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Application of a Tip-Fin Controller to the Shuttle Orbiter for Improved Yaw Control

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One of the major development problems of the space shuttle orbiter has been to obtain yaw control during entry while the orbiter is transitioning from a high angle of attack, low dynamic pressure regime to a low angle of attack, higher dynamic pressure regime (Mach number from 15 to 1.5). Since for most of this time the rudder is ineffective, aerodynamic yaw control is provided by the aileron. This dependence on the aileron for yaw control causes concern because: 1) the aileron-yaw characteristics are very dependent upon elevator trim position; and 2) there are uncertainties in extrapolating the aileron characteristics determined in the wind tunnel to flight conditions. In response to these concerns, a configuration modification that would add small wing tip-fin controllers and remove the vertical tail has been examined. Wind-tunnel data obtained on this configuration from Mach numbers of 0.3 to 4.63 show that the tip-fin controller is a very effective yaw-control device with essentially no roll interaction in the supersonic flight regime. Preliminary structural analysis indicates that this modification results in a significant weight savings, and six-degree-of-freedom entry stability and control analyses show that the reaction control system could be deactivated much sooner than is presently possible with the nominal orbiter configuration.

Nomenclature

b	= reference span, m
C_D	= drag coefficient = drag/qS
C_ℓ	= rolling-moment coefficient = rolling moment/qSb
C_n	= yawing-moment coefficient = yawing moment/qSb
C_{ℓ_β}	= $\partial C_\ell/\partial\beta$, deg^{-1}
C_{n_β}	= $\partial C_n/\partial\beta$, deg^{-1}
$C_{n_{\delta_a}}$	= $\partial C_n/\partial_a$, deg^{-1}
p	= roll rate about the body axis, deg/s
α	= dynamic pressure, Pa
S	= reference area, m^2
q	= angle of attack, deg
β	= angle of sideslip, deg
δ_a	= aileron deflection = $(\delta e_\ell - \delta e_r)/2$, deg
δ_e	= elevator deflection = $(\delta e_\ell + \delta e_r)/2$, deg
δ_{e_ℓ}	= left elevon deflection, positive when trailing edge is down, deg
δ_{e_r}	= right elevon deflection, positive when trailing edge is down, deg
$(\delta_e)_{\text{typical}}$	= representative elevator time history, deg
δ_{SB}	= speed-brake deflection, both controllers deflected outboard, deg
δ_{TF}	= tip-fin controller deflection, positive right controller deflected, deg
Φ	= roll angle, deg
Φ_c	= commanded roll angle, deg
$(\Delta C_D)_{\delta_{SB}}$	= increment in C_D due to speed-brake deflection
ΔC_ℓ	= increment in C_ℓ
ΔC_n	= increment in C_n

Introduction

ONE of the major development problems of the space shuttle orbiter has been to obtain yaw control during entry when the orbiter is transitioning from a high angle of attack, low dynamic pressure regime to a low angle of attack, higher dynamic pressure regime. This transition period, shown in Fig. 1, lasts 550 s during which the Mach number decreases from 15 to 1.5. For most of this time, the rudder is ineffective, since it is shielded from the flow by the body at high angles of attack.[1] During the transition, the adverse yaw, due to aileron deflection, is used for directional trim.

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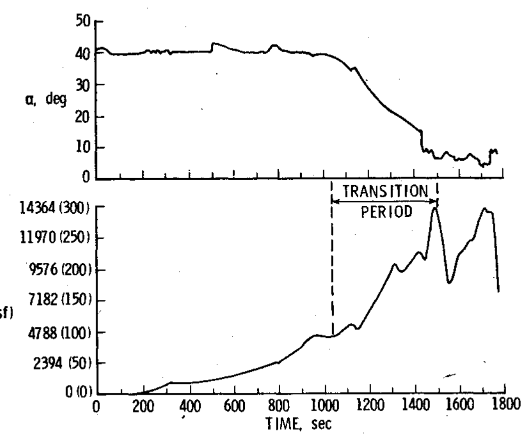

Fig. 1 Typical space shuttle orbiter entry.

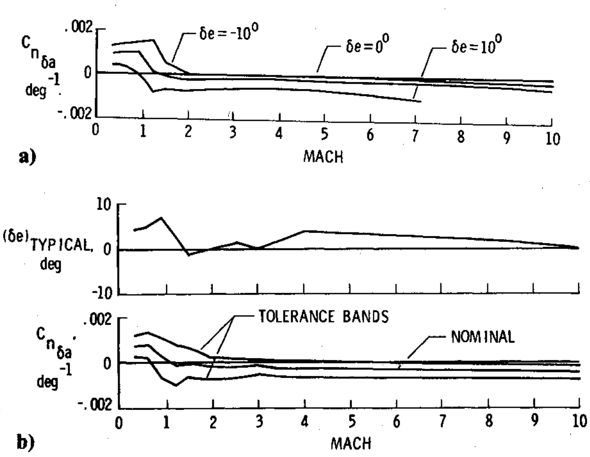

Fig. 2 Aileron yaw characteristics of space shuttle orbiter: a) sensitivity to δ_e; b) uncertainty boundaries using typical elevator history.

These requirements to use the ailerons for directional trim create two concerns. The first is that the aileron-yaw characteristics are a function of elevator trim deflection. The elevons are deflected symmetrically to provide pitch control (elevator), and differentially to provide lateral-directional control (aileron), and the body flap and speed brake are used to bias the pitch trim so that the elevator setting is always near the optimum position for aileron-yaw control. If the body flap and speed brake are extended to near their limits and cannot provide this pitch-trim bias, the elevator will move away from this optimum position. The second is that the uncertainties in the extrapolation of wind-tunnel-derived aerodynamic data to flight conditions result in a relatively large band of aerodynamic characteristics for the orbiter. For example, the aileron-yaw characteristics will switch from adverse to proverse somewhere during the entry. If the uncertainties are considered, this switch can occur anywhere between Mach 5 and Mach 1. Figure 2 illustrates the sensitivity of the aileron-yaw characteristics to elevator position and the band of uncertainties for a typical elevator history. These concerns have led to studies that would eliminate this high dependence on the yaw characteristics of the aileron for future space transportation systems.

One concept that may replace the space shuttle in the future is a single-stage-to-orbit (SSTO) vehicle. One solution found for the aileron dependence problem for the SSTO vehicle[2,3] was to replace the centerline vertical tail with small tip-fin controllers that were designed to provide control authority only, and were not designed to augment stability. These controllers not only reduced the dependence on the aileron to augment yaw control, but they also led to decreased inert weight and less reaction control system fuel consumption.[2] In addition, they allowed the reaction control system to be deactivated much earlier (Mach $\approx$ 10) than is possible with the current shuttle configuration (Mach = 1). This eases the reaction control system design problem, and eliminates the aerodynamic interference effects. Because the tip-fin controller proved to be such a promising candidate in these advanced vehicle studies, it is now being analyzed as a possible product improvement item for the shuttle orbiter.

Alterations to Current Orbiter Design

The suggested alterations to the space shuttle orbiter are shown in Fig. 3. Note that the only modifications are to remove the vertical tail and add the controllers. The details of attaching the tip-fin controller to the wing are shown in Fig. 4. The wing span has to be reduced slightly because the tip of the current orbiter wing is a carbon cap. This cap must be modified and the tip-fin controller attached to the main and rear spars. Preliminary inert weight reduction obtained by removing the vertical tail and adding the tip-fin controllers is estimated to be $\approx$900 kg (2000 lb). The final weight savings will not be known until the completion of: 1) detailed structural analyses, 2) aeroelastic evaluation, 3) heating analyses, 4) evaluation of tip-fin controller as a speed brake, and 5) cross-wind landing requirements.

Aerodynamic Data

The studies to date have concentrated on developing a flight-control system that utilizes the tip-fin controller. To obtain aerodynamic data that would be applicable, tip-fin controllers were added to an existing 0.165-scale orbiter model and tested in various NASA Langley Research Center wind tunnels to provide aerodynamic data from Mach 0.3 to Mach 4.63. Typical tip-fin controller data are shown in Fig. 5. The results from these tests and tests of a similar configuration show that the tip-fin controller is an effective yaw control device from subsonic to hypersonic speeds with the additional advantage that above Mach 1 there is very little roll interaction. Figure 6 shows the comparison of the lateral-directional characteristics of the orbiter with the vertical tail

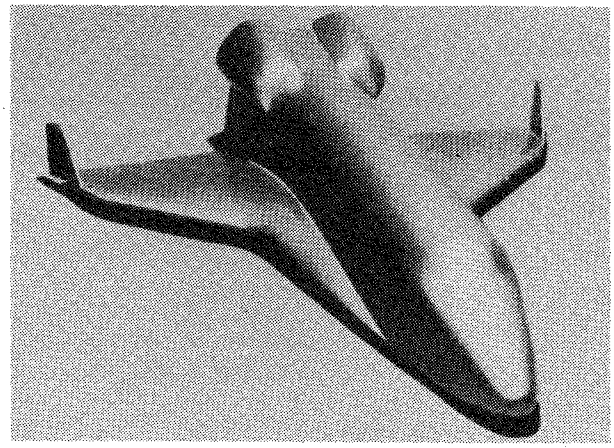

Fig. 3 Orbiter with tip-fin controllers.

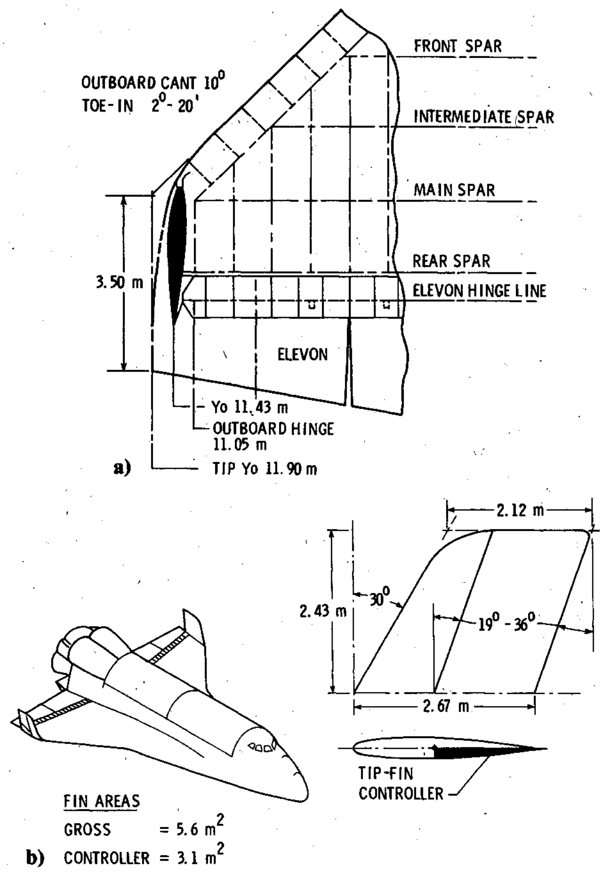

Fig. 4 Detail of tip-fin controller attachment to wing.

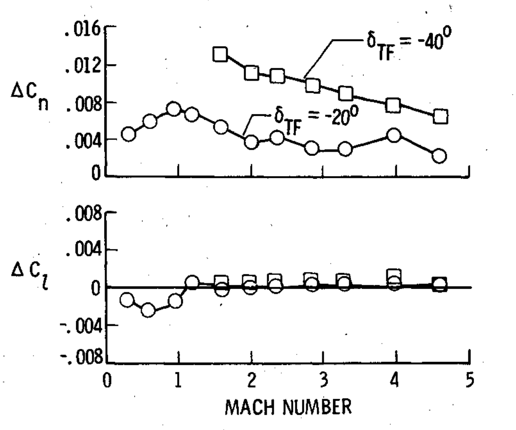

Fig. 5 Tip-fin controller effectiveness.

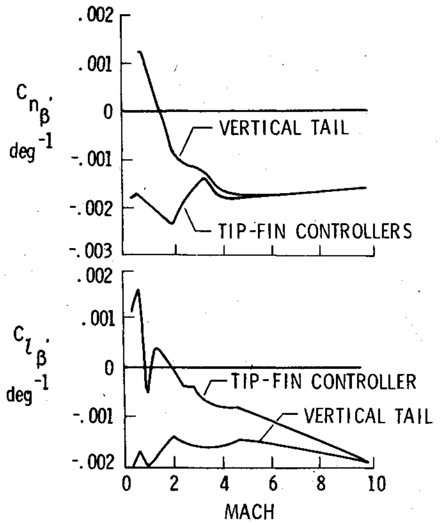

Fig. 6 Comparison of static lateral-directional characteristics of orbiter with vertical tail and with tip-fin controllers.

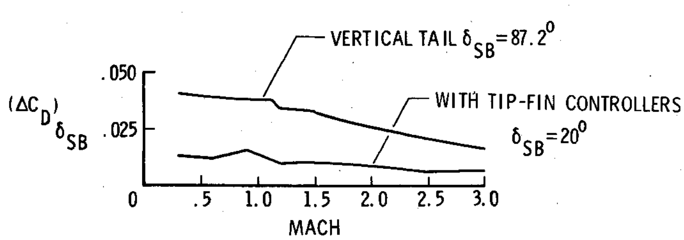

Fig. 7 Comparison of speed-brake effectiveness of orbiter with vertical tail and with tip-fin controllers.

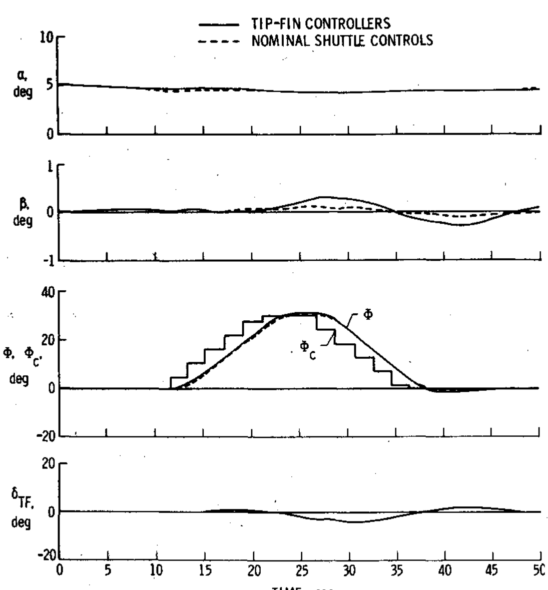

Fig. 8 Comparison of responses of orbiter with tip-fin controllers and with nominal controls to a commanded maneuver initiated at Mach 0.7.

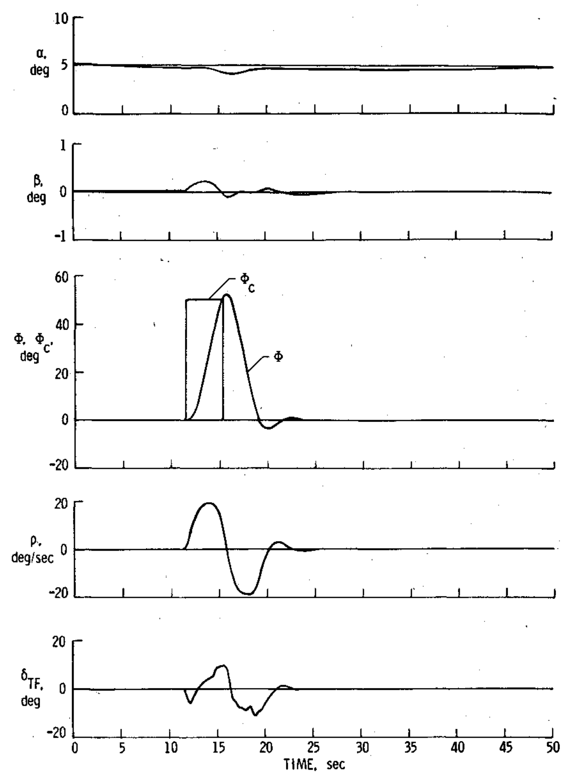

Fig. 9 Response of orbiter with tip-fin controllers to high roll-rate required maneuvers initiated at Mach 0.7.

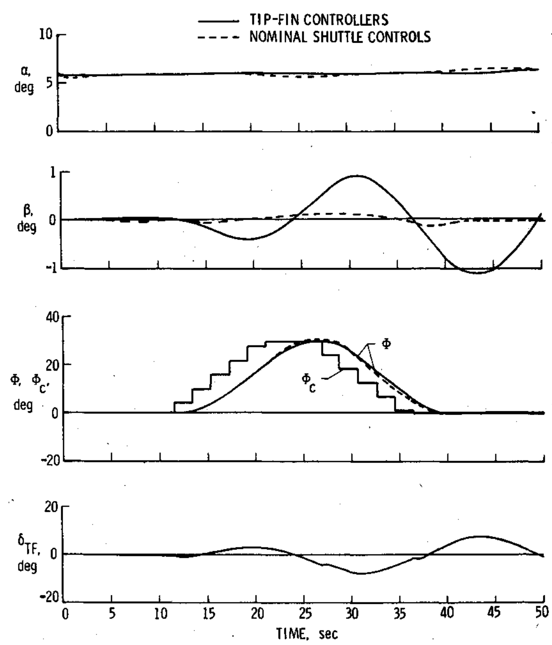

Fig. 10 Comparison of responses of orbiter with tip-fin controllers and with nominal controls to a commanded maneuver initiated at Mach 1.5.

and the orbiter with the vertical tail removed and tip-fin controllers installed. As expected, removal of the vertical tail reduces the lateral-directional static stability of the orbiter. The removal of the vertical tail also removed the speed brake. (Speed brake on the orbiter is provided by a flared rudder). Nominal control philosophy for the tip-fin controller is to deflect one control surface outward into the flow. In this study, the speed-brake function is provided by deflecting both controller surfaces symmetrically into the flow, and the deflection required for control is added to this symmetrical deflection. Figure 7 shows the speed-brake drag comparison between the orbiter with the vertical tail and the orbiter with the tip-fin controller. The nominal orbiter control philosophy does not activate the speed brake for energy management until Mach 0.9. Since the tip-fin controller, as currently designed, is not as effective as the orbiter speed brake, it is

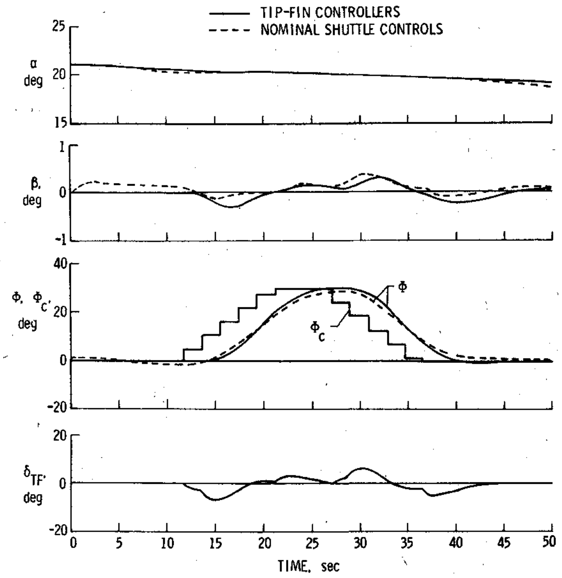

Fig. 11 Comparison of responses of orbiter with tip-fin controllers and with nominal controls to a commanded maneuver initiated at Mach 5.

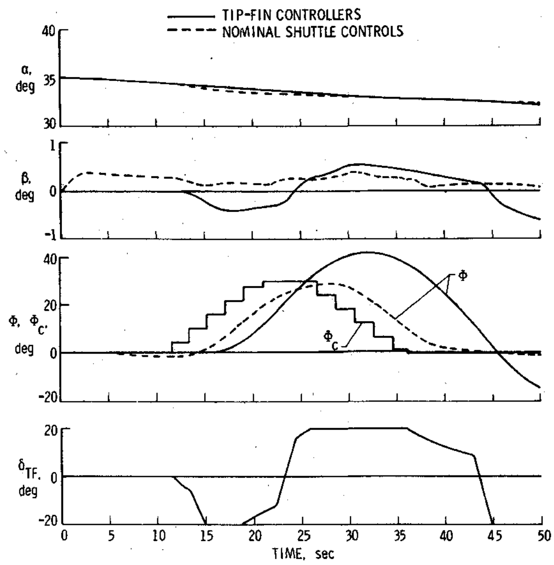

Fig. 12 Comparison of responses of orbiter with tip-fin controllers and with nominal controls to a commanded maneuver initiated at Mach 10.

activated earlier. Preliminary analysis shows that this is acceptable.

Flight Control System

The philosophy of the flight control system design was to modify a typical shuttle control system by removing the rudder circuit and adding a circuit for the tip-fin controller. This circuit was modeled after the one used for the yaw reaction control system with the addition of a trim loop. The gains were selected by a six-degree-of-freedom trajectory optimization and targeting program known as 6D POST.[4] This was done by choosing four design points (Mach numbers of 0.7, 1.5, 5, and 10) and having the program compute the optimal gain to follow a prescribed roll history.

This commanded roll history was formed by replacing the commanded roll angle logic of the guidance algorithm with one that required the orbiter to roll over and then roll back. The staircase effect shown in Figs. 8-13 is a result of the guidance algorithm only being interrogated every 1.92 s, which is typical for the orbiter during most of the entry.

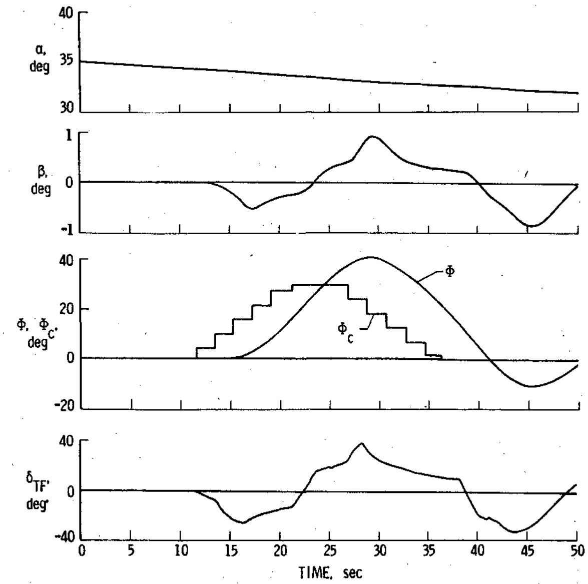

Fig. 13 Response of orbiter with tip-fin controller to a commanded maneuver initiated at Mach 10 with maximum deflection limits increased to 40 deg.

Figure 8 shows the design point initiated at Mach 0.7 using the tip-fin controller. The dashed lines show the response with the current orbiter to the same command. The only apparent difference between the two responses is that the tip-fin controller case has slightly more sideslip (β). For this initial study, the gains were chosen with no consideration of sideslip angles. If cases are found where the sideslip angles are unacceptable with this approach, the gains will have to be recomputed. At low speeds, the required roll rate could be higher than that used to design the control system. Figure 9 shows the response if a higher roll rate, in this case 20 deg/s, is required. Even at this higher rate, the maximum sideslip angle is small and the maximum tip-fin controller deflection is less than 12 deg.

Figure 10 shows the comparison for the maneuver initiated at Mach 1.5. In this case, sideslip angles are larger with the tip-fin controller, but the orbiter is still controllable. Figure 11 shows that the maneuvers are nearly identical at Mach 5. The nominal orbiter control requires the yaw reaction control system, but the tip-fin controller maneuver does not.

Figure 12 shows the comparison with the maneuver initiated at Mach 10. The entry control philosophy with the tip-fin controller is that, to minimize heating problems, it will not be activated until Mach 10. In addition, the maximum allowable deflection from initiation until supersonic speeds is 20 deg. Because of this, the tip-fin controller, with no aid from the reaction control system, cannot perform a satisfactory maneuver. Either the reaction control system will have to remain active until a lower Mach number, or a larger deflection of the controller will be required, or both. Figure 13 shows the maneuver with a maximum allowable deflection of 40 deg. This shows improved results, but it is still not completely satisfactory.

To confirm that the design points had resulted in a workable control system design, a complete entry was simulated with the tip-fin controller activated and the reaction control system deactivated at Mach 10. This maximum deflection of the controller at hypersonic speeds was limited to 20 deg. Figure 14a shows this entry, with Fig. 14b showing the nominal shuttle orbiter entry for comparison. Mach 10 occurs approximately 1100 s into the entry. A comparison of Figs. 14a and 14b shows that the roll maneuver that occurs near Mach 10 does overshoot, as was predicted by the design point; however, the orbiter recovers and executes a safe landing.

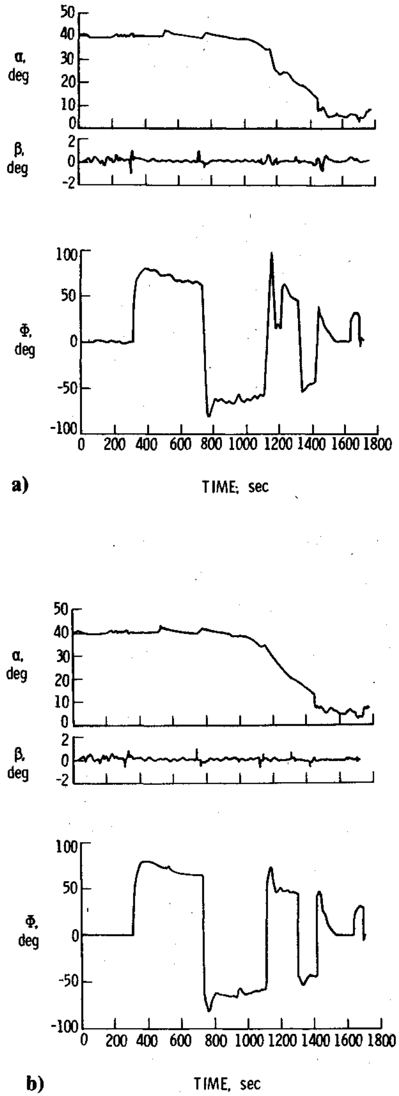

Fig. 14 Orbiter entry: a) tip-fin controller; b) nominal shuttle controls.

The total entry with the tip-fin controller consumed ≈75 kg (170 lb) less reaction control system fuel than the nominal entry. While this is not a large savings, two thoughts should be noted. The first is that if the orbiter encounters winds, has a larger lateral center-of-gravity offset, must maneuver more, etc., the fuel savings will increase. The second is that the tip-fin controller allows the reaction control system to be deactivated much sooner than for the nominal orbiter, which eliminates the uncertainties in the predicted aerodynamics because of interaction from firings of the reaction control system.

One major flight control analysis that must be conducted is to evaluate the ability of the tip-fin controllers to handle cross-wind landings. Additional low-speed wind-tunnel tests are planned to refine the data base. If the tip-fin controller is unable to handle cross-wind landings, then additional modifications will be required. Preliminary concepts include the deployment of an additional control surface with the nose gear, use of a crabbing landing gear, or a larger controller.

Conclusion

Both aerodynamic and flight control analyses have shown that use of the tip-fin controller and removal of the centerline vertical tail does result in improved flyability for the orbiter in the supersonic speed regime. Preliminary system design studies have shown that removal of the centerline vertical tail and installation of the tip-fin controllers could result in as much as a 900 kg (2000 lb) weight saving. Additional studies are being initiated to assess the aeroheating, aeroelastic, and cross-wing landing problems associated with use of the tip-fin controller.

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