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Unsteady Circulation Control Aerodynamics of a Circular Cylinder with Periodic Jet Blowing

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An experimental investigation was conducted into the unsteady circulation control aerodynamics of a circular cylinder with periodic tangential blowing from a narrow spanwise slot. Both steady and unsteady surface pressure data were obtained for a variety of slot angles, blowing frequencies, and mean blowing coefficients. The experiments were run both transition free and transition fixed. Measurements were made of the time-dependent pressures at discrete points around the cylinder and were numerically integrated to estimate the unsteady lift and pressure drag at a section at midspan. Significant hysteresis effects on the air loads were observed, with these effects increasing with increasing blowing frequency. The results showed that the dynamic lift augmentation ratio was significantly increased relative to the static lift augmentation ratio by the effects of periodic blowing. The maximum unsteady lift was also greater under unsteady conditions, although the mean lift was, in some cases, less than the static values for corresponding mean blowing levels. A frequency dependent jet detachment effect was also observed.

Nomenclature

C_d = pressure drag force coefficient
C_n = normal force coefficient
C_n^1 = first harmonic of unsteady normal force coefficient
C_p = pressure coefficient
C_μ = blowing coefficient, $\dot{m}V_j/q_\infty c$
C_μ^1 = first harmonic of unsteady blowing coefficient
c = cylinder chord, ft
h_j = slot height, ft
k = jet reduced frequency, $\omega c/2V_\infty$
$\dot{m}$ = mass flow rate per unit span, slug/ft s
p_d = duct total pressure, lb/ft^2
p_∞ = freestream static pressure, lb/ft^2
q_∞ = freestream dynamic pressure, $0.5\rho V_\infty^2$, lb/ft^2
R = universal gas constant, 1718 ft^2/(s^2°R)
T_d = duct total temperature, °R
t = time, s
V_∞ = freestream velocity, ft/s
V_j = jet velocity, ft/s
Γ = circulation, ft^2/s
γ = ratio of specific heats
θ = surface angle (relative to freestream velocity), deg
ρ = density of freestream flow, slug/ft^3
ω = blowing frequency, rad/s

Introduction

CIRCULATION control (CC) airfoils rely upon the Coanda effect to generate high lift independently of angle of attack. The Coanda effect is the tendency of a fluid issuing from a tangentially ejected jet to travel close to a surface contour, even if the surface curvature diverges from the jet axis.[1] As shown in Fig. 1, a balance of centrifugal force and reduced static pressure causes the thin jet to follow the blunt trailing edge. The jet is usually obtained by pressurizing a plenum inside the airfoil. At lower values of blowing (quantified by the coefficient C_μ), the jet initially acts as a very effective form of boundary-layer control due to flow entrainment on the upper surface. At higher blowing coefficients, boundary-layer control yields to supercirculation, which results in a large movement of the stagnation and/or separation points and produces significantly increased circulation. At some point downstream of the slot, the reduced static pressure and centrifugal force balance is ultimately lost, and the jet detaches from the Coanda surface. The location of the jet detachment depends mainly on the strength of the jet, the slot geometry, the curvature of the Coanda surface, as well as the characteristics of the boundary layer prior to the slot.

Circulation control was first investigated in depth by Cheeseman and Seed,[2] as well as Dunham,[3] and later by Kind,[4] and Kind and Maull.[5] Since the early 1970s, however, most circulation control work has been conducted at the David Taylor Research Center (DTRC). A detailed bibliography of DTRC research is provided by Englar and Applegate.[6] Most of this work is of an experimental nature and documents the behavior of CC airfoils operating under steady flow conditions over a wide range of Reynolds and Mach numbers.

Because of the high lift coefficients that can be attained with circulation control, it has been envisioned or applied for use on both fixed-wing aircraft as well as rotary-wing aircraft. For example, a Grumman A-6 aircraft affixed with a CC wing has shown substantial performance benefits in reducing takeoff roll distance and increased payload capacity. Circulation control technology also offers potential benefits when applied to

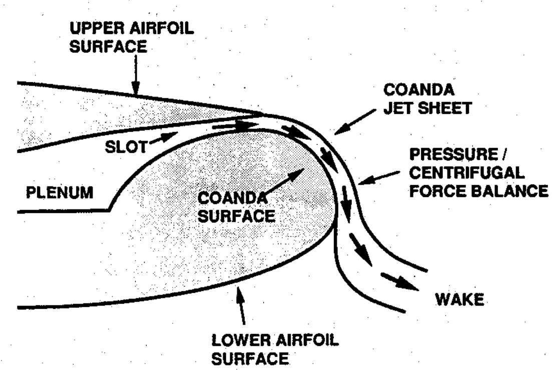

Fig. 1 Schematic of Coanda effect on CC airfoil.

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rotorcraft (see Refs. 7 and 8). In the early 1980s, Kaman built and flight tested a circulation controlled rotor on a HH-2D Seasprite, although only in hover[9] and low-speed forward flight. Other applications of CC technology to rotorcraft are the now ill-fated X-wing, as well as the very successful NOTAR antitorque tailboom.[10] The U.S. Navy is also studying the application of CC technology to the development of a stoppable rotor for an unmanned aerial vehicle.

Although offering considerable possibilities when applied to rotors, for either direct lift production or secondary lift control (higher harmonic lift), the behavior of CC airfoils operating in a rotor environment is poorly understood. In particular, there is a requirement to more fully understand both the CC aerodynamics and the associated blade aeroelasticity effects. In forward flight, a circulation control rotor encounters a time-varying flow environment in which both the angle of attack and local velocity vary periodically with azimuth position. Because the geometric pitch of the blade is generally held constant, jet blowing must be cyclically adjusted to maintain the aircraft in a trimmed state as well as to give directional control. This necessitates the modulation of the blade plenum pressure and, therefore, the jet blowing as a function of azimuth position. Thus, the rotor blade sections are subjected to a highly unsteady aerodynamic flowfield. Under these conditions, the dynamics of the Coanda sheet and the corresponding effects on the airfoil aerodynamic forces must be understood. As of yet, however, unsteady effects on CC airfoils are virtually unknown.

Early work on the theoretical modeling of circulation control airfoils in steady flow was carried out by Kind and Maull[5] and Dunham.[11] Later, Dvorak and Kind[12] incorporated integral and finite difference boundary-layer/jet mixing effects in an external potential flow model. With the advent of computational fluid dynamics (CFD), Shrewsbury[13] used Navier-Stokes methods in the analysis of circulation control. Computational work on CC airfoils under unsteady conditions is scarce. Some recent theoretical work by Raghavan et al.[14] using a surface singularity/boundary-layer method has been performed on circular cylinders and elliptical CC airfoils operating in an unsteady freestream flow and with unsteady blowing. Although this work neglects the effects of the unsteady

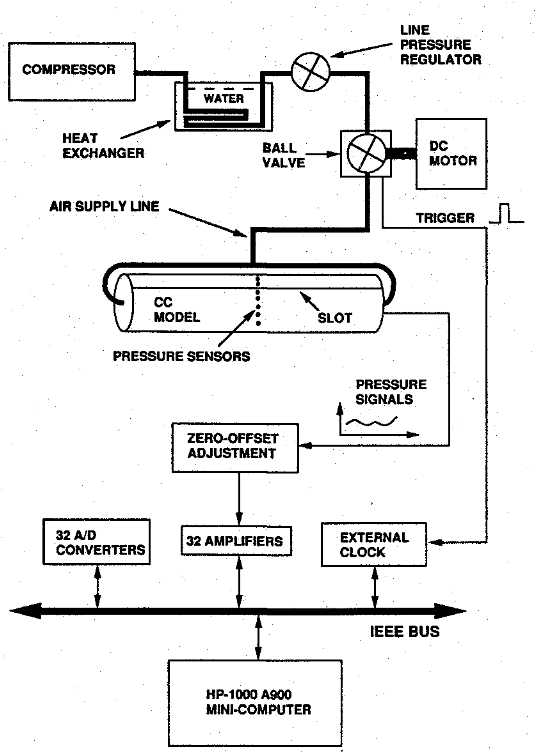

Fig. 2 Schematic of the experimental setup.

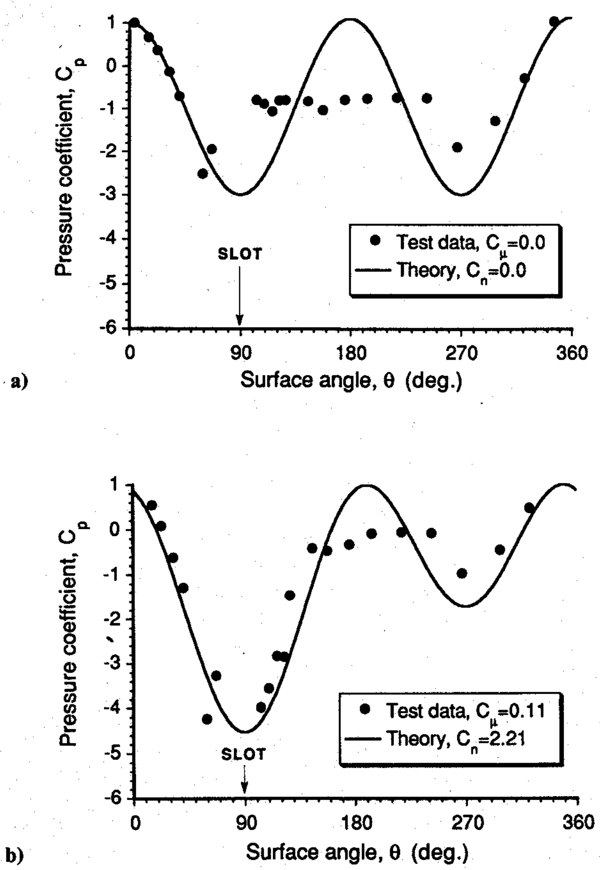

Fig. 3 Pressure coefficient vs cylinder surface angle for a) C_μ = 0.0; b) C_μ = 0.11.

shed wake, the results are still significant and have shown that CC airfoils will exhibit both a lift attenuation and a phase lag with respect to the blowing. More recently, Sun and Wang[15] have computed similar results for an elliptical CC airfoil even when the unsteady wake is more correctly accounted for.

Experimental studies on unsteady CC are very sparse. Early investigations were primarily centered on reducing the mass flow rate by pulsing the jet. Williams et al.[16] presented oscillograph traces of the unsteady pressure from several surface mounted transducers on an airfoil with a trailing-edge jet flap. This research showed that pulsed blowing reduced the mass flow required to prevent flow separation on the flap. Englar[17] presented results of pulsed blowing on a circulation controlled ellipse. These tests were reported as unsuccessful, but did provide useful information on hardware design for unsteady blowing. A study of pulsed CC for a cambered elliptical airfoil, performed by Walters et al.,[18] showed that pulsed blowing at certain frequencies caused as much as a 15% increase in the mean lift coefficients over those obtained for steady blowing at equal mass flow rates.

Schmidt[19] carried out the first experiments to consider the unsteady aerodynamic effects on an airfoil with a Coanda surface. In these experiments, the unsteady pressures on the airfoil were measured with a scani-valve system calibrated to compensate for the attenuation and phase lag of the pressure signal due to the pressure tubing. The lift transfer function of the airfoil was obtained as a function of blowing frequency. Schmidt reported a transportation lag effect between the duct pressure and the blowing, as well as a decrease in lift augmentation ratio with increasing blowing frequency. More recently, Lorber et al.[20] have investigated the unsteady aerodynamic behavior of an oscillating jet flap at a constant angle of attack and over a range of Mach numbers, albeit at limited blowing levels and at very low reduced frequencies. This work has also shown that significant phase lags exist between the application of blowing and the buildup of the air loads.

Table 1 Transducer locations relative to the free-stream velocity

Transducer	θ, deg	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		

In this paper, we report the results from an experimental study into the effects of periodic blowing on the unsteady aerodynamics of a circulation controlled circular cylinder. Such unsteady measurements have not previously appeared in the literature. The study has direct relevance to the general understanding of the unsteady aerodynamics of circulation controlled airfoils. The specific objectives of the present work were 1) to quantify the time dependent behavior of the CC aerodynamics for a range of conditions, including blowing magnitude and jet frequency, slot location, etc.; 2) to examine conditions under which the unsteady effects associated with the Coanda sheet may prove beneficial or detrimental to CC performance; 3) to derive the describing functions between the duct pressure and the lift response; and 4) to obtain a comprehensive data base of information that will help to validate analytical models of the unsteady behavior of airfoils using unsteady circulation control.

Description of the Experiment

The experiments were performed in the University of Maryland's 22- × 22-in. low-speed open-jet wind tunnel using a basic CC airfoil in the form of a circular cylinder 3.96 in. in diameter and 20 in. in length. The cylinder was mounted between two large end plates that extended one cylinder diameter upstream and two diameters downstream of the measurement location. The end plates helped to provide an essentially two-dimensional flow environment. The flow environment was examined by a flow survey. A single slot, with height h_j adjusted to 0.002 in., was provided along the length of the cylinder. The cylinder surface was sanded before testing to a uniform finish using up to 600 grit wet/dry paper.

For CC experiments, a circular cylinder has several advantages over any other shape. First, the position of the blowing slot relative to the freestream flow can be easily adjusted by rotating the cylinder. Previous studies have shown that for steady blowing the effectiveness of the Coanda sheet is significantly affected by the slot position. Therefore, the significance of slot position under unsteady blowing conditions constituted an important part of the present study. Second, a circular cylinder is the most basic shape available for theoretical analysis. The additional complexities and uncertainties introduced by the influence of airfoil shape, i.e., thickness, camber, leading-edge geometry, etc., no longer become critical variables influencing the Coanda jet sheet or its dynamics.

It is also important to note that an open-jet wind tunnel is highly desirable for CC experiments since the interference effects due to the tunnel walls on the Coanda jet sheet are not as critical as for a closed-jet tunnel and there is no possibility of the jet impinging on the tunnel floor. Wind-tunnel corrections for circulation control airfoils operating at high lift coefficients with steady blowing are, at best, difficult to determine, see for example Englar and Williams.[21] Corrections for unsteady blowing data are nonexistent. Because an open-jet tunnel was used for the present experiments, wind-tunnel boundary correction effects were considered relatively minor, and the data presented here are uncorrected. Generally, it would be expected that the uncorrected measurements would be more conservative than the corrected measurements.[22]

The CC cylinder was used in a previous experiment at the University of Maryland to study CC aerodynamics under steady blowing conditions.[23] In the current experiments, the cylinder was modified by installing 30 absolute pressure transducers (22 chordwise and 8 spanwise). The pressure transducers permitted the measurement of the mean pressure as well as the instantaneous (time-dependent) pressure at discrete points on the surface of the cylinder (see Table 1). The pressure measurements were then numerically integrated around the surface contour to obtain estimates of the instantaneous values of lift and pressure drag on a typical section at midspan.

The high pressure air for the blowing was obtained from a rotary vane compressor. The mean jet blowing level was adjusted by varying the supply pressure by means of a regulator. Unsteady blowing was achieved using a rotating ball valve driven by a variable speed dc electric motor. A schematic of the experimental setup is shown in Fig. 2.

The ball valve was situated in-line with the pressure supply to the cylinder and produced an almost sinusoidal time-varying pressure in the cylinder plenum. Yet due to the inherent pneumodynamic frequency response of the ball valve and the air ducting, smaller second and third harmonics of the pressure response were obtained at certain frequencies. Based on the fundamental jet frequency, reduced frequencies of up to approximately 0.54 were obtained. These were exceptionally high reduced frequencies and permitted a thorough study of the importance of frequency on the CC aerodynamics.

Two total pressure transducers and a total temperature probe were installed inside the cylinder, measurements from which were used to compute the jet momentum (blowing) coefficient from standard quasisteady isentropic flow relations. The instantaneously effective momentum coefficient

a)

b)

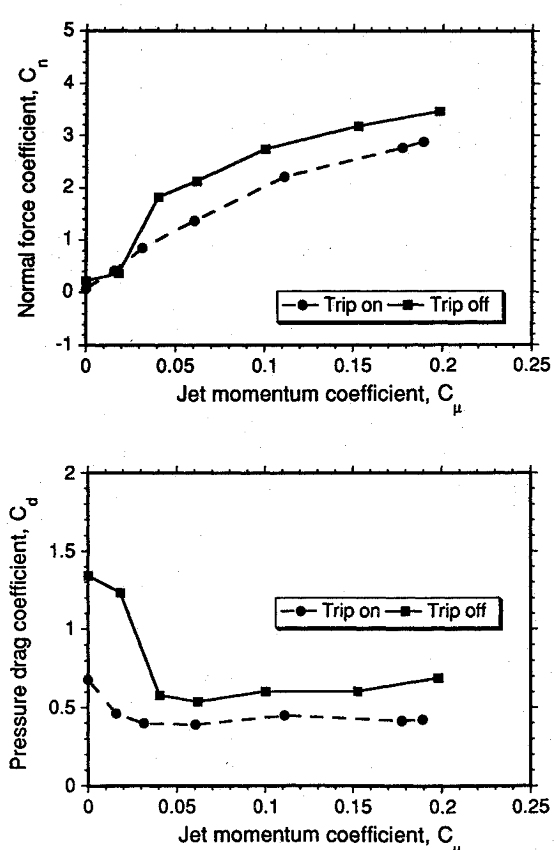

Fig. 4 Effects of steady blowing for a slot angle of 90 deg: a) C_n; b) C_d.

was determined from the computed mass flow and jet velocity at the slot using

$$C_\mu(t) = \frac{\dot{m}(t)V_j(t)}{q_\infty c} \tag{1}$$

where the jet velocity V_j was calculated by assuming an isentropic expansion from plenum total pressure to freestream static conditions, i.e.,

$$V_j(t) = \sqrt{2RT_d\left(\frac{\gamma}{\gamma-1}\right)\left[1-\left(\frac{p_\infty}{p_d(t)}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{2}$$

In a previous steady test, Ngo[23] used a Hoffer turbine flow meter to measure the mass flow rate. This device cannot be used to measure unsteady flow rates, therefore, the mass flow rate was computed analytically assuming isentropic unchoked flow, i.e.,

$$\dot{m}(t) = h_j p_d \sqrt{\frac{2\gamma}{(\gamma-1)RT_d}\left[\left(\frac{p_\infty}{p_d(t)}\right)^{\frac{2}{\gamma}} - \left(\frac{p_\infty}{p_d(t)}\right)^{\frac{\gamma+1}{\gamma}}\right]} \tag{3}$$

The entire experiment was controlled by a HP-1000 A900 minicomputer with a CAMAC high speed A/D data acquisition system. The outputs from the pressure transducers were interfaced with this system through a set of programmable amplifiers. In the present series of tests, 128 data samples from each pressure sensor were recorded over every blowing cycle. These data were stored in a memory buffer and downloaded to a hard disc after each run. Normally, 20 cycles of data were recorded for each test condition. After applying channel gains and transducer calibration factors, the data were ensemble averaged, processed into standard pressure coefficients, and integrated with respect to the surface angle to estimate the sectional lift and pressure drag. Further details of the experiment are given in Ref. 24.

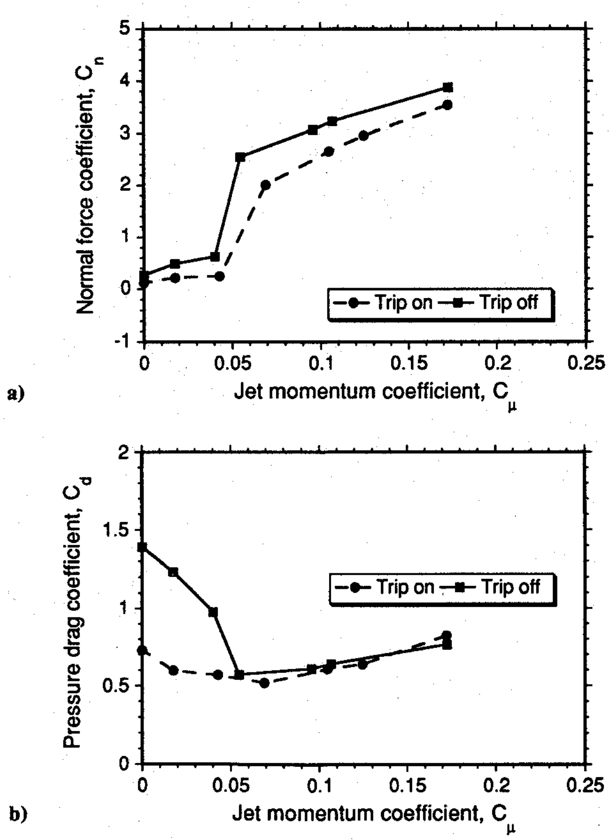

Fig. 5 Effects of steady blowing for a slot angle of 100 deg: a) C_n; b) C_d.

The data presented in this paper were obtained with a freestream velocity of 92 ft/s and a Reynolds number based on cylinder chord of approximately 1.9×10^5. The model was tested with the blowing slot positioned initially at 90 deg relative to the freestream, however, cases were also run at slot angles of 80, 95, and 100 deg relative to the freestream flow. Tests were run both transition free (tripped) and transition fixed. For the transition fixed cases, trips were located at $\theta = \pm 60$ deg to increase the effective Reynolds number and ensure a turbulent boundary layer prior to the slot. The design and placement of these two-dimensional trips were based on Ref. 25. The effective Reynolds number with the transition strips was estimated to be 3×10^6.

Results and Discussion

Steady Blowing

To provide a baseline, initial measurements were conducted under steady blowing conditions. Typical transition fixed pressure distributions for cases of no blowing and moderate blowing are shown in Figs. 3. With no blowing, shown in Fig. 3a, the flow separation points were situated at approximately $\theta = 100$ and -110 deg (or $\theta = 250$ deg). Downstream of separation, a constant base pressure region exists. A slight dissymmetry was also noted between the upper and lower pressure distributions due to the presence of the slot. Increasing the jet momentum coefficient quickly moved the upper separation point further toward the rear of the cylinder, as shown in Fig. 3b, to approximately $\theta = 140$ deg. The lower separation point remained relatively unchanged at $\theta = 250$ deg. Under these conditions, the high suction pressure over the upper surface of the cylinder clearly indicates the production of significant lift.

Also plotted in Fig. 3 for reference purposes is the pressure distribution given by incompressible potential flow theory from which the surface pressure coefficient is given by

$$C_p(\theta) = 1 - \left(2\sin\theta + \frac{\Gamma}{\pi V_\infty c}\right)^2 = 1 - \left(2\sin\theta + \frac{C_n}{2\pi}\right)^2 \tag{4}$$

where the circulation Γ has been related to the measured value of C_n. As might be expected, the agreement is good for parts of the cylinder where the flow is attached.

Typical steady lift and drag characteristics are plotted vs jet momentum coefficient in Figs. 4 and 5, both transition free and transition fixed, and for slot angles of 90 and 100 deg, respectively. It should be noted that for a CC airfoil operating in the supercirculation regime there is a general nonlinear dependency of C_n on C_μ, a square-root dependency appearing typical of most CC airfoils.[5] To assess the effectiveness of a CC airfoil, a lift augmentation ratio, $\partial C_n/\partial C_\mu$, is normally used and is a measure of the efficiency of the jet in producing lift through circulation control vs the case when the jet produces lift through vertical momentum transfer. Steady lift augmentation ratios of between 10 and 20 were obtained with the present CC cylinder, although augmentation ratios of up to 80 appear possible of many elliptical CC airfoils.[7] A comparison of other measurements of the lift augmentation ratios of circular cylinders was also undertaken, which showed that typical values ranged from 12 to about 17. This shows that the present results are in acceptable agreement with other measurements.

Considering first the 90-deg case shown in Fig. 4, it shows that there is a significant difference between the transition free and transition fixed cases. It appears that the state of the boundary layer, i.e., laminar vs turbulent, has a marked effect on both the lift and drag over a fairly wide range of jet momentum coefficients. Both the transition free and fixed cases showed an increase in lift and a decrease in drag as the jet blowing was increased. Yet, for the transition free case, a fairly sharp discontinuity was apparent in both the lift and drag coefficients near $C_\mu \approx 0.04$ compared to the transition fixed case, where the lift coefficient increased and the drag coefficient decreased in a continuous fashion with increasing jet blowing. At the highest blowing coefficients, the drag increases slightly again.

In contrast to the 90-deg slot case, the lift coefficient for the 100-deg slot case, presented in Figs. 5, showed a remarkably similar behavior for both transition free and transition fixed cases. High values of jet blowing were required to produce any useful lift, which exhibited a sudden increase above a C_μ of about 0.05. It is interesting that, although higher blowing was initially required to produce useful lift at this slot angle, the lift coefficients ultimately obtained were larger than those obtained for the 90-deg slot angle case. Yet this was not obtained without penalty since the corresponding drag coefficients for the 100-deg slot angle case were also slightly larger.

The behavior just described can be traced to the state of the boundary-layer prior to the slot. It has been suggested by Wood and Nielsen[7] that the ratio of the jet momentum to the boundary-layer momentum deficit determines the lift increment on a CC airfoil due to blowing. Conditions that thicken the boundary layer, and therefore increase the momentum thickness, tend to reduce the effectiveness of the jet for a given jet momentum and velocity difference. Since, for the 100-deg case, both the untripped and tripped boundary layer(s) are thicker than for the 90-deg slot angle cases, the jet is less effective at low values of blowing and thus requires a substantially higher critical jet velocity to entrain the outer flow. It is also noteworthy in Figs. 4 and 5 that the transition free cases exhibited higher maximum lift than for the transition fixed case. This behavior is, again, related to the state of the boundary layer as it approaches the slot. Since the thicker (tripped) boundary layer reduces the jet effectiveness, the transition fixed cases are less effective in providing lift compared to the transition free case.

The pressure drag coefficients for the 100-deg slot angle case in Fig. 5 were also qualitatively similar to the 90-deg case in Figs. 4. Again, it appears that, for the transition fixed case with no blowing, the trip is sufficient to cause the flow to remain attached for longer, thereby producing a smaller wake and less drag. Both the transition free cases shown in Figs. 4 and 5 had markedly higher drag coefficients with zero blowing compared to the tripped cases. This appears to be a classic case of laminar separation vs turbulent separation. The laminar

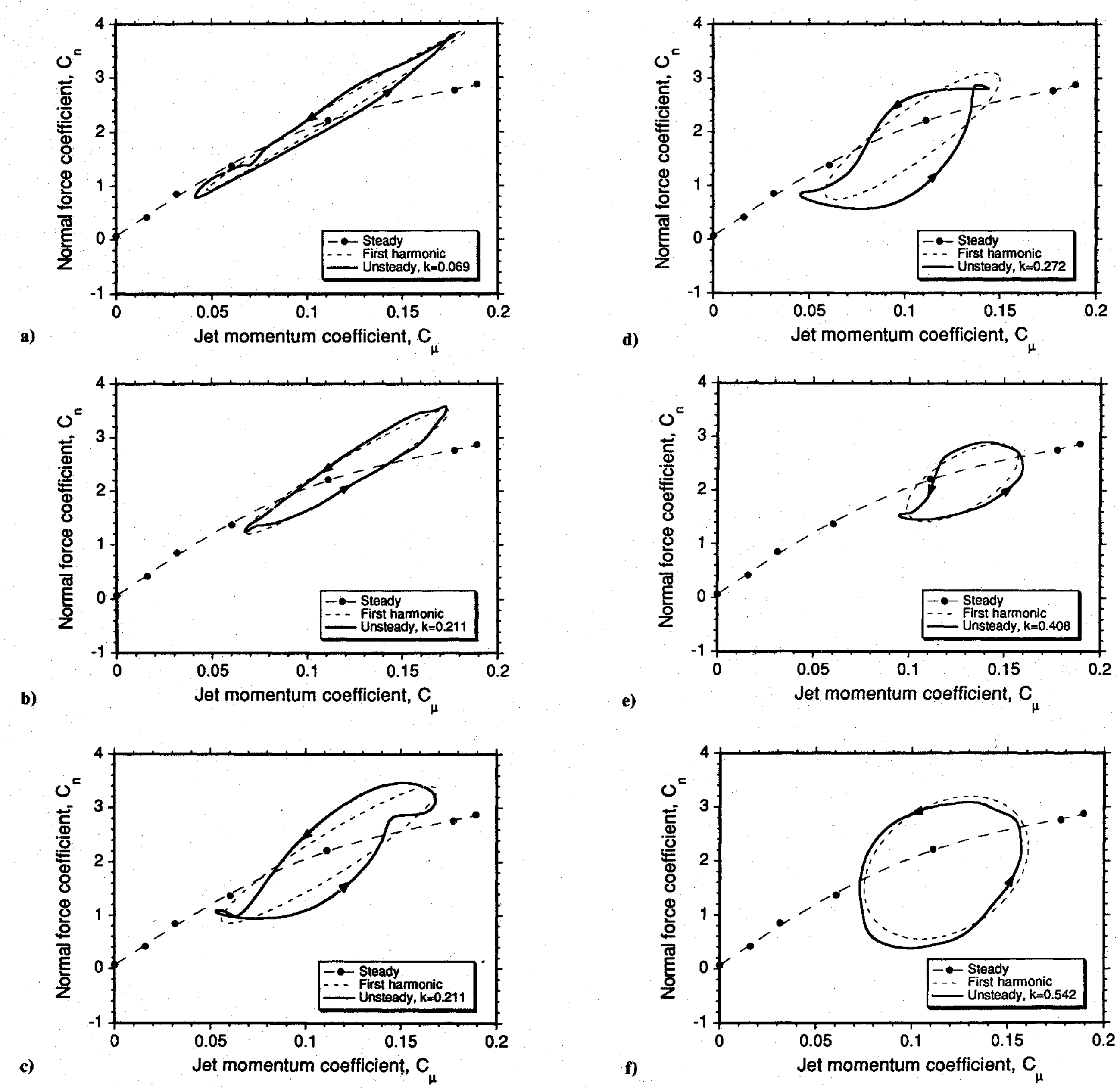

Fig. 6 Effects of reduced frequency on unsteady lift response, high mean blowing.

case separates much earlier than the turbulent boundary layer and, therefore, a larger separated wake and a correspondingly higher base drag coefficient is produced. When blowing is applied, the drag coefficients become less, particularly so for the untripped case. Ultimately, there are only slight differences in the drag coefficients between the tripped and untripped cases. As C_μ was increased to near 0.2, it is interesting that the drag begins to increase again. While the application of blowing delays the separation (jet detachment) point to a larger value of θ, the higher pressure drag arises because of the much larger suction pressures induced over the Coanda surface by the jet.

Unsteady Blowing

The static tests described earlier are of much interest and value, and lay the groundwork for further discussion. Yet, it must be remembered that for many practical applications, the environment in which a CC airfoil must operate is actually unsteady in nature. Thus, the normal way of measuring the performance of a CC device, namely, the static lift augmentation ratio and the maximum static lift, may not necessarily be reliable indicators of how a CC device will perform under unsteady conditions. Additional indicators, such as the dependence on blowing amplitude and, in particular, the reduced frequency of the jet blowing, become other factors governing CC performance.

To this end, the main objective of this experiment was to explore the unsteady behavior of the CC cylinder and to establish how its performance would change under different combinations of oscillatory blowing. Many of these conditions were selected to be typical of the forcing that a CC rotor blade section would encounter in forward flight. Unsteady pressure data were recorded for over 180 test conditions and consisted of systematic variations of mean blowing, jet frequency, and slot location.

Representative plots of the measured normal force (lift) coefficient on the CC cylinder are shown in Figs. 6 and 7 vs the unsteady jet momentum coefficient, for cases where the slot was positioned at 90 deg relative to the freestream. For these cases, transition strips were applied. Data are shown for six values of reduced frequency and at two nominal values of mean blowing. In each case, the unsteady data are compared

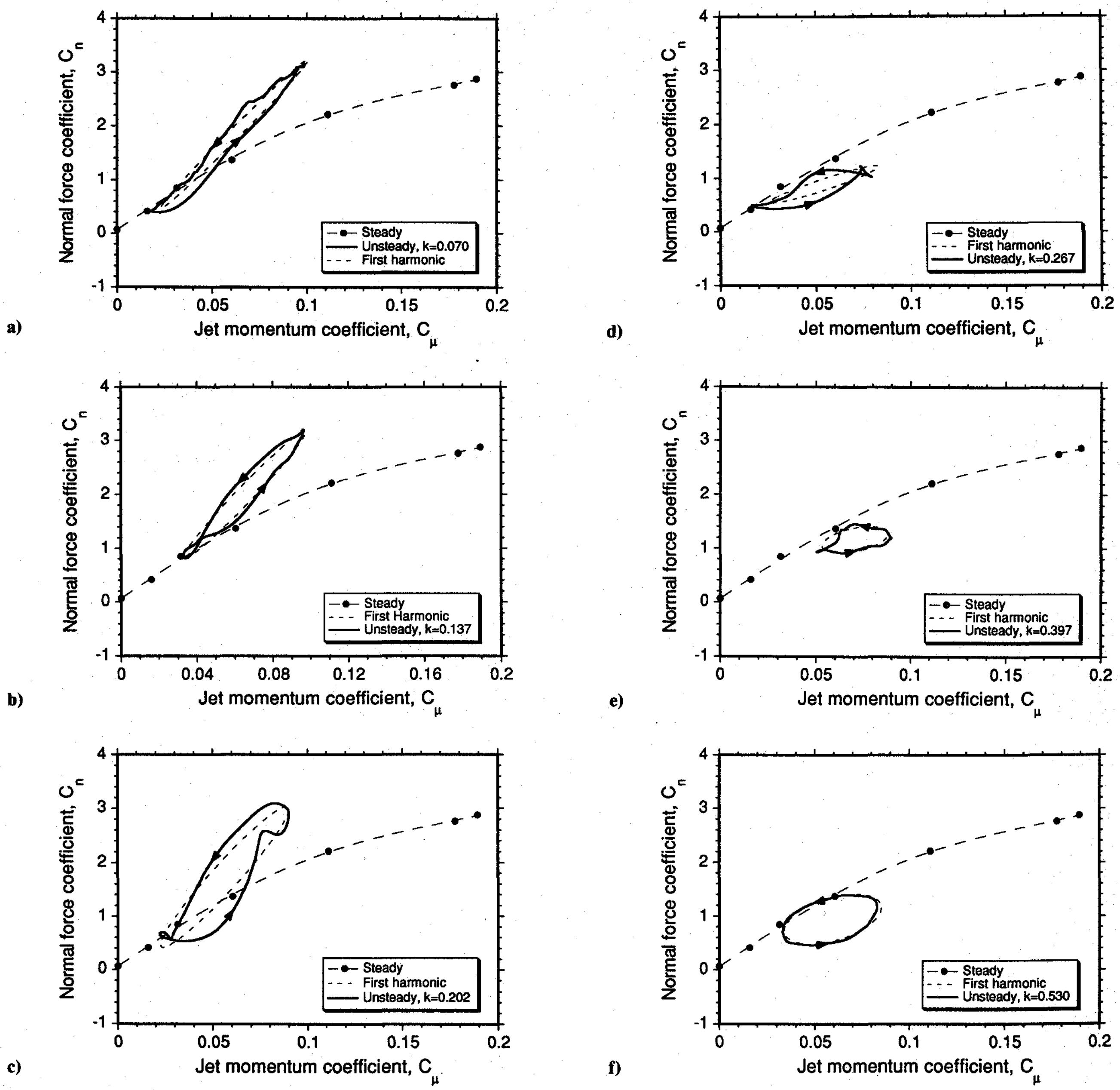

Fig. 7 Effects of reduced frequency on unsteady lift response, moderate mean blowing.

to the static (steady blowing) case. Also shown on these plots for reference purposes is the first harmonic of the unsteady response as obtained from a Fourier analysis of the raw data.

Generally, each reduced frequency produced similar elliptical hysteresis loop shapes, despite the mean blowing level, boundary-layer state, or slot angle. Furthermore, all hysteresis loops were found to advance in a counterclockwise direction, that is a phase lag effect, since increasing C_μ produced a normal force coefficient that was less than the normal force coefficient associated with decreasing C_μ. This effect is similar to the lift behavior of a conventional airfoil oscillating in angle of attack, but the phase angles in the present case are considerably greater.

One immediately apparent characteristic in Figs. 6 is that the mean lift augmentation ratio (the slope of the major axis of the ellipse) for the unsteady blowing cases is far greater than the augmentation ratio obtained for steady blowing. Since the efficiency of a CC airfoil is often measured in terms of augmentation ratio, it is significant that unsteady blowing causes such a marked increase in augmentation ratio. This result appeared to be the case for all conditions where the jet remained attached to the Coanda surface. For the case of steady blowing, a steady lift augmentation ratio of approximately 10 was found for both values of mean blowing. Yet, the unsteady lift augmentation ratio was found to be closer to 20 for the high mean blowing case, in other words, more than 100% greater than the lift augmentation ratio obtained under steady blowing conditions. As the reduced frequency was increased, the hysteresis was found to become progressively larger, although it was interesting that the lift augmentation ratio remained nominally constant. This effect will be discussed again later.

It is also significant to note in Figs. 6 that the maximum lift obtained with unsteady blowing was generally much greater than the corresponding static lift values at the same maximum value of C_μ. Although the unsteady lift values for a given value of C_μ were not, in general, always greater than the static values (for example at the lowest points in the C_μ cycle), the mean lift on the cylinder still was a little greater under unsteady blowing conditions. This however, was not always the case; see, for example, Figs. 6e and 6f where the mean lift is less than the static lift value. This is consistent with the results of Walters et al.,[18] who showed that pulsed blowing on a CC ellipse only at certain frequencies caused an increase in the mean lift relative to the steady case.

The same basic trends shown in Figs. 6 also held for the moderate mean blowing level shown in Figs. 7. Yet, in contrast to the highest mean blowing case, it was found that for reduced frequencies greater than 0.27 the lift augmentation ratios were much less than the corresponding static values. Subsequent study has identified this to be associated with a frequency dependent jet detachment effect, and this phenomenon will be discussed later in this paper.

The actual shape of the individual loops shown in Figs. 6 and 7 also appeared to be closely related to the frequency content of the jet blowing. As noted previously, the pneumodynamic response of the ball valve and air duct meant that small, but significant, second and third harmonics of the fundamental pressure were sometimes obtained inside cylinder plenum. The effects of this are shown in Figs. 6c and 6d, where a distortion in what probably would be almost a pure ellipse was obtained at the maximum and minimum values of the instantaneous blowing coefficients. Although the higher harmonics of the blowing affects the shape of the hysteresis loops, it should be noted that they are not the sole source of the hysteresis effect.

It is noteworthy that at the highest reduced frequency of 0.54, as shown in Figs. 6f and 7f, very large hysteresis effects were apparent, the phase angle between the blowing and the lift response being close to 80 deg. Also, the lift response at this frequency was almost entirely composed of the first harmonic. This is in agreement with the forcing C_μ, which was also found to be almost purely sinusoidal.

Examination of the pressure time histories for this latter reduced frequency at the high mean blowing level are presented in Fig. 8 and showed that the jet generated large oscillatory suction peaks on the Coanda surface downstream of the slot. There was clearly a significant time lag between application of the blowing and the build up of a suction pressure on the Coanda surface. The presence of the jet also affected the pressure distribution upstream of the slot. Remember that $C_\mu(t)$ is in-phase with the duct pressure $p_d(t)$ since C_μ is calculated using the isentropic flow relationships in Eqs. (2) and (3). Thus, the lag between the blowing C_μ and the pressure response on the surface must be due to both the dynamic effects on the Coanda sheet and also the feedback effects of the circulation shed into the wake.

The lag in the development of the Coanda jet sheet itself can be seen readily in Fig. 8 when the blowing is increasing with time, where notable phase differences exist between the pressure response at different points on the Coanda surface. Unfortunately, there is no direct way of separating out the dynamic effects on the Coanda sheet itself from that of the shed wake, as might be desirable for the purposes of validating any theory. This clearly illustrates the inherent difficulties in the mathematical modeling of the flowfield about unsteady CC airfoils. Compared to a conventional airfoil oscillating in angle of attack that can be assumed to have a fixed separation (stagnation) point at the trailing edge (i.e., the Kutta condition), a CC airfoil has a variable and time-dependent Kutta condition. This extra degree of freedom makes the theoretical analysis of unsteady CC airfoil flowfields much more difficult.

Unsteady Drag

With the application of unsteady blowing, the drag force behavior was considerably more complicated compared to the steady case. Selected plots of the pressure drag force coefficient C_d vs blowing coefficient are shown in Fig. 9 for the same forcing conditions presented in Figs. 6 and 7. It shows that the steady values of the drag coefficients initially exhibited a decrease with increasing blowing due to the delay in upper surface flow separation to points farther downstream on the cylinder. With further increases in blowing, the pressure drag then steadily increased due to the development of

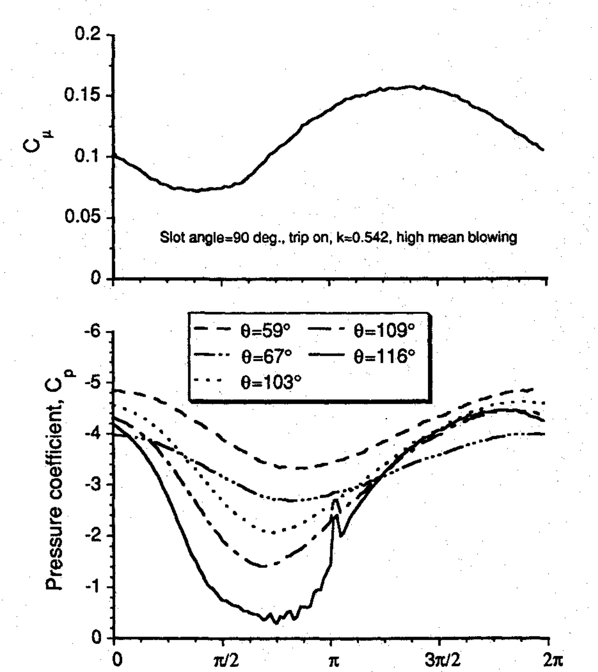

Fig. 8 Unsteady pressure response on Coanda surface, high mean blowing, $k = 0.54$.

high suction pressures on the Coanda surface that, while providing significant increases in lift, also provides an increasing pressure drag. Similar trends have been shown by Oh and Roberts[25] using a numerical solution for the flow about a CC cylinder.

It was generally observed that the mean drag coefficients with unsteady blowing were approximately equal to, or just less than, those measured with steady blowing. Because of the increased average circulation about the cylinder, unsteady blowing appears to locate the mean value of the flow separation point to greater values of θ, and is thus beneficial in helping to reduce pressure drag. In contrast to the unsteady lift behavior, no general characteristic is discernible in the data, that is, there was no distinctive hysteresis loop shape or consistent direction of hysteresis loop rotation. The complexity of the unsteady drag behavior is not unexpected since the drag on the cylinder is very sensitive to the interrelated effects of the size of the separated wake, as well as the magnitude of the suction pressures on the Coanda surface.

Lift Augmentation Ratio

Because the performance of CC airfoils are generally measured in terms of a lift augmentation ratio, the unsteady lift effects were generalized using a describing function in the form of a dynamic lift augmentation ratio (DLAR). The DLAR was defined as the amplitude ratio of the first harmonic lift response C_n^1 to the first harmonic of the blowing C_μ^1. These data, with the corresponding phase angles, are plotted in Figs. 10 and 11 vs jet reduced frequency for various slot angles and at two mean values of blowing. Typically, for cases without jet detachment, the DLAR normally varied from about 20 to 80% greater than the corresponding static augmentation ratio. In general, the DLAR remained either fairly constant or gradually increased over most of the reduced frequency range. Yet, there was often a significant increase in the DLAR as the highest reduced frequency of 0.54 was approached. For example, the high mean blowing case (Figs. 11) produced a substantial twofold increase in the lift augmentation ratio relative to the static case, which was unexpected. For

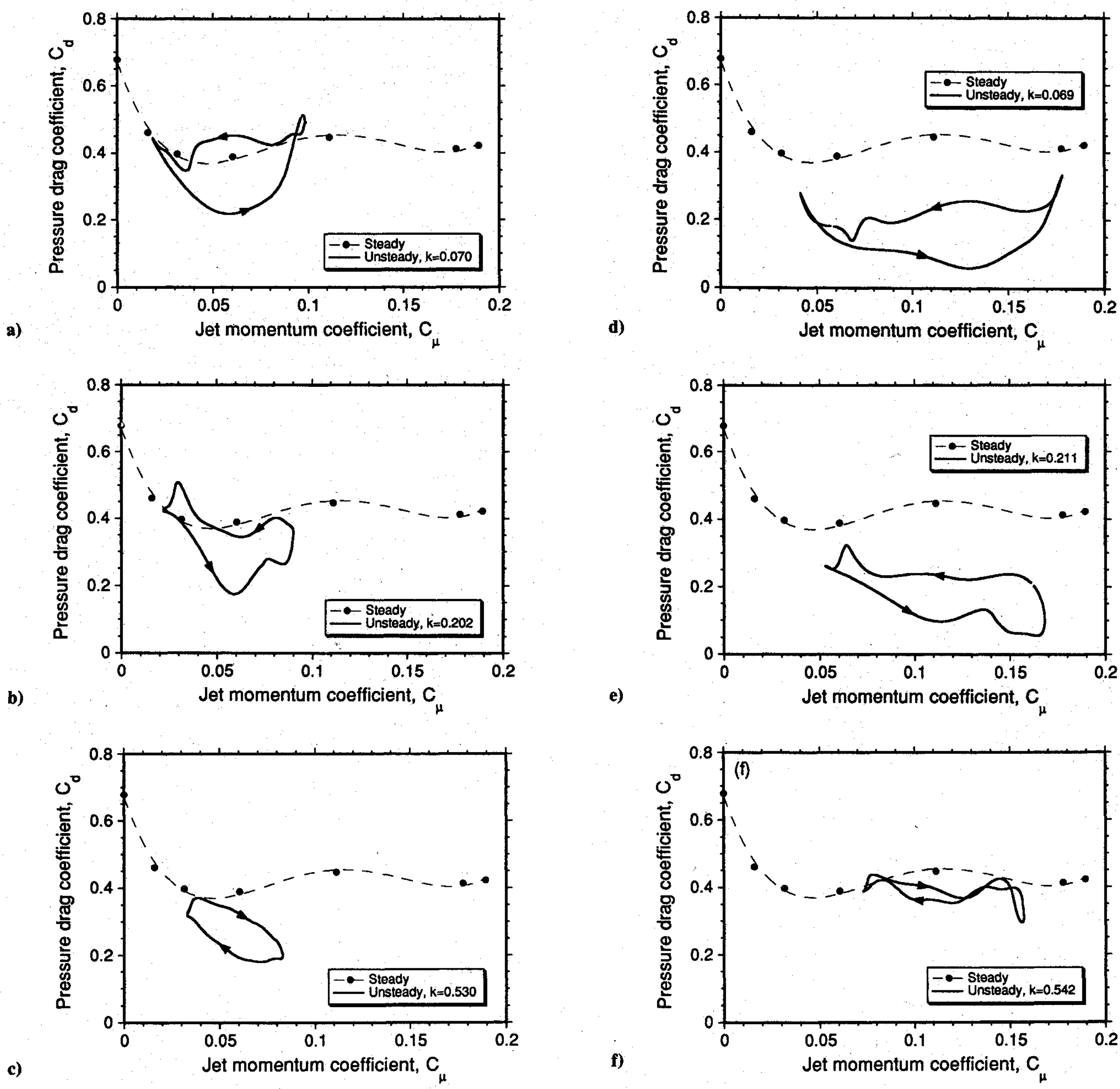

Fig. 9 Effects of reduced frequency on unsteady pressure drag response at moderate and high mean blowing.

medium mean blowing in the absence of jet detachment effects, the unsteady lift augmentation ratio was approximately three times the steady value.

These observations generally indicate a very favorable effect of unsteady blowing on the lift response and are consistent, to some extent, with the results obtained on a pulsed CC ellipse by Walters et al.[18] Yet these observations are at variance with the recent computational results presented for CC cylinders and ellipses by Raghavan et al.,[14] as well as by Sun and Wang.[15] Both of these studies have predicted that, for periodic blowing, the lift augmentation ratio will decrease with increasing blowing frequency. In other words, the predicted trends made by these theories are similar to the classical lift-curve-slope attenuation effect of a conventional oscillating airfoils, i.e., Theodorsen's theory. This again illustrates the difficulties in mathematically modeling the unsteady flowfield about a CC airfoil.

The corresponding phase angles indicated a very considerable lag between the blowing and the lift response, as also shown in Figs. 10b and 11b. With increasing reduced frequency, the phase angles were found to increase dramatically. Also, in contrast to the DLAR, the phase angles were somewhat unaffected by mean blowing level and slot angle position so long as the flow remained attached to the Coanda surface. It is of interest to note that the magnitude of the phase lag is considerably greater than would be obtained for an oscillating airfoil at the same value of reduced frequency; typically, maximum phase lag angles of about 20 deg are obtained on oscillating airfoils in incompressible flows. Also, the measured phase angles appeared to be considerably greater than those predicted by either of the unsteady CC theories reported in Refs. 14 or 15.

Significant effects of slot angle on the DLAR were observed, these results also being summarized in Figs. 10 and 11. For slot angles of 90 and 95 deg at a high mean blowing level, the jet sheet was well behaved and generally remained attached to the Coanda surface. Yet for a slot angle of 100 deg, the jet sheet exhibited a somewhat more complex behavior. Under

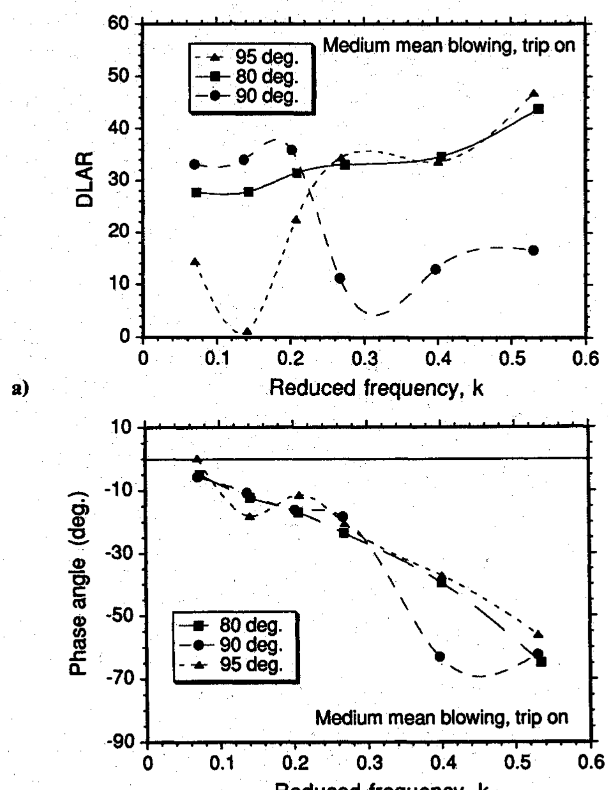

Fig. 10 Dynamic lift augmentation ratio (DLAR) and corresponding phase angle for varying slot angle (moderate mean blowing).

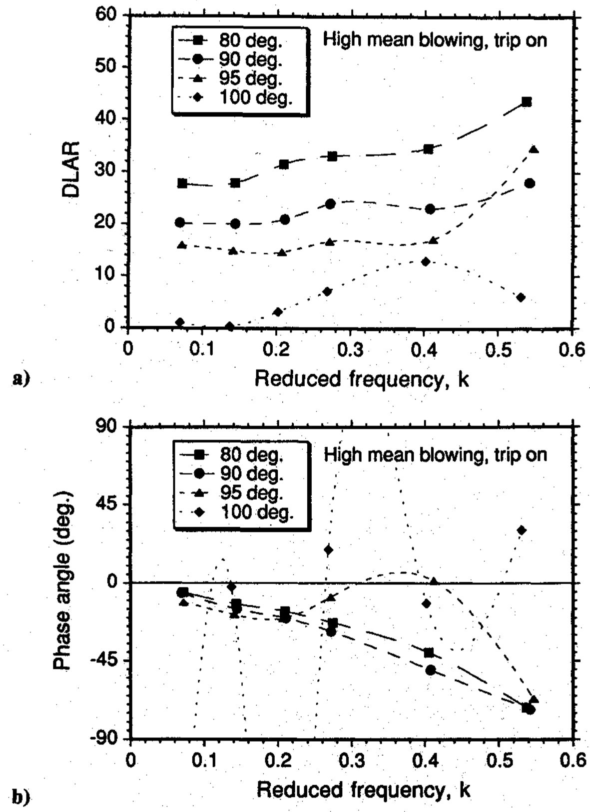

Fig. 11 Dynamic lift augmentation ratio (DLAR) and corresponding phase angle for varying slot angle (high mean blowing).

steady conditions at this slot angle, it has been shown previously in Fig. 5 that much higher values of blowing were required to produce the onset of useful circulation control. Nevertheless, above the critical blowing threshold, steady lift coefficients in excess of three were still normally obtained for this slot angle. On the other hand, under unsteady blowing conditions it was found to be very difficult to maintain attached flow on the Coanda surface at a slot angle of 100 deg. This is shown in the plot of phase angle in Fig. 11b, where the erratic changes in the phase lag indicate jet detachment.

Examination of the pressure time histories confirmed that the flow had detached from the surface just downstream of the slot, and hence very little lift was produced compared with the steady blowing case where the flow remained attached to the Coanda surface. Various combinations of mean blowing and blowing frequency were examined, still the results showed conclusively that for a slot angle of 100 deg the effects of unsteadiness were generally detrimental to CC airfoil performance.

Jet Detachment

It was noticed on several occasions (at a variety of slot angles) that the cylinder was seen to experience an unexpected jet detachment effect as the reduced frequency was increased above some critical value. This frequency dependent jet detachment may be defined as occurring when the DLAR becomes less than the static lift augmentation ratio. For example, as shown by Figs. 7d–f for a slot angle of 90 deg and at moderate blowing levels, the cylinder suffered a major loss of lift that was clearly associated with jet detachment from the Coanda surface. At either low or high mean blowing the jet was well behaved, but for the conditions shown in Figs. 7, the jet detached from the Coanda surface as the reduced frequency was increased through about 0.26, and the cylinder was ineffective in generating much circulatory lift above this frequency. This is also shown in Fig. 10a, where the DLAR dropped to almost half the value obtained at low reduced

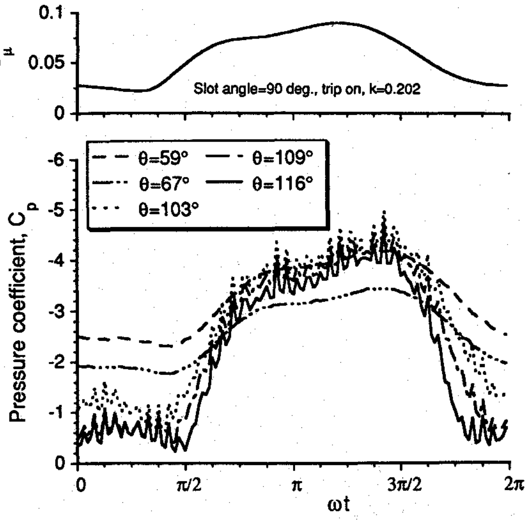

Fig. 12 Unsteady pressure response on Coanda surface (k = 0.202, jet attached).

frequencies. The jet remained detached from the Coanda surface even after increasing the reduced frequency to 0.54.

Further examination of the pressure time histories for the cases given in Figs. 7c and 7d showed that for $k = 0.2$ the jet generated large oscillatory suction peaks downstream of the slot (see Fig. 12). Even for this low reduced frequency, there was a significant time lag between application of the blowing and the build-up of a suction pressure on the Coanda surface. For the $k = 0.26$ case, shown in Fig. 13, the large suction pressure on the Coanda surface fails to develop. From the flat pressure time histories, it appears the jet is ineffective in generating much suction pressure on the Coanda surface and, consequently, the associated CC lift augmentation suffers. Evidence of jet detachment is shown by the nominally constant values of the pressure coefficients downstream of the slot. It was found that these values closely corresponded to the base pressures recorded for the unblown cylinder.

Further analysis of the measured data has shown that this reduced frequency dependent jet detachment effect is highly sensitive to the state of the unsteady boundary layer upstream of the slot, i.e., transition strip on or off. As such, the unsteady boundary layer is influenced by the complex and interrelated effects of slot angle, mean blowing level and reduced frequency. A limited investigation of the effect of Reynolds number on the reduced frequency jet detachment effect was also undertaken. Although no large dependence was observed, such a dependence cannot be ruled out categorically and requires further study. For the record, reduced frequency dependent jet detachment was found to be highly repeatable and independent of operating procedure, i.e., whether blowing was applied before or after the wind was turned on.

These examples illustrate the potential problems that may occur in the design of a CC airfoil for unsteady flowfield applications. That is, a CC airfoil or Coanda surface designed to work efficiently with steady blowing may not be acceptable when unsteady blowing is applied. In particular, the reduced frequency jet detachment effect is a potentially serious problem, and much further study must be pursued to clarify the full physics behind this phenomenon.

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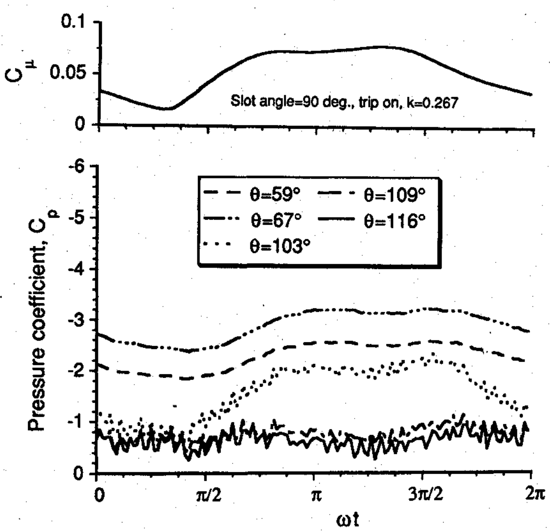

Fig. 13 Unsteady pressure response on Coanda surface (k = 0.267, jet detached).

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Conclusions

The results from the present study have provided an improved understanding of the effects of unsteady blowing on the aerodynamics of circulation controlled devices. This work has shown, for the first time, the dependence of the unsteady aerodynamics of a CC cylinder on reduced frequency, jet slot angle, boundary-layer condition, and mean blowing level. The work shows that the understanding of unsteady CC behavior is far from complete, but establishes the foundation for further experimental and theoretical research.

The following conclusions have been drawn from the present study:

1) The effects of unsteady blowing produced dynamic lift augmentation ratios that were significantly greater than the corresponding static values. This is a result that is at variance with previous computational results on CC cylinders and quasielliptical CC airfoils.

2) Very significant lift hysteresis effects were also observed, these effects increasing with increasing blowing frequency. Phase lag angles of up to 80 deg between the application of the blowing and the lift response were obtained at high reduced frequencies.

3) Maximum lift coefficients obtained under unsteady blowing conditions were often considerably greater than those obtained under steady conditions. Yet, the mean lift coefficients with unsteady blowing were, in some cases, less than the steady values at the same value of mean blowing.

4) A reduced frequency dependent jet detachment effect was observed. The physics behind this phenomenon are not yet clear and remain the subject for further research. However, these initial results show that a Coanda surface designed to work efficiently with steady blowing may not function when unsteady blowing is applied.

Acknowledgments

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