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SPECTRAL ANALYSIS OF THE BOUNDARY LAYER ON A PLUNGING AIRFOIL

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ABSTRACT

The effects of periodic unsteady flow through plunging motion on the boundary layer transition along the suction surface of a typical wind turbine blade section are experimentally investigated. The state of the boundary layer at different conditions was determined using multiple hot-film sensors through the frequency domain analysis. The appearance of laminar/turbulent spikes at dominated frequencies revealed the boundary layer characteristics. Power spectral of the hot-film signals showed that the transition locations as well as the separation region were a function of the reduced frequency and mean angle of attack.

INTRODUCTION

The flow on horizontal axis wind turbine rotors is highly unsteady due to the control input angles, blade flapping, structural response, wake inflow, periodic variations in local velocity and sweep angle. Thus, the unsteady aerodynamic behaviour of the blade sections must be properly understood to enable accurate predictions of the air loads and aero elastic response of the rotor system [1-5].

Furthermore, the laminar/turbulent properties of the flow field have a significant influence on the skin friction and separation that affect lift and drag characteristics of the blade. The effect of unsteady parameters on boundary layer transition is important to the design of wind turbine blades. For most wind turbine rotors with smooth surfaces, TS instability, laminar separation, or turbulence contamination govern the transition location [6].

Boundary layer of the oscillating airfoils have been studied in the past using multiple hot-films [7-9]. All of these studies have focused on pitching airfoils. The case of sinusoidal plunge oscillations has received much less attention in past years because a pure plunge oscillation was thought to have much less importance in practical applications. However, it has been known that most of the angle of attack changes that the rotor blades encounter are due to the variations in flapping and elastic bending of the blade, which is modelled with plunging type motion and also, a sinusoidally plunging wing can generate a thrust force [10-12].

NOMENCLATURE

PSD		Power spectral density
TS		Tollmien Schlichting
x	[m]	Distance from the leading-edge
c	[m]	Airfoil chord
f	[Hz]	Frequency
U_∞	[m/s]	Free stream velocity
k	[-]	Reduced frequency, $k=\pi fc/U_\infty$
h	[m]	Plunging displacement
$\bar{h}$	[m]	Plunging oscillation amplitide
t	[s]	time
Special characters		
α	[deg]	Angle of attack
α_0	[deg]	Mean incidence angle
$\bar{\alpha}$	[deg]	Amplitude of the pitching motion
τ	[-]	Dimensionless time
ω	[rad/s]	Angular frequency
Subscripts		
eq		Equivalent motion

Note, that in a plunging motion, the model moves vertically up and down inside the tunnel test section. Therefore, only pure angle of attack has the effective role and pitch rate effect due to the pitching motion is isolated from the problem.

In this study, the unsteady boundary layer behaviour of an airfoil oscillating in plunge is investigated using power spectrum density function to analyse the hot-film signals located on the suction surface of the model. The experiments were conducted at a free stream velocity of 30m/sec, corresponding to the Reynolds number of 0.42×10^6 and at oscillation amplitude of ±8cm. The behaviour of the boundary layer is examined at various reduced frequencies from low to moderate mean angles of attack.

EXPERIMENTAL APPARATUS

The experiments were conducted in a subsonic wind tunnel in Iran. It is of closed return type and has a test section of 80cm×80cm×200cm and operates at speeds from 10 to 100 m/sec. The inlet of the tunnel has a 7:1 contraction ratio with four large, anti-turbulence screens and honeycomb in its settling chamber to reduce tunnel turbulence to less than 0.1 percent in the test section.

The model has 25cm chord and 80cm span and is the critical section of a 660 kW turbine blade under construction in Iran. The hot-films that were used are special version of the flush-mounting DANTEC probe, Glue-on type. The sensor is deposited on a KaptonTM foil with thickness of about 50µm. Its sensor is connected to a gold-plated lead area. Eight hot-films were located along the chord at an angle of 20 degrees with respect to the model span to minimize disturbances from the upstream one, Figure 1. The position of each sensor on the model is given in table I. Data are obtained using constant temperature anemometer (CTA). Each CTA data was transformed to the computer through a 64 channel, 12-bit Analogue-to-Digital (A/D) board capable of an acquisition rate of up to 1000 kHz.

Raw data were then digitally filtered by a low-pass filtering routine. During the filtering process, cut off frequency were obtained using power spectrum estimation or frequency domain analysis. In this method the noise that dominates the signal in the time domain appears only as a single peak or spike in the frequency domain. Once the noise frequency is determined, it can be filtered and a clean signal is then obtained. Figure 2 shows an example of the PSD for one of the hot film channels. From this figure, the cut off frequency is identified and is found to be about 150 Hz. Above this frequency, there exists white noise in the signal.

The plunging system for the present experiments incorporates a crankshaft to convert the circular motion of the motor to the reciprocal motion, which is transferred to the model by means of rods, Figure 3. The pitch rotation point is fixed at about the wing quarter chord. The plunging displacement was varied sinusoidally as: $h = \bar{h}\sin(\omega t)$.

The tests were conducted at a Reynolds number of 0.42×10^6 for oscillation amplitude of ±8cm over a range of reduced frequencies, k=0.05-0.11, which are the effective reduced frequencies for this section of the wind turbine blade when operating in the field. The model was set to mean angles of attack of 5, 10 and 18 degrees that correspond to the regions before, around and beyond static stall angle of attack of the airfoil, respectively. The static stall angle of attack for this particular airfoil is about 11 degrees [13].

Figure 1 Model along with the location of the hot films

Figure 2 PSD of one channel for determining the cut off frequency

Figure 3 Plunging oscillation system

Table 1 Location of the hot film sensors

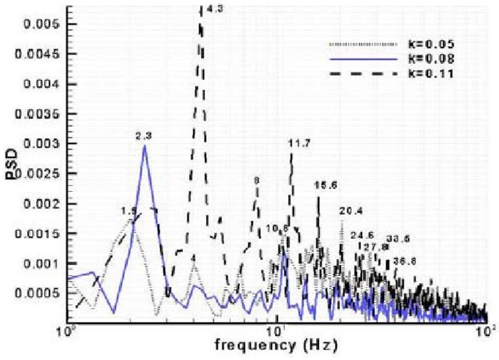
Hot film	Location (x/c)
s_1	0.08
s_2	0.14
s_3	0.22
s_4	0.29
s_5	0.37
s_6	0.47
s_7	0.57
s_8	0.68

RESULTS AND DISCUSSION

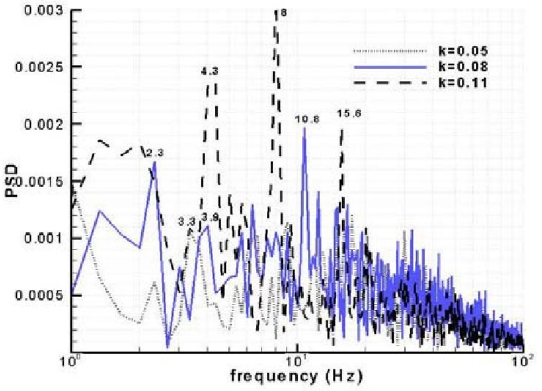
The boundary layer characteristics are determined through the frequency domain analysis. If the signal is laminar with low turbulent spikes, the lower part of the spectrum will show higher frequency range. However, if the flow is predominately turbulent with occasional laminar flow (laminar spikes), the signals will show a higher PSD in both upper and lower range of frequencies. A completely turbulent signal will show high PSD only in the higher frequency range.

Figure 4 compares the power spectral of the hot film signals at various reduced frequencies. In this figure the model is set to a mean angle of attack of 10 degrees. The frequencies corresponding to the PSD's peaks are indicated on the top of them in the spectrum plots. In the first two channels, Figs 4a and 4b, it is seen that the amplitudes of the spikes are lower than the other channels ones for all reduced frequencies. This means that there is laminar flow in the vicinity of the leading edge for all reduced frequencies. In channel s_3, Fig. 4c, the boundary layer instability frequencies and also the amplitudes of the spikes grow for the case of k=0.11. It means that for this reduced frequency, TS instability frequencies may be present at this location, while for the other two reduced frequencies, k=0.05 and 0.08, the flow is still laminar. The spectrum plots of channels s_4 and s_5, Figs 4d and 4e, show that for k=0.11, the amplitudes of the spikes grow more and the combination of laminar-turbulent flow is apparent in these locations of the airfoil surface. For k=0.08, the boundary layer instability frequencies are appeared in channel s_5, Fig. 4e, and for the lowest reduced frequency, k=0.05, they are seen in channel s_6, Fig. 4f. In the last two channels, Figs 4g and 4h, it is seen that there are spikes in the lower range of frequencies of the spectrum and they disappear at higher frequency range. It means that there is no turbulent flow in this region and the flow may be separated. In the entire spectrum plots, note that the first frequency of PSD's peak is proportional to the oscillation frequency, e.g., it is increased from f≈1.3Hz for k=0.05 to f≈4.3Hz for k=0.11. Further, there is a relation between the frequencies of the spikes in all spectrum plots. It seems that they are the coefficients of the oscillation frequency and are amplified when the boundary layer instability grows.

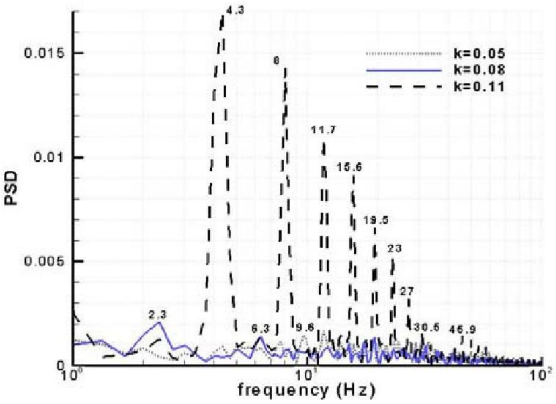
Fig. 5 shows the effect of the mean angle of attack on the power spectral of the hot film signals for the sensors s_2, s_5, and s_8. The reduced frequency is equal to k=0.08. It is seen that at x/c=0.14 the maximum amplitudes of PSD is related to the case of α_0=18º and for the other two mean angles of attack the flow is still laminar, Fig. 5a. At a location of x/c=37%, Fig. 5b, the maximum spikes are related to the case of α_0=10º, and for the lowest mean angle of attack the flow is still laminar. However, at a location of x/c=0.68, the maximum amplitudes of PSD is for α_0=5º and the PSD amplitudes of the other mean angles of attack are reduced with respect to the PSD of channel s_5. It means that with increasing the mean angle of attack, the appearance of laminar/turbulent spikes or TS instability frequencies move toward the leading edge.



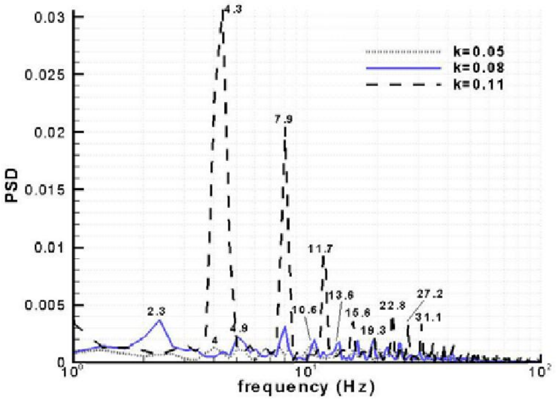
a) s_1, x/c=8%



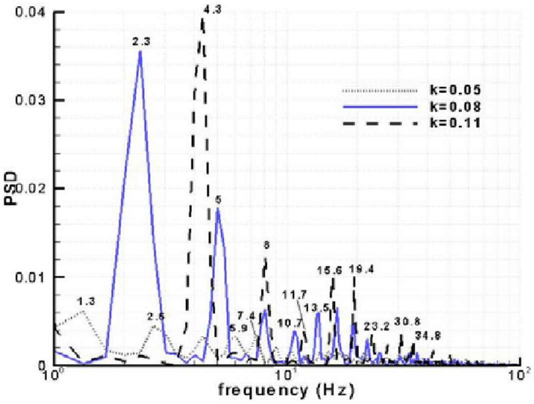
b) s_2, x/c=14%



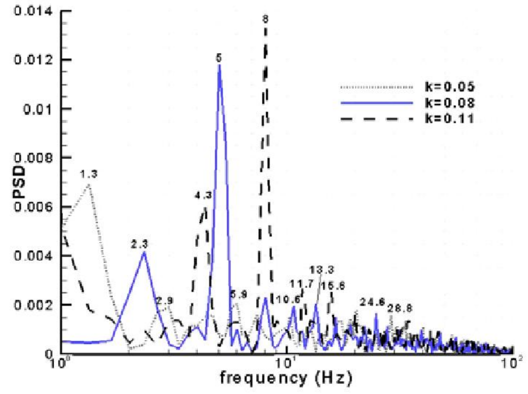
c) s_3, x/c=22%



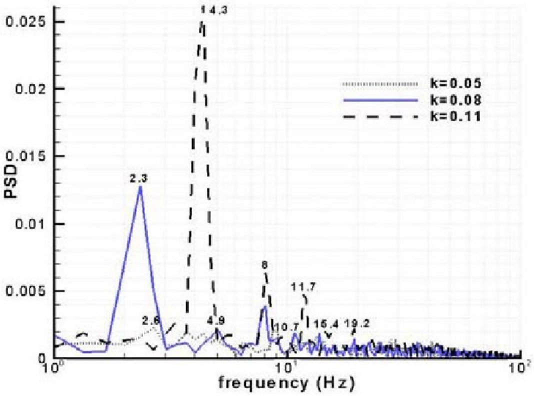
d) s_4, x/c=29%



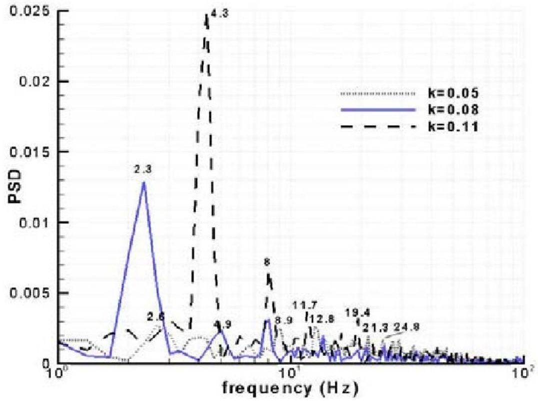
e) s_5, x/c=37%



f) s_6, x/c=47%

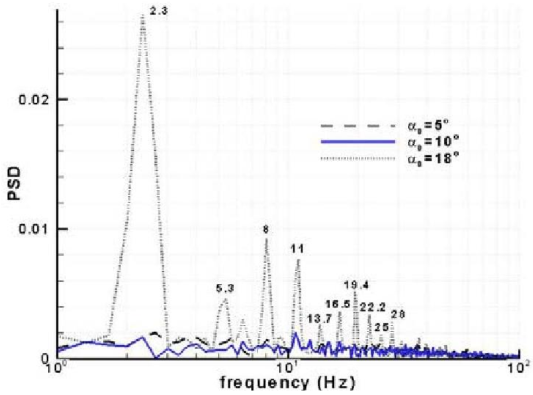


g) s_7, x/c=57%

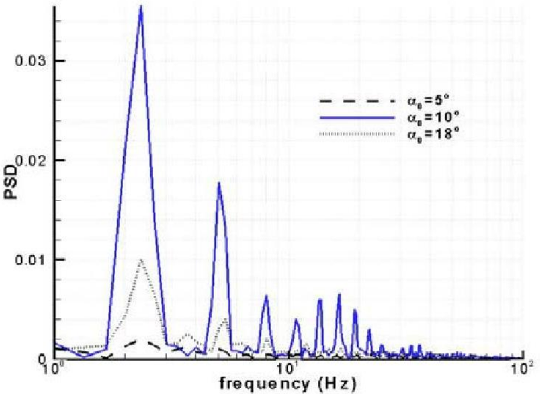


h) s_8, x/c=68%

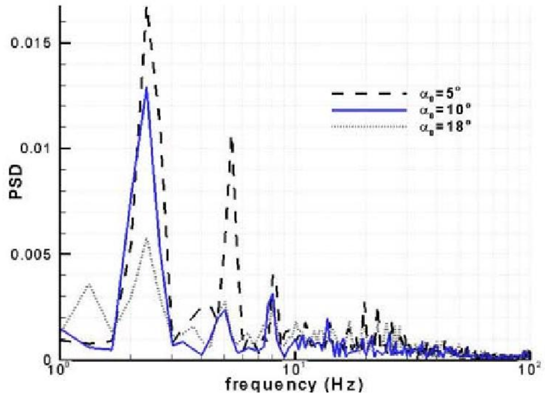
Figure 4 Variations of power spectral of hot film sensors with k, α_0=10º



a) s_2, x/c=14%



b) s_5, x/c=37%



c) s_8, x/c=68%

Figure 5 Variations of power spectral of hot film sensors with α_0, k=0.08

CONCLUSION

Frequency domain analysis of the hot film signals revealed that dominated frequencies of the boundary layer is a function of the reduced frequency and mean angle of attack. For almost all cases examined here, the flow was separated in the vicinity of the airfoil trailing-edge and the transition locations as well as the separation region were a function of the mean angle of attack.

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