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Two-dimensional Structure of the Wake behind a Pitching Airfoil with Higher Non-dimensional Pitching Rate

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Abstract**:** Two-dimensional flow patterns have been visualized by two kinds of dyes and a VTR camera in a water tunnel at $Re = 4.0 \times 10^3$ in order to study how flow patterns of vortex changed behind a pitching airfoil with various pitching rates and pitching amplitudes. The tested airfoil was NACA0010. The experiment was performed under the conditions such as the pitching motions with sinusoidal or triangular wave around its mid- or quarter-chord axis. The non-dimensional pitching rates were k = 1.97, 2.81 and 4.22. The pitching amplitudes were changed as $A = \pm 2^\circ$, $\pm 6^\circ$ and $\pm 12^\circ$, however the mean angle of attack was fixed at $\alpha_m = 0^\circ$. As a result, the followings were clarified. The flow pattern of thrust producing vortex street was observed in the wake behind the pitching airfoil with a higher non-dimensional pitching rate. Similar flow patterns of the vortex were observed in spite of the differences in the location of pitching motion axis, in the pitching motion wave profile and in the pitching amplitude. Moreover, the pitching motion around the quarter-chord axis with triangular wave could realize the thrust producing vortex street more easily.

Keywords**:** unsteady flow, dye visualization, pitching airfoil, wake, vortex street.

1. Introduction

Many studies on the unsteady separation around a moving airfoil have been carried out with the numerical (Mittal and Tezduyar, 1992) and experimental (Carr, 1990) approaches. Most of them have been performed at high Reynolds number region over $Re = 10^6$ (e.g., McCroskey, 1977; Walker et al., 1985). Recently, a few studies on the unsteady flow at low Reynolds number region have been developed by the interest in the micro-electro-mechanical-systems (MEMS) (Lissaman, 1983; Ho and Tai, 1996) based on the concept of flow control (Sunada et al., 1997; Sato and Sunada, 1995; Fuchiwaki et al., 1998a; Fuchiwaki et al., 1998b).

According to Jones et al. (1998), there were two vortex rows in the wake behind a plunging airfoil when the plunging rate was high. The upper row consisted of counterclockwise rotating vortices shed from the lower surface and the lower row clockwise rotating vortices from the upper surface. This flow pattern meant the thrust producing against the Karman vortex street. When the plunging rate was not so high, the vortices from the lower and upper surface stood in a line alternately so that neither the drag nor the thrust was generated. This case was called neutral.

Lai and Platzer (1999) and Jones et al. (1998) visualized the wake of a plunging airfoil, and reported that the vortex flow patterns changed from drag producing pattern to thrust producing pattern as the non-dimensional plunging velocity increased.

On the other hand, Fuchiwaki et al. (1999) visualized a big-scale cloud vortex behind a pitching airfoil with higher non-dimensional pitching rate with high angle of attack. However, few studies have been carried out on flow pattern behind a pitching airfoil and the basic structure of vortices in the wake has not been understood sufficiently. From the viewpoint of drag and thrust producing, it is important to study how flow patterns of vortex change behind a pitching airfoil as pitching rate and amplitude vary.

In the present study, the vortex flow pattern behind a pitching airfoil, NACA0010 with three kinds of non-dimensional pitching rate have been visualized by two kinds of dyes in a water tunnel at low Reynolds number region. Moreover, two-dimensional structure and basic flow patterns of the vortices in the wake have been discussed.

2. Experimental Systems

An experimental apparatus for flow visualization consisted of a water tunnel, a test airfoil, an equipment driving pitching motion, a halogen light sheet source, a plane mirror, a digital video camera and two kinds of dyes, as shown in Fig. 1.

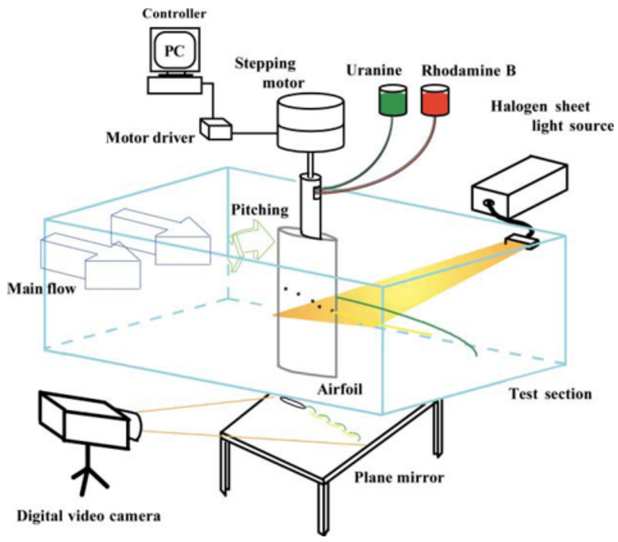


Fig. 1. Experimental apparatus for flow visualization.

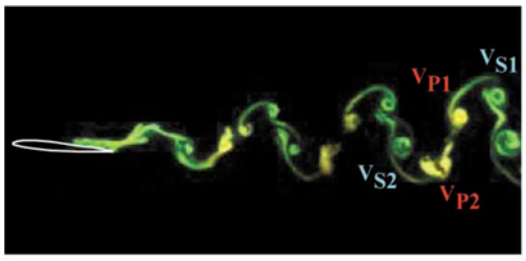
The tested airfoil was NACA0010. The chord and span length were 0.06 m and 0.2 m, respectively. The chord Reynolds number was $Re = 4.0 \times 10^3$. The test airfoil had some pinholes on the surface for the dye flow visualization. They had slightly different depth to keep the independence of dye flows and their diameter was $d = 0.5$ mm. Two kinds of dyes, uranine and rhodamin B, having the respective colors, green and yellow in halogen light sheet, flowed out from the pinholes located on the upper and lower surface, respectively.

Two kinds of pitching motion were performed along sinusoidal or triangular wave around its mid- or quarter- chord axis. The pitching motion with the triangular wave had high angular acceleration only at top and bottom dead positions. The pitching amplitudes were $A = \pm 2^\circ$, $\pm 6^\circ$ and $\pm 12^\circ$, and the mean angle of attack was fixed to $\alpha_m = 0^\circ$. The non-dimensional pitching rate was defined as $k = 2\pi f\,(c/2)\,/\,V_0$, where f was the pitching frequency [Hz], c was the airfoil chord [m] and V_0 was the main flow velocity [m/sec]. The rates, $k = 1.97$, 2.81 and 4.22 were realized in the present study.

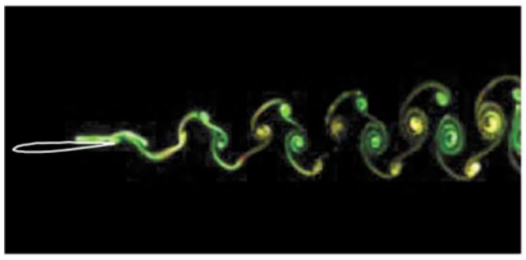
3. Results and Discussions

3.1 Vortex Flow Patterns under Sinusoidal Wave Motion

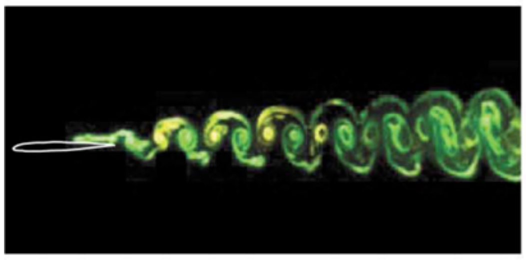
Figures 2 and 3 show the vortex flow patterns behind NACA0010 pitching along sinusoidal wave at $A = \pm 6^\circ$ around its mid- and quarter-chord axis, respectively. In Figs. 2 and 3, (a), (b) and (c), show the results at $k = 1.97$, 2.81 and 4.22, respectively.



(a) k = 1.97



(b) k = 2.81



(c) k = 4.22

Fig. 2. Vortex flow patterns at mid-chord, $A = \pm 6^{\circ}$ and sinusoidal wave.

(a) k = 1.97

(b) k = 2.81

(c) k = 4.22

Fig. 3. Vortex flow patterns at quarter-chord, $A = \pm 6^{\circ}$ and sinusoidal wave.

Four vortices rolled up regularly during one pitching cycle at k = 1.97 in Fig. 2(a). The mechanism was observed as follows; (1) Near at the bottom dead position ($\alpha = -6^{\circ}$), the vortex from the upper surface (V_{S1}) rolled up with clockwise rotation, (2) Immediately, the other vortex from the lower surface (V_{P1}) rolled up with counter clockwise rotation, (3) Near at the top dead position ($\alpha = 6^{\circ}$), the vortex from the lower surface (V_{P2}) rolled up with counter clockwise rotation, (4) Immediately, the other vortex from the suction surface (V_{S2}) rolled up with clockwise rotation. These flow patterns were similar to that behind a plunging airfoil reported by Lai and Platzer (1999) and represented the transition from the drag producing to neutral (zero drag) wake.

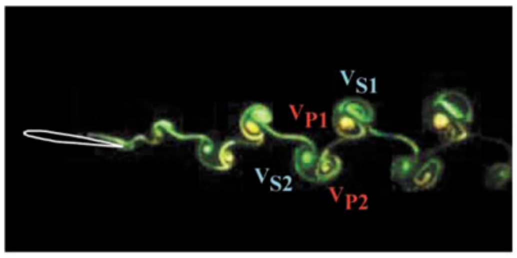
The rotations of V_{P1} and V_{S2} became stronger as the non-dimensional pitching rate increased. Finally at k = 4.22 in Fig. 2(c), the two vortices from the lower and upper surface rolled up alternately and stood in a line. This flow pattern meant neutral. When the non-dimensional pitching rate became much higher, the flow pattern turned out to be simple because a vortex was shed alternately from one side surface.

A vortex from each side surface rolled up alternately in the wake behind NACA0010 pitching around quarter-chord axis at k = 1.97 and 2.81, as shown in Figs. 3(a) and (b), respectively. The flow patterns were similar to the case of k = 4.22 in Fig. 2(c). At k = 4.22 in Fig. 3(c), the wake width became wider than the other cases because the rotation of rolled up vortices became much stronger. Especially, near the trailing edge, the upper row of vortices colored yellow had counterclockwise rotation and the lower row of vortices colored green clockwise rotation. This vortex street indicated the thrust producing vortex street.

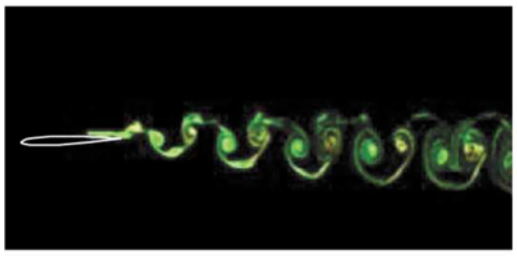
In the case of quarter-chord axis, the rotation of the rolled up vortices became stronger because the peripheral velocity at the trailing edge was larger than that in the case of mid-chord axis. Moreover, these vortices continued to grow up on the surface and separated to the wake before the trailing edge approached the dead positions. As a result, they constructed the thrust producing vortex street. This fact represented that the peripheral velocity at trailing edge played an important role to form the thrust producing vortex street.

3.2 Vortex Flow Patterns under Triangular Wave Motion

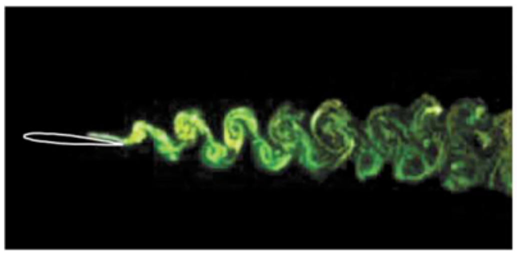
Figures 4 and 5 show the flow patterns behind NACA0010 pitching along a triangular wave at $A = \pm 6^{\circ}$ around its mid- and quarter-chord axis, respectively.



(a) k = 1.97



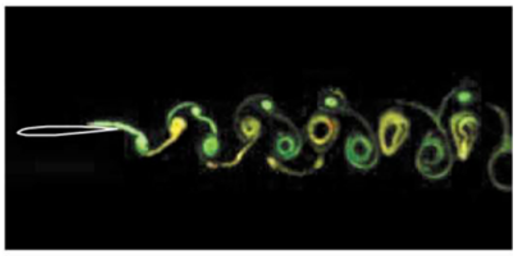
(b) k = 2.81



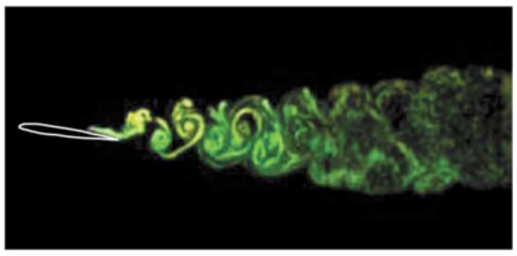
(c) k = 4.22

Fig. 4. Vortex flow patterns at mid-chord, $A = \pm 6^{\circ}$ and triangular wave.

(a) k = 1.97



(b) k = 2.81



(c) k = 4.22

Fig. 5. Vortex Flow patterns at quarter-chord, $A = \pm 6^{\circ}$ and triangular wave.

Figure 4(a) shows the flow pattern in which four vortices rolled up regularly during one pitching cycle in the pitching motion around the mid-chord axis at k = 1.97. The flow pattern of vortices was basically almost the same as that along a sinusoidal wave, as shown in Fig. 2(a), though there were two pairs of vortices such as V_{P1} + V_{S1} and V_{P2} + V_{S2}.

At k = 2.81 in Fig. 4(b), V_{P1} and V_{S2} were dominant in the wake. These vortices mainly formed a vortex street, in which the vortex from the lower surface located upper than that from the upper surface. This type of vortex street meant thrust producing. The thrust producing vortex street was also shown at k = 4.22 in Fig. 4(c).

Figures 5(a) and (b) show four vortices rolling up during one pitching cycle around quarter-chord axis at k = 1.97 and 2.81, respectively. These flow patterns were the same as that around mid-chord axis at k = 1.97 in Fig. 4(a). Similarly, V_{P1} and V_{S2} were dominant in the wake. In the pitching motion around the quarter-chord axis, even at k = 1.97 the thrust producing vortex street was formed in the flow pattern behind the pitching airfoil. At k = 4.22, the thrust producing vortex street was clearly formed, as shown in Fig. 5(c). The thrust producing vortex street was formed more clearly in the wake as the non-dimensional pitching rate increased.

In the case of triangular wave, the rolled up vortices had strong rotation and separated from the trailing edge at the both dead positions. Therefore, the thrust producing vortex street was formed in the wake more easily than in the case of sinusoidal pitching motion. Moreover, the pitching motion around quarter-chord axis formed the thrust producing vortex street more easily than around mid-chord axis even at low non-dimensional pitching rate.

3.3 Vortex Flow Patterns at $A = \pm 2^{\circ}$ and $\pm 12^{\circ}$

Figures 6 and 7 show the flow patterns behind NACA0010 pitching along triangular wave at $A = \pm 2^{\circ}$ around its mid- and quarter-chord axis, respectively.

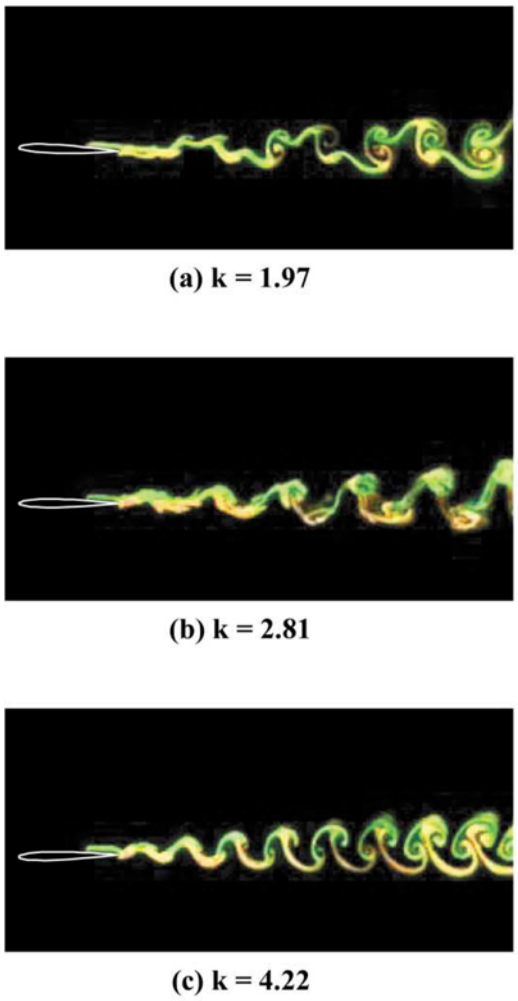


Fig. 6. Vortex flow patterns at mid-chord, $A = \pm 2^{\circ}$ and triangular wave.

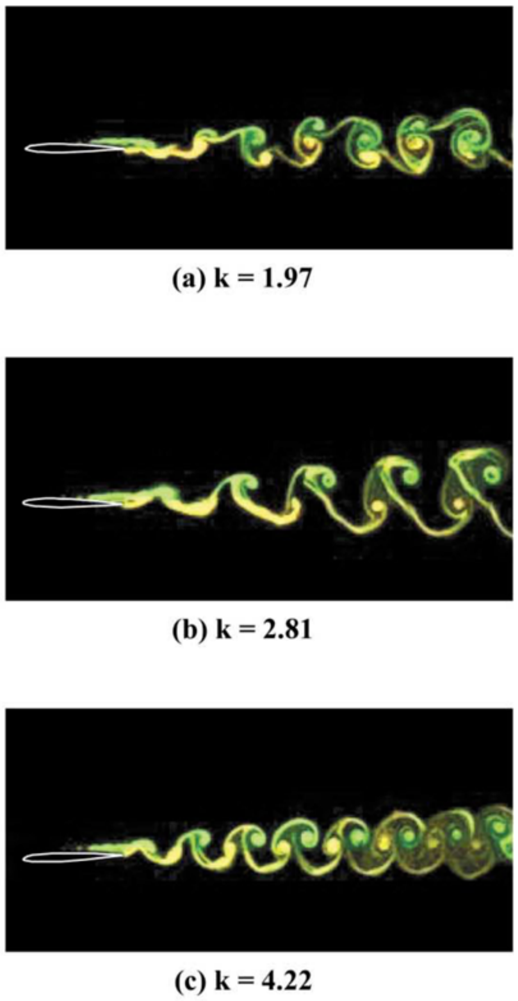


Fig. 7. Vortex flow patterns at quarter-chord, $A = \pm 2^{\circ}$ and triangular wave.

Figures 6(a) and 7(a) show the flow pattern in which four vortices rolled up regularly during one pitching cycle at $k = 1.97$ around mid- and quarter-chord axis, respectively. They are formed two pairs of vortices, similarly in Fig. 4(a). At $k = 2.81$ in Fig. 6(b) and 7(b), however, the flow patterns show the typical Karman vortex street, in which clockwise rotating vortices locate upper than counter clockwise rotating vortices. Even at $k = 4.22$ in Figs. 6(c) and 7(c), the Karman vortex street was formed. This result shows that it is impossible to construct the thrust producing vortex street in the wake even at a high pitching rate when the pitching amplitude is small.

Figures 8 and 9 show the flow patterns behind NACA0010 pitching along triangular wave at $A = \pm 12^{\circ}$ around its mid- and quarter-chord axis, respectively.

In both cases at $k = 1.97$ in Figs. 8(a) and 9(a), four vortices rolled up during one pitching cycle. Especially, in the case of the motion around quarter-chord axis, a vortex shed from the lower surface at the top dead position and another vortex from the upper surface at the bottom dead position rolled up strongly. As a result, the thrust producing vortex street was formed. At $k = 2.81$ and 4.22, the thrust producing vortex street was formed more clearly.

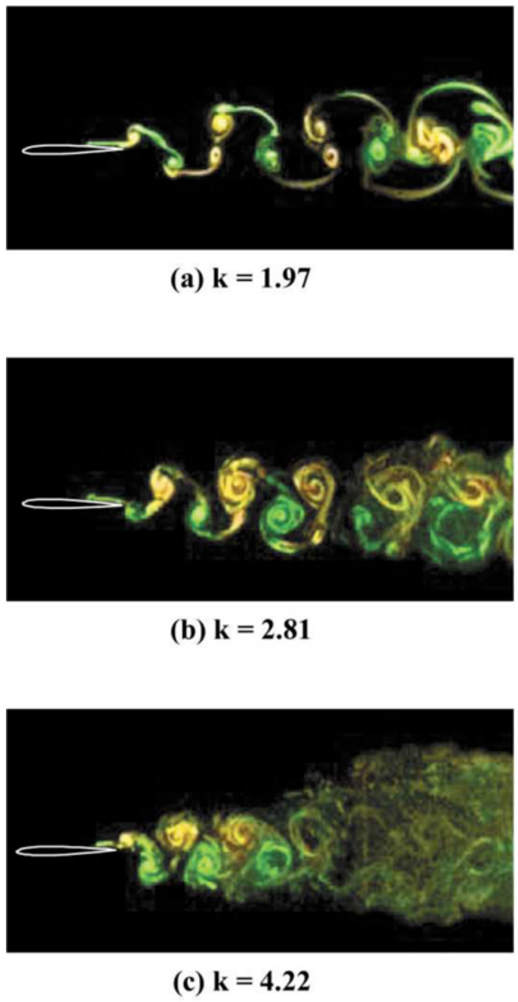


Fig. 8. Vortex flow patterns at mid-chord, $A = \pm 12^{\circ}$ and triangular wave.

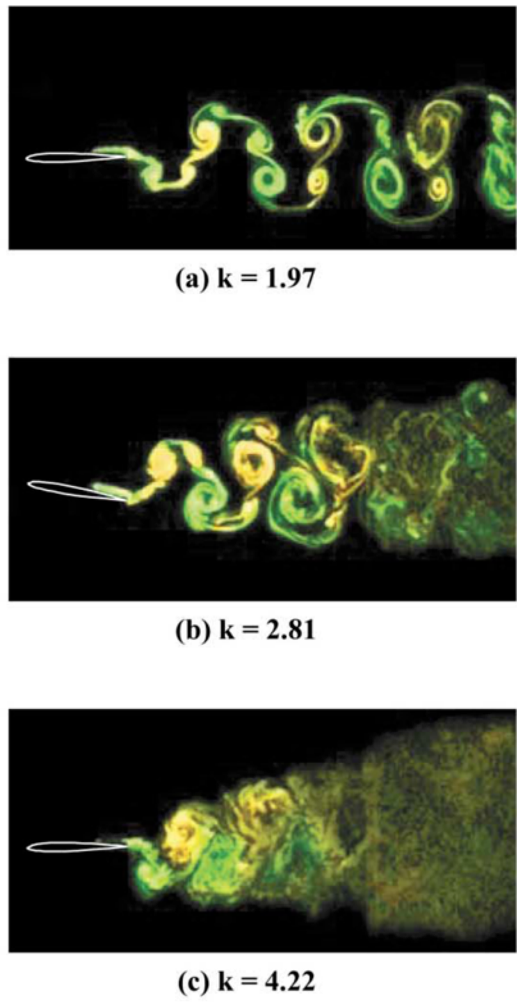


Fig. 9. Vortex flow patterns at quarter-chord, $A = \pm 12^{\circ}$ and triangular wave.

In the case of large pitching amplitude, the thrust producing vortex street could be formed easily even at $k = 1.97$.

4. Conclusion

The two-dimensional structure of the vortex flow patterns in the wake of NACA0010 pitching with higher non-dimensional pitching rate was visualized at $Re = 4.0 \times 10^3$ by using a water tunnel and two kinds of dyes.

As a result, it was possible to form the thrust producing vortex street by pitching motion at higher non-dimensional pitching rate. In the case of pitching motion around quarter-chord axis, the thrust producing vortex street could be formed in the wake more easily than in the case of the motion around mid-chord axis even at lower non-dimensional pitching rate. The peripheral velocity at the trailing edge played an important role to form the thrust producing vortex street.

In the case of pitching motion along triangular wave, the thrust producing vortex street could be formed in the wake more easily than in the case of sinusoidal wave at the same non-dimensional pitching rate. The angular acceleration at the top and bottom dead position played an important role to form the thrust producing vortex street.

In the case of small pitching amplitude, it was impossible to locate counter clockwise rotating vortices on the upper row and clockwise rotating vortices on the lower row, at an even much higher non-dimensional pitching rate. On the other hand, in the case of large pitching amplitude, the thrust producing vortex street could be formed easily even at $k = 1.97$.

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