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Experimental Investigation of Unsteady Laminar-to-Turbulent Transition over a Wind Turbine Blade Section

Hassan Akhlaghi[1,*], **Arash Divazi**[2], **Rasoul Shafiei**[3]

[1] Assist. Prof., Aerospace Engineering Department, College of Interdisciplinary Science and Technology, University of Tehran
[2] MSc. Graduate, Aerospace Engineering Department, College of Interdisciplinary Science and Technology, University of Tehran
[3] MSc. Graduate, Department of Mechanical Engineering, University of Kashan
* Corresponding author: hassan.akhlaghi@ut.ac.ir

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Abstract

In the present study, an experimental investigation of the laminar-to-turbulent transition of flow over the surface of a wind turbine airfoil section has been conducted. For this purpose, the Reynolds number range for the experiments was set between 0.13 and 0.53 million, and the angle of attack of the airfoil model was varied from -4 to 14 degrees. The experimental tests were performed on a model airfoil representing the blade section of a 660 kW wind turbine under static conditions. The measurement of the transition onset point was examined using various methods based on the output of pressure sensors and hot-film sensors. Two novel techniques based on the frequency analysis of hot-film signals were introduced and evaluated for determining the transition onset point. The results indicate that all the employed methods exhibit good agreement in identifying the transition onset point. As velocity and angle of attack increase, the transition onset moves backward and approach model's leading edge. Furthermore, the analysis of the separation bubble location reveals that at high angles of attack, the position of the separation bubble onset varies over time, leading to temporal variations in the spatial location of the flow transition onset.

Keywords: Laminar-to-Turbulent Transition, Laminar-Separation Bubble, Hot-Film Sensor, Pressure Transducer, Frequency Analysis.

1. Introduction

The boundary layer plays a fundamental role in the performance of aerospace vehicles, wind turbines, turbomachinery, and similar systems. Accurate determination of the onset of laminar-to-turbulent transition (LTT) is essential for analyzing performance and controlling flow in such systems. Modern design strategies aim to extend the laminar flow region on surfaces to reduce drag. Therefore, the location of transition onset has become an important design parameter. After the design stage, the actual transition onset position on wind turbine blades during operation is of great significance [1].

In this paper, an experimental study of laminar-to-turbulent transition over the surface of an airfoil model representing a 660 kW wind turbine blade section is presented. The transition onset location is determined using several methods, including the XFOIL code, second derivative of pressure distribution, standard deviation of hot-film signals, RMS values of hot-film signals, frequency analysis, and hot-film spectrograms. Among these, the application of spectrograms and RMS values of hot-film signals is newly introduced and evaluated in this study. Furthermore, the paper discusses the instability of laminar separation bubble onset and the resulting instability of transition onset at high angles of attack.

2. Experimental Set-up

An open-circuit subsonic wind tunnel with a rectangular test section of 80 × 100 × 200 cm was employed. To control the turbulence intensity of the incoming flow, three large anti-turbulence screens and a honeycomb structure were installed in the settling chamber. The turbulence intensity in the test section was measured to be within the range of 0.5–1.5% [2].

The test model was a wing section with a uniform profile, chord length of 25 cm, and span of 80 cm [3-6]. The model was made of fiberglass with a manufacturing accuracy of ±0.1 mm. The airfoil section corresponded to that of a 660 kW wind turbine blade located at 70% of the blade span from the hub.

For surface pressure distribution measurements, 63 pressure ports were installed, with higher density near the leading edge (Figure 1). Additionally, sixteen hot-film sensors were mounted on the upper surface of the airfoil within the range $0.204 \leq x/c \leq 0.752$. Their placement was selected to cover the expected spatial variations of transition onset in the planned experiments. The angle of attack was measured using a

14-bit encoder with an accuracy of 0.022°.

The measurement uncertainty for surface pressure values was estimated to be 0.21%, while that for the pressure coefficient was 0.7%. The uncertainties for the free-stream flow parameters were as follows: Reynolds number, 0.6%; free-stream velocity, 0.28%; density, 0.37%; temperature, 0.35%; and pressure, 0.12%.

The experimental tests were conducted at free-stream velocities ranging from 10 to 40 m/s, corresponding to Reynolds numbers between 0.13 and 0.53 million. At each free-stream velocity, the model's angle of attack was varied from -4° to 14°. For the tested model, within the considered Reynolds number range, the effective variations in the transition onset location occurred at angles of attack below 12°.

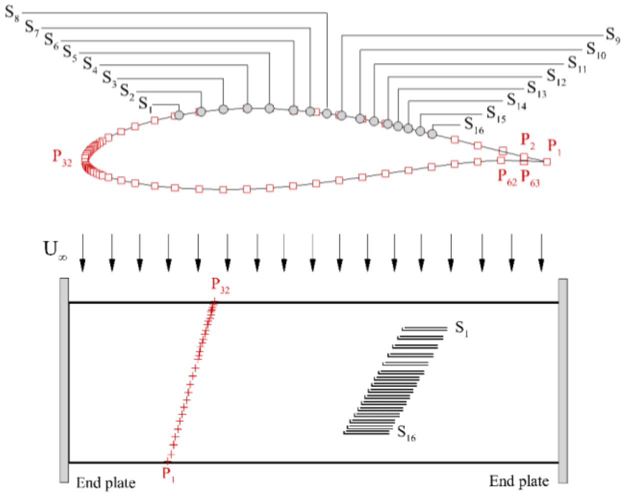

Figure 1. Model schematics with locations for the pressure transducers and hot-film sensors

3. LTT Detection via Standard Deviation in Hot-Film Signals

Uncalibrated hot-film signals are typically used to provide qualitative information regarding the state of the boundary layer on the surface. According to the approach proposed by Hodson [7] and Zhang et al. [8], the wall shear stress (τ) is defined as

$$\tau = \left(\frac{E^2 - {E_0}^2}{{E_0}^2} \right)^3 \tag{1}$$

In the above equation, E is the output voltage of the hot-film sensor, and E_0 is the offset voltage (the voltage measured in stationary flow at the ambient temperature of the experiment). In this study, the dimensionless hot-film output voltage is used for statistical analysis. Compared to Eq. (2), the dimensionless hot-film output is defined as

$$\hat{E} = \frac{E - E_0}{E_0} \tag{2}$$

The locations of the LTT onset, based on the maximum standard deviation of the hot-film output voltages for various angles of attack and flow velocities, are presented in Figure 2. As it is expected, LTT onset moves upstream as angle of attack increases. According to the results, the influence of flow velocity on the onset of transition is more pronounced at lower angles of attack.

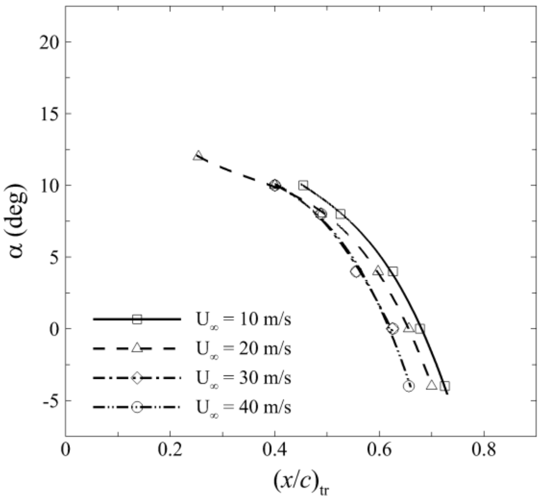

Figure 2. Spatial variation of LTT onset obtained by standard deviation of hot-film signals

4. Time-Frequency Analysis and LLT Onset

In this section, the detection of the transition onset location is presented based on the frequency analysis of hot-film signals. The airfoil model is considered at a zero-degree angle of attack and a free-stream velocity of 20 m/s. Using the discrete Fourier transform (DFT), a hot-film signal can be expressed as a finite series of waves with different amplitudes and frequencies.

Figure 3 shows the frequency spectrum plots of the sensors at different locations. The frequency spectrum plots represent the spectral power distribution of the hot-film signals. Sensors located in the spatial range between x/c = 0.204 and x/c = 0.524 exhibit spectral peaks at approximately 1.38 kHz. The frequency corresponding to these peaks can be attributed to Tollmien-Schlichting (TS) waves in the flow [9]. For sensors located in the range x/c = 0.556 to x/c = 0.626, a spectral peak occurs at approximately 1.26 kHz. The spectral peaks in this region also indicate the presence of TS waves. Based on the correlation provided in reference [9], the frequency of TS waves increases with the boundary layer thickness. According to Figure 3, it can be observed that the spectral peaks occur at approximately the same frequency or the frequency even decreases in the flow direction. This can be attributed to the strong pressure gradient on the model's suction surface. Due to the gradual growth of the boundary layer thickness in this region, the frequency of the TS wave may not change significantly or may even decrease. At the beginning of the boundary layer transition process, no spectral peak is evident in the TS wave frequency range. Consequently, the point x/c = 0.656 indicates the start of the transition at a velocity of

20 m/s and zero angle of attack, which agrees with the results from Figure 3. Tropea *et al.* [10] used spectrograms of pressure transducers to detect the bubble phenomenon. Similarly, in the present investigation, the spectrograms of the hot-film signals were used to identify the location of the Laminar-Turbulent Transition (LTT).

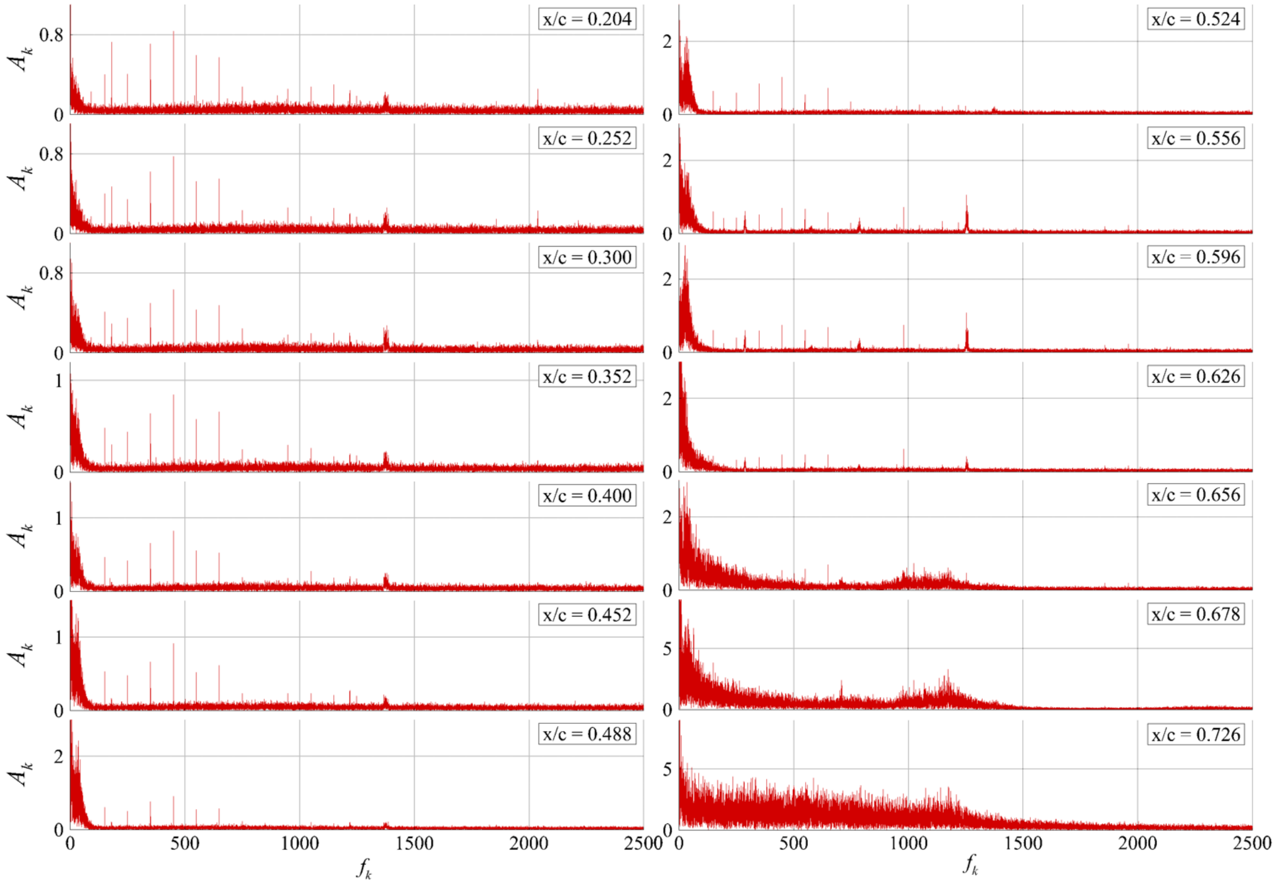

Figure 3. The frequency spectrum plots of the hot-film signals at a velocity of 20 m/s and zero angle of attack

5. Unsteady LTT Onset

This section examines the temporal instability LTT onset location. Based on the obtained experimental observations, the position of the Laminar Separation Bubble (LSB) can fluctuate at high angles of attack, a phenomenon detectable in the hot-film signals. Figure 4 displays the low-pass-filtered hot-film signals at a 10-degree angle of attack. The figure shows that phase reversal occurs between more than two sensors, indicating that the separation bubble initiates at more than two distinct points. The phase reversal phenomenon in the hot-film sensors is observed across three consecutive sensors located at positions x/c = 0.352, x/c = 0.400, and x/c = 0.452. To facilitate visualization, some phase reversal points are marked with arrows. As can be seen, at certain times, the signal from the sensor at $x/c = 0.400$ is in phase with the signal from the sensor at x/c = 0.352, while at other times, there is a 180-degree phase difference between the signals from these sensors. A similar phenomenon can be observed when comparing the signals from the sensors at positions x/c = 0.400 and x/c = 0.452. This indicates that during the sampling period, the LSB location shifts such that it sometimes occurs between the sensors at x/c = 0.352 and x/c = 0.400, and at other times between the sensors at x/c = 0.400 and x/c = 0.452. The LSB position is variable due to vortex fluctuations generated downstream of the model under high angle-of-attack conditions.

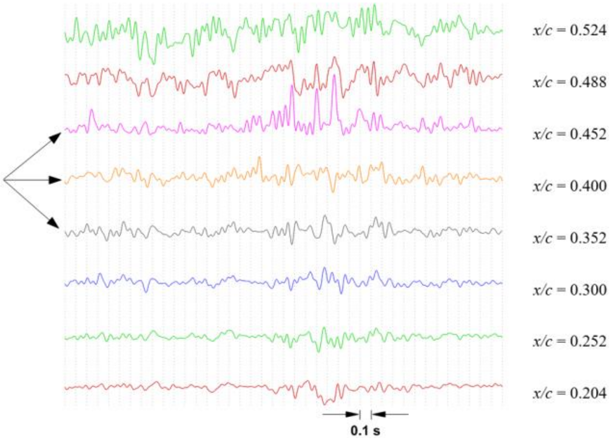

Figure 4. Low-pass filtered hot-film signals at a velocity of 20 m/s and an angle of attack of 10 degrees

6. Conclusions

This study presents an experimental investigation of the laminar-to-turbulent transition phenomenon on the airfoil surface of a wind turbine. Various methods for detecting the flow transition onset point, based on both pressure sensors and hot-film sensors, were utilized and evaluated. An increase in both the free-stream velocity and the angle of attack caused the location of the transition onset point to shift towards the model's leading edge. The results demonstrated that at high angles of attack, the position of the laminar separation bubble (LSB) onset fluctuates temporally, which leads to temporal variations in the spatial location of the flow transition. These temporal changes in the LSB onset point can be clearly observed through the 180-degree phase difference phenomenon between consecutive upstream and downstream hot-film sensors.

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