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Lateral Forces on a Slender Body and Their Alleviation at High Incidence

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A method for alleviation and control of the side force and yawing moment appearing on slender bodies at high angles of attack in symmetrical flight conditions is presented. The effect on lateral forces and moments is achieved by using small, symmetrical jet injection from the nose of the body. Experimental investigation includes the effects of Mach number, Reynolds number, transition strips, and injection rate. Visualization tests are used to demonstrate the effects of jet injection. The results indicate that the injection affects both the stabilization of the separation pattern close to the body and the vortex formation and stability downstream. Alleviation of side forces and yawing moments is achieved at high angles of attack over a large range of subsonic and also transonic speeds. This method can be used also for lateral control at the high angle of attack flight conditions.

Nomenclature

C_n = yawing moment coefficient, n/qSD
C_m = pitching moment coefficient, m/qSD
C_{nor} = normal force coefficient, F_{nor}/qS
C_Y = side force coefficient, Y/qS
C_μ = blowing rate coefficient, $\dot{m}_j u_j/qS$
D,d = reference chord (body diameter)
F_{nor} = normal force to the body
$\dot{m}_j$ = jet mass flow rate
M = Mach number
m,n = pitching and yawing moments (about nose tip point)
q = dynamic pressure, $\frac{1}{2}\rho V^2$
Re_D = Reynolds number, based on body diameter, $\rho VD/\mu$
S = reference area, body cross section, $\pi D^2/4$
u_j = theoretical jet velocity (assuming fully expanded isentropic flow)
V = freestream velocity
x = length measured from nose tip point, along body axis of revolution
Y = side force
α = angle of attack
ρ = air density
θ = geometrical angle
μ = air viscosity

Note: All forces and moments are given in body axes of reference.

Introduction

THE interest in the performance at high angles of attack of missiles and aircraft is growing. Efforts are made to investigate the behavior of slender and not so slender bodies at high angles of attack and to understand the phenomena related to the development of asymmetries in the separated vortex flow established about such bodies. This asymmetry in the flow causes large side forces and yawing moments which act upon the body at zero sideslip angles. Therefore, efficient means for alleviation and control of such lateral forces and moments are investigated.

The work presented here is an experimental investigation of the forces and moments acting on a cone-cylinder body at high angles of attack, in the subsonic and transonic speed ranges. This investigation studies the effect of injecting small symmetrical air jets from the nose of the body on the lateral forces and moments.

This research is a continuation of the previous experimental work presented by Sharir, Portnoy, and Rom,[1] and also by Rom and Almosnino.[2,3]

The investigation includes effects of Reynolds number and transition strips, rate of jet blowing, and Mach number on the forces and moments acting on the body at high angles of attack, and it also includes some flow visualization tests which help to understand the influence of jet injection on the flowfield close to the body surface.

Lateral Behavior of Slender Bodies at High Angles of Attack, at Subsonic and Transonic Speeds

Separation of the boundary layer occurs at moderate angles of attack because of the adverse cross-flow pressure gradient on the leeward side of the slender body.

The separated boundary layer then rolls up to form a system of distinct vortices (the description of separation is more complicated when the body is not slender[4,5]).

The rolled-up vortex sheet may stay close to the body and be continuously fed from the separated boundary layer, or it may leave the body entirely further downstream. A separation line may be expected to be found near the line of minimum pressure coefficient on the leeward side of the body, since the separation is caused by the adverse pressure gradient.[6]

Due to geometrical irregularities of the nose of the body and irregularities in the outer flow, one side of the boundary layer may separate first from the body, maintaining a certain vortex strength in the corresponding rolled-up vortex sheet. The other side of the boundary layer may remain attached and separate only further downstream on the body with a corresponding stronger vortex. In this manner the asymmetric vortex system is generated behind the body at high angles of attack. This description is supported for example by results presented in Ref. 7 where it is shown that the side forces are associated with the asymmetry of circumferential pressure distribution and the asymmetry of the vortex sheet separation. The separation line is shifted towards the windward side of the body as the angle of incidence is increased. Measurement

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of the circumferential angles of separation indicate that asymmetry of the separation increases as the angle of incidence is increased (in laminar boundary layer conditions). The maximum angular difference nearly coincided with the maximum measured side force. It was found[6-8] that as the angle of attack was high enough, several vortex separations occurred along the body.

The nose shape is a most significant parameter which affects the side forces.[9-12] References 13-16 for example show that reorientation of the nose about the body axis of revolution has a most considerable effect on the side force and yawing moment sign and magnitude.

Some information about the effects of Reynolds number and of Mach number on lateral forces and moments at zero side slip is found in Refs. 3, 12, and 15-23. The effect of Reynolds number is very strong within the region of transition. Mach number is found also to be an important parameter which affects side force and yawing moment magnitude and direction.

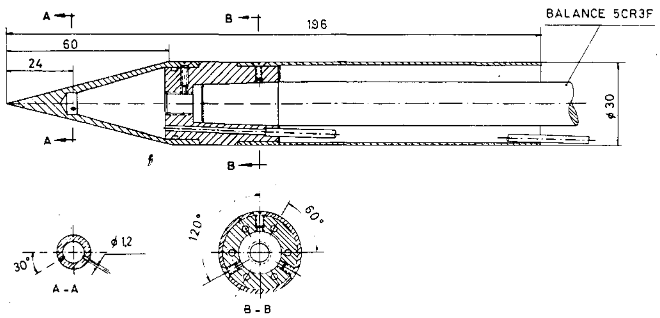


Fig. 1 The cone-cylinder model.

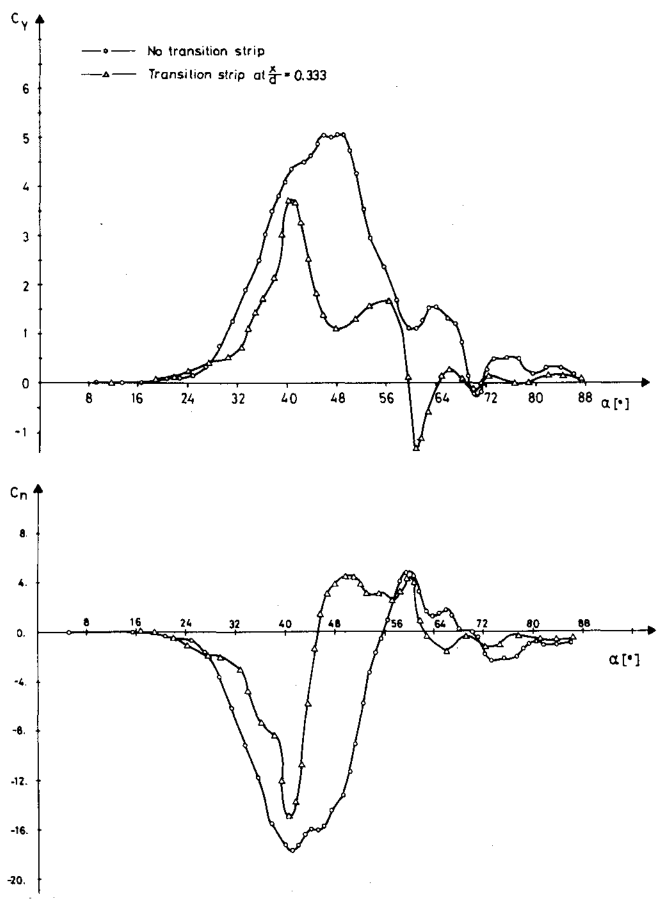


Fig. 2 Side force and yawing moment coefficients vs angle of attack, $V = 32$ m/s, $Re_D = 6.6 \times 10^4$, $C_\mu = 0$.

Side forces and moments may be potentially hazardous to the control and stability of slender configurations such as modern fighters and missiles maneuvering at high angles of attack. These side forces and moments may be overcome by sufficient control authority, or by aerodynamic devices which suppress the asymmetric vortex pattern.

The most common aerodynamic devices used for side-force alleviation are transition strips of all kinds[9,10,14,16,24] and vortex generators such as small strakes usually placed on the forebody or near the nose.[11-13]

A method for active control of asymmetric vortex effects is presented in Ref. 25, using rotation of portions of the body about the axis.

Another device for control of forebody vortex orientation is presented in Ref. 26, where tangential blowing to the body surface in small amounts helped to alleviate lateral forces and moments, and even to control them to some extent. A control device is proposed for further investigation. Effects of normal blowing of small jets on lateral forces and moments are described in Refs. 1-3 and also in Ref. 27, where it is shown that effective alleviation of side force and yawing moment is achieved with relatively small amounts of blowing. An extensive summary of the phenomena and devices described in this paper appears in Ref. 19.

It should be noted that some of the devices described above do suffer from certain defaults. Some of the transition strips used, reduced side forces but also had affected the normal force and pitching moment causing early "stall" effect. Strakes seem to be effective in alleviating side forces only in a certain limited range of angles of attack. In general, the role of these devices is a passive one, and apart from alleviating side forces, these devices could not be used for active lateral control of side forces and yawing moments at high angle of attack, for the benefit of improved maneuverability. Some of the other devices presented before seem to be too complicated for use.

The present research continues the investigation on the effect of small air jets blown from the nose of a body of revolution for the alleviation and also for the control of side forces and yawing moments at high angles of attack, in subsonic and transonic Mach numbers (previous results are reported in Refs. 1-3).

Model and Experimental Facilities in the Present Study

The experiments are conducted in the Subsonic Wind Tunnel of the Aeronautical Research Center of the Technion with a cross section of 1×1 m, and in the Transonic Wind Tunnel (blow down, induction type), with a cross section of 0.8×0.6 m. The model shown in Fig. 1 is a 3-cm-diam cylindrical body having an overall fineness ratio of 6. The nose of the body is a pointed cone, with length/diameter ratio of 2. Using the results of previous experiments[1,2] it was

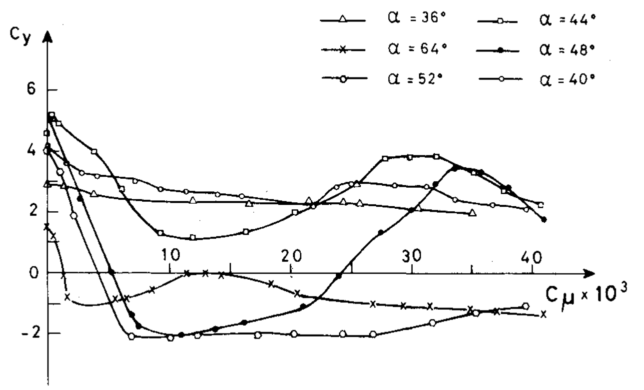


Fig. 3 Side force coefficient vs blowing rate coefficient at various angles of attack, $V = 32$ m/s, $Re_D = 6.6 \times 10^4$, no transition strip.

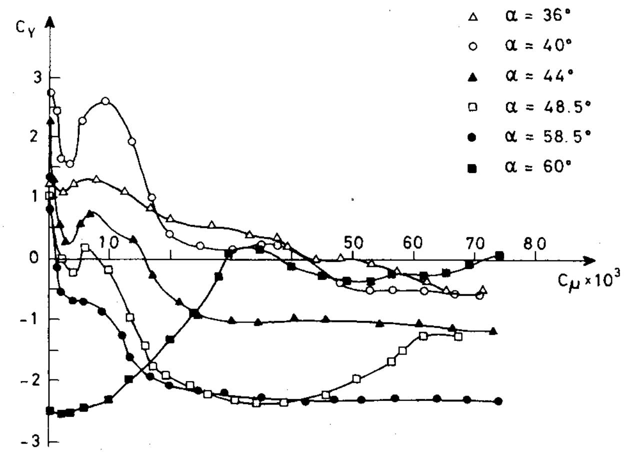


Fig. 4 Side force coefficient vs blowing rate coefficient at various angles of attack, $V = 32$ m/s, $Re_D = 6.6 \times 10^4$, with transition strip at $x/d = 0.333$.

decided to concentrate the tests on a sharp cone forebody, and to inject the air jets from a station which was close to the nose apex at angles of -30 deg to the horizontal plane of the body. The diameter of the holes was 1.2 mm each, perpendicular to the body axis of revolution.

A system of rigid and flexible tubing was arranged in the model so as to supply air for symmetrical blowing. A special device was developed and built, which enabled continuous change of the rate of blowing and its measurement.

Visualization tests have been performed using oil flow at low subsonic speeds and Schlieren photography at high subsonic and at transonic Mach numbers. Visualization tests have been carried out with and without injection, for comparison of the flow patterns.

Special measures were taken in the model installation to assure that the same angular position of the cone and the cylinder in each experiment is obtained in the tunnel so as to prevent any changes in the side-force direction and magnitude due to variation in model installation. Tests with and without injection were repeated so as to verify the repeatability of the results.

Results

Low Subsonic Tests

The low subsonic tests are carried out at 32 m/s in an angle of attack range of -10 deg to 90 deg. Comparison is made between tests without a transition device, and tests with a transition strip (ring) of 0.1-mm thickness placed at $x/d = 0.333$ from the nose tip. The effect of the jet blowing is also tested with and without a transition ring. The influence of the transition ring (Fig. 2) is quite large on the side force and yawing moment coefficients. There is a great reduction in the side force and yawing moment, using the transition ring, up to about 56-deg angle of attack, while peak position for the side force is being shifted down to about $\alpha = 41$ deg (from $\alpha = 48$ deg without the transition ring). The angle of onset of side forces is unaffected by the transition ring. It is also interesting to note that without a transition ring there is a difference in the position of the side-force peak compared to that of the yawing moment peak.

The effect of jet injection is demonstrated in Fig. 3 (no transition ring) and in Figs. 4 and 5 (with transition ring). In Fig. 3 it can be seen that jet blowing from the chosen station on the nose effectively alleviated side forces above $\alpha = 44$ deg. Blowing is ineffective below $\alpha = 44$ deg, without a transition ring. The very sharp change in C_Y and C_n at very low blowing rates might be caused by the jets, which act to trip the boundary layer. This effect of jet blowing on the transition of the boundary layer is seen in some of the oil-flow visualization

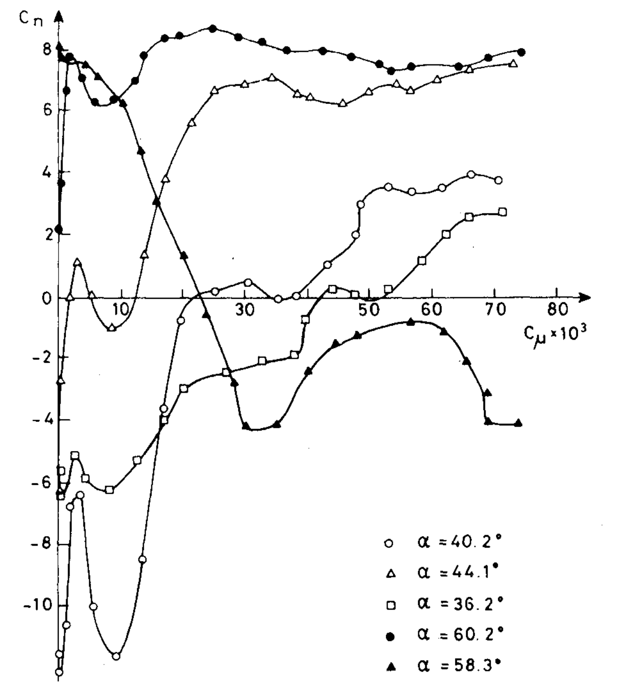


Fig. 5 Yawing moment coefficient vs blowing rate coefficient at various angles of attack, $V = 32$ m/s, $Re_D = 6.6 \times 10^4$, with transition strip at $x/d = 0.333$.

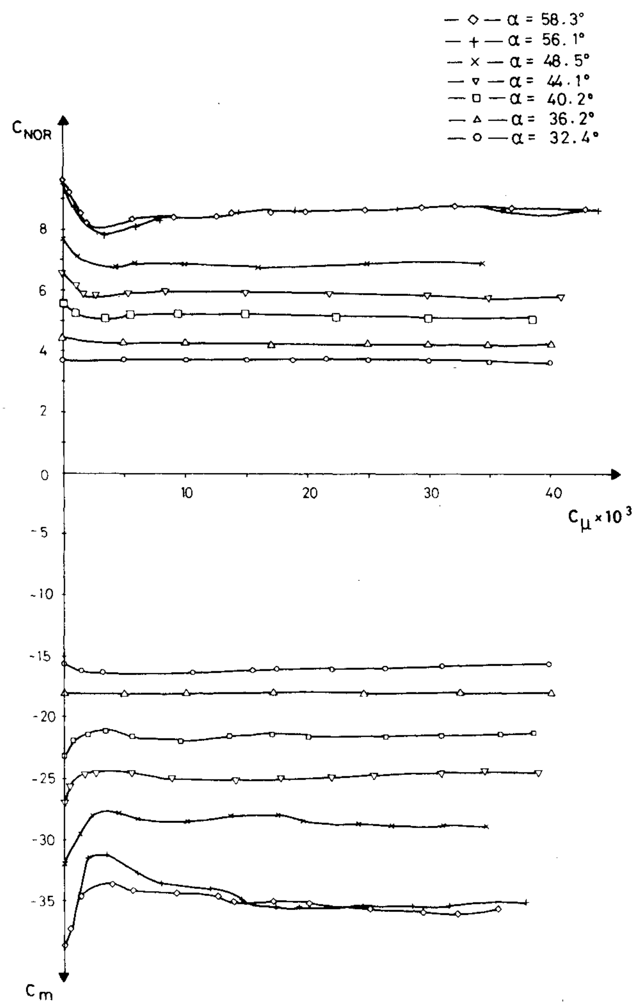


Fig. 6 Normal force and pitching moment coefficients vs blowing rate coefficient at various angles of attack, $V = 32$ m/s, $Re_D = 6.6 \times 10^4$, with transition strip at $x/d = 0.333$.

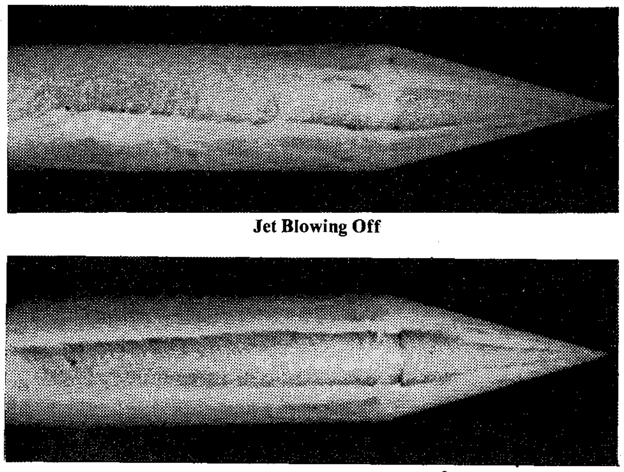


Fig. 7 Oil flow visualization of the cone-cylinder model at $V = 32$ m/s, $Re_D = 6.6 \times 10^4$, $\alpha = 55$ deg, no transition ring.

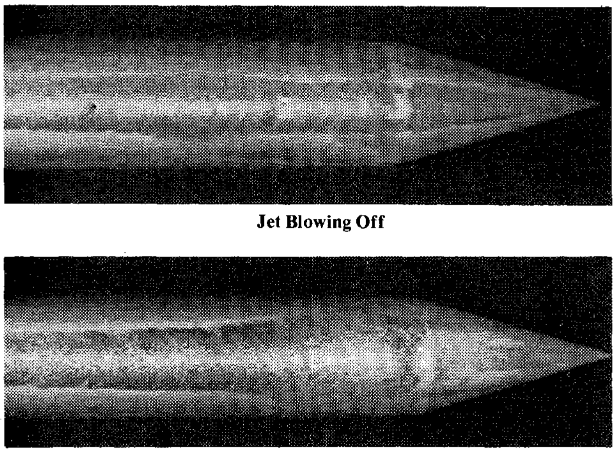


Fig. 8 Oil flow visualization of the cone-cylinder model at $V = 32$ m/s, $Re_D = 6.6 \times 10^4$, $\alpha = 40$ deg, with a transition ring at $x/d = 0.333$.

photographs (not shown here), in which there is a distinct curved pattern starting from the injection holes, rolling up along the conical nose, up to the shoulder or to the nearest separation lines. When a transition ring is present (Figs. 4 and 5), the sharp change in C_Y and C_n disappears at $\alpha = 36$ deg, and starts appearing again at $\alpha = 40$ deg up to about 58 deg. This can be explained by the fact that the small transition ring is more effective in reducing side forces at the lower range of angles of attack, but it is less efficient at the higher angle of attack range, where the cross-flow plane becomes more dominant, and there the effect of the jets is stronger. This view is supported also by the behavior of the normal force which is unaffected by the jets at $\alpha = 32$ deg, 36 deg with a transition ring, and starts being affected at higher angles of incidence (Fig. 6).

The influence of injection apart from transitional is clearly demonstrated in Figs. 7 and 8. Here the injection completely alters the separation pattern apart from making it more symmetrical. In Fig. 8 the pair of separation lines on the leeside of the cone which continues over the shoulder along the cylinder without injection, breaks at the shoulder when injection is present, and a new pair of separation lines appears on the cylinder. The shoulder between the cone and the cylinder has been observed to have its own effects on the flow

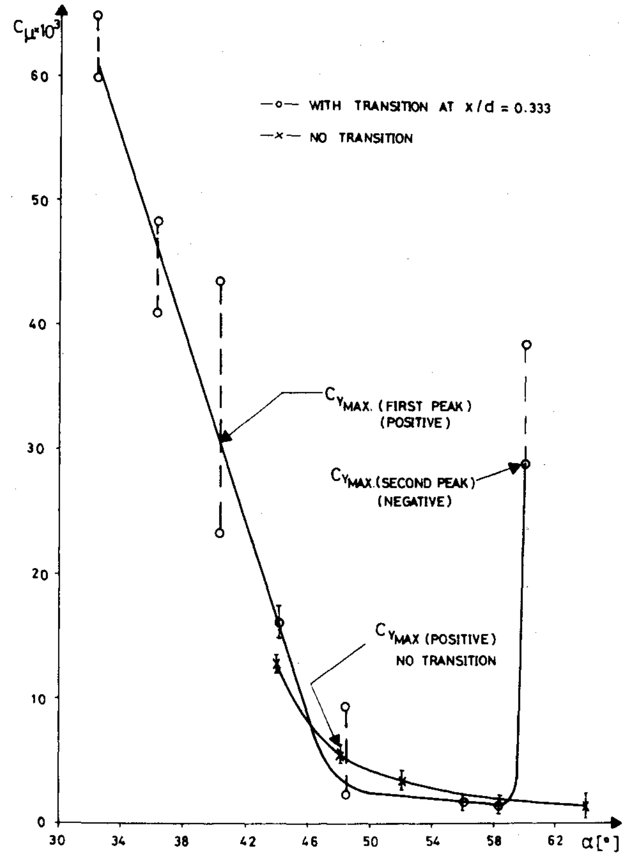


Fig. 9 Blowing rate coefficient needed for side-force alleviation at various angles of attack, $V = 32$ m/s, $Re_D = 6.6 \times 10^4$.

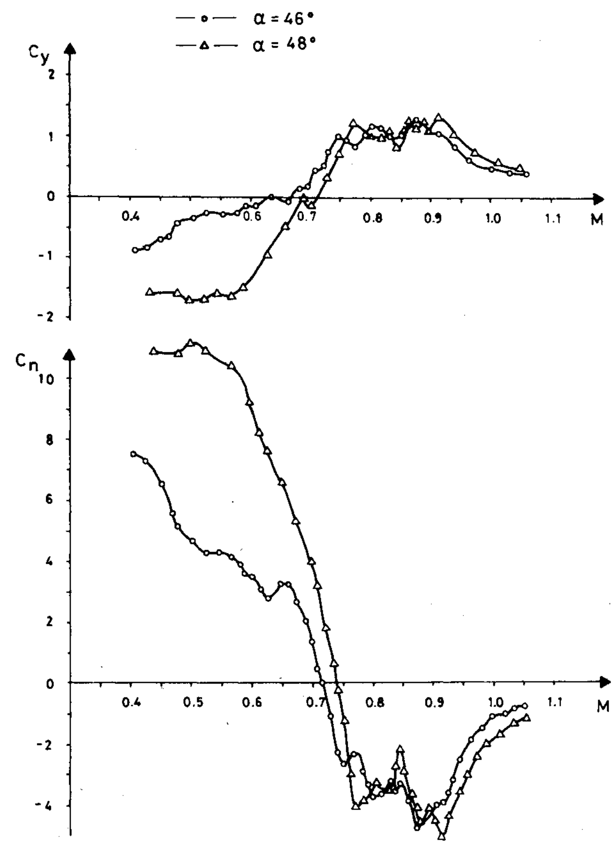


Fig. 10 Side-force coefficient vs Mach number at two angles of attack, $C_\mu = 0$, $2.8 \times 10^5 < Re_D < 5.0 \times 10^5$, no transition strip.

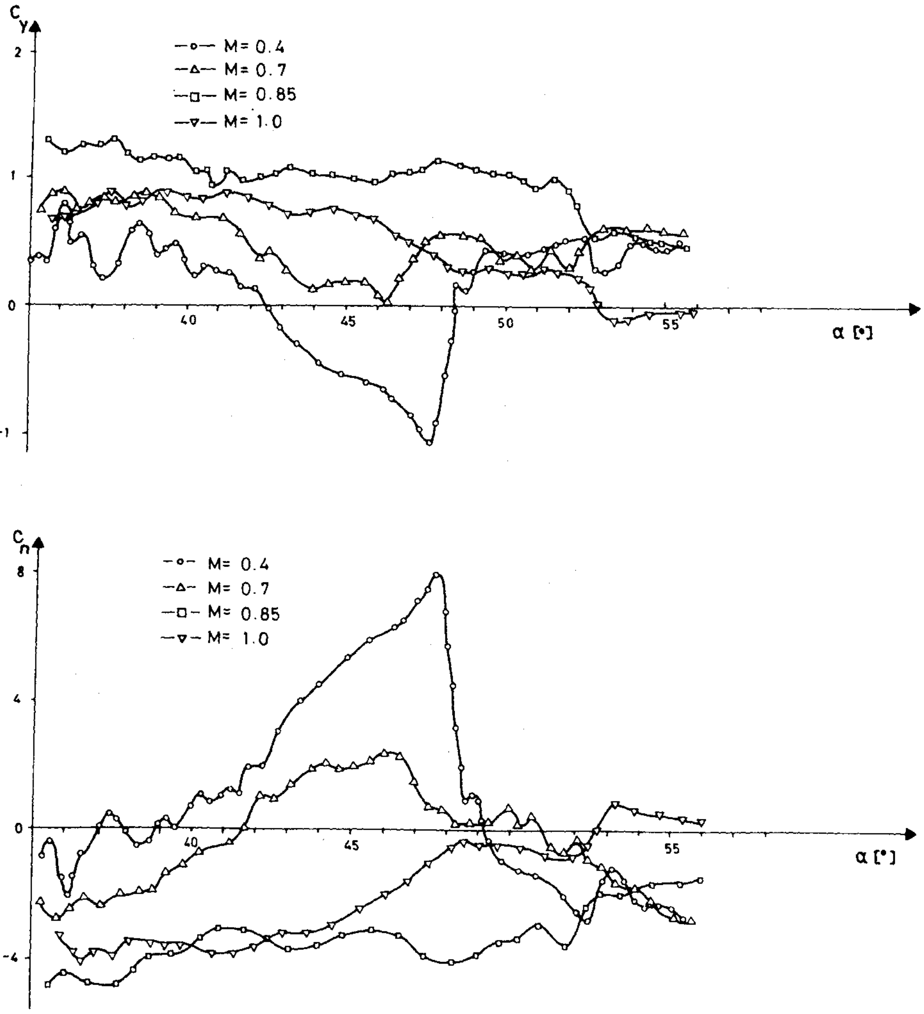


Fig. 11 Side force and yawing moment coefficients vs angle of attack at various Mach numbers $C_\mu = 0$, $2.8 \times 10^5 < Re_D < 5.0 \times 10^5$, no transition strip.

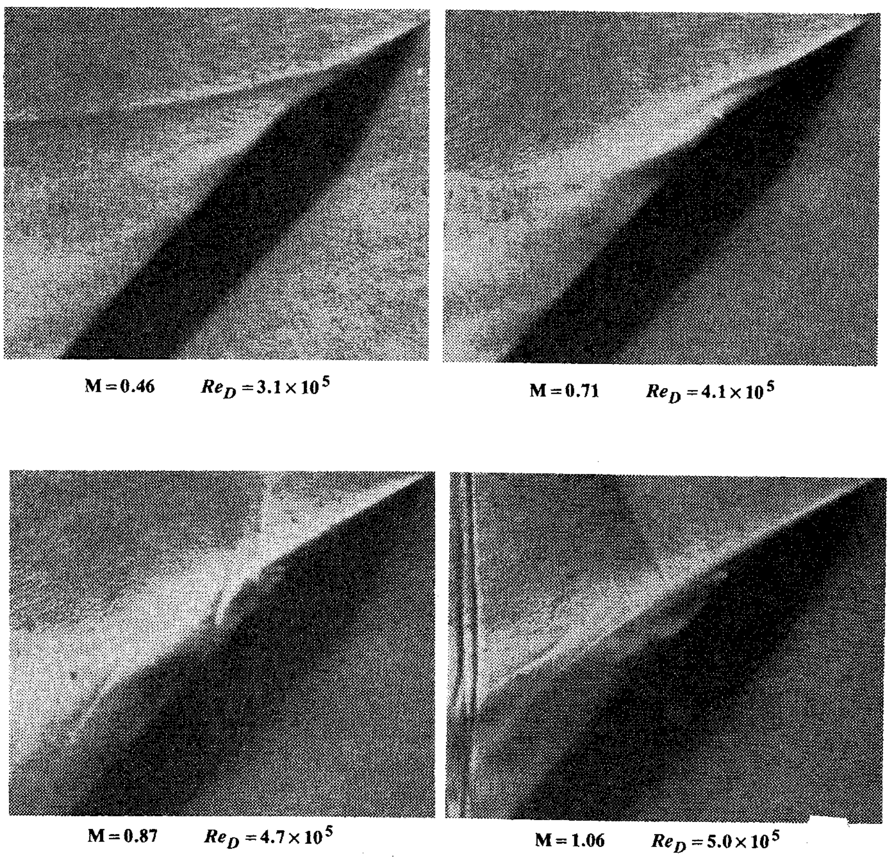


Fig. 12 Schlieren photographs of the cone-cylinder model at various Mach numbers, $\alpha = 47$ deg, $C_\mu = 0$, no transition strip.

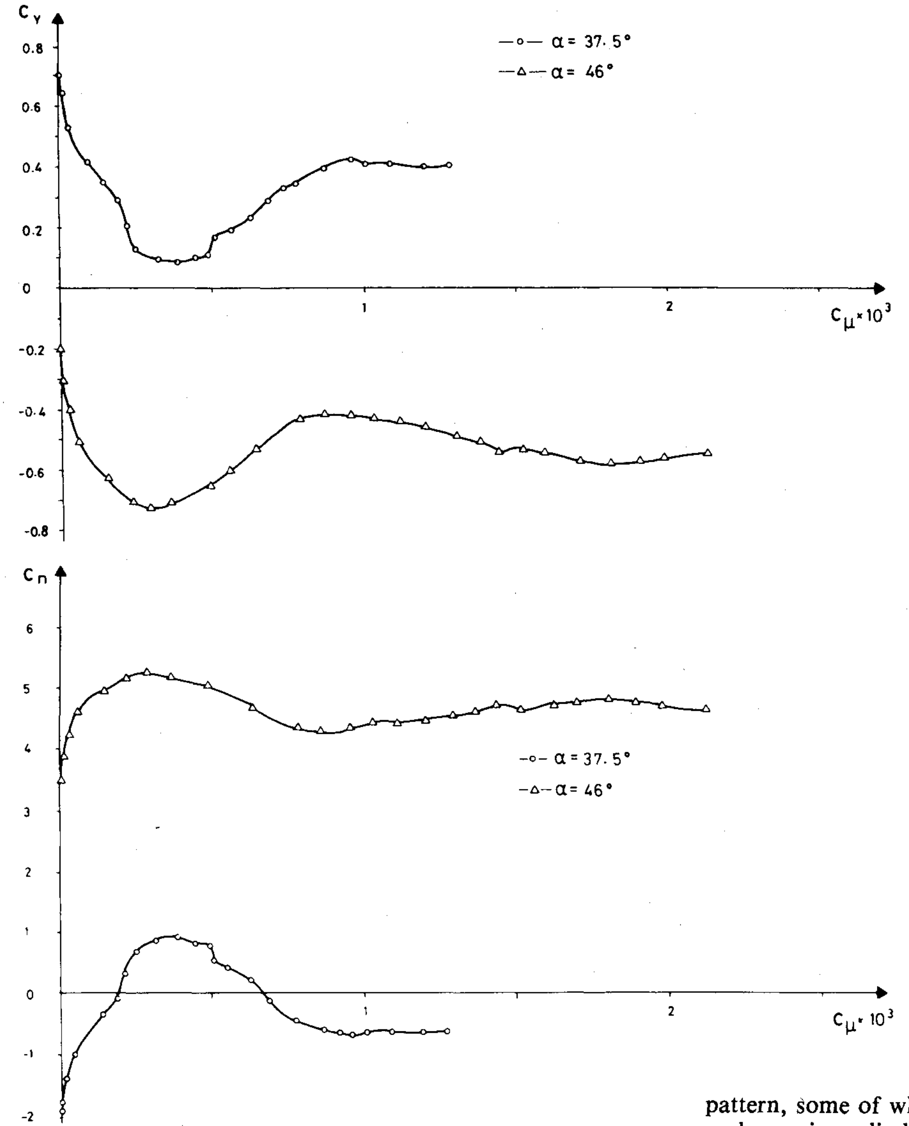
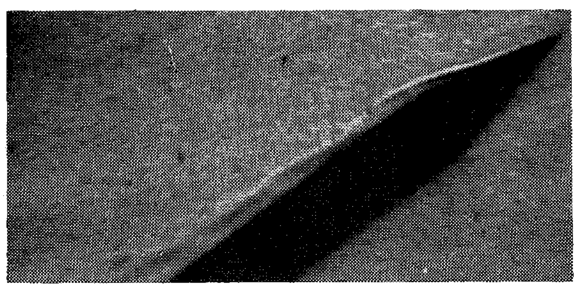
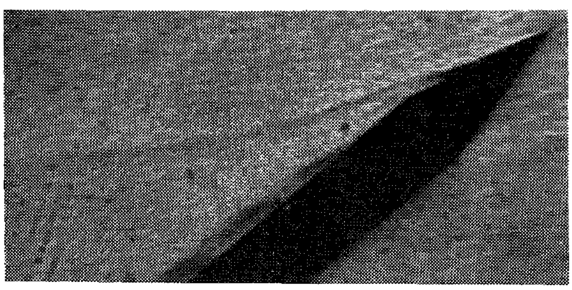


Fig. 13 Side force and yawing moment coefficients vs blowing rate coefficient at $M=0.7$, $Re_D=4.1\times10^5$ at two angles of attack, no transition strip.



Jet Blowing Off



Jet Blowing On, $C_\mu=0.25\times10^{-3}$

Fig. 14 Schlieren photographs of the cone-cylinder model at $M=0.7$, $Re_D=4.1\times10^5$, $\alpha=37.5$ deg, no transition strip.

pattern, some of which are weaker or nonexistent in models such as ogive-cylinder bodies.

The amount of flow-rate coefficient needed for side-force alleviation vs the angle of incidence is sketched in Fig. 9.

It is clear that a high blowing rate is needed at the lower range of α, up to about 46 deg or 48 deg. Then there is the range of α (48 deg to 58 deg with a transition ring, or 48 deg to 64 deg without it) where a very low blowing coefficient is needed to eliminate even high side forces. The sharp rise in the required blowing coefficient at $\alpha=60$ deg (with transition ring) corresponds with the negative peak of side force. The values of blowing rates for which the side force is effectively alleviated are indicated in Fig. 9 by the bar-line of values of C_μ.

Mach-Number Effect

Mach-number effect starts at about $M=0.63$ (at $\alpha=48$ deg). Side force changes its sign around $M=0.7$ (Fig. 10), because of Mach-number effects. (The reason might be connected with the first appearance of shock waves at that Mach number.) The C_Y curve then reaches an unstable peak between $M=0.77$ and $M=0.92$ (Fig. 10). There is a great reduction in the side force and yawing moment when the Mach number exceeds $M=0.92$. (Equivalent cross-flow Mach number is about 0.66.) The effect of several Mach numbers on C_Y and C_n is demonstrated in Fig. 11. Figure 12 shows the development of the flow as the Mach number grows from 0.4 to 1.1, using Schlieren photographs.

The rates of jet blowing coefficient become quite small as the Mach number is increased, so its effect is only partial. At $M=0.7$ (Fig. 13) there is a considerable alleviation of C_Y and

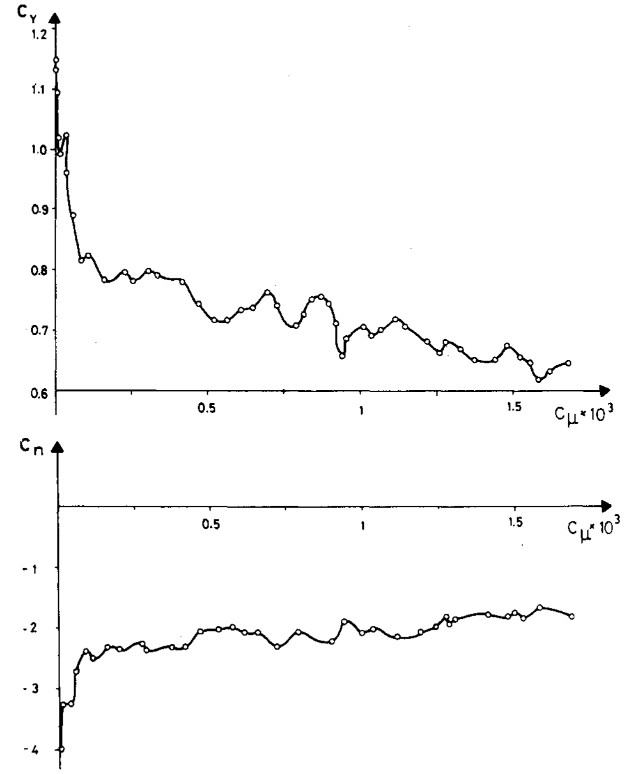


Fig. 15 Side force and yawing moment coefficients vs blowing rate coefficient at $M=0.85$, $Re_D=4.7\times10^5$, $\alpha=47$ deg, no transition strip.

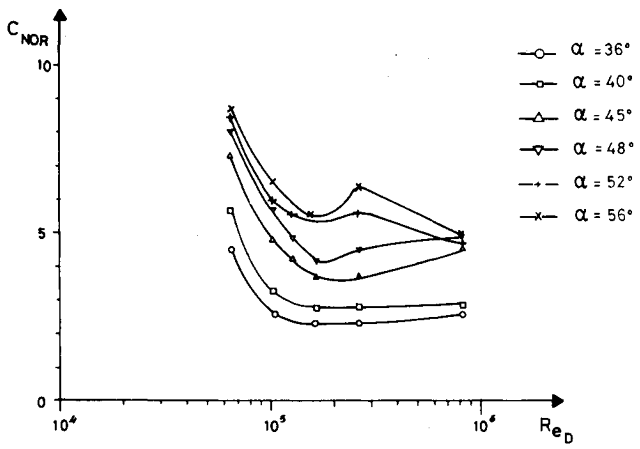


Fig. 16 Normal force coefficient vs Reynolds number at various angles of attack, no transition strip, $C_\mu=0$, $0.05<M<0.4$.

C_n at $\alpha=37.5$ deg, but the blowing caused higher C_Y and C_n at $\alpha=46$ deg, where the side force is initially close to zero. Schlieren photographs taken at $\alpha=37.5$ deg and at that Mach number with and without injection reveal some information about the effect of jet blowing in this case. It can be clearly seen in Fig. 14 that the main nose separated vortex line is broken near the shoulder of the cone without injection (possibly because of the small shock line starting at this point). Secondary separations are observed further on the cylindrical part. However, when using the blowing it can be seen that a distinct vortex is separated from the nose, trailing high above the cylindrical part and not broken in the shoulder region. Secondary separations are still observed on the cylinder. (The fact that jets can inhibit vortex breakdown is already known.) Jet blowing greatly reduces C_Y and C_n at $M=0.85$, $\alpha=47$ deg (Fig. 15). Experimental results (not shown on the figure) indicate that jet blowing becomes ineffective at $M=1.0$ possibly because of the relatively low

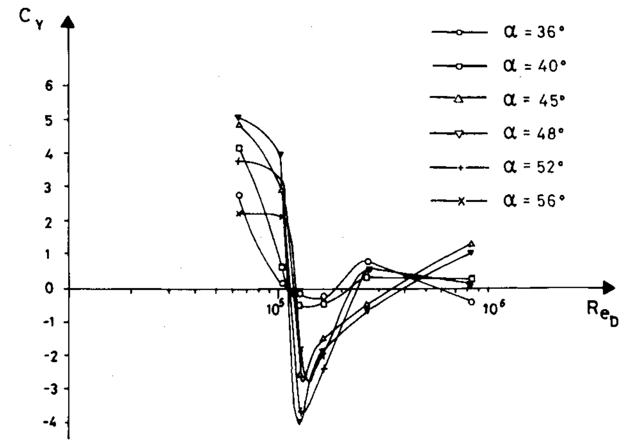


Fig. 17 Side force coefficient vs Reynolds number at various angles of attack, no transition strip, $C_\mu=0$, $0.05<M<0.4$.

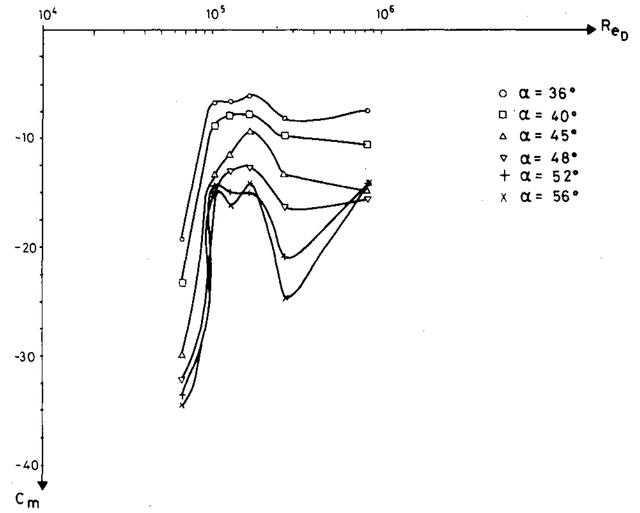


Fig. 18 Pitching moment coefficient vs Reynolds number at various angles of attack, no transition strip, $C_\mu=0$, $0.05<M<0.4$.

blowing coefficient and the position of blowing station relative to the shock. Side forces and moments at high subsonic and transonic Mach numbers are observed to be smaller (in relation to the corresponding normal forces) compared to those obtained in laminar conditions at low speeds.

Reynolds-Number Effect

Figures 16 and 17 show the effect of Reynolds number on C_{nor} and C_Y at various angles of attack. It is clear that there is a strong transition effect of Re_D on these forces at all angles of attack. It can be seen that there is a sharp change of sign in C_Y in the transitional region, and then a more moderate rise, changing sign again at higher Re_D. These results show clearly that the direction of side force might be changed because of Reynolds-number effects in the transition region. Figures 18 and 19 show the effect of Reynolds number on the pitching moment and on the yawing moment coefficients. The variation in the pitching and yawing moments at various Reynolds numbers indicates that unstable behavior of the model may occur at high angles of attack, requiring special attention in the control consideration of these designs at certain ranges of speeds and altitudes. In view of these phenomena, blowing of jets may be a useful method of stabilization and control at such flight conditions.

Conclusions

The experimental investigation performed on the cone-cylinder body revealed important features of such configurations at high angles of attack and their dependence on Mach number and Reynolds number. At least some of the so-

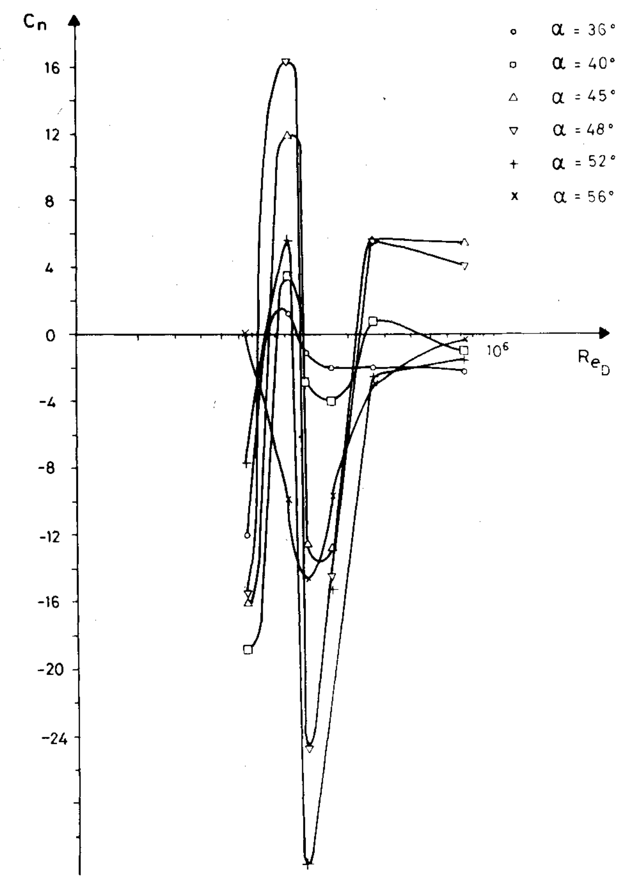


Fig. 19 Yawing moment coefficient vs Reynolds number at various angles of attack, no transition strip, $C_{\mu} = 0$, $0.05 < M < 0.4$

called uncertainties in the prediction of the general behavior of side forces and yawing moments are found to be clearly dependent on these parameters. The results of the experiments conducted at Mach numbers 0.1 to 1.1 and Reynolds numbers 0.6×10^5 to 0.5×10^6 indicate the strong effect of jet blowing in alleviating the lateral forces and moments at these flow conditions. At low subsonic speed, jet blowing at the chosen station may be used efficiently for side-force alleviation and even control, especially when a transition ring is present also. Jet blowing at small rates is sufficient to alleviate side forces in some cases at high subsonic and transonic Mach numbers, but the rate required for controlling these forces must be much larger and further investigation is needed in the transonic range in order to determine the effect of high rates of blowing and the optimal position of blowing stations.

The small amount of blowing rate needed and the symmetry of injection (without the need to detect the flowfield asymmetry in pressure distribution, for example) indicate that this method should be relatively simple to realize and attractive for aerodynamic design considerations.

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