Effect of an Airfoil Profile on Dynamic Lift Generation with Impulsive Incidence Variation

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Abstract: The purpose of this study is to investigate the relationship between unsteady fluid forces and airfoil profiles. It is necessary to know the unsteady properties determined from the vortex dynamics, as unsteadiness is known to increase the lift force. In this study, by using a rectangular airfoil and a discoid airfoil, the angle of attack of the airfoil was impulsively changed from 0° to an angle set beyond the static stall angle. When the airfoil was raised to form a large angle of attack, a delay of the stall was observed, and a high $C_{L_{\text{max}}}$ was attained. Also, $C_{L}$ gradually decreased after the airfoil stopped, and the value of $C_{L}$ asymptotically came to that of the static condition. For the discoid airfoil, the decrement of $C_{L}$, just after the airfoil stopped, was suppressed in contrast to the rectangular airfoil.

Keywords: Fluid dynamics, Flow visualization, Airfoil, Unsteady fluid force, Vortex dynamics

1. Introduction

The wings of traveling birds and insects execute complex motions whose most obvious component is flapping, whereas for a fishtail, the most obvious component is pitching [1, 2]. The propulsive forces of these animals are related to the unsteady fluid forces that are accompanied by the movement of vortices [3, 4], which are subject to the three-dimensionality of airfoils [5]. It has been reported that the behavior of tip vortices generated from the tips of three-dimensional airfoils is related to stall characteristics and unsteady lift [6, 7]. To understand the unsteady phenomena, it is necessary to study the unsteadiness and three-dimensional characteristics of airfoils in model movements.

Wagner [8] analyzed the generation of dynamic lift of airfoils by utilizing a two-dimensional potential theory, which is called the Wagner theory or the Wagner problem. Moreover, Jones [9] expanded it into a three-dimensional finite wing and calculated the unsteady lift functions for wings with a finite aspect ratio.

In this study, the effect of the airfoil shape on unsteady fluid forces is investigated by using a three-dimensional airfoil whose angle of attack is impulsively varied. A discoid airfoil is adopted as an experimental model, and it was used in the previous study [6] that measured the dynamic lift and precisely visualized the vortex structure. For comparison, a rectangular airfoil was also tested. The main difference between a discoid airfoil and a rectangular one is the induced velocity at the edge when the incidence is impulsively varied. To illustrate, the velocity of a rectangular airfoil is constant all along the straight leading edge, while a discoid counterpart changes its velocity along the edge due to its curvature. The purpose of this study is to investigate the influence on the unsteadiness of the induced velocity that is changed by the airfoil profile.

Fluid force measurements and smoke wire flow visualization were carried out for two types of airfoils when the angle of attack was impulsively changed from 0° to the terminal angle in a wind tunnel.

2. Experimental Apparatus and Methods

The experiments were performed in a low-speed wind tunnel, and Fig. 1 shows the schematic diagram of the experimental setup and the coordinate system. The inlet dimensions of the test section are 300 × 300 mm, and the origins of the coordinates $X$, $Y$, and $Z$ are defined as the center of the airfoil. The tested airfoils are shown in Fig. 2. The discoid airfoil was made by rotating the profile of a part of a NACA0015 cross-
section, where that part is from the leading edge to the maximum thickness, and its maximum thickness is 37.5 mm. In order to discuss the three-dimensional model effect on unsteady fluid forces, the NACA0012 profile was adopted as a typical rectangular airfoil with a thickness of 22.5 mm, as many researchers also investigated the same profile. Both airfoils have a chord \( c \) and a span of 150 mm, respectively.

The angle of attack \( \alpha \) is changed from 0° to the terminal angle by a stepping motor with a 0.072° per step. Three terminal angles were adopted in this study. Also, load cells (LVS-500GA, KYOWA) were used to measure the lift forces. In the static experiments, the angle of attack was increased (upstroke) or decreased (downstroke) by a c 1.44° angular step. The sampling rate of lift measurements is 2500 samples per second, and through each experimental run, 1000 samples were detected for each angle. The measurement error was within ±3%. Also, the lift for each angle was calculated by averaging five experimental runs. In the dynamic lift measurements, the airfoil movement was given at rapid angle of attack changes. In this experiment, impulsive incidence variation is an unsteady phenomenon that starts and stops rapidly at the terminal angle. The measurement error under the dynamic condition was within ±4%. Figure 3 shows the temporal change of the angle of attack. The horizontal axis represents the nondimensional time \( t U_0 / c \), where \( t \) is the time after the start of the airfoil movement, and \( U_0 \) is the freestream velocity in the wind tunnel. The dimensionless rise time \( T^* \) is defined as

\[
T^* = \frac{\alpha \ t}{U_0 / c}
\]

where \( \mu \) is the viscosity of the air. In this study, \( Re = 3.0 \times 10^4 \). For the visualization of the flow field, the smoke wire method was used. The wire was placed at \( X/c = 1.0 \) and \( Y/c = 0 \).

3. Results and Discussion

3.1 Fluid force characteristics

Figure 4 shows the lift curves under static conditions. The upstroke and downstroke indicated in the figure denote the increment and decrement of the angle of attack, respectively. The stall angles for the discoid airfoil and the rectangular one were 20.2° and 31.7°, respectively. The hysteresis was observed for the discoid airfoil in Fig. 4(a), while the results of the upstroke and downstroke for the rectangular airfoil were consistent.

Figure 5 shows the lift coefficients under unsteady conditions. The airfoil movement was given beyond the stall angle as rapid angle of attack changes, and the dimensionless rise time \( T^* \) was 5.0. The solid line represents the static lift coefficient at the same angle of attack obtained from the dimensionless time \( t U_0 / c \) of the airfoil movement. The results of the discoid airfoil experiments are shown in Fig. 5(a). The terminal angle for the discoid airfoil was 25.9°.
When the airfoil incidence was raised to the terminal, a higher value of $C_{L_{\text{max}}}$ was attained under the unsteady conditions than when under the static ones. Furthermore, the rectangular airfoil case is shown in Fig. 5(b). The terminal angle for the rectangular airfoil was 36.0°. When the rectangular airfoil incidence was raised to the terminal, a bigger lift force was also observed. Both the value of $C_{L}$ for the discoid airfoil and that for the rectangular airfoil attained the maximum shortly after the airfoil stopped and they asymptotically reached those of the static condition. In the case of the discoid airfoil, the decrement of $C_{L}$ just after the airfoil stopped was suppressed in contrast to the rectangular airfoil.

Temporal changes in the percentage of the lift coefficient divided by their static counterpart when $T^* = 5.0$ are shown in Fig. 6. The red line is of the rectangular airfoil, and the blue line is of the discoid one. The discoid airfoil is above the rectangular one when $5.0 \leq tU_0/c \leq 20.0$, and the unsteady aerodynamic characteristics of the discoid airfoil with impulsive incidence variation are effective. The reason will be discussed with the results of the flow visualization in Section 3.2.

3.2 Flow field visualization

The visualized flow field on the upper surface of the discoid airfoil is shown in Fig. 7. Figure 7(a) shows the instantaneous photograph in the $X$-$Z$ plane at $\alpha = 25.9^\circ$ under the static condition. The flow separation occurred from the leading edge of the airfoil and the reattachment on the upper surface was not observed. Figure 7(b) shows the flow under the dynamic condition when $tU_0/c = 5.0$ and $\alpha = 25.9^\circ$. The smoke flow along its upper surface was visualized. The smoke showed no large separation. The wake under the dynamic condition was narrower than when without variation at the same incidence.

Figure 8 shows the flow around the rectangular airfoil, and Fig. 8(a) was taken under the static condition when $\alpha = 36.0^\circ$.
36.0°. Flow separation from the upper surface was visualized. Under the static condition, the typical airfoil showed the flow separation and its large wake. Consequently, Fig. 8(b) was taken when \( tU_0 / c = 5.0 \) and \( \alpha = 36.0° \), and the separated flow from the upper surface was observed in contrast to the discoid airfoil.

It can be confirmed that the separation area with incidence variation is narrower than that without variation at the same incidence. Also, it seems that the flow near the upper surface with incidence variation tilts downward and is obviously attached to the surface and that the substantial incidence becomes less than when under the static condition. At these incidences under the static condition and from the results shown in Fig. 5, it can be seen that the flow is separated. So, it is presumed that the temporary flow around the airfoil increases the lift force as a result of decreasing its substantial incidence and suppressing flow separation.

Figures 9 and 10 shows the visualized Y-Z cross-section of the airfoils where \( X/c = 1.0 \). In the figures, the outline of the airfoil is represented with the red dash-dotted line. The visualized Y-Z cross-section of the wake of the discoid airfoil when \( tU_0 / c = 5.0 \) and \( \alpha = 25.9° \) is shown in Fig. 9(a). It is seen from Fig. 9(a) that tip vortices are visualized by dense smoke. In Fig. 9(d), the smoke flow is expanded or dissipates due to the weakened tip vortex. After that, the tip vortex collapses. Also, Fig. 10(a) shows the tip vortex pair in the wake of the rectangular airfoil when it stops. It is most clearly identified, and it immediately started collapsing (Figs. 10(b) and (c)). It was also observed that the duration of the discoid airfoil was longer than that of the rectangular one, which is consistent with the decrement suppression in the lift coefficient with the dimensionless time (Fig. 5).

### 3.3 Effect of angular velocity of a discoid airfoil on pre- and post-stall flow

Figure 11 shows the temporal lift coefficient \( C_L \) change versus the dimensionless time for the discoid airfoil when the terminal incidence was 17.4° and \( T^* = 2.5, 5.0, \) and 20.0. This incidence is estimated as the angle less than the stall angle (pre-stall) from the previous study. The dash-dotted line in the figure is the static lift coefficient, \( C_L = 0.4 \) (see Fig. 4(a)). All the maximum values of \( C_L \) became slightly larger than 0.4, which showed that the impulsive incidence variation obtained
little lift gain under the pre-stall condition. Figure 12 shows the change of $C_l$ when the terminal incidence is 25.9° (post-stall). The dash-dotted line in the figure is the static lift coefficient, $C_l = 0.3$ (see Fig.4(a)). Each maximum value obtained in this study became much larger than when under the static condition. So, it seems that the lift gain was obtained under the post-stall condition in the range of $2.5 \leq T^* \leq 20.0$.

4. Conclusions
In this study, unsteady fluid forces acting on airfoils and vortical fields during impulsive incidence variation were measured to investigate the effect of the shapes of airfoils and the relationship between unsteady fluid forces and the vortex behavior. The results are summarized as follows:

1. High lift was attained beyond the static stall angle for the airfoil with the impulsively varied incidence. $C_l$ gradually decreased after the airfoil stopped, and the value of $C_l$ asymptotically reached that of the static condition.

2. In the case of the discoid airfoil, just after the airfoil stopped, the decrement of $C_l$ was suppressed in contrast to the rectangular airfoil.

3. The tip vortex shed from the discoid airfoil kept its structure for a longer duration in comparison with the rectangular airfoil, which is consistent with the temporal decrement suppression of the lift coefficient.

Nomenclature

- $A$ plan area [m$^2$]
- $c$ chord length [m]
- $C_l$ lift coefficient [-]
- $Re$ Reynolds number [-]
- $t$ time [s]
- $t_a$ time period during which the angle of attack of the model is varied [s]
- $T^*$ dimensionless rise time [-]
- $U_0$ freestream velocity [m/s]
- $\alpha$ angle of attack [°]
- $\mu$ viscosity [Pa s]
- $\rho$ density [kg/m$^3$]

References


