Flow Visualization of an Oscillating Airfoil with Sawtooth Trailing Edge

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Introduction

THERE has been considerable interest in unsteady aerodynamics due to its application in such areas as wind turbines, helicopters, and maneuvering aircraft. A prime motivator in unsteady aerodynamics is the possibility of airfoil lift enhancement and stall delay. According to McCroskey,[1] the maximum lift of an airfoil undergoing pitch oscillation (in steady freestream) can greatly exceed the nonoscillatory lift. In oscillating freestream flow conditions (with stationary airfoil), Gursul et al.[2] report a phenomenal tenfold increase in the lift coefficient during some parts of the oscillating time period. By properly controlling the oscillation period, they were also able to increase the average lift value by a factor of 2.

A recent development in applied aerodynamics (i.e., stationary airfoil in steady freestream) is a device called the Gurney flap.[3] This flap consists of a short flat plate (about 2% of chord length) placed along the trailing edge of the airfoil and oriented perpendicular to the trailing edge on the pressure side. Myose et al.[4] found that the lift is significantly increased by using a Gurney flap. Although the flap is small in size, its presence not only alters the flow near the trailing edge but also affects the conditions over the entire airfoil. In another study, Gai and Sharma[5] three-dimensionally modified the trailing edge of an airfoil using a sawtooth shape for the trailing edge. They found that the base drag was reduced for such a three-dimensionally modified trailing-edge airfoil. Results from both the sawtooth trailing-edge airfoil and the Gurney flap suggest that the flow conditions at the trailing edge have a significant influence on the performance of an airfoil.

Although research continues in the two separate areas of trailing-edge modification and unsteady aerodynamics, an investigation that combines the two has not been undertaken. Crighton[6] points out that there is a general lack of understanding about the trailing-edge flow behavior of oscillating airfoils. Thus, the goal of this experiment is to obtain near-wake flow visualization information for oscillating airfoils with modified trailing-edge shapes.

Experimental Method

The experiment was conducted in the National Institute for Aviation Research 60 × 90 cm water tunnel at Wichita State University. The standard NACA 0011 airfoil used in the experiment had a 20 cm chord. Multicolor (food coloring) dye injection was provided on the airfoil through nine ports located at the midchord location with each port spaced 1.05 cm apart in span. Interchangeable flaps extended the airfoil chord length and modified the trailing-edge shape. The sawtooth shape incorporated a 4.2-cm extension at the sawtooth tip, no extension at the sawtooth valley, and spanwise distance between sawtooth tips of 8.4 cm. Other flaps included a no-extension standard NACA 0011 profile, a flat plate extension, and a sawtooth/flat plate combination. The results for these other cases are discussed in detail in Myose and Iwata.[7]

Airfoil pitch oscillation about the quarter chord was accomplished using a cam mechanism driven by a dc motor. Airfoil oscillation amplitudes were either $\Delta\alpha = \pm 2$ or ± 4 deg about a mean angle of zero (i.e., $\alpha_{\text{mean}} = 0$ deg). The nondimensional controlling parameter relevant in unsteady aerodynamics is the reduced frequency K given by $K = \pi f c / U_\infty$ where f is the airfoil oscillation frequency, c the airfoil chord length, and U_∞ the freestream velocity. Reduced frequencies of $K = 0.75$, 1.5, and 2.25 were tested in this investigation. For each case, plan view and side view images of the dye streak flow patterns were recorded using a VHS video camera. A freestream velocity of $U_\infty = 12.2$ cm/s resulting in a chord Reynolds number of 2.8×10^4 was used throughout the experiment.

Results

Under steady conditions (i.e., stationary airfoil), side views of the dye streak flow pattern show counter-rotating Kármán vortex pairs shed from the airfoil. With the sawtooth trailing-edge configuration, the vortices are shed slightly earlier in time at the valley region when compared with those shed from the tip region. Consequently, there is a small phase difference between vortices shed from these two different regions. Nevertheless, the vortex shedding frequency can be easily determined. The measured shedding frequency is 3.16 ± 0.02 Hz with the sawtooth trailing-edge configuration. This corresponds to a Strouhal number of 0.58 that is less than the 0.65 value measured with the standard NACA 0011 (no-extension) airfoil. Some work on circular cylinder flows[8] suggests that the drag coefficient is directly related to the inverse of the Strouhal number. This implies that the sawtooth configured stationary airfoil has a larger drag coefficient than the two-dimensional trailing-edge case. This is in contrast with the results of Gai and Sharma,[5] who found a reduction in drag using the sawtooth-shaped configuration.

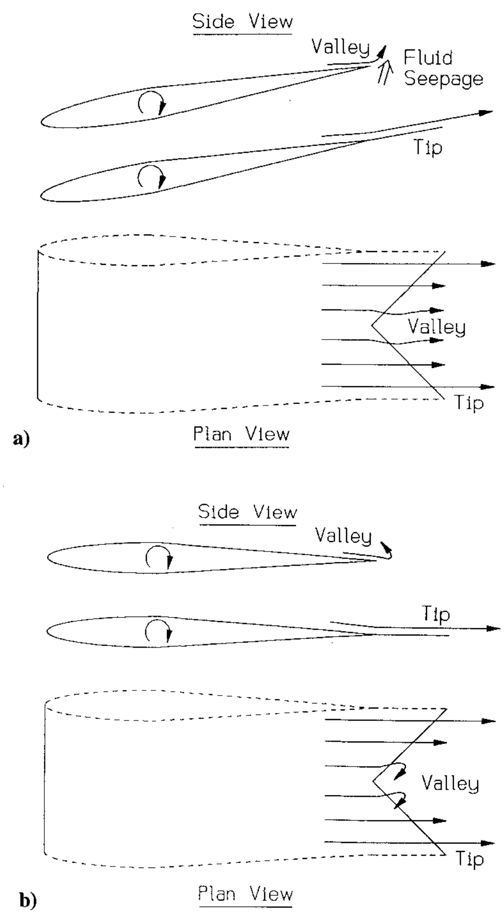

Fig. 1 Envisioned bound vortex formation process: a) start of pitch-up phase at peak negative angle of attack and b) middle of pitch-up phase at zero angle of attack.

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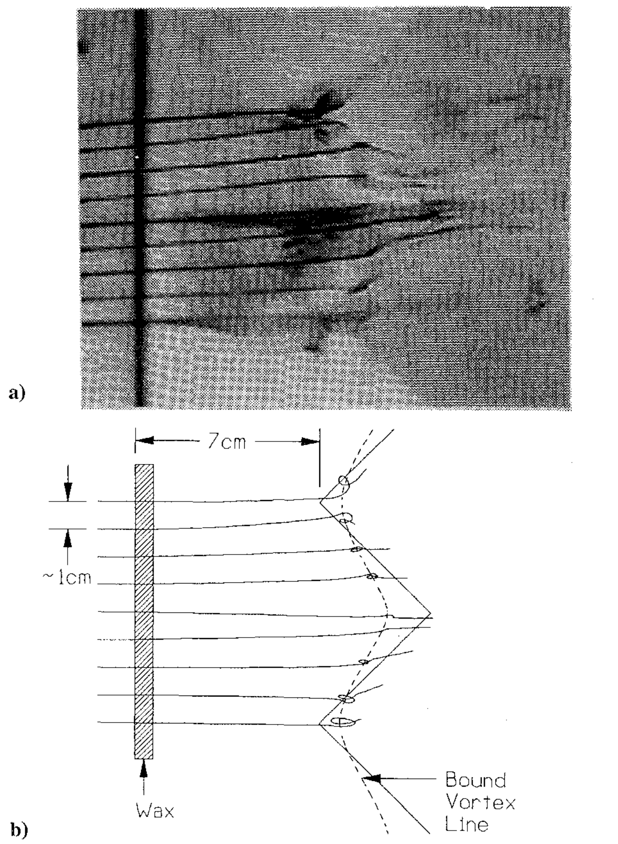

Fig. 2 Plan view (upper surface) flow visualization for the large sawtooth configuration at $K = 1.5$, $\alpha_{mean} = 0$ deg, $\Delta\alpha = \pm 2$ deg, and instantaneous $\alpha = +2$ deg: a) flow visualization result and b) envisioned bound vortex.

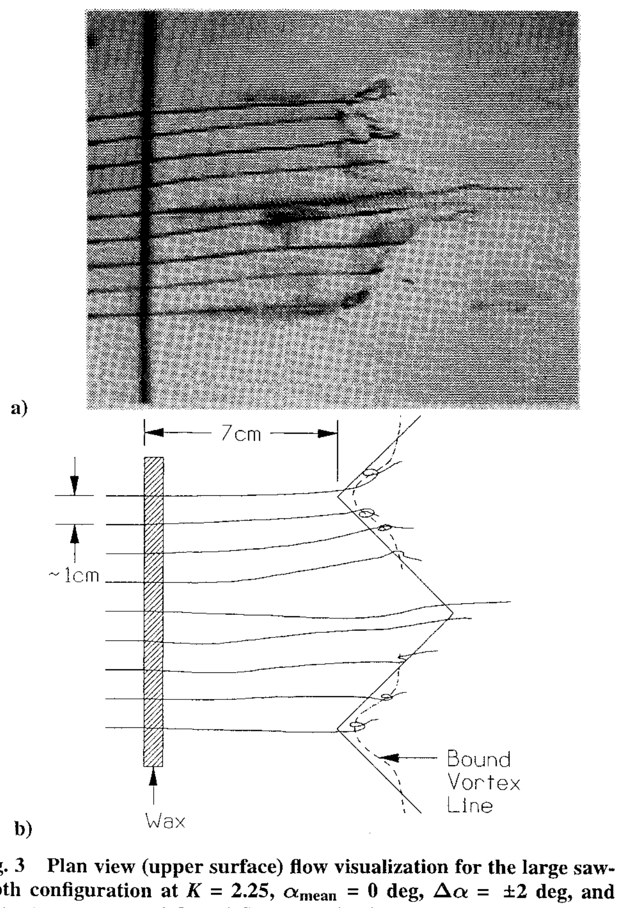

Fig. 3 Plan view (upper surface) flow visualization for the large sawtooth configuration at $K = 2.25$, $\alpha_{mean} = 0$ deg, $\Delta\alpha = \pm 2$ deg, and instantaneous $\alpha = +2$ deg: a) flow visualization result and b) envisioned bound vortex.

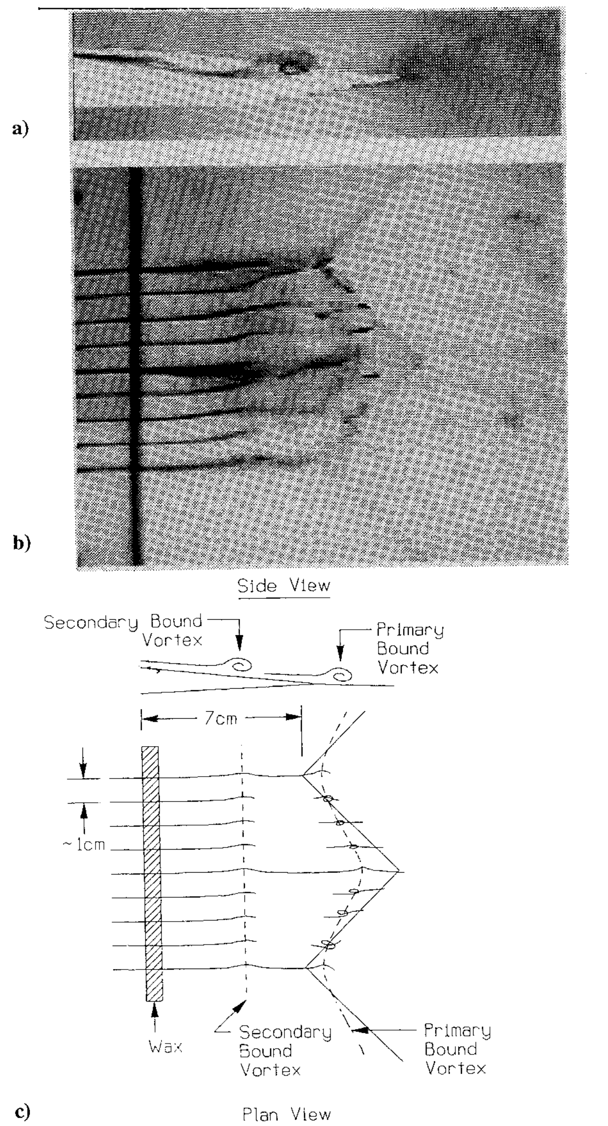

Fig. 4 Plan and side view flow visualization for the large sawtooth configuration at $K = 1.5$, $\alpha_{mean} = 0$ deg, $\Delta\alpha = \pm 4$ deg, and instantaneous $\alpha = +4$ deg: a) side view result, b) plan view (upper surface) result, and c) envisioned bound vortex system.

When the large sawtooth configuration is pitch oscillated, the resulting flow behavior becomes three dimensional and quite complex. Figure 1a shows schematically the flow behavior at the start of airfoil pitch-up (i.e., at peak negative angle of attack moving towards $+\alpha$). Dye streaks passing over the valley region are disturbed due to a seepage of fluid moving from the lower to the upper surface. Dye streaks over other spanwise regions are not disturbed because the flow is turned parallel to the airfoil chordline by the flat extension. As shown schematically in Fig. 1b, the fluid seepage motion results in reserved flow (i.e., a circulatory motion) at the valley region by the time zero angle of attack is reached. As the airfoil continues to pitch up, the circulatory motion spreads along the trailing edge from valley to tip, resulting in the formation of a bound vortex. Figure 2 shows the plan view flow visualization result at peak positive angle of attack ($\alpha = +2$ deg) for moderate reduced frequency ($K = 1.5$). In this case, the bound vortex is located slightly upstream of the trailing edge at the tip region. When the airfoil begins to pitch down (i.e., moving towards $-\alpha$), the vortex in the valley region is shed immediately, whereas the vortex in the tip region remains over the extension until $\alpha \approx +0.8$ deg. This imbalanced tip and valley shedding results in a very complicated three-dimensional wake vortex system during the peaks of airfoil oscillation. At other time frames, however, the shed vortex system in the wake resembles those seen in two-dimensional trailing-edge configurations.[7,9]

Because of the complex wake structure, it was not possible to determine the vortex shedding frequency when the airfoil is pitch oscillated. Since a mirror image flow behavior (between pitch up and pitch down) must take place, the shedding of the valley region vortex is likely to be associated with the seepage of fluid at the start of pitch down.

At low reduced frequency ($K = 0.75$), the flow behavior is quite similar to the moderate reduced frequency case discussed earlier. The only difference is that the bound vortex is located downstream of the trailing edge at the tip region. Thus, the bound vortex (line) is aligned with the sawtooth trailing edge in this case. A slightly different vortex system results at high reduced frequency ($K = 2.25$). In this case, a single connected bound vortex is not formed as was the case for the lower reduced frequencies. As was the case for the other reduced frequencies, the vortical motion first forms in the valley region and then spreads to the tip region. However, the vortex does not reach the tip before the oscillation completes the pitch-up phase. This situation is shown in Fig. 3. When the airfoil begins to pitch down (i.e., moving towards $-\alpha$), the vortex at the valley region is shed immediately, whereas a sort of disturbance remains over the tip region of the extension until $\alpha \approx -0.3$ deg.

Figure 4 shows the results when the oscillation amplitude is increased to $\Delta\alpha = \pm 4$ deg. Two bound vortices are formed in this case, a primary vortex near the sawtooth trailing edge and a secondary vortex on the main airfoil section. The primary bound vortex is shed immediately when the airfoil begins to pitch down (i.e., moving towards $-\alpha$). However, the secondary bound vortex remains over the airfoil and continues to disturb dye streaks for a short time duration.

Summary

The flow behavior near the trailing edge of an oscillating airfoil was investigated using dye flow visualization. With the sawtooth trailing-edge configuration, a seepage of fluid during a change in pitch direction resulted in the formation of a circulatory motion at the valley region. This circulatory motion then spread to the tip region. The resulting bound vortex was generally aligned parallel to the sawtooth trailing edge. When the pitch direction was changed, the vortex over the valley region was shed immediately, whereas the vortex over the tip region remained over the airfoil for a short time duration. The resulting shed vortex structure (during the oscillation peaks) was quite complex and three dimensional. These results provide insight concerning the bound and shed vortex structure due to trailing-edge modifications.

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Vortex-Wake Characteristics of a Supersonic Transport Wing Planform at Mach 2.5

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Introduction

THE renewed interest in the supersonic transport program has created a need for information on vortex-wake characteristics of airframe components in supersonic flows to address a variety of design and operation issues. However, experimental information of this type is quite sparse even though it has been pointed out in the literature as an important factor in evaluating the environmental impact of a supersonic transport fleet.[1–5] To broaden the existing database and to aid in the development of supersonic vortex-wake models and/or code validation, measured vortex-wake decay and trajectory characteristics of a generic supersonic transport planform in a Mach 2.5 stream are presented.

Experimental Setup

The experiments were performed in Polytechnic University's blowdown tunnel in its Mach 2.5 configuration. A half-wing model with a planform geometry closely following that of the NASA baseline 70–45 deg cranked arrow configuration[6] was tested at an angle of attack of 5 deg. The root chord and span of the half-wing model are 163 and 86 mm, respectively. Detailed information on the experimental setup, facility, and data acquisition is found in Ref. 7. Test results presented herein were carried out at a Reynolds number of 4.04×10^6 based on the mean aerodynamic chord of 95 mm.

Results and Discussion

A panoramic shadowgraph view of the flowfield shows three distinct structures in the vortex wake (Fig. 1). Features 5 and 7 are the wing-tip and leading-edge vortex cores, respectively. Based on data to be presented, feature 6 is a swirling structure as well. The shadowgraph illustrates that the core diameters for both the tip and leading-edge vortices remain virtually unchanged, suggesting that the diffusion effect for the vortices is small and are therefore likely to persist very far downstream. Meanwhile, compared with the vortices, feature 6 has diffused a great deal more within the same visualized area.

Figure 2 shows the results of a surface oil flow test that was made to help clarify the cause of flow feature 6 in the shadowgraph. The oil accumulation line along the leading edge of the 70-deg section is the outer edge of the leading-edge vortex,[8] whose continuing development over the delta planform is interrupted by the flow at the root chord of the outboard planform. This interaction is believed to be responsible for feature 6 in the vortex wake in Fig. 1. Additional discussion on the surface oil flow results is documented in Ref. 7.

A vertical survey through feature 6 with an uncalibrated five-hole cone probe was made at the $X/C_{tip} = 2.1$ location (where the tip chord $C_{tip} = 30$ mm and X is the downstream distance measured from the trailing edge of the wing tip) to determine the nature of the flow.[7] It was found that the structure is a swirling flow rotating in the counterclockwise direction (with respect to an observer in front of the model looking downstream). Meanwhile, based on physical intuition as well as experiments on unswept and delta wings,[8–12] both the wing-tip and the leading-edge vortices are known to be swirling in the clockwise direction. However, the swirling structure

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