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Wake Analysis of a Plunging Airfoil

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ABSTRACT

An experimental measurements of unsteady wakes behind a sinusoidally plunging airfoil was surveyed with a Hot-wire rake containing seven I-wires. The aim of these measurements was to study the velocity profiles behind the oscillating airfoil trailing edge. Influences of reduced frequency and angle of attack were studied in details. It was shown that the angle of attack and reduced frequency are the most important parameters which influence on the velocity profiles. The momentum deficit was relative to reduced frequency and amplitude of oscillation and its behaviours were changed after static stall angles. At the angle of attack beyond static stall angle flow separation causes increasing the momentum deficit. The velocity profile has approximately symmetric shape profile.
Data were taken at mean incidence angles of 0, 8 degrees at reduced frequencies of 0.09 to 0.56. The nondimensional amplitude of oscillation was 0.27. The corresponding Reynolds numbers, based on the chord length, were 25000 and 150000.

NOMENCLATURE

c	Airfoil chord
$\frac{h}{c}$	Nondimensional oscillation amplitude
Re	Reynolds number
k	Reduced frequency = $\omega c/2U_\infty$
T	Period of oscillation
U	Ensemble averaged stream wise velocity
U_∞	Free stream velocity
X	Downstream distance from trailing edge
Y	Vertical distance from chord line
α	Angle of attack
ω	Circular frequency of oscillation

INTRODUCTION

The problem of unsteady aerodynamics is very important and research into unsteady airfoils is quite extensive. In recent years, Considerable research has been conducted into the problem of unsteady aerodynamics of an oscillating airfoil. In many engineering applications, lifting surfaces experience unsteady motion or are perturbed by unsteady incoming flows such as helicopters, turbines and compressors[6]. Most of the previous research efforts in this area were directed to unsteady wing loading associated with dynamic stall phenomenon, as reviewed by McCroskey[5].

There are many practical situations where the unsteady wakes are involved. The wake blade interaction in turbomachinery flows is one example. Relatively scant attention, however, was given to the study of oscillating wakes. Ho and Chen [3] studied experimentally the unsteady wake of a plunging airfoil at incidence using a hot-wire rake. The velocity traces and the Reynolds-stress distributions in their study revealed that the wake had different turbulent structures in the upper and lower parts of the wake. They also showed that the phase averaged wake profiles are different at different phase angles. Satyanarayana[10] measured unsteady wakes of airfoils and cascades under a sinusoidally varying gust flow. Time-mean and time dependent wake profiles were presented and the discrepancies between these were discussed.

De Ruyck and Hirsch [2] reported the instantaneous velocity and turbulence intensity profiles of the wake of an airfoil oscillating in pitch. A trip wire was mounted over the airfoil surface and a single slanted rotating wire was employed for measurements. They found that the hystersis were present between the increasing and decreasing incidence, and that the turbulence levels in the unsteady case were smaller than in the corresponding static case at the same incidence. They also noticed that when the static stall limit was lightly exceeded, the wake did not appear to be stalled.

Park and Kim [8] measured the wakes behind an airfoil oscillating in pitch about zero mean incidence. They observed a sudden increase in wake thickness and concluded that this was due to the dynamic trailing edge stall. The instantaneous angle of attack at which the trailing edge stall occurred was much smaller than the static stall angle. They also found that the wake thickness increased with the reduced frequency.

The primary purpose of the present study is to investigate the characteristics of the near wakes behind an airfoil oscillating in plunge. Hot-wire anemometry and on-line data acquisition system was adopted to measure ensemble averaged velocity and turbulence intensity profiles. The airfoil was given a plunging oscillation about three different mean incidences and the resulting wakes were measured to delineate the effect of the mean incidence. Data were taken for the cases of four reduced frequencies (K=0.09 to 0.56) at a given combination of mean incidence and amplitude of oscillation.

EXPERIMENTAL APPARATUS

The experiments were conducted in a TE-44/C PLINT low speed wind tunnel of Amirkabir University of Technology (AUT) having a rectangular test section of 0.45m×0.45m×1.2m. Turbulence intensity in test section is 0.1%.The maximum speed of wind tunnel in test section is 45m/s. An airfoil of Eppler-361 profile was mounted horizontally in test section. The chord of the airfoil was 15 cm, and the aspect ratio was 3.0. The gap between the airfoil and the side wall was 1 mm. The ratio of the chord length to the height of the test section was 1:3. Figure 1 shows the block diagram of the data acquisition system.

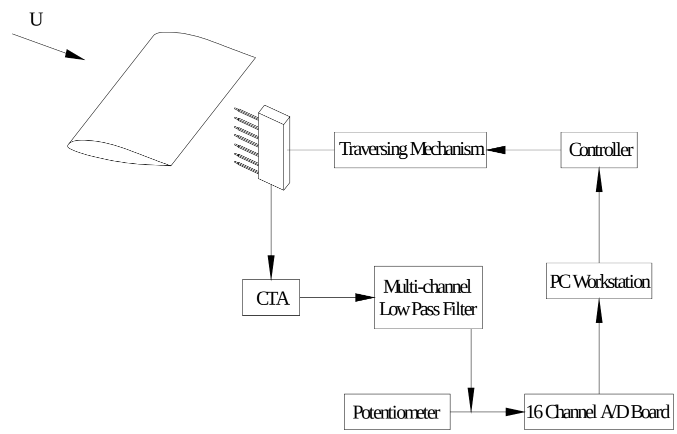
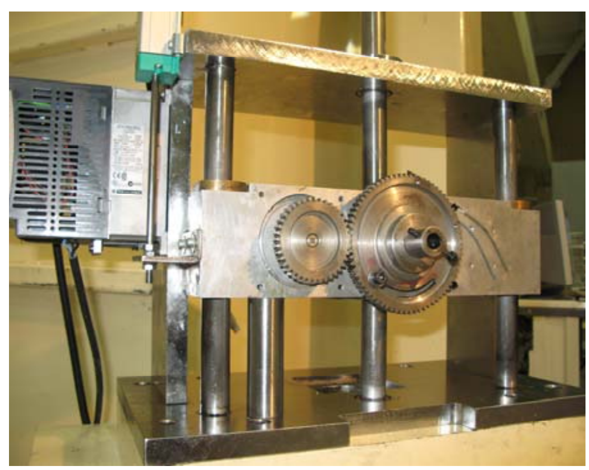


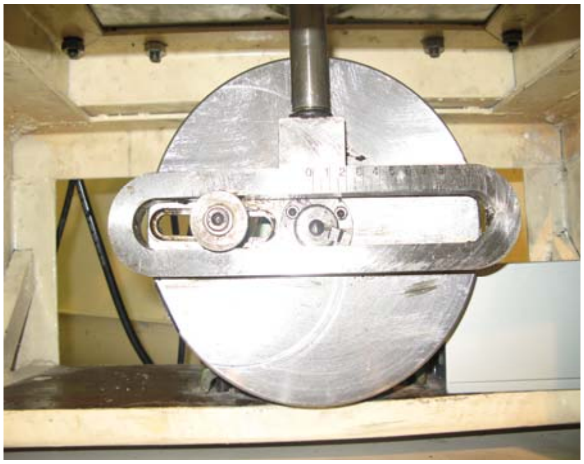
Figure 1 Block diagram of the data acquisition system.

Plunging oscillation was provided by a simple mechanism, Figure 2, which consists of a variable speed AC motor that can provide oscillation motion with frequency up to 3.0Hz and plunging amplitudes ranging from 4cm to 8cm. The angle of attack was given two values: 0^0 and 8^0. Values of the reduced frequency, K, were chosen: K=0.09 to 0.56.



a) Up section

Figure 2 Mechanism of plunging oscillation



b) Down section

Figure 2 continued Mechanism of plunging oscillation

The down section of the oscillating mechanism converts radial motion of motor to linear (up-stroke and down-stroke) motion of the airfoil.

The corresponding Reynolds numbers, based on the chord length, were 25000 and 150000. Measurements were done by use of seven 5μm diameter Hot-wire probe (FSS) with seven FSS constant temperature anemometers (CTA). Figure 3 shows FSS CTAs, figure 3 shows the FSS CTAs. The signals was low pass filtered. The hot-wire probes were calibrated versus wind speed and its signal was sampled at 2.5 KHz and mounted on a support in the test section behind the airfoil. A traverse mechanism was used to be able to span the wake vertically. Figure 4 shows close view of probes and airfoil in the test section.

Figure3 Seven FSS CTAs

DATA ACQUISITION AND REDUCTION

A potentiometer model LT-M-0200-S was used to initiate data sampling. It was connected to the oscillation mechanism and its output voltage was synchronized with the CTA outputs. A personal computer (P4) with a 16 channel A/D converter board also processed the data. Data was taken, at a given probes location. One hundred ensembles were used for averaging.

Measurements were carried out for one downstream station: x/c= 1.0. The vertical traverse was restricted from y/c= -1.0 to +1.0 moved by every 35mm for the measurements.

Figure 4 Eppler-361 airfoil in the test section

EXPERIMENTAL RESULTS

The motion of the airfoil was sinusoidally plunging oscillation. Figure 5 shows the schematic of motion at $\frac{h}{c} = 0.27$. Figure 6 show the velocity profile in the wake of airfoil.

It is shown that as reduced frequency was increased the magnitude of wake thickness and profile peak was increased. In other words drag was reduced. In the wind tunnel, velocity profiles were measured by hotwires and from velocity data the drag was computed using the equation (1). Variation of calculated drag versus k was shown in figure 7.

$$D = \int_h^b \rho_\infty \, U_\infty (U - U_\infty) dy \qquad (1)$$

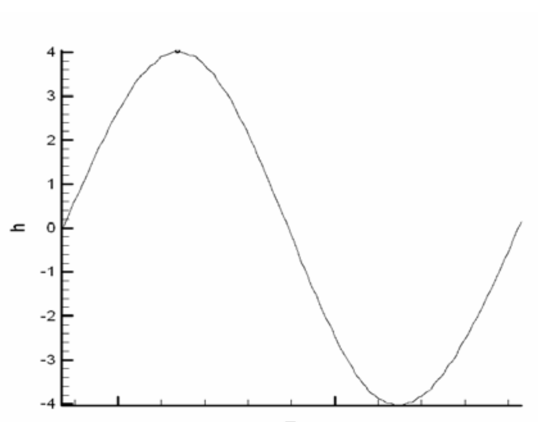


Figure 5 schematic of airfoil motion per one period of oscillation, h/c=0.27

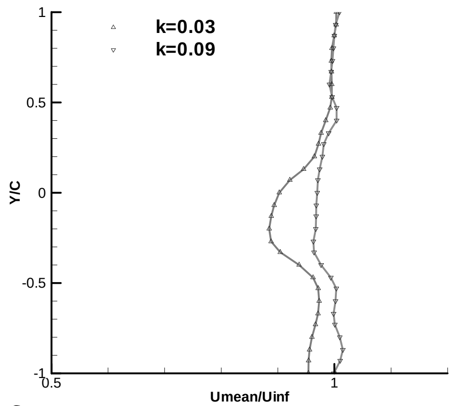


Figure 6
h/c=0.27, $\alpha=0^0$, Re=150’000**,** x/c=1.0

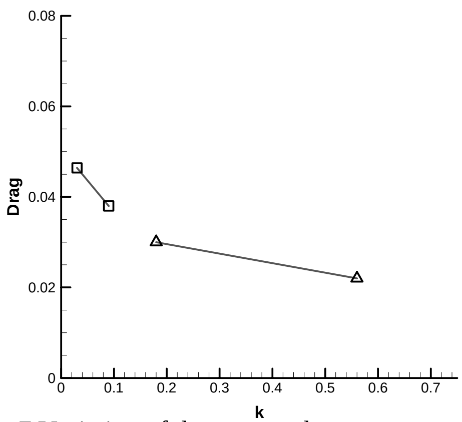


Figure 7 Variation of drag versus k

Figure 6 and figure 7 show that as the reduced frequency (k) was increased, the momentum deficit was decreased.
As seen in these figures the reduced frequency has the significant influence on velocity profile and reduces the drag. Reduced frequency gives accelerate and energy to vortices therefore friction in the wake was reduced.
In figure 8 the effect of angle of attack on the momentum deficit was shown. . As angle of attack was increased the flow separation over airfoil was increased and vortex shedding to the wake causes to increase the momentum deficit and the wake width. It is seen that the flow separation has significant effect on velocity profile.
Figure 8 and 9 show that as the mean angle of attack was increased, the wake thickness and drag were increased. Separated Vortices from the airfoil surface move to the wake and increase momentum deficit and drag.

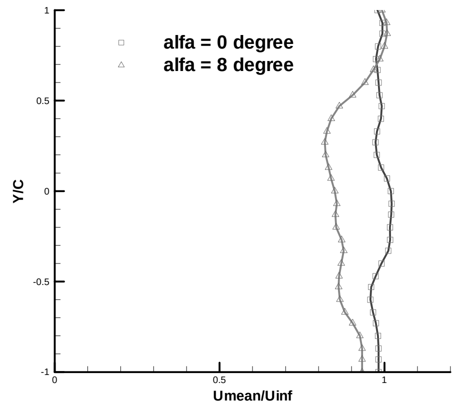


Figure 8
h/c=0.27,k=0.56,Re=25’000,x/c=1.0

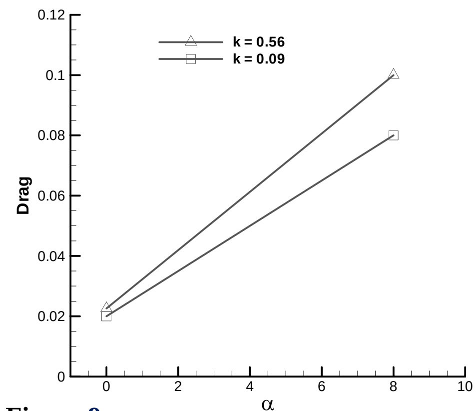


Figure 9
h/c=0.27,x/c=1.0

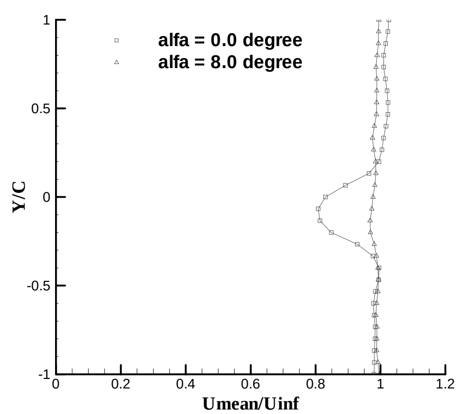


Figure11
Re=25000, x/c=1.0, α= 0 and 8(degree)

Figure 11 shows the static character of airfoil at x/c=1.0. The mean wake velocity consisted of a region of velocity deficit whose magnitude and size increased with larger angle of attack.

Figure 12 shows the velocity profile at static and dynamic (plunging airfoil) cases. In dynamic case the momentum deficit, hence the drag, and the wake width were larger than static case. In tables 1 and 2 the value of drag coefficient for static and dynamic cases at reduced frequency 0.56, is shown.

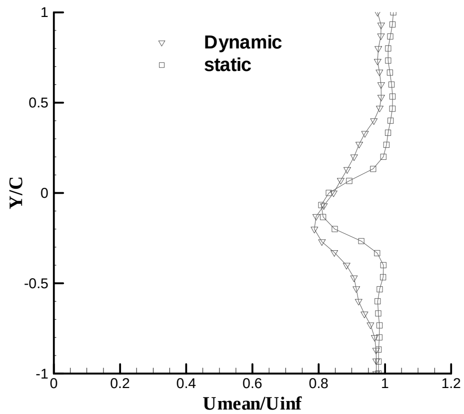


Figure12

(for dynamic case: h/c=0.27 k=0.56),x/c=1.0, $\alpha=8^0$

Table 1

$\alpha=0^0$	Drag coefficient
Static	0.02
Dynamic, k=0.56	0.04

Table 2

$\alpha=8^0$	Drag coefficient
Static	0.06
Dynamic, k=0.56	0.09

CONCLUSION

The results of this investigation have relevant several interesting features. The mean velocity profiles shows different behaviours as reduced frequency or angle of attack was changed. The influence of angle of attack on the velocity profiles is to increase the momentum deficit and wake thickness. As the angle of attack was increased near static stall angle, in down-stroke motion of the airfoil the incidence angle between airfoil and free stream was increased therefore the flow separation over airfoil surface was increased so airfoil surface vortices and trailing edge vortices were shedding in the wake hence the drag was increased. Reduced frequency has interesting effect on velocity profiles. As the reduced frequency was increased the momentum deficit and drag were decreased. The drag force coefficient was larger than its corresponding static value, increases with increasing the angle of attack in both static and dynamic cases, and decreases with increasing the reduced frequency in dynamic (plunging airfoil) case.

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