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Effects of Periodic Spanwise Blowing on Delta-Wing Configuration Characteristics

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Periodic leading-edge spanwise blowing was tested on a 60-deg swept delta-wing fighter aircraft model in a low-speed wind tunnel, up to an angle-of attack of α = 60 deg. At low frequencies, lift and drag coefficients correspond to the pulsating blowing pressure: when the valve is open, they reach the same values as with continuous blowing, and when it is closed, they agree with the no-blowing values. A lag in the response time is observed, which is equal at low incidences to the freestream convective time, but increases to 30 convective times at α = 30–40 deg. This response time is much longer when the valve closes than when the valve opens at α = 20–30 deg. These features are similar to those of delta wings in unsteady flows, such as in pitching or plunging motions. They are insensitive to the flow parameters and are valid at low blowing frequencies. At high frequencies, lift and drag coefficients do not correspond to the pulsating pressure, but remain at an intermediate value between those of continuous and no blowing. In both cases, the mean lift and drag coefficients are equal to the values obtained by continuous blowing at the same mean momentum coefficient.

Nomenclature

c	= wing root chord
C_D	= drag coefficient, $D/q \cdot S$
$\overline{C}_D$	= mean drag coefficient, $(1/T)\int_0^T C_D(t) \cdot dt$
C_L	= lift coefficient, $L/q \cdot S$
$\overline{C}_L$	= mean lift coefficient, $(1/T)\int_0^T C_L(t) \cdot dt$
C_μ	= jet-momentum coefficient, $(m \cdot V_j / q \cdot s)$
$\overline{C}_\mu$	= mean jet-momentum coefficient, $(1/T)\int_0^T C_\mu(t) \cdot dt$
d	= nozzle internal diameter
f	= blowing frequency
k	= reduced blowing frequency, $2\pi f \cdot c/V$
m	= jet mass flux
P	= static pressure downstream of the valve
q	= freestream dynamic pressure
r	= relative pulse length (pulse/period ratio)
R_c	= chord Reynolds number, $V \cdot c/\nu$
S	= wing planform area
T	= pulsating period
t	= time
t_r	= response time of the aerodynamic coefficients
t_r^*	= dimensionless response time, t_r/t_0
t_0	= convective time of the freestream on the wing, c/V
V	= freestream velocity
V_j	= jet exit velocity
α	= angle of attack
ν	= kinematic viscosity

Introduction

MOST modern fighter aircraft use vortex lift to increase their maneuverability. This nonlinear lift is created by flow separation over swept, sharp-edged wings, generating leading-edge vortices. These vortices induce a high velocity and low pressure on the upper side of the wing, resulting in a substantial and nonlinear increase in the total lift of the aircraft.

However, this additional lift gives rise to an increase in the induced drag, because the separating flow from the leading-edge directs the suction force normal to the wing surface and adds a component in the drag direction.[1] Also, this nonlinear lift decreases when the leading-edge vortices burst,[2] i.e., at vortex breakdown. Vortex breakdown also significantly increases the drag.

There are several ways to delay the vortex breakdown and reduce the drag, such as the addition of strakes, canards, or LEX before the wing. One of the methods that has been found to delay vortex breakdown is leading-edge spanwise blowing.

This method was first used on wings of small leading-edge sweep angle, in order to generate leading-edge vortices and obtain nonlinear lift.[3–12] Later on, the leading-edge spanwise blowing was also tested on highly swept wings.[13–18] It was shown that an increase in the lift,[3–16] an amelioration of the lateral stability,[5,12,13,16] and a delay of the vortex breakdown[5,12–15,17,18] can be obtained.

The main problem with this blowing is the high momentum needed to achieve a significant increase in the lift. It has been estimated[12] that if the blowing air were taken from the compression stage of the main jet engine, the specific excessive power would be smaller than without spanwise blowing. On the other hand, it has been estimated[8,11] that with engines designed for bleeding or a special small engine used just for blowing, the effective lift would increase because of spanwise blowing.

However, the large momentum needed to generate a lift increase is a major issue in the effectiveness of this blowing, and as a consequence, it was suggested to try to generate the same lift increase using a lower momentum by way of a pulsating blowing over a delta wing of a fighter aircraft.

Pulsating or unsteady blowing was chosen because of previously observed features of delta wings in unsteady flows,[19] such as accelerating flows,[20] or unsteady gusts,[21] and unsteady wing motions, such as oscillating pitching,[22–28] pitching with a constant pitch rate,[18, 29–31] oscillating plunging,[32,33] plunging with a constant incidence step,[34] and oscillating heaving.[35]

The main features, observed in pitching delta wings and relevant to this study, include a hysteresis loop in the leading-edge vortex position,[22,25,28] as well as in the lift curve,[24,26,27] and the leading-edge vortex delay/advancement during the upstroke/downstroke sequence.[18,29–31] As a matter of fact, a comparison between the vortex breakdown delay by blowing and pitching has also been recently presented.[18] A change in the vortex height was observed also in plunging motion,[32,34] and a hysteresis cycle was found in the vortex position in heaving motion (periodical streamwise acceleration).[35] In all these unsteady motions, the response time of the flow to the step in incidence was found to roughly agree with

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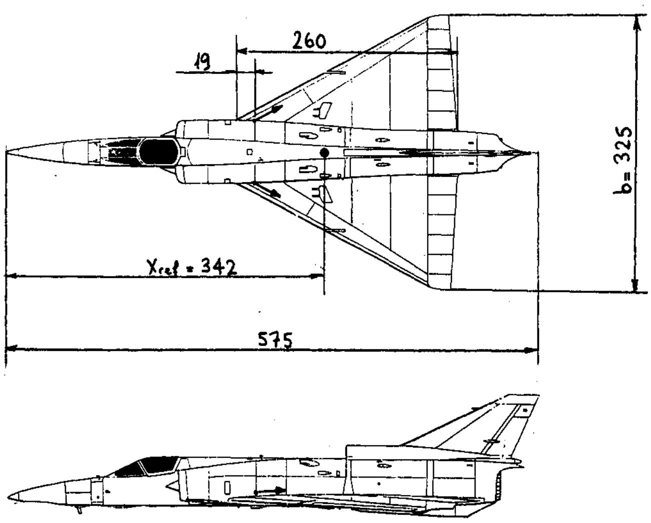

Fig. 1 Model and blowing ports.

the convective time of the mean flow ($t_0 = c/V$).[21,25,32,34] But at very high incidence angles, this response time was found to increase to up to 30 convective times.[23]

The effects of leading-edge periodical spanwise blowing were therefore investigated at low subsonic velocities in order to achieve a more effective blowing and analyze the resulting unsteady flow.

Experimental Apparatus

Experiments were conducted in the Technion 1 × 1 m low-speed wind tunnel over a 1:25 scale model of one of the early versions of the Kfir aircraft, up to an angle of attack of $\alpha = 60$ deg. The model had a low 60-deg swept delta wing, with a relatively sharp leading edge that had a conical droop. The model span was 32.5 cm and the wing root chord $c = 26$ cm. A schematic description of the model and location of the blowing ports is presented in Fig. 1.

The tests were conducted at an airspeed of $V = 8$ m/s and frequencies $f = 0.1$–7 Hz, and at $V = 27$ m/s and frequencies $f = 0.1$–7 Hz and $f = 30$ and 80 Hz. The corresponding Reynolds numbers, based on the root chord, were $R_c = 1.4 \times 10^5$ and 4.8×10^5, respectively, and the convective times were $t_0 = 0.033$ and 0.0096 s. The reduced frequencies varied in the range of $k = 0.006$–5.0.

Air was injected parallel to the leading edge, at stagnation pressures of up to 12 atm, through a pair of nozzles in the fuselage, 3 mm above the wing and 19 mm behind the wing apex. The internal diameter of the nozzles was $d = 2.3$ or 5.6 mm ($d/c = 0.0088$ or 0.022).

The pulse-generating apparatus, at frequencies smaller than 7 Hz, consisted of a solenoid valve activated by a pulse generator. Square signals were generated with several pulse lengths (pulse/period ratio $r = 0.2, 0.5, 0.8$). At frequencies $f = 30$ and 80 Hz, the pulse-generating mechanism consisted of a rotating valve, driven by an electric motor, that generated sinusoidal signals.

Aerodynamic forces and moments were measured by a high-sensitivity six-component internal strain-gage sting balance. The natural frequency of the model-balance system was found to be 15 Hz. A filter of 1000 Hz was used for the data acquisition and no other filter added, in order to record the unsteady behavior of the pressure and the aerodynamic coefficients. As a result, the natural oscillations of the model-balance system appear in the subsequent aerodynamic coefficients time histories. The response time of the balance was one order of magnitude shorter than 1 ms, which corresponds to the filter.

Aerodynamic forces were normalized by the freestream dynamic pressure q and wing planform area S. They were not corrected for the jet direct thrust, although the jet thrust was measured, because this research was aimed at a comparison of pulsating with constant blowing, both having an identical jet thrust. For pulsating blowing, mean lift and drag coefficients $\overline{C_L}$ and $\overline{C_D}$ also

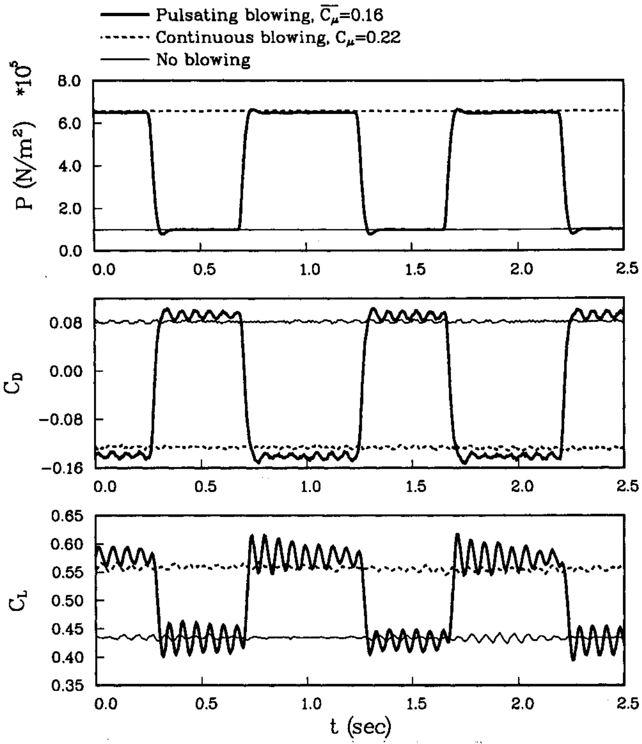

Fig. 2 Lift and drag coefficients vs time at $d/c = 0.022$, $R_c = 4.8 \times 10^5$, $\overline{C_\mu} = 0.16$, $k = 0.061$, $r = 0.5$, and $\alpha = 10$ deg.

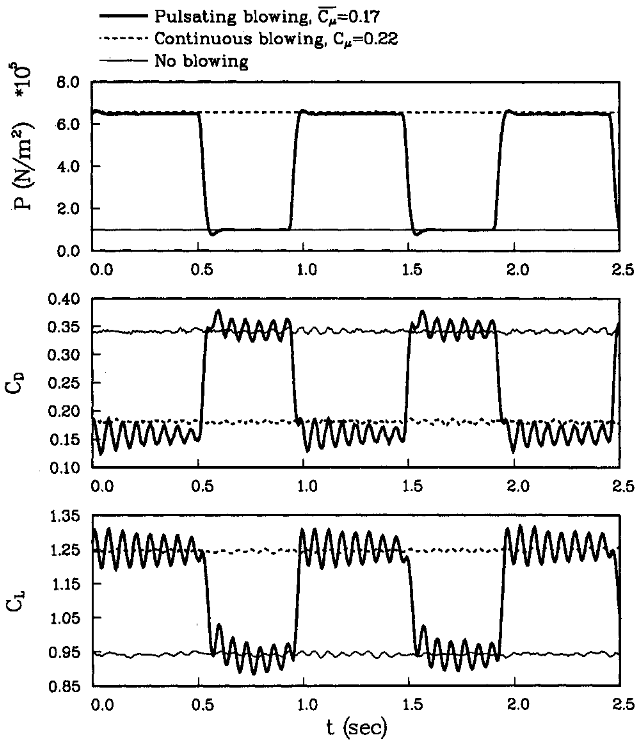

Fig. 3 Lift and drag coefficients vs time at $d/c = 0.022$, $R_c = 4.8 \times 10^5$, $\overline{C_\mu} = 0.17$, $k = 0.061$, $r = 0.5$, and $\alpha = 20$ deg.

were calculated for comparison with the constant blowing. The accuracy of the lift coefficient is about 0.02 at $V = 27$ m/s and 0.095 at $V = 8$ m/s. The accuracy of the drag coefficient at $V = 27$ m/s is about 0.01 for $\alpha \leq 20$ deg and 0.02 for $\alpha \geq 30$ deg. At $V = 8$ m/s and $\alpha = 40$ deg, it is 0.07.

The jet-momentum coefficient is $C_\mu = m \cdot V_j / q \cdot S$. With continuous blowing, m and V_j were measured directly. With pulsating blowing, the instantaneous m and V_j were calculated from the instantaneous pressure P measured after the valve, and a mean momentum coefficient $\overline{C_\mu}$ was evaluated. This jet-momentum

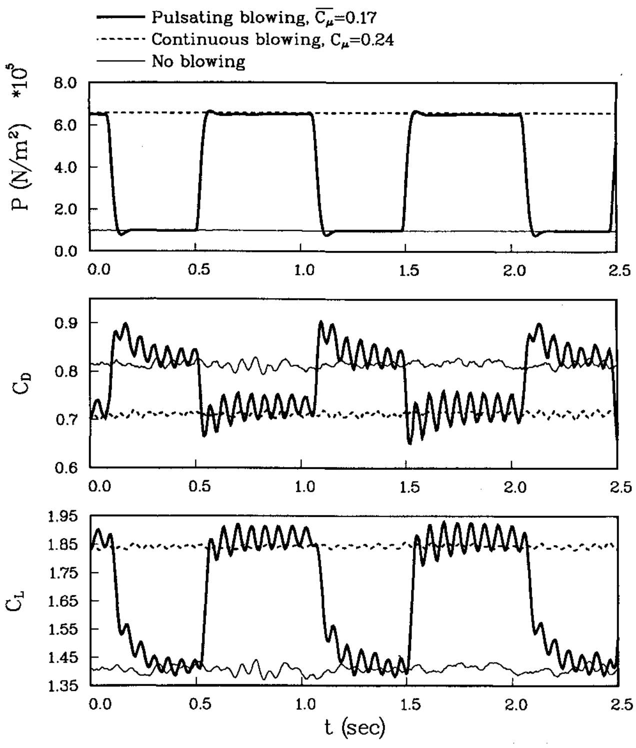

Fig. 4 Lift and drag coefficients vs time at d/c = 0.022, R_c = 4.8 $\times 10^5$, $\overline{C_\mu}$ = 0.17, k = 0.061, r = 0.5, and α = 30 deg.

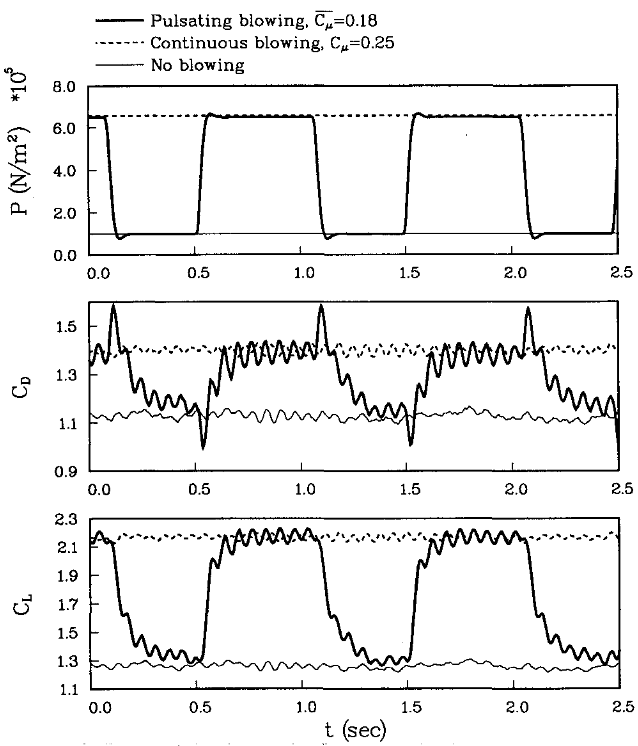

Fig. 5 Lift and drag coefficients vs time at d/c = 0.022, R_c = 4.8 $\times 10^5$, $\overline{C_\mu}$ = 0.18, k = 0.061, r = 0.5, and α = 40 deg.

coefficient $\overline{C_\mu}$ was evaluated. This jet-momentum coefficient $\overline{C_\mu}$ varied in the range 0.004–0.37. The accuracy of the jet-momentum coefficient may be assumed to be within 5%, because of the uncertainty in determining V_j from pressure measurements. The jet-momentum coefficient value was confirmed by the measurement of the direct jet thrust. The freestream dynamic pressure q was not strictly identical in the different tests, and as a result, the jet-momentum coefficient might have varied between different tests at constant blowing pressure. As an example, the dynamic pressure decreased when the angle of attack was increased.

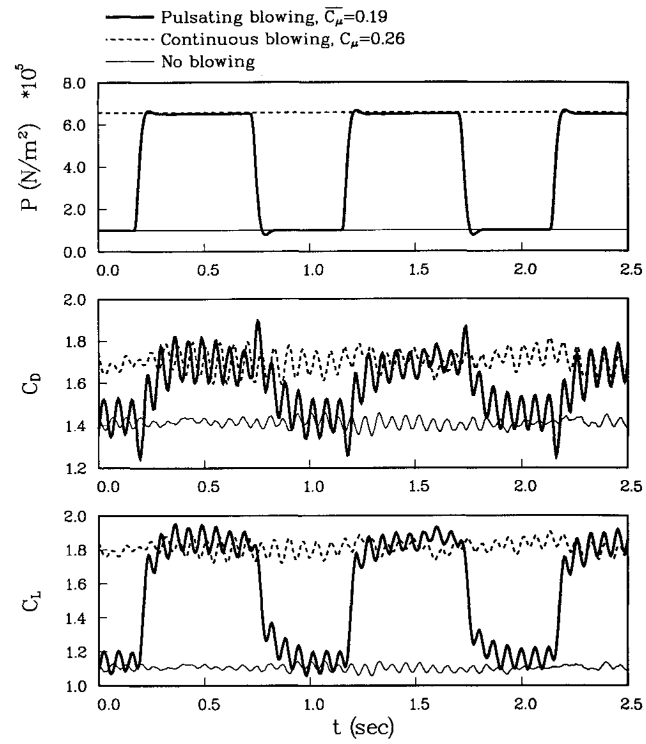

Fig. 6 Lift and drag coefficients vs time at d/c = 0.022, R_c = 4.8 $\times 10^5$, $\overline{C_\mu}$ = 0.19, k = 0.061, r = 0.5, and α = 50 deg.

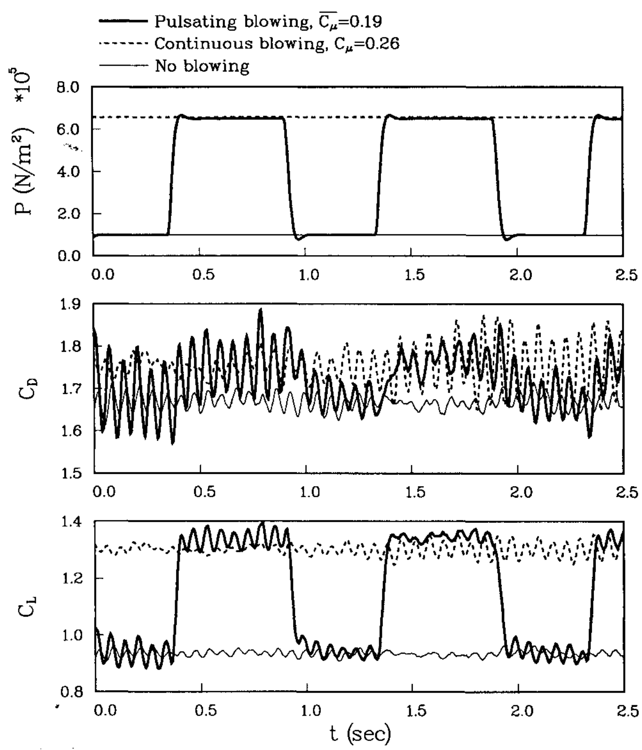

Fig. 7 Lift and drag coefficients vs time at d/c = 0.022, R_c = 4.8 $\times 10^5$, $\overline{C_\mu}$ = 0.19, k = 0.061, r = 0.5, and α = 60 deg.

The effects of the periodic spanwise blowing are presented mainly in the form of time histories of the lift and drag coefficients in order to investigate the unsteady aerodynamic characteristics, although statistical and spectral analyses of these coefficients were also available and used when necessary.

Low-Frequency Periodic Blowing

Influence of the Incidence Angle

Typical curves of the pressure P and the lift and drag coefficients C_L and C_D vs time for periodic blowing at a reduced frequency of k = 0.061 (this is a "low" reduced frequency, to be defined later) are presented in Figs. 2–7 at d/c = 0.022, R_c = 4.8×10^5, $\overline{C_\mu}$ ≈ 0.18, r = 0.5, and α = 10–60 deg. Additional curves in these figures are the corresponding values with continuous blowing at the same maximum pressure, and without blowing.

It is seen that after some initial response time (which will be discussed later), the variations in coefficients C_L and C_D correspond to the pressure P variations at all these incidences. When the valve is open, C_L and C_D have the same or slightly different values as with continuous blowing. When it is closed, they agree with the no-blowing values. Pulsating blowing has the same effect on the other aerodynamic coefficients, but the difference between the steady levels of continuous and no blowing is generally negligible. The results at continuous and no blowing emphasize the lift augmentation induced by spanwise blowing, which is present at all incidences and reaches a maximum at α = 30–50 deg, as indicated in a preceding study.[13]

The observed oscillations in the aerodynamic coefficients are the natural oscillations of the model-balance system, as shown by spectral analysis. Particularly, the frequency of these oscillations is the same for continuous, pulsating, and no blowing and is independent of the angle of attack. Without blowing, the oscillations' amplitude is low for $\alpha \le 20$ deg, then increases because of the vortex breakdown that occurs at about 30 deg.[2] With continuous blowing, the oscillations' amplitude remains low up to α = 30 deg, as the vortex breakdown is delayed.[13] With pulsating blowing, the oscillations' amplitude is much larger than in the steady cases, possibly because of an excitation of the balance-model natural frequency.

No significant overshoot is observed in the evolution of the lift coefficient C_L, except at α = 10 deg, although an overshoot was reported[26] in pitching motion of a 70-deg swept delta wing to α = 55 deg. The response time is short at small incidences ($\alpha \le 20$ deg) and longer at larger incidences ($\alpha \ge 30$ deg). Also, at α = 20– 30 deg, the response time is longer at the valve-closing phase than the valve-opening phase. Slight differences between the lift and drag coefficients of pulsating blowing at the valve opening and their value at continuous blowing may be related to differences in the freestream dynamic pressure, as discussed before.

A difference is observed between the steady values of the drag coefficient C_D at low and high incidences. At small incidences ($\alpha \le 30$ deg, see Figs. 2–4), the drag coefficient with blowing is lower than without blowing, because of the thrust effect of the blowing, amplified by the jet-induced suction on the leading-edge droop.[13] However, at higher angles of attack ($\alpha \ge 40$ deg, see Figs. 5–7), the drag component induced by the increased lift is larger than the thrust component, and the drag coefficient with blowing is higher than without blowing.

At high incidences ($\alpha \ge 30$ deg), the response of the drag coefficient to the pulsating blowing is complex (Figs. 4–7). After opening the valve, C_D first decreases, then increases to the constant blowing level, which may be lower (α = 30 deg) or higher (α = 40–50 deg) than the no-blowing level. It is suggested that at these incidences, the direct thrust response time is much shorter than the aerodynamic response time needed to rebuild the leading-edge vortices. Therefore, the drag coefficient first decreases under the thrust influence, then increases because of the increased lift on the wing. This analysis is confirmed by the measured values of the jet direct thrust. This complex reaction is not observed at α = 10–20 deg, because at these incidences, the aerodynamic response time is short and similar to the thrust response time, therefore, the drag coefficient reaches directly the constant-blowing level.

Influence of the Jet Parameters

The time evolution of the lift and drag coefficients C_L and C_D under periodic blowing was not significantly altered by a variation in the flow parameters, such as the jet-momentum coefficient, pulse length, nozzle diameter, and freestream velocity.

The jet-momentum coefficient was varied between $\overline{C_\mu}$ = 0.37 and 0.086, at α = 30 and 40 deg, without a significant effect on the unsteady behavior of C_L and C_D, although the steady coefficient levels varied according to the jet-momentum coefficient, corresponding to the continuous-blowing values. At still smaller jet-momentum coefficient values, $\overline{C_\mu}$ = 0.004–0.023, no conclusions could be drawn, as only very small differences existed between the steady values at constant and no blowing.

The periodic blowing was modified by changing the relative pulse length between r = 0.2 and 0.8. The jet-momentum coefficient varied with r between 0.06 and 0.21, but the time evolution of C_L and C_D was not altered qualitatively by this modification, although the periods of maxima and minima for C_L and C_D varied with the pulse length.

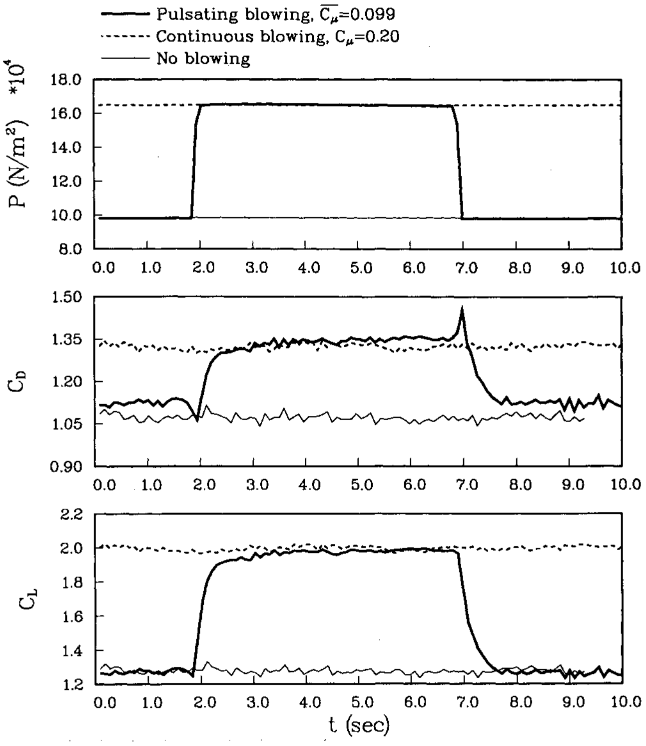

Fig. 8 Lift and drag coefficients vs time at d/c = 0.0088, R_c = 1.4×10^5, $\overline{C_\mu}$ = 0.099, k = 0.02, r = 0.5, and α = 40 deg.

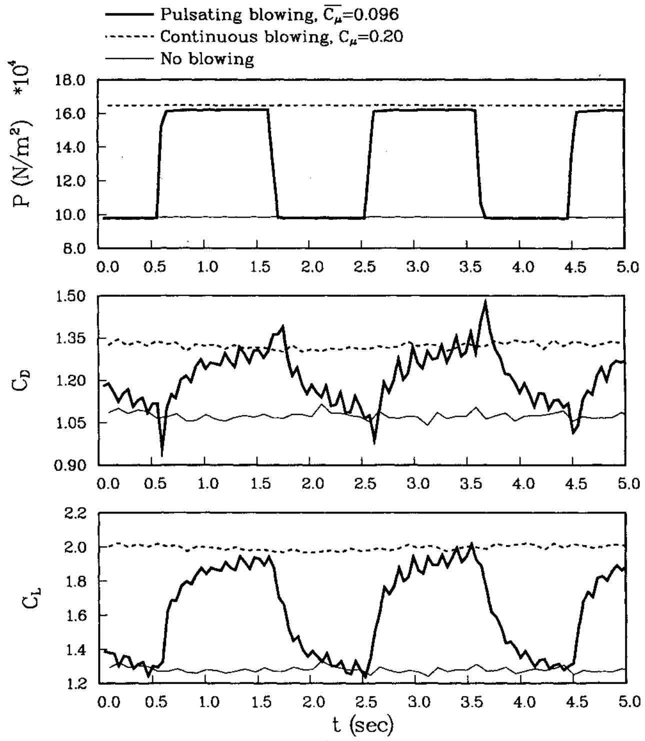

Fig. 9 Lift and drag coefficients vs time at d/c = 0.0088, R_c = 1.4×10^5, $\overline{C_\mu}$ = 0.096, k = 0.10, r = 0.5, and α = 40 deg.

Replacing this nozzle with a smaller one (with d/c = 0.0088) also did not significantly modify the time evolution of C_L and C_D of the periodic blowing. The jet-momentum coefficient $\overline{C_\mu}$ of the smaller nozzle varied from 0.034–0.13. This is in agreement with Ref. 11, which reported that the jet nozzle diameter had only a small influence on the steady-blowing results, if the diameters were small compared with the chord length.

Reduction of the freestream velocity to 8 m/s and the Reynolds number to $R_c = 1.4 \times 10^5$ did not significantly alter the time evolution of C_L and C_D of the periodic blowing. This evolution is presented in Fig. 8 with $d/c = 0.0088$, $\overline{C_\mu} = 0.099$, $k = 0.02$, $r = 0.5$, and $\alpha = 40$ deg. The lift and drag coefficients are identical to the steady values of continuous blowing, or without blowing, when the valve is fully open or closed. The response time in this case is longer than at the higher R_c, corresponding to the convective time. This will be discussed in the next section.

Increasing the blowing frequency increases the ratio of the response time to the pulsating period. The coefficients C_L and C_D will reach the steady values of continuous and no blowing if the response time is shorter than half of the pulsating period. In that frequency range, the response time is independent of the pulsating frequency, and the time evolution of the aerodynamic coefficients was previously described. At the limit of this frequency range, the response time increases to half of the pulsating period. Under these conditions, the time-dependent C_L and C_D curves hardly reach the steady values of continuous or no blowing. This is demonstrated in the time evolution of C_L and C_D presented in Fig. 9 for d/c = 0.0088, $R_c = 1.4 \times 10,^5$ $\overline{C_\mu} = 0.096$, $k = 0.10$, $r = 0.5$, and $\alpha = 40$ deg, as compared with Fig. 8.

Response Time

The response time t_r of the lift and drag coefficients to the opening and closing of the valve in pulsating blowing is defined as the time required for C_L and C_D to reach the continuous- or no-blowing steady values. The response times were estimated from the time evolution graphs (e.g., Figs. 2–9) and must be considered as representative, yet approximate quantities only. The significance of the response time can be judged when compared with the freestream convective time on the wing t_0, and a dimensionless response time is defined as $t_r^* = t_r / t_0$.

The dependence of the dimensionless response time t_r^* on the incidence is presented in Fig. 10 for two series of tests: at $R_c = 4.8 \times 10^5$ with $d/c = 0.022$, $\overline{C_\mu} = 0.18$, $k = 0.06$, and $r = 0.5$, and at $R_c = 1.4 \times 10^5$, with $d/c = 0.0088$, $\overline{C_\mu} = 0.09$, $k = 0.10$, $r = 0.5$. These values are representative of many results obtained at different test conditions, as the jet parameters (except of the angle of attack) did not significantly affect the time history of the aerodynamic coefficients.

It is seen that the normalized response time varies strongly with the incidence and has the same general character both for C_L and C_D. However, whereas for C_L it is rather independent of the jet parameters, it shows some dependence on C_μ for C_D. At $\alpha = 10$ deg, t_r* has values of 2–3 at $R_c = 4.8 \times 10^5$ and 4-8 at $R_c = 4.8 \times 10^5$. The response time of the solenoid valve itself in opening and closing was estimated to be about $1 \cdot t_0$ and $7 \cdot t_0$, respectively (because of the different nozzle sizes and freestream velocities). The net dimensionless response time value is therefore about 1.

The response time increases with incidence up to values of 30–35 at $\alpha = 40$ deg, with a marked difference between the valve opening and closing values at $\alpha = 20$ and 30 deg, as also seen in Figs. 3 and 4. At $\alpha > 40$ deg, the response time decreases to smaller values, with t_r^* reaching at $\alpha = 50$ and 60 deg about the same values as at $\alpha = 30$ and 20 deg, respectively.

It is interesting to compare this dependence of the response time on α with the characteristic times reported for unsteady delta wings. A response time of about $t_r^* = 1$ has been reported for unsteady motions at low or medium angles of attack.[19] It was estimated from the measured phase lag of the vertical vortex position in plunging motion,[32] the axial position of vortex breakdown in pitching motion,[25] the phase lag of the lift coefficient in the presence of unsteady gusts,[21] and the direct time history of the vortex position in plunging motion.[34] It must be noted that these unsteady

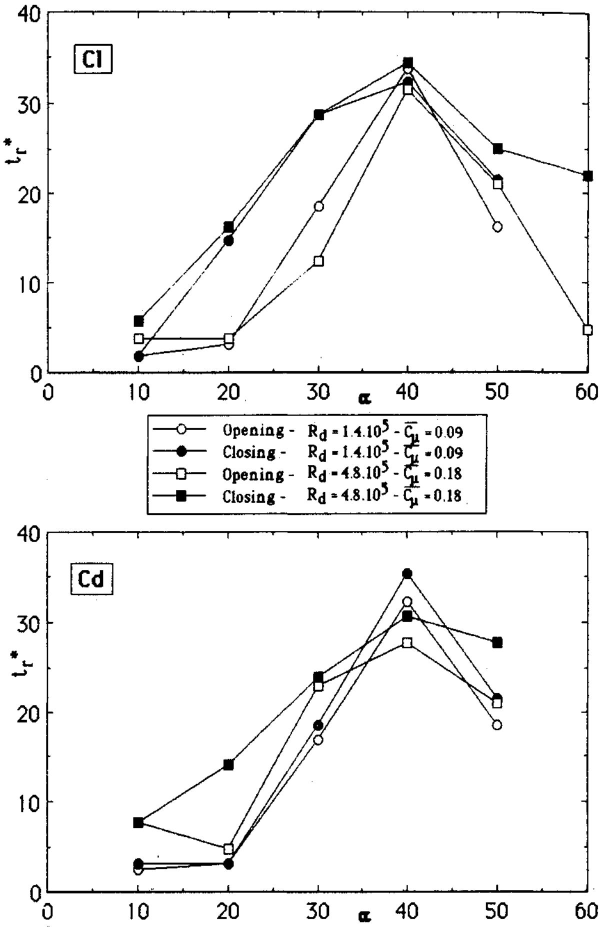

Fig. 10 Dimensionless response time for lift and drag coefficients vs angle of attack.

motions induce quite different flowfields. For instance, the pitching motion involves an incidence variation, as well as large pitching angular velocities.[34] The present study shows that a similar response time is obtained in periodic blowing, in which neither pitch nor incidence changes occur, but an alteration of the flow is induced by the leading-edge blowing.

Moreover, the increase in the response time to $t_r^* = 30$ at high angles of attack was reported also in pitching motions.[23] In an attempt to explain the variation in the response time with incidence, it is suggested that the long response time at $\alpha = 30$–40 deg results from the vortex breakdown that has already occurred over the natural (unblown) configuration, but is delayed by blowing. It then decreases at still higher incidences, where vortex breakdown affects even the blown wing.

The difference in the response time of the aerodynamic coefficients between the valve opening and closing conditions at $\alpha = 20$–30 deg (Figs. 3, 4, and 10) may be related to differences in the flow conditions as illustrated by flow visualizations obtained at $\alpha = 30$ deg with a smoke generator. Immediately before a blowing pulse, the flowfield is characteristic of an unblown 60-deg delta wing, with separated flow and vortex breakdown over the wing.[2] At the end of the blowing pulse, the flowfield is typical of spanwise-blown wings,[5,12–15,17] where the flow remains attached to most of the wing and the vortex breakdown is significantly delayed.

During the no-blowing part of the pulsating period, it is observed that the reaction to the closing of the valve is much slower than to the valve opening and the flow does not return to the unblown features at the same rate. Immediately after the closing of the valve, separation is observed only over the rear part of the wing, whereas over the fore part, the flow is still attached, as if the blowing were still effective there. Only at a later stage, requiring more time, the flow returns to the unblown features.

The time histories of C_L and C_D, as well as the flow visualizations, present an asymmetrical hysteresis between the blown and

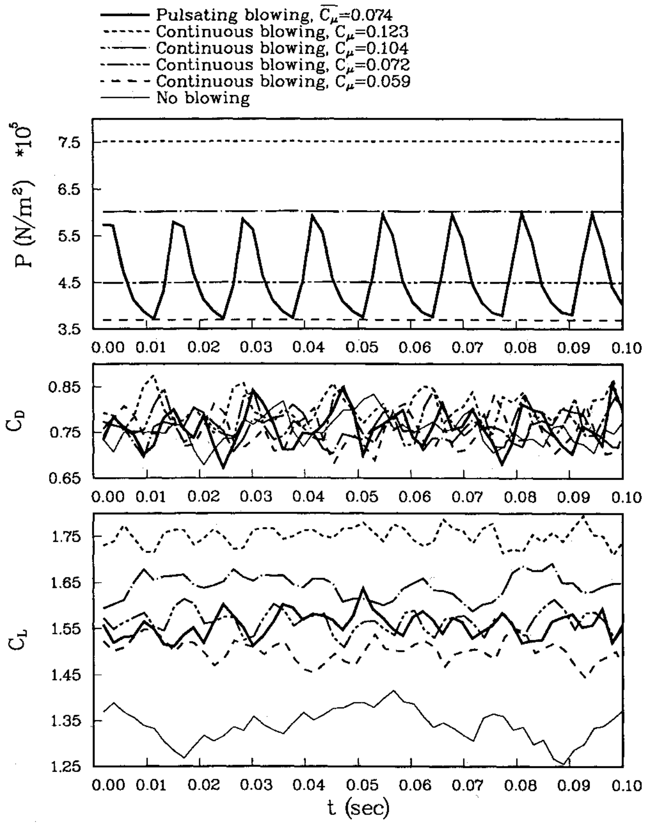

Fig. 11 Lift and drag coefficients vs time at d/c = 0.0088, R_c = 4.8 × 10^5, $\overline{C_\mu}$ = 0.074, k = 4.8, and α = 30 deg.

unblown flowfields. Similar hysteresis curves were observed for the vertical position of the vortex, axial position of vortex breakdown, and lift curve of delta wings in all the unsteady motions such as pitching,[22–31] plunging,[33,34] and heaving.[35] In particular, asymmetrical hysteresis curves were obtained for the vertical position of the vortex in plunging motion during a positive or negative step in incidence,[34] and for the axial position of breakdown when suction near the wing trailing edge was applied or removed.[36]

High-Frequency Periodic Blowing

The time history of the aerodynamic coefficients C_L and C_D just described is valid at low frequencies, namely when the pulsating period T is equal to or larger than twice the response time t_r:

$$T \geq 2 \cdot t_r \qquad (1)$$

As $t_r{}^* = t_r \cdot V/c$, and $k = 2\pi f \cdot c/V$, this condition implies

$$t_r{}^* \cdot k \leq \pi \qquad (2)$$

For incidences of α = 30–40 deg, where the response time $t_r{}^*$ is about equal to 30, the limit for the previously described time history of C_L and C_D is about k = 0.10, as in Fig. 9.

If the pulsating frequency is increased above this value, the coefficients C_L and C_D do not correspond to the pressure P curve, but remain at an intermediate level between their values for continuous and no blowing. This condition is fully developed when the pulsating period is much shorter than the response time (which was measured at low-frequency blowing), say, for

$$T \leq t_r/2 \qquad (3)$$

which is equivalent to

$$t_r{}^* \cdot k \geq 4\pi \qquad (4)$$

and, for t_r^* = 30, to

$$k \geq 0.42 \qquad (5)$$

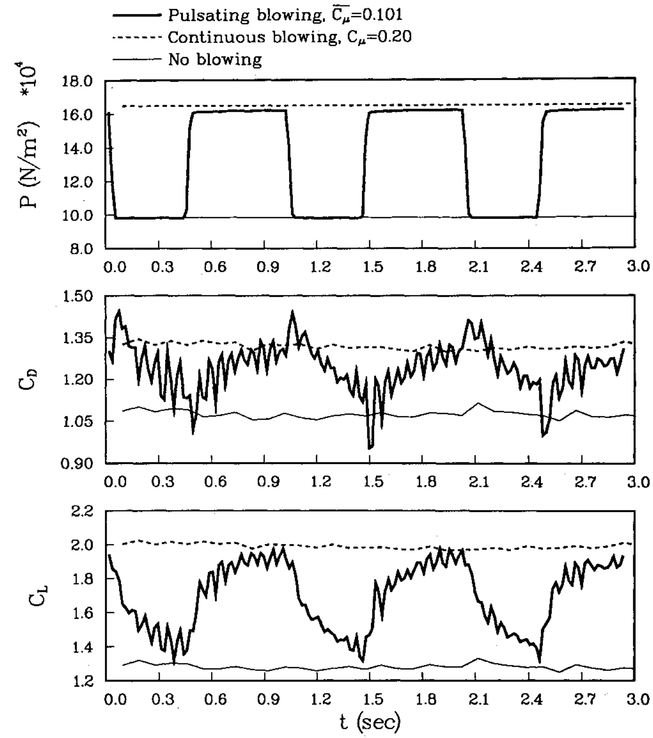

Fig. 12 Lift and drag coefficients vs time at d/c = 0.0088, R_c = 1.4 × 10^5, $\overline{C_\mu}$ = 0.101, k = 0.20, r = 0.5, and α = 40 deg.

A typical time history of C_L and C_D in high-frequency periodic blowing is presented in Fig. 11, at d/c = 0.0088, R_c = 4.8 × 10^5, $\overline{C_\mu}$ = 0.074, k = 4.8 (f= 80 Hz), and α = 30 deg. In this case, the pulse-generating mechanism was a rotating valve, generating a nearly triangular signal, as can be seen in the pressure curve in this figure. For comparison, continuous blowing was tested at pressures corresponding to the maximum, minimum, and mean pressures of the periodic blowing. It can be seen that C_L does not correspond to the pressure, but remains at an intermediate level between the values of the continuous blowing at the maximum and minimum blowing pressures. In fact, this level is equal to the level obtained with continuous blowing at a pressure equal to the mean pressure, i.e., with the same jet-momentum coefficient. The graph for C_D is not significant, as the differences between the curves are too small.

At intermediate pulsating frequencies, such as

$$t_r/2 < T < 2 \cdot t_r \qquad (6)$$

or

$$\pi < t_r{}^* \cdot k < 4\pi \qquad (7)$$

the time history of C_L and C_D varies in character between those at low and high frequencies. The aerodynamic coefficients do not reach as at low frequencies the steady values of the constant- or no-blowing curves, but they do not yet remain at the mean levels, as with high frequencies. An example of such a frequency is presented in Fig. 12, with d/c = 0.0088, R_c = 1.4 × 10^5, $\overline{C_\mu}$= 0.101, k = 0.20, r = 0.5, and α = 40 deg.

Mean Aerodynamic Coefficients

The effectiveness of periodic blowing relative to continuous blowing was judged by comparing the mean aerodynamic coefficients $\overline{C_L}$ and $\overline{C_D}$, of the periodic blowing with those of the continuous blowing, at the same mean jet-momentum coefficients C_μ. Typical curves of $\overline{C_L}$ and $\overline{C_D}$ vs $\overline{C_\mu}$ are presented in Figs. 13 and 14 at d/c = 0.0088, R_c = 4.8 × 10^5, k = 0.006–0.24, and α = 30 deg and at d/c = 0.0088, R_c = 1.4 × 10^5, k = 0.02–1.42, and α = 40 deg, respectively. These figures include data from periodic blowing at

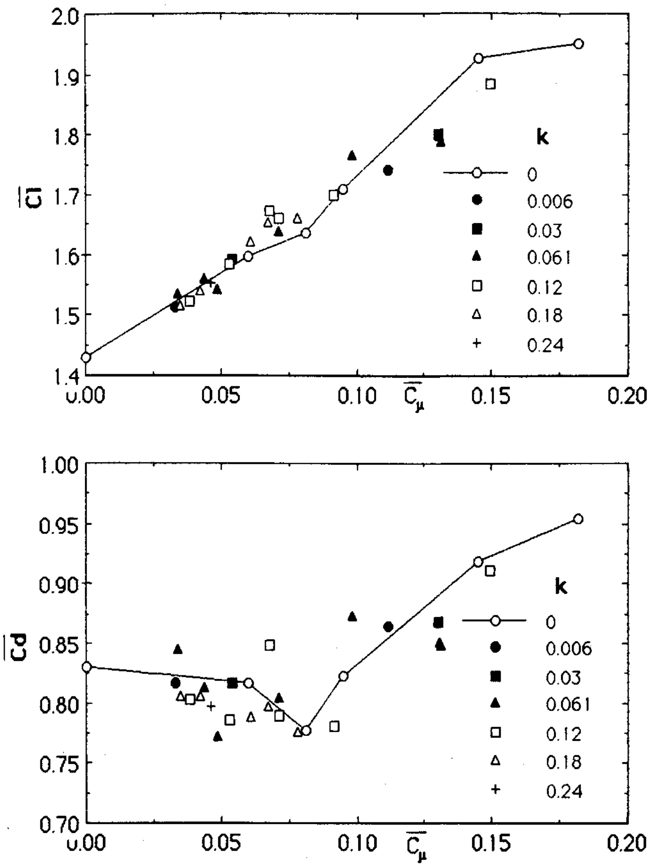

Fig. 13 Mean lift and drag coefficients vs mean jet-momentum coefficient at $d/c = 0.0088$, $R_c = 4.8 \times 10^5$, and $\alpha = 30$ deg.

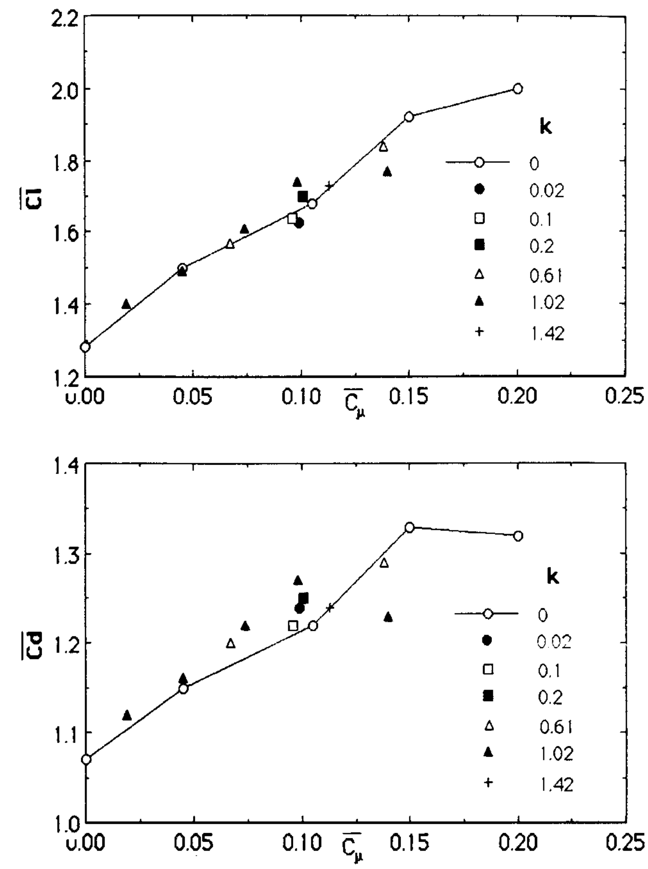

Fig. 14 Mean lift and drag coefficients vs mean jet-momentum coefficient at $d/c = 0.0088$, $R_c = 1.4 \times 10^5$, and $\alpha = 40$ deg.

low, medium, and high frequencies, with several pulse lengths. Similar results were obtained at the other incidence values.

It can be seen that the mean lift and drag of periodic blowing are similar to the lift and drag obtained by continuous blowing, at the same jet-momentum coefficient. This result is obtained in all the frequency ranges and all the types of time histories presented previously. This is probably due to either an identical response time at both the opening and closing of the valve ($\alpha = 40$ deg), or to the difference in the response times that is not sufficiently large to generate a significant lift augmentation ($\alpha = 30$ deg), or to the lift curve remaining at an intermediate level between those of continuous blowing (at high frequencies).

Although periodic blowing was not found to be more effective than constant blowing, it should be emphasized that the periodic, as well as constant blowing, induces a significant lift augmentation, at all incidences up to $\alpha = 60$ deg, whereas unsteady wing motions induce a local increase and decrease during the cycles that balance out and result in no overall gain in lift.

It should also be added that improvement of the mean lift may be obtained by a favorable coupling between the periodic blowing and leading-edge vortex layer receptivity.[37] Tangential periodic blowing through the leading edge of a delta wing was found to significantly affect the evolution of the leading-edge vortices, when the blowing frequency was a subharmonic of their natural shedding frequency.[38] However, such a favorable interaction was not obtained by spanwise blowing in the present range of blowing frequencies.

Conclusions

The concept of periodic leading-edge blowing on a fighter-aircraft model was investigated at several low subsonic speeds and several frequencies.

At low frequencies, lift and drag coefficients correspond to the pulsating blowing pressure. When the valve is fully open, they reach the steady values of continuous blowing. When it is fully closed, they agree with the no-blowing values. An aerodynamic response time is observed that is equal at low incidences to the freestream convective time over the wing, but increases to 30 convective times at $\alpha = 30$–40 deg. These values are similar to the response times reported in unsteady wing motions, such as pitching and plunging motions, although these concern different flow regimes where the incidence or both the incidence and angular velocity are varied. In this study, the vortex position varied while the incidence angle was constant.

It has also been shown by the lift and drag curves and by the flow visualization that at $\alpha = 20$–30 deg, the reaction of the flowfield to valve closing is much slower than to valve opening. This reaction also is similar to the asymmetrical hysteresis curves reported in plunging motion, or when suction was applied near the wing trailing edge.

These features were shown to be insensitive to the pulse length, nozzle diameter, freestream velocity, jet-momentum coefficient, and pulsating frequency. They are valid for low pulsating frequencies, such as $k < 0.10$, at $\alpha = 30$–40 deg. At higher frequencies ($k > 0.42$), C_L and C_D do not correspond to the pulsating pressure curve, but remain at an intermediate value between those of continuous and no blowing.

Periodic blowing was not found to be more effective than continuous blowing. The mean lift and drag coefficients were found to be equal to the lift and drag obtained by continuous blowing with a momentum coefficient equal to the mean momentum coefficient of the periodic blowing.

The Reynolds number effects on the foregoing results were not studied rigorously. However, the effects of adding a body to a delta wing to form a fighter-type aircraft on the lift and on the leading-edge vortex breakdown have been shown to be minimal.[14,30] On a sharp-edged delta wing, no effect of the Reynolds number on the vortex location and breakdown, as well as aerodynamic forces, has been found in a wide Reynolds number range.[39,19,38] Therefore, the present results may be seen as applicable to similar configurations and Mach numbers at flight Reynolds numbers.

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