FLUID FORCE AND PIV VISUALIZATION OF A PITCHING HYDROFOIL UNDER CAVITATION BREAKDOWN LOCK-IN

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ABSTRACT
It is well known that a cavitating hydrofoil falls into the self-induced oscillation under some oscillation frequencies and cavitation numbers. Especially, violent cavitation breakdown periodically occurs where the sheet cavity lengthens near at the trailing edge. It causes the unsteady and nonlinear fluid forces acting on the hydrofoil. This nonlinear phenomenon has not been clarified as yet when the breakdown frequency shedding the vortex cavitation locks in the pitching frequency of the cavitating hydrofoil. The experiment was carried out for the cavitating flow around a pitching NACA hydrofoil in the TMIT cavitation tunnel. The pitching lift coefficient was clarified by load cell measurement with non-dimensional cavity length and reduced frequency as parameters. In addition, particle and bubble image processing technique for PIV is applied to this cavitating flow. As the main result, in Subcavitation region, when the elongation of the sheet cavity can not follow to the variation of the pitching angle at high reduced frequency, the pitching coefficient offsets as if that of non-pitching oscillation. In Transition region where cavitation breakdown frequently occurs, the reduced frequency range for the pitching lift coefficient can be characterized roughly into Unlock-in, Quasi lock-in and Lock-in ranges whether the breakdown frequency synchronizes into the pitching frequency or not.

Keywords: Unsteady Fluid Force, PIV, Vortex Cavitaiton, Cavitation breakdown, Pitching Hydrofoil, Lock-in

INTRODUCTION
Recently, hydrofoil blades of hydraulic machinery are going to design to light weight and thin profile to accomplish the high performance. From the lack of the rigidity, the cavitating hydrofoil falls into the self-exited vibration or flutter [1-2]. Especially, when the cavity on the hydrofoil lengthens near at the trailing edge, the large vortex cavitation called cavitation breakdown is violently shed out and the unsteady fluid forces acting on the hydrofoil become nonlinear [3-5]. This nonlinear phenomenon has not been clarified as yet when the breakdown frequency locks in the pitching frequency of the hydrofoil [6]. Moreover, cavitation phenomenon is complex and statistical two-phase flow accompanied with phase change [7]. And it is hard to say that these measurements have been enough to evaluate the unsteady cavitating flow field qualitatively and quantitatively at the same time [8-13].

In this report, we mainly paid attention to the lock-in phenomenon when the breakdown frequency synchronizes into the pitching frequency. The experiment was carried out about the cavitating flow around a pitching NACA hydrofoil in the TMIT cavitation tunnel. The pitching lift coefficient was clarified by load cell measurement with non-dimensional cavity length and reduced frequency as parameters. Besides, particle and bubble image processing technique [14] for PIV is applied to this cavitating flow. This technique of our previous work is that two CCD cameras take each high quality image utilizing the difference of the scatter light intensity between seeding particles and bubbles. From both images, velocity information is obtained individually, and composed into one by using the cavity boundary determined with binary process of mode method [15] for luminous intensity. Consequently, the velocity vector and the vorticity maps including the inner cavity are able to visualize qualitatively and quantitatively.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>a</td>
<td>torsional axis (distance from leading edge)</td>
</tr>
<tr>
<td>b, c</td>
<td>NACA65-210 span, chord</td>
</tr>
<tr>
<td>c_{m}</td>
<td>mean lift coefficient = 2L/\rho U'^{bc}</td>
</tr>
<tr>
<td>c_{\mu}</td>
<td>mean drag coefficient = 2D/\rho U'^{bc}</td>
</tr>
<tr>
<td>c_{\kappa}</td>
<td>mean moment coefficient = 2M/\rho U'^{bc}</td>
</tr>
<tr>
<td>c_{l}</td>
<td>fluctuating lift coefficient = 2L/\rho U'^{bc}</td>
</tr>
<tr>
<td>c_{d}</td>
<td>fluctuating drag coefficient = 2D/\rho U'^{bc}</td>
</tr>
<tr>
<td>C_{\kappa}</td>
<td>fluctuating moment coefficient = 2M/\rho U'^{bc}</td>
</tr>
<tr>
<td>C_{l}</td>
<td>pitching lift coefficient = L/\rho U'b_{c}[\bar{e}]</td>
</tr>
<tr>
<td>d</td>
<td>projected plane width of hydrofoil with angle of attack</td>
</tr>
<tr>
<td>D, D'</td>
<td>mean drag, fluctuating drag</td>
</tr>
<tr>
<td>f</td>
<td>frequency</td>
</tr>
<tr>
<td>f_{b}</td>
<td>breakdown frequency</td>
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by using the signal of a rotary encoder as a trigger. In order to take the cavitation aspect, the high-speed video camera (600 frames per second) was used auxiliary.

Figure 2 shows the PIV measuring area around the cavitating hydrofoil. The origin of coordinate axes was defined as the torsional axis of the testing hydrofoil and the axes x and y were defined respectively as parallel and normal to the free stream. The measuring areas were employed three domains (36x36 mm²) with the center at (x, y) = (-8, 10), (17, 10) and (42, 10) which can represent the cavitation aspect enough. And the image magnification was 0.036 mm/pixel. The vorticity is dimensionless by using the projected plane width d as shown in Fig.2.

In order to take advantage of the difference of the scatter light intensity between seeding particle and bubble, Camera-A was set up to the aperture value F 4.0, which image luminosity was proportional to 1/F², to shot high quality image of seeding particle. On the other hand, Camera-B to shot high quality image of bubble was set up to F 11.0. The laser light pulse interval was set up to Δt=15 μs, which was computed from inspection domain size and free stream velocity in regard to measuring areas.

Experimental conditions were set at angle of attack α=9°, in water temperature T∞=19.7 °C and in the turbulent flow of Reynolds number Re=3.2x10⁵.

Figure 3 shows the cavitation number effect on the mean and the fluctuating forces at non-pitching oscillation. Every fluctuating lift, drag and moment begin to increase near at the non-dimensional cavity length l/c=0.5 in Subcavitation region and attain maximum peaks near at l/c=1.2 in Transition region from subcavitation to supercavitation. Because, cavitation breakdown occurs violently and the large vortex cavitation sheds out regularly in this Transition region. Accordingly, in order to examine the lock-in phenomena of the breakdown frequency synchronized into the pitching frequency at pitching oscillation, non-dimensional cavity length was employed at l/c=0.5 in Subcavitation region and 1.2 in Transition region. The reduced frequency was varied from k=0 to 1.00. Since the fluid forces such as lift, drag and moment showed qualitatively the troublesome mechanical inertia force can be removed in real time [16]. The fluid forces are measured at a sampling frequency of 1 kHz or 5 kHz, and a sampling number of 4096.

In the PIV measurement system, two CCD cameras (Camera-A: Camera-B, 1008x1018 Pixel) shot particle and bubble images respectively at the same time through a half mirror. The laser sheet of doubled pulsed Nd:YAG laser was 2 mm in thickness. The sheet irradiated from upside of the test section at right angle to flow direction and at 20 mm distance toward span direction from another sidewall in order to eliminate the boundary layer effect. The image processing was carried out utilizing PIV software (Flowmap system, DANTEC). The velocity information was computed by cross correlation method analyzing two images with time lag of laser light pulse interval Δt. The velocity informations of both images were composed into one by using the cavity boundary determined with binary process of mode method for luminous intensity. Furthermore, function generator enables to measure at arbitrary pitching phase θ by using the signal of a rotary encoder as a trigger. Therefore, the pitching oscillation of hydrofoil is cantilever supported on the same axle of the opposite side by another load cell. Thereby, the

![Diagram](image)

**FIG.1 PIV AND TORSIONAL VIBRATION SYSTEM**

Figure 1 illustrates the TMIT cavitation tunnel test section (80x500x1500 mm, Re=2.8x10⁵), a hydrofoil torsional vibration apparatus with built-in three component load cells and PIV measurement system being able to control two CCD cameras. The testing hydrofoil is NACA65-210 made from stainless steel with c=50 mm in chord length, b=80 mm in span width and torsional axis d=21.5 mm. The torque of a motor is transferred to the driving part by way of a flywheel and an auxiliary.

The rotation motion can be converted into the sine wave pitching oscillation (ω=9°). The hydrofoil is cantilever-supported by a load cell. At the pitching oscillation, in order to calibrate and simulate the mechanical inertia force acting on the hydrofoil, a dummy foil in air with the same profile as the hydrofoil in water is cantilever supported on the same axle of the opposite side by another load cell. Therefore, the
same unsteady response, we discuss only about the unsteady behavior of lift below.

![FIG. 2 PIV MEASURING AREA](image)

**FIG. 2 PIV MEASURING AREA**

![FIG. 3 MEAN AND FLUCTUATING LIFT, DRAG AND MOMENT COEFFICIENT](image)

**FIG. 3 MEAN AND FLUCTUATING LIFT, DRAG AND MOMENT COEFFICIENT**

**PITCHING LIFT**

Figure 4 shows the frequency $f$ or Strouhal number $S_t$ of the pitching lift coefficient $C_l$ versus the reduced frequency $k$ in Subcavitation region ($U/c=0.5$) and Transition region ($U/c=1.2$).

In Subcavitation region, $C_l$ has the pitching frequency $f_p$ and twice the number of $f_p$ shown by the broken line and the solid line areas. This means that, in Subcavitation region, the shed of large vortex cavitation such as cavitation breakdown does not occur at pitching oscillation as well as at non-pitching oscillation. From this, the reduced frequency range can be characterized roughly into three ranges where are Range-C ($0 \leq k < 0.35$), Range-D ($0.35 \leq k < 0.65$) and Range-E ($0.65 \leq k < 1.00$). Firstly, Range-C is defined as Unlock-in range where $f_p$ is a constant frequency independent of $f_p$. But, another frequency area gradually decreasing as the increase of $k$ also appears in this range. Secondly, Range-D is defined as Quasi lock-in range where $f_p$ is synchronized into twice the number of $f_p$. Thirdly, Range-E is defined as Lock-in range where $f_p$ is attracted and synchronized into $f_p$. 

![FIG. 4 FREQUENCY OF PITCHING LIFT COEFFICIENT FOR CAVITY LENGTH U/c=0.5, 1.2](image)

**FIG. 4 FREQUENCY OF PITCHING LIFT COEFFICIENT FOR CAVITY LENGTH U/c=0.5, 1.2**

Figure 5 shows the wave and the spectrum of the pitching lift coefficient $C_l$ of Range-A and B characterized above in Subcavitation region ($U/c=0.5$) and, for comparison with these, the fluctuating lift coefficient $C_l'$ at non-pitching oscillation $k=0$ which is rewritten with $C_l$ definition.

In $k=0$, the wave amplitude of $C_l$ fluctuates slightly and its spectrum does not have the peculiar frequency, because cavitation breakdown does not occur. In Range-A ($k=0.30$), $C_l$ has the pitching frequency $f_p=12.7$ Hz and twice the number of $f_p$, $f=25.4$ Hz shown as the solid line area in Fig.4. This frequency $f$ appears due to FFT analysis, because this wave is almost the same as triangular wave. And so, the frequency $f$ is not inherent phenomenon of Subcavitation region. At $k=0.50$ in
If the pitching angle $\theta$ is smaller than that of non-pitching oscillation $k_0 = 0$, this offset effect on the pitching lift coefficient will be discussed later by comparison with the cavitation aspect.

The top of the triangular wave becomes to distort although the RMS value of $C_l$ is nearly same as that of $k = 0$. In Range-B ($k = 0.75$), although $C_l$ still has the wave and the spectrum of $f_p$, it becomes weaker and the RMS value is approximately half of Range-A. Moreover, at $k = 0.90$ of the same range, the wave and the spectrum corresponding to $f_p$ become extremely weak. And the RMS value is almost the same as that of non-pitching oscillation $k = 0$. This offset effect on the pitching lift coefficient will be discussed later by comparison with the cavitation aspect.

Figure 7, 8, 9, and 10 show the average wave of the pitching lift coefficient $C_l$ during one pitching cycle (sampling frequency 5 kHz, L.P.F 200 Hz, the phase average wave of 10 pitching cycles) in Subcavitation and Transition regions which were defined in previous section, and the cavitation aspect by the high-speed video camera photography (600 FPS) which synchronized with load cell measurement. The pitching phase $\theta$ shown in each figure corresponds to the variation of the pitching angle $\theta$ at angle of attack $\alpha = 9^\circ$. Here, $\theta = 90^\circ$ is the bottom death point of $\theta$ and $\theta = 270^\circ$ is the top death point of $\theta = 1^\circ$. In addition, the broken line in each figure shows the wave of $C_l$ at non-cavitation under the same conditions for comparison. The cavitation aspect is fundamentally shown as every $30^\circ$, but the aspect of the other pitching phases, which represents the specific cavitation behavior, is also shown. Furthermore, those figures show the cavitation image of side view, the velocity vector and the vorticity maps obtained by PIV measurement with particle and bubble image processing. Also, these correspond to the characteristic waves of the pitching lift.
coefficient $\tau$ and the cavitation aspects during each one pitching cycle.

In (1) Subcavitation region ($U_c=0.5$), Range-A ($k=0.30$) of Fig.7, $\tau$ has the large wave amplitude and the phase delay as compared with the wave and the phase of non-cavitation having the same phase as the pitching angle $\theta$. Because the sheet cavity lengthens and shortens with short phase delay about $\theta=30^\circ$, synchronizing with the variation of pitching angle. Namely, the sheet cavity length is minimum at $\theta=120^\circ$ and maximum at $\theta=300^\circ$. During the decrease of $\tau$ from $\theta=300^\circ$ to $30^\circ$, the sheet cavity froths and small-scale bubble crowd detaches from the end of the sheet cavity. But some of these bubbles collapse quickly or shed out from the trailing edge toward the downstream and the survival cavity becomes short and stratified.

The PIV measurement results show the more detail of the characteristic pitching phase $\theta$ as above. At $\theta=60^\circ$ after the small-scale bubble crowd detached, the detach point occurs from near the mid chord, and the small-scale crowd has the weak rotating flow with the low velocity and the weak vorticity. At $\theta=240^\circ$ when the sheet cavity lengthens near the maximum, the inside of the sheet cavity has the long vorticity layer along the upper surface. But at $\theta=300^\circ$ when the sheet cavity begins to forth, the cavity and its vorticity layer becomes thick from the leading edge. And the velocity is very low inside of the cavity.

In (2) Subcavitation region ($U_c=0.5$), Range-B ($k=0.90$) of Fig.8, the pitching lift coefficient $\tau$ is not affected by pitching oscillation and offsets as if that of non-pitching oscillation. Because, the cavitation aspect represents that the cavity length does not change scarcely during one pitching cycle. Moreover, only the sheet cavity end near at the mid chord froths just as cloud-cavitation. And the small-scale bubble crowd detaches from here, which means the weak cavitation breakdown.

The PIV measurement results show the more detail of the characteristic pitching phase $\theta$. At $\theta=60^\circ$ after the small-scale bubble crowd detached, the crowd has the same order velocity with the free stream velocity ($U=6.57$ m/s) and the small vorticity. At $\theta=240^\circ$ when the sheet cavity takes almost same length as $\theta=60^\circ$, the cavity becomes thin and has the vorticity layer along the upper surface from the leading edge to the mid chord. Especially, the sheet cavity end has the same order velocity with the free stream velocity. But, at $\theta=360^\circ$ when the sheet cavity increases its thickness, the vorticity layer formed from leading edge becomes thick and the velocity are very low inside of the cavity where hardly elongates.

From these results, the cavity length dose not change by pitching oscillation. So it is the almost same cavitation aspect during one pitching cycle except the small-scale detached bubble crowd sheds out. Namely, expansion and contraction of the sheet cavity cannot follow to the variation of the pitching angle. It is considered as the reason that the pitching lift offsets independent of the pitching frequency $f_p$ shown in Fig. 4, 5.

In (3) Transition region ($U_c=1.2$, Range-C ($k=0.30$) of Fig.9, the wave of $\tau$ has three cycles as shown 1 and 2 during one pitching cycle riding on that of non-cavitation. This means that cavitation breakdown, which is the large-scale bubble crowd detaching and shedding out from the trailing edge, always occurs three times synchronizing with the same phases such as $\theta=26^\circ$, $121^\circ$, $240^\circ$. However, since the interval between these phases and the scales when the large-scale bubble crowd detaches are different from each other. This phase deviation yields the frequency $f$ which gradually decreases as the increase of pitching frequency $f_p$ shown in Fig. 4.

The PIV measurement results show the more detail of the characteristic pitching phase $\theta=0^\circ$, $90^\circ$ and $210^\circ$ just before when the large-scale bubble crowd is shed out from the trailing edge. The vicinity of the leading edge is covered with clear cavity but invisible. The sheet cavity has the unstable vorticity layer along the upper surface. The velocity is the same order with the free stream velocity on the top of the crowd but is small and slightly rotates under the bottom of it. Therefore, the large-scale bubble crowd begins to change into vortex cavitation.

In (4) Transition region ($U_c=1.2$, Range-E ($k=0.90$) of Fig.10, $\tau$ has the opposite phase against that of non-cavitation. Furthermore, there is only one breakdown during one pitching cycle. Namely, lock-in phenomenon occurs in this case. The detached bubble crowd sheds out from the trailing edge. Also there is a non-wetted surface between the sheet cavity and the detached bubble crowd at $\theta=30^\circ$ just after the sheet cavity detachment shown the remarkable peak of $\tau$. Thereafter, the sheet cavity lengthens near the trailing edge. And the detached bubble crowd thickens and is shed out toward the downstream in from $\theta=60^\circ$ to $180^\circ$. At $\theta=150^\circ$ when is the remarkable bottom of $\tau$, the sheet cavity reaches to the mid chord such as partial cavitation. On the other hand, the large-scale bubble crowd begins to shed out from the trailing edge. This shedding bubble crowd is larger than those of (3) Transition region, Range-C as described above. This is the feature of lock-in. And then, in from $\theta=210^\circ$ to $360^\circ$, the sheet cavity is frothed up as the cloud-cavitation and thicken toward the leading edge from the trailing edge against the free stream. This is considered as the cause that the bubble crowd detaches and cavitation breakdown occurs.

The PIV measurement results show the more detail of the characteristic pitching phase $\theta$. At $\theta=30^\circ$ when the large-scale bubble crowd detaches, the front side of the crowd has the high velocity represented the propagation of the detachment and the rear side of it has the weak rotating flow with the low velocity. The sheet cavity has the short vorticity layer along the upper surface and the crowd has some discrete vortices. At $\theta=120^\circ$ when the sheet cavity elongates, the velocity along the upper surface increase at the inside and back of the sheet cavity as compared with $\theta=30^\circ$. On the other hand, the large-scale bubble crowd becomes to increase its thickness and the same order velocity with the free stream velocity on the top of the crowd but is small and slightly rotates under the bottom of it. However, the some positive and negative vortices of the crowd do not still concentrate into one. At $\theta=240^\circ$ when the sheet cavity begins to thicken, the sheet cavity has the high velocity on the upper boundary near the leading edge of it and has the thick vorticity layer from leading edge to the mid chord. The large-scale bubble crowd sheds out from trailing edge and changes into the vortex cavitation on the alternative flow toward the down stream.
(1) Subcavitation region ($\ell/c=0.5$) Range-A ($k=0.30$, $f_p=12.7$ Hz) (2) Subcavitation region ($\ell/c=0.5$) Range-B ($k=0.90$, $f_p=38.1$ Hz)
(3) Transition region ($l/c=1.2$) Range-C ($k=0.30$; $f_p=12.7$ Hz)

(4) Transition region ($l/c=1.2$) Range-E ($k=0.90$; $f_p=38.1$ Hz)
CONCLUSIONS
In this report, we mainly paid attention to the lock-in phenomenon when the breakdown frequency synchronizes into the pitching frequency. The pitching lift coefficient was clarified by load cell measurement with non-dimensional cavity length and reduced frequency as parameters. In addition, particle and bubble image processing technique for PIV is applied to this cavitating flow. Consequently, the velocity vector and the vorticity maps including the inner cavity are qualitatively and quantitatively visualized. The main results can be summarized as follows.

1. In Subcavitation region ($\nu=0.5$), the pitching lift coefficient is related to the reduced frequency $k$. It depends on whether the sheet cavity can lengthen and shorten synchronizing with the variation of the pitching angle or not. Specially, when the elongation of the sheet cavity can not follow to the variation at high reduced frequency, the pitching coefficient offsets as if that of non-pitching oscillation.

2. In Transition region ($\nu=1.2$) where cavitation breakdown frequently occurs, the reduced frequency range of the pitching lift coefficient can be characterized roughly into three ranges where are Unlock-in range $0 \leq k \leq 0.35$, Quasi lock-in range $0.35 \leq k \leq 0.65$ and Lock-in range $0.65 \leq k \leq 1.00$ whether the breakdown frequency synchronizes into the pitching frequency or not.

3. Especially, in Lock-in range $k=0.90$, the breakdown frequency shifts into the pitching frequency. The pitching lift coefficient has the opposite phase against that of non-cavitation and cavitation breakdown occurs regularly and violently as compared other ranges.

4. Cavitation breakdown process is, in turn, that the sheet cavity elongates as long as the trailing edge, the sheet cavity is frothed up just as cloud-cavitation toward the leading edge against the free stream, the large-scale bubble crowd detaches near from the leading edge, the bubble crowd is shed out from the trailing edge and finally becomes into vortex cavitation.

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REFERENCES

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