Detailed Wake Structure behind an Elastic Airfoil*

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Abstract

An unsteady flow in a low Reynolds number region attracts attention in recent years. The authors measured vortex flow in the wake of the rigid flat plate, rigid NACA0010, elastic flat plate and elastic NACA0010 with heaving motions and evaluated accelerating flows induced by the vortex flow patterns and vortex flows in the wake of the airfoils. Furthermore, we measured dynamic thrusts acting on these airfoils with heaving motions and clarified their relations with vortex flows. Thrust producing vortex streets same as those of the airfoils can be formed in the wake of the elastic flat plate with heaving motions by giving an elasticity to the latter half of the flat plate. The dynamic thrusts that act on the rigid NACA0010, elastic flat plate and elastic NACA0010 are strongly dependent on the Strouhal number based on the trailing edge amplitude regardless of heaving amplitudes, heaving frequencies, airfoil shapes and elastic deformations.

Key words: Wake, Vortex, Elastic Airfoil, Heaving Motion

1. Introduction

A number of studies on unsteady flow at low Reynolds number regions have been performed in recent years since the Micro-Electro-Mechanical-Systems (MEMS) is developed with the aim of flow control and micro flight robot. The flow field above has also attracted significant attentions in bio-hydrodynamics for the need to understand the propulsion mechanisms of aquatic animals, birds and insects. Moreover, Micro-Air-Vehicle (MAV) and micro flight robots with these mechanisms are also being developed actively.

Recently, a study on vortex flow behind an unsteady airfoil in a low Reynolds number region has been reported. Kochesfahani visualized wakes of a pitching airfoil at Re = 12000. His result showed two- and three-dimensional structures of the wakes. Triantafyllou clarified that oscillating foils produce thrusts through development of jet-like average flow. Anderson measured fluid forces and mapped flow around a harmonically oscillating foil at zero average angle of attack. Lai and Platzer performed flow visualizations and LDV measurements of wakes of a plunging airfoil in the Reynolds numbers of 500 to 20000. Their result revealed that vortex flow patterns change from a drag producing type to a thrust producing type as non-dimensional plunging velocity increases. Ramamurti reported the vortex flow and characteristics of dynamic thrusts on flapping airfoil using a finite element incompressible flow solver. Fuchiwaki and Tanaka have visualized detailed wake structures behind a pitching airfoil and a heaving airfoil at Re = 4000 using dye flow visualizations and PIV measurements. Their result showed vortex flow patterns and jet characteristics behind the airfoils. Lewin presented a numerical model for two-dimensional flow around an airfoil undergoing heaving motions in viscous...
flow.

Meanwhile, it is known that insects and aquatic animals fly or swim by skillfully controlling wings that deform elastically and vortices generated around the body. A flow around an elastic body is treated as a coupled problem of a fluid and a structure and it has been studied mainly by numerical analyses so far. However, there are few reports that clarified vortical structures around a moving airfoil with elasticity and characteristics of their fluid forces experimentally. Heathcote et al.\(^{(15)(16)}\) reported study results of the wake of a moving body with a thin plate set on the trailing edge that deforms elastically. They revealed impacts of elastic strength on a stationary fluid and characteristics of a vortex flow, and fluid forces in the wake of a moving body with a thin plate that deforms elastically in a low Reynolds number region. However, impacts of elasticity on a flow field and differences from a flow field in the wake of a rigid airfoil have not been clarified yet.

The purpose of this study is to evaluate quantitatively the vortex flow formed in the wake of airfoils whose edge deforms elastically by a PIV measurement giving a heaving motion to the flat plate and NACA0010 in a low Reynolds number region. The authors aim at clarifying flow patterns of a vortex flow formed in the wake of the elastic flat plate and elastic NACA0010, their vorticity distributions and the accelerating flow induced by the vortex flow. Moreover, we aim at understanding the impacts of elasticity on a vortex flow of the wake by comparing the vortex flow in the rigid flat plate and that in the wake of the rigid NACA0010 airfoil.

Nomenclature

\[
\begin{align*}
    a & : \text{heaving amplitude} \\
    b & : \text{maximum trailing edge amplitude} \\
    c & : \text{chord length} \\
    C_T & : \text{thrust coefficient} \\
    f & : \text{heaving frequency} \\
    l & : \text{span length} \\
    Re & : \text{Reynolds number based on chord length} \\
    St & : \text{Strouhal number based on the maximum trailing edge amplitude} \\
    u & : \text{flow velocity in x direction} \\
    V_0 & : \text{main flow velocity} \\
    x & : \text{direction for main flow} \\
    y & : \text{vertical direction for main flow}
\end{align*}
\]

2. Experimental setup

2.1 Test airfoils

Figure 1 shows shape of the airfoil used for our experiment. Figures (a), (b), (c) and (d) show the rigid flat plate, rigid NACA0010, elastic flat plate and elastic NACA0010, respectively. Chord length and wing span length are \(c = 0.06\) m and \(l = 0.20\) m, respectively. The maximum thickness of the rigid flat plate, rigid NACA0010, elastic flat plate and elastic NACA0010 are 2.0 mm, 6.0 mm, 1.5 mm and 6.0 mm, respectively. The rigid flat plate and rigid NACA0010 shown in Figures 1(a) and (b) are made of aluminum and duralumin, respectively.

The blade nose of the elastic flat plate and elastic NACA0010 is made of a rigid body (stainless alloy) and its blade tail is made of an elastic body as shown in Figure 1 (c) and (d). The ratio of the rigid and elastic parts is 1:2. The elastic body of the elastic flat plate is silicon gum, and the Young’s modulus and solidity are 1.5 [MPa] and 50, respectively. On the other hand, the elastic body of the elastic NACA0010 is silicon gum, and the Young’s modulus and solidity are 0.5 [MPa] and 10, respectively. The authors confirmed that both elastic airfoils had a sufficient elastic deformation and did not have a three-dimensional
Fig. 1 Shapes of the airfoil used for our experiment

Fig. 2 Elastic deformation for the elastic airfoil

Fig. 3 Deformation volume of the trailing edge of the elastic flat plate and elastic NACA0010 in the deformation

When giving a heaving motion of Equation (1) to the test airfoils, the elastic deformation of the elastic airfoils shown in Figure 2 was seen. The heaving amplitude of the heaving airfoil was 12mm constantly.

\[ y = a \sin(2\pi ft) \]  

(1)

Figure 3 shows deformation volume of the trailing edge of the elastic flat plate and elastic NACA0010 deformed in running water. The horizontal axis indicates Strouhal number based on maximum trailing edge amplitude is defined as Equation (2) and the vertical axis indicates values for which maximum deformation volume of the trailing edge was nondimensionalized by heaving amplitude.

\[ St = \frac{2bf}{V_0} \]  

(2)
The deformation volume of the trailing edge of both elastic airfoils increases with an increase of the Strouhal number. In $St > 0.69$, the deformation volume of the trailing edge becomes about 1.5 times as great as the amplitude however it decrease after that. This is because the frequency of the heaving motion is high and the deformation of the trailing edge cannot follow it. Moreover, it is understood that elastic deformations of the elastic NACA0010 are small since Young's modulus and solidity of the elastic flat plate are low compared with those of the elastic flat plate.

### 2.2 PIV measurement system

PIV measurement equipment consisted of a water tunnel, test airfoil, excitation device, water-cooled Ar-ion laser, plane mirror and high-speed camera as shown in Figure 4. The dimension of the test section in the water tunnel was 0.7 [m] in length, 0.3 [m] in width and 0.2 [m] in depth. The main flow velocity of the water tunnel was 0.067 m/s constantly. ORGASAL (Kanomax) was used as a tracer particle with a diameter of approximately 50 µm. The excitation device consisted of by a DC servomotor and a ball screw. Rotary motions of the DC servomotor were transformed into translational motions by the ball screw. The clearance between the bottom of the water tunnel and the test airfoil was approximately 1.0 mm and the rolling up of three-dimensional vortices were controlled by setting a flat plate in the upper side of the water tunnel. We measured a vortex flow structure formed in the wake of the moving airfoil by three chord lengths. For all the airfoils, the Reynolds numbers based on the chord length was $Re = 4000$.

### 3. Results and discussion

#### 3.1 Vortex flow in the wake of the heaving airfoil and vorticity contour

Vorticity contours obtained from the wakes of the heaving airfoils with $St = 0.36$ and 0.64 are shown in Figures 5 and 6, respectively and the rigid flat plate, rigid NACA0010, elastic flat plate and elastic NACA0010 are shown in Figures (a), (b), (c) and (d), respectively. These results are instantaneous values at $y = 0.0$ when the airfoils heaved from the top dead point to the bottom dead point. The values in the figures indicate instantaneous vorticity. Positive and negative indicate counterclockwise and clockwise of a vortex, respectively.

As shown in Figures 5(a) and 6 (a), the flow separation occurs from the leading edge of the rigid flat plate and the flow field around the rigid flat plate is disturbed however a thrust producing vortex street, whose array is opposite from that of a Karman vortex street, is
formed in the wake of the rigid flat plate though it is not clear \(^{(9)(10)(11)(12)(13)}\). On the other hand, as shown in Figure 5(b) and 6(b), it is clearly observed that a thrust producing vortex street is formed in the wake of rigid NACA0010. Moreover, instantaneous vorticity of the vortex forming the thrust producing vortex street is high. It is clarified that when giving heaving and pitching motions to NACA0010, a clear thrust producing vortex street is formed in the wake of the airfoil with an increase of the Strouhal number. Moreover, the instantaneous vorticity of the vortices in a thrust producing vortex street formed in the wake of the airfoil with heaving motions is higher than that of the pitching airfoil therefore it is
clarified that a great accelerating flow is formed in the wake of the airfoil and a great dynamic thrust acts on the airfoil\textsuperscript{(12)(13)}. Furthermore, the vortex streets on the heaving and
pitching airfoils at $St > 0.5$ are formed extremely close therefore it is also clarified that a vortex street is formed inclining to the main flow by an interference of vortices rolling up from the pressure and suction sides (8)(10).

As shown in Figure 5(c), in the wake of the elastic airfoils, it was confirmed that a clear thrust producing vortex street is formed in the wake of the airfoil even at a comparatively low Strouhal number such as $St = 0.36$. Moreover, the clear thrust producing vortex street is formed in the wake of the elastic flat plate with an increase of the Strouhal number as shown in Figure 6(c). Similarly, the clear thrust producing vortex street is formed in the wake of the elastic NACA0010 as shown in Figures 5(d) and 6(d). Especially, instantaneous vortices forming the thrust producing vortex street in the wake of the elastic NACA0010 with $St = 0.64$ is extremely large. This result indicates that the clear thrust producing vortex street can be formed by giving elasticity to the latter part of airfoils. Furthermore, the vortices formed in the wake of an elastic airfoils always separate from the trailing edge at the top and bottom dead positions of a heaving motion therefore the vortex street is not close different from that of rigid NACA0010.

3.2 Accelerating flow formed in the wake of the heaving airfoil

Figure 7 shows a mean velocity profile in x direction one-chord length behind the heaving airfoil for one cycle. Figure (a), (b), (c) and (d) indicate results of the rigid flat airfoil, rigid NACA0010, elastic flat plate and elastic NACA0010, respectively. The horizontal and vertical axes indicate nondimensionalized flow velocity $u/V_0$ and airfoils’ positions $y/c$, respectively. $u/V_0 > 1.0$ indicates an accelerating flow. The orange, red and blue solid lines in the figure indicate results of $St = 0.36$, 0.50 and 0.64, respectively.

In the wake of the rigid flat plate, as shown in Figure 7 (a), an accelerating flow is seen at $St = 0.36$ and 0.50. However an accelerating flow becomes small at $St = 0.64$ because the thrust producing vortex street formed in the wake of the rigid flat plate is not clear and the flow field around the rigid airfoil is disturbed in a high Strouhal number region. In the wake of rigid NACA0010, as shown in Figure 7 (b), a formation of a clear accelerating flow is seen. Moreover, it is seen that the accelerating flow becomes large with an increase of the Strouhal number. At $St = 0.64$, the accelerating flow became twice as great as the main flow. The vorticity of vortices in the thrust producing vortex street was formed in the wake of the airfoil with an increase of the Strouhal number therefore the accelerating flow induced by the vortices becomes large. Moreover, as a result, it was revealed that dynamic thrust acting on the airfoil increased with an increase of the Strouhal number. When the Strouhal number becomes even higher, the interval of vortices forming a thrust producing vortex street becomes close as mentioned above therefore the vortex street is formed inclined to the main flow (8)(10). Furthermore, it was clarified that the mean velocity profile of one cycle in the accelerating flow in the wake of the airfoil was formed inclined to the main flow as a result (8)(10).

As shown in Figure 7 (c), it is clearly seen that a clear accelerating flow is formed in the wake of the elastic flat plate. The accelerating flow becomes large with an increase of the Strouhal number and it becomes twice as great as the main flow at $St = 0.64$. Even in the case of the flat plate, the accelerating flow in the wake becomes larger than that of rigid NACA0010 only by an elastic deformation on the tail of the flat plate. As shown in Figure 6(c), in the wake of the elastic flat plate, a thrust producing vortex street is formed with vortices having great vorticity. Furthermore, in the main flow of a vortex street forming a thrust producing vortex street, the vortex interval in the vertical direction is comparatively large and an interference of the vortices rolling up from the pressure and suction sides is small therefore the accelerating flow induced by these vortices becomes twice as large as the main flow.

As shown in Figure 7 (d), it is clearly seen that a clear accelerating flow is formed in
Fig. 8 Mean values of dynamic thrust acting on the heaving airfoils for one heaving cycle

the wake of the elastic NACA0010. Similarly in elastic flat plate, the accelerating flow becomes large with an increase of the Strouhal number. As shown in Figure 3, elastic deformations of the elastic NACA0010 were not great therefore great accelerating flow was not obtained. The authors presume that a slightly greater accelerating flow could be obtained by an elastic NACA0010 with the Young's modulus and solidity same as those of an elastic plate.

For rigid NACA0010 and the elastic NACA0010, some differences due to magnitudes of vorticity and their positions are seen in the accelerating flow formed in the wake of the airfoils however there are almost no differences in their tendencies. However, tendencies of flow fields and accelerating flow are significantly different in the rigid flat plate and the elastic flat plate. In the rigid flat plate, the flow that separation occurred from the leading edge affects the wake of the rigid flat plate. However in the elastic plate, turbulence caused by the flow separation from the leading edge is suppressed by the formation of vortices with strong revolutions in the wake with an elastic deformation of the trailing edge.

3.3 Dynamic thrust acting on heaving airfoils

Figure 8 shows mean values of dynamic thrust acting on the heaving airfoils for one heaving cycle. The dynamic thrust acting on heaving airfoils were measured by a six-axes sensor set between the test airfoil and the DC servomotor\(^{11)}\(12)\)\(^{13}\). The horizontal and vertical axes indicate Strouhal numbers and dynamic thrust, respectively. ◇, ■, ● and ▲ indicate results of the rigid flat plate, rigid NACA0010, elastic flat plate and elastic NACA0010, respectively.

For all the airfoils, it is seen that dynamic thrust tends to increase with an increase of the Strouhal number. Moreover, the dynamic thrust acting on the rigid flat plate, elastic flat plate and elastic NACA0010 depend on Strouhal number strongly and is independent of the elastic deformation.

As shown in Figure 7, the results are adequate judging from the fact that the accelerating flow is formed in the wake of the airfoils regardless of airfoil shapes and elastic deformations, the authors suppose. It has been found that even in the case of the rigid flat plate with its separation point fixed, it is sufficiently possible to produce thrusts equivalent to those of an airfoil by elastic deformations on the trailing edge.

For the rigid flat plate, tendencies same as those of other airfoils were not obtained. On the rigid flat plate, the separation point of the leading edge is fixed. Moreover, it does not
have elastic deformations on the rear side of the flat plate. Therefore, as shown in Figure 6(a), when the Strouhal number increases, the thrust producing vortex street formed in the wake of the heaving rigid flat plate is not clear and the flow field around the rigid flat plate is disturbed therefore thrusts acting on the flat plate tend to be different from those of other airfoils, the authors presume.

4. Concluding remarks

The authors measured vortex flow in the wake of the rigid flat plate, rigid NACA0010, elastic flat plate and elastic NACA0010 with heaving motions and evaluated accelerating flows induced by the vortex flow patterns and vortex flows in the wake of the airfoils. Furthermore, we measured dynamic thrusts acting on these airfoils with heaving motions and clarified their relations with vortex flows.

Thrust producing vortex streets same as those of the airfoils can be formed in the wake of the elastic flat plate with heaving motions by giving an elasticity to the latter half of the flat plate. Moreover, the flat plate with elastic deformations and the vortices forming thrust producing vortex streets in the wake of the airfoil have relatively high vorticities. Furthermore, they separate from the top and bottom dead positions of the heaving motions therefore vortex streets are not formed closely.

The dynamic thrusts that act on the rigid NACA0010, elastic flat plate and elastic NACA0010 are strongly dependent on the Strouhal number based on the trailing edge amplitude regardless of heaving amplitudes, heaving frequencies, airfoil shapes and elastic deformations. Vortex flow patterns of thrust producing vortex streets formed in the wake of these airfoils and their vorticities are different however the accelerating flow formed in the wake of the airfoils and dynamic thrusts are strongly dependent on the Strouhal number.

References


