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Unsteady Separated Flow Characterization on Airfoils Using Time-Resolved Surface Pressure Measurements

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Laminar boundary-layer separation and separated shear layer development on a NACA 0025 airfoil at low Reynolds numbers were studied experimentally. Flow visualization, hot-wire velocity measurements, and time-resolved surface pressure measurements were employed in this investigation. The results for two distinct flow regimes, namely, flow separation without subsequent shear layer reattachment and separation bubble formation, are discussed in detail. For both flow regimes, the transition occurs due to the amplification of natural flow disturbances in the separated shear layer. Initially, disturbances within a band of frequencies centered at some fundamental frequency are amplified. Further downstream, nonlinear interactions set in, leading to a breakdown to turbulence. Based on the spectral and correlation analysis of velocity and surface pressure fluctuations, it is demonstrated that the amplification of disturbances and the attendant fluctuations in the flow velocity give rise to distinct surface pressure fluctuations at the fundamental frequency. Thus, time-resolved surface pressure measurements can be employed to estimate important unsteady characteristics of the separated flow region on an airfoil operating in low Reynolds flows.

Nomenclature

Cp	=	pressure coefficient, $(p-p_0)/(0.5\rho U_0^2)$
c	=	airfoil chord
E_{pp}	=	normalized energy spectrum of p
E_{uu}	=	normalized energy spectrum of u
E_{vv}	=	normalized energy spectrum of v
f	=	frequency
f_0	=	fundamental frequency of the disturbances
p, p_0	=	local and freestream static pressure
Re_c	=	Reynolds number, $U_0 c/\nu$
U_0	=	freestream velocity in x direction
u, v	=	x and y fluctuating velocity components
x, y	=	streamwise and vertical coordinates
α	=	angle of attack
ν	=	kinematic viscosity of air
ρ	=	density of air
$\rho_{vp}(\tau)$	=	cross-correlation coefficient function
τ	=	time lag

I. Introduction

LAMINAR boundary-layer separation often occurs on an airfoil operating at Reynolds numbers below approximately 500,000 [1] and can have a profound detrimental effect on airfoil performance. The severity of this effect depends on the development of a separated shear layer, which forms due to boundary-layer separation (Fig. 1a). In particular, laminar-to-turbulent flow transition that takes place in the separated shear layer can lead to flow reattachment and the formation of a separation bubble (Fig. 1b). This flow regime is associated with less significant degradation of airfoil performance compared with the case when the separated shear layer fails to reattach, forming a wake (Fig. 1a). Thus, it is important to accurately evaluate the characteristics and the extent of a separated flow region for designing effective airfoils and assessing airfoil performance.

It has been shown in several studies that the initial stage of the transition process in a separated shear layer is associated with the growth of two-dimensional instabilities [2–4]. This is followed by nonlinear interactions between the disturbances, and three-dimensional breakdown of these disturbances results [2]. Also, coherent structures form during the transition process and these structures have been demonstrated by Lin and Pauley [5] to play a dominant role in separation bubble formation. Yarusevych et al. [6] established a link between the development of coherent structures in a separated shear layer and flow transition. It was shown that vortices form due to the roll up of the separated shear layer, which occurs when the disturbances are amplified sufficiently. Consequently, the roll-up vortices are initially shed at the frequency corresponding to that of the most amplified disturbance in the separated shear layer. The subsequent merging of the roll-up vortices, which resembles the process common to free shear layers, leads to flow transition.

Insight into physical phenomena occurring in the airfoil boundary layer in the presence of laminar separation is not only essential for assessing airfoil performance but can also be used to design and implement effective flow control methods aimed at improving airfoil characteristics. In particular, it has been demonstrated in several studies that introduction of periodic excitation at an appropriate frequency and amplitude can improve airfoil performance that is adversely affected by laminar separation [7]. Excitation applied at the frequency of the most amplified disturbance in the unexcited separated shear layer promotes flow transition [8]. As a result, earlier reattachment can be achieved, leading to the reduction of the

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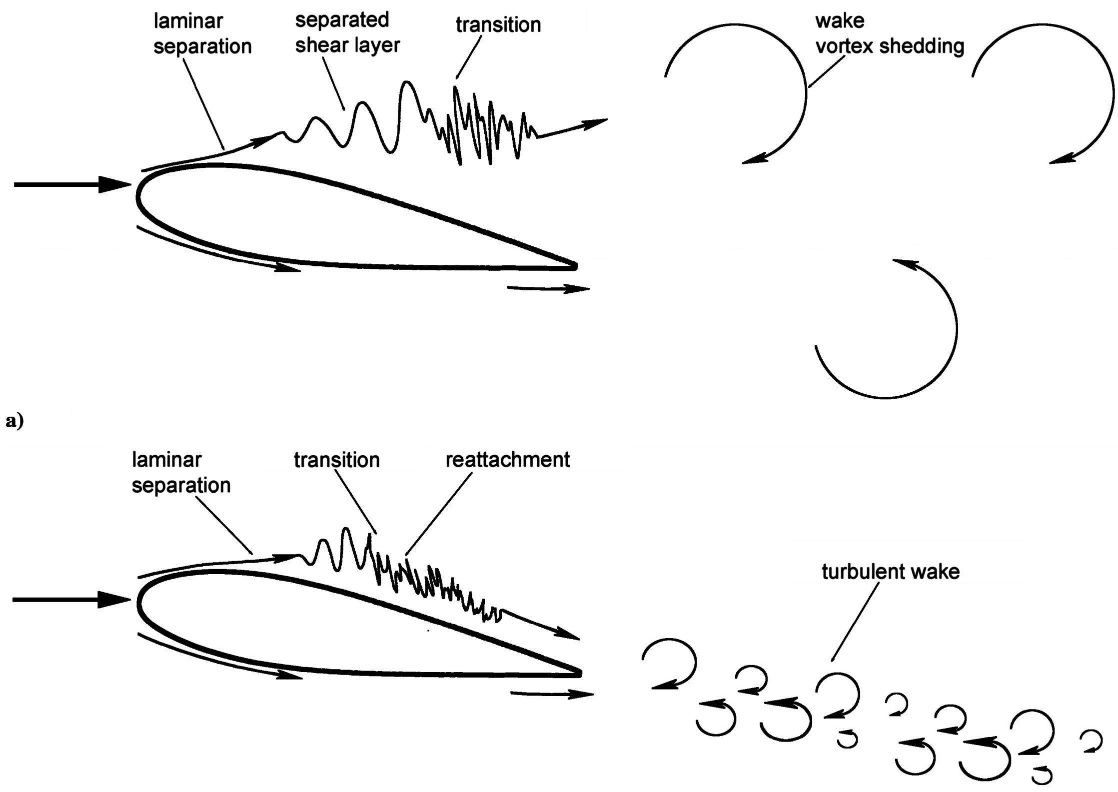


Fig. 1 Airfoil operating at low Reynolds numbers: a) laminar separation without reattachment and b) laminar separation with reattachment.

separated flow region and the consequent improvement of airfoil characteristics.

Because of the complexity of flow development on an airfoil in the presence of boundary-layer separation, experimental investigations often involve such measurement techniques as particle image velocimetry, laser Doppler velocimetry, and hot-wire anemometry. In many practical applications, for example, when active-feedback flow control is required, the use of these techniques can present real challenges. An alternative solution may be to employ surface pressure measurements. One distinctive characteristic of boundary-layer separation is the region of nearly constant static pressure downstream of the separation point [1]. If the separated shear layer fails to reattach, the constant-pressure region extends to the trailing edge of the airfoil. On the other hand, a sudden increase in pressure following the constant-pressure region serves to indicate transition in the separated shear layer, which leads to boundary-layer reattachment and the formation of a separation bubble. As noted by Tani [9], the location of the reattachment point can be estimated as the position where the pressure reaches the value found in the absence of boundary-layer separation. Therefore, the presence and the extent of the separation region can be assessed based on a surface pressure distribution.

Considering the unsteady nature of separated shear layer development, it is also important to capture the fluctuating surface pressure component. For instance, based on preliminary measurements, Weibust et al. [10] suggest that the growth of static pressure fluctuations may be linked to the transition process in the separated shear layer. To capture time-resolved pressure variations, a pressure sensor should have a sufficient frequency response and be able to accurately resolve pressure fluctuations within a given pressure range [11,12]. Recent developments in fast-response pressure measurement devices have allowed for time-resolved pressure measurements in turbomachinery [11–13] and have facilitated the developing of miniature pressure probes [12,14]. However, for an airfoil operating at low Reynolds numbers, the amplitude of the attendant surface pressure fluctuations is relatively small, and a pressure sensor with a rather large sensing element is required. Consequently, due to an increased displacement volume, the frequency response of such a sensor is reduced. The use of connecting tubing and Scanivalve modules can further reduce the response of the system, rendering accurate measurement of pressure fluctuations difficult.

The present investigation has been undertaken to gain added insight into separated shear layer development by analyzing surface pressure fluctuations. The goal is to correlate surface pressure fluctuation with velocity signals in the separated shear layer to assess the possibility of employing time-resolved surface pressure measurements for estimating significant characteristics of the separated flow region on an airfoil operating at low Reynolds numbers.

II. Experimental Description

All experiments were performed in a low-turbulence recirculating wind tunnel. The 5-m-long test section of this tunnel has a spanwise extent of 0.91 m and a height of 1.22 m. The freestream velocity U_0 is adjustable from 2.8 to 18 m/s, with a background turbulence intensity level less than 0.1%. During the experiments, the freestream velocity was monitored by a pitot tube, with an uncertainty estimated to be less than 2.5%.

A symmetrical NACA 0025 aluminum airfoil with a chord length c of 0.3 m and a span of 0.88 m was examined. The airfoil was mounted horizontally in the test section 0.4 m downstream of the contraction. To enable surface pressure measurements, the airfoil was equipped with 65 pressure taps positioned at the midspan symmetrically on the upper and lower surfaces. A pressure tap installed in the test section upstream of the model served to provide a reference freestream static pressure. Mean surface pressure distributions were measured with a Transicoil differential low-pressure transducer connected to the taps through a 64-channel Scanivalve module. The uncertainty associated with the mean surface pressure measurements was less than 2%. For spectral and correlation analysis, pressure data were acquired with an All Sensors differential high-response, low-pressure transducer. The transducer was connected directly to a pressure tap, bypassing the Scanivalve module. Each connecting tube had an inner diameter of 1.6 mm and a length of less than 1.2 m. Using results of Irwin et al. [15], the attenuation of the pressure signals due to the presence of the tubing was estimated to be less than 30%. However, the transducer in the aforementioned settings was verified experimentally to resolve pressure fluctuations imposed by a loudspeaker in the frequency range of interest (100–500 Hz). Within this frequency range, an uncertainty associated with determining central frequencies of broad spectral peaks was less than 6%.

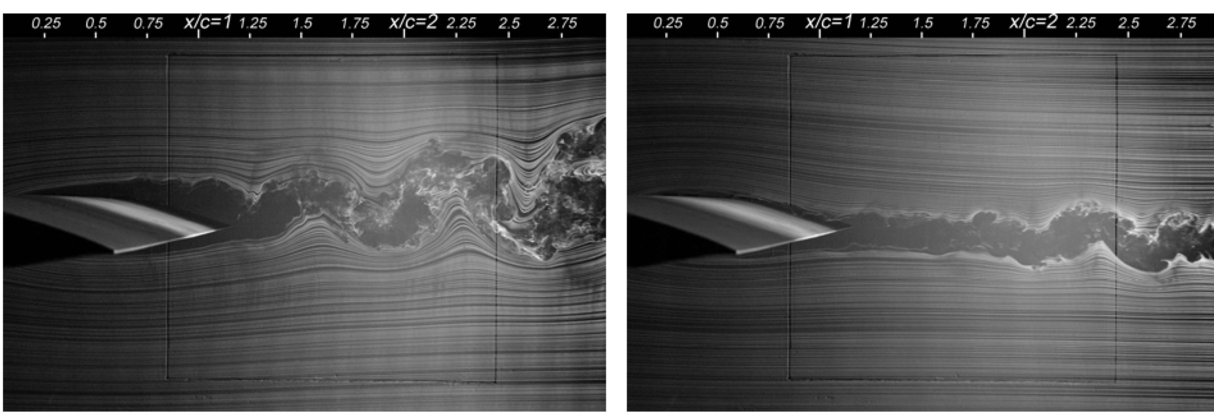
Velocity data were obtained with constant temperature anemometers. A normal hot-wire probe and a cross-wire probe were used. The probes were mounted on a remotely controlled traversing gear, which allowed probe motion in the vertical y and streamwise x directions with a resolution of 0.01 and 0.25 mm, respectively. All hot-wire measurements were carried out in the vertical midspan plane of the tunnel, with the origin of the coordinate system located at the leading edge of the airfoil. Based on the results of Kawall et al. [16], the maximum hot-wire measurement error was estimated to be less than 5%.

For spectral analysis of the velocity and pressure signals, sampled at 5000 Hz, the duration of a sampled signal segment was sufficiently large to provide a frequency resolution bandwidth of 0.6 Hz, adequate for resolving narrow peaks in the spectrum. Based on the number of averages involved in obtaining the corresponding spectra, the uncertainty of the spectral analysis was estimated to be approximately 4.5%. All presented spectra are normalized by the variance of the sampled signals, so that the area under each spectral curve is unity. To allow adequate comparison of the velocity spectra [6], velocity data intended for spectral analysis were obtained at y/c positions corresponding to $0.5U_0$ in the separated shear layer.

A smoke-wire technique was employed for flow visualization. A thin 0.076-mm-diam wire (304 stainless steel) installed 15 cm upstream of the leading edge was coated with smoke-generator fluid. The fluid was evaporated by inductively heating the wire, producing clear streaklines in the flow. The flow was illuminated with a remotely triggered speedlight, and the images were acquired with a digital camera.

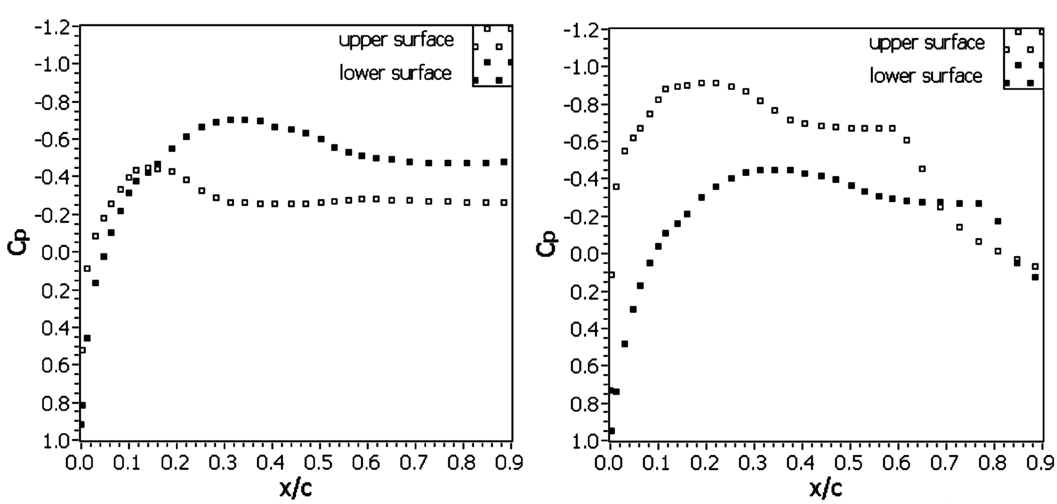
III. Experimental Results

The experiments were carried out for $Re_c = 100 \times 10^3$ and $Re_c = 150 \times 10^3$ at $\alpha = 5$ deg, as these two Reynolds numbers produce distinctly different flow regimes. Flow visualization results presented in Fig. 2 illustrate boundary-layer and wake development for the two cases studied. For $Re_c = 100 \times 10^3$ (Fig. 2a), the boundary layer on the upper surface of the airfoil separates and the separated shear layer fails to reattach to the airfoil surface. As a result, a wide wake is formed with large scale coherent structures forming in the near wake region. For $Re_c = 150 \times 10^3$ (Fig. 2b), boundary-layer separation also occurs on the upper surface of the airfoil. However, in this case, the separated shear layer reattaches, forming a separation bubble. Because of the formation of the separation bubble,



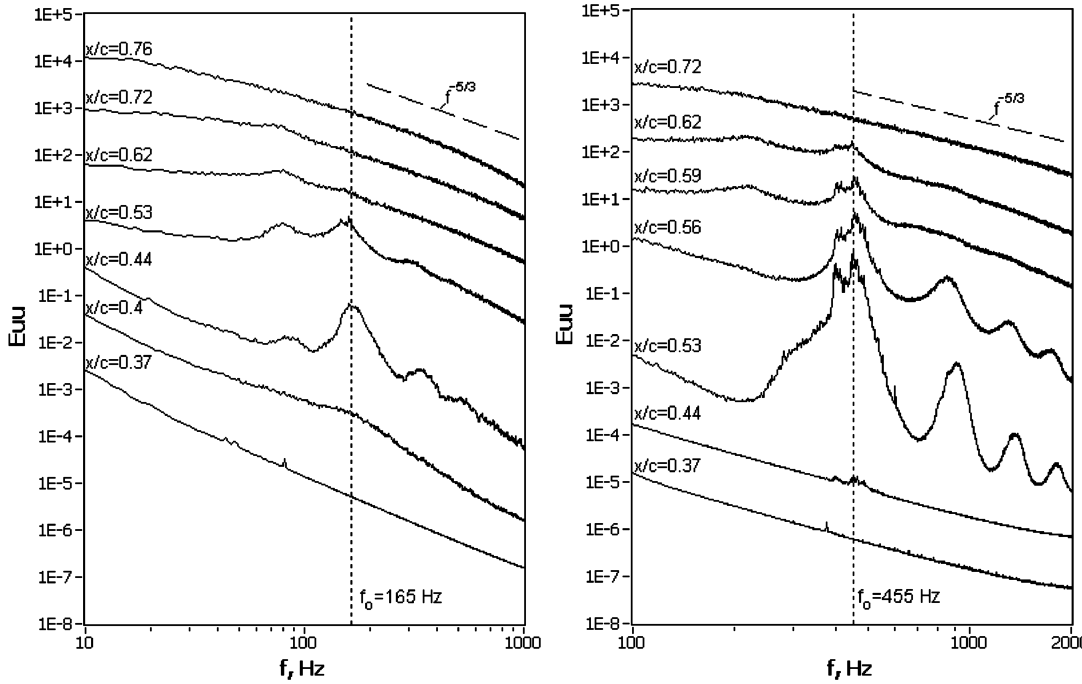
a) Re_c=100x10³ **b) Re_c=150x10³**

Fig. 2 Flow visualization at $\alpha = 5$ deg.



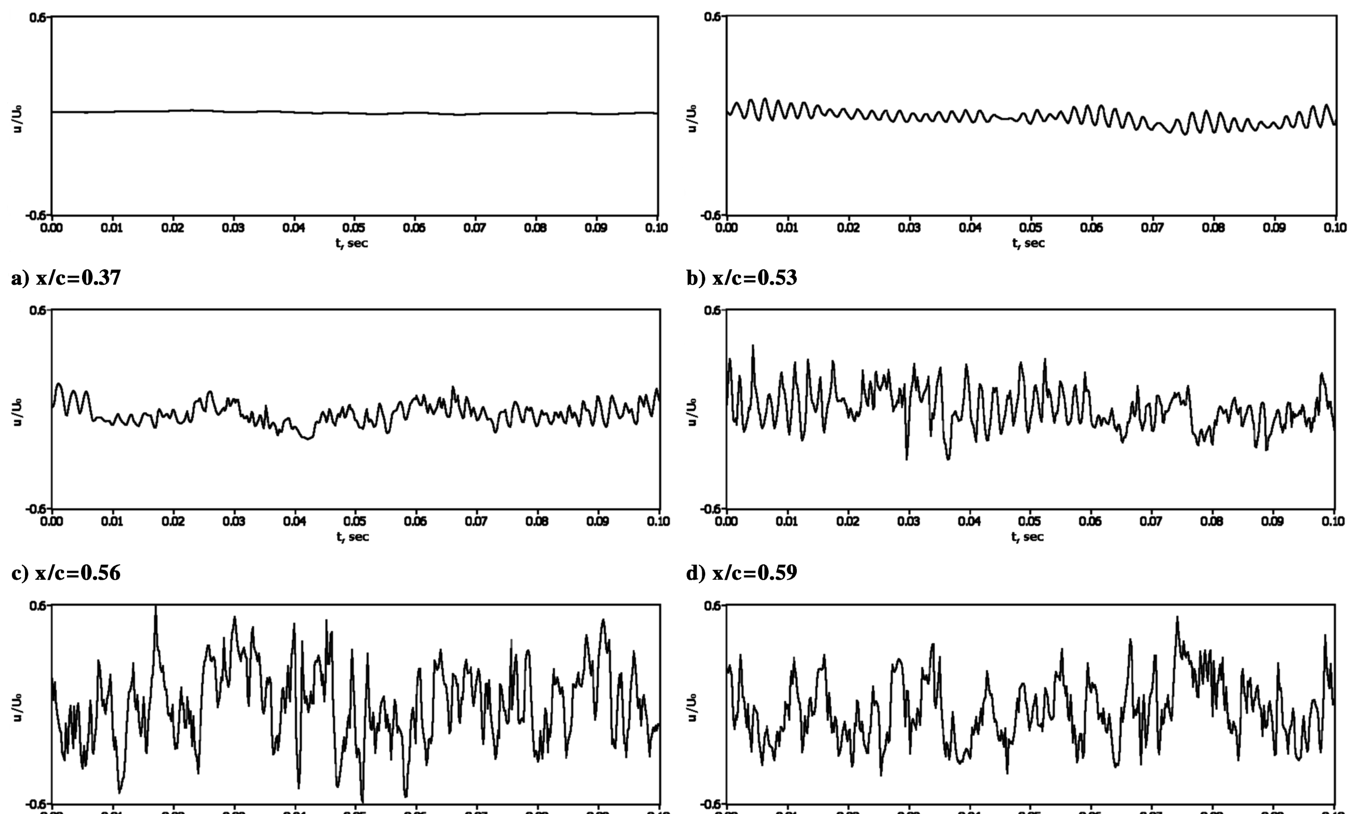
a) Re_c=100x10³ **b) Re_c=150x10³**

Fig. 3 Mean surface pressure distributions at $\alpha = 5$ deg.



a) b)

Fig. 4 Spectra of the streamwise fluctuating velocity component at $\alpha = 5$ deg for a) $Re_c = 100 \times 10^3$ and b) $Re_c = 150 \times 10^3$. The amplitude of each successive spectrum is stepped by one order of magnitude.



a) x/c=0.37 **b) x/c=0.53**

c) x/c=0.56 **d) x/c=0.59**

e) x/c=0.62 **f) x/c=0.72**

Fig. 5 Streamwise fluctuating velocity component signals at $\alpha = 5$ deg for $Re_c = 150 \times 10^3$.

a narrower wake is observed for $Re_c = 150 \times 10^3$ (Fig. 2b) than the wake for $Re_c = 100 \times 10^3$ (Fig. 2a). It should be noted that boundary-layer separation also occurs on the lower surface of the airfoil for both Reynolds numbers.

Quantitative characteristics of the separation region can be obtained from the analysis of mean surface pressure distributions, shown in Fig. 3. For $Re_c = 100 \times 10^3$ (Fig. 3a), the boundary layer on the upper surface separates at approximately $x/c = 0.3$ and fails to reattach, as evident from an essentially constant-pressure region over the aft 70% percent of the chord. Boundary-layer separation without subsequent flow reattachment also occurs on the lower surface at $x/c \approx 0.65$. For $Re_c = 150 \times 10^3$, a separation bubble is formed on the upper surface between approximately $x/c = 0.4$ and $x/c = 0.65$ (Fig. 3b). In this case, a separation bubble also develops on the lower surface of the airfoil, extending from approximately $x/c = 0.6$ to 0.75. It is evident from the comparison of the results (Fig. 3) that separated shear layer reattachment is associated with a substantial increase of a suction peak on the upper surface of the airfoil.

Despite pronounced differences in boundary-layer development, a similar transition mechanism takes place for both cases examined [6]. This is illustrated in Fig. 4, which shows spectra of the streamwise fluctuating velocity component obtained in the separated shear layer on the upper surface of the airfoil for $Re_c = 100 \times 10^3$ and $Re_c = 150 \times 10^3$. For clarity, the amplitude of each spectrum is stepped by an order of magnitude with respect to the spectrum at the previous upstream location. The spectral results suggest that disturbances within a band of frequencies, centered at a fundamental frequency f_0, are amplified in the separated shear layer. The initial growth of the disturbances is followed by the generation and growth of harmonics and a subharmonic of the fundamental frequency, leading to a laminar-to-turbulent transition. In particular, for $Re_c = 100 \times 10^3$ (Fig. 4a), a flat "laminar-flow" spectrum is observed at $x/c = 0.37$. As the separated shear layer develops downstream, a band of unstable Fourier components occurs centered at a fundamental frequency $f_0 = 165$ Hz. At $x/c = 0.44$, the generation

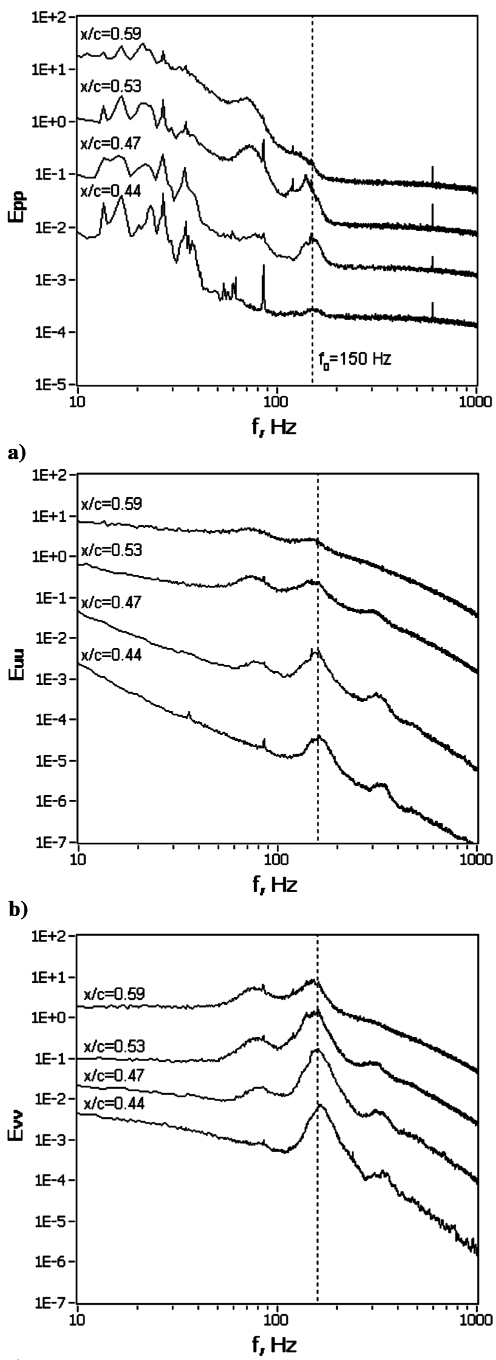


Fig. 6 Upper surface pressure and velocity spectra for $Re_c = 100 \times 10^3$ at $\alpha = 5$ deg: a) E_{pp}, b) E_{uu}, and c) E_{vv}. The amplitude of each successive spectrum is stepped by one order of magnitude.

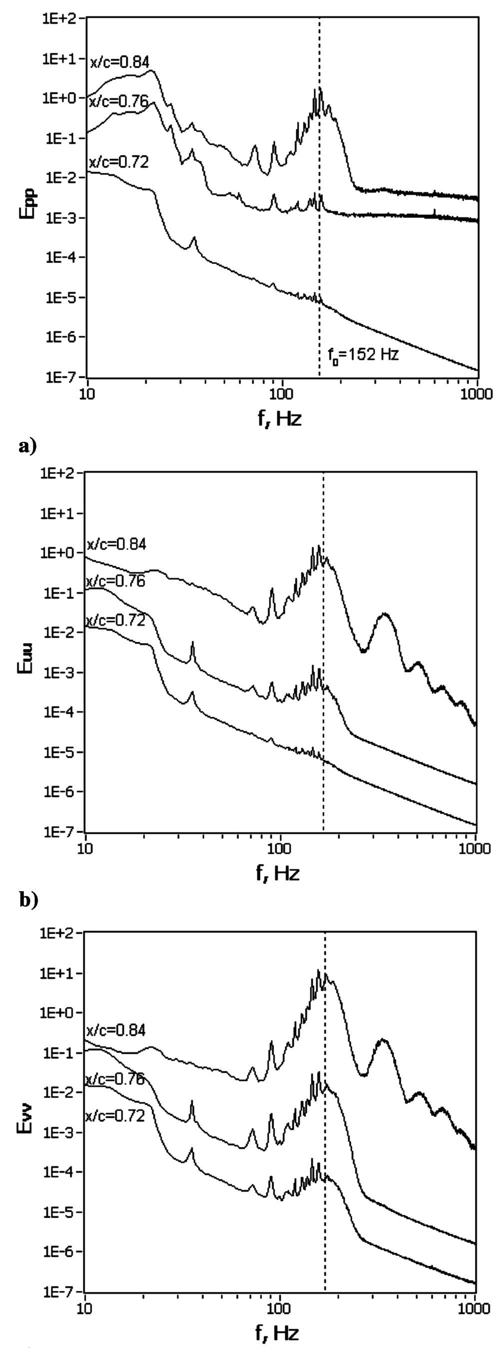


Fig. 7 Lower surface pressure and velocity spectra for $Re_c = 100 \times 10^3$ at $\alpha = 5$ deg: a) E_{pp}, b) E_{uu}, and c) E_{vv}. The amplitude of each successive spectrum is stepped by one order of magnitude.

of harmonics and a subharmonic suggests the presence of nonlinear interactions between the disturbances [2]. Subharmonic growth becomes dominant beyond $x/c = 0.53$ and leads to rapid transition, with a typical turbulence spectrum observed at $x/c = 0.76$. A similar trend is observed for $Re_c = 150 \times 10^3$ (Fig. 4b); however, for this Reynolds number, the band of the amplified disturbances in the separated shear layer is centered at a higher value of $f_0 = 455$ Hz. Past the separation point, a band of unstable frequencies occurs from 360 to about 500 Hz at $x/c = 0.44$. Further downstream, at $x/c = 0.53$, disturbances in this frequency band are substantially amplified, and the band itself broadens, remaining centered at the fundamental frequency $f_0 = 455$ Hz; in addition, harmonics are generated. Following rapid transition, a spectrum typical of turbulent flow occurs at $x/c = 0.72$.

It is instructive to consider the evolution of the streamwise velocity signal u during the transition process, which is depicted in Fig. 5. Initially, no significant fluctuations are observed in the laminar-flow velocity signal at $x/c = 0.37$ (Fig. 5a). The presence of amplified disturbances in the separated shear layer is reflected in a distinct periodic signal at $x/c = 0.53$ (Fig. 5b). Further growth of the disturbance amplitude downstream of this position is associated with the decline of periodicity in the velocity fluctuations (Figs. 5c and 5d). The amplification of the disturbances eventually leads to flow transition to turbulence, marked by the appearance of randomly fluctuating velocity signals at and beyond $x/c = 0.62$.

The presented results show that transition in the separated shear layer is caused by the amplification of disturbances associated with velocity fluctuations at the fundamental frequency. It is then

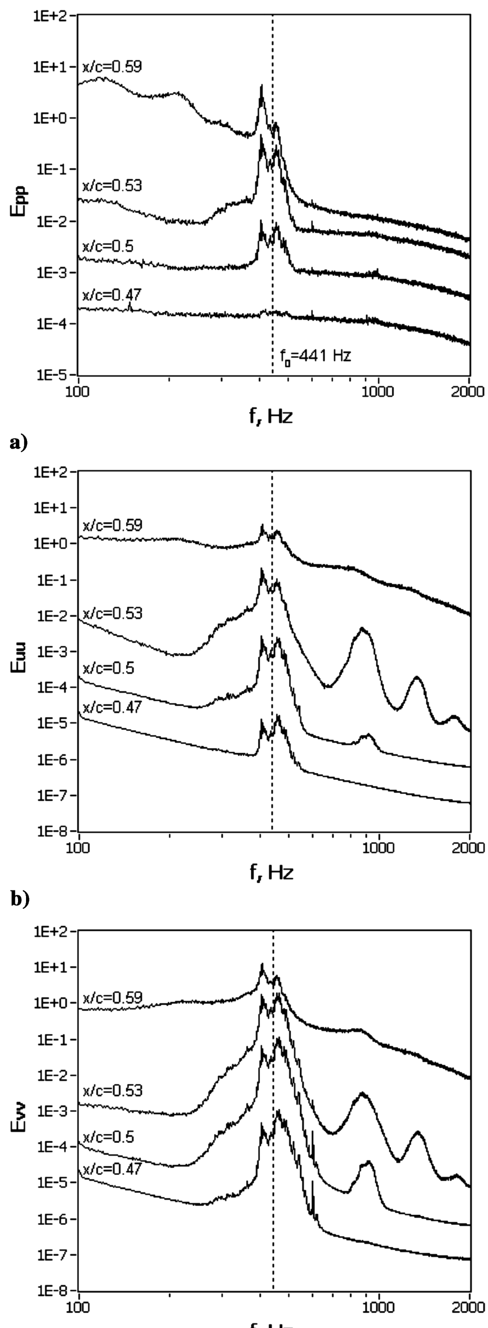


Fig. 8 Upper surface pressure and velocity spectra for $Re_c = 150 \times 10^3$ at $\alpha = 5$ deg: a) E_{pp}, b) E_{uu}, and c) E_{vv}. The amplitude of each successive spectrum is stepped by one order of magnitude.

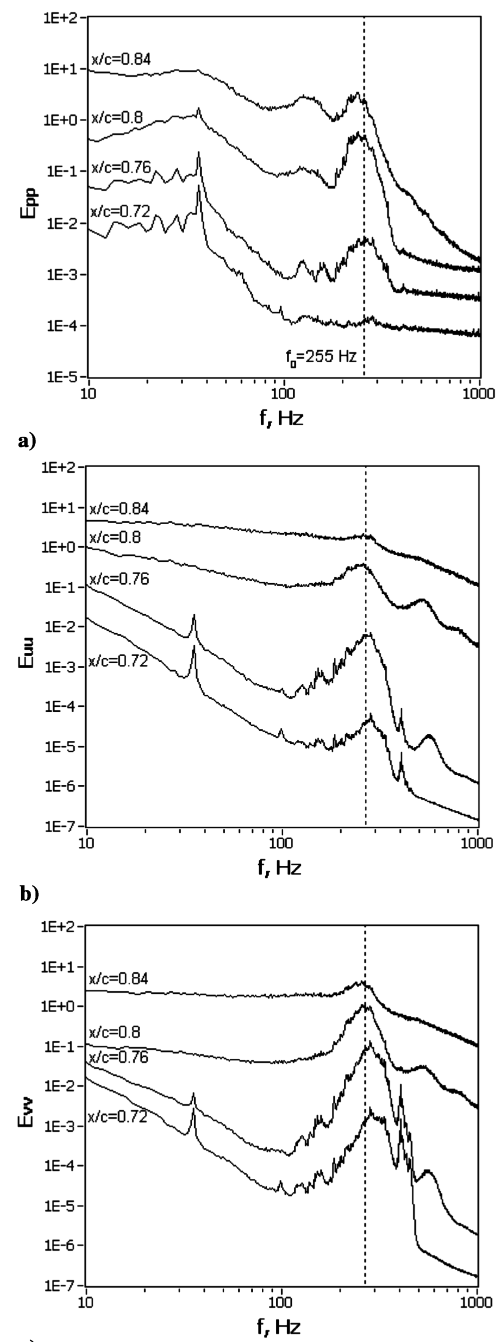


Fig. 9 Lower surface pressure and velocity spectra for $Re_c = 150 \times 10^3$ at $\alpha = 5$ deg: a) E_{pp}, b) E_{uu}, and c) E_{vv}. The amplitude of each successive spectrum is stepped by one order of magnitude.

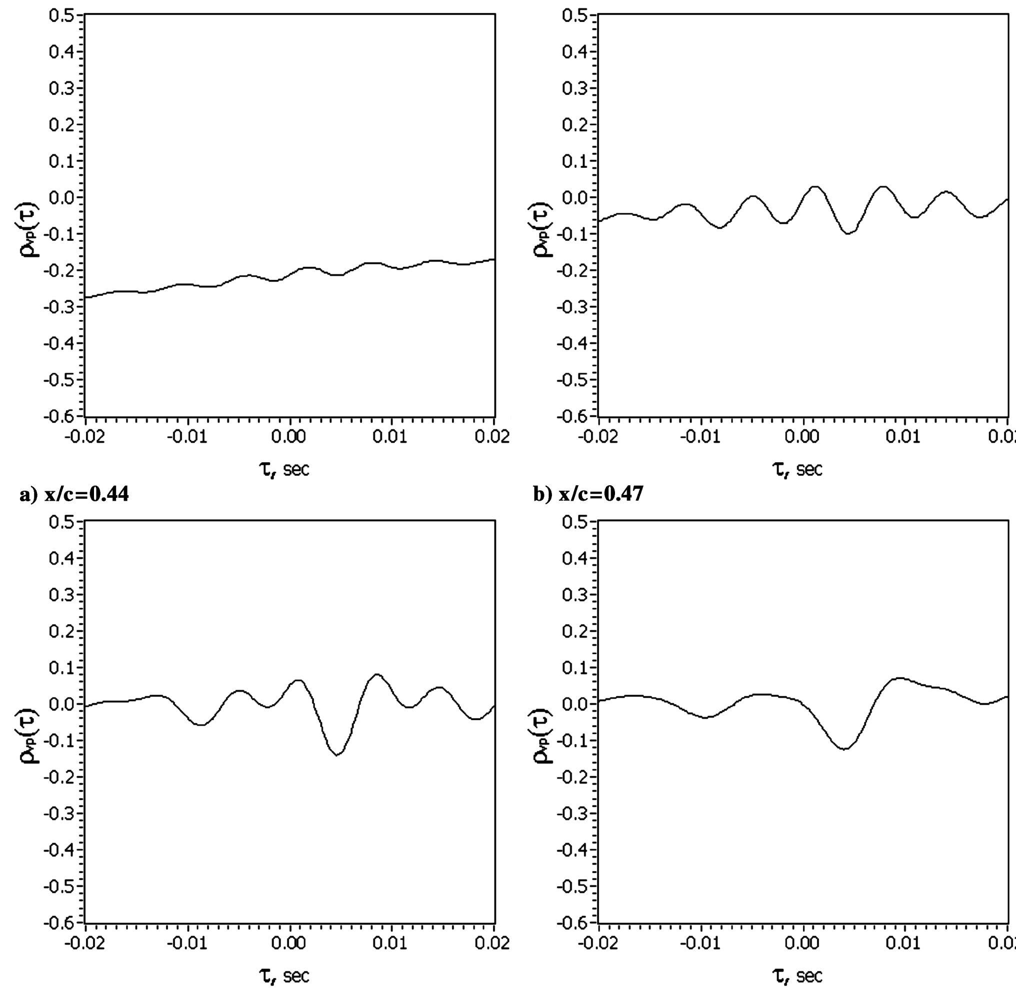


Fig. 10 Cross-correlation coefficient functions based on vertical velocity component *v* and surface pressure *p* obtained on the upper surface for $Re_c = 100 \times 10^3$ at $\alpha = 5$ deg.

reasonable to expect that there will be attendant surface pressure fluctuations. To investigate this, velocity measurements with a cross-wire probe positioned in the separated shear layer and surface pressure measurements at the corresponding streamwise locations were performed simultaneously.

The measurements were conducted within the transition region for $Re_c = 100 \times 10^3$ and $Re_c = 150 \times 10^3$. Spectra of the pressure and velocity signals at various x/c locations on the upper and lower surfaces of the airfoil are presented in Figs. 6–9. Note that spectra for both the streamwise and vertical velocity components are presented. For $Re_c = 100 \times 10^3$, surface pressure spectra E_{pp} pertaining to the upper surface of the airfoil (Fig. 6a) reveal a streamwise growth of a peak centered at approximately 150 Hz and its subharmonic at 75 Hz. A more distinct growth of Fourier components centered at 152 Hz is observed on the lower surface (Fig. 7a). As the Reynolds number is increased to $Re_c = 150 \times 10^3$, a well-defined peak centered at approximately 441 Hz occurs at $x/c = 0.5$ and its energy content grows as the flow evolves downstream (Fig. 8a). For this Reynolds number, the peak developing in the pressure spectra along the lower surface (Fig. 9a) occurs at a lower frequency of about 255 Hz.

For all cases presented, a comparison of the pressure spectra and the corresponding velocity spectra indicates that there is a correlation between the frequency-centered activity detected from the pressure signals and that attributed to the growth of the disturbances in the separated shear layer. Indeed, the shapes of the corresponding peaks and their center frequencies correlate well for both Reynolds numbers. For a more quantitative comparison, a correlation analysis of the fluctuating pressure and vertical velocity signals was carried out. The vertical velocity signals were chosen because they feature

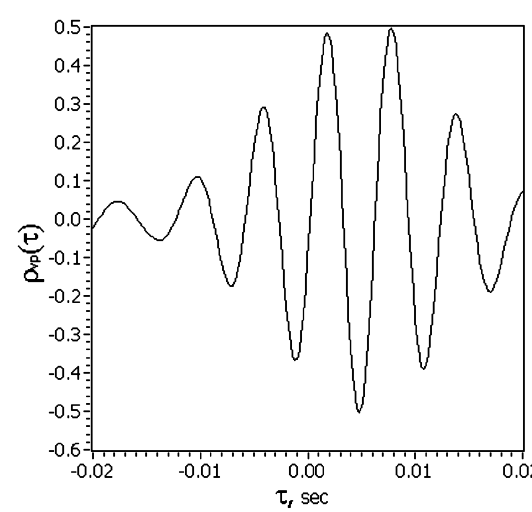


Fig. 11 Cross-correlation coefficient function based on vertical velocity component *v* and surface pressure *p* obtained on the lower surface for $Re_c = 100 \times 10^3$ at $x/c = 0.84$, $\alpha = 5$ deg.

more profound fluctuations associated with the amplification of disturbances in the separated shear layer; for example, compare E_{uu} and E_{vv} spectra in Figs. 6b and 6c. Cross-correlation coefficient functions $\rho_{\rm vp}(\tau)$ are presented in Figs. 10–12. The phase lag present in cross-correlation functions is due to the presence of the connecting

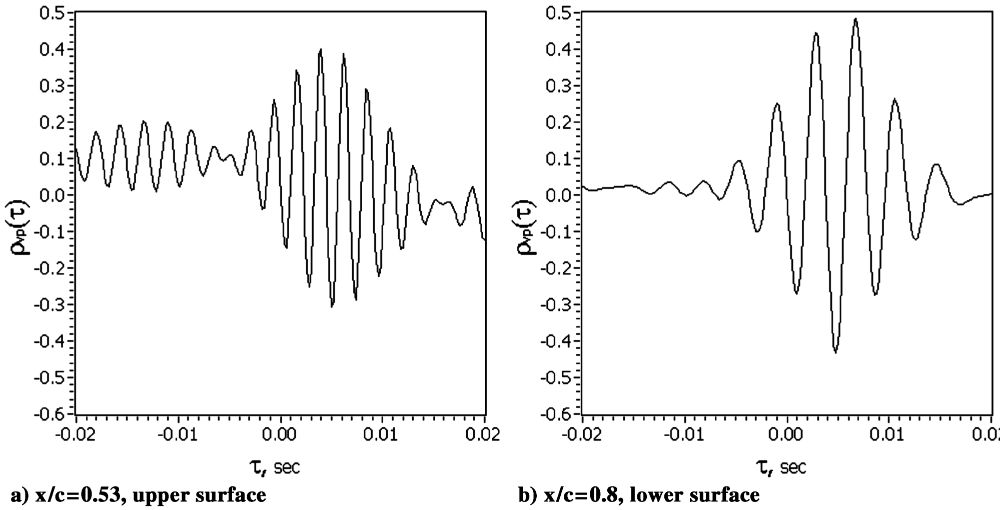


Fig. 12 Cross-correlation coefficient functions based on vertical velocity component v and surface pressure p for $Re_c = 150 \times 10^3$ at $\alpha = 5$ deg.

tubing. However, the oscillatory nature of $\rho_{vp}(\tau)$ for both Reynolds numbers signifies that the frequency-centered activity that occurs in the separated shear layer results in surface pressure fluctuations, with the period of oscillations corresponding to the fundamental frequency detected via spectral analysis. For $Re_c = 100 \times 10^3$, the amplitude of oscillations increases with an initial increase of x/c (Figs. 10a and 10b), agreeing with the growth of the corresponding spectral peaks centered at the fundamental frequency in Fig. 6. Downstream of $x/c = 0.47$, this growth is checked, and the period of oscillation observed at $x/c = 0.53$ starts to vary (Fig. 10c). Eventually, oscillations in the cross-correlation coefficient function occur at approximately $0.5 f_0$ (Fig. 10d). This is attributed to the growth of subharmonic disturbances in the separated shear layer during the nonlinear stage of transition (Fig. 6). Cross-correlation results pertaining to the lower surface (Fig. 11) show more pronounced oscillations for this Reynolds number, with the period of oscillation corresponding to the frequency of the most amplified disturbances in the separated shear layer (Fig. 7). As the Reynolds number is increased, resulting in the change of the boundary-layer flow regime, the frequency and the amplitude of the $\rho_{vp}(\tau)$ oscillations on the upper surface increase, consistent with the spectral results (Fig. 12). As in the case of $Re_c = 100 \times 10^3$, more pronounced oscillations in the cross-correlation coefficient function are observed on the lower surface for $Re_c = 150 \times 10^3$.

A comparative analysis of the presented results shows that growing disturbances in the separated shear layer produce surface pressure fluctuations at the corresponding fundamental frequency, which can be detected via surface pressure measurements conducted with a high-response, low-pressure transducer. The detection of surface pressure fluctuations within the separated flow region and, consequently, the ability to estimate the fundamental frequency of disturbances based on pressure measurements depends on both the distance between the separated shear layer and the airfoil surface and the amplitude of the disturbances at a given streamwise position. Evidently, stronger surface pressure fluctuations occur when the separated shear layer is closer to the airfoil surface and/or higher amplitude disturbances are present. For example, for $Re_c = 100 \times 10^3$, the pressure fluctuations on the lower surface produce more distinct peaks in the corresponding spectra compared with those on the upper surface (cf. Figs. 6a and 7a). This is because the distance from the separated shear layer to the wall on the lower surface is about half that on the upper surface; moreover, more distinct velocity fluctuations are observed on the lower surface. A similar comparison can be made of the results obtained on the upper surface for $Re_c = 100 \times 10^3$ and $Re_c = 150 \times 10^3$ (cf. Figs. 6 and 8). In this case, the height of the separation region is decreased and the velocity fluctuations in the shear layer become more pronounced with an increase of the Reynolds number. On the other hand, growing disturbances within the initial part of the transition region in the separated shear layer are difficult to identify from the pressure spectra despite their proximity to the wall, as can be seen from the spectra at $x/c = 0.44$ for $Re_c = 100 \times 10^3$ (Fig. 6) and at $x/c = 0.47$ for $Re_c = 150 \times 10^3$ (Fig. 8). For both Reynolds numbers, the peak in the pressure spectrum at the fundamental frequency develops further downstream, as the disturbance amplitude increases sufficiently.

IV. Conclusions

An experimental investigation of the boundary-layer development in the presence of laminar separation on a NACA 0025 airfoil operating at low Reynolds numbers was carried out. Flow visualization, hot-wire velocity measurements, and time-resolved surface pressure measurements were employed to investigate flow development over the airfoil. Detailed results are presented for $Re_c = 100 \times 10^3$ and $Re_c = 150 \times 10^3$ at $\alpha = 5$ deg, as these parameters produce two distinctly different flow regimes. For $Re_c = 100 \times 10^3$, the separated shear layer on the upper surface of the airfoil fails to reattach, forming a wide wake. In contrast, for $Re_c = 150 \times 10^3$, the separated shear layer reattaches to the upper surface of the airfoil, forming a separation bubble. Laminar boundary-layer separation also occurs on the lower surface of the airfoil for both cases examined.

The results show that flow transition plays a key role in separated shear layer development. For both Reynolds numbers investigated, a similar transition mechanism is observed. Specifically, transition occurs due to the amplification of disturbances centered at a fundamental frequency in the separated shear layer. The initial linear growth of these disturbances is followed by nonlinear interactions, associated with a half-harmonic growth, which leads to a rapid breakdown to turbulence. On the basis of the analysis of velocity and surface pressure signals, it can be concluded that growing disturbances in the separated shear layer produce pressure fluctuations that can be detected via surface pressure measurements conducted with a high-response transducer. The dominant frequency of the surface pressure fluctuations agrees with the frequency of the most amplified disturbance in the separated shear layer, i.e., the fundamental frequency. Thus, time-resolved surface pressure measurements can be employed as an alternative nonintrusive method for studying unsteady characteristics of the separated shear layer on airfoils operating at low Reynolds numbers. In particular, such a method is of interest to active-feedback flow control applications.

For lifting surfaces operating at low Reynolds numbers, one of the main challenges for capturing the fluctuating component of the surface pressure is associated with resolving low-amplitude pressure fluctuations occurring at relatively high frequencies. The present results establish that detecting pressure fluctuations produced by separated shear layer disturbances depends on the distance between the separated shear layer and the airfoil surface, as well as the amplitude of the disturbances, at a given streamwise position. Thus, surface pressure measurements only within a limited streamwise region, compared with that for velocity measurements, can be used to estimate salient characteristics of the separated shear layer transition, likely requiring several high-response pressure sensors to be mounted on a lifting surface. To this end, in future applications, transducers should be mounted adjacent to pressure taps so as to optimize frequency response and minimize distortion of pressure signals.

Acknowledgment

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