Experimental Study of Break-off Frequency in Cavitation Disappearance Phenomenon on NACA16-012 Hydrofoil

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Abstract. Under the specific angle of attack on NACA16-012 hydrofoil, generated cavitation suddenly disappears even in the low cavitation number condition in which cavitation normally develops. This cavitation disappearance phenomenon was confirmed to be unique to NACA16-012 hydrofoil in our previous research. It was experimentally confirmed that cavitation disappearance phenomenon occurs in a transient cavitation condition where the sheet cavity is periodically broken off and the cloud cavity is released. In the previous study, it was predicted that there is the frequency band in which sheet/cloud cavitation cannot exist and cavitation disappearance phenomenon occurs. In this study, the break-off frequency of NACA16-012 hydrofoil was experimentally investigated and relationship between the break-off frequency and cavitation disappearance phenomenon was considered. The pressure fluctuation was measured with the pressure transducer downstream region and the dominant frequency was estimated by the frequency analysis. As the results, cavitation disappearance phenomenon was confirmed at angles of attack of 6° and 7°. There was the region increasing the break-off frequency according to decreasing of cavitation number at angles of attack 6° to 12°. It means that the break-off frequency of NACA16-012 hydrofoil has unusual characteristics. When the break-off frequency was expressed by the Strouhal number, it was found that the Strouhal number took each same value immediately just before and after cavitation disappearance phenomenon in decompression experiment. It was suggested that the break-off frequency was related to cavitation disappearance phenomenon.

1. Introduction
In fluid machineries using liquid as working fluid, cavitation often occurs when the pressure of fluid is decreased the saturated vapor pressure. Cavitation causes some undesirable effects such as performance deterioration of fluid machineries, occurrence of erosion and generation of vibration and noise. Therefore to design fluid machineries, it is necessary to predict occurrence of cavitation and how the cavitation have an influence on fluid machineries. However accurate prediction is not easy because it is complicated phenomenon involving many flow factors. Therefore, a number of studies have been conducted using the hydrofoil for understanding of cavitation on the hydrofoil [1]. On the hydrofoil, the cavitation pattern changes depending on the angle of attack, the flow velocity, and the pressure. The flow velocity and the pressure are made dimensionless by the cavitation number. The cavitation number \( \sigma \) is defined as,

\[
\sigma = \frac{2(p_\infty - p_{sat})}{\rho_\infty U_\infty^2},
\]  

(1)
where $p_\infty$ is mainstream static pressure [Pa], $p_{\text{sat}}$ is saturated vapor pressure [Pa], $\rho_\infty$ is density of liquid [kg/m$^3$] and $U_\infty$ is mainstream velocity [m/s].

As the cavitation number decreases, cavitation grows and changes in various patterns such as back detachment cavitation, attached sheet cavitation, sheet/cloud cavitation, shear cavitation and supercavitation. On NACA16-012 hydrofoil, it was confirmed that cavitation disappears in a specific range of angles of attack, despite the low cavitation number conditions that normally occurs sheet/cloud cavitation [2]. Previous research reported that this cavitation disappearance phenomenon is unique to NACA16-012 hydrofoil [3]. However, the mechanism of cavitation disappearance phenomenon has not yet been elucidated.

Franc et al. reported that cavitation disappearance phenomenon occurs at the angle of attack in which laminar separation point and transition region move from the rear to the front part of the hydrofoil. Between two consecutive turbulent spots, the boundary layer is laminar and a sheet cavity can develop locally for a short time, before being swept out by the next turbulent spot [2]. However, this description cannot explain why once occurred cavitation disappears.

In this study, for the final purpose of elucidating mechanism of cavitation disappearance phenomenon, the break-off frequency of NACA16-012 hydrofoil was experimentally investigated. In particular, the frequency characteristics at various angles of attack were investigated and the break-off frequencies immediately before and after cavitation disappearance phenomenon were measured in detail.

2. Experimental set up

2.1. Experimental apparatus

This experiment was conducted by using a high pressure and high temperature water cavitation tunnel at Institute of Fluid Sciences, Tohoku University. The overview of cavitation tunnel is shown in figure 1. This tunnel consisted of a settling tank, pressure tank, a test section and a circulation pump. The pressure tank was above the settling tank, which made water and air independent in order to control the static pressure easily. The pressure tank was connected to the vacuum tank and the compressor through the valves to control. The pressure in the entire experiment apparatus was changed by opening or closing the valves. The mainstream velocity was controlled by the rotational speed of the pump, which can send water 500 liter per minute. The working fluid was a tap water whose chlorine was removed by filter. The temperature of the fluid can be changed from room temperature to 140 °C by the heater; in this study, the temperature of working fluid was at constant of 30 °C. Amount of dissolved oxygen was adjusted by vacuum pump and measured by dissolved oxygen meter. Basically, the value of dissolved oxygen was about 30 %. When the break-off frequency was measured, the value of dissolved oxygen was 10 % to measure the break-off frequency clearly.

The test section is 30 mm high, 20 mm wide and 330 mm long. The test section is shown in figure 2. The pressure fluctuation was measured using a pressure transducer installed at 80 mm downstream from the center of the hydrofoil. The signals from pressure transducers were recorded by the frequency analyser. The sampling frequency was determined by balance between data length and sampling frequency. Typical value of sampling frequency was 1280 Hz. The mainstream static pressure used to define the cavitation number was measured using a pressure transducer installed at 110 mm upstream from the center of the hydrofoil. The test hydrofoil was NACA16-012 with the chord length of 30 mm and the span length of 20 mm. The test section had an observation window at the hydrofoil cross-section direction and the appearance of cavitation from the hydrofoil surface was observed through it.
2.2. Experimental conditions
The mainstream velocity $U_{\infty}$ were 12.5 m/s, 13.0 m/s, 13.4 m/s, and 13.5 m/s. The angles of attack $\alpha$ were 0°, 2°, 4°, 5°, 6°, 7°, 8°, 10°, 12°, 14°, and 16°, especially, the pressure fluctuation in the downstream was measured over 5°. Behavior of unsteady cavitation was visualized by a high-speed camera with frame rate of 2000 fps and the shutter speed of 1/100000 s. FFT analysis was done using pressure fluctuation which is measured by a pressure transducer installed at 80 mm downstream from the center of the hydrofoil.

2.3 Estimation of the break-off frequency
In this study, the frequency was compared by two methods which were the pressure transducer and the high-speed camera. FFT analysis can easily measure the frequency, however there is no confirmation that the frequency is the break-off frequency. The high-speed camera can confirm that the frequency is the break-off frequency, however the frequency accuracy is poor. This experiment was conducted only 10° where sheet/cloud cavitation stands out. The region where sheet/cloud cavitation occurred was measured at 0.1 intervals of the cavitation number. The break-off frequency was calculated by counting the number of photos releasing cloud cavitation. As the result, it was confirmed that the frequency obtained by FFT was the break-off frequency.

The break-off frequencies just before and after the disappearance phenomenon were measured in decompression experiments at angle of attack 7°. The decompression experiments were conducted from quasi-steady cavitation to supercavitation. Dissolved oxygen was degassed to the minimum value of about 10 %.

3. Result and discussion

3.1. Cavitation patterns
The cavitation patterns were investigated at each angle of attack and cavitation number. The cavitation patterns map are shown in figure 3. The cavitation patterns were classified as “back detachment cavitation” that the cavitation generates from the rear of the hydrofoil, “attached sheet cavitation” that the cavitation does not break, “sheet/cloud cavitation” that the cavitation breaks and releases the cloud.
cavity, “shear cavitation” that the cavitation separates from the hydrofoil, and “supercavitation” that the suction side was covered with a quasi-steady cavity.

![Cavitation patterns map of NACA16-012 hydrofoil (U∞ = 13.4 m/s).](image)

It shows that sheet/cloud cavitation occurs from 5° to 10° and cavitation disappearance phenomenon was confirmed at 6° and 7° during the sheet/cloud cavitation. Cavitation disappearance phenomenon was defined as that the cavitation disappears after once the cavitation occurs by decreasing cavitation number or cavitation occurs after once the cavitation disappears by increasing cavitation number.

3.2. Unsteady characteristics of sheet/cloud cavity

The frequencies obtained by the signal of pressure transducer and high-speed camera were compared as shown in the figure 4. The frequency resolution of FFT is 0.04 Hz. On the other hand, the frequency that measured by high-speed camera had a large frequency difference due to the difference of one picture. For example, when the number of picture of cloud cavity releasing was 30 images, the frequency was 66.7 Hz, when it was 31 images, the frequency was 64.5 Hz. Therefore the accuracy of the frequency measurement was not high by shooting with high-speed camera. Looking at figure 4, the frequencies measured by the two methods were almost similar. Therefore, it can be said that the frequency characteristics created by FFT represent the characteristics of the break-off frequency.

Usually, the break-off frequency decreases with decreasing the cavitation number [4-7]. There is the region increasing the break-off frequency as the cavitation number decreased. The unique shape of this frequency characteristics of NACA16-012 is shown in figure 4. This shape is named “wedge shape” in this study.

In general, the cavity length grows as the cavitation number decreases and the breaking frequency decreases as the cavity length increases. The present relationship between the cavitation number and the cavity length was shown in the figure 5. The cavity length was measured from the leading edge of the hydrofoil in the main flow direction. Although the cavity length / chord length exceeded 1.0, however the aspect of cavitation was sheet/cloud cavitation. It was confirmed that the cavity length decreased with decreasing cavitation number. This suggests that the cavitation growth velocity decreases in the region where the break-off frequency increases as the cavitation number decreases.
Figure 4. Comparison of the frequency measured by pressure transducer and high-speed camera ($U_\infty = 13.4 \text{ m/s, } \alpha = 10^\circ$).

Figure 5. Relationship between the cavitation number and the cavity length ($U_\infty = 13.4 \text{ m/s, } \alpha = 10^\circ$).

The frequency characteristics obtained by FFT were shown in figure 6 about another angle of attack. At the angle of attack of $5^\circ$, the region of the cavitation number where sheet/cloud cavitation occurred was small, so the frequency characteristics could not be confirmed. Cavitation disappearance phenomenon was confirmed intermittently at $6^\circ$ and $7^\circ$. There was a region where the break-off frequency was not obtained because the rate of the disappearance time was long at $6^\circ$. The disappearance time was fairly short at $7^\circ$, so the break-off frequency was clearly obtained. The “wedge shape” of the frequency characteristics were observed from $6^\circ$ to $12^\circ$. 

(a) $\alpha = 5^\circ$

(b) $\alpha = 6^\circ$

(c) $\alpha = 7^\circ$

(d) $\alpha = 8^\circ$
The reason why the frequency characteristics become “wedge shape” was investigated. The two conditions where the break-off frequency became a constant value despite the different cavitation numbers were compared by shooting with a high-speed camera set at 10000 fps. The cavitation numbers were 1.4 and 1.7 and the break-off frequency was 71 Hz. The time variation of the cavity length is shown in figure 7. The time of 0 s represents the beginning of cavity growth. One cycle of sheet/cloud cavitation was about 14.2 ms, but the end of the cycle was not shown because re-entrant jet was observed and the cavity length could not be measured.

![Figure 6. Frequency characteristics \((U_\infty = 13.4 \text{ m/s})\).](image)

![Figure 7. Comparison of the cavity length at cavitation numbers of 1.4 and 1.7 \((U_\infty = 13.4 \text{ m/s}, \alpha = 10^\circ)\).](image)
The cavity growth rate were calculated by linear approximation of the region where the cavity length was growing clearly. The range of linear approximation of cavitation number 1.4 and 1.7 were up to 6 ms and 4 ms, respectively. NACA0015 hydrofoil and Clark Y-11.7% hydrofoil with same chord length as NACA16-012 were investigated in a similar way. The comparison of cavity growth rate are shown in the table 1. Sheet/cloud cavitation does not occur at cavitation number of 1.7 on Clark Y-11.7% hydrofoil, therefore the cavitation growth velocity is calculated at cavitation number of 1.6. There is a clear difference between high and low cavitation numbers only NACA16-012 hydrofoil. This suggests that the cavity growth rate is one of the factors of “wedge shape”.

| Hydrofoil       | High $\sigma$ (m/s) | Low $\sigma$ (m/s) |
|-----------------|---------------------|--------------------|
| NACA16-012      | 4.765 ($\sigma = 1.7$) | 5.836 ($\sigma = 1.4$) |
| NACA0015        | 4.380 ($\sigma = 1.7$) | 4.332 ($\sigma = 1.4$) |
| Clark Y-11.7%   | 4.067 ($\sigma = 1.6$) | 3.808 ($\sigma = 1.4$) |

3.3. Break-off frequency just before and after the disappearance

The break-off frequency just before and after disappearance phenomenon in decompression experiment result is shown in figure 8. It can be seen that the range of the cavitation number under cavitation disappearance phenomenon can be confirmed as almost the same at any mainstream velocity. However the break-off frequency was different at each velocity. Next, the break-off frequency was transformed to dimensionless parameter which is the Strouhal number. The Strouhal number $St$ is defined as,

$$St = \frac{f \cdot c}{U_\infty}$$

where $f$ is the break-off frequency [Hz], $c$ is the chord length of hydrofoil [m] and $U_\infty$ is mainstream velocity [m/s]. Figure 9 shows the dimensionless result of the decompression experiment result.

![Figure 8](image1.png)  
**Figure 8.** Relationship between the cavitation number and the break-off frequency of the decompression experiment ($\alpha = 7^\circ$).  

![Figure 9](image2.png)  
**Figure 9.** Strouhal number of the break-off frequency just before and after disappearance of the decompression experiment ($\alpha = 7^\circ$).  

From the figure 8 almost the same Strouhal numbers were taken each immediately just before and after in decompression experiments. The Strouhal numbers immediately before and after the disappearance was constant at about 0.15. Therefore, it was suggested that the Strouhal number was related to cavitation disappearance phenomenon. It was considered that the break-off frequency reaches a Strouhal number and cavitation disappearance phenomenon occurs, due to the unique frequency characteristics of NACA16-012 hydrofoil.
4. Conclusion
In this study, for the final purpose of elucidating mechanism of cavitation disappearance phenomenon, the break-off of NACA16-012 hydrofoil was experimentally investigating. As the results, the following knowledges of NACA16-012 and cavitation disappearance phenomenon were obtained.
1. It was confirmed that the frequency characteristics of the “wedge shape” observed in the angle of attack range were unique to NACA16-012 hydrofoil.
2. The variation of cavity growth rate with cavitation number was considered to be one of the factors of “wedge shape”.
3. When the break-off frequency immediately just before and after cavitation disappearance phenomenon in decompression experiment was expressed by the Strouhal number, it became roughly constant.
4. The unique frequency characteristics of NACA16-012 hydrofoil were suggested to be related to cavitation disappearance phenomenon.

References
[1] Weitendorf E A 2001 On the history of propeller cavitation and cavitation tunnels Fourth International Symposium on Cavitation (Pasadena: California Institute of Technology)
[2] J P Franc and J M Michel 1985 Attached cavitation and the boundary layer: experimental investigation and numerical treatment J. Fluid Mech 154 pp 63-90
[3] Y Odaira W Tsuru S Watanabe and Y Iga 2018 Experimental study of disappearance phenomenon of unsteady cavitation on NACA16-012 The 10th International Symposium on Cavitation (Baltimore) pp 424-429
[4] Morten Kjeldsen Roger E A Arndt and Mark Differtzs 2000 Spectral characteristics of sheet/cloud cavitation J. Fluids Engineering 122 pp 481-487
[5] T M Pham F Larrate and D H Frunman 1999 Investigation of unsteady sheet cavitation and cloud cavitation mechanisms Journal of Fluids Engineering 121 pp-289-296
[6] H Lohrberg B Stoffel R Fortes-Patella O Coutier-Delgosha and J L Reboud 2002 Numerical and experimental investigations on the cavitation flow in a cascade of hydrofoils Experiments in Fluids 33 pp 578-586
[7] Y Kawanami H Kato and H Yamaguchi 1998 Three-dimensional characteristics of the cavities formed on a two-dimensional hydrofoil Third International Symposium on Cavitation pp 191-196(Grenoble)