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AN EXPERIMENTAL INVESTIGATION OF PRESSURE DISTRIBUTION AROUND A HEAVING AIRFOIL

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ABSTRACT
Details of pressure distributions on a two dimensional heaving airfoil, at low-speed wind tunnel are presented. Dynamic heaving motion was produced by oscillating model up to $k = 0.05$. All experiments were conducted at $\mathrm{Re} = 2\times10^5$. The amplitudes of oscillations and mean angles of attack were varied to determine their effects on pressure distributions. At different amplitudes, the hysteresis loops in the pressure data was 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. At the aft portion, it seems that during the oscillatory motions the flow was mostly separated.

INTRODUCTION
In many engineering applications, lifting surfaces experience unsteady motion or are perturbed by unsteady incoming flows. High level dynamic loading and noise generation are inherent problems, due to unsteadiness [1]. The unsteady phenomena appear on helicopter rotor blades, rapidly maneuvering aircraft, wind turbines, jet engine compressor blades and even insect wings [2]. Helicopter rotor blade sections encounter large time dependent variation in angle of attack that are the result of control input angles, blade flapping, structural response and wake in flow. Thus, the unsteady aerodynamic behavior of the blade sections must be properly understood and carefully modeled to enable accurate predictions of the airloads and the aeroelastic response of the rotor system [3].

NOMENCLATURE

h	[cm]	Amplitude of oscillation
H	[-]	Sinusoidal displacement
$\bar{h}$	[-]	Non-dimensional amplitude
C_p	[-]	Pressure coefficient
c	[cm]	Chord
U_∞	[m/s^2]	Free stream velocity
ω	[s^{-1}]	Angular frequency
α_{eq}	[-]	Equivalent angle of attack
α_0	[-]	Mean angle of attack
τ	[-]	Non-dimensional time; t/T
k	[-]	Reduced frequency; $\omega c / 2U_\infty$

Studies of unsteady airfoil flows have been motivated mostly by efforts to avoid or reduce undesirable effects such as flutter, vibration, buffeting, gust response and above all dynamic stall. It is of vital importance when considering the design of the aerospace vehicles with rapid maneuvers and control deflections all of which must be investigated at the design stage. To prevent these phenomena, one must be able to predict the magnitude and phase of the unsteady aerodynamic loads on the lifting surfaces [4]. Many of the aerodynamic phenomena governing the behavior of wind turbine blades and helicopter rotors are known, but the details of the flow are still poorly understood and need to be predicted accurately. As a result of this inaccuracy the actual loading are under predicted [5].

The first studies of unsteady potential flow were done by Karman and Sears [6] and Theodorsen [7] for a thin profile in harmonic motion. The pressure and velocity distributions on a symmetric profile were calculated by Van De Vooren [8], and for cambered ones by McCroskey [9].

Excellent reviews and experiments on unsteady aerodynamics are given by McCroskey [4], Doligaslski et al. [10] and McCroskey et al. [11], respectively.

Due to the complicated behavior of unsteady forces during the heaving motion, numerical techniques are not able to predict accurately these variables yet, and relatively little experimental information is available about the precise fluid physics of oscillating airfoils.

Also pure heaving airfoil motion has received relatively less attention than pitching motion. Therefore the main purpose of this experimental work is to study the pressure distribution at various locations of the Eppler-361 airfoil undergoing sinusoidal heaving oscillation at low angle of attack and different amplitudes. Fourteen pressure transducers and the on-line data acquisition system have significantly facilitated the study of the pressure distribution in the heaving airfoil.

EXTERNAL FACILITY AND DATA PROSSESING

All experiments were performed in the low turbulence $\left(u'/U_0 < 0.1\% \right)$ wind tunnel at Amirkabir University of Technology, Department of Aerospace Engineering. The wind tunnel is closed return type, and has a test section of approximately 45 cm wide, 45 cm high, and 120cm long. The Maximum flow speed in the test section of this tunnel is approximately 45m/s. The airfoil used in this study has an E-361 profile. The chord of the airfoil is about 15 cm. To achieve two dimensionality of the flow, the airfoil span has been chosen the same size as the width of the tunnel. Figure 1 show the airfoil section along with the 14 pressure taps located on upper and lower surfaces used for static pressure measurements. The connections between pressure taps and Pressure Transducers are made by tubes. Therefore, extensive experiments were conducted to ensure that the time taken for the pressure to reach the transducers is much less than the frequency response of the transducers themselves [12]. The data was processed by using analog to digital board. Oscillatory data were then digitally filtered using various cut-off and transition frequencies to find the best frequencies to fit the original data. The filtering process is necessary to eliminate the electrical noise from the genuine data.

The Driving mechanism of the heaving airfoil has a simple and versatile design which consists of motor, gears, cam, and shaft. This mechanism can provide various frequencies (f), amplitudes (h) and mean angles of attack (α_0). The motor and gear combination develop a wide range of frequencies. The maximum frequency is 3Hz. The different amplitudes of oscillations (4, 6, 8 cm) are caused by using a cam system. Figure 2 show the picture of oscillation mechanism.

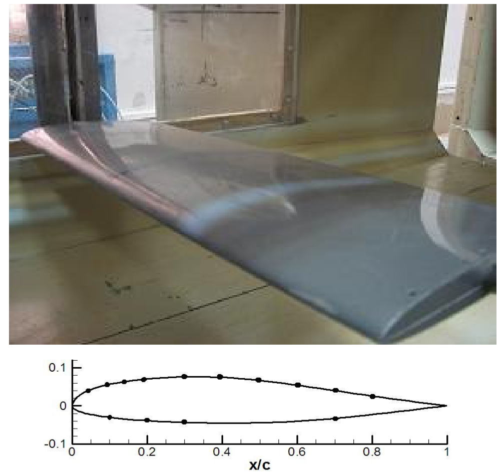


Figure 1 Airfoil section and location of pressure taps

Figure 2 Oscillation mechanism

To take into account the inertial effects for the dynamic cases, the data collected in wind tunnel “off” position are subtracted from those collected during “on” position of the wind tunnel.

RESULTS AND DISCUSSION

Both static and oscillatory test were conducted at $\mathrm{Re} = 2\times10^5$, $\left(U_\infty = 20m/s\right)$.

The instantaneous displacement of the model was measured using a potentiometer. The static pressures at angles of attack 0, 2, 4, 10, 12, 15, 17 and 20 were measured. The surface pressure distribution at mean angles of attack before static stall (0, 5 degree) and different amplitudes of oscillation (4, 6, 8cm) for a constant reduced frequency of $k = 0.05$ are presented in this paper. The effects of reduced frequency on the static pressure distribution in dynamic motion are presented in reference [13].

Figure 3a shows the sinusoidal variation of the different amplitudes with non-dimensional time for an oscillation frequency of 2Hz ($k = 0.05$). Relative motions between pitching and heaving airfoils are compared by equivalent angle of attack [14]. The phase difference between two motions is 90 degrees (Figures 3a- 3b). The height of oscillation and its equivalent angle of attack are defined as:

$$H = h\sin(\omega t)$$

$$\alpha_{eq} = \tan^{-1}\left(\frac{\dot{h}}{U_\infty}\right) = k\bar{h}\cos(\omega t)$$

Due to the relation of the equivalent angle of attack to the amplitude of oscillation, by increasing amplitude, the variation range of equivalent angle of attack becomes larger (figure 3-b).

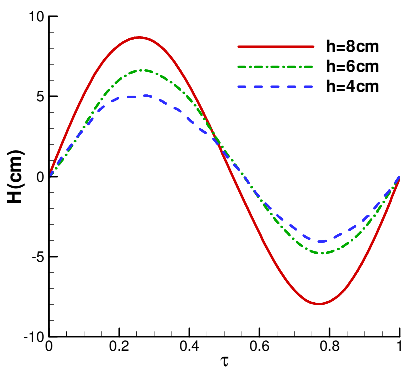


Figure 3-a Sinusoidal variations of amplitudes vs. τ ($\alpha_0 = 0$)

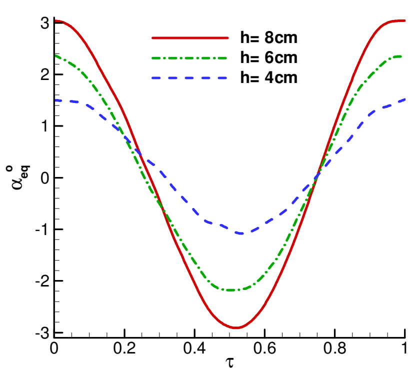
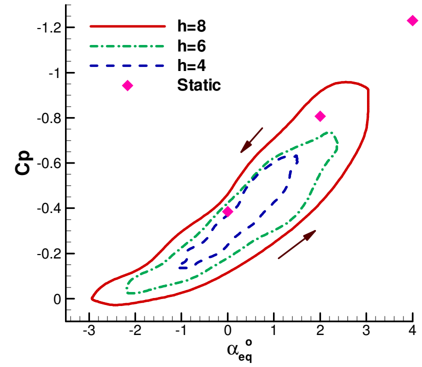


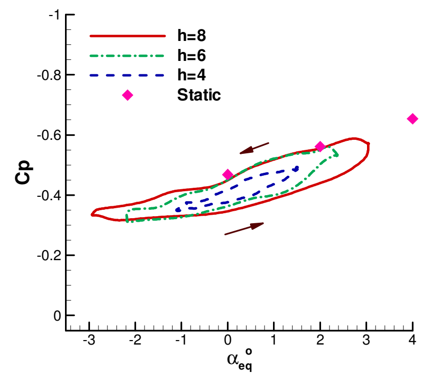
Figure 3-b Variations of equivalent angle of attack vs. τ ($\alpha_0 = 0$)

Figure 4 (a-c) shows the variations of the pressure coefficients against equivalent angle of attack at several positions, on both upper and lower surfaces at $\alpha_0 = 0$ for different amplitudes. The model was set at an angle of attack 0 degrees and oscillated in three different amplitudes (4, 6, 8 cm). The static data and direction of the variation of the equivalent angles of attack are shown too. It is to be noted that the direction of the motion to downward is assumed to be positive.

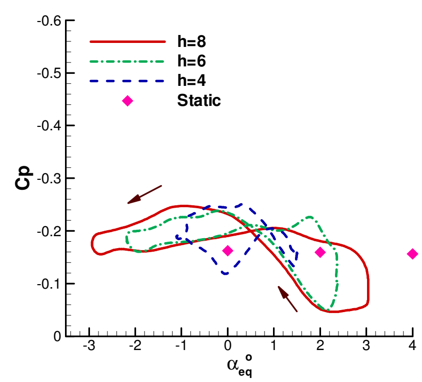
The differences in C_P values for the upstroke and down stroke motions create hysteresis loops where their shapes are functions of the mean angle of attack, the oscillation amplitude and the reduced frequency.



(a) Upper Surface, $x/c = 5\%$



(b) Upper Surface, $x/c = 40\%$



(c) Upper Surface, $x/c = 70\%$

Figure 4 Variations of pressure coefficient at different position on upper surface of the airfoil, ($\alpha_0 = 0$)

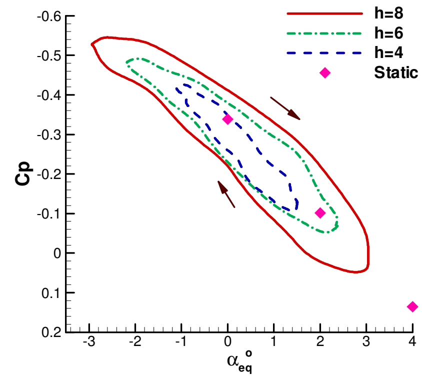
As shown in these figures, hysteresis loops in the upper surface of the airfoil at $x/c = 5, 40\%$ are counter clockwise. This indicates that the flow in increasing the equivalent angle of attack lags that of the decreasing equivalent angle of attack. It is due to the wake effects that are shed to the free stream. By increasing the amplitudes of oscillations, continuous shedding of vortices to free stream is increased and the flow becomes more unsteady. Therefore variations of C_P vs. α in figure 4, shows that the hysteresis loops become larger as amplitude of oscillation increase.

Figure 4a shows that the maximum pressure coefficients occur near the leading edge at $x/c = 5\%$. Furthermore at $x/c = 70\%$, Figure 4c, hysteresis loops show an "8" shape. Consequently there is a crossover point, the upstroke and down stroke pressure are the same, for a specific angle of attack. By investigating in this figure, overshoot in the pressure coefficient is observed at high equivalent angle of attack that indicates flow separation has accrued, because of the airfoil geometry at this position. By increasing the amplitudes of oscillations the related angle of attack to crossover point is decreased which shows an earlier separation of the flow in high amplitudes. In this position the direction of the hysteresis loops changes from counter clockwise to clockwise (lag to lead).

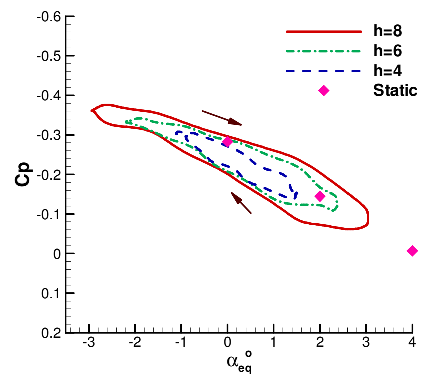
On the lower surface, figures 5(a-c), the directions of the hysteresis loops are clockwise and define that the motion has a lead phase. There is a lower pressure variations on the lower surface compared to the upper surface. Near the trailing edge of the airfoil the pressure variations become negligible.

Figures 6 and 7 show variations of pressure coefficient against time, at different positions on upper and lower surface of the airfoil, at $(\alpha_0 = 0, 5^\circ)$ respectively, and high amplitude of oscillation $(h = 8\,cm)$.

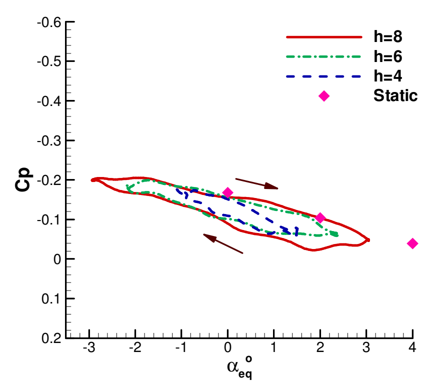
Variations of pressure coefficient on the aft portion of the airfoil, figure 6a, differ from that on forward portion. At the wide range on upper surface ($x/c = 5\%$ to $x/c = 60\%$), variation of C_P with τ is almost like cosine curve, and follow the variations of the equivalent angle of attack, which indicate that no flow separation has occurred and the flow is attached yet. By inspecting in figure 6a, at the aft portion of the airfoil $(x/c = 70, 80\%)$, the flow is separated and the pressure variations decrease drastically.



(a) Lower Surface, $x/c = 10\%$



(b) Lower Surface, $x/c = 30\%$



(c) Lower Surface, $x/c = 70\%$

Figure 5 Variations of pressure coefficient at different $(\alpha_0 = 0)$ position on Lower surface of the airfoil,

As shown in figure 6a the maximum pressure suction is on the upper surface, near the leading edge ($x/c = 5\%$), but it does not happen at $\tau = 0$, at which the equivalent angle of attack is maximum But $|C_p|_{\max}$ is delayed to occur at $\tau = 0.1$. It is due to lag effects of the oscillation of the wake.

Figure 6b shows the pressure variations on the lower surface of the airfoil. Pressure variations on lower surface of the airfoil in comparison with the upper surface are less. On $\left(x/c = 10\%\right)$ lower surface, pressure variations are almost more considerable; in this position maximum suction occurs at $\tau = 0.6$ which the airfoil reaches to the lowest equivalent angle of attack.

Finally because of asymmetric geometry of this airfoil, flow unsteadiness has fewer effects in the lower surface positions.

By inspecting this figure it is clearly observed that only positions near the leading edge $\left(x/c = 5,10,15\%\right)$ are almost like cosine curve, and from $x/c = 20\%$ to trailing edge, pressure variations with non-dimensional time is look like a smooth line.

Figure 7b shows variations of C_P vs. τ on lower surface positions. By comparing with figure 6b, pressure coefficients signatures are positive and effects of unsteadiness are fewer than the other case.

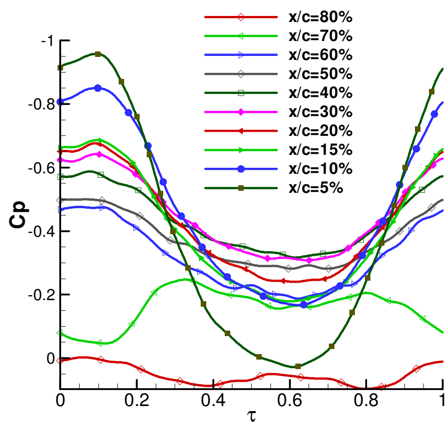


Figure 6a Variations of C_P with time ($\alpha_0 = 0, h = 8cm$) Upper surface taps

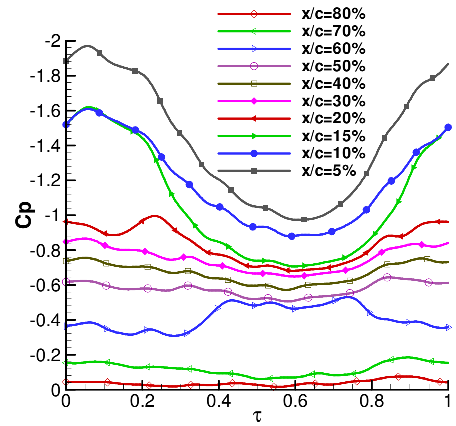


Figure 7a Variations of C_P with time ($\alpha_0 = 5^\circ, h = 8cm$) Upper surface taps

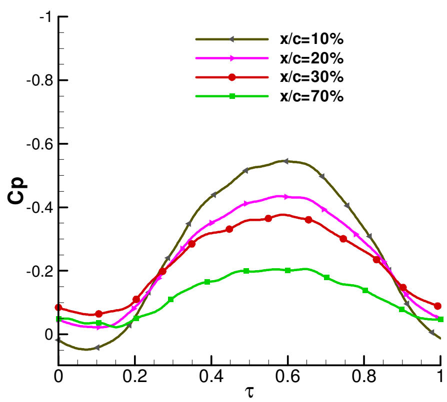


Figure 6b Variations of C_P with time ($\alpha_0 = 0, h = 8cm$) Lower surface taps

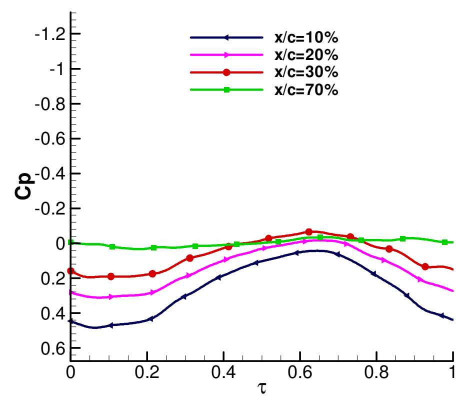


Figure 7b Variations of C_P with time ($\alpha_0 = 5^\circ, h = 8cm$) Lower surface taps

Figure 7(a, b) shows pressure coefficient as a function of non-dimensional time at $\alpha_0 = 5^\circ$ and $h = 8cm$.

By increasing mean angle of attack to 5° as shown in figure 7a, the value of maximum suction pressure on upper surface is increased about $|\Delta C_p| = 1.01$, furthermore, from this figure it is noted that the flow separation is moved forward and occurred at $\left(x/c = 20\%\right)$.

CONCLUSION

An extensive experimental study was conducted to investigate the flow phenomena over the heaving airfoil. Static pressure distributions at 14 positions over and below the model were measured. At these mean angles of attack, hystresis loops in forward portion of the airfoil were counter clockwise and the flow was attached. Near the trailing edge of the airfoil where the flow was separated, hysteresis loops formed an "8" shape and at lower surface hysteresis loops were clockwise. The crossover point was varied with the different amplitudes of oscillations. Three different amplitudes of oscillation were used for the heaving motion in low mean angle of attack. The higher amplitude resulted larger hysteresis loop which was due to strong effects of unsteadiness.

The maximum pressure suction with little time delay was happened in the upper surface and near the leading edge $x/c = 5\%$. Increasing the mean angle of attack to 5° caused higher maximum pressure suction at the leading edge and flow separation point was moved forward of the airfoil, $\left(x/c = 20\%\right)$.

REFERENCES

[1] McCroskey, W. J., "Recent Developments in Dynamic Stall," Symposium on Unsteady Aerodynamics, Vol. 1, Univ. of Arizona, March 1975, pp. 1-34

[2] Carr L. W., "Progress in Analysis and Prediction of Dynamic Stall," Journal of Aircraft, Vol.25, No.1, ,January 1988,PP. 6-17

[3] Joseph C. Taylor, J. Grodon Lishman "An Analysis Pitch and Plunge Effects on Unsteady Airfoil Behaviour" 47th Annual Forum of American Helicopter Society, May 6-8, 1991.

[4] McCroskey, W. J. ,"Unsteady Airfoils", Annual Report of Fluid Mechanics, Vol. 14, pp:285-311, 1982.

[5] Johansen, J. "Prediction of Laminar/Turbulent Transition in Airfoil flows" Riso-R-987 (EN),Riso National Laboratory 1977.

[6] Karman, T. and Sears,W.R., "Airfoil Theory for Non-Uniform Motion," Journal of Aero-Sciences, Vol.5, No.10, 1938, pp.379-390.

[7] Theodorsen Theodore, "General Theory of Aerodynamic Instability and the Mechanism of Flutter", NACA Report NO.496, 1935.

[8] Van De Vooren and Van De Vel, "Unsteady Profile Theory in Incompressible Flow," Archiwuam Mechaniki Stosowanej, Vol.3, No.16, 1964, pp. 709-739.

[9] McCroskey, W. J., and Philippe, J.J., "Unsteady Viscous Flow on Oscillating Airfoils," AIAA Journal, Vol.13, No.1, January 1935

[10] Doligaslski, T.L., Smith, C.R. & Walker, J.D.A. "Vortex Interactions With Wall," Ann. Rev. Fluid Mech. 26, 1994, pp. 573-616

[11] McCroskey, W. J., McAlister, K.W., Carr, L.W. and Indegrannd, R.F. "Dynamic Stall on Advanced Airfoil Sections," J. Am. Helicopter Soc.26,1981, pp. 40- 50.

[12] Mani, M. , Soltani M.R. and Tolouei E., "An Experimental Study of Time Lag Pressure Measurement in Different Tubes," Amirkabir,Vol.16, No.61-B, Spring 2005

[13] Ajalli F., Mani M., Soltani M. "Pressure Distribution around E-361 in Plunging Oscillation", the 6th conference of Iranian Aerospace Society (Persian Language), Feb. 2007, Tehran Iran.

[14] Carta, F.O. "A Comparison of the Pitching and Plunging Response of an Oscillating Airfoil" NASA CR-3172, 1979.