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Effect of Amplitude and Mean Angle of Attack on Wake of an Oscillating Airfoil

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***Abstract*—**The unsteady wake of an EPPLER 361 airfoil in pitching motion has been investigated in a subsonic wind tunnel by hot-wire anemometry. The airfoil was given the pitching motion about the one-quarter chord axis at reduced frequency of 0182. Streamwise mean velocity profiles (wake profiles) were investigated at several vertically aligned points behind the airfoil at one-quarter chord downstream distance from trailing edge. Oscillation amplitude and mean angle of attack were varied to determine the effects on wake profiles. When the maximum dynamic angle of attack was below the static stall angle of attack, weak effects on wake were found by increasing oscillation amplitude and mean angle of attack. But, for higher angles of attack strong unsteady effects were appeared on the wake.

***Keywords*—**Unsteady wake, amplitude, mean angle, EPPLER 361 airfoil.

I. INTRODUCTION

THE unsteady aerodynamic theory of oscillating airfoils has received considerable attention in past years, especially problem of airfoil stall. The classical unsteady aerodynamic theory of oscillating airfoils was developed as a result of interest in aircraft flutter problems by Theodorsen [1] and Von Karman and Sears [2]. Later, Lighthill [3] and Wu [4] extended this theory using propulsion modeling of certain spaces of aquatic animal, birds and insects. In comparison with the many theoretical and numerical studies that have been devoted to the subject of oscillating airfoil, quite a few experimental results appear to be available. Experimental unsteady aerodynamic researches have very important role in both understanding the essential physics of the problem and validating the results from the computational studies. Most of the previous investigations were directed to unsteady wing loading and dynamic stall process, as reviewed by McCroskey [5] and Carr [6]. Recently, Tolouei et al [7] investigated experimentally the unsteady pressure distribution over an EPPLER 361 airfoil. They found that pressure coefficients in the low angle of attack range showed little overshoot when compared with the static values, while for the large angle of attack cases the differences were significant. They considered that the large overshoot in the dynamic pressure coefficient for the high angle of attack case is probably due to the existence of the stable dynamic vortex, which is created near the leading edge and moves downstream. Soltani et al [8] showed that by increasing the oscillation frequency, the motion of the airfoil could not adjusted the free-stream flow, and the hysteresis loop of pressure coefficient will change into straight line. In addition in high angles of attack the hysteresis loop grows, so that preventing wing stall and increasing the lift. But this is just applied to smaller speeds. Ajalli et al [9] showed that at different amplitudes for unsteady airfoil, the hysteresis loops in the pressure data were both clockwise and counter clockwise when plotted against the equivalent angle of attack. It was found that heaving amplitudes had strong effects in pressure distribution, near the leading edge of the airfoil. Mani et al [10] measured Surface static pressure distribution on the upper and lower sides of the model, during the oscillating motion. It was found that reduced frequency had strong effects on the pressure distribution, near the leading edge of the airfoil.

In spite of less attention about studying the characteristic of the wake in comparison with the measuring the force on oscillating airfoils, several important researches have been conducted into the problem of downstream wake. Satyanarayana [11] measured unsteady wakes of airfoils and cascades under a sinusoidally varying gust flow. Time-mean and time-dependent wake profiles at low frequency behind the airfoil were reported in his work, and the distinctions between these were discussed. Koochesfahani [12] studied experimentally the vortical flow patterns in the wake of a NACA0012 airfoil pitching at small amplitudes and showed that the oscillation wave form has an important effect in the vortical pattern shapes and mean velocity profiles in the wake. He found that there is a critical value for the oscillation frequency that the usual velocity defect profiles in the wake changes to excessive momentum similar to a jet flow and the airfoil produces trust force. Also, he showed that in special cases mean velocity profiles have two peak of velocity defect, that this is symptom of a double-wake structure. Park, Kim and Lee [13] measured the velocity field in the wake of a

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NACA0012 airfoil and checked the effect of increasing mean angle of attack. They observed that after a special mean angle of attack the velocity profiles were stretched extremely, and considered that this is due to large separation on airfoil surface. Recently, an experimental measurement of unsteady wake behind a sinusoidally unsteady airfoil was performed by Mani et al [14]. They were shown that the angle of attack and reduced frequency are the most important parameters which influence on the velocity profiles. Also, they found that the influence of angle of attack on the velocity profiles is to increase the momentum deficit and wake thickness.

The objectives of the present study are to examine the unsteady wake of an airfoil oscillating sinusoidally in pitch at various conditions. The airfoil was EPPLER 361. The velocity in the wake was measured using the hot-wire anemometry. The airfoil was given at different mean angles of attack and oscillation amplitudes, and the resulting wakes (mean velocity profiles) were measured to understand the effects of them.

II. EQUIPMENTS

In order to measure the velocity profiles on wake of an oscillating airfoil, hot wire anemometer system were used throughout the measurements.

A. *Wind Tunnel*

The experiments were conducted in the subsonic wind tunnel. The tunnel is of closed return type and has a test section of 0.457 m × 0.457 m × 1.2 m. The nozzle contraction of the tunnel is about 7.31, and the turbulence intensity is less than 0.1% in the test section. Fig. 1 shows a view of the wind tunnel.

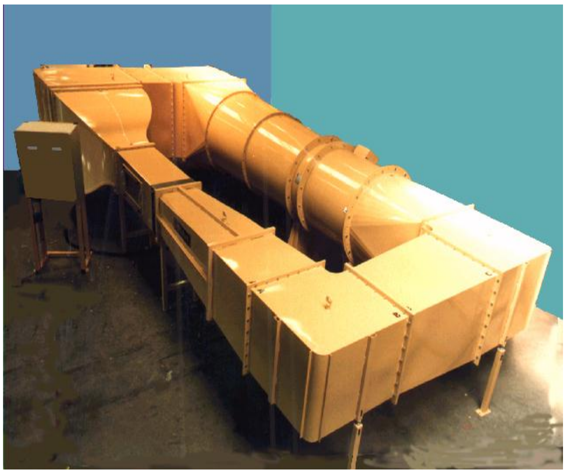

Fig. 1 Schematic of wind tunnel

B. *Airfoil*

An EPPLER 361 airfoil, with Chord, *C*, of 14.5 cm and a span of 45 cm was used in the investigations.

C. *Oscillating System*

A specially oscillation mechanism capable of pitching the model at various amplitudes, mean angles of attack and reduced frequencies was used in the present experiment. The pitch rotation axis was fixed at the wing quarter chord. Fig. 2 shows the picture of oscillation mechanism.

Fig. 2 Oscillating System

D. *Hot-Wire*

A constant temperature hot-wire anemometer (CTAs) was employed for the velocity measurements. The hot-wire probes were mounted on a support in the center plane of the test section behind the airfoil as shown in Fig. 3. Each sensor of probe was made of tungsten and the diameter of sensor was about 5μm.The overheat ratio and DC offset voltage for each hot-wire sensor carefully adjusted such that each sensor nearly the same operating conditions. Data were acquired and processed by a 12 bit 16 channel A/D converter board capable of sample rates up to 200 kHz.

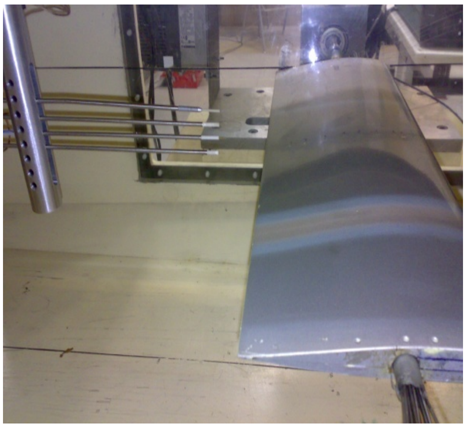

Fig. 3 Model and hot-wire probes in the tunnel test section

III. EXPERIMENTAL PROCEDURE

The effect of mean angle of attack and oscillation amplitude on wake of an oscillating airfoil is investigated by measuring the mean velocity distribution for the following cases:

- Case 1: maximum dynamic angle of attack was below the static stall angle of attack.
- Case 2: maximum dynamic angle of attack was beyond the static stall angle of attack.

The dynamic angle of attack, α, can be expressed as

$$\alpha = \alpha_0 + A \sin 2\pi f t$$

Here, α_0 is mean angle of attack, *A* is the oscillating amplitude, *f* is the frequency of oscillation and *t* is the time.

The experiments were conducted at a set of mean angles of attack and oscillation amplitudes that covered angles of attack from -12.5 to 20 degrees. It should be note that the static stall angle of this airfoil was about 12.5 °. The value of reduced frequency *k*, define as $k = 2\pi f\, C/\, 2U\infty$, was considered about *k*=0182. The free stream velocity and the frequency of oscillation were set at U∞ =5 m/s and *f* =2 Hz, respectively.

Measurements were carried out for one downstream station: X/*C*=0.25. The vertical traverse was restricted from Y/*C*=-0.63 to 0.63.

IV. RESULTS

The results of investigation will be described in three subsections. First, the effect of mean angle of attack will be discussed. In the second subsection, the effect of oscillation amplitude will be discussed. The differences between profiles at different amplitudes and mean angles, when maximum angles of attack are the same, will be pointed in subsection three. Also, it is necessary to mention that streamwise mean velocities and vertical distances are non-dimensioned by free stream velocity and airfoil chord, respectively.

A. Effect of Mean Angle of Attack

Figs. 4 and 5 illustrate the mean velocity profiles at two mean angles of 0° and 2.5° for oscillation amplitudes of *A*=8° and *A*=10°, respectively. The amplitudes and mean angles of attack were selected such that during one oscillation cycle, the model would oscillate below static angle of attack. At these mean angles, flow remains attached throughout the oscillation cycle on airfoil surface and vortices form the wake with arranged mutation. These figures show no particular effects on wake profiles with mean angle of attack.

In order to compare profiles, when maximum angle of attack exceeded static angle of attack, mean angles of attack were set 2.5° and 5° at oscillation amplitude *A*=8° , Fig. 6. In this case, airfoil could oscillate bellow static angle of attack at α_0 =2.5° and beyond static angle of attack at α_0 =5°, respectively. It is seen that the profiles are considerably different from each other. When airfoil exceeds static stall angle, flow reversal occurs in boundary layer. This eventuates that formed vortices in the wake become larger with irregular mutation. As seen in Fig. 6, the velocity defect and wake thickness increase with mean angle. Also, the profiles for the aforementioned mean angles were plotted at *A*=10°. As the angle of attack continues to increase further, larger eddies appear in boundary layer and flow reversal spreads over much of airfoil chord. Then, flow separation starts at leading-edge. These processes make more alteration on vortices behind the airfoil.

Finally, mean angles of attack were selected such that the maximum angle of attack was quite beyond static angle of attack, Fig. 8. Increasing mean angle of attack initiates vortex development earlier in the oscillation cycle. Figure 8 shows a great increasing of wake thickness and velocity defect with mean angle. when the mean angle of attack is 10 °, a very broad region of large velocity defect and wake thickness is noted, which is absent for the cases of 0°, 2.5 °or 5 °. This is evidence of a large region of separated flow on the airfoil surface during the motion at α_0 =10°. This huge separation causes that airfoil surface vortex goes into the wake and a sudden growth on vortices size and wake thickness appears.

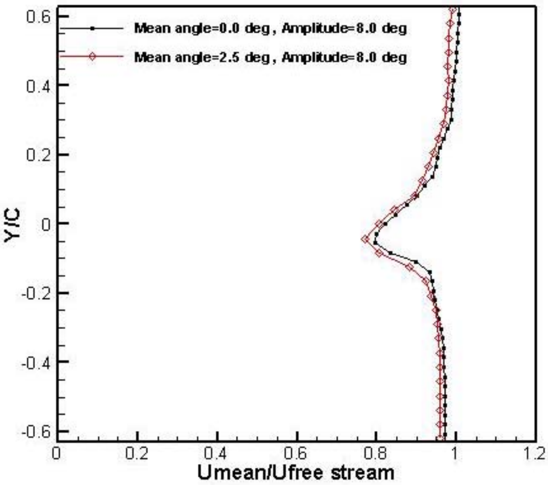

Fig. 4 Mean velocity profiles ($\alpha_0 = 0°, \alpha_0 = 2.5°$) at *A*=8°

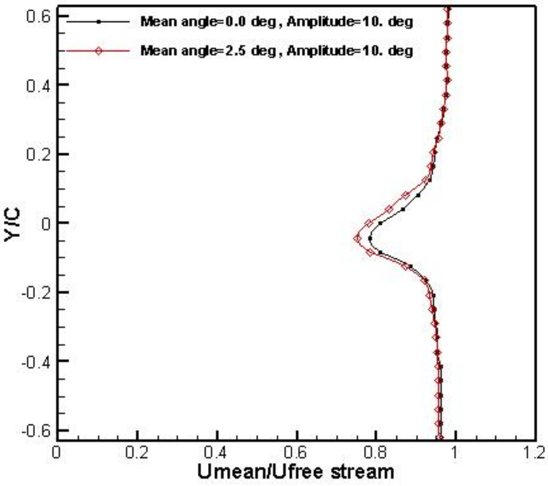

Fig. 5 Mean velocity profiles ($\alpha_0 = 0°, \alpha_0 = 2.5°$) at *A*=10°

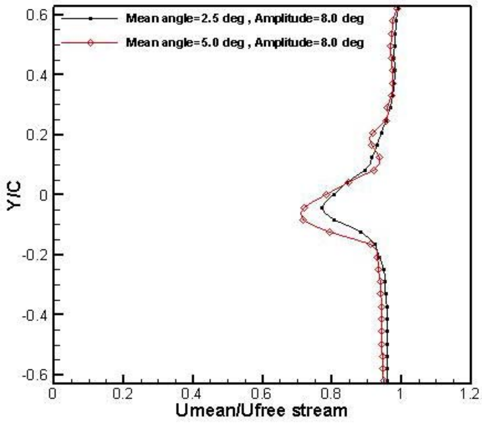

Fig. 6 Mean velocity profiles ($\alpha_0 = 2.5°, \alpha_0 = 5°$) at *A*=8°

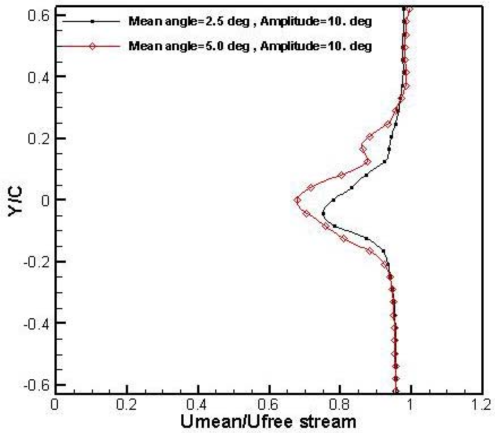

Fig. 7 Mean velocity profiles ($\alpha_0 = 2.5°, \alpha_0 = 5°$) at *A*=10°

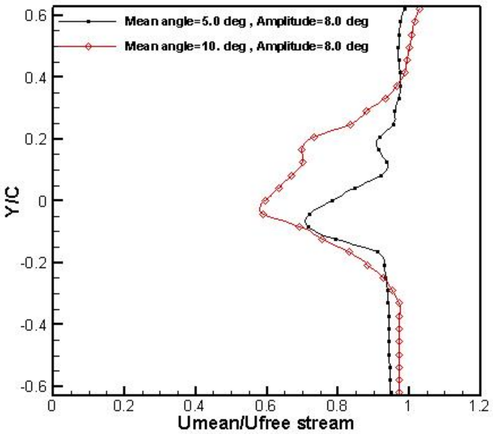

Fig. 8 Mean velocity profiles ($\alpha_0 = 5°, \alpha_0 = 10°$) at *A*=8°

B. *Effect of Amplitude Oscillation*

When maximum angle of attack was below the static angle of attack, the effects of enhancement of amplitude oscillation were indicated in Figs. 9 and 10.The results clearly show the weak effects of amplitude changing because of the surface attached flow, on wake profiles.

Fig. 11 shows a huge growth of wake thickness and velocity defect for *A*=15°case, whereas maximum angle of attack exceeds static angle of attack, in comparison with *A*=8° and *A*=10°cases. This is due to increase of separation on airfoil surface and larger vortices formation behind the airfoil.

The influences of oscillation amplitude, for maximum angle of attack beyond the static angle, are depicted in Fig.12. In this case, increasing amplitude initiates vortex development earlier in the oscillation cycle and also the size of separation increases.

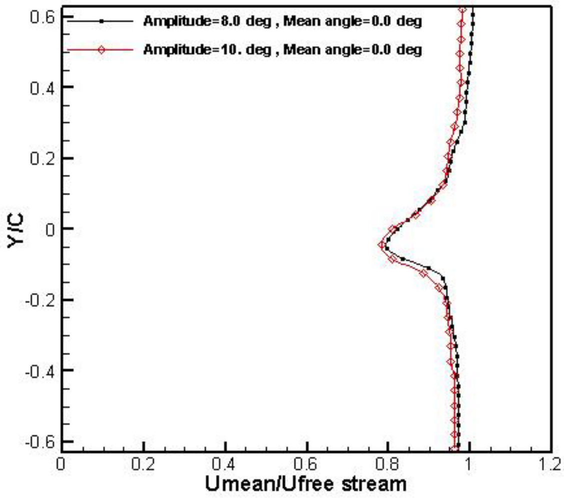

Fig. 9 Mean velocity profiles ($A = 8°, A = 10°$) at $\alpha_0 = 0°$

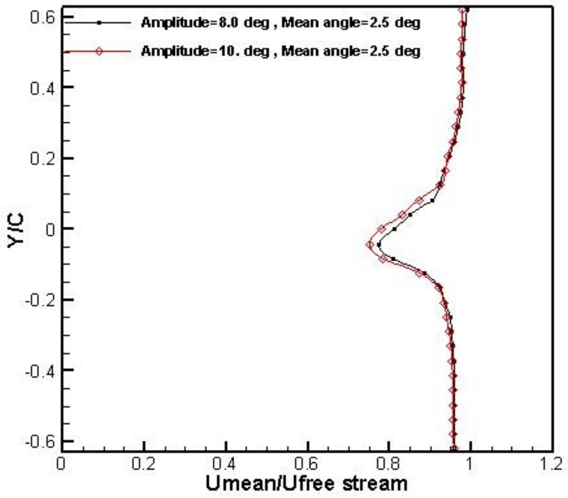

Fig. 10 Mean velocity profiles ($A = 8°, A = 10°$) at $\alpha_0 = 2.5°$

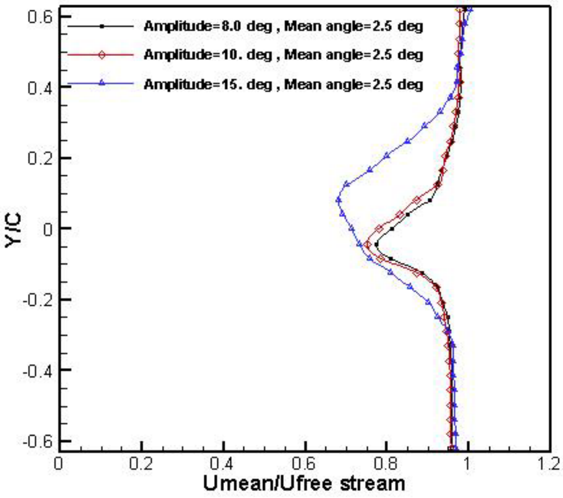

Fig. 11 Mean velocity profiles ($A = 8°, A = 10°, A = 15°$) at $\alpha_0 = 2.5°$

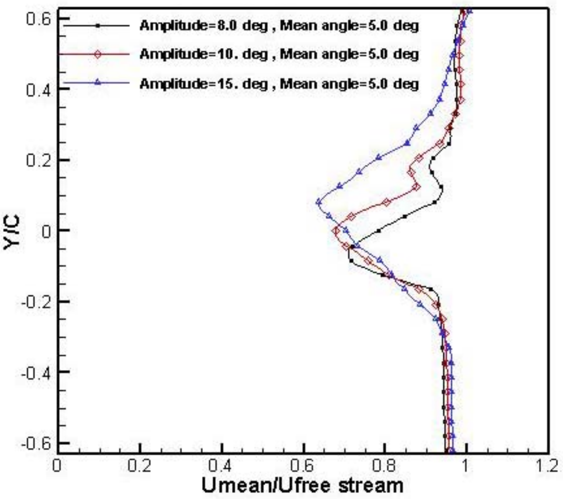

Fig. 12 Mean velocity profiles ($A = 8°, A = 10°, A = 15°$) at $\alpha_0 = 5°$

So, it is noted that the change of wake thickness and velocity defect are more considerable than the cases that maximum angle of attack is below or near static angle of attack.

C. *Different Amplitudes and Mean Angles of Attack*

The mean velocity profiles at different amplitudes and mean angles were plotted in Fig. 13, such that maximum angles of attack were same. It is seen that at the case of *A*=10° and α_0 =10° the wake profiles are thicker than the case of *A*=15° and α_0 =5°. So it was found that the effect of mean angle of attack on wake thickness is more than the effect of oscillation amplitude.

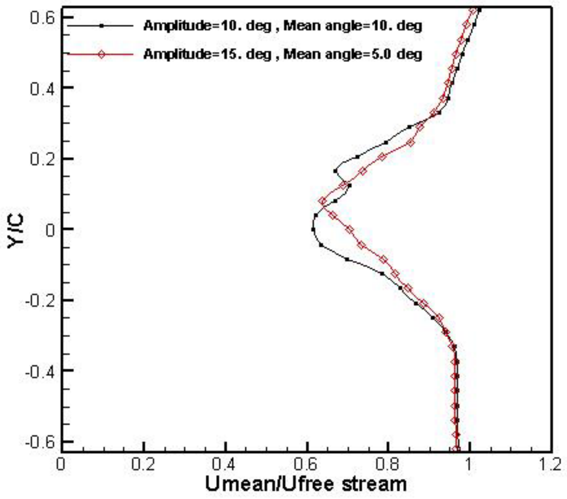

Fig. 13 Mean velocity profiles ($A = 10°, \alpha_0 = 10°$ and $A = 15°, \alpha_0 = 5°$)

V. CONCLUSION

The results of the present investigation have revealed the effect of changing mean angle of attack and oscillation amplitude on wake profiles. When maximum angle of attack was below the static angle, weak effects of amplitude and mean angle were observed. This is due to attached flow on airfoil surface. The considerable effects were appeared after static angle whereas larger vortices formed the wake. A huge growth of wake thickness after special mean angle of attack and oscillation amplitude were considered to be result of large separation on airfoil surface. Also, it was found that the effect of mean angle of attack on wake thickness was more considerable than the effect of oscillation amplitude.

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