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Boundary Layer and Pressure Measurements on a Cylinder with Unsteady Circulation Control

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Unsteady boundary-layer and surface pressure measurements were made on a circular cylinder with time-varying blowing applied from a narrow spanwise slot. The effects of mean blowing level, blowing frequency, and boundary-layer trip location were examined at a Reynolds number of 2.2×10^5 based on cylinder diameter. Time-resolved pressures were recorded using pressure sensors located on the Coanda surface and around the circumference of the cylinder. Flush-mounted hot film probes were positioned both upstream and downstream of the slot to provide a qualitative measurement of the boundary-layer characteristics. The results have shown that the shear stress just downstream of the slot was always in-phase with the plenum pressure. However, increasing reduced frequency generally resulted in increasingly larger phase lags between the application of blowing and the development of the flow over the remainder of the Coanda surface. For both steady and unsteady blowing, the jet entrained the outer flow at the slot and remained attached to the Coanda surface, provided a fully attached laminar or turbulent boundary layer was obtained just prior to reaching the slot.

Nomenclature

C_D = pressure drag coefficient
C_N = normal force coefficient
C_N^1 = first harmonic of unsteady C_N
C_p = pressure coefficient, $(p - p_\infty)/q_\infty$
C_μ = jet momentum coefficient, $\dot{m}V_j/q_\infty d$
C_μ^1 = first harmonic of unsteady C_μ
d = cylinder diameter, m
k = reduced frequency, $\omega d/2V_\infty$
$\dot{m}$ = mass flow rate per unit span, kg/s
p = local static pressure, N/m^2
p_∞ = freestream static pressure, N/m^2
q_∞ = freestream dynamic pressure, N/m^2
Re = Reynolds number, $\rho_\infty V_\infty d/\mu_\infty$
t = time, s
V_∞ = free stream velocity, m/s
V_j = jet velocity, m/s
Γ = circulation, m^2/s
θ = cylinder surface angle relative to freestream, deg
μ = dynamic viscosity, kg/m · s
ρ_∞ = freestream density, kg/m^3
ω = blowing frequency, rad/s

Introduction

THE basic feature of circulation controlled (CC) airfoils is a high lift capability at low freestream dynamic pressures and at low angles of attack. This CC lift capability is produced by discharging a thin high-velocity jet tangentially to the surface of a rounded trailing edge. The jet is produced by the expansion of pressurized air from a plenum inside the airfoil through a narrow spanwise slot. The tendency of this high-velocity jet to follow the curved trailing edge surface is known as the Coanda effect[1] and underlies the operation of all CC airfoils. Basically, the jet remains attached to the rounded trailing edge due to a balance between centrifugal and pressure forces. Increased levels of mean blowing, conventionally quantified by the jet momentum coefficient C_μ, generally results in increasingly greater circulation and lift produced by the airfoil.

The maximum lift coefficients produced by CC airfoils are typically several times those of conventional airfoils.[2] Therefore, in principle, substantial improvements in aircraft STOL performance can be gained by applying these airfoils to fixed-wing aircraft[3–5] as well as rotary-wing aircraft. On rotorcraft, the CC concept has been successfully implemented for antitorque purposes.[6] For rotors themselves, the CC concept is also attractive, yet because of the highly nonsteady flow environment, unsteady blowing is required for lift control. A CC rotor having blades with blowing slots at both the leading edge and trailing edge can feasibly make the blade sections independent of freestream flow direction and offers the potential of a stoppable rotor aircraft.[7] It also is feasible that rotor vibrations may be reduced by using higher harmonic blowing control on a CC rotor.[8] It is clear, however, that the unsteady aerodynamics of CC airfoils must first be properly understood before such airfoils can be successfully applied to rotor blades.

Early work on circulation control was conducted by Cheeseman and Seed[9] and Kind and Maull.[10] Considerable experimental research in the field of steady-state circulation control aerodynamics has also been carried out by Abramson et al.,[12] Wood and Nielsen,[2] and Englar and Williams,[11] among others. Parallel analytical investigations of the behavior of CC airfoils under steady blowing conditions have been carried out by Dunham[13] and Kind.[14] More recently, Sun et al.,[15] Solimon et al.,[16] and Tadghighi and Thompson[17] have used finite difference methods, discrete vortex modeling techniques, and conformal mapping techniques, respectively, to investigate the aerodynamic characteristics of circular and elliptical CC airfoils.

There is a dearth of research on the unsteady behavior of CC airfoils. Because of the difficulties in conducting experiments on this problem, most previous studies have been analytical. Raghavan et al.[18] extended the panel method developed by Sun et al.[15] to study elliptical and circular CC airfoils with unsteady jet blowing. The method predicted that sinusoidal blowing would not appreciably affect the peak-to-peak value of the lift, although the mean value of the lift would be reduced. Also, the phase lag between the application of blowing and the lift response was found to be only slightly affected for increasing blowing frequencies—perhaps an unexpected result at reduced frequencies as high as 0.5. Also, Sun and Wang[19] analytically investigated unsteady blowing over an elliptical CC airfoil. Their results showed that a sinusoidally varying C_μ decreased the amplitude of the lift response and increased the phase lag at higher reduced frequencies.

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One of the earliest experiments into unsteady effects on CC airfoils was reported by Schmidt.[20] The effects of an oscillating jet on an elliptical CC airfoil were studied, but the unsteady pressures were not measured directly. A scanivalve system was calibrated to compensate for the attenuation and phase lag of the pressure signal due to the pressure tubing, thereby providing the lift transfer function of the airfoil as a function of blowing frequency. A transportation lag effect between the duct pressure and the blowing was observed, as well as a decrease in lift augmentation ratio with increasing blowing frequency. Other work on CC airfoils in an unsteady flow environment is discussed by Walters et al.,[21] Lancaster,[22] and Lorber et al.[8]

Recently, Ghee and Leishman[23] have investigated the behavior of a CC circular cylinder with periodic jet blowing operating in a steady freestream. In this experiment, time-resolved pressures around the cylinder were recorded and used to determine unsteady lift and pressure drag acting on a section at midspan. A variety of interesting results were obtained. However, no boundary-layer instrumentation was used which significantly limited the scope of this experiment. The present work reports an extension of this experiment, the main objective being to obtain a better understanding of the behavior of the boundary-layer flow environment near the slot and around such a CC airfoil under unsteady blowing conditions. The work also provides a further basis for parallel theoretical studies of the problem.

Description of the Experiment

The experiments were conducted in a 0.56 × 0.56 m (22 × 22 in.) low-speed open-jet wind tunnel. This tunnel has a turbulence intensity of less than 0.2% at 30 m/s. The airfoil was a circular cylinder 0.52 m (20.5 in.) in length and 0.1 m (3.96 in.) in diameter, giving an aspect ratio of 5.18. A narrow slot with a nominal gap of 0.051 mm (0.002 in.) was provided along the full span of the cylinder. A variation of this model has been previously used to study CC aerodynamics under steady blowing conditions,[24] and more recently under unsteady conditions.[23,25] The cylinder was mounted in a test stand between two large endplates, and positioned immediately downstream of the open jet.

Pressurized air for blowing was obtained using two rotary vane compressors. The air from the compressor was first cooled to near room temperature by a heat exchanger. The mass flow rate entering the cylinder plenum was controlled by a pressure regulator. For the unsteady tests, a rotating ball valve driven by a variable speed motor was situated in-line between the compressors and the plenum. This created an oscillating pressure inside the plenum, and therefore an oscillating jet was obtained on the cylinder.

Twenty-two chordwise pressure sensors and four flush mount hot film probes were positioned at or near the midspan of the model. These sensors recorded the time histories of the absolute pressure and boundary-layer shear stress on the surface of the cylinder, respectively. The pressure sensors were located below a small pressure tap in the surface. The hot films were located as closely as possible to the pressure sensors. However, physical constraints prevented placement at coincident angular locations. The locations of the sensors were also staggered to avoid localized interference effects. Figure 1 shows the locations of the sensors, and Tables 1 and 2 give the angular locations.

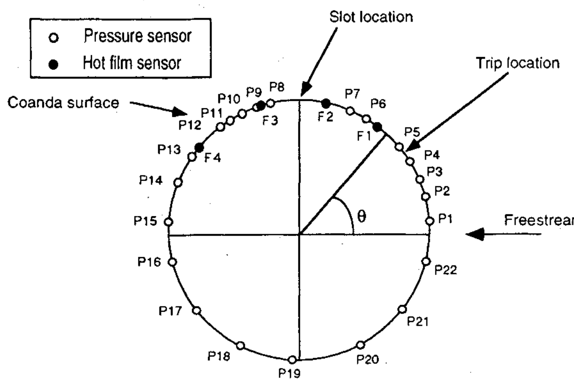


Fig. 1 Location of pressure and hot film sensors.

The pressure sensors typically had a nominally flat frequency response up to at least 3 kHz. This was well beyond the current range of interest (fundamental frequencies up to 60 Hz). Two additional pressure sensors were enclosed in the cylinder plenum and used to measure the unsteady duct pressure. All the pressure sensors were statically calibrated in situ and were also calibrated for temperature effects.

The hot film probes were TSI noncylindrical flush mount types and were connected to a constant temperature anemometer system (CTA). Two hot films were placed upstream of the slot, and two hot films were placed on the Coanda surface. No formal calibrations were performed on the hot film sensors since only a qualitative measurement of the state of the boundary layer was sought in this investigation. Without calibration, the relationship between shear stress and CTA output voltage is nonlinear. However, the output voltage increases with increasing heat transfer from the sensor surface, which, in turn, is related by the Reynolds analogy to the shear stress on the surface. Maximum values of shear stress were typically obtained with a fully attached boundary layer. On the other hand, a low shear stress signal corresponded to a boundary layer that either had separated or was on the verge of separation. Signals between these limits were interpreted based on their overall characteristics and correlations with pressure data.

Test Procedure

Data collection was enabled in a phase-locked sense by a trigger pulse from an optical sensor on the shaft of the ball valve. A programmable external clock controlled the sampling frequency. The entire process of pressure and hot film data collection was controlled by a high-speed multichannel A-D converter system that communicated with a computer over an IEEE interface. Further details of the experimental setup are given in Ref. 26.

Twenty cycles of data were recorded simultaneously from each pressure and hot film sensor during the unsteady tests. The pressure data were digitized at 1024 points/blowing cycle and were subsequently ensemble averaged into a 128 points/cycle buffer. During the steady tests, 20 s of pressure data were recorded and ensemble averaged into a single value of pressure coefficient for each sensor location. Hot film data were digitized at 1024 points/cycle during unsteady tests and 1024 points/s during the steady tests. The hot film data were unaveraged to preserve the inherent random fluctuations present in turbulent boundary layers.

Jet Momentum Coefficient

The strength of the jet was quantified by using the customary jet momentum coefficient C_μ. It was assumed that the only unsteady

Table 1 Angular locations of pressure sensors

Pressure transducer	θ, deg	Pressure transducer	θ, deg
1	4	12	127
2	15	13	145
3	23	14	158
4	32	15	176
5	40	16	194
6	59	17	218
7	67	18	243
Slot	90	19	267
8	103	20	298
9	109	21	322
10	116	22	346
11	122		

Table 2 Transducer locations relative to the freestream velocity

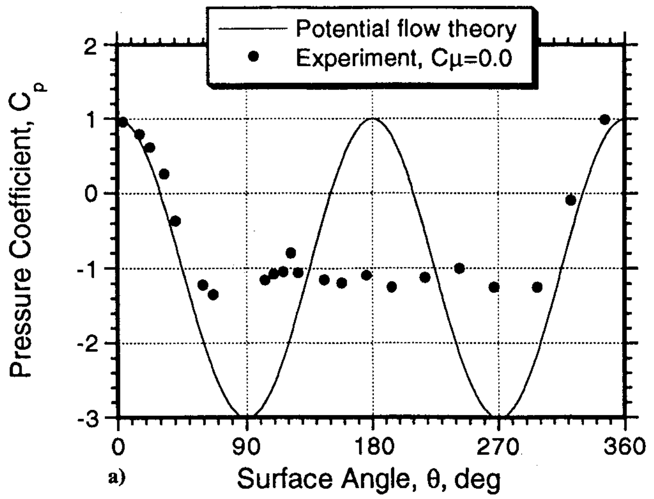
Hot film	θ, deg
1	53
2	78
3	107
4	140

parameter affecting the jet momentum coefficient was the time-dependent plenum pressure. Measurements of shear stress immediately downstream of the slot were always found to be in-phase with the plenum pressure, thereby confirming the validity of a quasisteady assumption. The jet velocity and mass flow rate were computed via isentropic flow relations from measurements taken of the total pressure and total temperature inside the cylinder plenum. The jet velocity V_j was computed by assuming the pressurized air in the plenum expands isentropically to atmospheric pressure p_∞. The mass flow rate per unit span $\dot{m}$ was determined by assuming isentropic unchoked flow. Measurements of mean blowing and blowing amplitude were obtained in real time and were adjusted to the required levels prior to the test run by means of the pressure regulator.

Experimental Uncertainty

It was estimated that the ensemble averaging procedure minimized the uncertainty of the pressure coefficients to no more than ±0.05. Most of this uncertainty was due to zero drift of the pressure transducers because of thermal effects associated with the compression of the air inside the cylinder plenum. This error was minimized by restricting the run time between zero measurements. The lift (normal force) and pressure drag coefficients, C_N and C_D, respectively, were obtained by numerically integrating the pressure distributions around the section. Based on the pressure coefficient uncertainty, the lift and drag coefficients had a maximum uncertainty of ±0.1, although most results presented here have uncertainties considerably less than this. The frequency of the ball valve was estimated to have an uncertainty of ±0.05 Hz, corresponding to a maximum uncertainty in reduced frequency of ±0.005. In the present tests, the slot was redesigned from that used in Refs. 24 and 25 to achieve a slot gap tolerance of less than ±0.0127 mm (±0.0005 in.) along the span. As a result, the jet momentum coefficient was estimated to have a maximum uncertainty of ±0.005.

The data presented in this paper are uncorrected for different interference effects such as solid blockage, wake blockage, or tunnel wall constraints. The estimation of these effects is difficult for CC airfoils, and the present tests were deliberately conducted in an open-jet tunnel to ensure that most interference effects could be considered as small. Also, the cylinder was inverted so that the jet wake development was unimpeded by the test stand or supports.



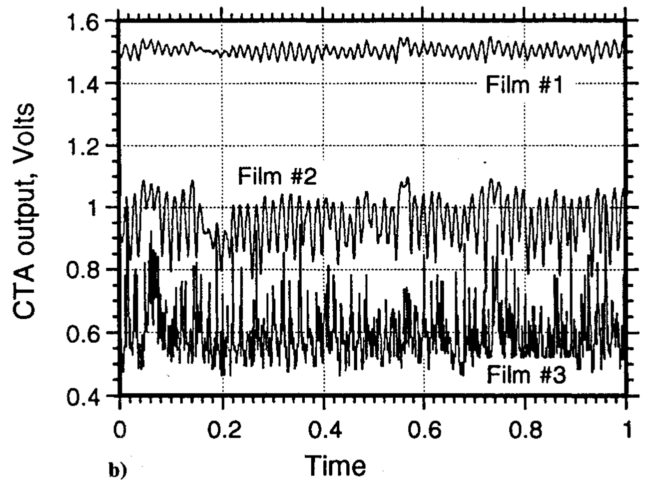


Fig. 2 For unblown cylinder (transition free): a) pressure distribution and b) hot film responses vs time.

Test Conditions

Steady and unsteady blowing tests were performed in four different configurations. The first tests were conducted transition free, that is, with natural transition. For the remaining three tests boundary-layer trips were located upstream of the slot. The trips consisted of 150-grade grit in spanwise bands 4.76 mm (3/16 in.) wide and were placed on both the upper and lower surfaces. For the three fixed transition configurations, trips were positioned at $\theta =$ ±37, ±55, and ±63 deg. The slot angle for the present tests was set at 90 deg relative to the undisturbed freestream. The effect of slot position has been previously investigated by Ghee.[25] Unless otherwise stated, the Reynolds number based on cylinder diameter was 2.2×10^5.

Results and Discussion

Steady Blowing

To provide a reference, the steady results will be discussed first. Figure 2a shows the pressure distribution around the midspan of the cylinder for the transition-free case with no blowing. Also plotted for reference is the pressure distribution corresponding to classical steady potential flow theory, in which the circulation Γ has been related to the measured value of C_N by means of the Kutta-Joukowsky theorem. Figure 2a indicates that flow separation occurred between θ = 60 and 80 deg on the top surface, and between θ = 280 and 300 deg on the lower surface. Downstream of the upper and lower separation points, a constant pressure region exists, which is a well-known characteristic of a fully separated flow region.

Figure 2b shows the corresponding outputs of hot films 1, 2, and 3 (located at θ = 53, 78, and 107 deg, respectively) for the unblown cylinder. Hot film 1 confirms the presence of a fully attached laminar boundary layer due to the somewhat low Reynolds number of this flow. The regular oscillations present in the responses from all the hot films are of some interest and are caused by periodic vortex shedding at the rear of the cylinder. Measurements of the shear stress on a circular cylinder made by Mangalam et al.[27] show similar results. The frequency of these periodic shear stress fluctuations was equal to 62 Hz, giving a Strouhal number (fd/V_∞) of 0.2. This is consistent with other measurements on circular cylinders (see, for example, Schlichting[28]).

The smooth but higher amplitude fluctuations of the shear stress shown by hot film 2 (θ = 78 deg) still suggested the presence of a laminar boundary layer at this point with no strong evidence of transition or separation. The larger fluctuations arise because of the larger fluctuating surface velocity at this point induced by the periodic vortex shedding. In conjunction with the pressure data, it can be inferred that flow separation on the unblown cylinder occurred just slightly downstream of θ = ±78 deg, but prior to the slot. The random fluctuating characteristics of the signal from hot film 3 at θ = 107 deg, along with the low relative output, clearly confirms the existence of a separated flow region. A similar response was obtained from hot film 4 at θ = ±140 deg (not shown), which was also in the separated flow regime.

Because of this natural laminar flow separation just upstream of the slot, it was found that a minimum jet momentum coefficient of about 0.04 was required to produce any useful CC lift. This minimum blowing threshold was required to entrain the upstream flow and produce attached conditions prior to the slot. Note that it has been postulated by Wood and Nielsen[2] that conditions that thicken

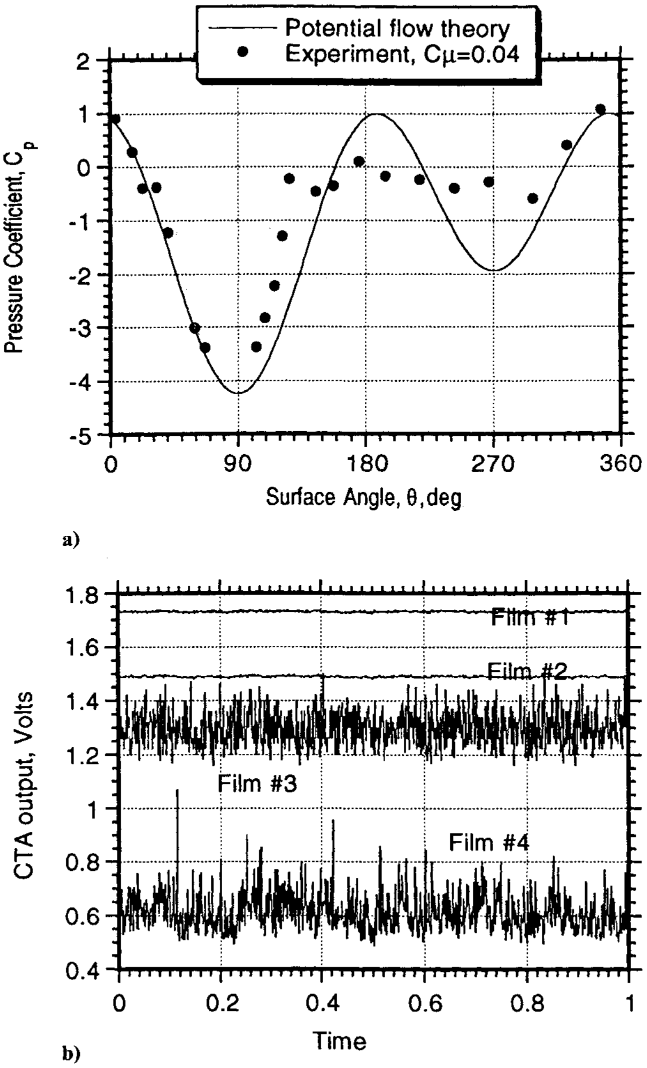


Fig. 3 For conditions at minimum blowing threshold (C_μ = 0.04, transition free): a) pressure distribution and b) hot film responses vs time.

the boundary layer at the slot, and therefore increase the momentum thickness, tend to reduce the effectiveness of the jet for a given jet momentum. Figure 3a shows the pressure distribution at this minimum blowing threshold. It is apparent that the upper surface separation point has now moved rearward to approximately θ = 140 deg on the upper surface, i.e., about 60 deg downstream of the separation location on the unblown cylinder. This subsequently resulted in the creation of a significant amount of circulation (C_N ≈ 2). The lower surface separation occurred just downstream of the maximum cylinder thickness at about θ = 260 deg. The better agreement of the measurements with the attached flow theory confirms that at this level of blowing the jet acts to suppress almost all flow separation and vortex shedding.

Figure 3b shows the corresponding hot film responses. Films 1 and 2 (θ = 53 and 78 deg, respectively) show a shear stress behavior characteristic of a fully attached laminar boundary layer. However, the absence of regular periodic fluctuations confirmed that this minimum blowing had successfully suppressed vortex shedding. Hot film 3 (on the Coanda surface) detected evidence of the high velocity turbulent boundary layer associated with the jet, but the signal from hot film 4 further downstream at θ = 140 deg was more characteristic of separated flow. This is consistent with the upper surface separation point location previously inferred from the pressure data.

To simulate a turbulent boundary layer prior to the slot, boundary-layer trips were successively positioned at three separate locations. Figure 4a shows the pressure distribution around the cylinder for zero blowing with the trips at the furthest upstream locations, i.e., $\theta = \pm$ 37 deg. Readily apparent from Fig. 4a is a greater suction pressure at θ = 60 and 300 deg relative to unblown transition-free case. Also, there was a noticeable increase in base pressure, implying an immediate reduction in pressure drag. The effects of such boundary-layer trips is a well-known result for a circular cylinder, since the ensuing turbulent boundary layer remains attached to the surface longer compared to the transition-free case.

The corresponding hot film data for this run are shown in Fig. 4b. Upstream of the slot, the results showed high-frequency random fluctuations, which verifies that boundary-layer transition had occurred downstream of the trips. The trips also eliminated periodic vortex shedding, yet the nonregular fluctuations at the rear of the cylinder still suggest the presence of separation and a highly turbulent bluff body type wake.

The normal force coefficient vs the blowing coefficient for both the transition-free and transition-fixed (tripped) cases is presented in Fig. 5a. Compared to the transition-free case, the tripped case produced useful CC lift from the onset of blowing. This was because an attached (turbulent) boundary layer existed prior to the slot and more readily mixed with the jet. At higher values of blowing coefficient, note that the lift of the transition-fixed case was somewhat less than that of the transition-free case. This difference is due to the formation of a larger wake behind and below the cylinder for the transition-free case. This wake created a more positive pressure coefficient and contributed favorably to the lift coefficient. For the trip on case, flow separation on the lower surface was considerably delayed (due to artificial transition), and the attached flow over more of the lower surface produced a larger suction pressure region that subsequently subtracted from the lift.

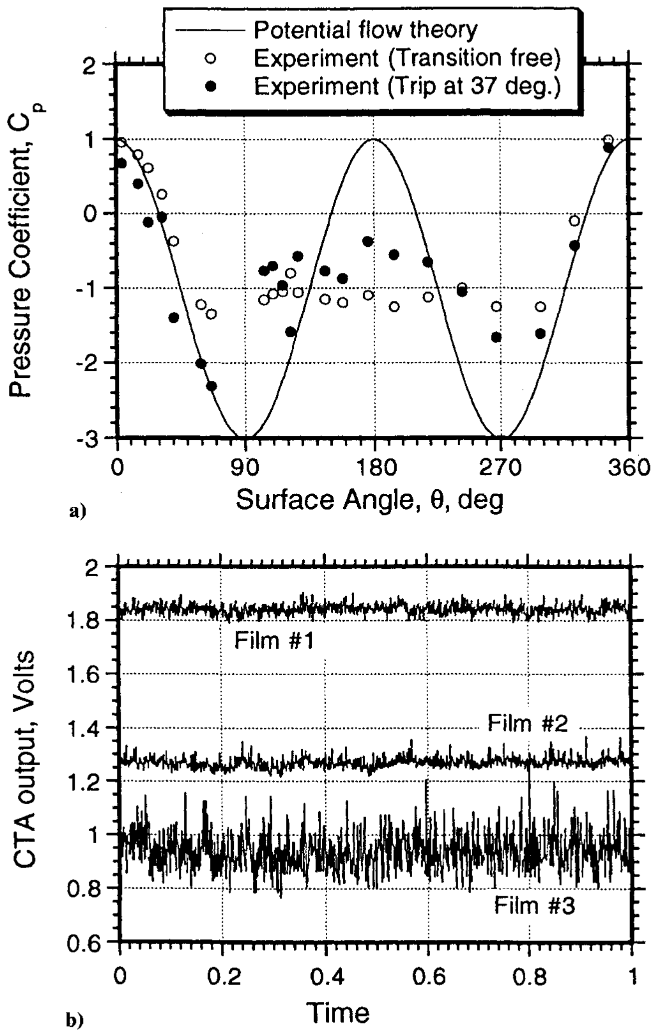


Fig. 4 For conditions for unblown cylinder (transition fixed at $\theta = \pm$ 37 deg): a) pressure distribution and b) hot film responses vs time.

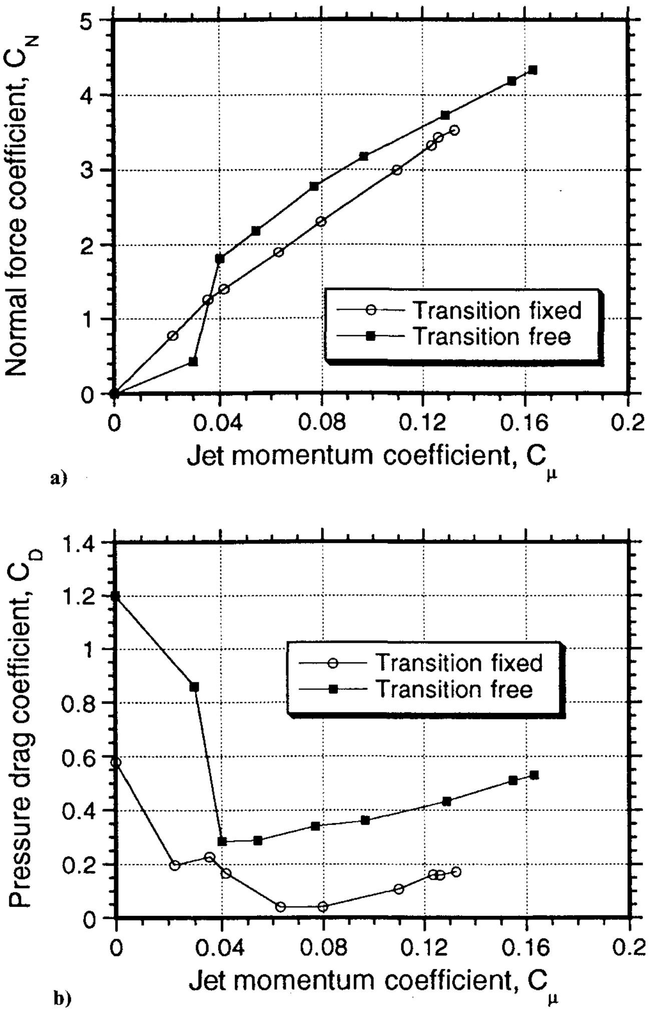


Fig. 5 Steady blowing, transition free, and transition fixed at $\theta = \pm 37$ deg: a) normal force and b) pressure drag coeffecients vs blowing coefficient.

The larger wake of the transition-free case did, however, produce a larger drag coefficient (see Fig. 5b).

The static lift augmentation ratio $\partial C_N/\partial C_\mu$ can be considered as a measure of the efficiency in producing CC lift vs lift due to vertical momentum transfer. For the trip on case, partial $\partial C_N/\partial C_\mu$ was found to be higher at low values of C_μ than at higher C_μ. This nonlinear lift behavior with blowing is typical of CC airfoils, in general.[29] The present results for lift augmentation ratio were in close agreement with those in Ref. 29. Also, note that the maximum levels of blowing obtained in this experiment were limited by the compressor pressure. In no test was there any evidence of a breakdown of the jet or detachment from the Coanda surface at higher levels of blowing.

The pressure drag coefficient vs the jet momentum coefficient is presented in Fig. 5b. Both the transition-free and transition-fixed results are shown. The trends with increasing blowing are essentially the same for both cases, however there are some notable differences. Initially, at $C_\mu = 0$, flow separation was delayed due to artificial transition at the trip, which made the boundary layer turbulent, and therefore delayed separation further downstream and reduced the pressure drag. It has been shown previously that a minimum blowing created pressure distributions closer to the theoretical potential flow values. This result accounts for the very low drag coefficients obtained at intermediate values of blowing. However, a rise in drag was observed for the higher blowing levels. This rise was a result of much higher suction pressures created on the Coanda surface that produced a more positive increment in pressure drag.

Two other tests were carried out with boundary-layer trips positioned at $\theta = \pm 55$ and ± 63 deg, successively. It was noted that the jet was not always able to entrain the outer flow in these cases. Either fully attached or fully separated flow occurred for extended periods of time. The reason for this behavior was the formation of a transitional or undeveloped turbulent boundary layer initiated by a trip located too close to the slot. Small disturbances in the flow were found sufficient to cause either reattachment or separation at the slot. When the trips were located at $\theta = \pm 37$ deg, the boundary layer was fully developed prior to reaching the slot, and the jet was always well behaved.

Unsteady Blowing

In unsteady flow, there were also significant differences between the results for "natural" or untripped flow and those obtained with a trip. For the untripped case, it was determined that a transitional boundary layer was obtained just prior to the slot, which did not ensure complete mixing with the jet. As a consequence, a nonrepeatable jet detachment phenomenon was often obtained. The same result was obtained with a transition strip located too close to the slot. It was with the transition strip located at 37 deg that the jet fully mixed with the upstream flow. Therefore, all unsteady results presented in this paper were obtained with the transition strip at $\theta = \pm 37$ deg.

For the unsteady tests, the jet momentum coefficient consisted of a mean value and an unsteady portion. Although higher harmonic blowing contributions were occasionally obtained, we will confine our attention mainly to the first harmonic for which the blowing coefficient can be represented as $C_\mu(t) = \overline{C_\mu} + C_\mu^1 \sin \omega t$,

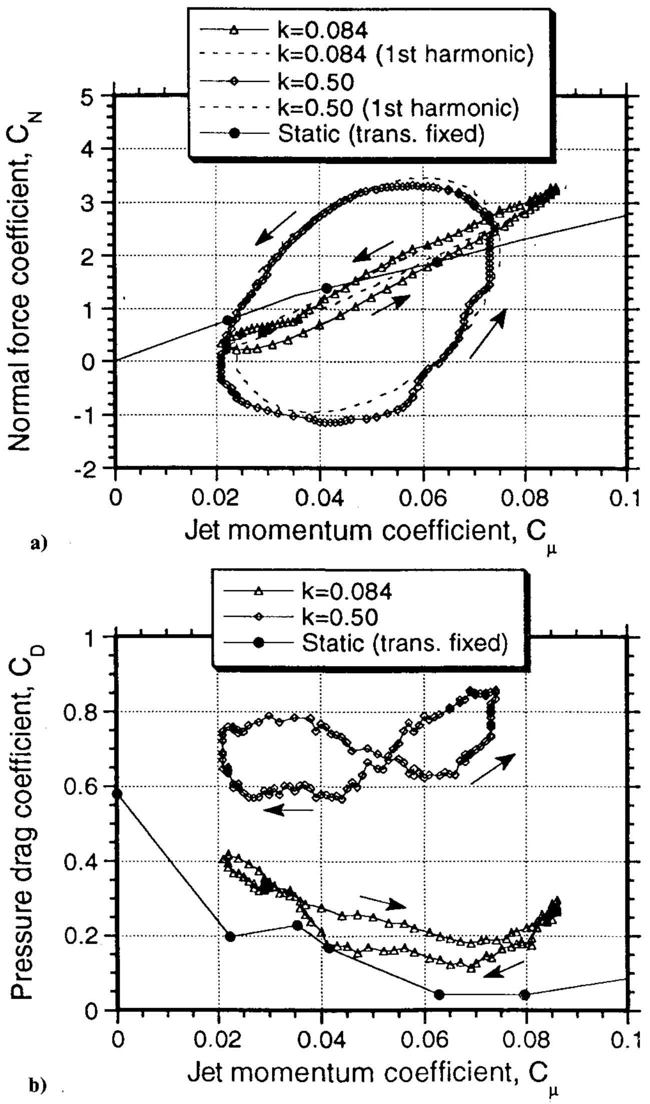


Fig. 6 Transition fixed at $\theta = \pm 37$ deg, $k = 0.084$: a) unsteady normal force and b) pressure drag coefficients vs blowing coefficient.

where $\overline{C}_\mu$ is the mean blowing level. The higher harmonic components of the blowing were mostly the result of the pneumodynamics of the blowing system. In the present tests, the reduced frequency k, which is a measure of the unsteadiness of the flow, was normally varied from 0.07 to a maximum of 0.5.

Figure 6a shows the instantaneous normal force coefficient plotted vs the instantaneous jet momentum coefficient for low and high values of reduced frequency. The lift response shows a hysteresis effect similar to the effect obtained on an oscillating airfoil in angle of attack. As shown by Ghee and Leishman,[23] a dynamic lift augmentation ratio can be defined as the ratio of the first harmonic of the unsteady lift amplitude to the first harmonic of the unsteady blowing amplitude, i.e., C_N^1/C_μ^1. This quantity can be considered the unsteady analog of the steady lift augmentation ratio, which is essentially a measure of the ability of the airfoil to produce lift by means of CC vs that produced by vertical momentum transfer. As the reduced frequency increased, Fig. 6a shows that the lift augmentation ratio also increased and was considerably greater than the corresponding static value. Increasing reduced frequency also caused increasing phase lags between the application of the blowing and the lift response. For a reduced frequency of 0.084 the phase lag was only 4 deg. However, for a reduced frequency of 0.5, the lift response lagged $C_\mu(t)$ by as much as 80 deg. Note that these results are qualitatively different from the theoretical results of Raghavan et al.[18] and Sun and Wang,[19] who predicted a decrease in lift augmentation ratio with increasing blowing frequency. Further measurements for the unsteady lift transfer function are given by Ghee.[25]

At the highest reduced frequency of this test ($k = 0.5$), an unexpected phenomenon was observed in which positive blowing produced negative lift coefficients (as low as −1.0) in the unsteady lift hysteresis loop (see Fig. 6a). This phenomenon was found to be a result of significant suction pressure developing on the underside

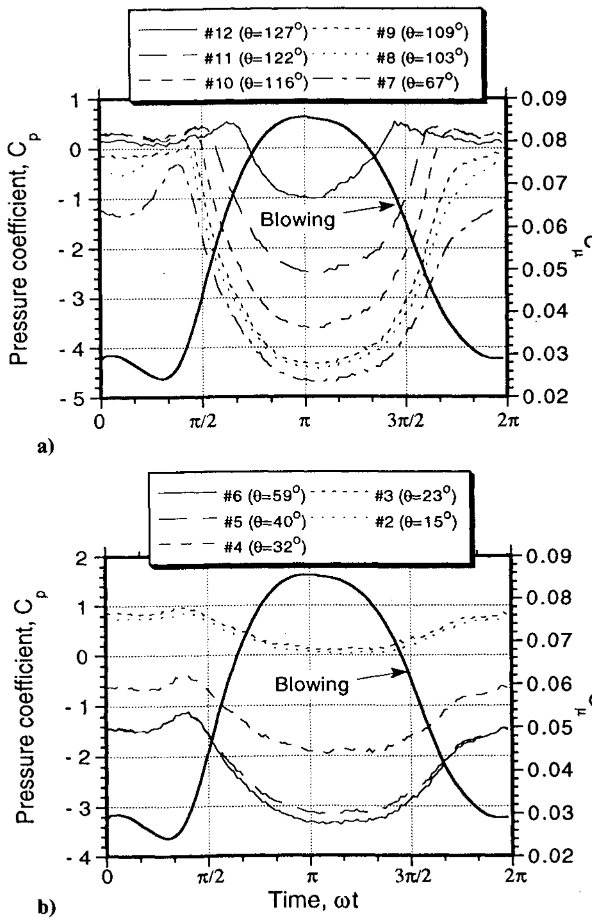


Fig. 7 Pressure a) on Coanda surface and b) upstream of slot for unsteady blowing, $k = 0.5$.

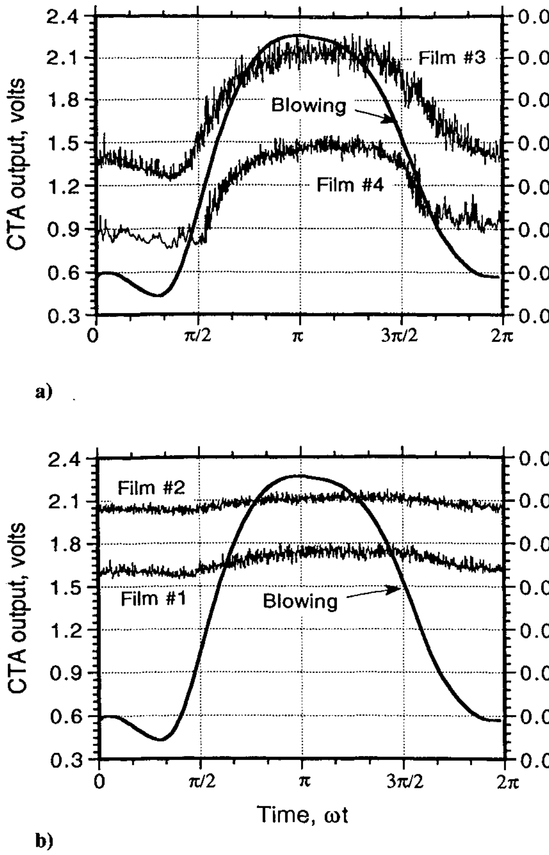


Fig. 8 Pressure a) on Coanda surface and b) upstream of slot for unsteady blowing, $k = 0.084$.

of the cylinder when the suction pressure over the top of the cylinder was at a minimum. Examination of the pressure distribution showed that the leading edge stagnation point and the rear separation points moved onto the upper surface of the cylinder due to the development of negative circulation. This development is an interesting flow state in which the net circulation alternates between negative and positive values, even though the mean blowing coefficient always remains positive. This behavior is due to the large lag in the development of the flow over the Coanda surface as well as to the large influence of the shed vorticity in the wake.

The corresponding unsteady pressure drag on the cylinder for these latter two cases is shown in Fig. 6b. Note that in both cases the mean pressure drag is greater than the static values for the same value of mean blowing. It is significant that the higher frequency case ($k = 0.5$) shows a mean drag close to that of the unblown cylinder. Note that in both cases, the hysteresis loops show what is essentially a second harmonic drag variation with blowing, particularly so at the higher frequency. Recall from the steady results that the initial effect of increasing blowing during the cycle is to suppress separation and reduce the pressure drag. Similarly, in the unsteady case at higher levels of blowing, the suction pressures on the Coanda surface dominate, and produce increasing drag. The process essentially reversed during the decreasing blowing part of the cycle. At low jet frequencies, the basic unsteady effect of blowing is a first harmonic drag behavior, since all the pressures around the cylinder essentially lag the blowing by approximately the same amount. However, as the jet frequency increases, the pressures on the Coanda surface begin to lag more than at other points, especially at higher values of blowing coefficient. This essentially produces two unsteady sources of pressure drag—one due to the localized effects occurring on the Coanda surface and the other due to unsteady pressures acting on the remainder of the cylinder. At higher values of blowing the suction pressures on the Coanda surface dominate the overall drag, and the phasing obtained is essentially responsible for the second harmonic drag response.

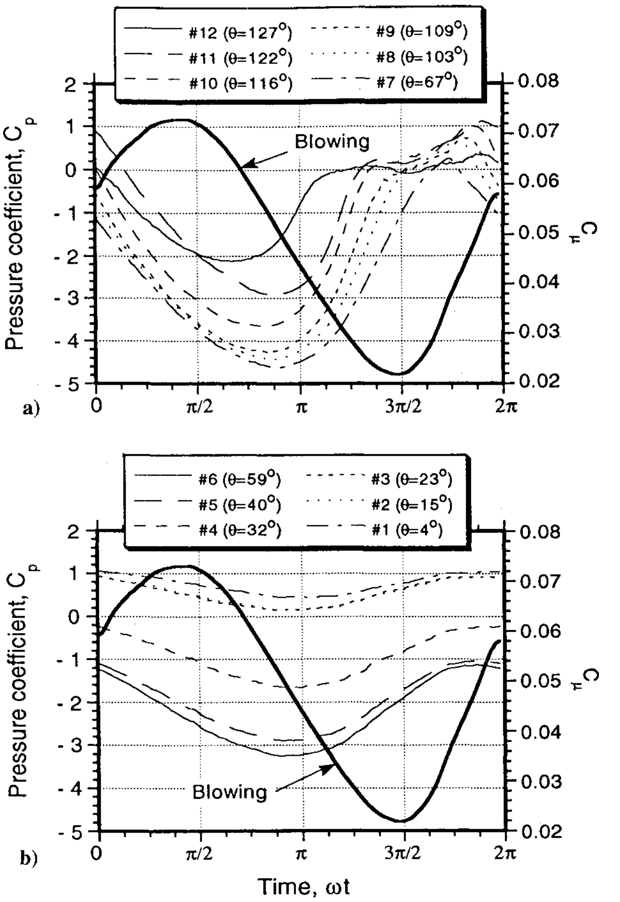


Fig. 9 Pressure a) on Coanda surface and b) upstream of slot for unsteady blowing, k = 0.5.

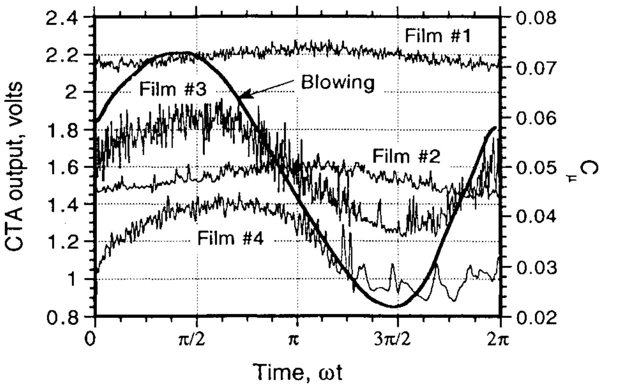


Fig. 10 Surface shear stress, k = 0.5.

Figure 7a shows the outputs of the hot films on the Coanda surface vs time for a reduced frequency of 0.084. Figure 7b shows the corresponding hot film outputs upstream of the slot. These data represent one complete blowing cycle. The output of hot films 3 and 4 essentially reflect the time-dependent development of the jet over the Coanda surface. For reference purposes, the time history of the blowing is also presented. Note that C_μ was in-phase with the boundary-layer shear stress at the slot exit, i.e., hot film 3 at θ = 107 deg. Comparing these data with those of Fig. 7b shows that the change in shear stress upstream of the slot was somewhat small compared to the change in shear stress downstream on the Coanda surface. This effect is expected since the effects of the jet will be felt mainly on the Coanda surface.

Figures 8a and 8b show the corresponding unsteady surface pressures for one blowing cycle at k = 0.084. Again, the time history of blowing is also presented for reference. Very high suction pressures (C_p values exceeding – 5) were created over the Coanda surface. When C_μ was lowest at the beginning of the cycle, the flow over the Coanda surface separated relatively far downstream at an approximate angular location of 140 deg. With increasing C_μ, the jet required a small but finite amount of time to initiate attached flow over the remainder of the Coanda surface. Clearly, for all points on the Coanda surface, a suction pressure progressively builds with increasing C_μ, but there is a measurable time lag between the maximum blowing and the creation of the peak suction pressure. With decreasing blowing, the reverse process occurs, and the flow progressively separates (separation point moves upstream toward slot) from the Coanda surface. Note that the flow separation process occurs slightly more slowly with respect to the blowing compared to the flow reattachment process. Similarly, Fig. 8b shows that the pressures at points upstream of the Coanda surface also lag with respect to the blowing by approximately the same angle.

Figures 9a and 9b show the unsteady surface pressures for one blowing cycle at the higher frequency of k = 0.5. Figure 9a shows that the flow separates from the Coanda surface as the blowing decreases but rapidly reattaches as the blowing increases again. Note that the separation front moves forward toward the slot. Also note that on the Coanda surface not only does the build up of suction pressure significantly lag with respect to the build up of C_μ, but the pressures also lag with respect to each other. Upstream of the slot, the pressures lag C_μ, but Fig. 9b shows that they are essentially in-phase with each other.

Figure 10 shows the corresponding (adjacent) hot film responses for this high reduced frequency of 0.5. The pressure at location 12 (θ = 127 deg) suggests that separation occurs when $C_\mu \approx 0.035$, and this suggestion is confirmed by the response from film 4 (θ = 140 deg). Note that C_μ was again in-phase with the boundary-layer shear stress at the slot exit, i.e., hot film 3 at θ = 107 deg. This

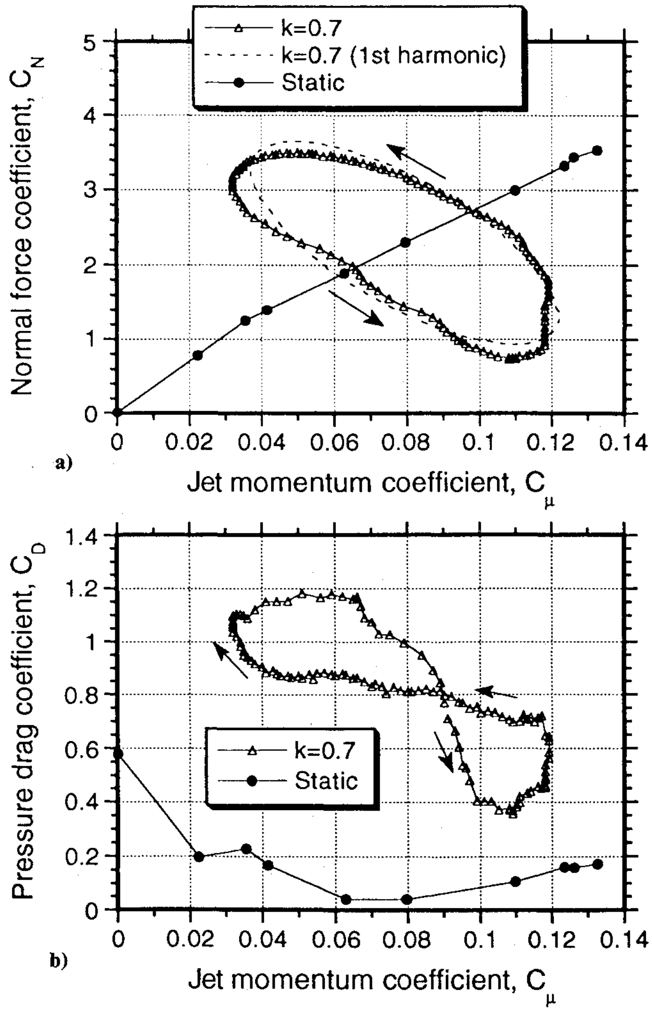


Fig. 11 Unsteady a) normal force and b) pressure drag coefficients vs blowing coefficient at high reduced frequency, transition fixed at θ = ±37 deg, k = 0.70.

result essentially justifies the quasisteady assumption used when computing the unsteady jet momentum coefficient, i.e., that the sole time-varying parameter determining the jet velocity and mass flow rate is the plenum pressure.

Slightly higher levels of C_μ were obtained by lowering the wind tunnel dynamic pressure, giving a new Reynolds number of 1.6×10^5. For these conditions, jet detachment did not occur at any reduced frequency. This result suggests that the trips were normally successful in promoting boundary layer transition at lower Reynolds numbers, by that causing the boundary layer to remain attached prior to reaching the slot. The lower velocity also allowed the creation of an exceptionally high level of reduced frequency equal to 0.7. The lift response vs blowing for this case is presented in Fig. 11a. A large phase lag of 145 deg was measured between the application of the maximum level of blowing and the production of the maximum lift. Note that the mean slope of the unsteady lift hysteresis loop becomes negative. However, the dynamic lift augmentation ratio remains positive. The unsteady pressure drag shown in Fig. 11b again exhibits the characteristic second harmonic variation with respect to the blowing, emphasizing the large unsteady effects taking place on the Coanda surface.

Concluding Remarks

A series of tests have been conducted to examine the boundary-layer effects associated with the operation of a circular cylinder with unsteady circulation control. The primary purpose of these tests has been to help understand the time development of the Coanda jet sheet and to examine the conditions under which the jet will operate successfully in unsteady flow.

It was found that the jet attached to the Coanda surface only when the flow upstream of the slot was fully attached and showed no evidence of a transitional state. Otherwise, intermittent jet detachment occurred, resulting in a nonrepeatable attached/separated flow behavior during successive blowing cycles. Trips located closer to the slot resulted in a poorly developed or transitional boundary layer, which proved to be detrimental to the operation of the jet under both steady and unsteady blowing conditions.

An interesting feature of unsteady circulation control is that increasing blowing frequency increased the unsteady lift augmentation beyond the steady values, so long as the jet remained attached to the Coanda surface. For some high reduced frequency tests, positive blowing produced negative normal force coefficients in the unsteady lift hysteresis loops. Increasing reduced frequency also resulted in increasing phase lags between the application of blowing and the lift response, and sometimes these phase lags were as much as 145 deg. However, it was noted that the unsteady cylinder duct pressure was always in phase with the unsteady jet velocity near the slot exit. This result means that the lag in the CC response was related primarily to the dynamic development of the jet sheet over the downstream part of the Coanda surface.

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