Stereo PIV measurements of vortex behavior produced by a pitch-oscillating discoid airfoil

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Abstract

Flying animals and insects flap their wings using a combination of pitching and heaving oscillations. Unsteady fluid forces presumably play an important role in the flight mechanism, and also in the propulsive force of swimmers performing the front crawl. In particular, the crawl stroke invokes a unique S-shaped pull motion, in which the direction of circulation around the hand changes during a single stroke cycle. We intend to elucidate the relationship between unsteady fluid forces and the three-dimensional vortex structure in the case of high reduced frequency. In the present study, pitch-oscillating motion was carried out as a basic unsteady motion. The vortex structure and behavior of a discoid airfoil (simulating a swimmer's hand) were investigated during pitch-oscillating motion. Vortical flow fields were measured by a particle image velocimetry (PIV) technique. Vortical field was evaluated in a wind tunnel test, which allows the easy alteration of the complex parameters affecting unsteady phenomena. Throughout one cycle of the pitch-oscillating motion, vortices grew to a large size and were eventually released into the wake close to the airfoil. Fluid force increased as the vortex grew near the airfoil, peaking twice during the pitching cycle. Thereafter, the fluid force decreased as the vortex was shed and traveled in the downstream direction.

Key words : Unsteady flow, Vortex, Wake, Unsteady fluid force, Pitching oscillation, Discoid airfoil

1. Introduction

In recent years, much research has been devoted to biological flight dynamics (Wang, 2000 and Sane, 2003). However, the unsteady propulsion systems of birds, insects, and fishes remain sparsely investigated and poorly understood. The complex motions of travelling birds and insects are most clearly observed as flapping (Birch, et al., 2004 and Lentink and Dickinson, 2009), whereas fish tails chiefly undertake pitching motions (Brucker and Bleckmann, 2007). The fluid forces acting on wings, predicted by a quasi-steady approach, indicate that such flight is impossible (Ellington, 1984). The existence of biological flight indicates an important role of unsteady fluid forces in the flight mechanism. These forces also underlie the propulsive force of front crawl swimmers and the flat scull technique in synchronized swimming. In particular, the unique S-shaped pull of the front crawl and flat scull motions alter the circulation direction around the hand throughout one stroke cycle (Matsuuchi, et al., 2009). In a previous study, basic unsteady pitch-oscillating motion was utilized to investigate the effect of airfoil shape on unsteady fluid forces, and the differences in the effect of unsteadiness on the discoid and the NACA0012 airfoils were considered (Hasegawa, et al., 2010).

Our aim is to clarify the unsteady mechanism in the generation of propulsive force in front crawl swimming and to investigate three-dimensional vortex structure around the discoid airfoil simulating a human hand during pitch-oscillating motion, which represents the fundamental unsteady motion. During one cycle of the pitch oscillation,

the leading edge of the discoid airfoil displaces the trailing edge. Unsteady mechanisms are generally difficult to elucidate because unsteady flow phenomena are governed by several parameters. However, the parameters affecting unsteady phenomena can be easily changed in a wind tunnel test. In this study, three-dimensional unsteady flow field generated by a pitch-oscillating discoid airfoil was measured using a stereoscopic particle image velocimetry (PIV) technique at several downstream positions and three components of velocity measurements were synchronized to the airfoil movements. From momentum conservation of the flow field, the unsteady fluid forces generated by the pitch-oscillating airfoil were then calculated.

2. Experimental apparatus and method

Figure 1 shows a schematic of the experimental setup. The inlet dimensions of the test section are 300 mm $\times$ 300 mm. The center of the model is the origin of a Cartesian coordinate system with axes labeled x , y , and z . The velocity is denoted by components (u, v, w) in the directions (x, y, z) . The test model is a discoid airfoil with a NACA0015 profile. The discoid airfoil is made by rotating the profile of NACA0015 from the leading edge to the maximum thickness around its mid chord axis (see Fig. 2 (b)). The airfoil edge is smooth and half-rounded. Pitch-oscillating motion was generated by a five-phase stepping motor with 0.072° per step around its mid-chord axis. In the following analysis, the non-dimensional time t' is defined as $t' = t/T$, where t is the time and T is the cycle period. Figure 3 plots the angle of attack α of the airfoil model as a function of nondimensional time t' . This function is given by $\alpha = A \sin(2\pi ft) + \alpha_c$, where A is the amplitude, α_c is the angle of the pitching center, and f is the oscillation frequency. Upstroke and downstroke indicate the increment and decrement of the angle of attack, respectively. In this experiment, the pitch-oscillating motion was carried out at $A = \pm 20.16^\circ$, $\alpha_c = 90^\circ$ and $f = 6$ Hz. The free-stream Reynolds number is defined as $Re = cU_0/\nu$, where U_0 is the free-stream velocity, and ν is the kinematic viscosity of air. The experiments were conducted at $Re = 3.0 \times 10^4$ and 5.0×10^4 , which typify the flows generated by a swimmer's hand. The reduced frequency k is defined as $k = \pi fc/U_0$. The experiments were conducted at $k = 0.19, 0.31, 0.58$ and 0.97 . Flows are known to become unsteady at $k > 0.2$ (Azuma, 1993); the effect becomes remarkable at $k > 1$. The flow fields were

Fig. 1 The schematic of the experimental setup.

Fig. 2 Test model.

measured by 2-component particle image velocimetry (2CPIV) and a stereoscopic PIV method. The 2CPIV system chiefly comprises a CCD camera and an Nd-YAG laser. The laser sheet, vertically arranged in the x - z plane, was deflected by a mirror set affixed at the top of the test section. 2CPIV measurements were performed in the region $y/c = 0-0.5$ at equal intervals of $y/c = 0.1$ in the x - z plane. Figure 4 shows a schematic of the stereoscopic PIV setup, comprising two CCD cameras and an Nd-YAG laser. The particle image was captured by two CCD cameras placed on both sides of the test section. The PIV cameras were mounted on a specially designed rig with an adjustable viewing

Fig. 3 The temporal change of α during pitch-oscillating motion.

Fig. 4 The schematic of the stereoscopic PIV setup.

Fig. 5 The measurement region of stereoscopic PIV.

angle. To satisfy the Scheimpflug condition, the angle between the optical axes of the two cameras was set to approximately 90° . The vertical laser sheet was irradiated from the side of the test section in the y - z plane. Figure 5 shows the measurement region of stereoscopic PIV, set to approximately (300×300) mm in the y - z plane. Stereoscopic PIV measurements were performed in the region $x/c = 0-1.0$ at equal intervals of $x/c = 0.033$ in the y - z plane. To synchronize the image capture with the airfoil motion, the flow field measurements were governed by a timing cycle produced by a pulse generator trigger. In this experiment, the flow field is estimated by ensemble averaging over 20 measurements to enhance the measurement accuracy, and the error in PIV measurements is less than 1 %. A shear layer produced by the discoid airfoil would make the vortex shape unclear, and a quick way of avoiding this difficulty is to use an iso-surface of the vorticity strength because the vortex is not weak enough to be cleared away by the shear layer. We selected the iso-surface of the vorticity to visualize the three-dimensional vortex structure. The three-dimensional vortex structure was depicted by plotting the iso-vorticity surface calculated from the reconstructed velocity data. The vorticity components are given by

$$(\omega_x, \omega_y, \omega_z) = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}, \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}, \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right). \quad (1)$$

3. Results and discussion

3.1 Vortical field in the x - z plane

Figures 6 and 7 show vorticity contour maps in the x - z plane at $y/c = 0$ and $y/c = 0.4$, respectively. The color bar indicates the strength of the vorticity. In these figures, the airfoil profile is depicted to clarify the airfoil position at the measured angle of attack. At $y/c = 0$, the downstroke generates successive negative vortices near the upper edge of the airfoil. Vortex growth is promoted by the pressure difference between the front and back sides of the airfoil. A large vortex is released from the upper edge of the airfoil at $t' = 0.4$. During the upstroke, this vortex travels in the downstream direction. The distance from the pitching axis to the edge of the discoid airfoil shortens in the spanwise direction because of the airfoil edge curvature. Consequently, the relative velocity between the oscillating airfoil and the free-stream becomes larger at $y/c = 0$ than at other spanwise positions. This enhanced relative velocity induces stronger vortices at $y/c = 0$ than at $y/c = 0.4$. The vortex structure developed around the discoid airfoil depends on the

Fig. 6 Vorticity contour maps in the x - z plane at $y/c = 0$ ($Re = 3.0 \times 10^4$ and $k = 0.97$).

Fig. 7 Vorticity contour maps in the x - z plane at $y/c = 0.4$ ($Re = 3.0 \times 10^4$ and $k = 0.97$).

Fig. 8 Control volume for evaluating the unsteady fluid force acting over a pitch-oscillating cycle.

Fig. 9 The time history of the fluid force throughout one pitch-oscillating cycle at $Re = 3.0 \times 10^4$ and $k = 0.97$.

spanwise position. The fluid forces generated by the airfoil model were calculated using a momentum conservation law applied to the flow field around the airfoil. Figure 8 shows the control volume for evaluating the unsteady fluid force acting over a pitch-oscillating cycle. The control volume surrounds the discoid airfoil, and the fluid force is estimated from the momentum change in the control volume. We confirmed that the variation of the fluid force calculated from this method has the same tendency as that of the fluid force measured by a load cell (LVS-50GA, KYOWA) at $Re = 5.0 \times 10^4$. The time history of the nondimensional fluid force P throughout one pitch-oscillating cycle is plotted in Fig. 9. The fluid force increases as the vortex grows near the upper edge of the airfoil from $t' = 0$ to 0.25 (see Fig. 6 (a) and (b)). The peak in the fluid force curve was observed approximately at $t' = 0.25$. After that time, the vortex is shed in the wake and the fluid force decreases. During upstroke, the fluid force curve was observed approximately at $t' = 0.75$. There are two peaks in the fluid force variation throughout one pitching cycle. It is confirmed that the vortex structure and behavior are related to the fluid force variation.

3.2 Three-dimensional vortex structure constructed from stereoscopic PIV measurements

For stereo PIV measurements, the three dimensional flow fields were measured to visualize the 3D vortex structure. Figure 10 shows the three dimensional vortex structure of $|\omega|$ obtained by stereoscopic PIV. $|\omega|$ is given by

$$|\omega| = \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2}. \quad (2)$$

The red and yellow regions of Fig. 10 show the vorticity iso-surfaces $|\omega c/U_0| = 9$ and $|\omega c/U_0| = 6$, respectively. A circular vortex ring forms near the wake of the airfoil at $t' = 0$. During the downstroke, vortex growth is promoted near the upper edge of the airfoil. This is because the pressure difference between the front and back sides of the airfoil becomes larger by increment of the relative velocity between the upper edge and the free-stream. The strong vortex

Fig. 10 Three-dimensional vortex structure around the airfoil during one pitch-oscillating cycle at $Re = 3.0 \times 10^4$ and $k = 0.97$.

Fig. 11 Three-dimensional vortex structure of each vorticity component around the discoid airfoil during one pitch-oscillating cycle at $Re = 3.0 \times 10^4$ and $k = 0.97$.

Fig. 12 Time history of each vorticity component throughout a pitch-oscillating cycle.

exists near the upper edge of the airfoil at $t' = 0.33$. In contrast, the vorticity iso-surface $|\omega c/U_0| = 9$ is not observed at both left and right extremities of the discoid airfoil. Because, the distance of the pitching axis from the discoid airfoil edge becomes smaller as y/c increases. Figure 11 shows the three-dimensional vortex structure of each vorticity component around the discoid airfoil. In this figure, the green, red, and blue regions indicate the nondimensional vorticity iso-surfaces $|\omega_x c/U_0| = 3$, $|\omega_y c/U_0| = 6$, and $|\omega_z c/U_0| = 6$, respectively. ω_x is diminished in the wake of the airfoil throughout the cycle. In contrast, ω_y is strengthened near the upper edge of the airfoil during the downstroke. ω_y increases near the upper edge of the airfoil from $t' = 0$ to 0.33. ω_y decreases near the upper edge of the airfoil from $t' = 0.33$ to 0.5. ω_y variation during pitch-oscillating motion was affected by the relative velocity between the upper edge of the airfoil and the free-stream. On the other hand, ω_z observed at both left and right extremities was not affected by the pitching motion. It is seen from Fig. 11 that the profile of iso-surface ω_z does not change during pitch-oscillating motion, because the relative velocity due to the pitching motion is small near the pitching axis. Figure 12 plots the time history of each vorticity component throughout a pitch-oscillating cycle. Here, the vertical axis denotes the average nondimensional vorticity in the wake of the airfoil. ω_y most widely varies among the three vorticity components, while ω_y varies in synchrony with the fluid force (see Fig. 9). The propulsive force generated by the pitch-oscillating airfoil is largely determined by ω_y .

4. Conclusions

The vortical flow fields during pitching oscillation of a discoid airfoil were measured by a stereoscopic PIV technique. The fluid force was calculated from the momentum conservation law. The main conclusions of this study are summarized below:

1. Vortex growth is promoted near the upper edge of the airfoil during the downstroke. The fluid force peaks twice throughout one pitching cycle, as the vortex grows near the airfoil. Thereafter, the fluid force decreases as the shed vortex travels downstream.
2. During the downstroke, strong vorticity ω_y develops near the upper edge of the airfoil. Throughout the pitch-oscillating cycle, ω_y varies in synchrony with the fluid force. ω_y largely determines the propulsive force generated by the pitch-oscillating airfoil.

References

- Azuma, A., Fluid dynamics, Asakura Publishing Co., Ltd (1993), pp.20-21(in Japanese).
- Birch, J. M., Dickson, W. B. and Dickinson M. H., Force production and flow structure of the leading edge vortex on flapping wings at high and low Reynolds number, The Journal of Experimental Biology, Vol.207 (2004), pp.1063-1072.
- Brucker, C. and Bleckmann, H., Vortex dynamics in the wake of a mechanical fish, Experiments in Fluids, Vol.43 (2007), pp.799-810.

- Ellington, C. P., The aerodynamics of hovering insect flight. I. The quasi-steady analysis, Philosophical transactions of the royal society, B 305 (1984), pp.1-15.
- Hasegawa, H., Watanabe, J. and Matsuuchi, K., Effect of 3-dimensional airfoil shape on unsteady fluid forces in pitching motion, Journal of Fluid Science and Technology, Vol.5, No.2 (2010), pp.270-280.
- Lentink, D. and Dickinson, H., Rotational accelerations stabilize leading edge vortices on revolving fly wings, Journal of Experimental Biology, 212 (2009), pp.2705-2719.
- Matsuuchi, K., Miwa, T., Nomura, T., Sakakibara, J., Shintani, H. and Ungerechts, B. E., Unsteady flow field around a human hand and propulsive force in swimming, Journal of Biomechanics, Vol.42, No.1 (2009), pp.42-47.
- Sane, S. P., The aerodynamics of insect flight, Journal of Experimental Biology, Vol.206 (2003), pp.4191-4208.
- Wang, Z. J., Vortex shedding and frequency selection in flapping flight, Journal of Fluid mechanics, Vol.410 (2000), pp.323-341.