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UNSTEADY SURFACE PRESSURE MEASUREMENT ON A PITCHING AIR FOIL

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ABSTRACT

An experimental analysis of the unsteady pressure distribution on a two dimensional pitching Eppler-361 airfoil was conducted by using transducers at low speed wind tunnel. Dynamic pitching motion was produced by oscillating the model over a range of reduced frequencies, k=0.02355- 0.1413. In addition, Static data were recorded as base line for analysis and comparison. Both static and oscillatory tests were conducted at Reynolds numbers of $1 \times 10^5 < R_e < 2 \times 10^5$. The angle of attack of the model was varying between 0 to 15 degrees. Surface static pressure was measured for both upper and lower surfaces. Pitch rate, Reynolds number and oscillation amplitudes and mean angle of attack were varied to determine the effect on pressure distributions. During the test a series of the quasi-sinusoidal pitching motion were imposed to the model. At different reduced frequency the hysteresis loops were observed in variation of C_p vs.α. Hysteresis loops when plotted against the angle of attack were both clockwise and counterclockwise. It was found that pitching amplitudes, reduced frequency had strong effects in pressure distribution, near the leading edge of the airfoil.

NOMENCLATURE

C_p = Pressure coefficient

ω = Angular frequency

U_∞ = Free stream velocity

α = Amplitude angle of attack

α_0 = Mean angle of attack

τ = t/T non-dimensional time

k = Reduced frequency

INTRODUCTION

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 unsteady aerodynamic loads on lifting surfaces [1]. The effects of unsteady motion on aircraft stall characteristics, especially on the dynamic retreating blade stall problems of helicopters, a well-known limiting factor for the high-speed performance of modern helicopters that accompanies high lift and torsional loadings and advance ratios, have been recognized and have received considerable attention. Numerous experimental and computational investigations have shown that the unsteady flow can be separating or reattaching over a large portion of the top surface of the airfoil, and that the predominant feature of dynamic stall is the formation, shedding and convection over the upper surface of the airfoil of a vortex-like disturbance from the leading edge of the airfoil. This induces a nonlinearly fluctuating pressure field and produces transient variations in forces and moments that are fundamentally different from their steady-state counterparts. After the leading-edge vortex passes the airfoil trailing edge and goes into the wake, the flow progresses to a state of full separation over the upper surface. This is accompanied by a sudden loss of lift and decrease in pitching moment. Furthermore, if and when the angle of attack becomes low enough, the flow will finally reattach again from the leading edge [2]. In many cases, dynamic stall becomes the primary limiting factor in the performance of the associated vehicle. Due to the strange behavior of unsteady forces and moment generated during the pitching motion, and rapidly changing time dependent nature, numerical techniques are not able to accurately predict these variables yet [3]. McCroskey (1982), in his review, focused on the role of unsteady effects in an important class of flow problems, namely two-dimensional oscillating airfoils, and on the advances that have been made within the past decade toward understanding these special and challenging flows [1]. Details of the unsteady solution can be found in Theodorsen (1935),Postel & Leppert (1948), Fung (1969) and McCroskey(1973) [1]. Until now sufficient information has not been available to determine the relative importance of various unsteady flow effects, such as the time-varying inviscid pressure gradient and the unsteady viscous boundary condition at the wall [4]. L.E.Ericsson and J.P.Reding (1984) by the experimental results provided the needed information, revealing how the mode of oscillation for the airfoil determines which unsteady flow effect will dominate [4]. F.Ajalli, M.Mani, M.R.Soltani presented pressure distribution on a two dimensional heaving E361 airfoil in a low-speed wind tunnel [5]. M.R.Soltani, M.Mani, E.Tolouei conducted an experimental study of the aerodynamic behavior of an airfoil undergoing pitching motion in an incompressible regime [6]. This experimental investigation was conducted for unsteady pressure distributions on a two dimensional pitching E361 airfoil at the high pitching rate rather than the last reference for further analysis and comparison.

EXPERIMENTAL APPARATUS AND PROCEDURES

The experiment was performed in a rectangular test section of 0.45 m × 0.45 m × 1.2 m low speed wind tunnel in the low turbulence intensity[$^{u'}/_{U_0} < 0.1\%$] at Amirkabir University of Technology (AUT). The maximum obtainable speed in the test section is approximately 45 m/s. An Eppler-361 airfoil, fabricated from solid aluminum, with chord length, c, of 15 cm and span of 45 cm, was used as the test model. A specially designed crank and rocker and flywheel oscillation mechanism, capable of oscillating the airfoil quasi- sinusoidally at various amplitudes and frequencies (f = 0.1 to 3 Hz), was used in the present experiment. The airfoil pitch axis was located at $^1/_4$-chord.of the airfoil. The airfoil was oscillated with a reduced frequency,$k = {}^{\pi f c}/_{U_\infty}$, ranging between 0.0353and 0.07065. The surface pressure distributions were obtained from 14 pressure taps (of 1.2 mm in diameter), distributed over the upper and lower surface of the model. Figure 1 show the airfoil section that equipped with 10 pressure taps on the upper surface and 4 on the lower surface for static pressure measurements, which are located along the chord.

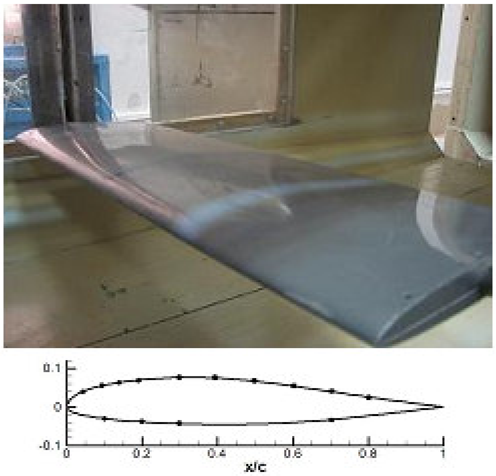


Figure1 Airfoil section and location of pressure tap

Figure2 Data acquisition system

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 [7]. Data are obtained using pressure transducers in a data acquisition system. The data was processed by using analog to digital board. One of the channels of analog to digital board was utilized to show the variation of angle of attack of the pitching airfoil with time by potentiometer. Oscillatory data were 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. 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

The main purpose of this experimental study is to examine the behavior of pressure at various locations of the airfoil, undergoing quasi-sinusoidal pitching oscillation at low to high angle of attack and at various reduced frequencies. Static data were also recorded as a baseline. In this paper both static and oscillatory test were conducted at $Re = 1.7 \times 10^5$ $(U_\infty = 20\frac{m}{s})$ are presented. The test defined baseline conditions for steady state angles of attack from -6 degrees to 23 degrees and examined unsteady behaviors by oscillating the model about its quarter chord axis for different mean angles of attack and reduced frequencies and amplitudes. In this paper the surface pressure distribution at mean angle of attack before static stall (0, 5) and different reduced frequencies for constant amplitude of oscillation (±8 degrees) are presented. Figure 3a shows the quasi- sinusoidal variation of the amplitude with non-dimensional time.

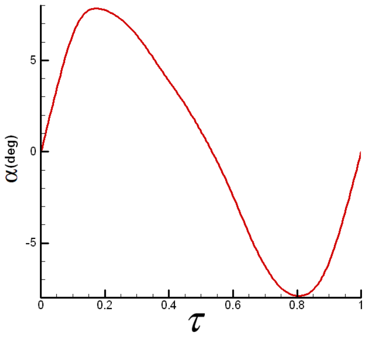
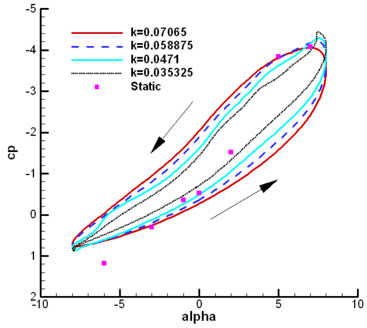
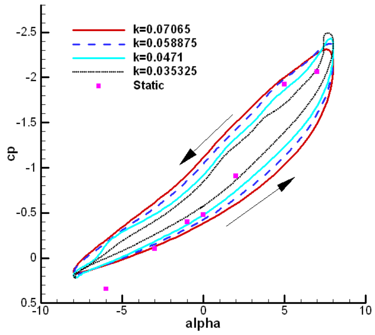


Figure 3a quasi-Sinusoidal variations of amplitude vs.τ

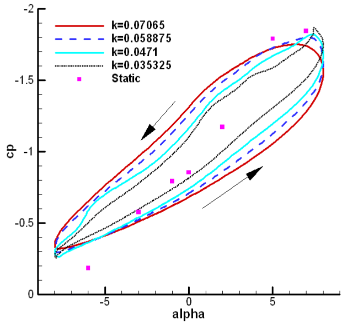
Figure 4, 5 shows static and dynamic variations of pressure with angle of attack at several positions, on both upper and lower surfaces at $\alpha_0=0$ for different reduced frequencies (k=0.07065,0.0589, 0.0471 and 0.0353). The model was set to an angle of attack of 0 degrees and oscillated ±8 degrees at various oscillation frequencies. 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.



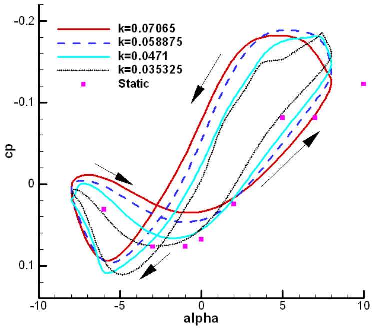
(a) Upper Surface, x/c=5%



(b) Upper Surface, x/c=10%



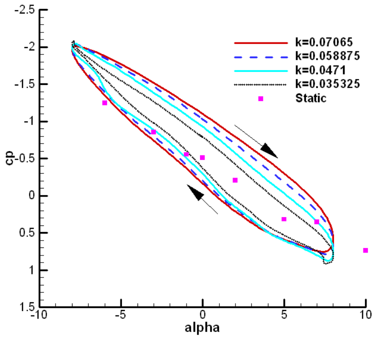
(c) Upper Surface, x/c=30%



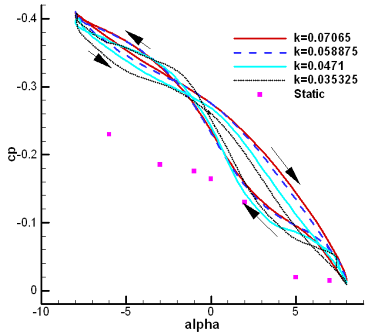
(d) Upper Surface, x/c=80%

Figure 4 Variations of pressure coefficient with alpha at different position on upper surface of the airfoil,(α_0=0).

As shown in these figures, hysteresis loops in the upper surface of the airfoil at x/c=5-30% are counter clockwise. This indicates that the flow in increasing the angle of attack lags that of the decreasing angle of attack. It is due to the wake effects that are shed to the free stream. By inspecting this figure it is clearly seen that the reduced frequency has pronounced effect on the surface pressure near the leading edge, For these pressure ports, x/c=5% and 10%, as the reduced frequency is increased from k=0.035 to k=0.0706, the width of the hysteresis loop increased. It found that by increasing the reduced frequency, continuous shedding of vortices to free stream is increased and the flow becomes more unsteady. Therefore variations of C_p with alpha in figure 4 shows that the hysteresis loops become larger as reduced frequency increase. Figure 4a shows that the maximum pressure coefficients occur near the leading edge at x/c=5%. Furthermore x/c=80%, figure 4d, 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, in this position flow separation has occurred, the direction of the hysteresis loops changes from counter clockwise to clockwise (lag to lead).



(a) lower Surface, x/c=10%



(b) lower Surface, x/c=70%

Figure 5 Variations of pressure coefficient with alpha at different position on lower surface of the airfoil,(α_0=0).

Figures 5(a-b) shows variation of pressure coefficient on the lower surface. The directions of the hysteresis loops at x/c=10% are clockwise and define that the motion has a lead phase. But in figure 5b, hysteresis loops show an "8" shape. In this position (x/c=70%) the direction of the hysteresis loops changes from counter clockwise to clockwise (lag to lead) and flow separation has occurred. By investigating in this figure the lead loop by increasing the reduced frequency become larger than the lag loop it found that by increasing the reduced frequency shedding the vortices to free steam is increased and the unsteadiness effects were strong. There is a lower pressure variation on the lower surface compared to the upper surface. Near the trailing edge of the airfoil the pressure variations become negligible. Figure 6-7 shows variation of the dynamic pressure coefficient with dimensionless time for upper and lower surface pressure taps, (x/c= 5-80%, upper-x/c=10-70%, lower) and for reduced frequency, k=0.07065. For this figures,(6a-6b) the model was set to an angle of attack 0 degree and for the figures,(7a-7b) to an angle of attack 5 degrees and oscillated at amplitude of ±8 degrees. By inspecting figure 6a, it is clearly seen that for pressure taps located at x/c=5% magnitude of C_p start to increases sharply by further increasing the angle of attack. 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 variation of C_p with non dimensional time follow the variations of the 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=60, 70, 80%) the flow is separated and the pressure variations decrease.

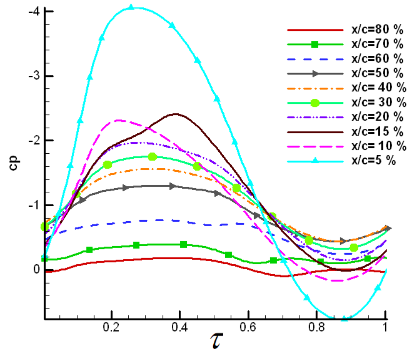


Figure 6a Variations of C_p with non dimensional time, τ ,(α_0=0).upper surface taps (k=0.07065)

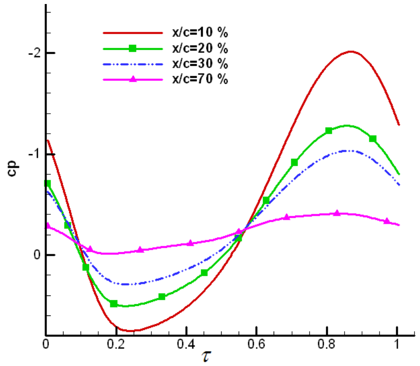


Figure 6b Variations of C_p with non dimensional time τ ,(α_0=0).lower surface taps (k=0.07065)

As shown in figure 7a the maximum pressure suction is on the upper surface, near the leading edge (x/c=5%) and about $|C_p|_{max}$=6. That is larger than the maximum pressure suction in figure 6a $|C_p|_{max}$=4. It found that increasing the mean angle of attack increase the maximum pressure suction furthermore flow separation is moved forward. The pressure variations on the lower surface of the airfoil in comparison with the upper surface are less. Because of asymmetric geometry of this airfoil, flow unsteadiness has fewer effects in the lower surface positions.

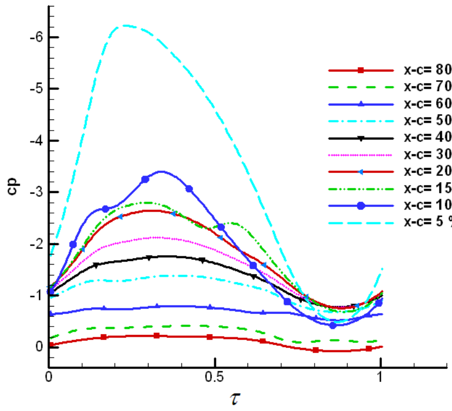


Figure 7a Variations of C_p with non dimensional time τ ,(α_0=5).upper surface taps (k=0.07065)

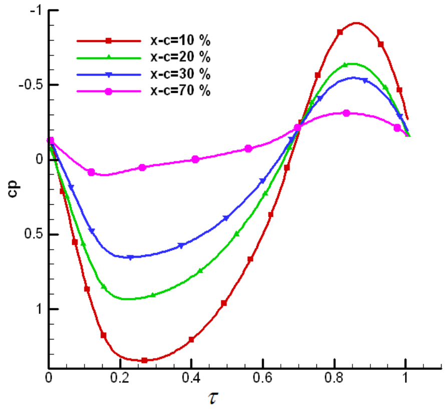


Figure 7b Variations of C_p with non dimensional time, τ ,(α_0=5).lower surface taps (k=0.07065)

Figure 7b shows variation of C_p with non dimensional time on lower surface positions. By comparing with figure 6b, pressure coefficients signatures are positive and effect of unsteadiness are fewer than other case.

In this section, effects of increasing the reduced frequencies on the shape and size of pressure coefficient hysteresis through the stall onset to light and deep stall were presented. Figure 8a shows variation of C_p versus angle of attack near the leading edge (5%) on upper surface at oscillation with 5 degrees mean angle of attack and 8 degrees amplitude. Throughout most of the upstroke motion flow remained attached to the upper surface of the airfoil. At low reduced frequencies hysteresis loop represents beginning down stroke flow separates and light stall occurs. The effect of the increasing the reduced frequency is to delay the phase or angle within oscillation cycle at which the various boundary layer and stall events occurred. Therefore high reduced frequency causes to delay the light stall to stall onset.

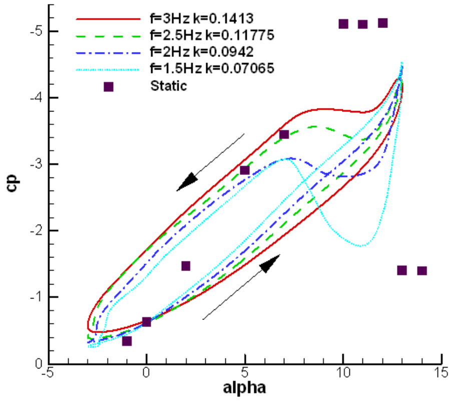


Figure 8a Variations of C_p with alpha, (α_0=5) and amplitude 8 degrees

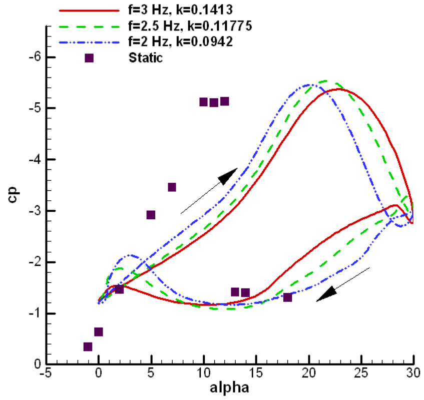


Figure 8b Variations of C_p with alpha, (α_0=15) and amplitude 15 degrees

Figure 8b shows variation of C_p with angle of attack at oscillation with 15 degrees mean angle of attack and 15 degrees amplitude. The results also show that the reduced frequency not only caused a systematic delay in onset of dynamic stall, but also determined whether the airfoil stalled well before α_{max} , or near the top of the oscillation cycle . For the figure 8b, the airfoil oscillation exceeded the static stall by a big margin. Flow reversals take place in boundary layer at the trailing edge. Flow separation at the leading forms strong vortex- like disturbance. By further increasing the angle of attack, vortex convects over chord. Vortex reaches trailing-edge, flow progresses to a state of full separation. When angle of attack becomes low enough, flow reattaches front to back. The hysteresis loops shows the deep stall phenomena and the powerful effect of reduced frequency. Vortex formation and decreasing the leading edge pressure suction is delayed with increasing the reduced frequency.

CONCLUSION

An extensive experimental study was conducted to measure the unsteady pressure and investigate the flow phenomena over a pitching airfoil from low to high angles of attack. At these mean angles of attack, hysteresis 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 reduced frequencies. Four reduced frequencies of oscillation were used for the pitching motion in low mean angle of attack. The higher reduced frequencies resulted larger hysteresis loop which was due to strong effects of unsteadiness. Furthermore, the effect of reduced frequency on dynamic stall events is presented. The onset of trailing-edge flow reversal and leading edge vortex formation occurred at an angle that increased with increasing reduced frequency. In addition, vortex shedding is delayed with increasing reduced frequency. At the same time, increasing the reduced frequency delays the onset of flow separation to a higher angle of attack and also delays the onset of flow reattachment.

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