Effect of Oscillation Amplitude on the Aerodynamic Behaviour of a Pitching Wing

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Abstract. A series of experimental study is conducted to explore the effects of oscillation amplitude on a harmonically pitching wing where the cross section is used in a 660 kW wind turbine under construction. The corresponding lift and real time pressure coefficients at three sections of the model are examined. The test covers a wide range of angles of attack at prestall, stall, and deep stall regions. The results show that amplitude of the motion is of great importance in the unsteady study and affects the maximum aerodynamic coefficients, onset of separation, hystersis loops, and stall characteristics significantly.

Key words: oscillation amplitude, wind turbine, separation, hysteresis, stall.

1. Introduction

Renewable energy devices such as wind turbines are playing a significantly increasing role in the generation of electrical power. However, these devices work in complicated unsteady flow fields. Such problems include the challenges in understanding and predicting the unsteady blade airloads and rotor performance. Wind turbines are also subjected to complicated environmental effects such as atmospheric turbulence, ground boundary layer effects, directional and spatial variations in wind shear, thermal stratifications, and the possible effects of an upstream unsteady wake from a support structure, tower shadow. Because the blade loads and performance of a wind turbine are directly determined by unsteady aerodynamic forces, a better understanding of the underlying fluid dynamics is essential if accurate modeling of the rotor aerodynamics and acceptable predictions of the turbine loads and power generation are to be made [1-7].

Although there is extensive information on forced unsteady surface pressure and the corresponding aerodynamic loads on two and three dimensional airfoils undergoing various motions, unfortunately less attention is paid to the effect of oscillation amplitude on the aerodynamic coefficients of a harmonically pitching wing. Soltani, et al have conducted a series of experimental study over a pitching airfoil and have investigated its effect on the aerodynamic efficiency [7].

Thus, to examine the effect of oscillation amplitude an extensive experimental study is conducted on a rectangular pitching wing. The airfoil used in this wing is presently used in a 660 kW wind turbine blade under construction. Surface pressure readings were recorded to extract the lift coefficients at tip, middle, and root sections of the model. Moreover, steady experiments were done and the results are compared with those of unsteady measurements. The test matrix was such that it contained all of the possible working conditions of the wind turbine. The mean angle of attack, α_0, was set to 5 degrees; the oscillation amplitude, d, to ±5, ±8, ±11 deg.; and the reduced frequency, k, was set to 0.026.

2. Experimental facility

All tests were conducted in the subsonic wind tunnel where its schematic is shown in Fig.1. The tunnel is of closed return type and has a total dimension of 3.8×6.5×18 meters where the wind speed in the working section reaches 100m/s. The tunnel has a closed square test section of 80×80×200 cm^3.

The model used in this investigation had 25cm chord and 60 cm span bounded by its root section to the tunnel wall through a splitter plate (Fig. 2).Three sections were considered on the model at tip, middle, and root areas to study the pressure variations at different conditions. Each section had 25 pressure holes connected to a differential pressure transducer. The oscillation system to produce harmonic pitching oscillations included an inverter, an AC motor, and connecting arms such that all the test conditions in the test matrix could be done.

3. Results

As mentioned before, the main purpose of this experimental study is to examine the effects of changing the oscillation amplitude on the aerodynamic coefficients of a rectangular pitching model. The corresponding lift and pressure coefficients are presented in the following paragraphs as well as the disscussion about the effects of the amplitude.

3.1. Effect of Oscillation Amplitude on the Lift Coefficients

The effects of amplitude on the lift coefficients at the tip section of the model are shown in Fig.3. As illustrated, higher oscillation amplitude causes the lift coefficient to increase rapidly. However, the homocentric manner of the lift curves shows the same lift coefficient slope for all curves shown in Fig. 3. Another effect of the amplitude on the C_l data is the increase in the width of the hysteresis loops at higher angles of attack, as seen from Fig.3. Lift values in the upstroke motion are affected more by the amplitude than the C_l values during the down stroke one. Indeed, in the up stroke motion the differences between the lift coefficients from d = 5 to d = 8 deg. remain the same as those from d = 8 to d = 11 deg., Fig. 3.

Furthermore from Fig.3 it is seen that in the upstroke motion the lift values show phase lag at each angle of attack relative to their corresponding static data for all oscillation amplitudes examined here. In contrast, in the down stroke motion the lift coefficiets have phase lead relative to their static values. Besides, the angle of attack at which the maximum lift coefficients occur are $\alpha = 10$ at d = 5, $\alpha = 13$ at d = 8, and $\alpha = 16$ at d = 11. Figure 3 also shows that as the oscillation amplitude increases, C_{l_α} in the down stroke part of the motion decreases slightly while in the upstroke motion its value is almost independent of the oscillation amplitude.

Figure 4 shows variations of the lift coefficients for the middle section of the model versus angle of attack for the aforementioned oscillation amplitudes. Similar to the tip section, Fig.3, the maximum lift coefficient is increased from d = 5 to d = 8 deg, but, as the amplitude increases to 11 deg., $C_{l,\max}$ does not vary significantly. This behavior is due to the onset of flow separation, characterized by the figure eight shape phenomenon which occurs at $\alpha \approx$ 13 deg., Fig. 4. This limits further increase of the maximum lift coefficients for the higher amplitudes. Another fact about Fig.4 is that initially at d = 5^o dynamic $C_{l,\max}$ is higher than its corresponding static value. At d = 8 deg. it is approximately equal to its static value, and falls lower than the static C_l for higher oscillation amplitude, d = 11. This phenomenon is mainly due to the onset of separation.

The lift curve slopes in Fig.4 are the same for d = 5 and d = 8, but as the flow approaches the onset of separation, d = 11, the slope varies significantly. By increasing the oscillation amplitude, the hysteresis loops grow like those of the tip section. However, at d = 11 deg. the phase lag and lead in the upstroke and down stroke motions are converted to the phase lead after $\alpha \cong$ 5 deg. Comparison between Figs. 3 and 4 reveals that although the flow is separated in part of the airfoil at the middle section, the lift coefficients are higher at this station, mainly because of the downwash effect at the tip section which reduces the effective angle of attack and consequently the corresponding lift coefficients.

Variations of the lift coefficient for the root section of the wing versus angle of attack are shown in Fig.5. The maximum lift coefficient is increased by increasing the oscillation amplitude. The $C_{l,\max}$ at the root section occurs after the onset of separation, but the effect of amplitude on its value is different from those of the tip and middle sections, Figs.3 and 4. Moreover, the maximum lift coefficients for all amplitudes are higher than their corresponding static one.

The lift curve slope for the Fig. 5 data, in contrast to the previous figures(Figs. 3 and 4), does not change prior to $\alpha \approx 5$ deg., Fig. 5. As the amplitude increases, the width of the hysteresis loops increases too, Fig.5. Another effect of the oscillation amplitude is on the figure eight shape phenomenon which delays the onset of separation. In other words, the figure eight phenomenon happens at $\alpha \approx 8$ for d = 5, $\alpha \approx 8$ for d = 8, and $\alpha \approx 11$ for d = 11 deg. in the down stroke motion. In addition, for d = 5 both the up and down stroke motions have phase lead relative to their static values which are converted to a phase lag in the up stroke motions at higher oscillation amplitudes, Fig. 5.

3.2. The Effect of Oscillation Amplitude on Pressure Coefficients

The real time pressure coefficients versus the location of pressure taps(x/c) at the tip section are shown in Figs. 6-8. Pressure data for both suction and pressure sides of the model are shown in the figures.

Increasing the oscillation amplitude increases the maximum pressure coefficient, $C_{p,\max}$, noticeably. The maximum pressure coefficient occurs at the leading edge area of the model where its value is $C_{p,\max} = 1$ at $\tau \approx 0.3$, 1.3 at $\tau \approx 0.35$, and 1.5 at $\tau \approx 0.4$. This means that the higher oscillation amplitude causes a time lag in the curves.

Another important effect is that for d = 5 deg dynamic C_p becomes almost constant for $x/c \geq$ 0.4 which indicates that the flow over the rest of the airfoil does not contribute in producing lift, however by increasing the amplitude to d = 8 and 11 degrees as seen from Figs. 6-8, the flow remains attached over a larger portion of the wing. Figures 9-11 show the pressure variations for the middle section of the wing and Figs. 12-14 are for the root section. These figures show the same trends as those of the tip section. The comparison between the pressure coefficients at the three sections shows the highest maximum pressure coefficients at the middle section and the lowest one at the tip section. The noticeably lower coefficients at the tip section are due to the downwash effects and its interaction with the leading edge vortex, causing the lowest $C_{p,\max}$.

3. Conclusion

An extensive experimental study is conducted over a three dimensional pitching wing. The section of the model belongs to a 660 kW wind turbine under construction. Static and dynamic pressure variations recorded from the three sections over the model and were used to extract the lift and pressure coefficients to investigate the effects of changing the oscillation amplitude on the aerodynamic coefficients. The results show considerable influence of the oscillation amplitude on the maximum lift coefficients, lift curve slopes, onset of separation, stall characteristics, and hysteresis loops. Moreover, at higher oscillation amplitudes the amount of separated region and also the role of different locations on the model in the determination of aerodynamic coefficient values are changed considerably.

Figure 1. The Schematic view of the wind tunnel

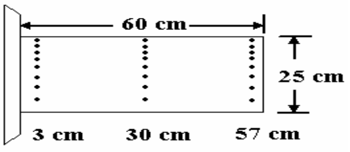

Figure 2. The upper view of the model and pressure ports

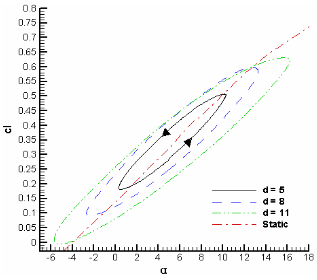

Figure 3. Effect of oscillation amplitude on the lift coefficients at the tip section

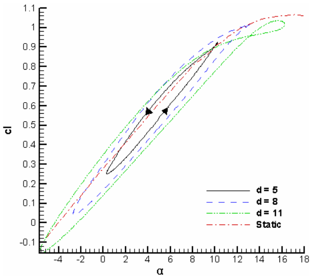

Figure 4. Effect of oscillation amplitude on the lift coefficients at the middle section

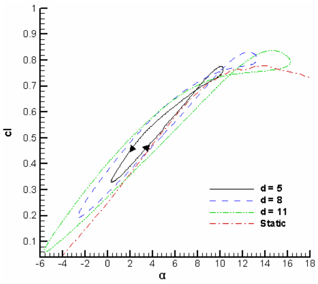

Figure 5. Effect of oscillation amplitude on the lift coefficients at the root section

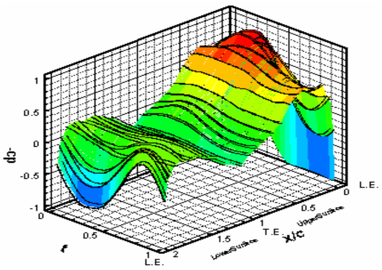

Figure 6. Real time variations of the C_p for Pressure ports located at the tip section, d = 5 deg.

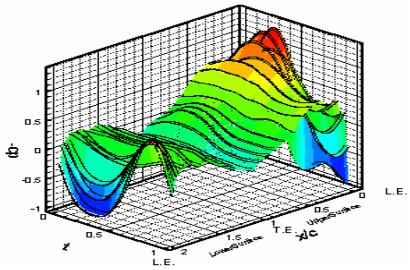

Figure 7. Real time variations of the C_p for Pressure ports located at the tip section, d = 8 deg.

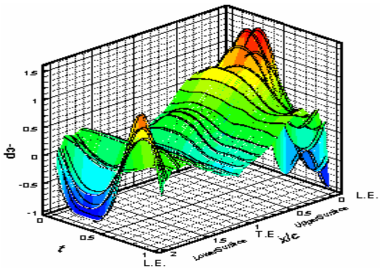

Figure 8. Real time variations of the C_p for Pressure ports located at the tip section, d = 11 deg.

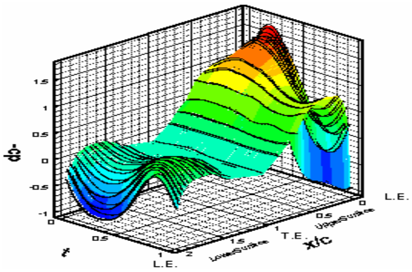

Figure 9. Real time variations of the C_p for Pressure ports located at the middle section, d = 5 deg.

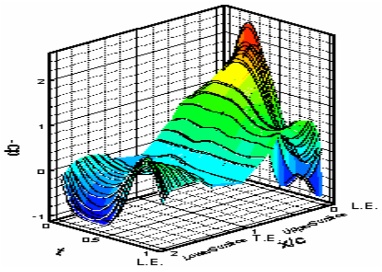

Figure 10. Real time variations of the C_p for Pressure ports located at the middle section, d = 8deg.

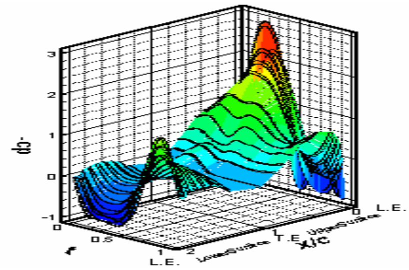

Figure 11. Real time variations of the C_p for Pressure ports located at the middle section, d = 11 deg.

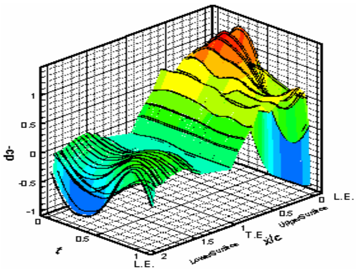

Figure 12. Real time variations of the C_p for Pressure ports located at the root section, d = 5 deg.

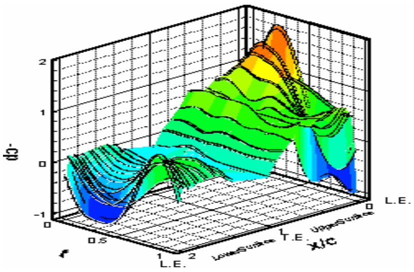

Figure 13. Real time variations of the C_p for Pressure ports located at the root section, d = 8 deg.

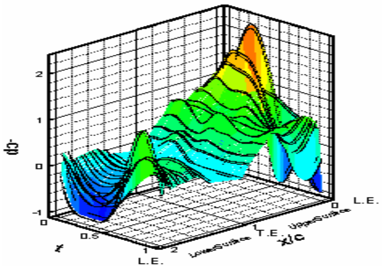

Figure 14. Real time variations of the C_p for Pressure ports located at the root section, d = 11 deg.

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