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Thoughts on Conical Flow Asymmetry

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A thorough analysis of experimental results obtained on slender bodies of revolution at high angles of attack has revealed that conical flow asymmetry does indeed exist, but only for very slender cones, where the asymmetric flow separation starts developing well below an angle of attack of 30 deg. When the asymmetry starts at 30-deg or higher angles of attack, the asymmetry is not conical even for purely laminar flow conditions, but is very similar to that occurring on cylindrical afterbodies. Furthermore, it is found that an asymmetric vortex pair cannot develop from symmetric crossflow separation unless symmetric crossflow attachment is prevented.

Nomenclature

c = reference length, d
d = maximum diameter
L = body length
M = Mach number, $M_c = M_\infty \sin \alpha$
N = normal force, coefficient $C_N = N/(\rho_\infty U_\infty^2/2)S$
n = yawing moment coefficient, $C_n = n/(\rho_\infty U_\infty^2/2)Sc$
Re = Reynolds number, usually $Re = U_\infty d/\nu_\infty$, $R_{L\infty} = U_\infty L/\nu_\infty$
S = reference area, $\pi d^2/4$
U = horizontal velocity
x = axial body-fixed coordinate
Y = side force, coefficient $C_Y = Y/(\rho_\infty U_\infty^2/2)S$
α = angle of attack
α_{AV} = angle of attack for incipient asymmetric crossflow separation
θ_c = cone half-angle
ν = kinematic viscosity
ρ = air density
ϕ = body azimuth

Subscripts
AV = asymmetric vortices
c = cone
CP = center of pressure
s = separation
∞ = freestream conditions

Introduction

IT has long been recognized that asymmetric vortex shedding can occur on bodies of revolution at high angles of attack.[1–7] The early concern was the interference of the shed vortices with downstream tail surfaces. Only later was it realized that large side forces could be generated on the body itself by asymmetric flow separation, even at zero sideslip. Experimental results have shown that the separation-induced side force can exceed the normal force.

The seriousness of the problem was illustrated by wind-tunnel test results for the F-111, which showed the separation-induced yawing moment to exceed, by an order of magnitude, the available control capability through full rudder deflection.[8] The problem can be cured by the use of nose strakes and by other types of body reshaping that cause the flow separation to be symmetric.[9] There are, however, many missiles that do not fly coordinated maneuvers, in which case the problem is more complex. In fact, vehicle roll can cause the side force and yawing moment to switch suddenly from left to right, or vice versa.

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Thus, the designer of the rolling missile must be able to predict the effects of this flow asymmetry for his flight regime. This is no simple task. In spite of extensive efforts, no reliable theoretical method has been developed that can predict forces and moments generated at zero sideslip by asymmetric flow at high angles of attack.

The asymmetric flow on a slender conic nose has received special attention by theoreticians because of the expected pseudoconical type of flow. The present paper examines available experimental results in regard to the presence or absence of pseudoconical asymmetric flow on slender, pointed cones at zero sideslip.

Discussion

In a recent publication,[10] it was shown that flow-visualization results obtained on a 5-deg sharp cone at high angles of attack defined the topological structure sketched in Fig. 1, where the

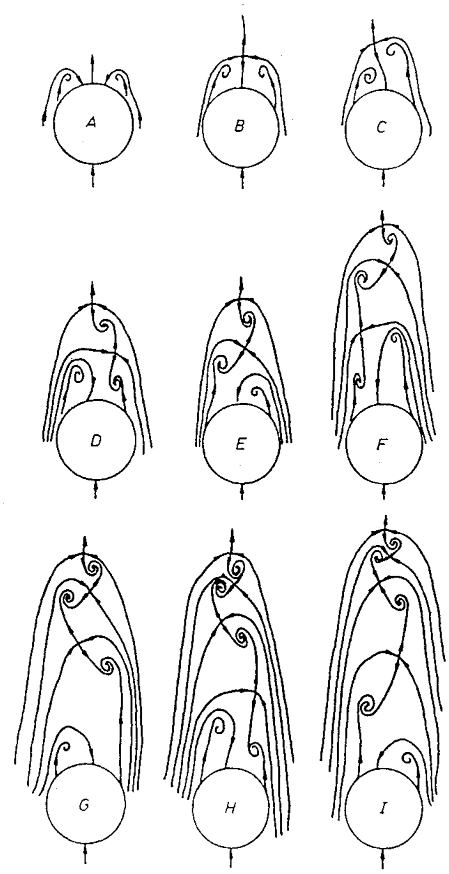

Fig. 1 Crossflow topology of a 5-deg cone at laminar incompressible flow conditions (Ref. 10).

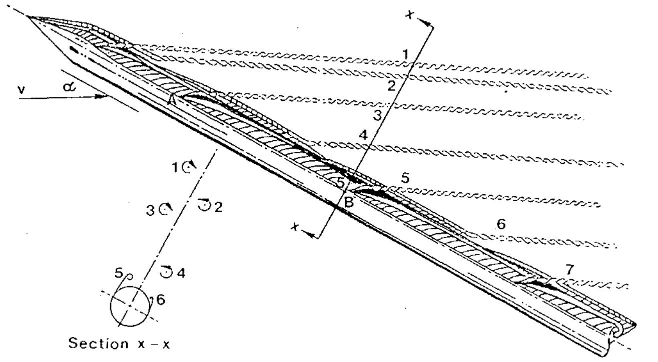

Fig. 2 High-alpha vortex pattern on cone-cylinder body (Ref. 11).

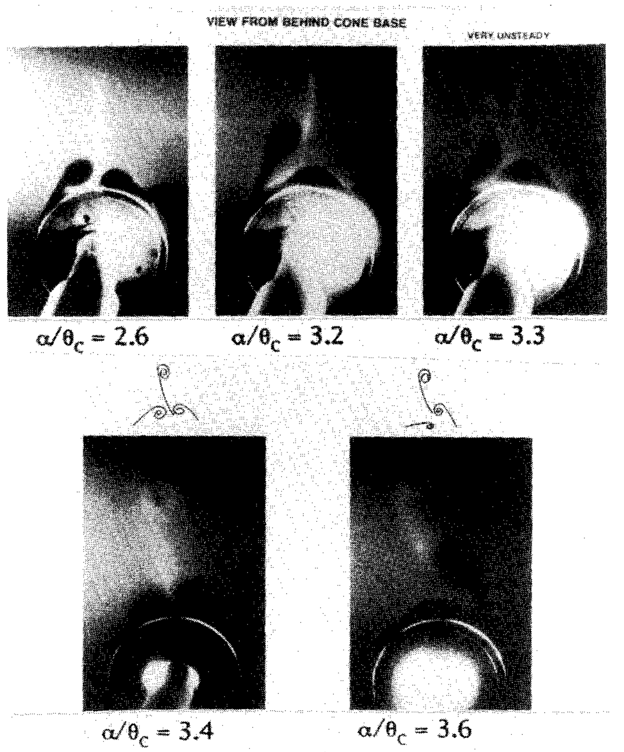

Fig. 3 Crossflow pattern at $x/L = 0.70$ on a 5-deg cone at $M_\infty = 0.6$ and $Re = 2.2 \times 10^6$ (Ref. 12).

angle of attack is increased from 5 deg < α < 10 deg in A to α ≤ 40 deg in I. For the laminar test conditions, $0.0125 < Re \times 10^{-6} < 0.25$, the topological structures were all conical at A, B, and C in Fig. 1, becoming nonconical when more than two vortices existed. The switch from one geometry to another, e.g., between D and E, was very abrupt. At the critical angle of attack, the flow structure actually switched back and forth between the two adjacent vortex geometries in a random fashion. At very high angles of attack, "higher than around 60 deg the flow pattern approached that observed on other slender bodies, with alternate vortex shedding down the length of the body. However, this remained essentially steady" (Ref. 10). That is, it looked similar to that observed at α < 60 deg on a cylindrical afterbody[11] (Fig. 2).

Because of the very slender geometry, $\theta_c = 5$ deg, the cone in Fig. 1 starts developing asymmetric vortices already at α > 10 deg (Ref. 7), when there is still a strong axial flow component. Thus, one may expect a different space-time analogy to exist for a very slender cone than that observed at α > 30 deg on a cylinder[11] (Fig. 2). Tests with a 5-deg cone, performed at $M_\infty = 0.6$ under mainly turbulent flow conditions,[12] $Re = 2.35 \times 10^6$, showed that vortex topology E in Fig. 1 was obtained at $\alpha/\theta_c > 3.3$ (Fig. 3). Also in this test the vortex geometry was unsteady at the critical angle of attack, $\alpha = 3.3\theta_c$.

Asymmetric Loads

Incompressible laminar test results for an 8.13-deg cone[13] show the asymmetric loading to be conical up to α = 40 deg ($\alpha/\theta_c = 4.9$) but to become nonconical at higher angles of attack (Fig. 4). Figures 5 and 6 show that the asymmetric loading on a 5-deg cone becomes nonconical at α ≥ 25 deg ($\alpha/\theta_c \geq 5$) for $M_\infty = 0.51$ and $M_\infty = 1.81$, respectively. At the high Reynolds number of the test,[14] crossflow boundary-layer transition occurs close to the apex and its nonconical geometry[15] has a very limited axial extent. This explains why it did not prevent the establishment of global conical flow asymmetry. At $M_\infty = 2.25$ and higher Mach numbers, no significant conical-type asymmetric loading was measured, although the side force was not insignificant at these Mach numbers.[14] The probable reason for this Mach number trend is that, as the Mach number increases, a higher and higher angle of attack is required before the initial flow asymmetry is established. This is demonstrated by the experimental results for slender cones[14,16,17] in Fig. 7 (Ref. 4). Thus, as the Mach number increases a higher and higher angle of attack is needed before asymmetric flow separation is established, resulting in a decrease of the axial flow component. As a consequence, at $M_\infty = 2.94$, the flow picture for a 7.5-deg cone[18] (Fig. 8) becomes very similar to that for a cone-cylinder body[11] (Fig. 9).

The similarity between unsteady vortex shedding at α = 90 deg from slender cones and a cylinder has been investigated by Gaster[19] (Fig. 10). He found that "the vortices peel off with the

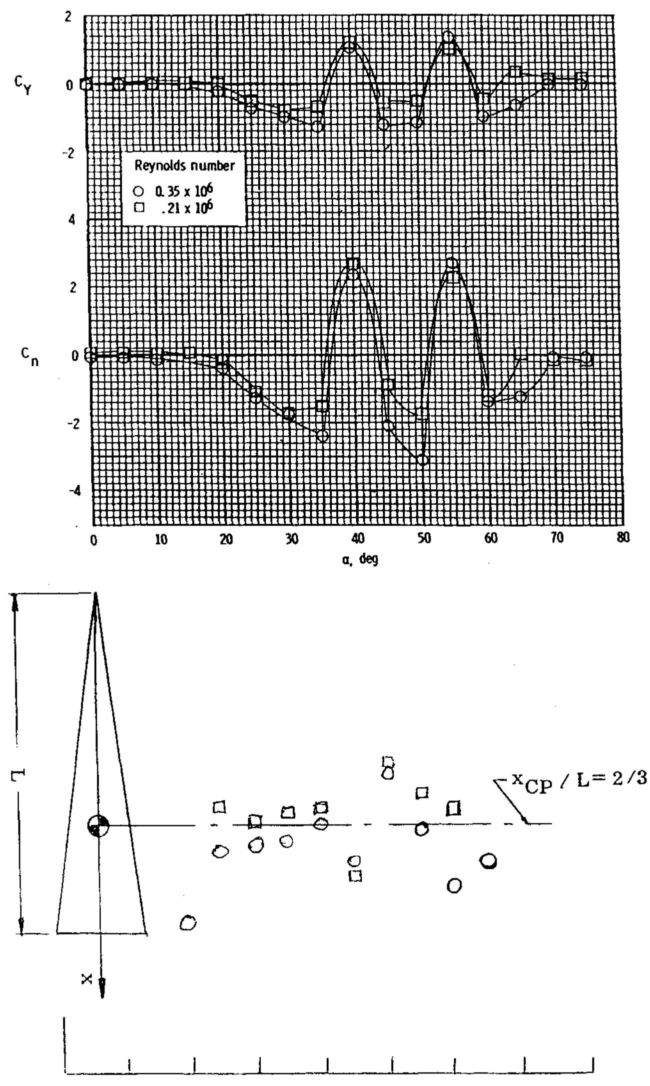

Fig. 4 Asymmetric loading on an 8.13-deg sharp cone at α = 40 deg (Ref. 13).

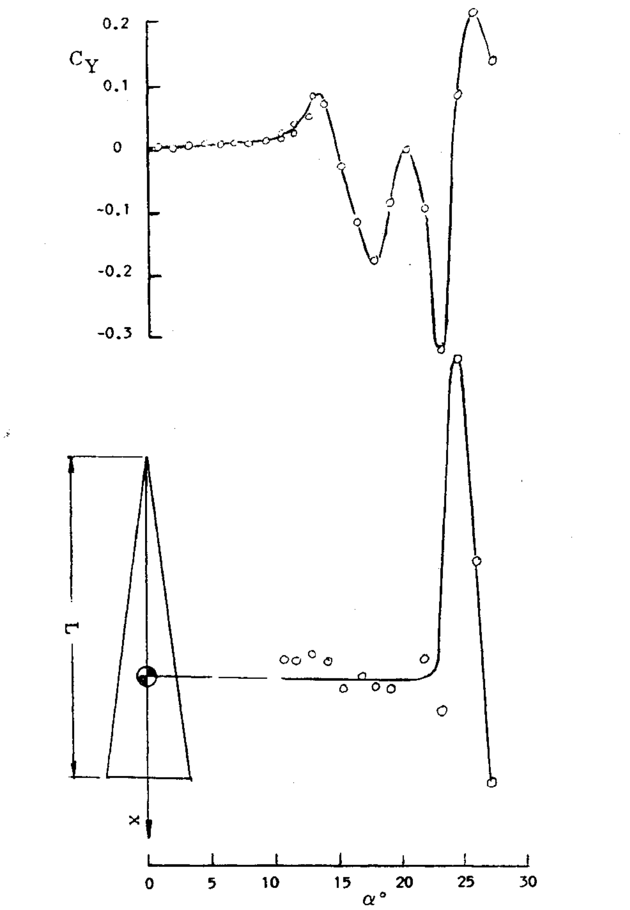

Fig. 5 Center of pressure of side force on a 5-deg cone at $R_{L_\infty} = 35 \times 10^6$ and $M_\infty = 0.51$ (Ref. 14).

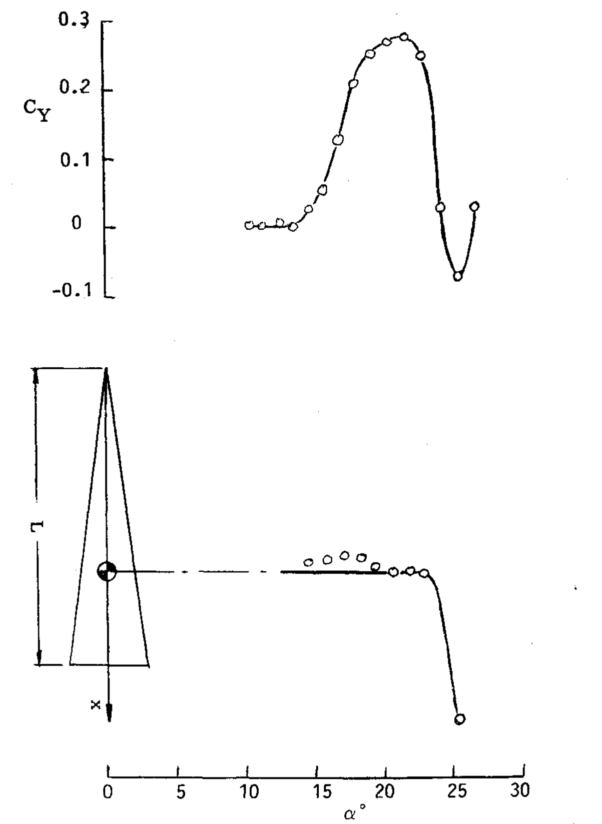

Fig. 6 Center of pressure of side force on a 5-deg cone at $R_{L_\infty} = 35 \times 10^6$ and $M_\infty = 1.81$ (Ref. 14).

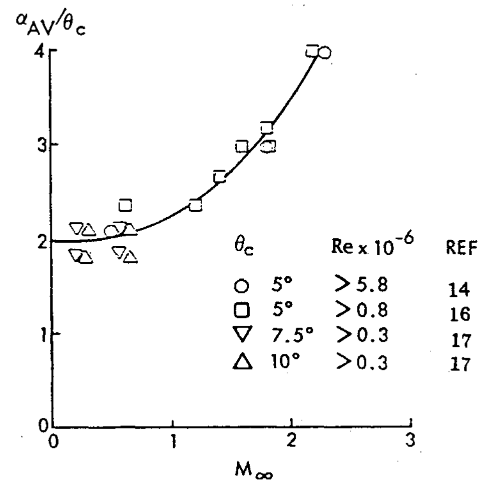

Fig. 7 Effect of Mach number on incipient asymmetric flow separation on slender sharp cones (Ref. 4).

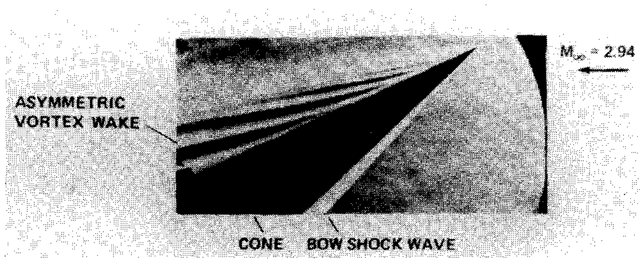

Fig. 8 Supersonic flow over a 7.5-deg cone at $M_\infty = 2.94$ and $\alpha = 34$ deg, i.e., at $\alpha/\theta_c = 4.53$ (Ref. 18).

point of detachment or formation traveling towards regions of larger diameter and lower frequency. Since the pattern is also convected downstream the vortices are inclined to the axis." This suggests that at $\alpha > 30$ deg the unsteady Karman-type vortex pattern on a slender cone could "freeze" to a steady pattern similar to the one on a cylindrical aft body. This is in agreement with the results shown in Figs. 8 and 9, and also with the results in Ref. 10, which apparently showed steady asymmetric vortex shedding to exist beyond $\alpha = 60$ deg, the limiting value for a cylindrical afterbody.

Conical Flow Asymmetry

Thus, a careful review of existing experimental results shows that conical flow asymmetry does indeed exist, but only up to moderate angles of attack, $\alpha < 30$ deg, where the axial flow component still has a strong influence on the crossflow-separation characteristics. The next question is whether or not asymmetric vortices can be generated when the crossflow separation is symmetric. The experimental results shown in Figs. 11 and 12 for 5.8-deg (Ref. 20) and 5.0-deg (Ref. 16) cones, respectively, show clearly that the flow separation is asymmetric. These results are for high test Reynolds numbers where an asymmetric crossflow-transition geometry could have played a role. However, laminar water-tunnel results[21] for a 7.5-deg cone at $\alpha/\theta_c = 3.5$, shown in Fig. 13, demonstrate that when the flow separation is symmetric, the vortex geometry is also symmetric. Thus, symmetric vortex topology was observed for the cones through the tested α range, corresponding to $\alpha/\theta_c \leq 3.5$ and $\alpha/\theta_c \leq 5.5$ for the 12.5-deg and 7.5-deg cones, respectively[21] (Fig. 14).

It has been found that assuring symmetric flow separation by use of lateral strakes effectively eliminates the flow asymmetry and associated side loads at zero sideslip.[9] This is also demonstrated by the experimental results[13] for the 8.13-deg cone shown in Fig. 4 earlier (see Fig. 15). As is discussed in Ref. 9, if the strakes had been extended forward to the apex, they would have been even more effective.

In an investigation of the effect of strakes on a 4-deg cone in incompressible flow,[22] the crossflow picture illustrated in Fig. 16

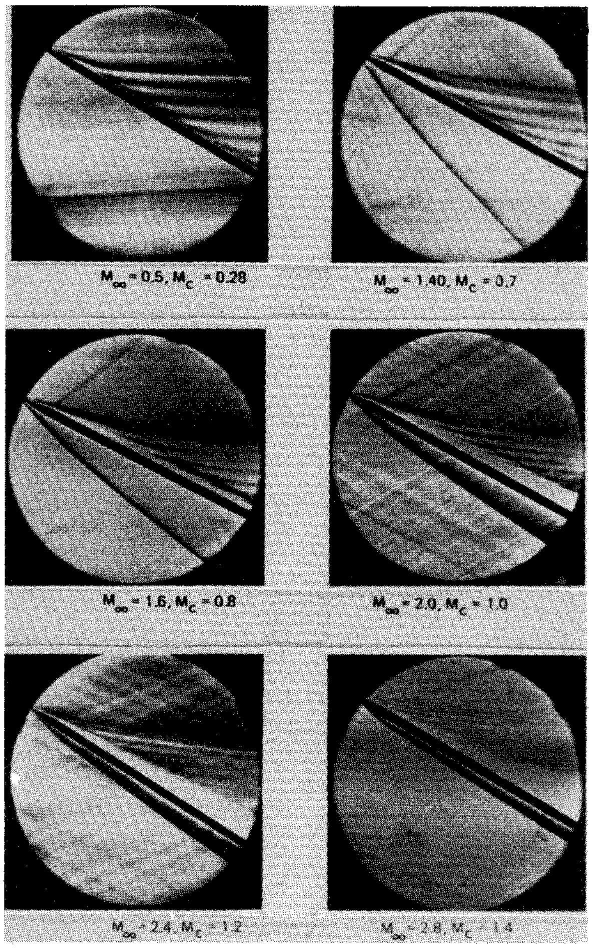

Fig. 9 Effect of crossflow Mach number on the vortex pattern of a cone cylinder at $\alpha \approx 30$ deg and $Re < 0.46 \times 10^6$ (Ref. 11).

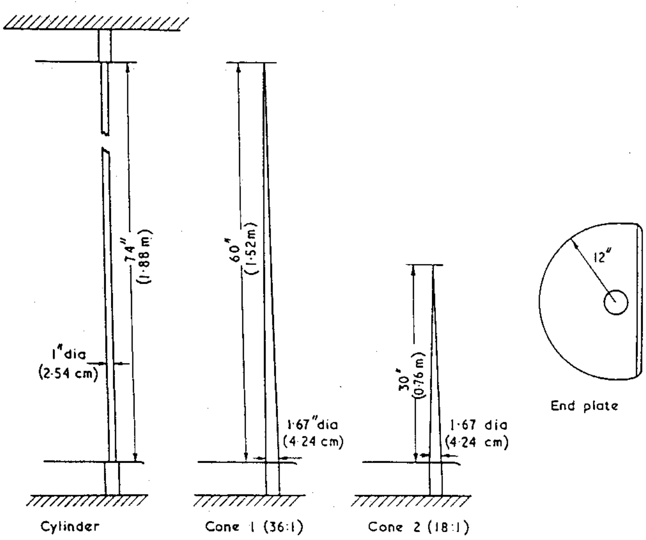

Fig. 10 Circular cylinder and cones investigated by Gaster (Ref. 19).

was visualized. In that investigation the main purpose was to use the strakes to increase the lift. However, spanwise pressure distribution results showed that a strake with a "semispan" equal to 10% of the local body radius eliminated the flow asymmetry present for the pure cone. The flow sketch for $2 < \alpha/\theta_c < 4$ in Fig. 16 shows the "preseparation" effect[23] discussed in Ref. 9. The reattaching flow from the strake-induced limited separation can withstand separation farther around the cross section than the crossflow in absence of the strake. The effect of a strake is, in this case, similar to that of a boundary-layer trip. The latter, by causing transition to

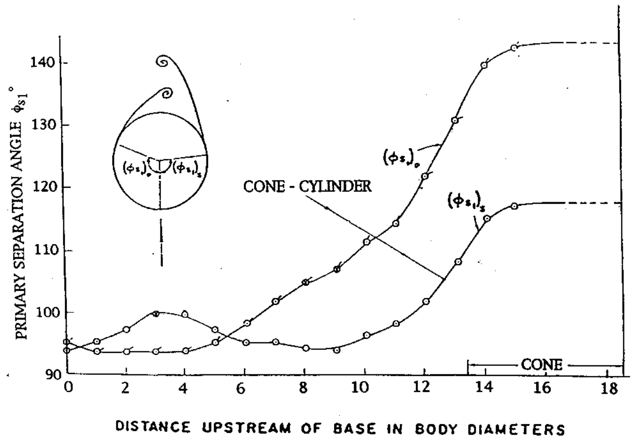

Fig. 11 Crossflow separation lines on a 5.8-deg cone cylinder at $M_\infty = 0.6$ and $Re = 1.9 \times 10^6$ (Ref. 20).

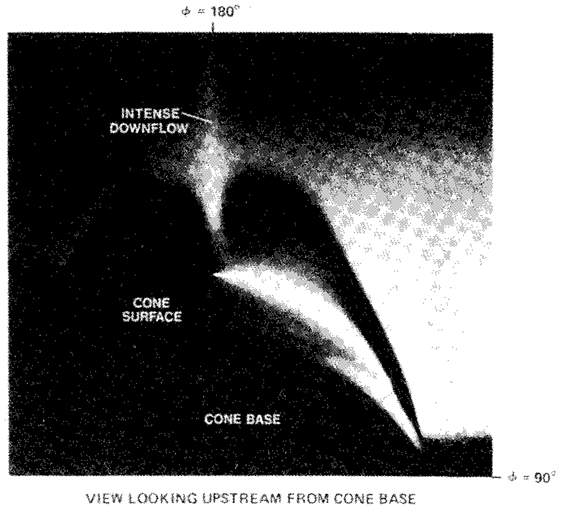

Fig. 12 Laser vapor screen picture of asymmetric crossflow separation on a 5-deg cone at $\alpha/\theta_c = 2.9$ and $M_\infty = 0.6$ (Ref. 16).

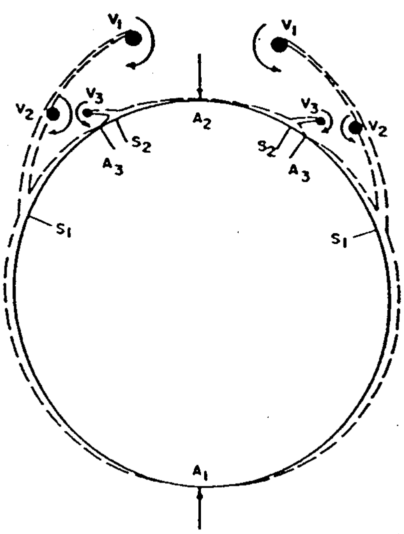

Fig. 13 Crossflow patterns on a 7.5-deg cone at $\alpha/\theta_c = 3.5$ (Ref. 21).

turbulent crossflow, delays separation when placed sufficiently far ahead of the lateral meridian, but causes flow separation when placed at or near it.[9]

Recent static experiments[24] have demonstrated that leading-edge vortices from sharp-edged slender delta wings remain symmetric until vortex breakdown occurs at very high angles of attack, as long as the crossflow conditions remain symmetric (zero angles of sideslip and/or roll). Furthermore, careful analysis of dynamic

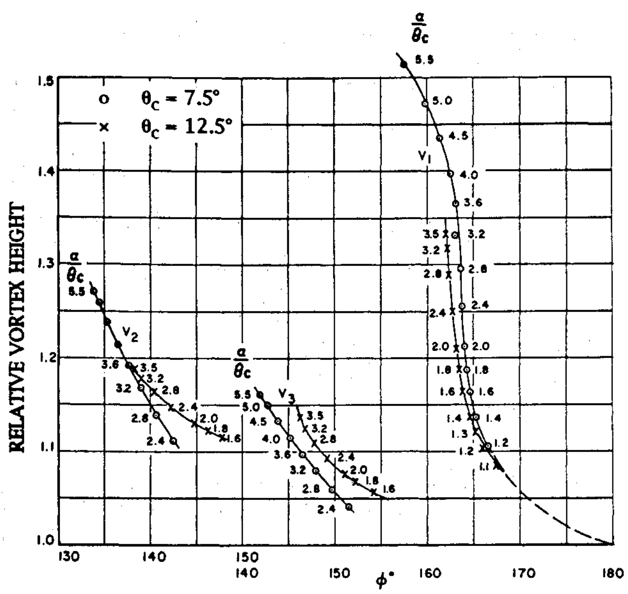

Fig. 14 Vortex core positions in water-tunnel tests of 7.5-deg and 12.5-deg sharp cones at various α/θ_c (Ref. 21).

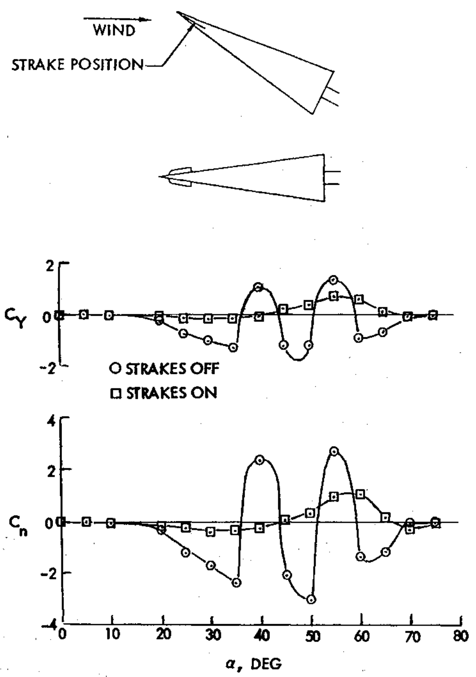

Fig. 15 Effect of nose strakes on lateral loads on an 8.13-deg sharp cone (Ref. 13).

test results for slender delta wings describing wing rock oscillations show also that asymmetric crossflow conditions are required for asymmetric vortex shedding to occur.[25] Thus, a careful examination of existing experimental results reveals that no asymmetric vortex geometry can be generated from symmetric crossflow separation, with one exception. It is shown in Ref. 26 that if the cross-sectional geometry is such that symmetric reattachment of the separated flow is prevented, an asymmetric vortex geometry will result even when the (primary) flow separation is symmetric.

Conclusions

A study of available experimental results obtained at zero sideslip on slender, pointed noses at large angles of attack has shown the following: 1) conical flow asymmetry does exist on very slender cones because of the still-present strong axial flow component at $2\theta_c < \alpha < 30$ deg. However, on not-so-slender cones, where asymmetric flow separation does not start until $\alpha > 30$ deg, the

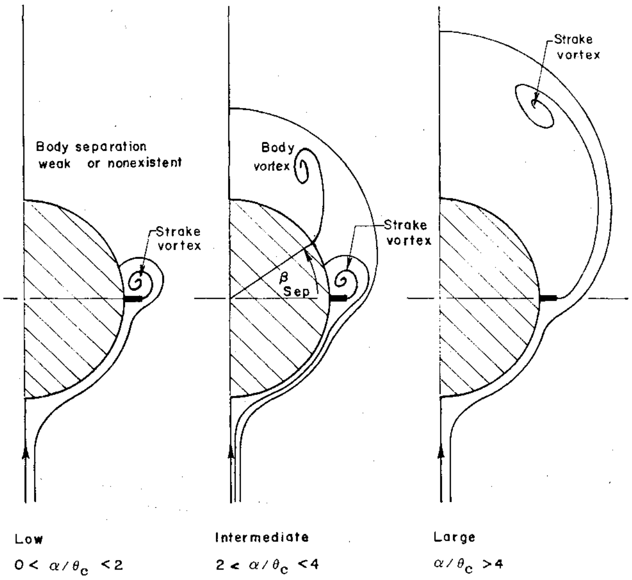

Fig. 16 Effect of lateral strakes on crossflow pattern over a 4-deg sharp cone in incompressible flow (Ref. 22).

asymmetric flow pattern is nonconical and very similar to that established on cylindrical afterbodies and 2) conical vortex asymmetry cannot develop from symmetric flow separation unless symmetric crossflow reattachment is prevented.

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References

[1]Wardlaw, A. B., Jr., "High Angle of Attack Missile Aerodynamics," Paper 5, AGARD LS-98, March 1978.

[2]Jorgensen, L. H., "Prediction of Aerodynamic Characteristics for Slender Bodies Alone and With Lifting Surfaces to High Angles of Attack," Paper 28, AGARD-CP-247, Oct. 1978.

[3]Ericsson, L. E., and Reding, J. P., "Steady and Unsteady Vortex-Induced Asymmetric Loads on Slender Vehicles," *Journal of Spacecraft and Rockets*, Vol. 18, No. 3, 1981, pp. 97–109.

[4]Ericsson, L. E., and Reding, J. P., "Review of Vortex-Induced Asymmetric Loads—Part I," *Z. Flugwiss. Weltraumfahrt*, Vol. 5, 1981, pp. 162–174.

[5]Ericsson, L. E., and Reding, J. P., "Review of Vortex-Induced Asymmetric Loads—Part II," *Z. Flugwiss. Weltraumfahrt*, Vol. 5, 1981, pp. 349–366.

[6]Hunt, B. L., "Asymmetric Vortex Forces and Wakes on Slender Bodies," AIAA Paper 82-1336, Aug. 1982.

[7]Ericsson, L. E., and Reding, J. P., "Asymmetric Vortex Shedding from Bodies of Revolution," *Tactical Missile Aerodynamics*, edited by M. J. Hemsch and J. N. Nielsen, Vol. 104, Progress in Astronautics and Aeronautics, AIAA, New York, 1986, pp. 243–296.

[8]McElroy, G. E., and Sharp, P. S., "An Approach to Stall/Spin Development and Test," AIAA Paper 71-772, July 1971.

[9]Ericsson, L. E., and Reding, J. P., "Alleviation of Vortex-Induced Asymmetric Loads," *Journal of Spacecraft and Rockets*, Vol. 17, No. 6, 1980, pp. 546–553.

[10]Lowson, M. V., and Ponton, A. J. C., "Symmetric and Asymmetric Vortex Flows at High Angle of Attack," *AIAA Journal*, Vol. 30, No. 6, 1992, pp. 1576–1583.

[11]Thomson, K. D., and Morrison, D. F., "The Spacing, Position, and Strength of Vortices in the Wake of Slender Cylindrical Bodies at Large Incidence," *Journal of Fluid Mechanics*, Vol. 50, Pt. 4, 1971, pp. 751–783.

[12]Peake, D. J., Owen, F. K., and Johnson, D. A., "Control of Forebody Vortex Orientation to Alleviate Side Forces," AIAA Paper 80-0183, Jan. 1980.

[13]Coe, P. L., Jr., Chambers, J. R., and Letko, W., "Asymmetric Lateral-Directional Characteristics of Pointed Bodies of Revolution at High Angles of Attack," NASA TN D-7095, Nov. 1972.

[14]Rainbird, W. J., private communication of unpublished experimental asymmetric loads on a 5 deg cone at Mach numbers from 0.51 to 4.27, April 5, 1968.

[15]Keener, E. R., "Flow Separation Patterns on Forebodies," NASA TM-86016, Jan. 1986.

[16]Peake, D. J., Owen, F. K., and Higuchi, H., "Symmetrical and Asymmetrical Separations about a Yawed Cone," AGARD Symposium on High Angle of Attack Aerodynamics, Paper 16, AGARD CP-247, Sandefjord, Norway, Oct. 1978.

[17]Keener, E. R., and Chapman, G. T., "Onset of Aerodynamic Side Forces at Zero Sideslip on Symmetric Forebodies at High Angles of Attack," AIAA Paper 74-770, Aug. 1974.

[18]Bannink, W. J., and Nebbeling, C., "Measurements of the Supersonic Flow Field Past a Slender Cone at High Angles of Attack," Paper 22, AGARD CP-247, Oct. 1978.

[19]Gaster, M., "Vortex Shedding from Slender Cones," *Proceedings of IUTAM Symposium on Recent Research on Unsteady Boundary Layers*, Vol. II, Laval Univ., Quebec, Canada, May 1971, pp. 1499–1534.

[20]Rainbird, W. J., Crabbe, R. S., Peake, D. J., and Meyer, R. F., "Some Examples of Separation in Three-Dimensional Flows," *Canadian Aeronautics and Space Journal*, Vol. 12, Dec. 1966, pp. 409–423.

[21]Rainbird, W. J., Crabbe, R. S., and Jareviez, L. S., "The Flow Separation About Cones at Incidence," *DME/NAE Quarterly Bulletin*, Ottawa, Canada, July 1963, pp. 1–105.

[22]Levinsky, E. S., and Wei, M. H. Y., "Nonlinear Lift and Pressure Distribution of Slender Conical Bodies with Strakes at Low Speeds," NASA CR-1202, Oct. 1968.

[23]Ericsson, L. E., "Aerolastic Instability Caused by Slender Payloads," *Journal of Spacecraft and Rockets*, Vol. 4, Jan. 1967, pp. 65–73.

[24]Stahl, W., Mahmood, M., and Asghar, A., "Experimental Investigations of the Vortex Flow on Delta Wings at High Incidence," *AIAA Journal*, Vol. 30, No. 4, 1992, pp. 1027–1032.

[25]Ericsson, L. E., "Slender Wing Rock Revisited," *Journal of Aircraft* (to be published).

[26]Ericsson, L. E., "Sources of High Alpha Vortex Asymmetry at Zero Sideslip," *Journal of Aircraft*, Vol. 29, No. 6, 1992, pp. 1086–1090.