Importance of Unsteady Aerodynamics for Space Shuttle Ascent Aeroelastic Stability

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Nomenclature

C_N = normal force coefficient
C_p = pressure coefficient
x/c = nondimensional axial coordinate
α = angle of attack
ζ_a = aerodynamic damping, fraction of critical
$\Delta^i C$ = interference increment

Subscripts

O = orbiter
P = plume
α = $\partial/\partial\alpha$

Theme

QUASI-steady techniques are used in a preliminary, order of magnitude, analysis of the aeroelastic stability of the space shuttle ascent configuration. The analysis shows that interference effects will result in negative aerodynamic damping of one or more of the low frequency free-free elastic modes. The implication of these results, i.e., the possibility of undamped, divergent, oscillations leading to structural failure is serious enough to warrant further analytic and experimental investigations. Since the quasi-steady technique evaluates the effect of each component of the aerodynamic load distribution on the aerodynamic damping of the elastic modes, the loads responsible for adverse dynamic effects are revealed. Thus, the analysis shows that booster-plume-induced separation and orbiter bow shock impingement on the booster are two possible sources of modal undamping.

Contents

The veracity of the quasi-steady technique developed by Lockheed for evaluating the dynamic effects of separated flows is well documented.[1,2] Briefly, the technique deals with aerodynamic interference effects where flow conditions at one vehicle station influence the loads at another. Due to the finite flow convection velocity the interference loads lag the vehicle motion. The time lag causes a phase lag in the rate term that can cause aerodynamic undamping of low frequency elastic modes. The general rule for such interference effects is that if the load is statically stabilizing it will be aerodynamically undamping.[1]

Oil flow photographs obtained on a recent shuttle boost configuration reveal the interference flowfield sketched in Fig. 1.[3] Local flow separations occur on hydrogen-oxygen (HO) tank and solid rocket motors (SRM's due to the impingement of the orbiter bow shock, and on the HO tank sides due to the SRM shocks. All these separations are vented via shed vortices. It is these vortices that couple the forward and aft flowfields.‡

Wind tunnel results for simulated solid and gaseous exhaust plumes on the 040A boost configuration show that the plume induced separation causes a reduction of the orbiter $C_{N\alpha}$ ($\Delta\, ^iC_{N_{\alpha P}}<0$).[3] It is postulated that this is the result of two effects: 1) suppression of the plume-induced separation by the separation-venting vortices which entrain freestream flow thereby strengthening the boundary layer and shrinking the plume-induced separation; and 2) by flow jetting through the SRM-HO tank gaps which also energizes the boundary layer and reduces the plume-induced separation (Fig. 2).

The portion of $\Delta\, ^iC_{N_{\alpha P}}$ affected by forebody vortices is subject to a time lag due to the finite convection speed of the vortices. Aeroelastically $\Delta\, ^iC_{N_{\alpha P}}$ tends to restore the orbiter to its null position for the 3.64 Hz symmetric mode (see insert in Fig. 3). Thus, $\Delta\, ^iC_{N_{\alpha P}}$ is statically stabilizing, and consequently is undamping. Unfortunately it is not presently known how much of the plume-induced load is due to local

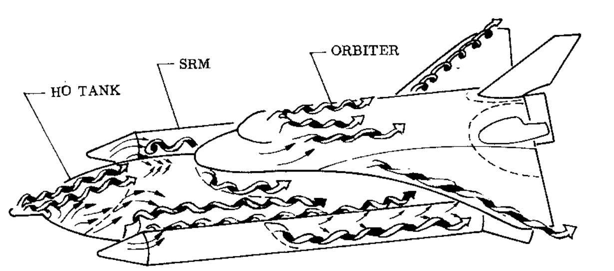

Fig. 1 Interference flowfield at $M = 1.46$

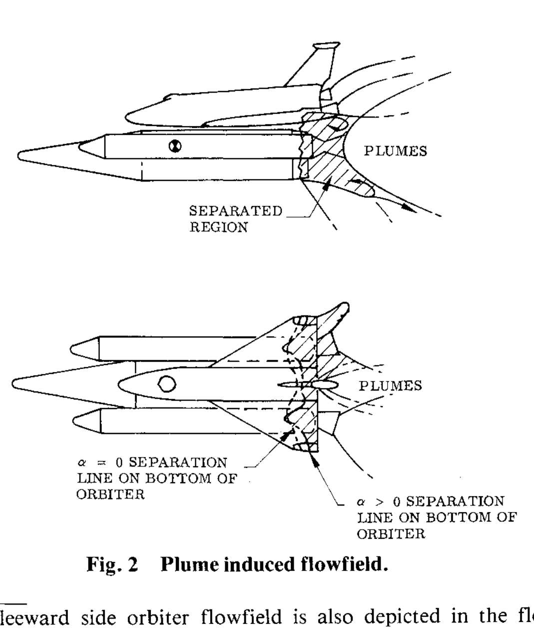

Fig. 2 Plume induced flowfield.

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Index categories: Aeroelasticity & Hydroelasticity; Nonsteady Aerodynamics; Jets, Wakes and Viscid-Inviscid Flow Interactions.

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‡The leeward side orbiter flowfield is also depicted in the flow sketch for completeness.

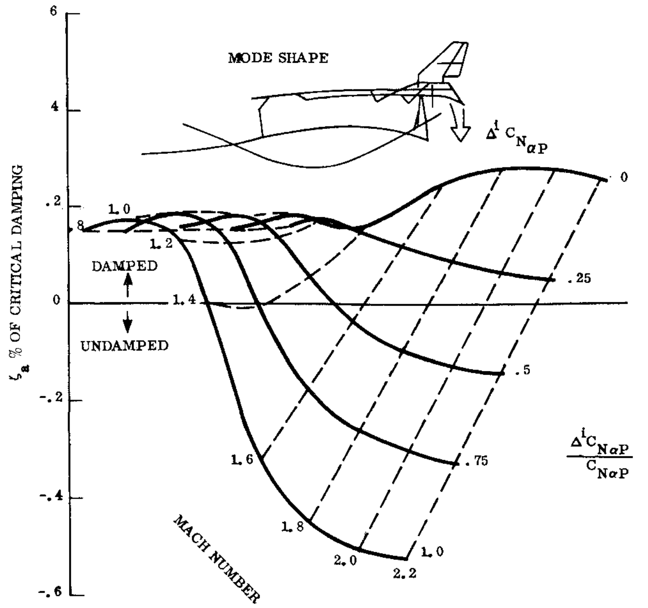

Fig. 3 Effect of plume induced loads on 049 booster damping for the 3.64 Hz symmetric mode.

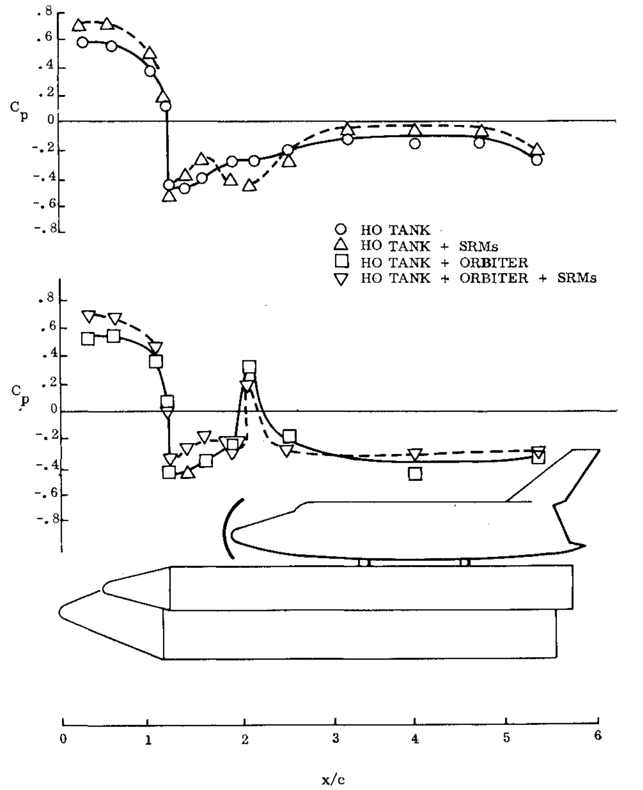

Fig. 4 Effect of SRMs and orbiter on HO tank pressures for the 049 booster at $M = 1.2$.

crossflow and how much is due to the forebody vortex effect. The modal damping is, therefore, presented in carpet plot form (Fig. 3). If the entire plume-induced effect were due to the forebody vortices, $\Delta\, ^iC_{N_{\alpha P}}/C_{N_{\alpha P}} = 1.0$, and if it were all due to flow through the gaps $\Delta\, ^iC_{N_{\alpha P}}/C_{N_{\alpha P}} = 0$.

There seems to be a significant possibility for aerodynamic undamping, since according to past experience, the interference load due to forebody crossflow effects usually is

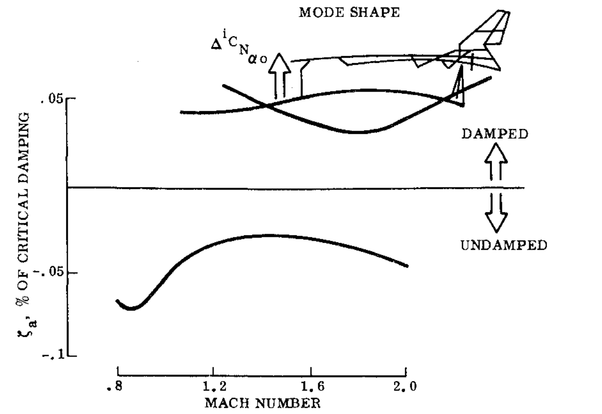

Fig. 5 Effect of shock induced separation on 049 booster damping for the 3.64 Hz symmetric mode.

substantially larger than the local derivative. If the rule-of-thumb value of 1% of critical ±0.5% is assumed for the structural damping, the aerodynamic undamping comes dangerously close to dominating the structural damping. How solid plume results were corrected for gaseous plume effects is described in the back-up paper where also references to the experimental data used in the analysis and details of the analysis are given.

The orbiter bow shock also has a significant effect on the elastic vehicle dynamics. Load distribution results for the 049 ascent configuration show that the orbiter bow shock causes a positive C_{N_α} locally on both the HO tank and the SRM. This is contrary to the usual shock induced separation effect.[1] The explanation is as follows: Pressure data show that the expansions from the SRM shoulders impinge in the region of the orbiter bow shock, generating a favorable pressure gradient[3] (Fig. 4). This causes the separation to decrease with increasing angle of attack explaining the positive $\Delta\, ^iC_{N_{\alpha O}}$. The vortices shed from the separation on the HO tank likewise cause a positive $\Delta\, ^iC_{N_{\alpha O}}$ on the SRM's. These HO tank and SRM loads are associated with a time lag and can cause aerodynamic undamping of the 3.64 H_z symmetric mode of the 049 shuttle ascent configuration (see Fig. 5).

It should be emphasized that no leeward side orbiter effects, such as local flow separations, leading edge vortices, or booster interference with the leeward side orbiter flow, have been included. All of these effects are present, though they are as yet undefined.[3] Furthermore, Dods' vapor screen photos (published with his permission in Ref. 3) indicate that the exhaust plumes could interact with the orbiter leading edge vortices to cause vortex burst. All these effects are potentially very powerful, as they influence the delta wing lift. They therefore require further investigation. Steps that can be taken to alleviate the adverse damping effects already discovered are pointed out in the back-up paper. Perhaps the most universally effective action is to add mechanical damping to all interstage structures to increase the effective structural damping of all elastic modes.

References

[1] Ericsson, L. E., and Reding, J. P., "Analysis of Flow Separation Effects on the Dynamics of a Large Space Booster," *Journal of Spacecraft and Rockets,* Vol. 2, July-Aug. 1965, pp. 481-490.

[2] Rainey, G., "Progress on the Launch Vehicle Buffeting Problem," *Journal of Spacecraft and Rockets,* Vol. 2, May-June 1965, pp. 289-299.

[3] Reding, J. P., and Ericsson, L. E., "Unsteady Aerodynamic Analysis of Space Shuttle Vehicles, Part III: Booster Interference Effects," LMSC-D352320, Part III, Aug. 1973, Contract NAS 8-28130, Lockheed Missiles & Space Company, Inc., Sunnyvale, Calif.