mode will be. However, the time for the flap to reach the top position shows only a slight influence.

Acknowledgment

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Sweep Effect on Parameters Governing Control of Separation by Periodic Excitation

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Nomenclature

C_l = airfoil lift coefficient
C_p = pressure coefficient
c = airfoil chord
c_{fl} = flap chord
c_μ = steady blowing momentum coefficient, $\equiv J/cq$
$\langle c_\mu \rangle$ = oscillatory blowing momentum coefficient, $\equiv \langle J \rangle/cq$
F^+ = reduced frequency, $\equiv fc/U_\infty$
f = oscillation frequency, Hz
h = slot height
J = average momentum at slot exit
q = freestream dynamic pressure, $\equiv \rho U_\infty^2/2$
Re = chord Reynolds number
U_∞ = freestream reference velocity
$\langle u' \rangle_f$ = phase locked rms level of velocity fluctuations
x/c = normalized streamwise location
α = angle of incidence
δ = flap deflection angle
Λ = sweep angle
ν = kinematic viscosity
ρ = density

Subscripts

2D = two-dimensional flow
3D = swept wing conditions

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Introduction

PERIODIC injection of momentum is a very promising tool in the control of separation. Its effectiveness was proven in two dimensions over a wide range of flow parameters such as Reynolds number, Mach number, and different geometries. Under favorable conditions the maximum lift generated on a flapped airfoil was doubled while its drag was reduced fourfold. However, the effect of sweep on this method of boundary-layer control was never investigated. Thus, to prove the efficacy of the method in applications involving swept-back wings, the effects of sweep have to be known. Furthermore, if the method is to be used as a design tool, a set of transformations is needed to convert data obtained in two dimensions to the cases involving sweep. The purpose of the present investigation is to provide these transformations and verify their validity experimentally.

Experiment

The wind-tunnel facility, oscillatory blowing apparatus, calibration procedure, and measuring techniques are described elsewhere.[1] The specific installation related to the present experiment will be described in this section. The experiment was carried out on a NACA 0018 airfoil (Fig. 1), having a chord of 180 mm. The small chord enabled mounting the airfoil across the larger span of the 0.6 by 1.2 m test section without causing prohibitive wind-tunnel interference. This arrangement provided a sufficiently large aspect ratio making the flow independent of the spanwise location at all yaw angles considered. The maximum aspect ratio was approximately 10.

The airfoil was made of composite materials and was hollow. Because the internal volume served as a settling chamber for the imposed oscillations the thicker airfoil section chosen improved the area ratio between the slot and the settling chamber. The airfoil was equipped with a flap whose total length was 30% of the chord. The blowing slot located above the flap shoulder was 0.9 mm high.

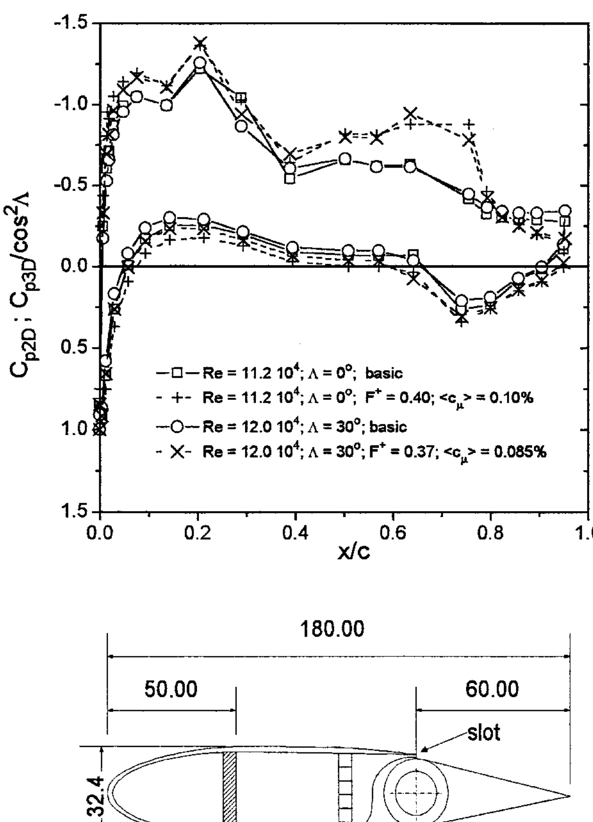

Fig. 1 Comparison of C_{p2D} (Λ = 0 deg) and $C_{p3D}/\cos^2\Lambda$.

The experiments were carried out at relatively low Reynolds numbers ($6 \times 10^4 < Re < 16 \times 10^4$), partly because of the small chord of the airfoil. Roughness strips were added near its leading edge to reduce the dependence of the results on Re. The forcing frequencies did not exceed 400 Hz, and the mean harmonic contamination of the required oscillatory momentum coefficient was approximately 6%

$$\langle c_\mu \rangle = 2(h/c)(\langle u' \rangle_f / U_\infty)^2 \tag{1}$$

This number is not precise because the hot wire used for calibrating the input oscillations rectifies the reverse flow. One is therefore never sure as to the real difference between the suction cycle and the blowing one. Steady blowing from the slot was also considered for the sake of comparison. Because the sole purpose of this experiment was to assess the sensitivity of the periodic excitation to yaw, comparative results sufficed in most instances. Consequently, many of the inaccuracies in the present experimental setup, e.g., some nonuniformities of the flow emanating from the slot, lost their significance.

Definition of Relevant Parameters

The Reynolds number is a very important parameter affecting the performance of airfoils. It is defined in two dimensions by

$$Re_{2D} = c_{2D} U_\infty / \nu \tag{2}$$

When the same airfoil is yawed or swept back, its geometry relative to the oncoming flow remains intact provided one considers the velocity component normal to the leading edge only. Because the retention of geometrical similarity is the first step in any comparison to be made, the corresponding Re for a swept-back airfoil is

$$Re_{3D} = (c_{2D} U_\infty \cos \Lambda)/\nu \tag{3}$$

One might have argued that sweep back merely increases the chord length parallel to the oncoming flow and thus increases the effective Reynolds number. This argument neglects the effects of pressure gradient that determine to a large extent the evolution of the boundary layer along the chord and, thus, the location of separation on the airfoil.

The pressure distribution on a two-dimensional airfoil is determined by taps located on its surface and the normal and tangential components of a force coefficient are obtained by numerical integration. Consequently, by yawing a wing of infinite aspect ratio through an angle Λ, the pressure and lift coefficients satisfy the equations

$$C_{p3D} = C_{p2D} \cos^2\Lambda \tag{4}$$

$$C_{l3D} = C_{l2D} \cos^2\Lambda \tag{5}$$

The reduced frequency in two-dimensional flow represents a ratio of lengths, e.g., the length of the separated region (the length of the deflected flap in this case) to the wavelength of the harmonic perturbation

$$F^+_{2D} = f \cdot c_{fl2D} / U_\infty \tag{6}$$

Because the phase of the periodic perturbations does not vary along the span of the slot and the latter is parallel to the trailing edge of the airfoil, the phase of the perturbation along the flap scales with the normal component of the freestream velocity, yielding

$$F^+_{3D} = \frac{c_{fl2D}}{(U_\infty \cos \Lambda / f)} = \frac{F^+_{2D}}{\cos \Lambda} \tag{7}$$

The oscillatory momentum input was scaled by the dynamic pressure and by the chord to give a momentum coefficient in two-dimensional flow

$$\langle c_{\mu 2D} \rangle = 2 \frac{h}{c_{2D}} \left(\frac{\langle u' \rangle_f}{U_\infty} \right)^2 \tag{8}$$

This represents the momentum required to overcome separation over a prescribed area (in this case the flap). By yawing the airfoil the total head in the direction normal to the slot is reduced by $\cos^2\Lambda$, giving

$$\langle c_{\mu 3D} \rangle = \frac{\langle c_{\mu 2D} \rangle}{\cos^2\Lambda} \tag{9}$$

The addition of steady blowing in the yawed airfoil case is no different

$$c_{\mu 3D} = \frac{J}{q c_{2D}} = \frac{c_{\mu 2D}}{\cos^2\Lambda} \tag{10}$$

Discussion of Results

Preliminary flow visualization experiments on a yawed circular cylinder suggested that a large fraction of the flow was independent of the spanwise direction provided the aspect ratio

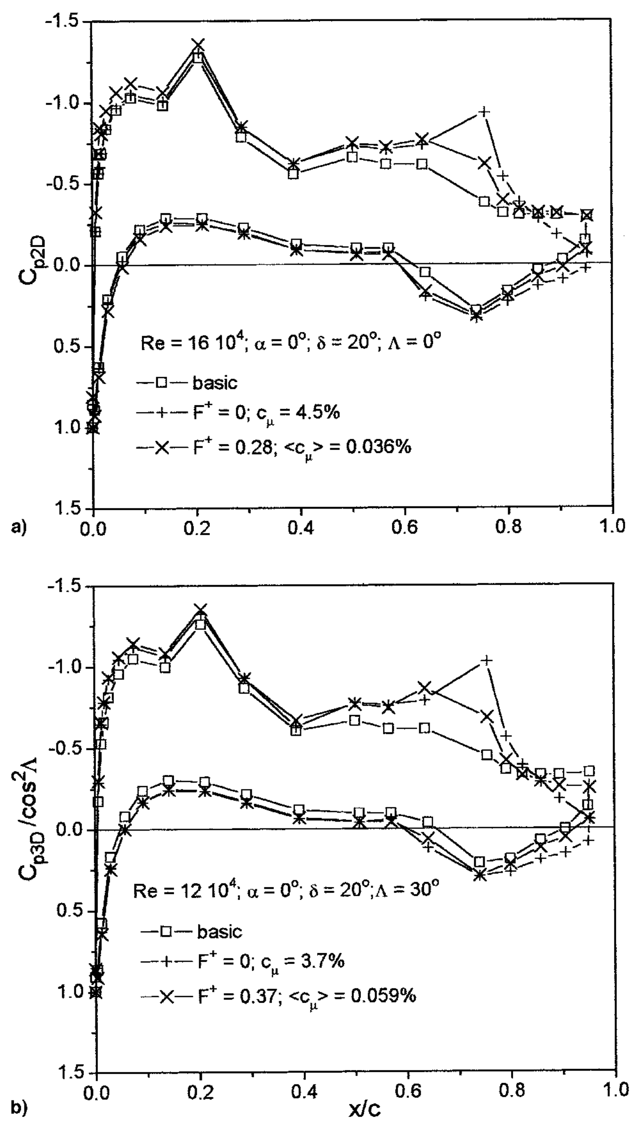

Fig. 2 Pressure distributions.

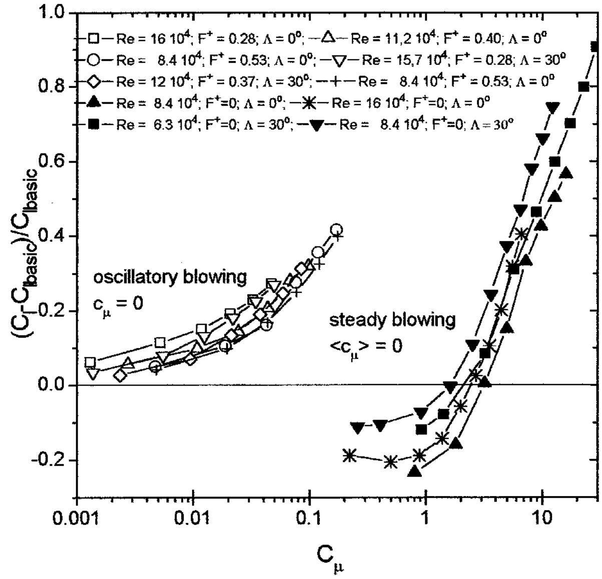

Fig. 3 Effect of oscillatory vs steady blowing on C_l improvement. $\alpha = 0$ deg and $\delta = 20$ deg.

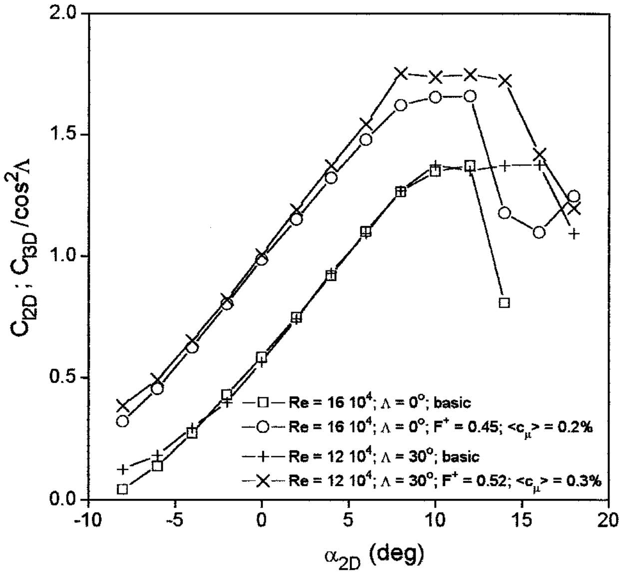

Fig. 4 C_L vs α.

was approximately 6. Thus, an aspect ratio of 10 was chosen for the NACA 0018 airfoil at a sweep angle of 30 deg. Wake traverses carried out at various spanwise locations corroborated this finding, and surface flow visualization indicated that most of the wall interference occurred within one chord length along the span. The interference stems from the image system associated with the tunnel wall relative to which the airfoil is swept forward. It appears that 90% of the span is free from wall interference. Most of the wall interference affects the separation and reattachment of the leading-edge bubble. The flow over the flap, which was deflected at 20 deg to the chord, remained separated over its entire span.

Four pressure distributions on the airfoil are presented in Fig. 1. The data were acquired at $Re \simeq 1.2 \times 10^5$ at two sweep angles $\Lambda = 0$ and 30 deg with and without periodic excitation. There is a good agreement between these two sets of forced and unforced results measured at different sweep angles, suggesting that the effect of forcing did not deteriorate as a result of the sweep. This figure demonstrates also the validity of the transformations suggested earlier, the most important of which is the one allowing the comparison of the pressure distributions at various angles Λ [Eq. (4)]. The validity of this transformation is demonstrated near the front stagnation points where $C_p \simeq 1$, regardless of Λ. The comparison is not perfect in the reattachment zone of the leading-edge bubble that occurs around $x/c \simeq 0.3$. One may also note that the flow over the flap was separated in the absence of forcing. Periodic excitation, which forced the flow to reattach over the flap, resulted in the reinstitution of the adverse pressure gradient at $x/c > 0.7$ and an increase in circulation over the entire airfoil.

Another comparison of pressure distributions that includes the effect of steady blowing is shown in Fig. 2. One may observe that steady blowing affects mainly the local flow over the flap, while oscillatory addition of momentum at a much lower input level has a global effect on the flow upstream and, thus, on the circulation over the entire airfoil. Therefore, comparable increases in lift are obtained when the input of momentum was approximately two orders of magnitude lower (Fig. 3). For $c_\mu \leq 1\%$, steady blowing was always detrimental.

The validity of the transformations resulting from the increase of sweep angle are shown by comparing the dependence of C_l on α for both the basic and the forced flow (Fig. 4). The two sets of data collapse prior to the occurrence of stall regardless of Λ, even though the values of $\langle c_\mu \rangle$ and F^+ were not identical.

It may be concluded that the transformations suggested are valid and that sweep does not adversely affect the control of separation by the periodic addition of momentum.

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