Aerodynamic Control of the Space Shuttle Orbiter with Tip-Fin Controllers

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A feasibility study to assess the benefits/penalties of installing tip-fin controllers on the Space Shuttle Orbiter has been conducted. The results from the aerodynamic and stability and control assessment of this study are presented. These results show that using tip-fin controllers with the centerline vertical tail removed provides adequate control for entry. The orbiter basic maneuvering capability is maintained, and symmetrical deflection of the controllers provides adequate speedbrake authority for energy management. Gust analyses of the orbiter with the tip-fin controller configuration have demonstrated no compromise of existing cross-wind landing capability. Six-degree-of-freedom simulations have shown the tip-fin controllers can provide adequate control for entry with no degradation in vehicle capability.

Nomenclature

b = reference span, ft
C_D = drag coefficient = drag/q S
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}
q = dynamic pressure, psf
S = reference area, ft^2
t = time, s
YAW RCS = number of yaw reaction control system thrusters firing (positive—right side thrusters)
α = angle of attack, deg
β = sideslip angle, deg
δ_a = aileron deflection, $(\delta_{e_\ell} - \delta_{e_r})/2$, deg
$\delta_{e\ell}$ = left elevon deflection (positive down), deg
δ_{e_r} = right elevon deflection (positive down), deg
δ_r = rudder deflection (positive trailing edge left), deg
δ_{SB} = speed-brake deflection, deg
$\delta_{SB,c}$ = commanded speed-brake deflection, deg
δ_{tf} = tip-fin controller deflection $(\delta_{tf,\ell} - \delta_{tf,r})/2$, deg
$\delta_{tf,c}$ = Commanded tip-fin controller deflection, deg
$\delta_{tf,\ell}$ = left-side tip-fin controller deflection, deg
$\delta_{tf,r}$ = right-side tip-fin controller deflection, deg
ϕ = roll angle, deg
ϕ_c = commanded roll angle, deg
ω = gust frequency, rad/s

Introduction

THE NASA Langley Research Center is currently conducting studies to identify technology requirements that would be necessary to develop a second-generation space transportation system that could replace the Space Shuttle in the post 2000 time frame. One of the major development problems for winged entry vehicles (such as the Space Shuttle) is to obtain yaw control during entry while the vehicle is transitioning from a high angle-of-attack, low dynamic pressure regime to a low angle-of-attack, higher dynamic pressure regime. Since, for most of this time, a vertical tail would be shielded from the flow and thus ineffective, yaw control would have to be provided by the ailerons augmented by the reaction control system (the control concept used by the Space Shuttle).

Because of the problems inherent in depending on the aileron as the only aerodynamic yaw producer, and because the vertical tail can only be used at low angles of attack during the last few minutes of flight, alternative designs are being investigated. References 1 and 2 describe initial studies on the most promising alternative approach to date. This approach involves removing the vertical tail and adding small tip-fin controllers to the wing tips. These controllers are small and are not designed to provide stability. They only provide yaw control. A feasibility study has been conducted because of the following advantages found from using this approach[1,2]: 1) a weight savings when compared to the vertical tail configuration, 2) the reaction control system can be deactivated at low hypersonic speeds (as compared to Mach 1 for the Space Shuttle), 3) reduced dependence on the yawing moment of the aileron, and 4) improved payload handling because of the removal of the vertical tail.

The Space Shuttle was chosen for this feasibility study because of the availability of detailed data and the opportunity to compare the tip-fin controller configurations to an operational vehicle. In this study, wind-tunnel tests have been made to determine the orbiter aerodynamics with the tip-fin controllers and to measure the aerodynamic heating on the fin and adjoining wing structure. A thermo-structures analysis has been made to design the structure and thermal protection necessary to add the tip-fin controller to an orbiter, and six-degree-of-freedom entry simulations have been made to assess the stability and controllability using the controllers with the vertical tail removed.

This paper will discuss the following: 1) a comparison of the aerodynamics of the two configurations (Space Shuttle with and without tip-fin controllers); 2) the design of an entry flight control system; 3) a comparison of the response of the two configurations to a commanded roll maneuver at selected points along the entry; 4) the feasibility of using the tip-fin controllers as speed brakes, since the removal of the vertical tail of the Space Shuttle also removes the speed brake; 5) the impact of gusts on landing.

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Alterations to Current Orbiter Design

The alterations to the Space Shuttle Orbiter that were studied are (shown in Fig. 1) removal of the vertical tail and addition of the tip-fin controllers. The tip-fin controller shown in the figure has a total area (per side) of 60 ft^2, with a 33 ft^2 movable portion. This compares to the total area of the current vertical tail of 369.1 ft^2 of which 97.1 ft^2 is a movable rudder. The maximum tip-fin controller deflection is 60 deg. compared to approximately 27 deg for the rudder, and the tip-fin controller rate is 60 deg compared to a maximum of 14 deg for the rudder. Because of heating considerations, the tip-fin controller is not deflected above Mach 10 and the deflection is limited to 45 deg at Mach 10. This limit increases with decreasing Mach number so that at Mach 8, the maximum deflection of 60 deg is available.

Aerodynamic Data

The aerodynamic data for the Space Shuttle with tip-fin controllers were obtained from wind-tunnel tests at the NASA Langley Research Center and the NASA Ames Research Center. The initial data indicated that at low Mach numbers ($M<1$), the configuration exhibited a large negative dihedral effect ($C_{l_\beta}>0$).[2] These data were obtained in the NASA Langley Research Center's 8-Foot Wind Tunnel, which provided a Reynolds number, based on body length, of only 5×10^6 Mach 0.6, which is much lower than the flight Reynolds number of 216×10^6.

Figure 2 indicates that at the higher Reynolds numbers the large negative dihedral effect was reduced to near zero. Figure 3 shows the control characteristics measured in these tests. Shown also for comparison are the characteristics of the baseline Space Shuttle Orbiter. The figures show that the tip-fin controller is an effective yaw control device at hypersonic to subsonic speeds with the additional advantage that there is very little roll interaction above Mach 1. However, subsonically the tip-fin controller is less effective than a 10-deg rudder deflection for the current orbiter. No wind-tunnel data are available for tip-fin controller deflections of 60 deg between Mach 1 and 3. In addition to having less control authority subsonically, the tip-fin controller configuration is directionally unstable, whereas the current Shuttle orbiter is stable. Also, the tip-fin controller configuration has a lower dihedral effect than the current Shuttle configuration.

The removal of the vertical tail also removed the speed brake. (Speed brake on the current orbiter is provided by a flared rudder.) The nominal control philosophy for the tip-fin controller is to deflect the control surface outward into the flow. For this study, the speed-brake function is provided by deflecting both controller surfaces symmetrically into the flow. This was implemented into the control system as follows. Since the speed brake is the average of the tip-fin controller deflection, $\delta_{SB}=0.5\ (\delta_{tf,l}+\delta_{tf,r})$, a tip-fin controller deflection command will also command a speed-brake deflection related by $\delta_{SB,c}=0.5\delta_{tf,c}$. If the commanded speed-brake deflection is larger than this, both surfaces are commanded to deflect so that both the desired tip-fin controller deflection and speed-brake deflection are commanded. If this would command one surface beyond its 60 deg limit, the speed-brake command is modified to keep the maximum commanded surface deflection at 60 deg.

Figure 4 shows the speed-brake drag comparison between the orbiter with vertical tail and the orbiter with the tip-fin controllers. The speed-brake deflection was limited to 40 deg for the tip-fin controller configuration, as compared to 87.2 deg for the baseline orbiter. As seen in Fig. 4, the maximum speed-brake drag capability of the tip-fin controller configuration is less than the baseline speed-brake drag capability. Thus the guidance algorithm was modified to command the speed brake for energy management to begin at Mach 2.5 instead of the Mach 0.9 currently used for the Shuttle.

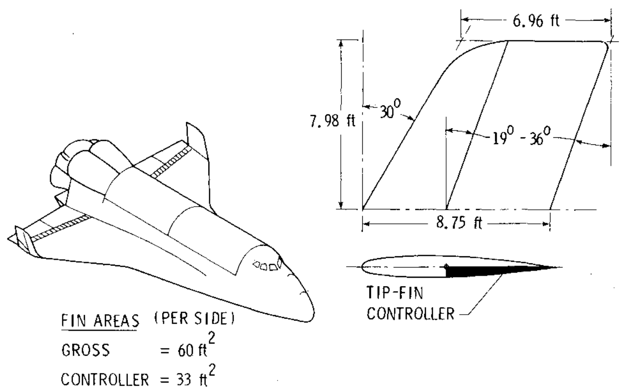

Fig. 1. Orbiter with tip-fin controllers.

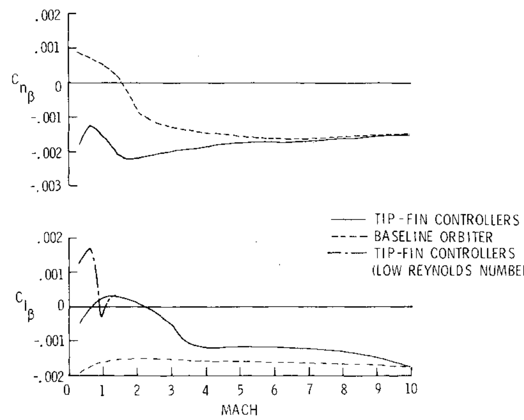

Fig. 2 Comparison of static lateral-directional characteristics of orbiter with vertical tail and with tip-fin controllers.

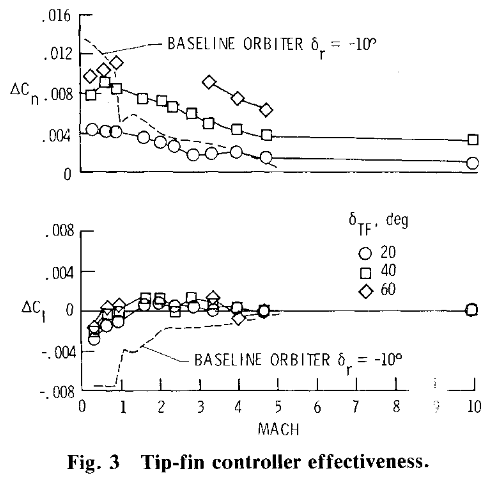

Fig. 3 Tip-fin controller effectiveness.

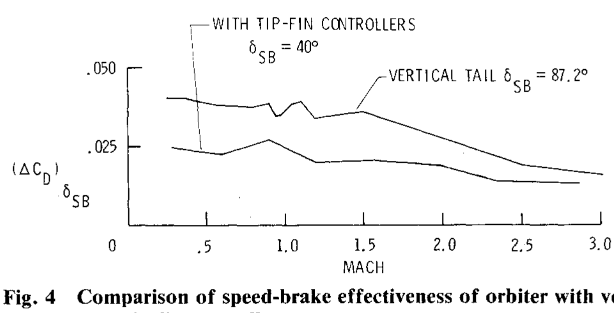

Fig. 4 Comparison of speed-brake effectiveness of orbiter with vertical tail and tip-fin controllers.

Flight Control System

The philosophy of the flight control system design was to develop separate designs for Mach numbers greater than and less than 4. The design above Mach 4 is a Space Shuttle Orbiter control system modified to include a circuit for the tip-fin controller. The commanded tip-fin controller deflection is based on the commanded yaw reaction control system, (RCS) signal. In addition, the RCS is deactivated at Mach 7 instead of Mach 1 for the baseline orbiter. Reference 3 describes the entry flight control system for the baseline orbiter. Because of the different lateral-directional stability characteristics and directional control characteristics for Mach numbers less than 4, a new control system design was required.

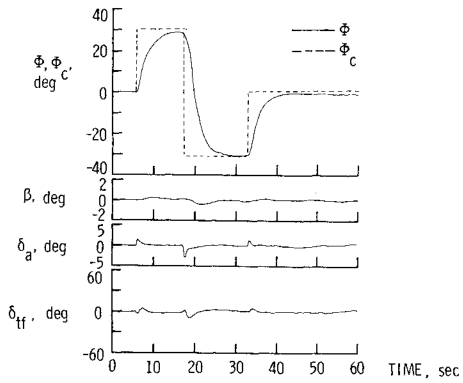

Fig. 5 Shuttle with tip-fin controllers response to a Mach 0.6 maneuver.

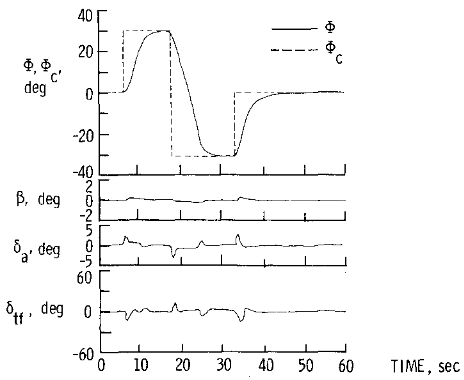

Fig. 6 Shuttle with tip-fin controllers response to a Mach 1.5 maneuver.

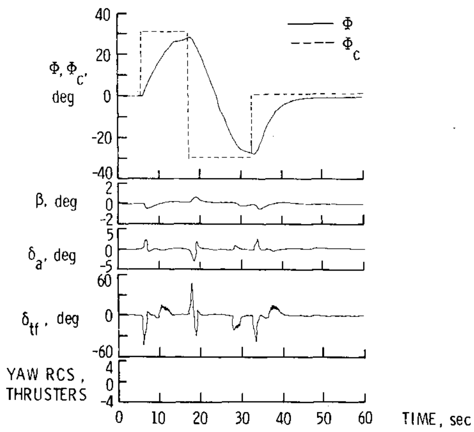

Fig. 7 Shuttle with tip-fin controllers response to a Mach 5.0 maneuver.

Figures 5-8 show the basic capability of the tip-fin controller configuration to maneuver at various points along the entry. To stress the control system, the ϕ_c signal from the guidance algorithm was replaced by one which required the vehicle to roll from 0 to 30 deg, then roll to -30 deg, and then to 0 deg. This ϕ_x is shown by the dashed lines of Figs. 5-8. The ϕ and β responses at Mach 0.6 and 1.5, Figs. 5 and 6, indicate that the orbiter is controllable without requiring excessive tip-fin controller deflections. The Mach 5 responses, Fig. 7, show that this vehicle is controllable at low hypersonic speeds without requiring the use of the RCS. The response at Mach 10 is shown in Fig. 8. The control system utilizes both the tip-fin controller and the RCS. A complete entry was simulated using the tip-fin controller configuration and a similar simulation for the current Space Shuttle. The responses during the entry were nearly identical, except that the tip-fin controller configuration uses approximately 100 lbs less RCS fuel. Overall, the basic responses of the tip-fin controller configuration is similar to the current Space Shuttle.

Speed-Brake Capability

As mentioned in the aerodynamic data section, the speed-brake capability of the tip-fin controller is less than that of the current Shuttle. To compensate for this difference, the terminal area energy management (TAEM) guidance algorithm was modified so that the speed brake would be used for energy management when the Mach number reached 2.5 instead of 0.9. The TAEM algorithm directs the Shuttle from Mach 2.5 until it is subsonic and aligned with the runway. The current

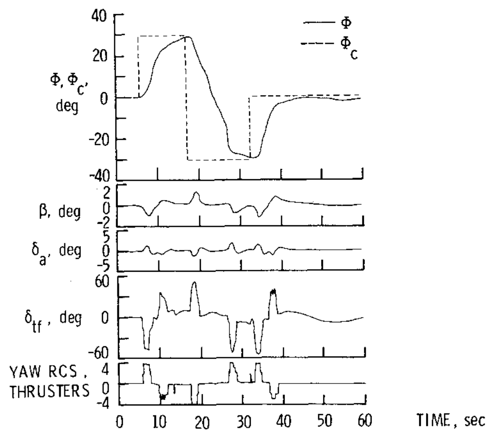

Fig. 8 Shuttle with tip-fin controllers response to a Mach 10 maneuver.

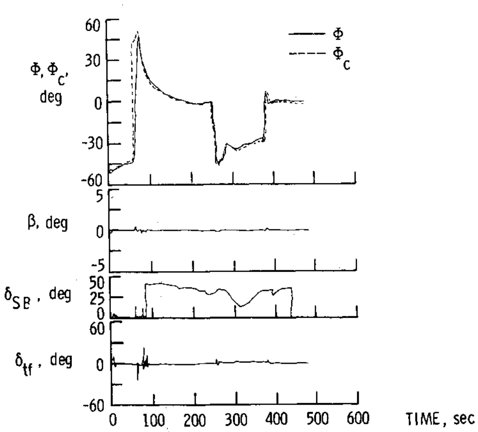

Fig. 9 Shuttle with tip-fin controllers response from Mach 4 to touchdown with no wind.

Shuttle configuration schedules the speed brake from Mach 10 to 0.9 to aid in pitch trim. Figure 9 shows responses of the tip-fin controller configuration from Mach 4 to touchdown with no wind. Examination of the response of the tip-fin controller configuration shows that the speed brake is commanded to its limit of 40 deg upon entering the TAEM phase (about 80 seconds after Mach 4), and then it starts modulating for energy control.

To stress the speed brake, steady-state winds of 50 ft/s (about 30 knots) were simulated. These winds were initiated at an altitude of 50 kft and continued until touchdown. The tip-fin controller configuration was subjected to a head wind (Fig. 10), a cross wind, and a quartering head wind. The analysis showed that this configuration does have an adequate sped brake with the modifications to the TAEM guidance algorithm.

Gust Analysis

Because the tip-fin controller configuration does not have the yawing-moment capability of the rudder of the current Shuttle configuration, an analysis was made of the tip-fin controller configuration landing in a cross wind with gusts. The TAEM guidance algorithm directs the vehicle down to about 10 kft above the runway. At this point, the vehicle is aligned with the runway, and very little roll maneuvering is required.

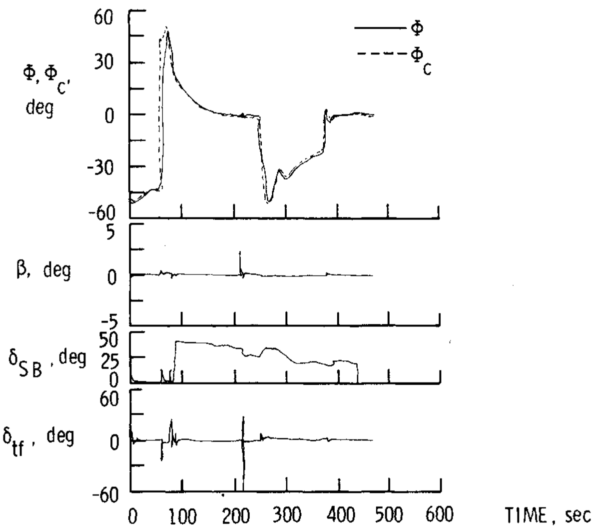

Fig. 10 Shuttle with tip-fin controllers response from Mach 4 to touchdown with 50 ft/s head wind.

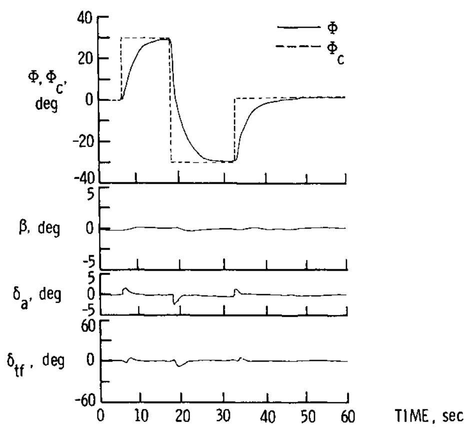

Fig. 11 Shuttle with tip-fin controllers response to a Mach 0.6 maneuver with a 50 ft/s cross wind.

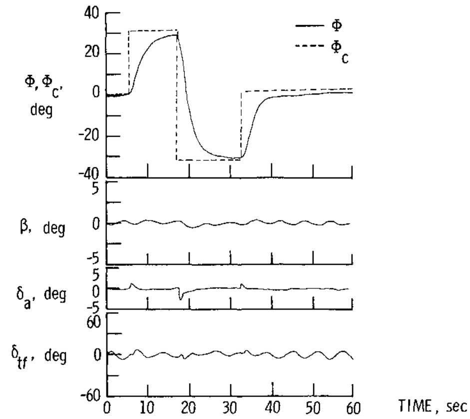

Fig. 12 Shuttle with tip-fin controllers response to Mach 0.6 maneuver with a 40 ft/s steady-state cross wind and a 10 ft/s gust at a frequency of 1 rad/s.

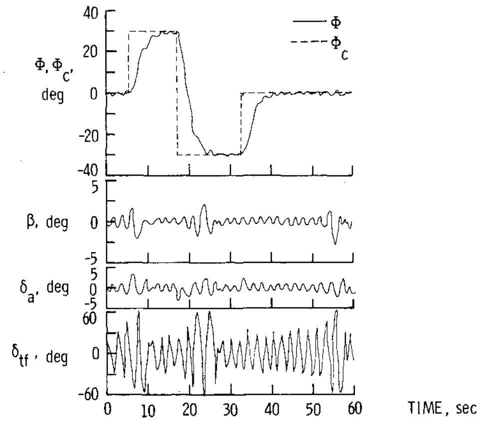

Fig. 13 Shuttle with tip-fin controllers response to Mach 0.6 maneuver with a 40 ft/s steady-state cross wind and a 10ft/s gust at a frequency of 3 rad/s.

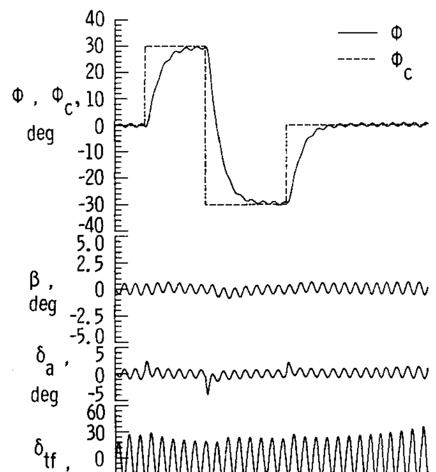

Fig. 14 Shuttle with tip-fin controllers to a Mach 0.6 maneuver with a 40 ft/s steady-state cross wind and a 10 ft/s gust at a frequency of 3 rad/s with a maximum tip-fin controller deflection rate of 80 deg/s.

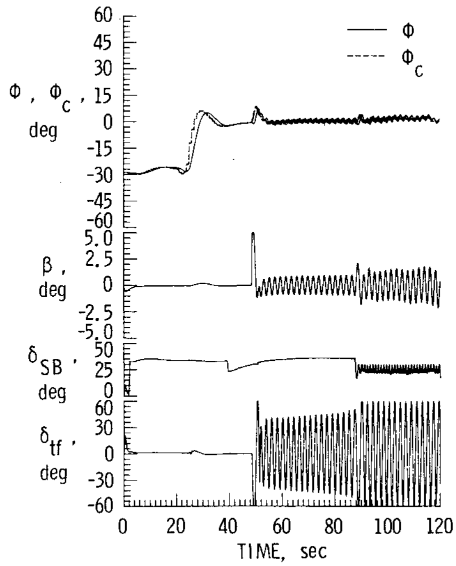

Fig. 15 Shuttle with tip-fin controllers response from an altitude of 20 kft to landing with a 40 ft/s steady-state cross wind and a 10 ft/s gust at frequency of 3 rad/s.

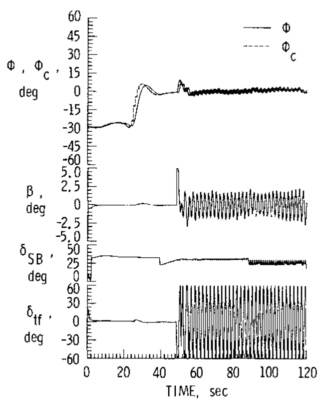

Fig. 16 Shuttle with tip-fin controllers response of orbiter with tip-fin controllers from an altitude of 20 kft to landing with a 40 ft/s steady-state cross wind and a 20 ft/s gust at a frequency of 3 rad/s with a maximum tip-fin controller deflection rate of 80 deg/s.

Therefore, maneuvering in gusts, using the same commanded maneuver that was used for the basic maneuvering analysis was considered. The gust was modeled as a cosine function with an amplitude of 10 ft/s (10 cosωt), where the frequency was varied from 0 to 10 rad/s to determine if there was a critical frequency. This gust was added to a steady-state wind component of 40 ft/s, and this combination was applied to the vehicle as a cross wind. This method of analysis was chosen to stress the vehicle more than would be expected in actual flight. Figure 11 shows the response with $\omega = 0$, which corresponds to a steady-state wind of 50 ft/s. The vehicle performed the required maneuver satisfactorily. Figure 12 shows the response with $\omega = 1$ rad/s. This gust frequency can be seen in the β response. The vehicle performed this maneuver well also. The critical frequency for the tip-fin controller configuration is shown in Fig. 13. (The current Shuttle does not have a critical frequency in this frequency range of $\omega = 0 - 10$ rad/s.) At $\omega = 3$ rad/s, $|\beta|$ reached a maximum of 2.5 deg, and the tip-fin controller reached its deflection limit often during the maneuver. Figure 14 shows the case at the critical frequency of 3 rad/s with the maximum tip-fin controller deflection rate increased from 60 to 80 deg/sec. With this increased rate, the $|\beta|$ was reduced to 1 deg, and the tip-fin controller never reached its deflection limit.

Once the critical frequency was determined, the actual landing maneuver was examined. Figure 15 shows the entry from 19 kft to touchdown with a cross wind simulated from an altitude of 10 kft to touchdown. This cross wind had a steady-state component of 40 ft/s and a gust component of 15 ft/s with a frequency of 3 rad/s, which is the critical frequency. The gust velocity of 15 ft/s is representative of the Space Shuttle design requirement. The vehicle entered the wind about 50 s after the initiation of the maneuver, as can be seen by the large β excursion, and it landed successfully. The gust velocity was increased to 20 ft/s (Fig. 16) to demonstrate the margin available with the tip-fin controller. Even though the controller reached its deflection limits often during the landing maneuver, the vehicle remained controllable.

Conclusions

The flight control analysis for the Space Shuttle Orbiter utilizing tip-fin controllers instead of the centerline vertical tail has shown that the tip-fin controller can adequately control the orbiter during entry. The basic maneuvering capability of the two configurations (current Shuttle orbiter and Shuttle orbiter with tip-fin controllers) are similar. The drag capability of the tip-fin controllers when used as a speed brake is only approximately 65% of that for the current Shuttle speed brake. This reduced drag capability requires a modification to the terminal area energy management guidance algorithm. The gust analysis showed that the tip-fin controller configuration would be able to tolerate gusts during landing. Overall, the Shuttle orbiter with tip-fin controllers can successfully perform the required maneuvers during entry.

References

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[2]Powell, R. W. and Freeman, D. C. Jr., "Application of a Tip-Fin Controller to the Shuttle Orbiter for Improved Yaw Control," *Journal of Guidance, Control and Dynamics,* Vol. 19, July-Aug. 1982, pp. 325-329.