of partial cavity oscillation. It is interesting to see that
there is no cavity except for the tip region during \( E \) to \( F \), but the lift coefficient does not take the
maximum value. After that, the cavity begins to develop from the tip side, and the lift coefficient
increases until the time \( G \). Finally, the cavity becomes the super cavity again at time \( H \), and the lift
coefficient takes the smaller value as similar as at the time \( \alpha \).

4. Conclusions
In the present study, we have carried out the detailed measurements of lift and drag forces of
cavitating Clark Y-11.7% hydrofoil as well as the high-speed video observations of cavity behavior.
Main results can be summarized as follows.
(a) The lift coefficient steeply decreases with the sufficient reduction of the cavitation number for all
examined attack angle cases (2 to 10\(^\circ\)). However, the cavity behavior is different between small
and large angles of attack.
(b) For larger angle of attack (4 to 10\(^\circ\)), the lift force slightly increases with the development of stable
partial cavitation. Once the partial cavity oscillation occurs, the lift force slightly decreases but
then increases again for the attack angle of 8 to 10\(^\circ\). After the further decrease of the cavitation
number, the transitional cavity oscillation occurs, and the lift coefficient steeply decreases.
(c) For smaller angle of attack (2\(^\circ\)), no stable partial cavitation is observed and the lift force suddenly
decreases just after the cavitation instabilities start to occur.
(d) During the cavity oscillation, the typical events of cavity behavior such as the formation and the
convection of cloud cavity, the elongation and the collapse of sheet cavity and so on can be related
to the behavior of instantaneous lift force and pressure. Specifically, the vortical cloud cavity is
found to reduce the lift force when it moves around the trailing edge of the hydrofoil.
(e) The instantaneous lift force, then the unsteady behavior of cavitation, is essential for the cavitation
performance of hydrofoil especially at the stage of the performance breakdown.

The above obtained results indicate that, for the precise prediction of the performance of
hydrofoils as well as those of pumps and hydroturbines by CFD, reproduction of the unsteady
phenomena as those observed in the experiment seem to be necessary. We hope presented data are
useful for the development and validation of new cavitation model.

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