

# Space Shuttle Solid Rocket Booster Control Limitations Due to Failure of an Hydraulic Power Unit



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# Space Shuttle Solid Rocket Booster Control Limitations Due to Failure of an Hydraulic Power Unit

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The Space Shuttle solid rocket boosters (SRBs) each have two nozzle actuators to provide thrust vector control (TVC). Two hydraulic power units (HPUs) provide hydraulic pressure to drive the actuators and are capable of driving both gimbals simultaneously at 5°/s. One HPU, however, is only designed to drive both gimbals simultaneously at a combined rate of 6°/s. Reduced gimbal rate capability due to failure of an HPU can limit the gimbal's ability to keep up with commands and the development of large command-position deltas could cause loss of control of the actuator. Due to SRB thrust authority during the Shuttle's first stage, loss of control of an SRB TVC could result in loss of the vehicle. To study the effect of a failed HPU during nominal ascent profiles, an SRB actuator was modeled in SIMULINK and the gimbal drive rate was limited to simulate the failure. The maximum resulting command-position deltas were calculated to determine control limitations. The required gimbal rate summation limit to cause loss of control of an SRB actuator in response to an HPU failure during nominal ascent demands is also estimated. Through this analysis, large margins are demonstrated against this failure scenario. The availability and feasibility of an operational response are discussed.

## I. Introduction

THE majority of thrust for the Space Transportation System's (STS) first stage is provided by two solid rocket boosters (SRBs). Since the thrust provided by the Space Shuttle main engines (SSMEs) is negligible compared to the SRBs, the SRBs also provide the majority of control authority with two nozzle actuators on each SRB. Each SRB has two hydraulic power units (HPUs) to provide hydraulic pressure to move the SRB gimbals. When one HPU fails, a switching valve allows the other HPU to drive both actuators, but with decreased capability.

An actuator driving with decreased capability may not be able to keep up with the command resulting in loss of control of the actuator. Due to the control authority of the SRBs in first stage, loss of control of an SRB actuator can result in loss of the vehicle.

The nominal ascent SRB actuator profile was modeled in SIMULINK and the gimbal movement was limited to simulate the effects of a failed HPU. The resulting control limitations were quantified to assess the likelihood of losing control of an SRB actuator due to an HPU failure during Shuttle ascent.

## II. SRB Thrust Vector Control (TVC) Background

Each SRB provides thrust vector control (TVC) with two nozzle actuators in the "rock" and "tilt" directions which are offset from the vehicle pitch and yaw axes by 45° as shown in Fig. 1<sup>1</sup>. Each actuator is commanded by four ascent thrust vector controllers (ATVCs) which also command the six actuators on the three SSMEs. An ATVC and the hydraulic lines commanded by the ATVC

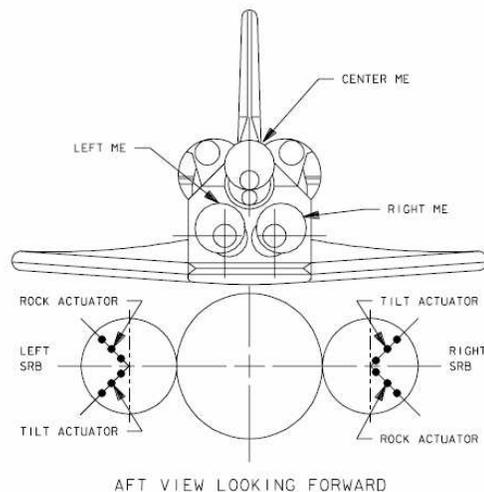
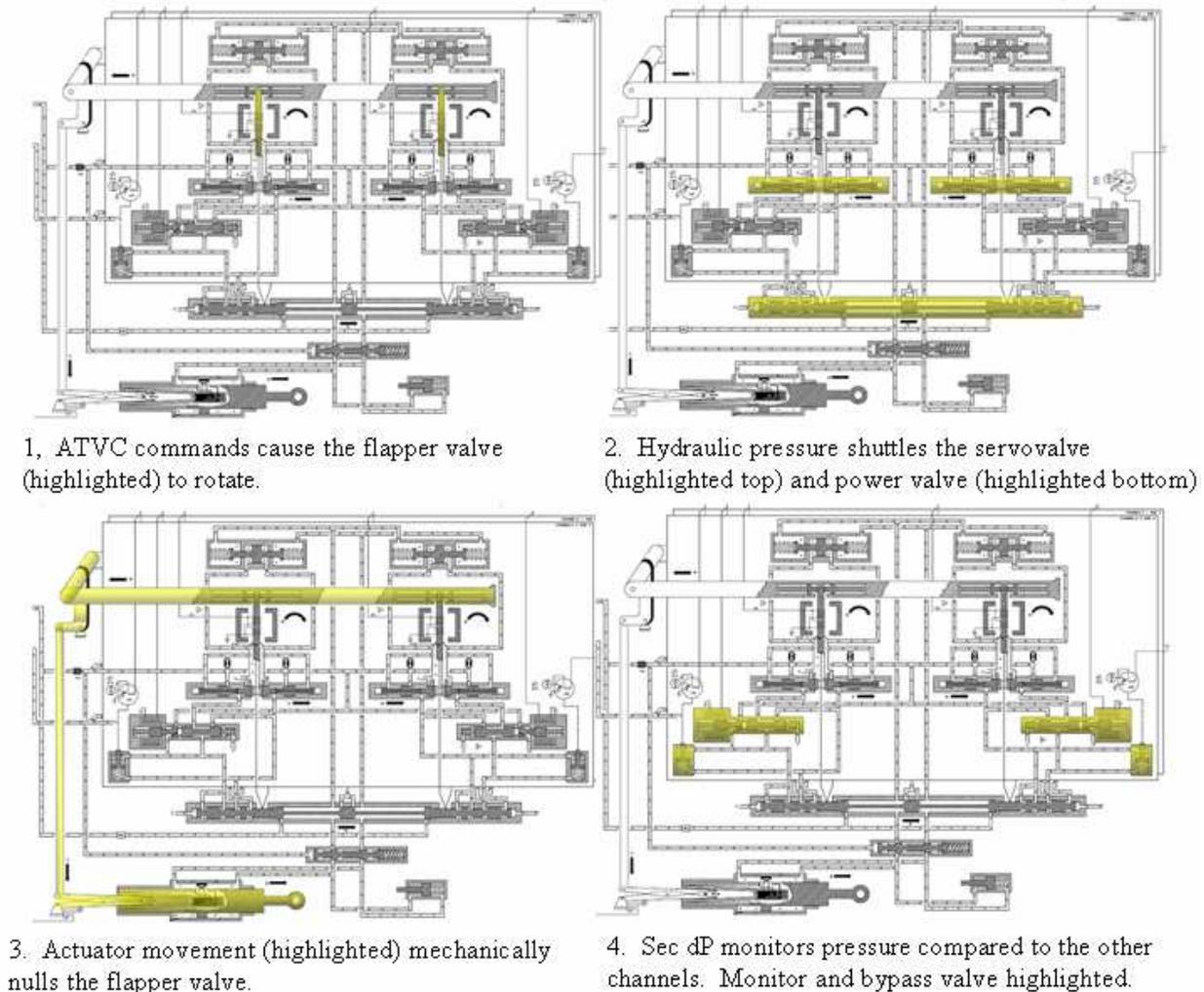


Figure 1. SRB rock and tilt axis definition <sup>2</sup>.

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is called a flight control system (FCS) channel. Thus, each shuttle actuator is driven by four FCS channels<sup>3</sup>.

Fig. 2 shows FCS channels 3 and 4 for an SRB actuator. In the hydraulic schematic, channels 1 and 2 are exactly the same as 3 and 4 and are represented by the box behind the latter channels. Commands sent to the channel from the ATVCs cause the flapper valve to rotate, building up hydraulic pressure on one side of the valve. This pressure build up causes the servovalve to shuttle left or right again causing a pressure build up which then commands the power valve to shuttle left or right. All four FCS channels command the power valve for a specific actuator allowing a single gimbal to be driven by the four channels. Movement of the power valve causes the actuator to extend or retract. For the SRBs TVC actuators, this movement is mechanically fed back to null the rotation of the flapper valve<sup>3</sup>.



**Figure 2. SRB actuator hydraulic schematic<sup>2</sup>.**

The secondary delta pressure (sec dP) monitor measures the hydraulic resistance of the power valve compared to the movement commanded by a single channel and is shown in Fig 3. For example, if channel 4 is commanding the actuator to extend and the other three channels are commanding the actuator to retract, the power valve would command the actuator to retract due to the majority vote of the FCS channels where more hydraulic power is trying to retract the actuator than extend. The force of channel 4 fighting against the movement of the power valve would cause the sec dP for channel 4 to build up.

When sec dP exceeds 2200 psi for 120 ms, an isolation command is issued on the channel for the specific actuator. This causes piston I of the bypass valve shown in Fig. 3 to move right against the spring allowing hydraulic fluid to move into chamber “A”. The hydraulic pressure pushes piston II to the left equalizing the return/feed line from “B” to “C”. This removes the dissenting channel’s ability to command movement of the power

valve for the specific actuator, referred to as a “port”. Bypassing or isolating an actuator is called “popping” a port<sup>3</sup>.

The FCS channels are commanded by four switches in the Shuttle cockpit center console between the commander and pilot seats. These switches allow the entire channel to be placed in OFF, AUTO and OVRD (override). A channel turned off is bypassed across all Shuttle and SRB actuators and does not command any actuator. A channel in AUTO or OVRD commands actuators as described above but when the channel is in OVRD, automatic bypasses are prohibited for all actuators on the channel<sup>3</sup>.

Hydraulic power through the FCS channels for the SRBs is provided by the two HPUs with HPU “A” nominally driving the rock actuator and HPU “B” driving tilt<sup>1</sup>. Similarly, the Shuttle SSMEs and aerosurface actuators are powered with three Shuttle Auxiliary Power Units (APUs) which are independent of the HPUs<sup>3,4</sup>. When the hydraulic pressure provided by an HPU drops below 2050±50 psia, a hydraulic switching valve provides hydraulic pressure to the gimbal from the other HPU<sup>1</sup>.

Two HPUs can drive both SRB actuators at 5°/s simultaneously. However, one HPU is designed to drive both actuators at a combined rate of 6°/s. If the vehicle is commanding a pure pitch or yaw, this design capability would be divided evenly and both actuators would drive at 3°/s<sup>1</sup>. At present, the exact rates at which both actuators could be driven with one HPU is unknown. ATK is conducting a hot-fire test in November 2007 which will intentionally fail an HPU to measure hydraulic capability<sup>5</sup>.

The shuttle flight control software also has logic called “equalization” for each actuator. Equalization biases commands from the ATVCs for an actuator to help keep the commands of all four channels in agreement. This logic helps limit the build up of high sec dPs and can keep the effects of many failures (such as driver biases, position feedback errors) from growing and resulting in a port pop<sup>3</sup>.

When an APU fails on Shuttle, software called priority rate limiting (PRL) software notifies the flight control software of reduced drive rate capabilities for the SSME and aerosurface actuators. This allows flight control to generate actuator commands which account for new drive rate limits<sup>6</sup>. The SRBs, however, do not have PRL software. Thus if an HPU fails, flight control does not have knowledge that the SRB actuators are driving with decreased capability.

The drive rate reduction limits the rock and tilt actuators’ ability to keep up with commands. Decreased capability increases the magnitude of developed command-position deltas. If the gimbal rate capability is limited enough, large command-position deltas can push the power valve into the hard stop increasing sec dP on all four channels. It is possible that a bypass of all four channels could occur simultaneously resulting in a loss of control of the actuator. Due to the control authority of the SRBs during first stage, loss of control of a SRB actuator could result in loss of control of the vehicle.

An SRB actuator is most vulnerable to a four-channel bypass if it is commanded to a large deflection angle at a high rate. The large deflection produces a high spring load while the higher rate results in a local supply pressure drop reducing the actuator’s ability to counteract the load. The actuator then stalls and the cmd-pos error increases causing high servovalve pressures which can lead to a four-channel bypass. Historical analysis showed that with no hydraulic failures, gimbal rates of 4.9°/s with slew commands of 4.9° will cause a four-channel bypass if loads are 140% of the expected value<sup>7</sup>. Analysis has also shown a four-channel bypass will occur if loads are 160% of their expected value, an HPU failure occurs, and the gimbals are driving with a combined rate of over 6.8°/s while being commanded to a large angle<sup>7</sup>.

Table 1 shows the effect of increasing command-position deltas on the actuator. Equalization begins at a sec dP of 1175 psid which corresponds to a cmd-pos delta of 0.313°. Equalization is maxed out at a driver bias of 9.3

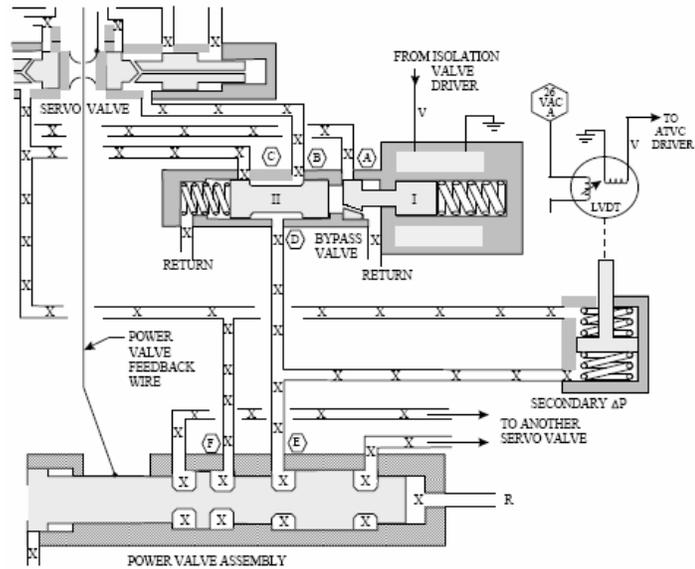


Figure 3. Bypass valve and secondary delta pressure monitor<sup>3</sup>.

milliamps or a cmd-pos delta of 1.257°. At a cmd-pos delta of 1.95°, the sec dPs are high enough to potentially yield a four channel bypass.

While this failure condition has never happened in flight, the prospect of a four channel bypass due to an HPU failure is a serious scenario since it would represent a potential loss of vehicle case due to a single failure. This analysis examines the nominal shuttle ascent profile to determine if SRB gimbals rate commands could allow such a condition to develop.

Variability in SRB gimbals rate demands for a Shuttle ascent can depend on many factors. Occasionally, the left and right SRBs do not provide equivalent thrust levels causing one rocket to fire for a longer duration than the other. The asymmetric thrust can increase SRB gimbals rates near the end

Cmd-Pos Delta	Effect
0.313°	Reaches the start of Equalization at 1175 psid sec dP.
0.824	<i>Largest cmd-pos delta seen in flights analyzed</i>
1.257°	Upper limit of equalization driver bias, 9.3 ma.
1.514°	Reaches failure detection level of 2200 psid.
1.95°	Could result in a four channel bypass.

**Table 1. Actuator effects for varying command-position deltas.**

of first stage when the first SRB begins to “tail off.” High winds can also cause trajectory perturbations and contribute to SRB gimbals rates. The day of a Shuttle launch, the environmental conditions (winds, pressure, temperature, etc.) at KSC are measured with a series of weather balloons and observations. The ascent trajectory is tweaked to account for the day of launch (DOL) conditions and variables in the guidance routine such as pitch and yaw data, throttle bucket times, thrust settings, and guidance reference times are modified with a DOL I-load update (DOLILU) <sup>8</sup>. If the vehicle encounters environmental parameters not accounted for in the DOLILU, such as wind gusts, the ascent trajectory can be perturbed causing higher gimbals rates as the vehicle steers back on course.

### III. Model Development and Verification

In this investigation, an SRB actuator was modeled in SIMULINK and then the gimbals rate movement was limited to simulate the hydraulic capability of operation with a single HPU. The resulting command-position delta was then calculated and compared to the 1.95° limit.

SRB actuator commands from the seven Space Shuttle flights with the historic highest gimbals rates were used as input for the simulation. There are four times during the ascent profile where the SRB gimbals are under high rates: SRB ignition, roll program initiation and correction, and the separation null. At a mission elapsed time (MET) of seven seconds, and after the Shuttle has cleared the launch tower, the vehicle begins a roll maneuver to orient the vehicle in a heads down attitude. This allows downrange velocity to increase in order to achieve main engine cutoff (MECO) targets in second stage. The roll program also generates the required negative angle of attack to alleviate structural loading as well as improved communication S-band look angles, performance gain and decreased abort maneuver complexity <sup>9</sup>. At the end of first stage after ~124 seconds, the gimbals are commanded to a safe null position for SRB separation at “tail off”.

Telemetry from the vehicle is very noisy and must be filtered. Table 2 shows the highest filtered rates experienced during the Shuttle program for each of the four SRB actuators at the four ascent events of interest. These eight data points bound the seven high gimbals rate missions used as simulation inputs. The actual actuator command is sampled in the telemetry downlist at 5 Hz and is too slow to be used as input for the simulation. Instead, the actuator driver is used which is sampled from flight data at 25 Hz.

STS #	Event	Experience Base (Retraction/Extension)
87/41G	Ignition	-2.97/3.58
41G/41	Roll Initiation	-4.24/3.84
49/5	Roll Correction	-3.38/4.00
65/6	Separation Null	-4.97/4.40

**Table 2. Space Shuttle historic highest SRB gimbals rates <sup>10</sup>.**

Fig. 4 shows the linear single FCS channel simplex SRB actuator model which was built in SIMULINK and used as the basis for the HPU failure model. Table 3 shows the nominal values for the model variable constants. This simplex, single-channel model is fifth order and was developed to conduct ascent flight control stability assessments.



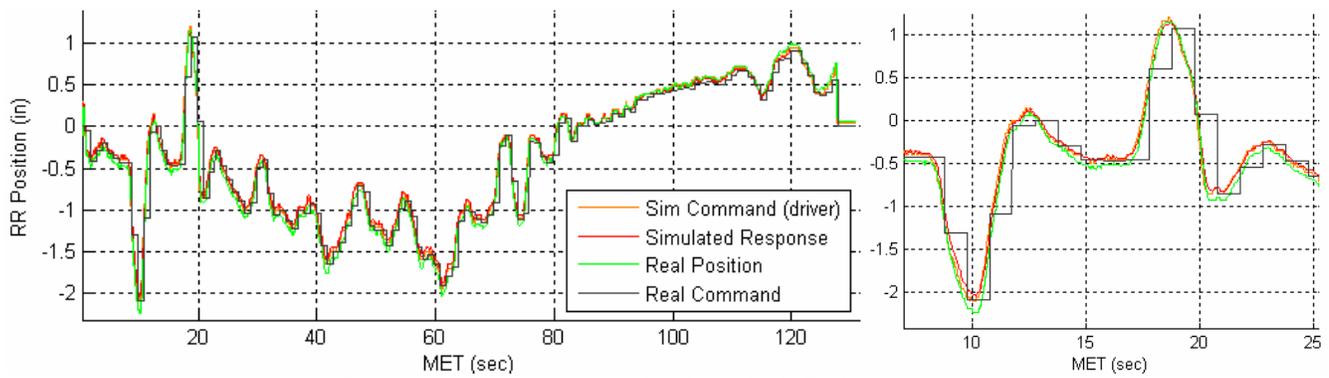


Figure 5. Right rock actuator profile from STS-5 with roll program detail.

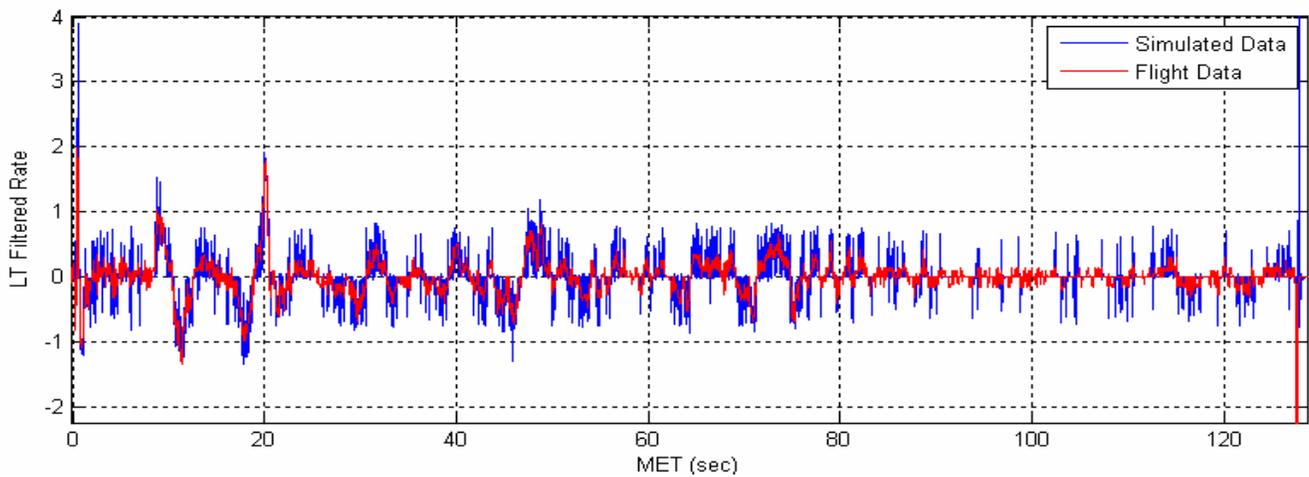


Figure 6. Left tilt gimbal rates flight data and simulation comparison for STS-5.

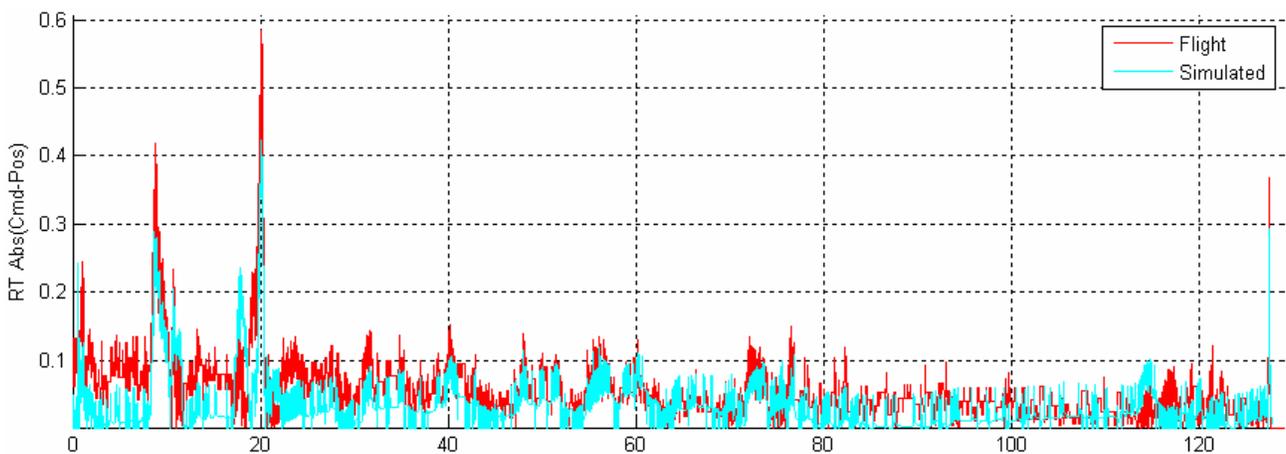


Figure 7. Right tilt cmd-pos delta flight data and simulation comparison for STS-5.

actuator cannot be controlled. At the beginning of the slew, the resulting command-position delta is high enough to cause equalization to be entered and thus shows the same observations as the United Space Alliance test. Equalization is not modeled in the SIMULINK model and the presence of equalization would have helped control the actuator during the slew.

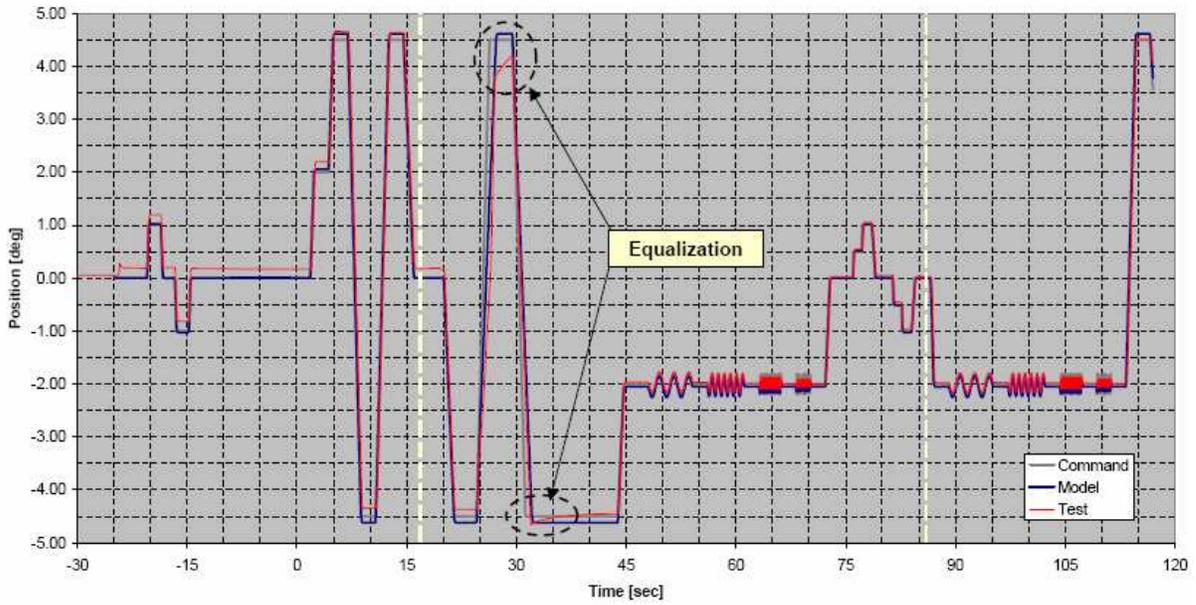


Figure 8. United Space Alliance results of the motor-off APU failure capability test<sup>12</sup>.

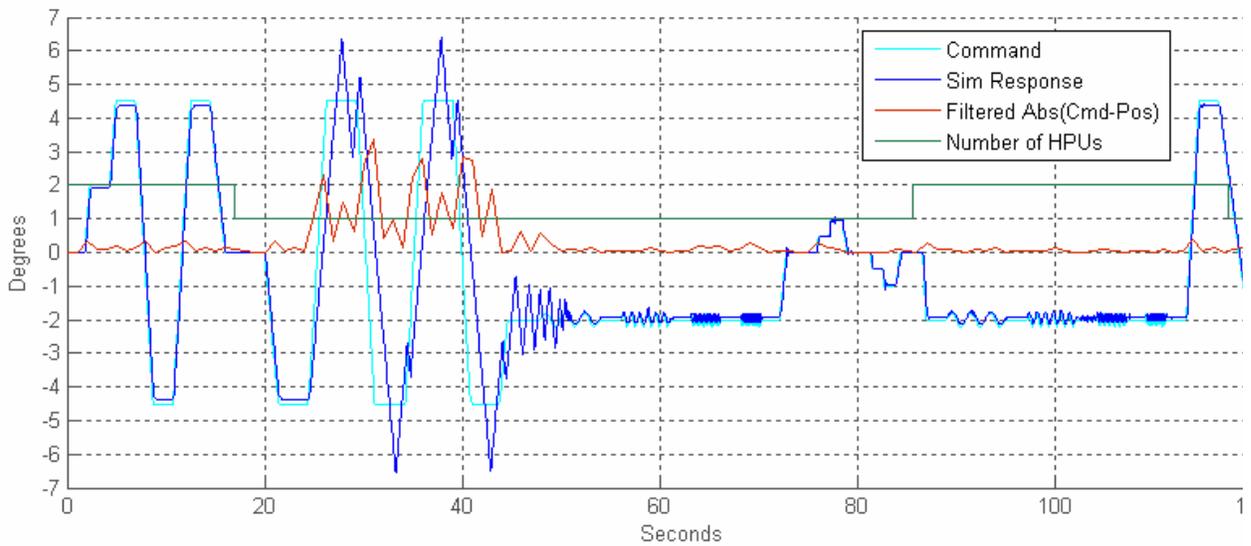


Figure 9. Hot fire test profile as modeled with the developed SIMULINK simulation showing the entrance

The effects of nonlinearities were also evaluated. Hysteresis due to piston drag, SRB travel limits and rotational friction were added to the SIMULINK model. Figs. 10, 11 and 12 show the roll program profile from STS-5 as well as the gimbal drive rates and cmd-position deltas respectively for right tilt (RT) from STS-5 for the linear and non-linear models. The figures demonstrate that including these nonlinearities has negligible effect on the simulation results. Since the non-linear model required substantial runtime, the linear model was used for the remainder of the analysis.

In order to model an HPU failure, the gimbal rates in the SIMULINK simulation were limited to a combined rate of 6°/s. Since it is unknown how the actuators will behave under single HPU operation, two methods of rate limiting were developed to help ensure the analysis would bound the actual system behavior. Method I assumes each actuator has priority for the available hydraulic capability. Thus, if one actuator is driving less than 3°/s, it is allowed to drive at its commanded rate. The rest of the hydraulic capability, the rest of the 6°/s, is provided to the other gimbal. For example, if rock is driving at 4°/s and tilt at 2.5, tilt will be allowed to drive at the commanded 2.5°/s while rock is limited to 3.5°/s. If both actuators are driving at a rate greater than 3°/s, both gimbals are limited to 3°/s.

Method II assigns the  $6^\circ/s$  in the same ratio as the actuator cmd-pos deltas as shown in the system of equation 1. An actuator with larger cmd-pos deltas will have more hydraulic pressure commanding the actuator back towards the command. Thus, the actuator with the larger cmd-pos delta should have higher priority for hydraulic capability. Thus, method II is a more realistic model of how the system is likely to behave.

$$\left\{ \begin{array}{l} \frac{|\text{Rock Cmd - Pos Delta}|}{|\text{Tilt Cmd - Pos Delta}|} = \frac{|6 - \text{Tilt Gimbal Rate}|}{|\text{Tilt Gimbal Rate}|} \\ 6 = \text{Tilt Gimbal Rate} + \text{Rock Gimbal Rate} \end{array} \right. \quad (1)$$

The gimbal rate limiting was enforced with an embedded MATLAB function inside the SIMLINK model as shown in Fig. 13. Fig. 13 shows the HPU fail model for the left SRB only but the right SRB has the same format. As evident, the model of Fig. 4 is the basis for the HPU fail model. When the rate is calculated in the feedback loop it is broken out and sent to the rate limiting logic. When the combined drive rates of rock and tilt exceeds  $6^\circ/s$ , the rates are limited in the embedded function and then fed back to the feedback loop.

#### IV. HPU Fail Simulation Results

The actuator driver commands from the seven analyzed flights were run through the developed HPU fail model using both rate limiting assumptions. An example of simulation output is shown in Fig. 14, 15 and 16 for the right SRB from STS-5. STS-5 had the highest gimbal rate summation of all the flights at  $6.75^\circ/s$  during roll correction.

Fig. 14 shows the gimbal rate summation from flight data along with the corrected gimbal rate summation with the enforced rate limit to simulate an HPU failure. The HPU fail rate limit is enforced during the roll program correction when the flight gimbal rate summation reaches  $6.76^\circ/s$ .

Fig. 15 and 16 show the absolute value of the cmd-pos delta from flight data as well as the simulation for the equal rate limiting and cmd-pos delta limiting assumptions respectively.

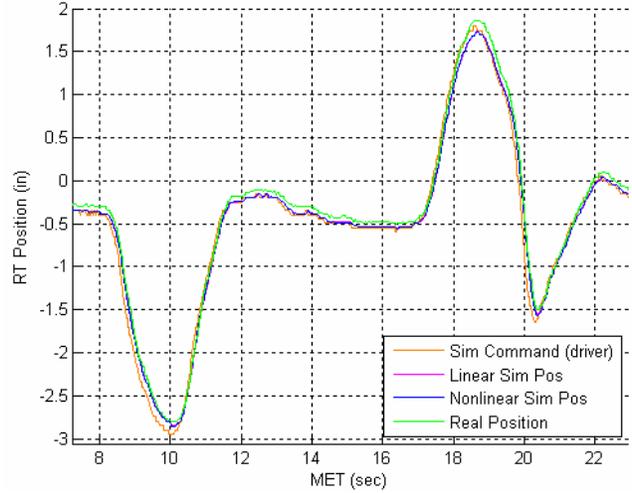


Figure 10. STS-5 RT roll program profile modeled with the linear and non-linear simulations.

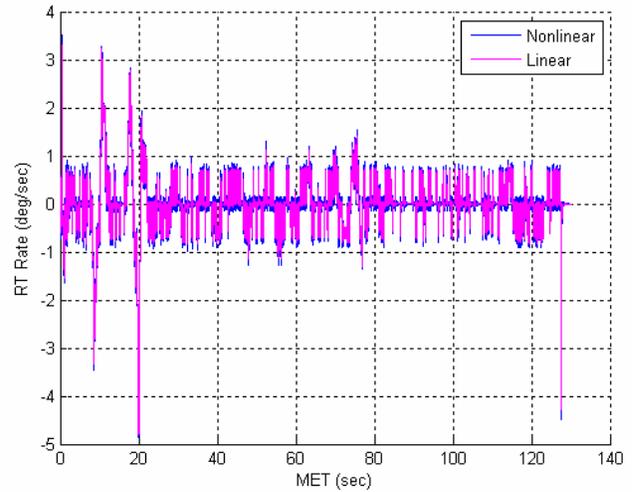


Figure 11. STS-5 RT gimbal rates from the linear and non-linear simulations.

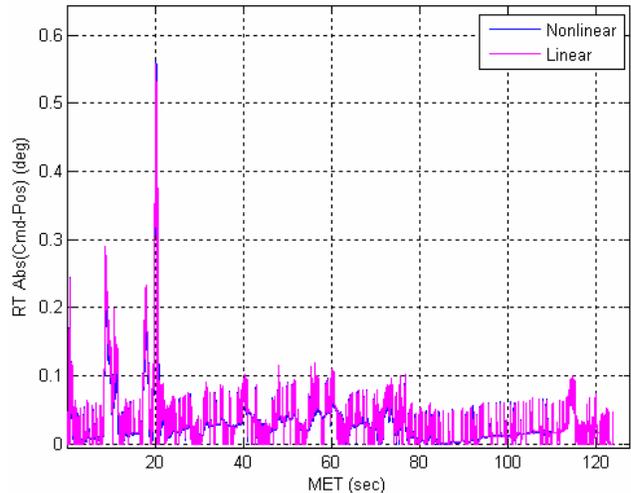


Figure 12. STS-5 RT cmd-pos delta from the linear and non-linear simulations.

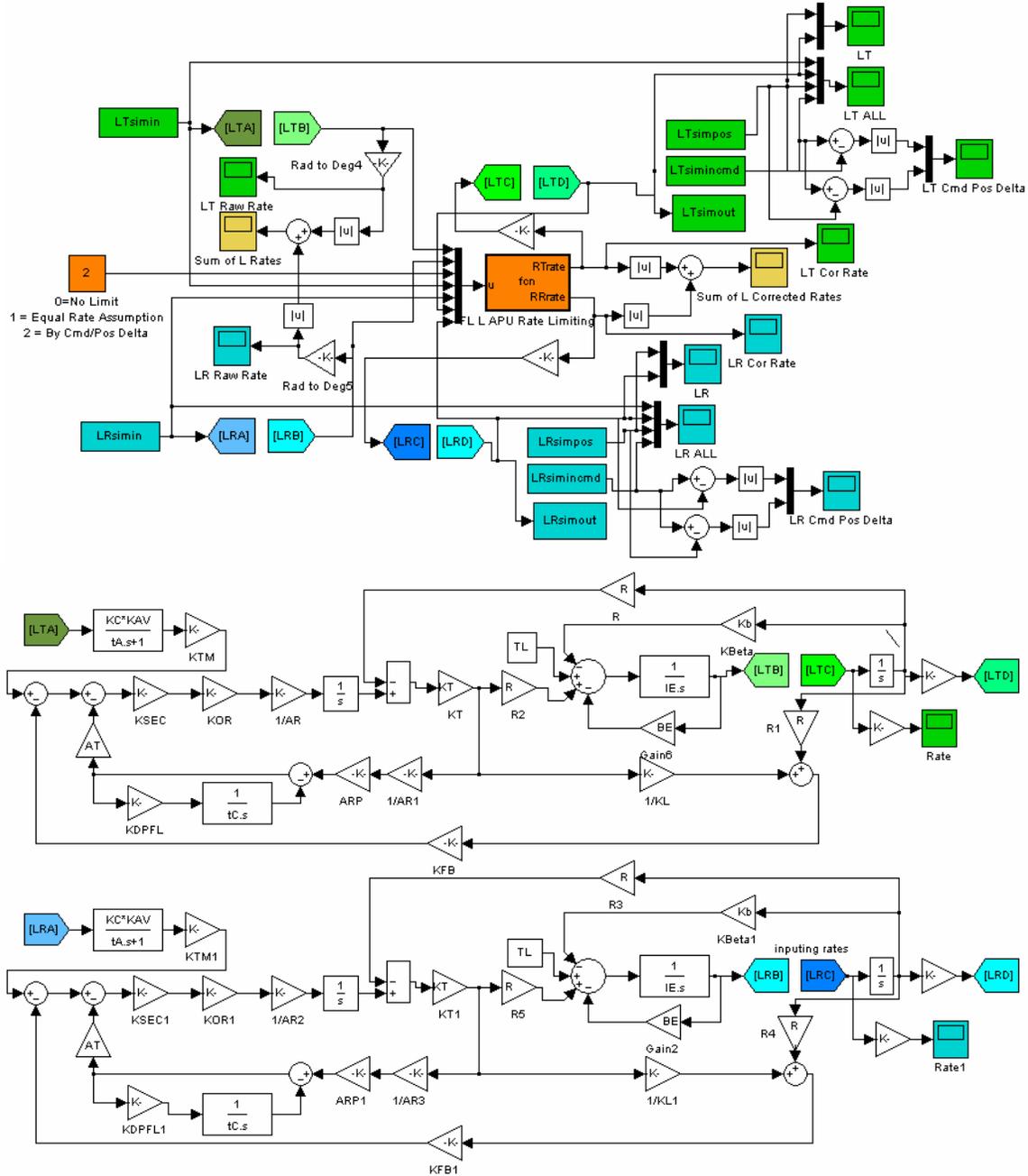


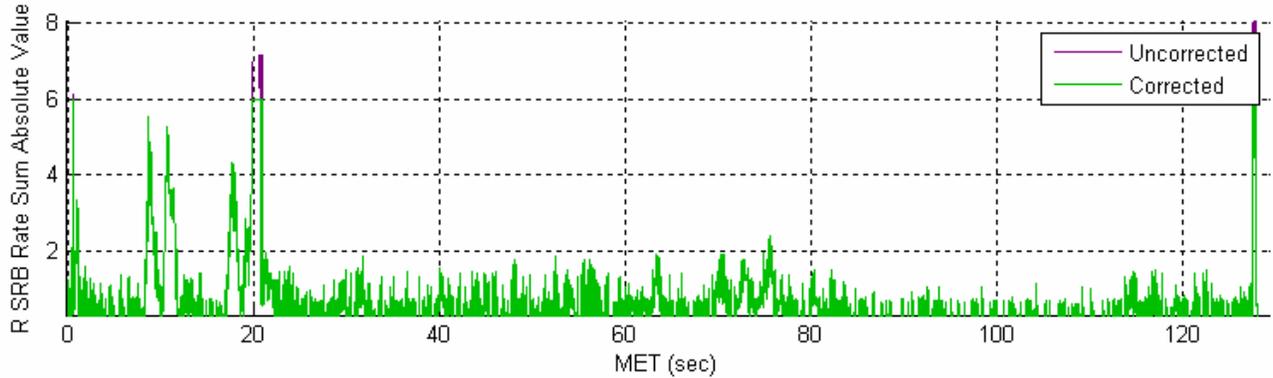
Figure 13. SIMLINK HPU fail model for the L SRB.

The RT plots show a spike in the simulation cmd-pos delta above what was seen during flight during the roll program correction. The rate limit prevents the actuator from keeping up with the command and causes increased cmd-pos deltas. However, the magnitude of the rate limited cmd-pos delta is only about  $0.3^\circ$  which is well below the  $1.95^\circ$  required for a four-channel bypass.

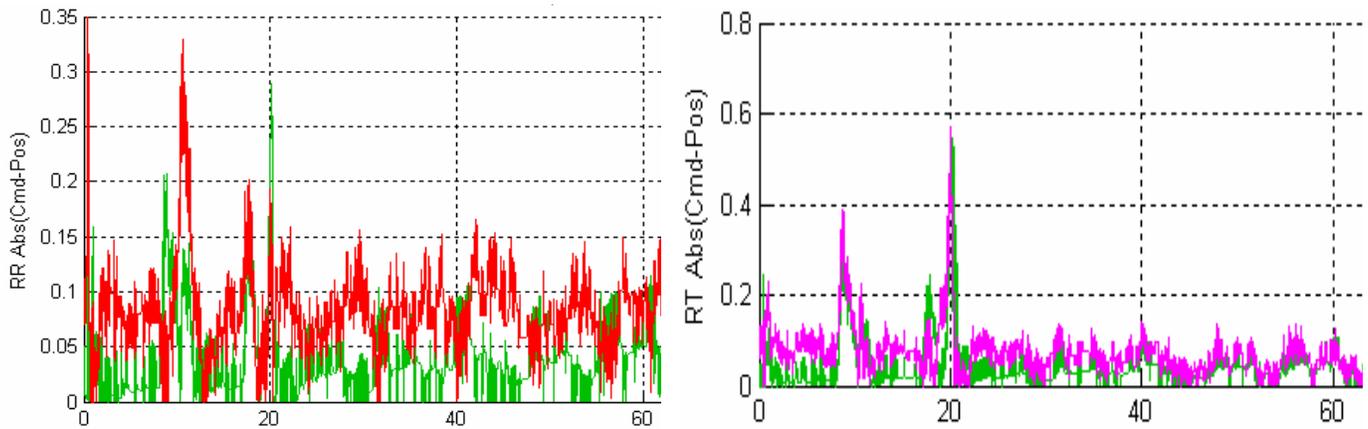
Fig. 17 shows the maximum cmd-pos delta evident in flight data as well as the two rate limiting methods for each flight analyzed. Rate limiting does not add any significant cmd-pos delta over what is witnessed during flight. The highest cmd-pos delta seen for the flight analyzed is just over  $0.8^\circ$  which is still far from the required  $1.95^\circ$ . STS-65 rate limiting cmd-pos delta is the same as flight since the gimbal rate summation never exceeds  $6^\circ/s$  and thus no rate limiting occurs. Many flights shown in Fig. 17 have cmd-pos deltas slightly higher than what was seen during the HPU failure simulation. This shows there are actuator characteristics not modeled in the simulation that

are more significant than rate limiting. However, these differences are not significant within the estimation capability of the simulation and the analysis shows there is plenty of system control margin to account for any simulation estimation.

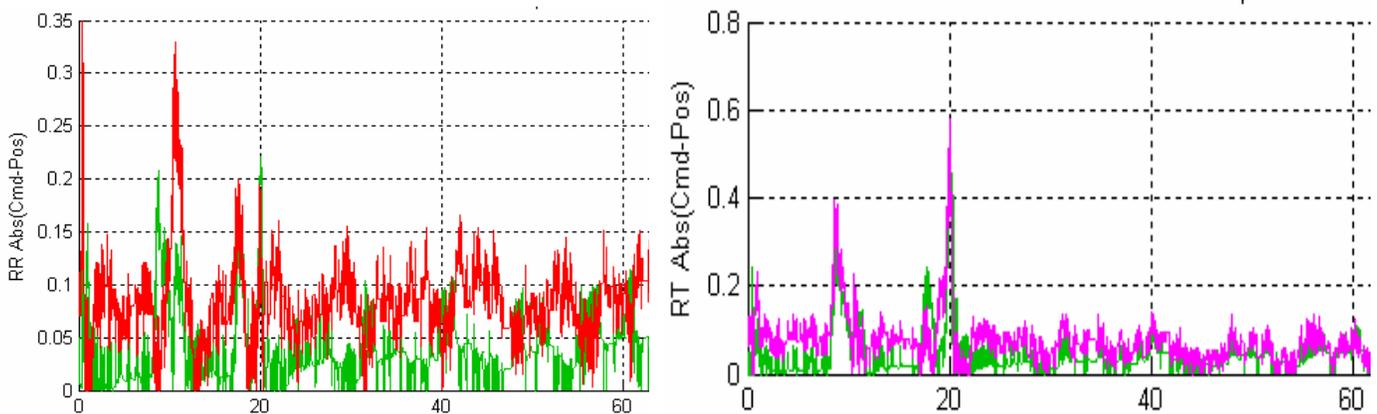
The maximum cmd-pos delta in flight and in the simulation runs shown in Fig. 17 always occurs on the RT actuator during roll program. The vehicle always rolls to the right during the roll program, however, it simultaneously pitches as well. The concurrent roll and pitch commands place more demand on the RT actuator which causes it to slew further from null than the rest of the actuators. This also means that an early HPU failure on the right SRB would be more critical than on the left.



**Figure 14. STS-5 right SRB absolute value gimbal rate summation from flight data and the HPU failure simulation.**



**Figure 15. HPU Failure simulation cmd-pos deltas for STS-5 R SRB using the equal rate limiting assumption.**



**Figure 16. HPU Failure simulation cmd-pos deltas for STS-5 R SRB using cmd-pos delta limiting.**

The gimbal rate summation limit of 6°/s is the design requirement for the HPUs. However, the true hydraulic capability of a single HPU is unknown and could theoretically be lower. The gimbal rate summation limit required for a four-channel bypass was estimated with the developed HPU failure model.

Since the flight data shows the RT actuator is the most demanded SRB actuator, the R SRB was used as a worse case scenario for the estimation of the required gimbal rate summation limit. For each flight analyzed, the gimbal rate summation limit was gradually lowered and the resulting cmd-pos delta was calculated. The rate limit was varied from 6.5°/s (the limit determined by the average of all the cmd-pos deltas was taken at each rate

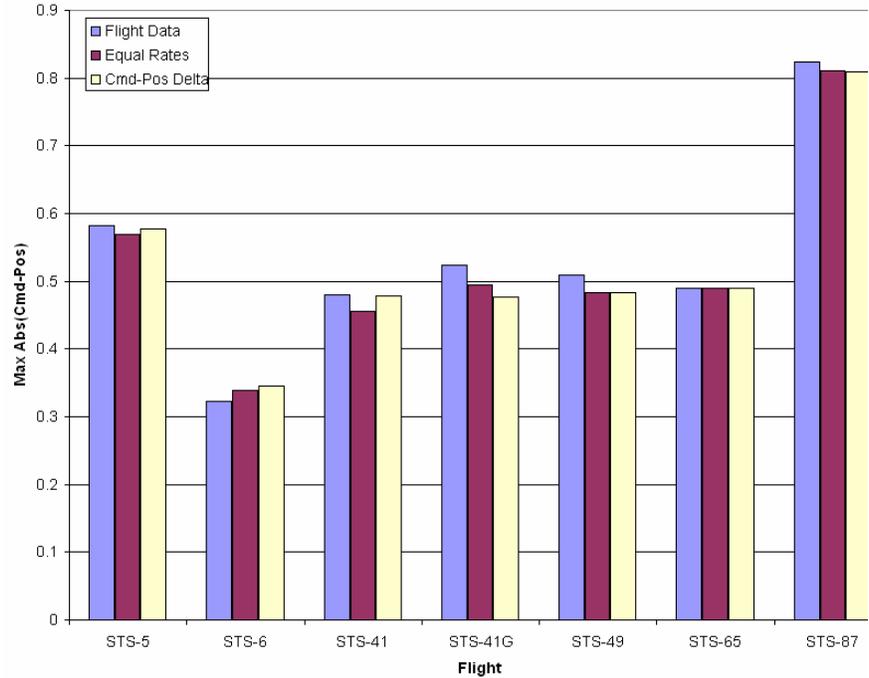


Figure 17. Maximum cmd-pos delta from flight as well as HPU failure simulation for the seven analyzed flights.

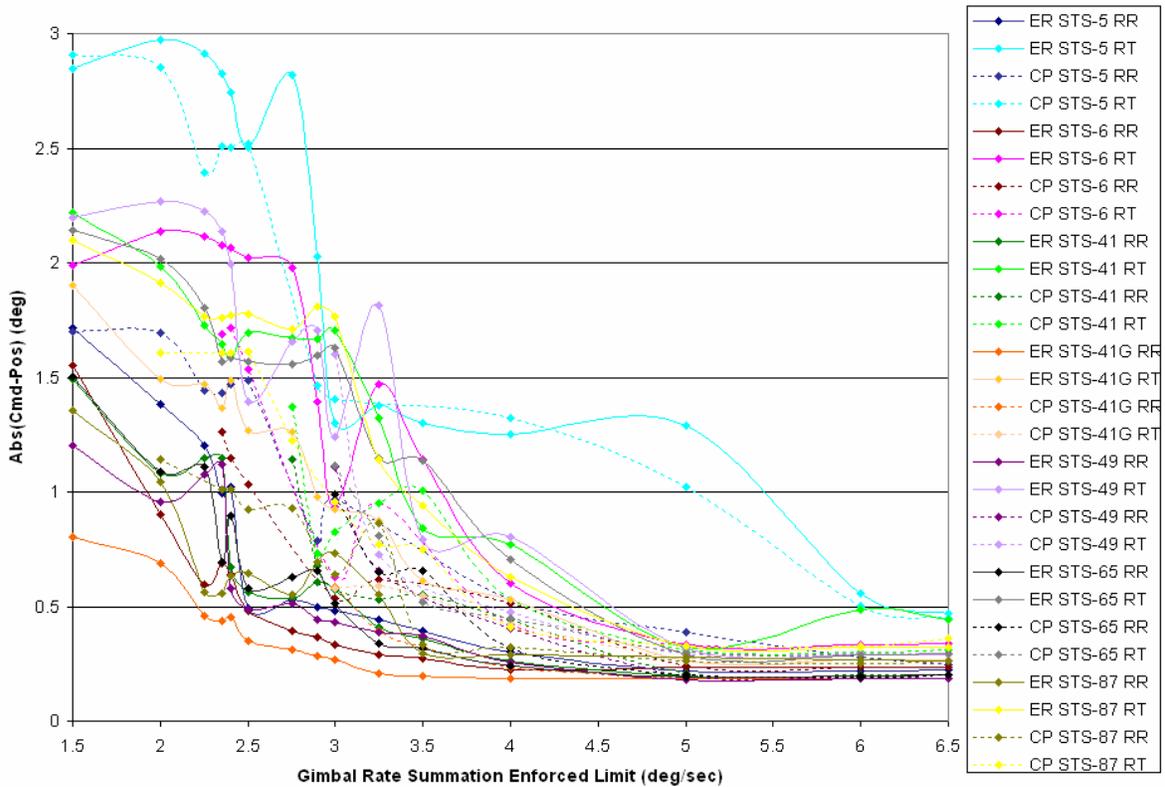
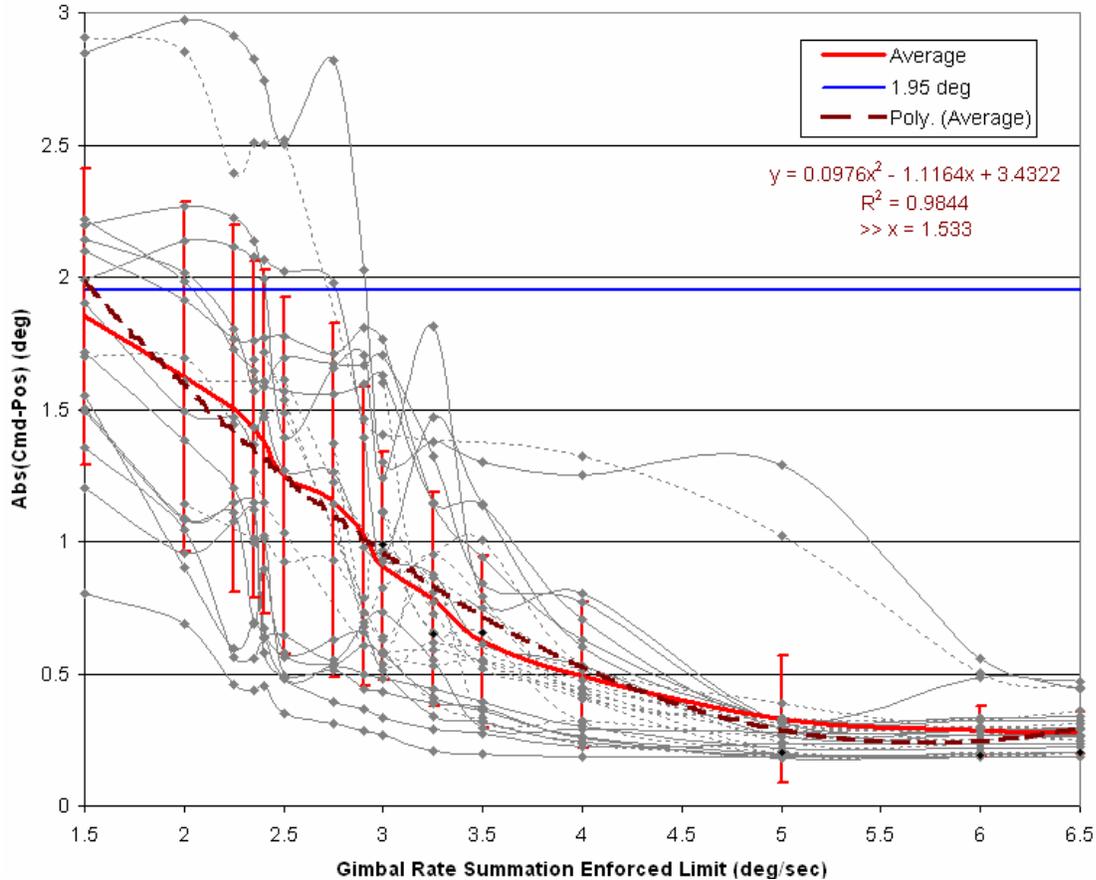


Figure 18. Cmd-Pos deltas resulting from varying gimbal rate summation limits for all analyzed flights with both rate limiting methods.

limit and a second-order polynomial was fitted to the averages. The trendline was then solved for the rate limit which produces a cmd-pos delta of 1.95°.

Fig. 18 shows the cmd-pos delta for the varying rate summation limits for both right SRB actuators and both rate limiting assumptions. The flights are color coded and the cmd-pos delta rate limiting assumption runs are shown with dotted lines to contrast the equal rate assumption runs. Fig. 18 shows the STS-5 RT actuator does not follow the same trend and thus it was treated as an outlying case.

Fig. 19 shows the same data with the average trendline overlaid for all cases with one sigma error bars. The calculated trendline equation, RSS value and corresponding value of “x” (rate limit required) to yield a 1.95° cmd-pos delta are shown.



**Figure 19. Average cmd-pos deltas for each gimbal rate summation limit with trendlines. (Error bars on the average curve represent 1 sigma deviation.)**

Comparison of the resulting required gimbal rate summation limit reveals the different rate limiting methods produce a required limit different from the other by 0.174° after STS-5 RT is removed. While there is some variability, the effect of the rate limiting assumption is small which shows the method of estimating how the gimbals will be limited due to an HPU failure is not significant and the exact mechanism need not be known. Fig. 19 shows that no flights violate the 1.95 deg limit for a rate limit larger than ~3 deg/sec again

Runs Incorporated	All Flights/Gimbals	Without STS-5 RT
All Runs	1.533	1.298
CP Runs Only	1.924	1.424
ER Runs Only	1.403	1.250
RT Runs Only	2.186	2.076
RR Runs Only	0.718	---

**Table 4. Gimbal rate summation limit (deg/sec) required for a four-channel bypass as calculated with varying data subsets.**

indicating a large margin against a four-channel bypass possible with STS-5 RT providing the upper bound. Thus, there is adequate system robustness to account for potential errors due to the rate limiting method assumptions. The variability between the RT and RR actuators is almost eight times larger with a required limit difference of 1.358° (again removing STS-5 RT). Since RT is more likely to develop a large cmd-pos delta, it is more likely to have hydraulic pressure priority over RR and this preference would help keep RT on command during single HPU operations. Thus, the actual gimbal rate summation limit required for a four-channel bypass on RT may be lower than the 2.076° stated above.

The data in Table 4 is not meant to imply the Space Shuttle could safely complete its mission with the shown combined gimbal rate limits. This is a best estimate of the combined gimbal rate limit required to produce a four-channel bypass during nominal ascent profile conditions. With these low gimbal rates, the vehicle is not going to be able to maintain the design trajectory, even if the actuators have not lost control. The gimbal rate limits calculated in Table 4 suggest structural load and trajectory constraints would likely be broken well before an actuator loses control due to a four-channel simultaneous bypass.

## V. Operational Response

Even though the system has adequate margin, an operational response could be taken to prevent a four-channel bypass in the event of a HPU failure. Simply taking one channel, any channel, to OVRD would prevent ports on that channel from bypassing assuming no additional failures. When the secondary delta pressures build up, the three channels in AUTO would bypass but the single channel in OVRD would not allowing control of the actuator to be maintained.

The ascent SRB gimbal profiles show there are four events of high gimbal rate: ignition, roll program initiation, roll program correction and separation null. Table 2 shows the latter three events have higher gimbal rates than ignition, and since these events occur after SRB ignition, they are the limiting events. If an HPU fails and ignition is successfully controlled, the other three events must still be controlled as well. However, during the movement to null positions at SRB tail-off, the SRBs have reduced thrust authority as the propellant is largely burned away. Thus, the SSME engines have more control authority at this time and can provide control in the event a SRB actuator loses control. Thus, roll program is the most critical ascent event for SRB gimbal rate capability.

The roll program occurs from MET 7.2 seconds to 20.6 seconds. Space Shuttle launch commit criteria (LCC) state the shuttle will not launch with a failed HPU<sup>13</sup>. Thus, there is a 20 second vulnerability window where an HPU failure could reasonably be a concern during nominal shuttle ascent. Even though the operational response of taking a single channel to OVRD involves a single switch throw, it is unlikely it could be performed in time to make a difference.

The above analysis showed the ascent event with the greatest risk to a four-channel bypass due to an HPU failure is roll program. Thus, an operational response for a HPU failure after roll program is not necessary. If the failure occurs right at liftoff, there is seven seconds to respond before roll program. If the failure occurs right after roll program initiation, there is ~10 seconds to respond before roll program correction will occur. Thus, if the failure occurs at the optimum time for the maximum operational response window (right after roll program initiation) there is no more than 10 seconds of response time available. The onboard crew has limited insight into the SRBs and it is likely Mission Control Center (MCC) would have to recognize the HPU failure and call the failure up to the crew. Given the telemetry lag time, time to recognize the failure, time to call for a response in MCC, time to call the response up to the crew and the time for the crew to flip the switch, the 10 second response window is not adequate for such a response to be feasible.

The first stage of space shuttle ascent is very bumpy and it is difficult for the crew to flip switches or make keyboard item entries. Therefore, only required actions are usually taken during first stage. Due to the system margin available, I would not recommend a channel be taken to OVRD in response to a HPU failure. The switch throw is not required and the crew could accidentally flip a different switch. The large system margin also makes it unnecessary to launch with a channel in OVRD. Placing a FCS switch in OVRD will prevent all Shuttle and SRB actuators on that channel from bypassing automatically for any detected failure. Given the system margin, placing a switch in OVRD before launch preemptively to prevent a four-channel bypass is more likely to not allow a problem on that channel to be isolated than to prevent loss of an actuator control due to an HPU failure.

## VI. Conclusions

Simulation of a failed HPU during nominal shuttle ascent has shown there is large SRB hydraulic capability margin against a four FCS channel bypass of an actuator. Analysis showed that failure of an HPU does not cause significant cmd-pos deltas above what is nominally seen during flight and that no analyzed flights reach a four channel bypass condition with a rate limit greater than 3 deg/sec. While failure of an HPU limits hydraulic capability, the shuttle ascent SRB gimbal profile does not command fast slews of long enough duration for a large cmd-pos delta to build.

The above analysis is a limited, but conservative study. Equalization logic was not modeled. Also, the HPU failure model simulated one SRB hydraulic channel when four concurrently command the power valve. However, the presence of equalization and additional hydraulic channels would only help keep the actuator on command and help reduce sec dP to prevent port bypasses.

The USA SRB analysis predicts SRB actuator control problems will occur at simultaneous gimbal rates of 6.5°/s during one HPU operation<sup>12</sup>. This analysis used a simultaneous gimbal rate limit of 6°/s adding to the conservatism. Even with the conservative nature of the analysis, adequate hydraulic margin was shown.

Data from the November HPU failure SRB hot fire test can be used to further validate and refine this analysis once the system capability is understood with more precision. Similar analysis should also be conducted for future programs utilizing SRBs and HPUs since the gimbal profile and demands would change for a different vehicle.

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