A COMPLIANT WALL SENSOR ARRAY FOR DETECTING PRESSURE FLUCTUATION SIGNATURES IN SEPARATING BOUNDARY LAYERS

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Abstract

An array of surface pressure fluctuation transducers, employing a compliant wall as the sensing element, has been used to investigate steady and unsteady flow separation on an NACA-0012 airfoil and a circular cylinder. The spatial and temporal distribution of the sensed signals were found to contain characteristic signatures of the separation process. The signals can be correlated to the set of events leading to flow separation on pitching airfoils, thereby providing a precursor to the oncoming stall.

Nomenclature

\( C_L \) = Lift coefficient
\( c \) = Chord length of airfoil
\( d \) = Cylinder diameter
\( f_v \) = Vortex shedding frequency (Hz)
\( f \) = Airfoil pitching frequency (Hz)
\( k \) = Pitch rate = \((x/v)/U_\infty\)
\( p \) = Pressure fluctuation
\( Re \) = Reynolds number
\( Re_a \) = Reynolds number based on airfoil chord
\( Re_d \) = Reynolds number based on cylinder diameter
\( U_\infty \) = Upstream velocity
\( \alpha \) = Angle of attack
\( \theta \) = Angular position on the cylinder surface from the mean stagnation point
\( x, y \) = Streamwise and crossstream coordinates from airfoil leading-edge

Introduction

Controlling unsteady separating flows is of importance in a wide variety of aerodynamic and hydrodynamic applications. These range from alleviating the effects of dynamic stall on helicopter rotors to delaying the onset of cavitation on pump impellers. An energy efficient method for controlling unsteady separation necessitates the use of suitable sensors which can indicate where and when an attached boundary layer is about to separate. A small disturbance of the appropriate type, such as controlled blowing or suction, can then be effectively utilized to prevent or delay separation.

An oncoming separation may be detected by sensing wall shear stress variation, near-wall velocity profiles or flow-induced wall pressure fluctuations. In this study, wall pressure fluctuations were sensed. An array of surface pressure fluctuation sensors, employing a compliant wall as the sensing element, was used to estimate characteristic pressure fluctuation footprints in some typical unsteady and steady separating boundary layers on a circular cylinder and an NACA-0012 airfoil in wind-tunnel experiments. The intent was to capture the spatial and temporal variation of the intensity of wall pressure fluctuations from the output signals of the compliant wall sensors. These can be expected to yield not only the proper phase relation of the unsteadiness but also illuminate the boundary layer flow physics just prior to flow separation. It is therefore expected that for each flow

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situations a set of unique characteristics can be determined which may then be used in a feedback control strategy for the control of stalling flows. The advantage of this method is that measurements can be nearly instantaneous if the signal processing time is minimized. In comparison, the responses of shear sensitive liquid crystal coatings or pressure sensitive paints generally limit their applications to relatively slower or quasi-steady phenomena. Additionally, the sensor array is simple in design and can span the entire surface. Therefore, it can be used for a wide range of flow conditions.

Scales in Separating Boundary Layers

In this study, the nominally two-dimensional geometry of the sensors allowed the measurement of streamwise variation of the fluctuation field only, though incipient separation is commonly characterized by the formation of three-dimensional cell-like structures. The flow near the separation point is dominated by the effect of the local pressure gradient on the boundary layer velocity profile. Theoretically, such flows are best described using a triple-deck description of the boundary layer, with each layer being scaled differently. The non-dimensional length-scales of the flow structures are then characterized in terms of exponents of the flow Reynolds number. In the case of a large-scale two-dimensional steady separation, the streamwise length scale of the separation is \( O(Re^{1/3}) \) of the characteristic length, whereas the boundary layer thickness is \( O(Re^{1/7}) \) of the characteristic length. The characteristic length for most external flows can be assumed to be the length of the body. For unsteady separation on an impulsively started flow over a circular cylinder, the streamwise scale of the near separation structures is \( O(Re^{1/3}) \), while for marginal separation on a “thin” airfoil, the streamwise length scale is \( O(Re^{1/9}) \). These length scales give an estimate of the spatial scales of pressure fluctuations expected. The size of the sensor elements has to be small enough to resolve these scales.

Construction of the Sensor-Array

The array of sensors consisted of a thin flexible dielectric (Mylar) membrane with its outer surface metallized (Figure 1). The thicknesses of the membrane was 6-μm. The membrane was stretched over an array of thin and nearly flush-mounted metallic strips. These metallic strips had dimensions of 1-mm x 300-mm, with a 1-mm gap between strips, for most of the experiments. In the initial experiments they were made out of individual silver strips glued to the aerodynamic surface. Subsequently, they were built by etching out a thin metal-clad polyamide sheet. The etched sheet was then glued on the aerodynamic surface. In both cases, a thin layer of air was trapped between the Mylar membrane and the metallic strips. Thus, each strip along with the metallized coating of the membrane formed two plates of an electrical capacitor, with the air gap and Mylar forming the dielectric. This air gap, along with the larger air pockets between consecutive metallic strips constituted the visco-elastic substrate of the compliant Mylar wall.

A D.C. bias voltage (60 to 400 volts for the present study) was applied between each of the sensing elements and the outer surface of the flexible wall. It helped in keeping the wall close to the elements by electrostatic attraction in the presence of flow induced suction. The magnitude of the mean air gap depends on the balance between the electrostatic and pressure forces. This defines the stiffness and damping characteristics of each capacitor-type sensor. The maximum permissible bias voltage depended on the electrical breakdown characteristics of the Mylar membrane-air gap combination.

When the array of sensors is mounted on an aerodynamic surface, the unsteady flow causes the membrane to vibrate. The output voltage from each strip-shaped sensor element, with the D.C. bias isolated, is proportional to the change in capacitance for the particular sensor. The wall pressure fluctuations above each strip are primarily responsible for changing the cell capacitance by inducing fluctuations in the air gap between the Mylar membrane and the metallic strips.

Flows over passive compliant walls often result in the occurrence of surface instabilities in the form of static divergence or traveling wave flutter. The frequency and mode of the wall vibration depends on the coupling of the flow with the compliant wall. Therefore, the response of the sensors to flow-induced surface instabilities play a crucial role. The effect of wall shear-stress on the measurement of pressure fluctuations is minimal as long as the D.C. bias voltage is high enough to prevent large-scale shear-induced buckling of the compliant wall. Higher order interactions between the shear and pressure may occur.

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However, electrical signals due to such interactions will usually be negligible compared to those induced by the pressure fluctuations alone.

**Experiments**

The first set of experiments involved an unsteady separating flow over a 152-mm diameter circular cylinder in a subsonic wind-tunnel (Figure 2). The Reynolds number, based on cylinder diameter, was varied between $1.2 \times 10^5$ to $1.7 \times 10^5$. The unsteady nature of separation at these subcritical Reynolds numbers was dominated by the large amplitude oscillations due to vortex-shedding ($f_c = 25$ Hz at $Re_c = 1.5 \times 10^5$). The mean point of separation was at $\theta = 82^\circ$, where $0$ is the angle measured from the forward stagnation point of the cylinder. The sensor array (with 1.6-mm wide strips with 1.6-mm gaps parallel to the cylinder axis) was mounted at an angular location of $\theta = 65^\circ$-$100^\circ$, so that the variation of pressure fluctuations could be observed near the point of separation.

The second experiment investigated the flow over a 300-mm chord NACA-0012 airfoil in a higher velocity closed circulation wind-tunnel. The sensor array covered the region between $x/c = 0$ to $0.08$ of the suction side of the airfoil and comprised of twelve 1-mm wide strip elements as shown in Figure 3. The chordal Reynolds number ($Re_c$) was varied between $4 \times 10^4$ to $8.5 \times 10^4$. The lift-coefficient ($C_L$) increases monotonically with angle of attack ($\alpha$) at this range of Reynolds numbers till the stall angle was reached. The angle of attack was set such that it was just below the steady stall angle for the particular $Re_c$. Pressure-fluctuations were studied near the leading edge of the airfoil.

The final set of experiments were run on the same airfoil while it was being pitched approximately sinusoidally for $\alpha$ between $5^\circ$-$25^\circ$ about its 1/4-chord axis. These experiments were designed to identify wall-pressure fluctuation precursors for predicting an oncoming dynamic stall. A new test section incorporating a pitching NACA-0012 airfoil was built as shown in Figure 4. A microcomputer-based data acquisition system incorporating eight 8-bit 20-MHZ A/D boards was used to capture pressure-fluctuation data simultaneously from eight sequential transducer strips. The high acquisition speed is essential to sample adequate data points around the instant of separation.

The separation process was monitored using smoke flow visualization. The approximate $\alpha$ at which the flow was observed to separate for a given $k$-$Re_c$ combination was measured using a digital shaft encoder (with a 0.1$^\circ$ resolution). This was used to trigger the data acquisition process.

**Results:**

Preliminary results were encouraging. Figure 5 shows the time-averaged spectrum of wall pressure fluctuations, as measured by a sensor element on the cylinder surface at $\alpha = 78^\circ$. The broadband peak at 2.25 kHz points to a separation instability due to fluctuations in pressure. The rms of the surface pressure fluctuations increased as the mean point of separation was approached. The characteristic peak around 2.25 kHz was detectable in sensors located from $0 = 78^\circ$ to $0 = 82^\circ$. In terms of streamwise spacing, the $\Delta(Re_{c,cr})$ structure corresponds to an angular spacing of $4.5^\circ$. Hence, these experiments showed that this feature could be used to detect the separation location, as long as the sensor element had sufficient spatial resolution in the streamwise direction. Additionally, the instability signature at 2.25 kHz could be successfully used as a perturbation frequency for transitional flow control over the cylinder by Sinha and Pal.

The time-averaged pressure fluctuation spectrum on the suction surface of the steady NACA-0012 airfoil is shown in Figure 6. The Reynolds number was $4.3 \times 10^4$. At an angle of attack of $11^\circ$, the spectrum shows that high frequency fluctuations start dominating the flow near the separation point ($x/c = 0.06$). Flow visualization revealed the onset of separation at $\alpha = 12^\circ$. In their experimental study of wall pressure fluctuations ($p'$) in a separating turbulent boundary layer, Simpson et al. suggested that $p'$ increases till the point of detachment and decreases downstream. Similar variation of pressure fluctuations could be observed for the pre-stalled flowfield near the leading-edge of the airfoil. In order to determine whether the sensed peaks in the frequency spectrum had any significance in terms of exciting the just separated boundary layer to achieve reattachment, multiple strips near the leading edge were excited in phase at various frequencies. The effect of excitation was sensed using a hot film sensor downstream of the excitation point (Figure 7). Maximum changes were noted at 2-kHz and 4.75-kHz. These frequencies are close to the frequencies of the two major pressure.
fluctuation peaks observed in Figure 6. However, they do not exactly coincide. Flow visualization revealed that excitation at 2-kHz resulted in intermittent reattachment, while a complete reattachment occurred at 4.75-kHz.

For the experiments on the pitching airfoil, the Reynolds number was maintained at 10^4. Experiments were carried out at two pitching frequencies; 6.4-Hz \( (k = 0.12) \) and 11.6 Hz \( (k = 0.22) \). Flow visualization, using a video camera, revealed that the flow separation occurred between 21° to 24° for an \( x/c \) location of about 0.03 in both cases. A closer identification was not possible. Therefore trigger angles were selected around these ranges to acquire pressure fluctuation data. The signal from each sensing element was sampled at 10-MHZ for about 0.8-msec starting with the instant of trigger. Figure 8 shows the spatial variation \( (x/c = 0.02-0.067) \) of pressure fluctuations within this time interval at \( k = 0.12 \). Since the array of transducers was not calibrated, the pressure, fluctuation levels are shown in arbitrary units. However, the response of the strips was reasonably uniform as verified by earlier studies by Sinha and Pal. This permits comparison between the signals sensed by each of the strips. Figure 8 shows that at \( \alpha = 21.5° \), sensors located between \( x/c = 0.02-0.033 \) detected fluctuations above the base level. The level of the signal detected by the other sensors is very low (base level). The maximum fluctuation levels increase as \( \alpha \) increases. At \( \alpha = 22° \), the fluctuations reach a maximum between \( x/c = 0.02 - 0.053 \). Higher values of \( \alpha \) yield severely diminished fluctuation levels on all sensor elements. Wall pressure fluctuations are expected to maximize around the point of eruption of the boundary layer. This implies that the flow separates at \( \alpha = 22° \) at the chordal location \( x/c = 0.06 \). Figure 9 shows similar trends for the higher pitching frequency \( (k = 0.22) \), with the flow separating at \( \alpha = 23.5° \) and \( x/c = 0.053 \).

On the basis of the acquired pressure fluctuation data, a spectral analysis of the sensed signals was performed. Figure 10 shows the Fourier transform and phase of the pressure fluctuation signals obtained from the compliant wall sensors at different streamwise locations at \( k = 0.12 \) and \( \alpha = 22° \). The fluctuation spectra show large amplitude peaks in the frequency range of 1-6 kHz over the entire streamwise location of \( x/c = 0.02 - 0.067 \). Phase velocities were computed as a function of frequency on the basis of the phase-difference information between consecutive sensor elements \( (c) \). The strip closest to the leading edge was used as a reference for computing phase differences.

The prominent peaks in the phase velocities are seen between 1.3 to 2.9 kHZ for the entire array. Using the information on phase velocities, frequencies and sensor location, the wavelengths of surface waves were computed. These ranged from 0.17-0.45 mm. This compares well with the \( \Omega(Re)^{1/2} \) streamwise length scale of 1.68-mm for this case. Figure 11 shows the frequency domain plots and velocities for the higher pitch rate \( (k = 0.22) \). The wavelengths were approximately in the same range from 0.16-0.49-mm. This is not surprising, since the reduced frequencies varied only by a factor of two between the two cases.

**Conclusions:**

A compliant wall transducer comprising of an array of strip shaped sensors has been used to sense pressure fluctuations just prior to and during unsteady and steady boundary layer separation. On circular cylinders, at subcritical to critical Reynolds numbers, the sensors detected a characteristic pressure fluctuation frequency. This frequency was found to have significance in reattaching the separated shear layer. The amplitude of pressure fluctuation signals from the array of sensor strips directly indicated the location of the separation point. Similar data was also obtained from the sensors when used on a steady airfoil operating just under stalling conditions.

In the experiments on pitching airfoil, the array of compliant wall sensors was found to sense small-wavelength traveling surface waves near the instantaneous separation point. These waves are likely to occur during the process of dynamic stall. The array of sensors is capable of sensing smaller streamwise length scales than the streamwise dimension of the sensors themselves. This is due to the fact that the pressure fluctuations are sampled temporally at a very high rate. The high sampling rate, in turn, compensates for the insufficient spatial resolution of the sensor-array. It is, however, important to note that in order to use such an array of compliant wall sensors in practical applications involving unsteady turbulent boundary layers, the spatial resolution has to be improved to sense smaller turbulent scales. Sinha et al. discussed the prospect of using an improved elastomeric substrate for the compliant wall...
to avoid such limitations.

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References:


Figure 1. Schematic of the compliant wall sensor array.
Figure 2. Wind-tunnel testing facility. All dimensions in ft.

Figure 3. Arrangement of the compliant wall sensor array on the NACA-0012 airfoil.

Figure 4. Schematic of the dynamic stall facility.
Figure 5. Time-averaged pressure fluctuation spectrum of pre-separation boundary layer in the absence of compliant wall actuation. $Re_x = 1.5 \times 10^5$. Measurement location: $\theta = 78^\circ$.

Figure 6. Time-averaged pressure-fluctuation spectrum on the suction surface of the steady NACA-0012 airfoil ($x/c = 0.067$). $\alpha = 11^\circ$. $Re_x = 4.3 \times 10^5$.

Figure 7. Effect of excitation frequency on NACA-0012 airfoil wake velocities (mean and fluctuation). Measurement with hot-film sensor at $x/c = 1.55$, $y/c = +0.083$. Multi-element excitation at airfoil leading-edge ($x/c = 0.02$). $Re_x = 4.3 \times 10^5$. 

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Figure 8. Spatial Variation of Pressure-fluctuation signatures near the dynamic stall angle. 
(a) $\alpha = 21.5^\circ$,  (b) $\alpha = 22.0^\circ$,  (c) $\alpha = 22.5^\circ$,  $k = 0.12$,  $Re_c = 10^6$
Figure 9. Spatial Variation of Pressure-fluctuation signatures near the dynamic stall angle. 
(a) $\alpha = 22.5^\circ$, (b) $\alpha = 23.5^\circ$, (c) $\alpha = 25.0^\circ$, $k = 0.22$, $Re_c = 10^6$. 

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Figure 10. Spectral Analysis of Pressure-fluctuation signals.
(a) Fourier Transform Magnitude (b) Phase (degrees)
(c) Phase Velocity (m/sec)
Angle of attack (\(\alpha\)) = 22.0\(^\circ\), Reduced frequency (\(k\)) = 0.12,
Reynold Number (Re\(_c\)) = 10\(^6\).
Figure 11. Spectral Analysis of Pressure-fluctuation signals.
(a) Fourier Transform Magnitude  (b) Phase (degrees)
(c) Phase Velocity (m/sec)
Angle of attack (α) = 23.5°. Reduced frequency (k) = 0.22,
Reynold Number (Reₗ) = 10⁵.