Control Techniques to Improve Space Shuttle Solid Rocket Booster Separation

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The present Space Shuttle's control system does not prevent the Orbiter's main engines from being in gimbal positions that are adverse to solid rocket booster separation. By eliminating the attitude error and attitude rate feedback just prior to solid rocket booster separation, the detrimental effects of the Orbiter's main engines can be reduced. In addition, if angular acceleration feedback is applied, the gimbal torques produced by the Orbiter's engines can reduce the detrimental effects of the aerodynamic torques. This paper develops these control techniques and compares the separation capability of the developed control systems. Currently with worst case initial conditions and each Shuttle system dispersion aligned in the worst direction (which is more conservative than will be experienced in flight), the solid rocket booster has an interference with the Shuttle's external tank of 30 in. Elimination of the attitude error and attitude rate feedback reduces that interference to 19 in. Substitution of angular acceleration feedback reduces the interference to 6 in. The two latter interferences can be eliminated by less conservative analysis techniques, that is, by using a root sum square of the system dispersions.

Nomenclature

c.g. = center of gravity
g = acceleration of gravity (32.2 ft/s^2)
G_R = angular acceleration feedback roll gain
G_Y = angular acceleration feedback yaw gain
I.C. = initial condition, vehicle state
P = roll rate
Q = pitch rate
$\bar{Q}$ = dynamic pressure
R = yaw rate
rss = root sum squared
t_i = time to initiate angular acceleration feedback
t_f = time to end angular acceleration feedback
α = angle of attack
β = angle of sideslip
δ = engine gimbal angle

Background

THE Shuttle solid rocket boosters are separated from the Orbiter/external tank after their thrust-to-weight ratio becomes less than that of the Orbiter/external tank with one Orbiter engine out. They are attached to the external tank at one point on the forward end and at three points on the aft end. The forward attach point is used to transfer the thrust force from the boosters to the external tank and, at separation, requires the severing of only one bolt for the boosters to separate. The aft attach points consist of three struts which require the severing of three bolts (one in each strut) to separate. Simultaneously with the severing of the bolts, a signal to fire eight booster separation motors on each booster is given. Four booster separation motors are located in the forward frustum of the boosters and four on the aft skirt. These booster separation motors cause the boosters to move away from the external tank so that the Orbiter thrust can accelerate the Orbiter/external tank axially ahead of the boosters.

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The solid rocket booster separation is complicated by several factors. Since a rocket is coming off each side, the Orbiter cannot make a maneuver to the side to aid the separation. Consequently, the Orbiter simply flies in an attitude-hold mode. This leaves the booster separation motors to move the boosters out from the external tank and down from the Orbiter's wing while the Orbiter engines move the Orbiter forward of the boosters. However, the Orbiter engines are significantly above the Orbiter/external tank c.g. The Orbiter engines are canted for moment balance which causes the Orbiter's wings to move in the z direction (Fig. 1) toward the boosters. The booster separation motors must have sufficient thrust away from the wings so that the boosters will stay below (with respect to pilot orientation) the Orbiter wing until the axial acceleration puts the Orbiter/external tank ahead of the boosters.

The Orbiter/external tank is aerodynamically stable but the boosters are unstable; consequently, the aerodynamics cause opposite moments on the bodies which leads them to rotate toward each other. The aerodynamics are complicated by the bodies being in close proximity and a seven-way interpolation is required for the simulation. Since the Orbiter/external tank has a 0.9 g acceleration at nominal separation, the Orbiter/external tank does not move away from the boosters quickly. Also, the boosters' thrust decay is long, resulting in some residual thrust at separation and further lengthening the time for the booster to separate.

The solid rocket booster separation system has a design requirement[1] to provide a safe separation for the following initial conditions of separation: dynamic pressure $\bar{Q}$ of 0-75 psf, angle of attack in the range of ± 15 deg, angle of sideslip in the range of ± 15 deg, roll rate in the range of ± 5 deg/s, and pitch and yaw rates in the range of ± 2 deg/s. These values are derived from the maximum values that have occurred in early design ascent simulations. Estimations of the dynamic pressure are made by onboard calculations and to these are added the maximum uncertainty in the calculation. The separation is inhibited if the combination exceeds 75 psf. The ± 15 deg angle of attack and sideslip is a constraint on the attitude control system to assure that the vehicle is at or below these limits at the time of separation. The rates have inhibitors to prevent the separation from occurring when the design values are exceeded.

The analysis technique that is used to verify the adequacy of the separation system calls first for the examination of the worst combination of initial design conditions in conjunction with the worst combination of systems dispersions. If no interferences occur for this severe case, the system is verified. If an interference does occur, the effects of the system dispersions are root sum squared (rss). If no interference occurs, the system is verified. If an interference persists, the system is considered inadequate and ways to improve the separation are studied.

For the initial Shuttle flights where the dynamic pressure has been well below 75 psf, the separation system has been verified by this technique; however, at 75 psf significant separation interferences occur when using worst-on-worst techniques. This is caused primarily by the large aerodynamic uncertainty coefficients (tolerances). These coefficients are large because of several factors connected to the very complicated wind-tunnel tests. One of the major contributors to the uncertainty is the calibration of the thrust of the wind-tunnel model's booster separation motors. The effect of this thrust on the wind-tunnel sting supporting the solid rocket booster is large compared to the aerodynamics; consequently, an error in calibrating this thrust effect could be larger than the aerodynamic effect for which measurement is sought.

The prospective solid rocket booster separation collisions are with the external tank or with the Orbiter wings. Previous analysis has shown that the booster separation motors have sufficient thrust to prevent the boosters from colliding with the wings. Also, the interference aerodynamics at the nose of the boosters are sufficient to prevent a collision at the forward attachment of the boosters to the external tank. The separation at the aft attachment between the boosters and the tank remains the only persistent problem and, in particular, the interference of the booster's skin and the tank's lower strut stub (Fig. 2). Several factors contribute to this circumstance, some of which were mentioned in preceding paragraphs. The c.g. of the Orbiter/external tank is forward near the Orbiter nose; therefore, the lateral forces due to Orbiter engine deflections have a large moment arm and produce large movements at the aft end of the tank. Since the control system positions the engines and since engine positions play an important role in the separation, the control system will have an important part in either preventing or causing an aft end collision.

Control System Modifications

The present control system used during booster separation is an attitude-attitude rate scheme. When separation occurs, the attitude commands are initially set to the actual attitude to reduce adverse torques from the Orbiter engines. At separation the pitch trim command is updated to account for the c.g. shift at separation. The Orbiter engines' gimbal angles will be set initially at a position which will attempt to set the rates and attitude errors to zero. Because the attitude command is set equal to the actual attitude, the attitude error is initially set to zero, and the engines will be commanded to a position that will attempt to set the rates to zero and will also zero any new attitude errors that begin to accumulate due to rates.

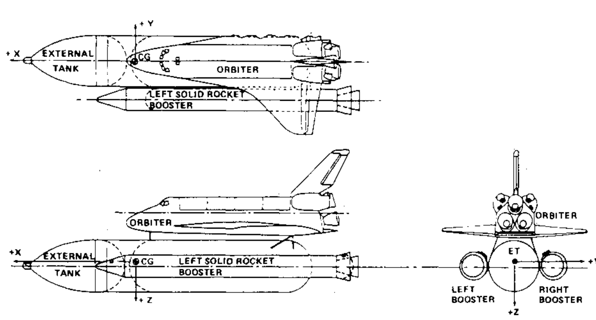

Fig. 1 Shuttle configuration.

The most desirable separation conditions are for the separating bodies not to accelerate toward each other. This means that the yaw and roll angular accelerations should be minimal, that is, the Orbiter yaw and roll rates should remain constant during separation. The same is true of the boosters, but the boosters are ballistic bodies of flight except for the impulse of the booster separation motors. Since the Orbiter has a control system, it is the only body that can be intelligently manipulated. If the engines were pointed at the c.g., then only the aerodynamics would produce the undesirable accelerations. If angular acceleration feedback were employed, the control system would attempt to set the Orbiter's angular accelerations to zero which is the desired solution.

Computer searches were made of the available literature and no information was found that is directly applicable to this study. Two papers were discovered that utilized angular acceleration feedback. Cheronis[2] utilized angular acceleration feedback to replace the elevator deflection feedback signal of an aircraft, and Greif[3] employed angular accleration hand-controller feedback on a VTOL for pilot rating purposes. Neither of these studies yielded germane information. Since angular acceleration feedback attempts to maintain rates, it is destabilizing for flight and has very limited application for flight control. However, since angular accelerations are detrimental to parallel-type separations, they are an ideal feedback signal to prevent collisions during separation.

Acceleration Feedback

One of the ground rules in developing an alternative control scheme for booster separation is to minimize the changes to the present Shuttle control system. Figure 3 is a simplified block diagram of the present control scheme with an accelerometer feedback added to the roll and yaw channels. Rather than using additional hardware to provide angular acceleration, a simple numerical differentiation is used which will require only software to implement in the flight vehicle. The differentiator is based on a 25 samples/s update. The switch is thrown at a fraction of a second before separation occurs and is returned to the position shown at a fraction of a

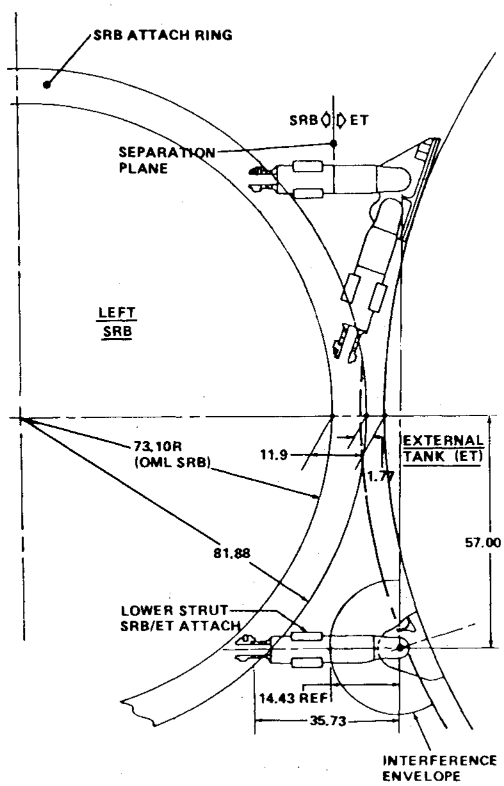

Fig. 2 Aft attachment struts.

second after separation. The transient effect of control system switching is simulated in the computer program; however, the "tail-wags-dog" effect is not included.

One objective of this analysis is to determine the time t_i to throw the switch, the time t_f to reset the switch, and the roll gain G_R and yaw gain G_Y which would significantly improve the booster separation. Generally, this would be an easy task, but for booster separation the figure of merit is the clearance between the booster skin and the tank's lower strut. This clearance is a function of the dynamics of three bodies, each with six degrees of freedom. Since symmetry exists on each side of the pitch plane, the problem will be constrained to the right booster. This will reduce the number of computer runs required by one-half, since either booster will produce the same results with opposite conditions. Studying only one booster's clearance involves the other booster dynamics because the Orbiter/external tank aerodynamics depend on the relative location of both boosters.

No attempt is made in this study to determine the optimum values of t_i, t_f, G_R, and G_Y because of the large number of computer runs required (over 850 separation simulations were performed in this analysis without optimization). The task at hand is to determine a reasonable set of values as shown by the computer simulations and a set that is rational based on the understanding of the Shuttle control system and its booster separation.

Duration of Angular Acceleration Feedback

The duration of the acceleration feedback in the control system should be minimized because the vehicle will be deviating from the desired path during this time, and angular acceleration feedback systems inherently excite flexible body reactions. Sufficient low-pass filtering will prevent high frequencies from becoming a problem, and a short duration will give unstable low frequencies insufficient time to reach a troublesome amplitude. The low-pass filter could be located at the input or the output of the angular acceleration generating software, thereby preventing the filter from affecting other phases of flight since it would be switched in and out as the acceleration signal is switched.

The acceleration feedback should start with sufficient time before separation so that the Orbiter main engines can be repositioned to be countering angular accelerations at separation. Since the maximum gimbal rate of the engines is approximately 10 deg/s, 1 s prior to separation would be adequate time to reposition the engines. Therefore, the study will limit the time t_i to initiate acceleration feedback to no earlier than 1 s prior to separation. The time that the tank's lower strut separation clearance reaches a minimum is between 0.6 and 1 s after separation; therefore, the study will limit the time t_f for acceleration feedback to end to 1 s after separation.

Before parameter variations are made, a set of reasonable gains, G_R and G_Y, must be selected. The first set of gains was chosen based on the amount of engine gimbal angles required to offset roll and yaw aerodynamic torques at an angle of attack and sideslip of 10 deg (that is, $G_R = 2$ and $G_Y = 4$). Using the worst combination of initial conditions in conjunction with the worst combination of system dispersions which produce the maximum interference of 30 in. for the present Shuttle control system, a parameter variation of t_i and t_f was performed for the angular acceleration feedback system. The results indicate that a t_i as small as 0.5 s yields adequate results which leads one to conclude that a half of a second is adequate time to reposition the engines. A t_f greater than 0.25 s yields adequate results, even though the minimum clearance occurs at 0.84 s. Little is gained by leaving the acceleration feedback in beyond 0.25 s and no improvement was achieved after 0.5 s.

The gains were changed to $G_R = 4$ and $G_Y = 10$ to determine the effect of gain change on the selection of t_i and t_f. The gain change did not change the characteristic of the time to end acceleration feedback t_f, but the time to begin the acceleration feedback t_i shows a larger change in the clearance between 1 and 0.5 s before separation. With the gains of $G_R = 4$ and $G_Y = 10$ and time of $t_i = 0.5$ and $t_f = 0.5$, 32 cases of initial conditions were run to determine the worst combination of initial conditions for this angular accelerations feedback system. With this set of initial conditions, another parameter variation on t_i and t_f was performed. Again, the results showed that $t_i = t_f = 0.5$ were satisfactory times to start and terminate acceleration feedback.

Gains for Roll and Yaw Feedback

It is desirable to use gains which maximize the clearance between the booster skin and the tank's lower strut. However, the gains should be kept as small as possible to minimize any flexible body reactions that may occur with angular acceleration feedback control systems. Consequently, the smallest gains that yield satisfactory clearances will be selected.

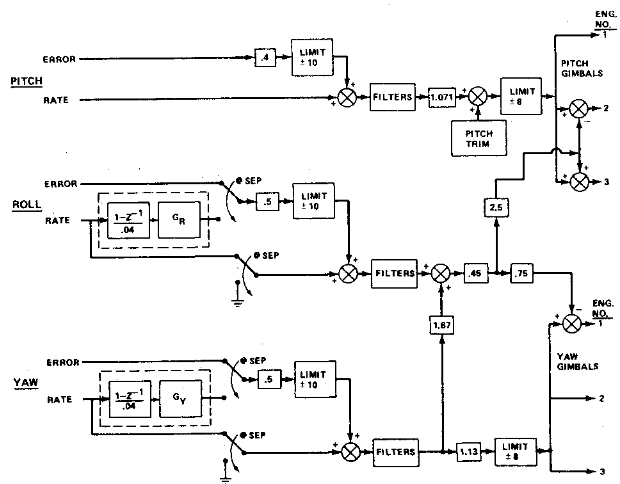

Fig. 3 Space Shuttle control system during separation (proposed addition of angular acceleration feedback shown inside dotted lines).

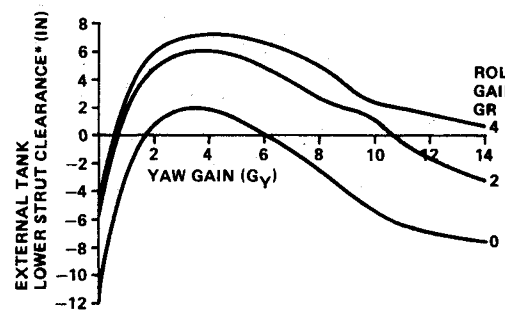

Fig. 4 Effect of angular acceleration gains on strut clearance (worst initial conditions for the present Shuttle control system).

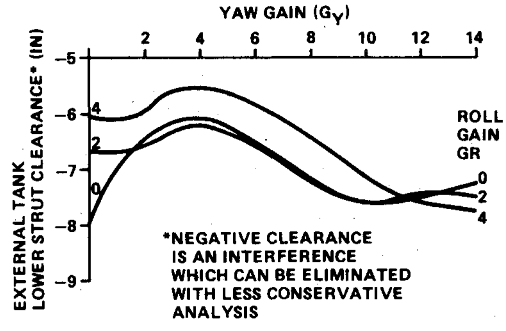

Fig. 5 Effects of angular acceleration gains on strut clearance (worst initial conditions for control systems gains of $G_R = G_Y = 4$ and G_R, $G_Y = 4$).

To determine the best gains, a parametric study of the gains (G_R, roll channel, and G_Y, yaw channel) vs the tanks lower strut clearance was performed. The gain variations were centered around those gains that would position the Orbiter engine so that the engine torques would offset the aerodynamic torques at an angle of sideslip and angle of attack of 10 deg. Figure 4 shows that the clearance is maximized when the yaw gain is 4, and that the clearance is still increasing at a roll gain of 4. However, the clearance only increased 1 in. when the roll gain was increased from 2 to 4 which indicates that the clearance is not very sensitive to roll gain. In fact, the clearance at $G_R = 0$ and $G_Y = 4$ is only 5 in. smaller than for $G_R = G_Y = 4$.

A new set of initial conditions was found which was worst for both sets of gains ($G_R = 4$, $G_Y = 4$ and $G_R = 0$, $G_Y = 4$). Figure 5 shows the results of gain variation using this worst combination of initial conditions. The best set of gains still appears to be $G_R = 4$ and $G_Y = 4$, realizing that higher values of G_R may provide less interference. It is important to note that the clearance for this set of initial conditions is not sensitive to variations of G_R or G_Y. The maximum interference of approximately 8 in. occurs at $G_R = G_Y = 0$, and at $G_R = G_Y = 4$ the minimum interference of 5.5 in. occurs which is only a 2.5 in. variation.

If the only criterion for gain selection was to minimize interference, $G_R = G_Y = 4$ would be the choice, but the obvious insensitivity to gain leads one to look at lower gains. If $G_R = 0$ and $G_Y = 4$ was selected, the worst interference for this worst-on-worst study would be approximately 6.1 in. (a 0.6 in. increase over $G_R = G_Y = 4$). When a gain is set to zero, that control channel is set to zero, which results in the Orbiter engines being commanded to null from that channel. Null means that the engine's torque will be small. A simplified rss treatment of the system dispersions (simplified means treating all aerodynamic uncertainties as one dispersion) for $G_R = G_Y = 4$ and $G_R = 0$, $G_Y = 4$ results in a clearance of 3.6 and 2.7 in., respectively. This means that both control systems are viable solutions to improving the booster separation.

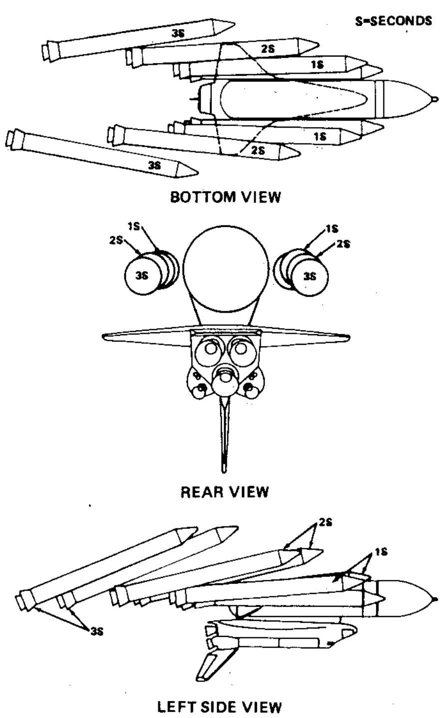

Fig. 6 Typical booster separation from actual initial conditions of ascent.

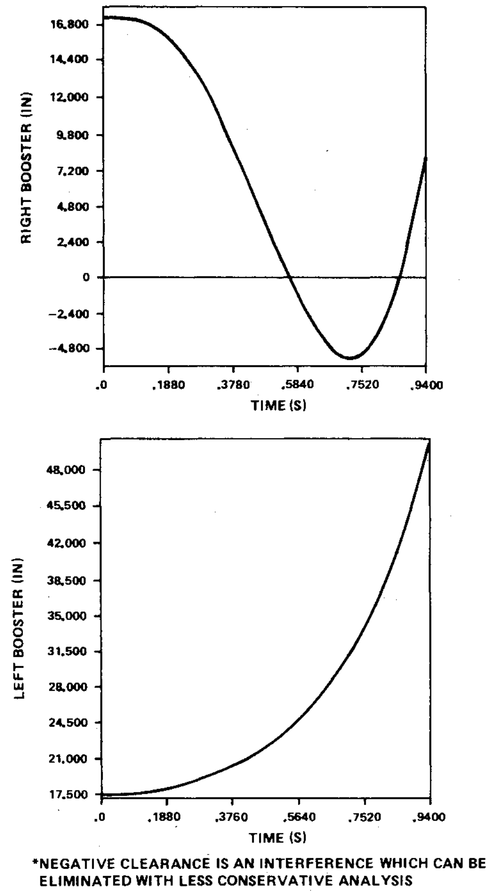

Fig. 7 Clearance between booster skin and tank lower strut for angular acceleration feedback.

Table 1 Clearance between right booster skin and tank's lower strut stub for various control schemes

Acceleration gains G_R	G_Y	Initial conditions worst for[a]	Initial conditions α, deg	β, deg	P, deg/s	Q, deg/s	R, deg/s	Type study	Clearance Magnitude
4	4	WC	−15	+15	−5	+2	−2	WOW	−5.5
4	4	WC	−15	+15	−5	+2	−2	srss	+3.6
0	4	WC	−15	+15	−5	+2	−2	WOW	−6.1
0	4	WC	−15	+15	−5	+2	−2	srss	+2.7
0	0	WC	+15	+15	−5	−2	−2	WOW	−19.0
0	0	WC	+15	+15	−5	−2	−2	srss	−1.4
0	0	Nominal	+15	+15	+5	+2	−2	rss	+6.4
Attitude		WC	+15	+15	+3	−2	+2	WOW	−29.7
and rate		WC	+15	+15	+3	−2	+2	srss	−13.7
feedback		Nominal	−15	+15	+2	+2	+2	rss	−1.6

[a] WOW – worst combination of system dispersions and initial conditions. WC – worst combination of system dispersions. rss – root sum square analysis. srss – simplified rss (aero tolerance combined into one system dispersion).

Table 2 Effects of the various control schemes on the roll and yaw rate changes during separation

Initial conditions Acceleration gains G_R	G_Y	WOW Roll change,[a] deg/s	Yaw rate change,[a] deg/s	Clearance[b] booster strut, in.	Shuttle second launch Roll rate change,[a] deg/s	Yaw rate change,[a] deg/s	Clearance[c] booster strut, in.
4	4	7.1	0.1	−5.5	0.415	0.272	+17.25
0	4	12.0	0.1	−6.1	0.694	0.374	+17.25
0	0	17.3	3.3	−19.0	0.905	0.067	+17.25
Attitude and rate		18.1	5.2	−29.7	0.927	0.051	+17.25

[a] Change between separation initiation and 1 s afterward.
[b] Negative clearances are interferences which are eliminated with rss treatment except for attitude and rate feedback control.
[c] 17.25 in. in the initial clearance.

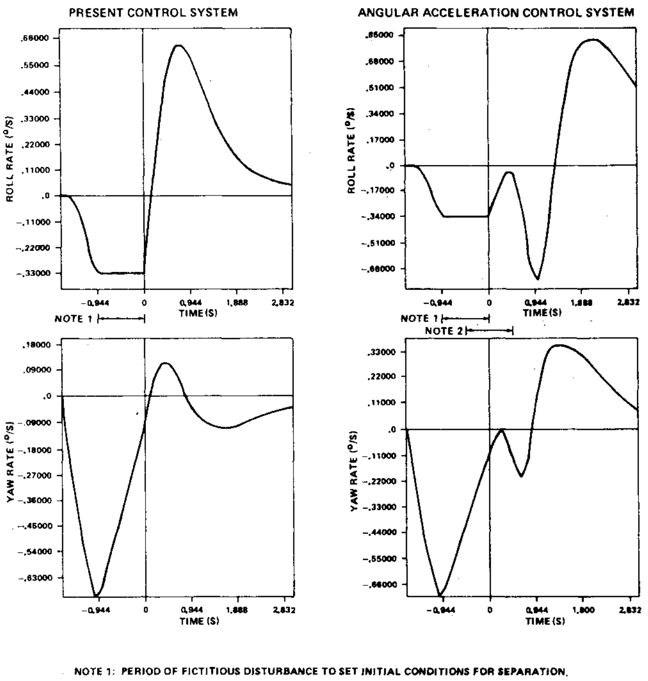

Fig. 8 Rates at separation with initial conditions of Shuttle's second launch.

Consider $G_R = G_Y = 0$ as a candidate control technique. Zero gains would certainly eliminate concern about flexible body reaction. Using $G_R = G_Y = 0$, the worst set of design initial conditions was determined. The worst set of initial conditions in conjunction with the worst combination of system dispersions results in an interference of 19 in. A simplified rss treatment was performed and an interference of 1.4 in. occurred. The full rss analysis using the initial conditions which are worst for no system dispersions produced a clearance of 6.4 in. This rss analysis shows that setting the Orbiter engines to null for roll and yaw from 0.5 s before separation to 0.5 s after separation is a possible solution to verifying the adequacy of the booster separation. Although this technique does not provide as much conservatism in clearance as does the angular acceleration feedback scheme, it is easier to implement and does not possess the possibility of a stability problem.

Control Technique Comparisons

The analysis has shown that three modifications to the present Shuttle control system will provide an improvement in the capability of the solid rocket booster separation system, that is, 1) substituting angular acceleration in the roll and yaw channel for attitude error and rate feedback, 2) substituting angular acceleration in the yaw channel and putting zero into the roll channel, and 3) putting zero into both the roll and yaw channels. A comparison of these control techniques along with the present Shuttle attitude-rate feedback control system is shown in Table 1 in order of the techniques which provide the greatest separation capability. The acceleration feedback control schemes (that is, $G_R = G_Y = 4$ and $G_R = 0$, $G_Y = 4$) did not require as much analysis as did the other system to prove that they are adequate to perform a safe separation. That is the reason that Table 1 does not show results for an rss analysis with initial conditions that are worst for no system dispersions.

Figure 6 shows picture plots of the booster separation using the actual initial separation conditions of the Shuttle's second flight. The type of control system makes little difference in the overall appearance of these separations; consequently, only one set of picture plots is shown. Figure 7 is a time plot of right booster to the tank's lower strut stub clearance using the angular acceleration feedback control system. The present control system reaches a minimum clearance at 0.98 s which is 0.26 s later than the acceleration feedback scheme. Figure 8 shows the roll and yaw rates with the present and the angular acceleration feedback control systems using the initial conditions of the second launch's separation.

The objective of the control system changes was to reduce the angular accelerations during separation, thereby reducing the change to the rates. Table 2 shows the changes in the roll and yaw rates during the first second of separation for worst-on-worst separation conditions and for the separation conditions of the Shuttle's second launch. The acceleration feedback schemes did reduce the angular rate changes that occurred during the separation for the worst-on-worst cases and resulted in reduced interferences.

The only failures examined were a single Orbiter engine loss of thrust and a single booster separation motor failure to start. Since it is considered too conservative to have three-sigma (standard deviations) system dispersion all aligned in the worst direction in conjunction with a malfunction, the system dispersions were reduced to one sigma. The aft booster separation motor and the No. 3 Orbiter main engine were found to reduce the strut clearances the most. All three control modification schemes were simulated, as well as the present control scheme, and the results are shown in Table 3.

Table 3 Clearances for one standard deviation of system dispersions

Control type Angular acceleration feedback gain	Lower external tank strut stub clearance, in. No failures	Booster separation motor out	Orbiter engine No. 3 out
$G_R = G_Y = 4$	11.65	10.80	9.51
$G_R = 0, G_Y = 4$	10.75	9.59	7.10
$G_R = G_Y = 0$	8.52	6.15	7.25
Attitude-rate feedback	0.14	−3.10	0.41

No interferences were encountered except for the booster separation motor failure in the present control scheme. However, design for this failure is not a requirement. The three control system modifications show a significant improvement over the present control system.

Conclusions

The Orbiter's main engines play an important part in the success of the solid rocket booster separation. They are the primary separating force, and they can be the primary cause of recontact if they are in deleterious gimbal positions. This analysis has shown three control system techniques which improve the present separation system's capability by reducing the detrimental effects of the Orbiter engines. The improvements were sufficient to allow the separation system to be verified for initial design conditions for operational flight. The improvements were obtained by two techniques and the combination of the two techniques, i.e., 1) replacing the attitude and rate feedback with angular acceleration feedback in the roll and yaw channel and 2) nulling the Orbiter engines by putting zero into the roll and yaw channels. The first technique sets the Orbiter engines in a position to counter external torques, thereby reducing angular accelerations. The second technique sets the Orbiter engines in a position that will reduce angular torques from the engines. Both techniques reduce angular acceleration during separation, thereby increasing the separation system's capability.

Angular acceleration feedback schemes inherently have flexible body stability problems. No attempt was made to study the stability of these control schemes. The duration of these control modifications is 1 s of flight time which should eliminate low-frequency instabilities. Higher frequencies could require additional filtering.

Acknowledgments

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