Observations of Oscillating Cavitation on a Flat Plate Hydrofoil*

Kotaro SATO**, Masayuki TANADA***,
Sachie MONDEN***** and Yoshinobu TSUJIMOTO*****

An experimental investigation was made to clarify the characteristics of oscillating cavitation on a flat plate hydrofoil in a water tunnel. Dynamic behavior of oscillating cavitation is discussed from the unsteady pressure measurements at the upstream of the blade and the visual observations of cavitation phenomena using high-speed video recording. It was found that the mean cavity length characterizes the fundamental characteristics of cavity oscillation. The cavity oscillations are categorized into two types, i.e. the transitional cavity oscillation and the partial cavity oscillation.

Key Words: Cavitation, Unsteady Characteristic, High-speed Photography, Jet

1. Introduction

If the cavity length of partial cavitation on a hydrofoil extends beyond 75% of the chord length, oscillating cavitation with change of cavity volume occurs. This kind of oscillating cavitation has been recognized as a transitional process between partial cavitation and supercavitation, standing on theoretical results obtained by the steady-linear analysis of Geurst^{(1),(2)}. This is herein called "transitional cavity oscillation". This transitional cavity oscillation, brought to attention by Wade and Acosta⁽³⁾ in 1966, has been studied by many researchers such as Kamono et al.⁽⁴⁾, Kuwako et al.⁽⁵⁾ and Matsudaira et al.⁽⁶⁾ However, these investigations were only fragmentary examples, leaving the systematic understand-

ing of oscillating characteristics to be clarified.

On the other hand, for the case of cavity length less than 75% of the chord length, another type of cavity oscillation has been observed by Kubota et al.⁽⁷⁾, Kamono et al.⁽⁴⁾, Le et al.⁽⁸⁾ and Kawanami et al.⁽⁹⁾ In the present paper, we call it "partial cavity oscillation". It is reported by Tanimura et al.⁽¹⁰⁾ that the oscillating partial cavity forms a re-entrant jet during its collapse, followed by a release of vortex cavity toward the downstream periodically. However, only few attempts⁽¹¹⁾ have been made to date to clarify the similarity or difference of the oscillating characteristic between the transitional cavity oscillation and the partial cavity oscillation.

For the understanding of this phenomena, it is important to distinguish between the local flow instability around hydrofoil and the system instability, which is often associated with the change of total cavity volume. In traditional investigations, the cavitation number σ is recognized as one of the most important parameters to characterize the steady or unsteady cavitation phenomena. In the case of cavitation on a hydrofoil, the angle of attack α is also an important parameter. It is well known that the steady cavity length is determined by $\sigma/2\alpha$ based on the linear analysis. Recently, Watanabe et al.⁽¹²⁾ have shown theoretically that the characteristics of un-

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** Department of Basic Engineering in Global Environment, Kogakuin University, 1-24-2 Nishi-shinjuku, Shinjyuku, Tokyo 163-8677, Japan. E-mail: at 12164@ns.kogakuin.ac.jp

*** Toyota Motor Corporation, 1 Toyota, Toyota, Aichi 471-8571, Japan

**** Mitsubishi Electric Corporation, 8-1-1 Tsukaguchi-honcho, Amagasaki, Hyogo 661-8661, Japan

***** Graduate School of Engineering Science, Division of Mechanical Science, Osaka University, 1-3 Machikaneyama, Toyonaka, Osaka 560-8531, Japan

steady cavitation depend on the value of $\sigma/2\alpha$. Kjeldsen et al.⁽¹¹⁾, Pham et al.⁽¹⁴⁾ attempted to correlate the experimental results on unsteady cavitation with $\sigma/2\alpha$.

In the present study, we attempt to categorize the above-mentioned oscillating cavitations on a flat plate hydrofoil according to the non-dimensional cavity length based on the hydrofoil chord. The relationship between the characteristics of oscillation and type of cavitation (i.e. sheet cavitation and cloud cavitation) is discussed from the high-speed flow observations and fluctuating pressure measurements. The influence of the water tunnel system on the oscillating characteristics is also discussed. By the way, Watanabe et al.⁽¹⁵⁾ shows that a linear time marching analysis using a closed cavity model without re-entrant jet can predict the frequencies of partial and transitional cavity oscillation. Re-entrant jets were observed by means of dye injection and their effects on transitional cavity oscillation are discussed.

2. Experimental Method

The experimental apparatus is shown in Fig. 1. The tank volume is 2.2 [m³] and 70~80 percent of the volume is filled with deaired tap water. A three bladed inducer is used as the recirculating pump at the flow rate coefficient of $\Phi=0.1$, which is larger than the design flow coefficient of $\Phi=0.078$. It was confirmed by preliminary experiments that the operating conditions were out of range of flow instability produced by the inducer pump system, such as rotating cavitation or surge throughout the present experiments. The experiment was carried out at the inlet pressure of $p=12$ [kPa], and the cavitation number was controlled by changing the flow velocity in the range of $U=2.0\sim4.5$ [m/s], by adjusting the rotational speed of the recirculating inducer pump. The effects of the difference of the Reynolds number on the fundamental characteristics of cavity oscillation were not identified. Figure 2 shows the test section of the water tunnel. A nozzle with a cross section area ratio of 4.65 was placed upstream of the hydrofoil. In this

Fig. 1 Experimental apparatus

figure, Ld is defined as the distance between the nozzle and the leading edge of hydrofoil. Ld was changed to examine the system dependence of the cavity oscillations. Flat plate hydrofoil with chord length 70 [mm] and span 70 [mm] was employed in the present experiment. The shape of the hydrofoil is shown in Fig. 3. The angle of attack is defined as the angle between main flow and suction surface (the side with flat surface) of the blade. Mean flow velocity and pressure fluctuation were measured by an electromagnetic flow meter and a pressure transducer, respectively. The behavior of cavity on the hydrofoil was observed by a high-speed video recording system (NAC HSV-500) with a strobe lighting system. A frame rate of 250 [fps] was used. In the present paper, cavity length L is defined as distance from the leading edge to end of continuously distributed cavity which is estimated from the high-speed video picture.

3. Inlet Pressure Fluctuation

Figure 4 shows the power spectrums of the inlet pressure fluctuation for various normalized cavity lengths $Lc^*=Lc/C$, where Lc is the mean cavity length, C the chord length. Figures 4(a) and (b) are typical results at angles of attack of $\alpha=1.5$ [deg] and 5 [deg], respectively. Before discussing the characteristics of cavity oscillation, a few remarks should be made concerning the type of cavitation. Several examples of photographs will be shown in the next section. When the angle of attack is $\alpha=1.5$ [deg], sheet cavitation is observed for all cavity lengths. In the case of $\alpha=5$ [deg], both sheet and cloud cavitations are observed for longer cavities ($Lc^*\geq 0.75$) but only cloud cavities are observed for shorter cavities

Fig. 2 Test section ($C=70$ [mm], $Ld=373$ [mm], 672 [mm], 903 [mm])

Fig. 3 Foil shape (Chord $C=70$ [mm], Span $B=70$ [mm])

Fig. 4 Power spectra of inlet pressure fluctuation

($Lc^* < 0.75$). In the present paper, it is categorized as the sheet cavitation if it appears some part of the cavity. The characteristics of cavity oscillation are represented by the non-dimensional amplitude of the inlet pressure fluctuation Ap^* , and the Strouhal number Stb based on the hydrofoil chord C . In both Fig. 4 (a) and (b), the frequency components caused by the transitional cavity oscillation can be seen at $Stb = 0.13$ under the condition that the non-dimensional cavity length Lc^* is around unity (cf. (1) or (2) in Fig. 4(a) and (b)). It will be shown in the next section that the frequency of inlet pressure fluctuation agrees with the frequency of cavity length oscillation. On the other hand, in spectrums (4) - (6), the pressure fluctuation with broadband frequency caused by the partial cavity oscillation can be observed for shorter cavities. The peak frequencies shown by the arrows are considered as the representative frequencies and are used in the following discussions. Furthermore, the Strouhal number Stb for $\alpha = 1.5$ [deg] is smaller than that for $\alpha = 5$ [deg]. In the case of the transitional cavity oscillation, we cannot identify the fundamental difference between $\alpha = 1.5$ [deg] and 5 [deg] from (1) and (2). Thus the Strouhal number for the transitional cavity oscillation is independent of the angle of attack.

In Figs. 5 and 6, the relations between the non-dimensional cavity length Lc^* and Strouhal number measured with various distances between the nozzle

and hydrofoil are shown to examine the effect of the system on the characteristics of cavity oscillation. Figure 5 is for $\alpha = 1.5$ [deg] and Fig. 6 $\alpha = 5$ [deg] where (a) shows the Strouhal number Stb based on chord length and (b) represents Stc based on mean cavity length. In Fig. 6, experimental data by other researchers are also plotted to compare with the present result. Figure 5(a) and Fig. 6(a) show that the Strouhal number Stb is nearly constant over $0.75 < Lc^* < 1.2$ and is independent of the angle of attack and inlet conduit length including the data by other researchers. Therefore we can say that Stb of transitional cavity oscillation is not largely affected by the cavity length, angle of attack, shape of hydrofoil and experimental equipment system. Let us consider the partial cavity oscillation. For the partial cavity oscillation with $Lc^* \leq 0.25$, the Strouhal number Stb based on the chord length increases with decreasing non-dimensional cavity length Lc^* . For $\alpha = 5$ [deg] (see Fig. 6(a)), with cloud cavitation, Stb for identical Lc^* decreases approximately in inverse proportion to $\sqrt{Ld}$ where Ld is the distance from the nozzle to the leading edge of the hydrofoil. This tendency is in agreement with an analytical result obtained by a 1-D flow model, which assumes that the pressure fluctuation near the leading edge is caused by the inertia of the fluid in the inlet conduit, associated with the cavity volume change. For $\alpha = 1.5$ [deg], the effect of Ld/C is not evident. The difference between $\alpha =$

(a) Strouhal number $Stb = fC/U$ (b) Strouhal number $Stc = fLc/U$

Fig. 5 Relation between cavity length and Strouhal number obtained by inlet pressure fluctuation for smaller angle of attack

5 [deg] and $\alpha = 1.5$ [deg] may be associated with the difference of type of cavitation cloud type for $\alpha = 5$ [deg] and sheet type for $\alpha = 1.5$ [deg].

Figures 5(b) and 6(b) show the relation between the non-dimensional cavity length Lc^* and the Strouhal number Stc based on cavity length. In the case of sheet cavitation (all data in Fig. 5(b) and for the data with $0.75 < Lc^*$ in Fig. 6(b)), Stc distributes over a narrow range between 0.1 and 0.2. However, Stc for the partial cavity oscillation with cloud cavitation ($0 < Lc^* < 0.75$ in Fig. 6(b)) depends significantly on the inlet conduit length. In the present experiment, it is noticed that values of Stc for cloud cavitation are generally greater than those for sheet cavitation. Similar results as shown in Figs. 5 and 6 have been obtained by Kjeldsen et al.⁽¹⁶⁾ for a NACA

(a) Strouhal number $Stb = fC/U$ (b) Strouhal number $Stc = fLc/U$

Fig. 6 Relation between cavity length and Strouhal number obtained by inlet pressure fluctuation for larger angle of attack

0015 hydrofoil. The major difference is that they observed more distinct partial cavity oscillations with discrete spectrum. However, it is more important to note the fact that the two types of cavity oscillations are observed with completely different hydrofoil shapes and in different systems.

4. Photographic Observation

Photographs and sketches of the transitional cavity oscillation for $\alpha = 5$ [deg], $Lc^* = 1$ are shown in Fig. 7. The arrows in the figures indicate the cavity trailing edge in each frame. In this figure, t , T and U denote the time, the period of the cavity oscillation and the main flow velocity, respectively. Therefore t/T and Ut/C are non-dimensional times. The period of cavity oscillation T agrees with the period of oscillation determined from the inlet pressure fluctuation (see Fig. 8). We can observe the growth phase of cavity in (a) - (f) and the collapse phase in (f) - (j). It can be seen that the sheet cavitation appears near the leading edge of the hydrofoil in (d) and (e), but it changes to cloud cavitation and is separated from the main cavity and is shed downstream in (h) and (i). In this condition, the frequency of the cloud cavity shedding is equivalent to

Fig. 7 Pictures and sketches of transitional cavity oscillation (↓ : end of cavity) ($\alpha=5$ [deg], $\sigma=0.77$, $C=70$ [mm], $U=3.21$ [m/s], $Ld=373$ [mm], $Lc^*=1.0$)

Fig. 8 Change of cavity length and inlet pressure with time in case of transitional cavity oscillation ($\alpha=5$ [deg], $\sigma=0.77$, $C=70$ [mm], $U=3.21$ [m/s], $Ld=373$ [mm])

the frequency of the cavity length change with time. Figure 8 shows the change of cavity length and inlet pressure with time for transitional cavity oscillation. (a) is cavity length and (b) inlet pressure change. In Fig. 8(a), (a) to (j) in the figure shows the instant of time corresponding to Fig. 7(a) to (j). Non-dimensional pressure fluctuation is defined as $P^* = p' / (\rho U^2 / 2)$ where ρ is the density and p' is the pressure fluctuation component. We notice that the phase of the cavity length fluctuation differs by π (half period) as compared with that of inlet pressure fluctuation i.e. their fundamental waveforms are opposite. From this figure or Fig. 4, it is also seen that the period of the transitional cavity oscillation is almost identical for each cycle.

Figure 9 shows typical pictures and sketches of the partial cavity oscillation for $\alpha=5$ [deg], $Lc^*=0.5$. Since cloud cavitation starts from leading edge of the hydrofoil in this situation, the pictures are not clear. Cloud cavity is shed in the collapse phase of the cavity on the blade. Figure 10 shows the cavity length and

Fig. 9 Pictures and sketches of partial cavity oscillation ($\downarrow$: end of cavity) ($\alpha=5$ [deg], $\sigma=1.18$, $C=70$ [mm], $U=2.86$ [m/s], $Ld=373$ [mm], $Lc^*\approx 0.5$)

Fig. 10 Change of cavity length and inlet pressure with time in case of partial cavity oscillation ($\alpha=5$ [deg], $\sigma=1.18$, $C=70$ [mm], $U=2.86$ [m/s], $Ld=373$ [mm])

inlet pressure change corresponding to the pictures shown in Fig. 9. It is seen that the period of oscillation changes significantly for each cycle as compared with the transitional cavity oscillation. This is the reason for the broadband spectrum of inlet pressure fluctuation. This figure shows that the cavity oscillation correlates with the inlet pressure fluctuation even in the case of partial cavity oscillation with broadband spectrum and smaller magnitude. Therefore, the inlet pressure fluctuation measurement is appropriate to evaluate the characteristics of both the transitional cavity oscillation and the partial cavity oscillation. The behavior of the partial cavity oscillation with sheet cavitation for $\alpha=1.5$ [deg], $Lc^*=0.5$ is shown in Fig. 11. We can recognize the re-entrant jet toward leading edge of hydrofoil in (d) and (e).

5. Observation of Re-entrant Jet

Tanimura et al.⁽¹⁰⁾ introduced three proposed mechanisms to explain cavity oscillations, i.e. re-entrant jet, surface wave and impinging jet. They attempted to control the re-entrant jet by a bar attached to the hydrofoil experimentally. It is reported that the pressure fluctuation resulting from the partial cavity oscillation is suppressed by the bar. However, no studies have ever been made to explain the relation between the transitional cavity oscillation and the re-

Fig. 11 Photographic observation of partial cavity oscillation ($\downarrow$: end of cavity, $\downarrow$: re-entrant jet) ($\alpha=1.5$ [deg], $\sigma=0.68$, $C=70$ [mm], $U=3.47$ [m/s], $Ld=373$ [mm], $Lc^*\approx 0.5$)

entrant jet. We present the observation of the re-entrant jet on a hydrofoil by means of dye injection for the case of transitional cavity oscillation to discuss the effect of a bar on the characteristics of oscillating cavitation. The bar, which has square cross section 3 [mm] $\times 3$ [mm], is attached at $1/3C$ from the leading edge. Figure 12 is the behavior of the re-entrant jet on a hydrofoil without a bar and Fig. 13 is for the case of a hydrofoil with a bar. We can observe the region colored by the dye injected near the trailing edge migrate upstream in these figures. This shows that the re-entrant jet also appears for the transitional cavity oscillation at the collapse phase of the cavity. Without a bar, as shown in Fig. 12, dye reaches the leading edge. With a bar, as shown in Fig. 13, the re-entrant jet is stopped by the bar. A cloud of cavity is shed after the re-entrant jet collides with the bar. Figure 14(a) shows the typical observation of the cavity shed from the location of the bar. In Fig. 14(b), the locations of the re-entrant jet and the shed cavity are plotted against time. This figure clearly shows that the cloud of cavity is shed each time the re-entrant jet reaches the leading edge or the bar. However, the period of cavity shedding is not affected by the existence of the bar. Figures 15 and 16 are power spectrums of the inlet pressure fluctuation for

Fig. 12 Observation of re-entrant jet on foil without bar ($\alpha=3.8$ [deg], $\sigma=0.88$, $U=3.50$ [m/s], $Ld=373$ [mm], $Lc^*\approx 1.0$)

the cases with and without a bar. The spectrum is not affected substantially by the existence of the bar. These results lead to the conclusion that the transitional cavity oscillation is not controlled by the re-entrant jet and the associated cavity shedding, although they do appear to be associated with the cavity oscillation. The present results suggest that the re-entrant appears as a result of transitional cavity oscillation rather than being the cause of it.

6. Conclusion

An experimental study was made to clarify the characteristics of oscillating cavitation on a flat plate hydrofoil in a water tunnel. The following conclusions can be drawn.

(1) The oscillating cavitations can be grouped into two types: the transitional cavity oscillation and the partial cavity oscillation. They depend mainly on

Fig. 13 Observation of re-entrant jet on foil without bar ($\alpha=3.8$ [deg], $\sigma=0.80$, $U=3.59$ [m/s], $Ld=373$ [mm], $Lc^*\approx 1.0$)

Fig. 15 Power spectrums of inlet pressure fluctuation in case of foil without bar ($\alpha=3.8$ [deg], $\sigma=1.00$, $C=90$ [mm], $U=3.50$ [m/s], $Ld=373$ [mm], $Lc^*\approx 1.0$)

the mean cavity length. The transitional cavity oscillation occurs when the non-dimensional cavity length is in the range of $0.75 < Lc^* < 1.2$. For transitional cavity oscillations, the Strouhal number Stb based on the chord length of transitional cavity oscillation is nearly constant over the range of the cavity length ($0.75 < Lc^* < 1.2$), and is not affected by the angle of

Fig. 14 Location of re-entrant jet and shed cavity

Fig. 16 Power spectrums of inlet pressure fluctuation in case of foil without bar ($\alpha=3.8$ [deg], $\sigma=1.00$, $C=90$ [mm], $U=3.59$ [m/s], $Ld=373$ [mm], $Lc^*\approx 1.0$)

attack, shape of the hydrofoil and experimental system. For non-dimensional cavity length less than 0.75, partial cavity oscillation is observed. The Strouhal number Stb of partial cavity oscillation increases with decreasing cavity length.

(2) When the angle of attack is small, sheet cavitation appears. In this situation, Strouhal number Stb does not largely depend on the inlet conduit length. On the other hand, cloud cavitation is observed under the condition with larger angle of attack. In the case of cloud cavitation, the Strouhal number Stb depends on the inlet conduit length.

(3) For the case of transitional cavity oscillations, re-entrant jets were observed using dye injection, with and without a bar on the foil to stop the re-

entrant jet. It was found for both cases that the re-entrant jet is associated with cavity shedding. Even if we stopped the reentrant jet with the bar, both the frequency and the magnitude of oscillation did not change. From this observation, the re-entrant jet is not the cause of transitional cavity oscillation but rather a result of cavity oscillation.

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