Time-Frequency Analysis and Transitional Boundary Layer Investigation over a Pitching Airfoil

Hassan Akhlaghi\(^1\), Mohammad-Reza Soltani\(^2\)*, Mohammad-Javd Maghrebi\(^3\)

\(^1\) PhD Candidate, Department of Aerospace Engineering, Sharif University of Technology, Tehran, Iran
\(^2\) Professor, Department of Aerospace Engineering, Sharif University of Technology, Tehran, Iran (Presently, Visiting Professor, William E. Boeing Department of Aeronautics and Astronautics, University of Washington, Seattle, WA, USA)
\(^3\) Professor, Department of Mechanical Engineering, Faculty of Engineering, Ferdowsi University Of Mashhad, Mashhad, Iran

Abstract. Transitional boundary layer over a pitching airfoil at low Reynolds number (Re = 2.7×10\(^5\)) is experimentally investigated through the space-frequency and time-frequency analyses of hot-film signals. Boundary layer events are visualized based on the space-frequency and time-frequency plots. The precursor phenomena for turbulent as well as fully separated flows are presented based on the time-frequency analysis. A new technique based on the time-frequency analysis of hot-film signals is presented to measure the transition onset as well as the relaminarization locations. This technique is based on the analysis of high-frequency disturbances of the measured data. Special attention is focused on the spatial/temporal progression of the transition onset and the relaminarization points, compared to the static values, for different oscillation frequencies and amplitudes. Investigations are performed prior to, within and beyond the static stall angle of attack conditions. The results obtained by the new technique will be discussed and compared with the observations from the previous investigators.

Keywords: Pitching Airfoil, Hot-Film Sensor, Time-Frequency Analysis, Space-Frequency Analysis, Transition Onset, Relaminarization.

* Author to whom correspondence should be addressed, Tel: +98 (21) 66164601, +98 (935) 5932356, Fax: +98 (021) 66022731, Email: msoltani@sharif.edu
NOMENCLATURE

\( A \) = wave amplitude
\( c \) = airfoil chord (m)
\( E \) = output voltage of hot-film sensor (mV)
\( E_0 \) = offset voltage (mV)
\( E_{HP} \) = high-pass filtered signal (mV)
\( E_{LP} \) = low-pass filtered signal (mV)
\( E_{RMS} \) = a root-mean-squared parameter obtained from hot-film signal (mV)
\( f \) = wave frequency (Hz)
\( f_0 \) = frequency for model oscillation (Hz)
\( \text{Re} \) = Reynolds number based on the chord
\( x \) = spatial location along the chord (m)
\( \alpha \) = angle of attack (deg)
\( \alpha_a \) = the amplitude of pitching oscillation (deg)
\( \alpha_m \) = mean angle of attack of pitching oscillation (deg)
\( \alpha_{ss} \) = stall angle of attack for static condition (deg)
\( \kappa \) = reduced frequency of model oscillation
\( \tau \) = quasi-wall-shear stress
\( \text{AOA} \) = angle of attack
\( \text{BL} \) = boundary layer
\( \text{CTA} \) = constant temperature anemometer
\( \text{FS} \) = fully separated
\( \text{FT} \) = fully turbulent
\( \text{LEV} \) = leading-edge vortex
\( \text{LTT} \) = laminar-to-turbulent transition
\( \text{LSB} \) = laminar separation bubble
\( \text{QWSS} \) = quasi-wall shear stress
\( \text{RA} \) = reattached
\( \text{RMS} \) = root-mean-squared
\( \text{TO} \) = transition onset
\( \text{TS} \) = Tollmien-Schlichting

1. INTRODUCTION

Boundary layer transition plays an essential role in the performance of aerospace vehicles, wind turbines, turbomachines, etc. Detailed investigation of the laminar-to-turbulent transition (LTT) location could be beneficial for performance analysis as well as the flow control of such machines. Aerodynamic designers try to increase the range of laminar flow over the bodies to reduce drag; thus the transition position has become an important design parameter [1].
A brief review of the literature survey shows that experimental detection of the boundary layer (BL) events have been traditionally performed using different approaches based on the surface pressure data, hot-wire and hot-film data, acoustic data, and flow visualization techniques. The hot-film sensors have first been used primarily as a pointwise skin friction indicator [2]. Hot-film anemometry is a relatively nonintrusive technique and allows transition detection with high temporal resolution. The measurement principle is based on the convective heat transfer from the heated element to the fluid. The hot-film anemometry has successfully been used to investigate BL events at both steady and unsteady conditions. Interpreting the BL events based on the raw data of the hot-film outputs in the form of voltages or quasi-wall shear stress values, is the most common method. Stack and co-workers [3-4] developed a technique based on the hot-film output voltages to detect separation points. In their technique, the adjacent hot-film sensors, located before and after the separation point, exhibit a 180 deg phase-shift in their output signals. Based on their proposed technique, separation and reattachment points could be detected. This technique is applicable for both steady and unsteady airfoils. However, it is more effective for unsteady airfoils, where separation and reattachment points due to the body motion is more pronounced. Hodson et al. [5] proposed a formula for determination of a quasi-wall shear stress parameter based on the hot-film voltages. Using this formula, one could determine qualitatively wall shear stress distribution along the BL from the hot-film measurements. Stack et al. [3] measured the frequency of the Tollmien-Schlichting (TS) waves based on the frequency analysis of the hot-film data. The field contours of the hot-film voltages were employed to visualize the BL events such as laminar separation bubble (LSB), dynamic stall vortex, transition and relaminarization, and reattachment processes over a pitching airfoil [6-7]. Lee and co-workers [8-9] detected BL events over a pitching airfoil from the raw data measured by the closely-spaced multiple hot-film sensors. Rudmin and co-workers [10-11] measured the
separation and transition locations for a pitching airfoil based on the cross-correlation and spectra of the hot-film data. Gardner and co-workers [12-14] investigated laminar, transitional, and turbulent BL over a pitching airfoil from the hot-film raw voltages. Following the previous experimental measurements of the BL events from the hot-film sensors, the current work investigates the unsteady transitional BL over a pitching airfoil using time-space and time-frequency interpreting of the hot-film outputs that to the authors’ knowledge, is not reported extensively in the literature survey. Also, a new RMS parameter is defined based on the time-frequency analysis of the hot-film signals which could be employed for unsteady transition and relaminarization onset detection. This work follows the previous investigations of Soltani and co-workers [15-19] on explaining the aerodynamic behavior of the current airfoil model in steady and unsteady conditions.

2. EXPERIMENTAL SETUP

All experiments were conducted in a low-speed wind tunnel. It is an open circuit tunnel with a rectangular test section of 80×100×200 cm$^3$. The inlet of the tunnel has three large, anti-turbulence screens and honeycomb in its settling chamber to reduce the tunnel turbulence level and to produce a uniform flow in its test section. Measurement inaccuracies of the freestream parameters are listed in Table 1. A model with 25 cm chord and 80 cm span has been used in this investigation. The model has been constructed of fiberglass with a measured accuracy of ±0.1 mm. To measure the pressure distribution over the surface of the model, 63 pressure taps were used, congested more at the leading edge (Fig. 1). The surface pressures were measured using differential pressure sensors with pressure ranges from 0.075 to 1.0 psi and with a maximum full span error of 0.15%. Sixteen hot-film sensors are located on the airfoil’s upper surface at $0.204 \leq x/c \leq 0.752$; see Table 2. The employed hot-film sensor is manufactured by
Senflex®, model SF9902 which is a single-element hot film sensor on a 120 mm × 20 mm substrate. The substrate is 2-mil thick Upilex® S polyimide film. Hot-film sensors have been installed over the model surface using a suitable adhesive. The adhesive has a thickness of 3 mil and has been designed for the environment temperature. The lead wires were soldered to the ends of the sensors and were carried to the connector. The length of the wire from the surface to the CTA was about 4 meters. Un-calibrated hot-film data were used to define the quasi-wall-shear stress and provided semi-quantitative information about the state of the boundary layer development. Hot-film outputs were obtained by DANTEC constant temperature anemometer (CTA). All hot-films were sampled at a frequency of 5 kHz. An overheat ratio of 0.9 was selected for all hot-films in order to obtain a much more appropriate response and to avoid the film deflection. To eliminate white noise from the signals, a low pass filter was employed.

A specially designed mechanism for pitching, plunging, and combined pitching-plunging oscillating motions, capable of oscillating the airfoil sinusoidal at various amplitudes and frequencies is designed and manufactured for the present experiment. Figure 2 shows a schematic of the aforementioned mechanism. The accuracy of pitching actuation is 0.0013 deg. The oscillation frequency was measured with an accuracy of ±0.02 Hz. The angles of attack were measured using a 14-bit encoder with an accuracy of 0.022 deg. Different sources of errors that may cause erroneous measured data are non-uniformity in the flow and turbulence level, angle of attack (AOA) setting, pressure sensors, airfoil model construction, encoder, A/D board, hot-films, pressure tap locations on the airfoil, wall effect, model blockage, etc. An extensive error analysis was performed to validate the acquired data.

3. PHYSICAL DESCRIPTION

For a low Reynolds number flows over an airfoil, there exists a laminar-to-turbulent transition (LTT) zone over the suction side of the airfoil, after a laminar separation bubble
(LSB). The LTT zone is somewhere between the laminar separation and the turbulent reattachment points. Actually, transition occurs when there is an increase in the pressure in the boundary layer due to the formation of a separation bubble [20]. The reattachment process is due to a turbulent wedge that spreads from a point in the detached shear layer. For an oscillating airfoil, the BL events vary during the oscillation cycle. Figure 3 shows output voltages for hot-film sensors installed over the upper surface of the airfoil for a pitch oscillation with a frequency of 1.02 Hz, an amplitude of 2 deg, and about AOA of 6 deg. The BL events from laminar flow to turbulent one could be captured from the figure. As it is seen, the mean values of the output of each sensor vary with time according to the motion of the body. This variation is due to the fact that each sensor experiences different values of shear stress with time as the angle of attack is changed. In the laminar flow region, i.e., signals (a) and (b) in Fig. 3, both sensors have low voltage amplitudes. As the boundary layer become unstable, periodic turbulent bursts start to appear with an associated increase in the hot-film output amplitudes as it is seen in signal (c). The initial appearance of the peak values corresponds to the transition onset. The amplitude reaches maximum at peak transition (d). In the turbulent region, there is a slight decrease in the amplitude level; see signals (e) and (f) in Fig. 3.

4. RESULTS AND DISCUSSIONS

In the present section, the experimental results obtained from the hot-film sensors are reported and discussed. The results from hot-film sensors are investigated and interpreted in four different categories, i.e. hot-film voltages, space-frequency analysis, time-frequency analysis, and transition/relaminarization onset detection based on the time-frequency analysis. The mean AOA was varied from zero to ten degrees that would cover all ranges of the attached and separated flows corresponding to before, within, and beyond the static stall
angle of attack ($\alpha_{ss}$) of the present airfoil. It should be noted that the static stall AOA for the current airfoil is about 11 deg for the present test condition. Two different oscillation frequencies ($f_0$) of 1.02 Hz and 2.55 Hz were considered that correspond to the reduced frequency values ($\kappa = \pi f_c U_{\infty}$) of 0.04 and 0.1, respectively. The wind tunnel velocity is set to 20 m/s. The airfoil pitch axis was located on the chord and at c/4 distance from the leading edge. The instantaneous angle of attack changes during the oscillation cycle as $\alpha(t) = \alpha_m + \alpha_a \sin(2\pi f_c t \cdot \pi)$. Figures 4 and 5 show the hot-film output voltages for different mean AOAs and for oscillation amplitudes of 2 deg and 5 deg. The trends for AOA have been indicated by thick gray lines in the figures. Time signals of the hot-film sensors reveal the flow characteristics over the model surface. For the cases with $\alpha_m = 0$ deg and $\alpha_m = 6$ deg, the output signals of the sensors placed in the upstream locations are smooth and have a sinusoidal shape. This indicates that these sensors are located in the laminar region. Moreover, the voltage changes for these sensors are small during the oscillation cycle. It is due to the fact that for these sensors, variations of the wall shear stress with respect to the angles of attack are small. As mentioned previously, the spatial and the temporal domains of the transitional and turbulent flows over the surface of the model could be observed from the output signals of hot-films. Some hot-film sensors experience all flow regimes, i.e. laminar, transitional, and turbulent flows in an oscillation cycle. According to Stack et al. [3], the adjacent hot-film sensors located before and after the separation point, have a 180 deg phase shift in their output time signals. For example, for the pitching case with a reduced frequency of 0.1 oscillating around a mean AOA of 0 deg, with an amplitude of 5 deg, Fig. 5(b), flow separation in the laminar flow region or LSB onset first occurs between the hot-film sensors located at $x/c = 0.524$ and $x/c = 0.556$. Moreover, for this case, the LSB ends somewhere between $x/c = 0.656$ and $x/c = 0.678$, Fig. 5(b). Separation in the turbulent flow is also could be detected by the 180 deg phase-shift technique too. For example, for the pitching case with
a reduced frequency of 0.1, oscillating around a mean AOA of 10 deg, with an amplitude of 5 deg. Fig. 5(b), turbulent flow separation could be first detected somewhere between $x/c = 0.204$ and $x/c = 0.252$. The most downstream location for the turbulent flow separation in the mentioned case occurs between $x/c = 0.626$ and $x/c = 0.678$. One could see from figures 4 and 5 that both separation and reattachment points vary with the instantaneous changes of AOA, mean AOA, and reduced frequency. Higher mean AOA and higher reduced frequency move both separation and reattachment points upstream.

In the following section, the space-frequency analysis of the hot-film outputs will be fully explained. The method along with an indepth derivation of the equations used will be explained. This method will be used to analyze the present experimental data. The un-calibrated hot-film data is used to provide semi-quantitative information about the state of the boundary layer development over the airfoil surface. The quasi-wall shear stress ($\tau$) is defined as [5]:

$$\tau = \left( \frac{E^2 - E_0^2}{E_0^2} \right)^3$$

(1)

Where, $E$ and is the instantaneous hot-film voltage and $E_0$ is the hot-film voltage at zero-flow condition. Using the Fourier series, a measured quasi-wall shear stress (QWSS) signal could be stated as:

$$\tau(x) = \sum_{n=0}^{\infty} A_n \sin(2\pi f_n x)$$

(2)

Where, $A_n$ denotes wave amplitude of the signal for each frequency. The space-frequency analysis of the QWSS parameter could be performed through plotting the contours of the wave amplitudes in the space-frequency domain, as it is shown in Figures 6 and 7. The colors correspond to the values of $\log(A_n)$. The results have been reported for different pitching cases with different oscillation frequencies, mean AOAs, and oscillation amplitudes.
Different events of the boundary layer could be detected from these space-frequency plots. The TS waves are indicated as the high energy frequencies before the transition occurs as marked in Figs. 6 and 7. The onset of the laminar separation bubble could also be captured from these figures where the amplitudes are minimum. At the separation point, the shear stress reaches its minimum value. Laminar, transitional, and turbulent regions of BL could be easily detected from the space-frequency plots. Laminar and turbulent flow regions are marked by L and T in Figs. 6 and 7. The transitional region occurs after LSB onset and it is indicated by large amplitudes that have a non-uniform frequency distribution. The transitional region is followed by the turbulent region with very high amplitude and with a uniform distribution in the frequency. At larger oscillation amplitude, Fig. 7, the regions of transitional and turbulent flows are larger. For oscillations around the mean angle of 10 deg, i.e., oscillation within and beyond $a_{ss}$ for this airfoil, all hot-film sensors experience turbulent flow. However, because of the unsteady motion of the model, separation points and transitional flow regions vary with time and this leads to complex realizations of these phenomena in the space-frequency plots.

For an oscillating body or even for a static model in the presence of the transitional flow which is unsteady, the signal of hot-film output is non-stationary. For a non-stationary signal, the statistical properties (such as mean, variance, spectral content, etc.) all change with time. As indicated by Trapier et al. [21], this kind of signal has to be studied using spectral descriptions that are functions of both time and frequency. In this study, the BL events are investigated using the spectrogram plots for the hot-film sensors. Similar investigations were previously done for interpreting the pressure transducers data for the intake analysis by Soltani and co-workers [22]. The idea behind the spectrogram is to apply FT to a windowed part of the signal with a finite duration instead of applying the entire signal. The details of the procedure could be found in [21]. Figure 8 (a-l) show the time-frequency analysis in the form
of spectrogram plots and are obtained from the hot-film outputs for different oscillation cases. The vertical axis corresponds to the frequencies of disturbances that range from zero up to 2.5 kHz. The horizontal axis indicates time which is equal to two oscillation cycles. The spectrogram plot represents the contour of the wave amplitudes for a hot-film output signal in the time-frequency domain. Each contour is reported for a specified spatial point that corresponds to a specific hot-film sensor. The variations of the BL events with time are observed in the spectrogram plots. The TS waves could be detected as dominant high frequency waves in the spectrogram plots for the sensors located in the laminar flow region, e.g. Fig. 8 (b). The laminar flow regions are domains with low-amplitude but high-frequency waves. These domains are marked by L in the spectrogram plots, Fig. 8 (b). Turbulent flow regions are visualized as the spatial/temporal domains with high-amplitude high-frequency waves. These domains are marked by T in the Fig. 8 (a-l). The transitional flow domains have high-amplitude mid-frequency waves and are marked by Tr, Fig. 8 (a). A hot-film sensor may be located in a place where it faces the transition onset during a portion of the oscillation cycle, Fig. 8 (a-c), marked by TO. The separated flow zones are domains with the high-amplitude high-frequency waves that are continuous and do not change during a certain period of time. These domains are indicated by S in the spectrogram plots. The separated flow could be reattached when the AOA decreases in the oscillation cycle. The reattached flows are marked by RA as shown for example in Fig. 8 (d). The sensors that are located in the downstream may experience separated flow during the entire oscillation cycle and are indicated by FS, Fig. 8 (e). Several sensors may experience fully turbulent flow within the oscillation cycle and are marked by FT in the plots, Fig. 8 (l).

The better realization of the flow fluctuations in time signals could be detected by removing the low frequency waves, especially the wave related to the body motion. This could be performed via high-pass filtering of the hot-film signals. To do so, a cut-off frequency of 10
Hz is considered in this investigation. Figures 9 and 10 show the high-pass filtered time signals for different oscillation cases. By comparing these figures with Figs 4 and 5, it is noted that the spatial/temporal domains of laminar, transitional, and turbulent flows could be easier to recognize from the present figures, Figs. 9 and 10. The spatial/temporal laminar flow regions could be detected as straight lines with approximately no significant fluctuations. The transitional regions are those where fluctuations are significant and non-uniform. From Figs. 9 and 10, one could conclude that an increase in the oscillation frequency may reduce the fluctuations. According to the results shown in these figures, as the mean angle is increased, from left to right, the number of the hot-film sensors that experience the transitional flow increases. It is also true for the effect of frequency amplitude. The spatial transitional flow regions are relatively wide for $\alpha_a = 5$ deg, Fig. 10. The fully turbulent or the separated flow regions are signals with uniform fluctuation distributions in time. The points of transition onset and relaminarization are well distinguished from the figures too.

From to Figs. 9 and 10, the hot-film signal could be decomposed as:

$$E = E_{LP} + E_{HP}$$  \hspace{1cm} (3)

Where, the terms $E_{LP}$ and $E_{HP}$ correspond to the low-pass filtered and high-pass filtered parts of the signals, respectively. Using the time-frequency analysis, i.e., Fourier series over finite duration times, the high-pass filtered signals could be described as:

$$E_{HP}(t) = \sum_{n=1}^{N_p} A_n \sin (2\pi f_n t)$$  \hspace{1cm} (4)

Where, $N_p$ is the number of discrete points in the finite signal array, $f_n$ and $A_n$ are the frequency and amplitude of the $n$-th component wave, respectively, and $m$ is the index corresponding to the cut-off frequency. The unsteady characteristics of a hot-film signal regardless of the model motion is revealed through $E_{HP}(t)$. The RMS of a signal is a suitable
means of cumulative oscillation amplitude measurement. This parameter describes the strength of an alternating signal. The RMS of Eq. (4) is given by [22] as:

\[ E_{RMS}(t) = \frac{1}{\sqrt{2}} \sum_{n=1}^{N_c} A_n \]  

Although \( E_{RMS} \) is proportional to the summation of the wave amplitudes at different frequencies, it can be used as a sensor to detect the transition onset. The transition onset is where \( E_{RMS} \) starts to rise significantly. Figure 11 shows the hot-film signal history, zero-mean high-pass filtered signal, and RMS distribution with respect to the pitch angle for an oscillating case with \( \kappa = 0.04, \alpha_m = 6 \) deg and \( \alpha_a = 5 \) deg. The various BL events such as laminar, transitional, and turbulent temporal regions, transition onset, relaminarization point, and transition peak are detected and are shown in this figure based on the time-frequency analysis of the hot-film signals. In the laminar and turbulent flow situations, the RMS distribution is approximately uniform while at the peak transition the RMS has its maximum value, Fig. 11. After the turbulent flow, as the pitching cycle is further proceeded, the transitional flow occurs which is followed by the relaminarization process. The temporal location of the turbulent flow takes place at the highest angles of attack, while the laminar flow occurs at the lowest ones.

Based on Eq. (5) and from the descriptions of Fig. 11, one can obtain transition onset and relaminarization points for various oscillation cases. Figure 12 presents the variations of the transition point versus angle of attack for the current investigation. The data are compared with those obtained by the Xfoil code and by the previous experimental studies using the same model [15, 18]. The results are shown for the static condition, i.e. the angle of attack is changed statically, pitch-pause motion. The transition points predicted by the Xfoil code for different amplification factors (\( N_{crit} \)) are indicated by various lines. Different amplification factors correspond to various levels of turbulence in free stream flow. It could be seen that
the present time-frequency analysis results are in good agreement with the results of Ref. [18] and Xfoil prediction.

The spatial locations for the transition onset and the relaminarization points are presented in Figure 13 for oscillation cases with $\kappa = 0.1$ and $\alpha_o = 5$ deg. The measurement inaccuracy for the transition onsets is less than 5% in all test cases. The results are related to the oscillation cases below (squares), within (triangles), and beyond (circles) the static stall angles of attack of the present model. The filled symbols correspond to the transition onset locations that occur during the pitchup and the open symbols indicate the relaminarization processes that points are take-place during the pitchdown portion of the sinusoidal oscillation cycle. The solid line corresponds to the locations of the transition onset points for the static test obtained at a Reynolds number of $2.7 \times 10^5$. During the pitchup motion, the body motion improves attachment of the flow over the surface that delays the transition onset with respect to the static condition; compare solid line with filled symbols in Fig. 13. On the other hand, during the pitchdown phase of the motion, the body motion promotes flow separation that enhances the transition. Hence, the relaminarization points during pitchdown occur at an earlier spatial locations when compared to the transition onset for the static test. It could be observed that for cases $\alpha_m = 0$ deg and $\alpha_m = 6$ deg, the transition onset locations for the static condition are between the transition onset locations for the pitchup and for the pitchdown conditions. According to Fig. 13, for the oscillation case with $\alpha_m = 10$ deg, the transition points for the static conditions are close to those for the pitchdown portion of the sinusoidal motion. For an airfoil oscillating beyond the $\alpha_{ss}$, the boundary layer events became more complicated. It is because of the growth and convection of an energetic leading-edge vortex (LEV) that forms at high angles of attack [9]. The LEV for these oscillating cases improves the flow attachment that delays the transition onset.
Figure 14 investigates the effect of reduced frequency on the locations of the transition onset and on the relaminarization points for oscillating cases with $\alpha_s = 5$ deg and $\kappa = 0.1$. The results are presented for two cases of $\alpha_m = 6$ deg and $\alpha_m = 10$ deg. Higher reduced frequency leads to higher hysteresis loop of the transition locations. Higher frequency of oscillation leads to higher accelerations in the body motion. This leads to further delay in transition onset during the pitchup. This is similar to the effect of reduced frequency on the load hysteresis loop that has been previously reported [9,15,16,19]. Also, for oscillation beyond $\alpha_{ss}$ ($\alpha_m = 10$ deg), the hysteresis loop for transition onset locations is larger.

5. CONCLUSION

The time-frequency and space-frequency analyses of the hot-film data are used to interpret the BL events over a pitching airfoil. To the authors’ knowledge, these methods have not been used previously in the BL analysis, or if they have been used, the results and descriptions are not available. Laminar, transitional, and turbulent regions of boundary layer are all detected in the space-frequency and time-frequency (spectrogram) plots. However, because of the unsteady motion of the model, the spatial/temporal locations of the boundary layer events are tracked better from the spectrogram plots. The spectrogram plots introduced two precursor phenomena for the spatial/temporal locations of the turbulent flow and for the spatial location of the flow separation. Prior to the turbulent flow, regions of dominant high-frequency disturbances in spectrogram plots were developed. In addition, before the spatial regions with fully separated flow, the pattern of spectrogram shows oscillation with larger period time compared to the body motion oscillation. The flow then becomes fully separated during the oscillation cycle. A new technique based on the time-frequency analysis of the hot-film signals was presented to obtain both the transition onset and the relaminarization points. This technique is based on the high-frequency fluctuations in the hot-film outputs. The results
provided through the new technique compare well with the experimental observations and with the previous investigations.

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FIG. 1 Schematic view of the airfoil model with the pressure taps and hot-film sensors

FIG. 2 Schematic view of the airfoil model installation configuration on wind turbine blade motion simulator in wind tunnel test section

FIG. 3 Hot-film signals for a pitch oscillation with $\alpha = (6\pm2) \ deg$

FIG. 4 Hot-film output signals for oscillations with an amplitude of 2 deg

FIG. 5 Hot-film output signals for oscillations with an amplitude of 5 deg

FIG. 6 Space-frequency plots for oscillations with an amplitude of 2 deg

FIG. 7 Space-frequency plots for oscillations with an amplitude of 5 deg

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(b) $\kappa = 0.04$, $\alpha_m = 6$ deg and $\alpha_a = 2$ deg.

(c) $\kappa = 0.04$, $\alpha_m = 10$ deg and $\alpha_a = 2$ deg.
(d) $\kappa = 0.04$, $\alpha_m = 0$ deg and $\alpha_a = 5$ deg

(e) $\kappa = 0.04$, $\alpha_m = 6$ deg and $\alpha_a = 5$ deg

(f) $\kappa = 0.04$, $\alpha_m = 10$ deg and $\alpha_a = 5$ deg
(g) $\kappa = 0.1$, $\alpha_m = 0$ deg and $\alpha_a = 2$ deg

(h) $\kappa = 0.1$, $\alpha_m = 6$ deg and $\alpha_a = 2$ deg

(i) $\kappa = 0.1$, $\alpha_m = 10$ deg and $\alpha_a = 2$ deg
(j) $\kappa = 0.1$, $\alpha_m = 0$ deg and $\alpha_a = 5$ deg.

(k) $\kappa = 0.1$, $\alpha_m = 6$ deg and $\alpha_a = 5$ deg.

(l) $\kappa = 0.1$, $\alpha_m = 10$ deg and $\alpha_a = 5$ deg.

FIG. 8
FIG. 9

(a) $\kappa = 0.04$

(b) $\kappa = 0.10$
FIG. 10
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FIG. 13

FIG. 14

Table 1

| $\Delta T/T$ | $\Delta P/P$ | $\Delta \rho/\rho$ | $\Delta U/\infty$ | $\Delta Re/Re$ |
|--------------|--------------|--------------------|-------------------|----------------|
| 0.033        | 1.421        | 0.035              | 2.009             | 2.010          |
Table 2

| Sensor ID | x/c | Sensor ID | x/c |
|-----------|-----|-----------|-----|
| S₁        | 0.204 | S₉        | 0.556 |
| S₂        | 0.252 | S₁₀       | 0.596 |
| S₃        | 0.300 | S₁₁       | 0.626 |
| S₄        | 0.352 | S₁₂       | 0.656 |
| S₅        | 0.400 | S₁₃       | 0.678 |
| S₆        | 0.452 | S₁₄       | 0.700 |
| S₇        | 0.488 | S₁₅       | 0.726 |
| S₈        | 0.524 | S₁₆       | 0.752 |

**Biographies**

**Hassan Akhlaghi** received B.S. and M.S. degrees from Sharif University of Technology, Tehran, Iran, in 2007 and 2010, respectively, all in Aerospace Engineering (Aerodynamics). He is currently a PhD candidate in Aerospace Engineering at Sharif University of Technology. His research interests include *Experimental Aerodynamics, Unsteady Aerodynamics, Rarefied Gas Dynamics*.

**Mohammad Reza Soltani** received Ph.D. degree in Applied Aerodynamics from University of Illinois, Urbana-Champaign, USA in 1991. He is Professor of Aerospace Engineering Department at Sharif University of Technology, Iran. He is currently Visiting Professor in William E. Boeing Department of Aeronautics and Astronautics at University of Washington, Seattle, USA. His research interests include *Unsteady Aerodynamics, Applied Aerodynamics, Design and Building of Wind Tunnels and Wind Turbines, Design, Build, and Implementation of Wind Tunnel Instruments, and Measurement Methods*.

**Mohammad Javad Maghrebi** received Ph.D. degree in Mechanical Engineering from Monash University, Australia, in 1999. He is currently Professor of Mechanical Engineering Department at Ferdowsi University of Mashhad, Iran. His research interests include *Computational Fluid Dynamics, Wind Turbine, and Heat Transfer*.