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SOME ASPECTS OF VORTEX ASYMMETRY AND ITS CONTROL ON SLENDERBODIES AT HIGH ANGLES OF ATTACK

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ABSTRACT: There have been considerable interest and research addressing the problem of vortex asymmetry and induced side forces on slenderbodies at high incidence. We present here a brief review highlighting some of the developments that have taken place in the broad understanding of this complex phenomenon and control of side forces, which are very important for engineering applications. Results are presented from two recent studies (carried out in NAL, India) showing in some detail the effectiveness of nose bluntness and axial nose blowing for side force control.

1. INTRODUCTION:

The problem of vortex asymmetry and the associated side forces (and yawing moments) on pointed forebodies at high angles of attack and zero side slip has received considerable attention in literature (Fig.1). Beyond a certain angle of attack (depending primarily on the nose apex angle), the symmetric vortex flows become asymmetric resulting in side force generation; the side force generally increases with α and reaches a maximum typically in the α range of 40-50 deg. This regime of three-dimensional separated flow over a pointed slenderbody is nominally steady and the forces / moments generated are generally repeatable for a given model and given roll position in a wind tunnel. Our broad knowledge of this complex flow involving vortex asymmetry has been the result of extensive experimental results on axisymmetric bodies during the last three decades, which have revealed the important parameters affecting the onset of vortex asymmetry and the magnitude of side forces; the primary geometrical parameters are the nose apex angle, forebody cross- sectional shape and fineness ratio of the slenderbody. The side forces generated are strongly Reynolds number dependent and the effects gradually decrease with increase in flight Mach number – the problem is essentially predominant at low to subsonic speeds in which regime the high alpha maneuvers of combat aircraft and missiles normally occur. Excellent reviews on the subject have been published over the years [1,5,6,8,20]; the problem is still intractable to modeling and predictions, even in an engineering sense.

In this paper, we present a brief review highlighting some of the developments that have taken place in the broad understanding of this complex phenomenon and control of side forces, which are very important from a technological viewpoint. No attempt is made here to survey all the papers on the subject that have been published in literature.

It is now recognized that geometric imperfections or micro-asymmetries in the nose region of a model is an important factor for the occurrence of vortex asymmetry and generation of a side force; these possibly result in the roll sensitivity of side force generated on any model. In all experimental studies of vortex asymmetry at high alpha, it is necessary to go through a “roll search” and determine the “stable roll position” for each model/configuration [8]; stable roll position corresponds to (max) side force generated. This problem, being a nose triggered phenomenon, it has often been the practice in experimental studies to rotate the nose section alone, every 30 or 45 deg and then identify the stable roll for further data generation.

Several papers in literature have focused attention on the cause of asymmetry and have attempted to provide explanations based largely on inviscid arguments. Keener and Chapman [9], by comparing the similarities between asymmetric flows on bodies and slender, sharp delta wings (which have symmetric separation lines) suggested that asymmetry may occur due to the hydrodynamic instability of symmetric vortex flows. Dyer et.al. [4], carried out inviscid modeling of vortex flows on a cone with “separation line fixed or known”; they showed that symmetric separation lines can lead to an asymmetric solution. Based on an analysis of experimental results on crossflow separation characteristics and vortex asymmetry onset data obtained on elliptic cones at low speeds, (Figs.2,3) Viswanath [19] suggested that inviscid mechanisms may play a key role in triggering asymmetry of vortex flows. Similar observations have been made by Rajan Kumar et.al.[16,17] recently with side force control, which we will discuss later. Computational studies employing Navier-Stokes (NS) equations have attempted to provide some insight towards understanding this complex phenomenon. Accurate laminar NS solutions [2,3] have shown the importance of geometric disturbances near the nose apex for triggering side force generation and also that asymmetry may be a result of convective-type instability.

2. CONTROL OF VORTEX ASYMMETRY AND INDUCED SIDE FORCES:

In the context of combat aircraft and missile applications, the magnitude of side force and adverse yawing moments generated can be large and cannot be easily controlled (e.g. rudder power in an aircraft). Driven by technological needs, there have been numerous attempts in literature to reduce and possibly eliminate the undesirable asymmetric forces and moments employing both passive and active devices. The basic idea in most studies is of course to symmetrize the flow and reduce the level of side forces. Some of the control techniques investigated include different types of nose strakes [10,14,21], boundary layer trips [10,13,18], nose bluntness [11,12,15] and active control using nose tip rotation [7] and the beneficial effects of many of the above devices have been demonstrated over a limited range of flow parameters like Reynolds number and Mach number. The review paper by Williams [20] may be seen for details. Here we report certain important results from two recent studies [16,17] carried out (at the National Aerospace Laboratories, NAL, India) on nose blunting and axial nose blowing for side force control

Rajan Kumar et.al., [16,17] carried out detailed experiments assessing the effectiveness of nose blunting and axial nose blowing against the oncoming flow for side force control. They utilized two cone models of half angle (θ_c) 8 and 12 deg. and nose bluntness ratio was varied from 0-21% in discrete steps (Fig. 4a). For the nose blowing experiments, the cone models (with θ_c = 8 and 12 deg.) were mildly blunted in order to ensure accurate, axial nose blowing (Fig. 4b). All the tests were made in two facilities, namely, the NAL 1.5x1.5m Low Speed Wind Tunnel and 1.2m Trisonic Wind Tunnels, the order to cover a wide range of Reynolds number considered important for the study. Accurate force/moment measurements were made using internal strain gauge balances and surface pressure measurements (around the circumference) were made on the 12 deg. models at two longitudinal locations. More details on the experimental studies may be seen in Refs.16,17.

Typical results of side force coefficient (C_s) at a Reynolds number based on diameter (Re_D) of 0.9×10^6 for the 8 and 12 deg. cones and shown in Fig. 5. Nose blunting results in a delay in the onset of vortex asymmetry and a decrease in the side force (SF) magnitudes as seen in earlier work (e.g. Ref.8); the SF values progressively decrease with nose bluntness ratio upto a certain value, shows a small increase and then finally decrease for large values of bluntness ratio. Fig. 6 shows results of angle of attack at vortex asymmetry onset (α_{onset}) plotted against Re_D for different nose bluntness ratio. A spectacular feature is that α_{onset} on each blunted cone is virtually independent of freesteam Reynolds number over a wide range tested; also the semi-apex angle θ_c is the relevant scaling for α_0 even with nose blunting. These results strongly suggest that vortex asymmetry even in the presence of nose blunting is essentially triggered by inviscid flow mechanisms. The characteristics of α_{onset} and (abs) magnitude of (max) C_s with bluntness ratio for the 12 deg. cone are presented in Figs. 7 and 8.

We present here selected results [17] showing the performance of nose blowing (Figs. 9-12). Results of side force coefficient (C_s) with α as dependent on blowing velocity ratio (U_j/U_∞) clearly bring out the effectiveness of axial nose blowing for SF control. Significant and progressive reduction in SF magnitude with (U_j/U_∞) may be seen upto a value around 1.0, then a small increase, followed by a further decrease (Fig. 10). The results show that it is adequate to blow through a narrow hole, thus saving mass flow requirements. A correlation (Fig. 11) for the vortex asymmetry onset (α_0) for the two cone models shows interesting features; nose semi-apex angle (θ_c) is the relevant scale and the data for the two cones collapse upto a value of (U_j/U_∞) ~ 0.7, and then branch off. Also, the blowing velocity ratio is the relevant parameter for characterizing the effectiveness of blowing. The α_0 correlation is virtually independent of Re_D, over the wide range tested here, suggesting once again, that inviscid mechanisms may play a key role in triggering vortex asymmetry even with nose blowing. Finally, Fig. 12 shows results bringing out effectiveness of SF control at higher Reynolds numbers, more realistic of flight applications. Based on broad similarities in the trends of SF reduction with nose blowing (Fig. 10) and nose bluntness (Fig. 8), Rajan Kumar et. al. [16,17], suggested that interaction of axial jet flow with freestream results in possibly what we may call “Fluid Dynamic Blunting”.

3. CONCLUDING REMARKS:

Some progress has been made over the years in the understanding of certain broad flow features of this complex problem of vortex asymmetry on slenderbodies at high α. It appears that geometric imperfections / micro-asymmetries in the nose region have a significant influence in triggering vortex asymmetry and modeling such effects in calculation methods are very challenging. There is growing evidence from experimental results to suggest that inviscid flow mechanisms may play a dominant role in triggering vortex asymmetry. A variety of side force control techniques have been explored, which may have future applications. Wind tunnel simulation will remain vital for optimizing the nose geometry or adapting a suitable flow control device for minimizing/eliminating the out of plane forces in aircraft design.

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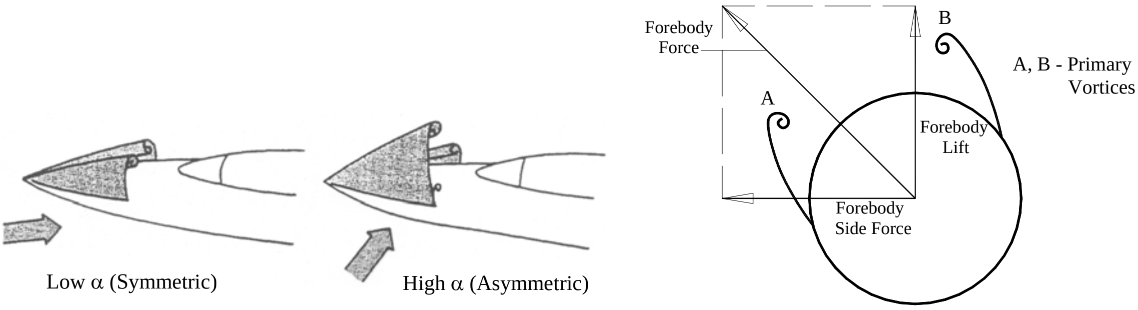

Fig. 1. Schematic of forebody vortex patterns

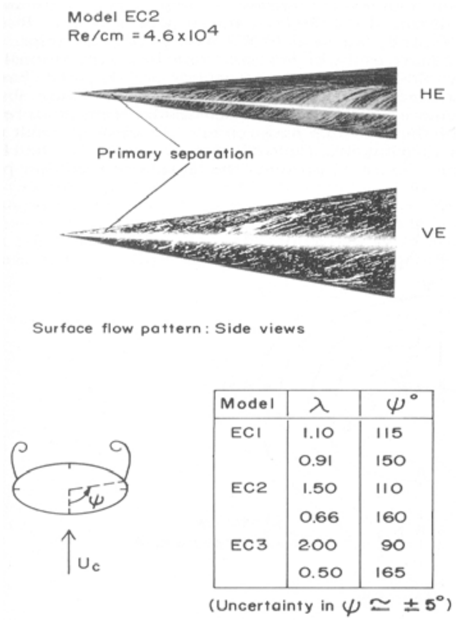

Fig. 2. Some features of crossflow separation (taken from Ref. 19).

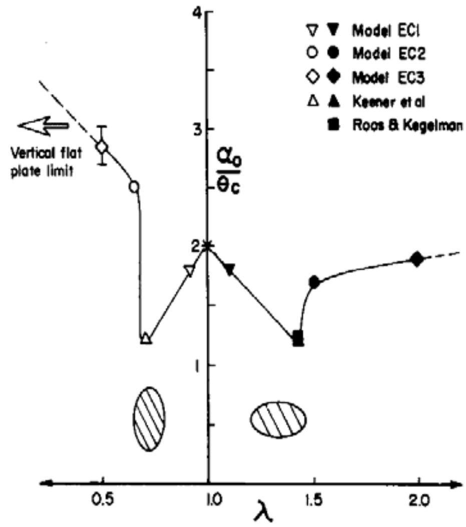

Fig. 3. Correlation of angle of attack for onset of side force on elliptic cones (taken from Ref. 19).

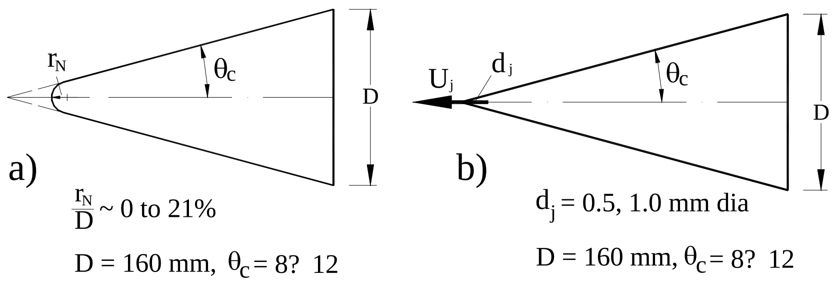

Fig. 4. Geometric details of cone models used [16,17]

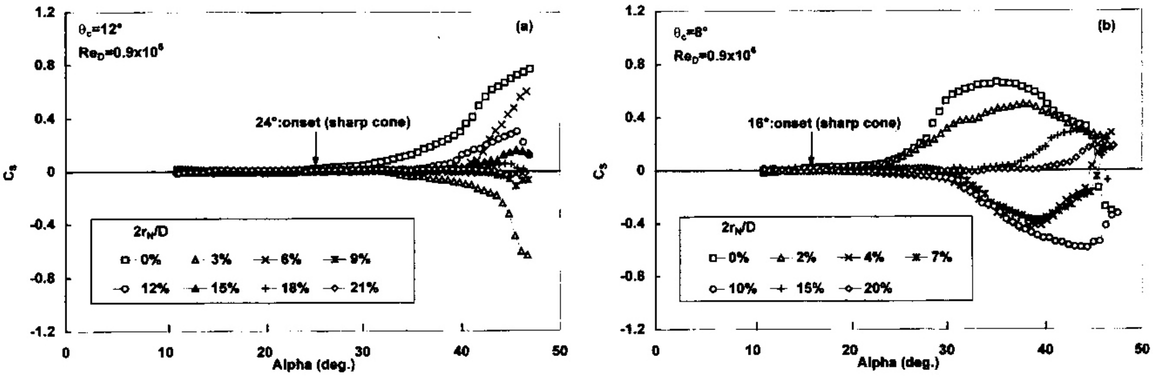

Fig. 5. Side force characteristics with nose blunting [16]

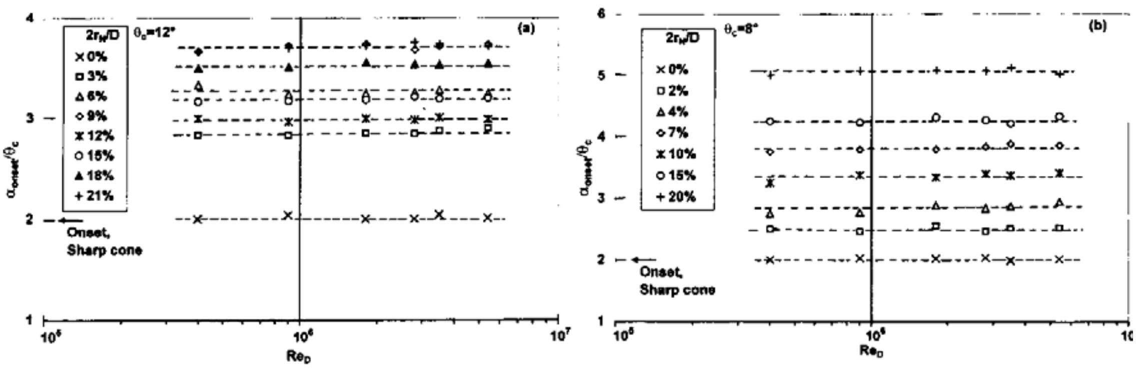

Fig. 6. Effect of Reynolds number on vortex asymmetry onset [16]

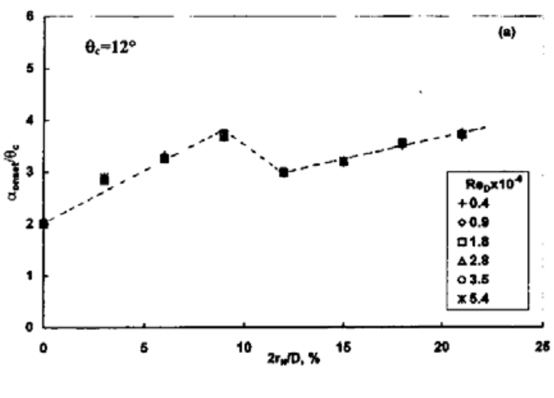

Fig. 7. Variation of onset of vortex asymmetry with nose bluntness ratio [16]

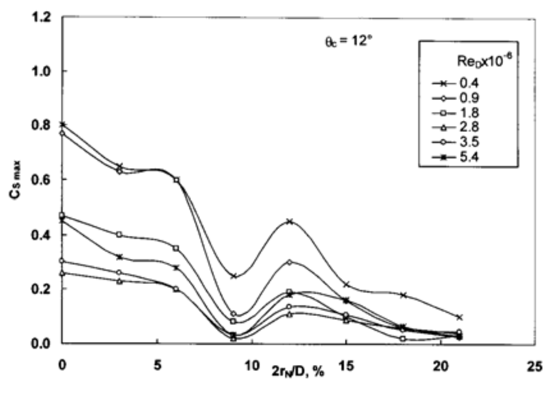

Fig. 8. Variation of maximum side force characteristics with bluntness ratio [16]

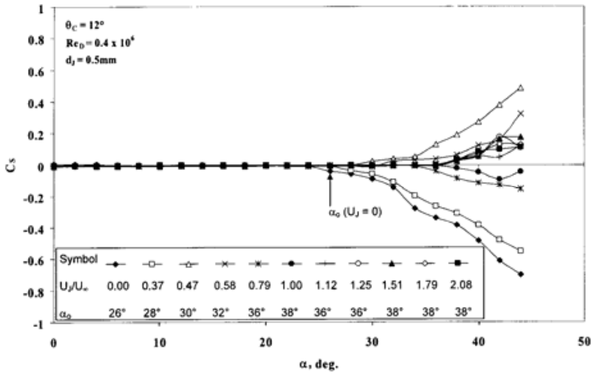

Fig. 9. Side force characteristics with nose blowing (12 deg. Cone) [17]

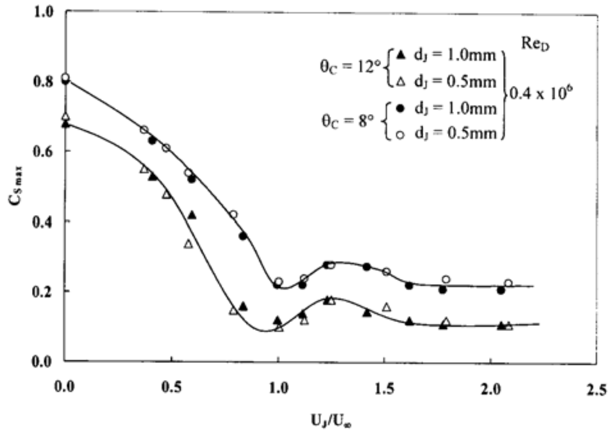

Fig. 10. Reduction in max. side force characteristics with nose blowing [17]

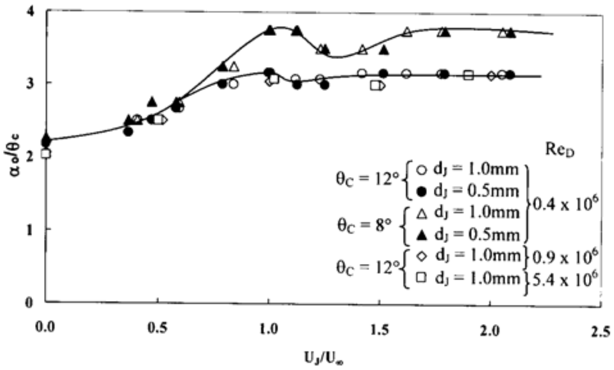

Fig. 11. Correlation of vortex asymmetric onset with nose blowing [17]

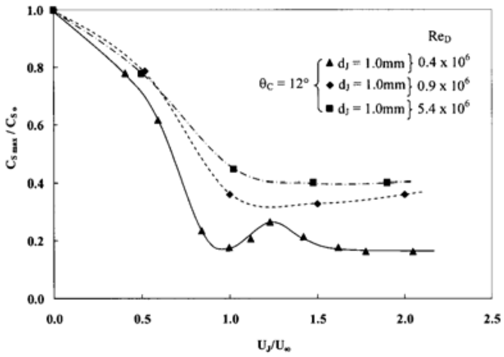

Fig. 12. Effect of Reynolds number on the reduction of (max) side force levels with nose blowing [17]