Computational Investigation of Supersonic Boundary Layer Transition over Canonical Fuselage Nose Configurations

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Abstract: Boundary layer transition over axisymmetric bodies at non-zero angle of attack in supersonic flow is numerically investigated as part of joint research between the Japan Aerospace Exploration Agency (JAXA) and National Aeronautics and Space Administration (NASA). Transition over four axisymmetric bodies with different axial pressure gradients (namely, Sears-Haack body, semi-Sears-Haack body, straight cone and flared cone) has been studied to elucidate (i) the effect of axial pressure gradient on instability amplification, (ii) potential influence of surface roughness details on the transition onset front, and (iii) nonlinear breakdown mechanism associated with transition along the leeward ray.

Keywords: Laminar-Turbulent Transition, Direct Numerical Simulation.

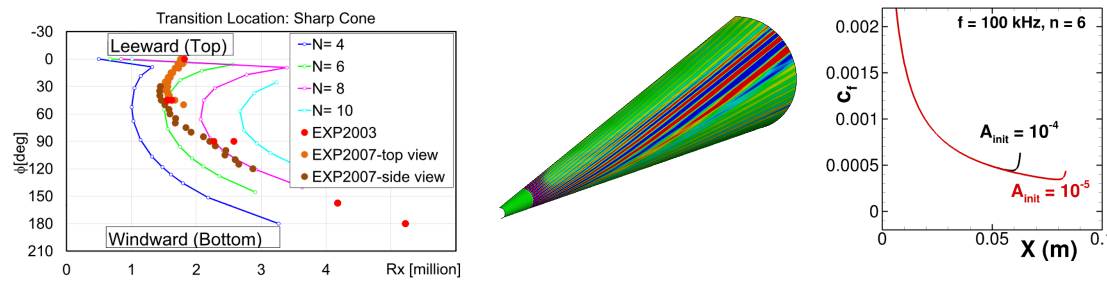
1 Introduction

Extending the region of laminar flow over the fuselage surface offers significant potential for improved aerodynamic efficiency of a supersonic aircraft, especially when laminar flow technology is already incorporated into the aircraft lifting surfaces. Reliable assessment of fuselage drag reduction requires accurate yet efficient transition prediction techniques for slender body configurations at a small, nonzero angle of incidence. To that end, transition characteristics for four different canonical axisymmetric configurations (namely, Sears-Haack body, semi-Sears-Haack body, straight cone and flared cone) at a fixed, finite angle of attack are investigated using a hierarchical set of methods ranging from linear stability theory (LST), line and surface marching parabolized stability equations (PSE), and direct numerical simulations (DNS). The effect of axial pressure gradient on first mode transition along the leeward plane of symmetry and crossflow transition between the windward and leeward planes has been examined for the first time. Furthermore, comparisons between predictions from different variants of linear stability correlations as well as code-to-code comparisons are used in conjunction with the wind tunnel measurements reported in a related paper [1] to explore error and uncertainty quantification in the context of transition prediction for fully 3D boundary layer flows.

2 Illustrative Results

Illustrative results for the case of a straight cone at 2-degree angle of incidence are shown in Fig. 1. Figure 1(a) displays the contours of constant N-factors (i.e., logarithmic amplitude ratios relative to the neutral stability location where the disturbances first begin to amplify) obtained from LST and the transition front extracted from infra-red imaging of the cone surface during two separate wind tunnel entries. Details of the measurements are described in Ref. [1]. The approximate correlation between

N-factor curves and the measured transition front confirms the dominance of crossflow instability during transition; however, the noticeable discrepancy in the correlating N-factor as well as the azimuthal location of the transition front apex underscores the inherent fundamental difficulties in applying linear stability methods to strongly inhomogeneous 3D boundary layers and the importance of initial amplitude spectra, i.e., receptivity mechanisms associated with the generation of the instability waves. DNS is used to compute the development of unstable perturbations from simplified canonical sources. Fig. 1(b) shows the pattern of stationary crossflow disturbances arising from an azimuthally periodic distribution of roughness elements at a far upstream solution. It is seen that the strongest vortices are confined to a narrow region over the side of the cone and they originate from roughness elements closer to the windward ray (along the bottom of the cone in Fig. 1(b)). Along the leeward plane of symmetry, there is no crossflow and, hence, the onset of transition is caused by oblique first mode waves. Numerical computations are also used to investigate the nonlinear breakdown mechanism associated with these waves and to characterize the dependence of transition onset location on the initial amplitudes of instability waves or, equivalently, on the level of free-stream disturbances (Fig 1(c)).



a) N-factor contours based on LST compared with measured transition front

b) DNS of roughness induced stationary crossflow modes

c) Skin-friction variation based on computations of oblique mode breakdown along leeward ray

Figure 1: Transition on straight cone at 2-degree angle of incidence

3 Significant Findings

Axisymmetric bodies at an angle of incidence exhibit a rich array of instability mechanisms including first mode instabilities as well as stationary and traveling crossflow modes. Except when the axial pressure gradient is sufficiently favorable, accumulation of secondary flow near the leeward plane of symmetry leads to a local increase in boundary layer thickness and inflectional velocity profiles. Both the extent of boundary layer thickening and the amplification of inflectional instabilities become progressively weaker as the pressure gradient varies from adverse (flared cone) to favorable (Sears-Haack body). In contrast, the overall amplification of crossflow instabilities in the lateral region is relatively insensitive to the body shape. Yet, the measured onset of transition within the crossflow region moves progressively downstream as the axial pressure gradient varies from nearly zero values (straight cone) to a favorable distribution (Sears-Haack body), leading to a noticeable scatter in the correlating N-factors based on linear amplification. The azimuthal location of the predicted onset of transition is found to be outboard (i.e., away from the leeward line of symmetry) when compared with the apex of the crossflow transition front inferred from measurements. Direct numerical simulations indicate that the discrepancy in the azimuthal location of transition could be explained by the upstream history associated with instability excitation and, in particular, by the effect of spatial inhomogeneities in roughness height distribution near the windward ray.

References

[1] N. Tokugawa et al. *Transition along Leeward Ray of Axisymmetric Bodies at Incidence in Supersonic Flow*. Submitted to AIAA Fluid Dynamics Conference, New Orleans, LA. 2012.