USE OF MICROGRAVITY SENSORS FOR QUANTIFICATION OF SPACE SHUTTLE ORBITER VERNIER REACTION CONTROL SYSTEM INDUCED ENVIRONMENTS

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In the modeling of spacecraft dynamics it is important to accurately characterize the environment in which the vehicle operates, including the environments induced by the vehicle itself. On the Space Shuttle these induced environmental factors include reaction control system plume. Knowledge of these environments is necessary for performance of control systems and loads analyses, estimation of disturbances due to thruster firings, and accurate state vector propagation.

During the STS-71 mission, while the Orbiter was performing attitude control for the mated Orbiter/Mir stack, it was noted that the autopilot was limit cycling at a rate higher than expected from pre-flight simulations. Investigations during the mission resulted in the conjecture that an unmodelled plume impingement force was acting upon the orbiter elevons. The in-flight investigations were not successful in determining the actual magnitude of the impingement, resulting in several sequential post-flight investigations.

Efforts performed to better quantify the vernier reaction control system induced plume impingement environment of the Space Shuttle orbiter are described in this paper, and background detailing circumstances which required the more detailed knowledge of the RCS self impingement forces, as well as a description of the resulting investigations and their results is presented. The investigations described in this paper applied microgravity acceleration data from two shuttle borne microgravity experiments, SAMS and OARE, to the solution of this particular problem. This solution, now used by shuttle analysts and mission planners, results in more accurate propellant consumption and attitude limit cycle estimates in preflight analyses, which are critical for pending International Space Station missions.

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INTRODUCTION

Reaction jet plume characterization is often performed using computational fluid dynamics and associated techniques. This characterization includes the self impingement components of the rocket plume which impact the orbiter surfaces each time an attitude control engine is fired. The inclusion of these effects becomes extremely difficult when uncertainties in the position of articles in the engine plume are included. For the orbiter aft down firing vernier thrusters, the subject of this investigation, this includes main engine bells, the body flap, and the elevons. The Space Shuttle has been flying for 17 years, yet it was discovered on the STS-71 mission that the induced vernier reaction control system environments and associated plume self-impingement had been poorly quantified.

PROBLEM DESCRIPTION

The Space Shuttle orbiter accomplishes attitude control when in orbit through the use of 44 reaction control system (RCS[‡]) thrusters. The 38 Primary RCS thrusters are arranged in 14 groups to provide both automatic rotational control and manual translation control. The six Vernier thrusters are arranged about the vehicle in orientations that allow three axis rotational control. Each of the 14 PRCS thruster groups and each of the six VRCS thrusters has an associated acceleration vector, called an angular acceleration increment, used to determine which thruster to select in the presence of a given command and to estimate the vehicle rate change in response to a thruster firing. These acceleration increments are calculated by the Shuttle computers using pre-flight determined models of the vehicle mass properties and orbiter RCS, including plume impingement components. The overall thruster arrangement is shown in Figure 1.
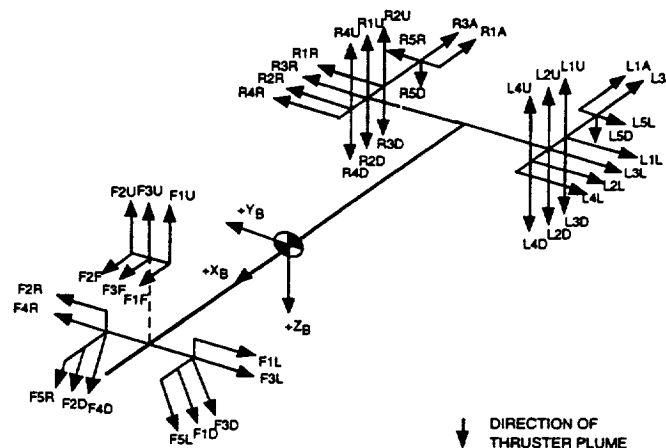

Figure 1 Shuttle Orbiter Thruster Locations and Plume Directions
A 5 Indicates Vernier Thrusters, All Others are Primary Thrusters

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[‡] All acronyms used are defined in the accompanying notations section.

During the STS-71 mission, while the Orbiter was performing attitude control for the mated Orbiter/Mir stack, it was noted that the Orbiter Digital Autopilot (DAP[7]) was limit cycling at a rate higher than expected from pre-flight simulation results. This resulted in propellant expenditures roughly twice pre-flight predictions for some of the inertially held attitudes. Analysis of the DAP performance showed that the actual vehicle acceleration experienced for a minus Pitch command differed significantly from the DAP expected values. The DAP expected acceleration is calculated based upon transferring the torque about a reference CG to the predicted mission CG using the cross product of the jet forces and the difference between the reference and flight estimated CG positions. These predicted accelerations are then used in the feed-forward loop of the autopilot to estimate rate changes due to a thruster firing. When a difference between the predicted rate change (calculated) and the actual rate change (derived from IMU data) is seen, the DAP updates its estimate of undesired accelerations. These are then used to update the switching lines in the DAP phase plane controller. The STS-71 mated vehicle flight derived accelerations are compared to the DAP estimates and shown in Table 1, while Figures 2 and 3 display representations of the nonlinear Orbit DAP Pitch axis phase plane both from pre-flight expectation, and from in-flight experience.

Table 1
STS-71 MATED VEHICLE PREDICTED AND FLIGHT DERIVED ACCELERATIONS

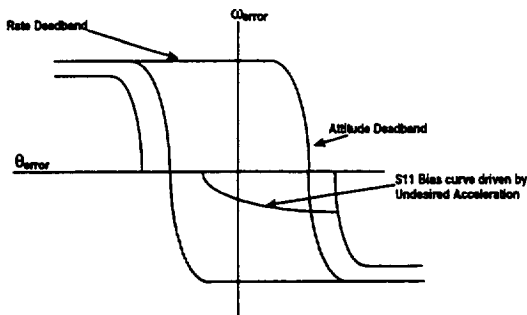| Axis	Positive		Negative	
	Actual (d/s^2)	Predicted (d/s^2)	Actual (d/s^2)	Predicted (d/s^2)
Roll	0.0025	0.0028	-0.0023	-0.0024
Pitch	0.0030	0.0029	-0.0019	-0.0026
Yaw	0.0118	0.0110	-0.0130	-0.0110

Figure 2 Typical Pitch Axis Phase Plane with Representative Switching Lines
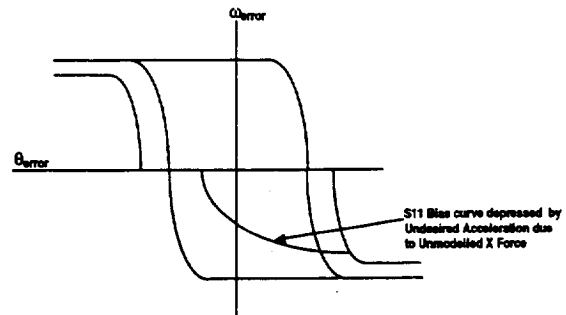
Figure 3 STS-71 Pitch Axis Phase Plane with Biased S11 Switching Line

Separate phase planes are maintained for each of the three rotational axes, with the switching lines defined from desired rate and attitude deadbands to determine when a control action is required. The autopilot maintains the vehicle state inside the bounds of these rate and attitude limits. The switching lines are derived based upon estimates of the available control and disturbance accelerations to provide propellant efficient operation, i.e. low rate one or two sided limit cycles. In the absence of substantial disturbances a two sided limit cycle is commanded, while in the presence of

disturbances, a single sided limit cycle is commanded. The efficiency of the limit cycles is therefore dependent upon the accuracy of the disturbance acceleration estimation.

As a result of the investigations conducted during the STS-71 mission, it was concluded that the errors in the DAP acceleration estimate were most probably due to an unmodelled force acting in the +X (Orbiter Body Axis) direction. This force was assumed to be primarily impingement forces from the aft downward firing vernier thrusters R5D and L5D acting upon the orbiter elevon and body flap. The VRCS plume model in use prior to STS-71 was derived from flight data after testing on STS-1 revealed that original (pre-STS-1) estimates for VRCS plume forces and moments significantly underestimated the effects of impingement on the Orbiter elevon and bodyflap[1]. This model was derived for orbiter surfaces at trail (0.0 degrees deflection) and, unlike the PRCS thrusters, does not have a modifier to correlate changes in orbiter self-impingement with aerosurface deflections. The STS-71 in-flight investigation, its progress, and its attendant conclusions are completely documented in various post-flight reports and papers[2,3,4]

Following the STS-71 mission, analysts from the NASA/JSC Engineering Directorate Applied Aeroscience and CFD Branch used a plume analysis tool to generate impingement forces and torques which, when used in off-line simulations, matched STS-71 mated flight signatures. None of these models were able to provide a satisfactory match to flight signatures for the mated configuration without unacceptably affecting the orbiter alone signatures. It was the opinion of the analysts that a full CFD analysis be funded or alternately, a flight derived model be pursued[5]. The decision was made to pursue derivation of a model based on flight data.

APPROACH

To develop the new model, it was decided to capitalize on the sensitivity of two accelerometer payloads (SAMS and OARE) on the STS-73 microgravity mission to measure translational accelerations from VRCS thruster firings. A DTO was designed which required 19.6 second firings from both a single aft down-firing VRCS thruster, and 2 simultaneous down-firing aft thrusters[6]. These were done at a fixed (-7.5 degree) elevon position. The accelerations due to the thruster firings were analyzed post-flight to determine a flight-derived plume model. This model was compared against signatures from several shuttle flights. It was also compared against similar data from STS-78, a micro-gravity mission where the DTO was performed twice in an effort to quantify elevon position effects on VRCS plume impingement. The STS-78 results were used to verify the STS-73 derived model. Small changes in the STS-73 derived model resulted from analysis of the STS-78 data. The resulting model was compared against data from several missions and orbiter configurations (mated to the Mir, and Orbiter alone)

DISCUSSION

STS-73 Shuttle Accelerometer Measurement System (SAMS) and Orbiter
Accelerometer Research Experiment (OARE) data was downloaded from the
NASA/Lewis Research Center Microgravity Services Lab via Internet FTP. This data
was first evaluated using the data viewers made available through the FTP site. A
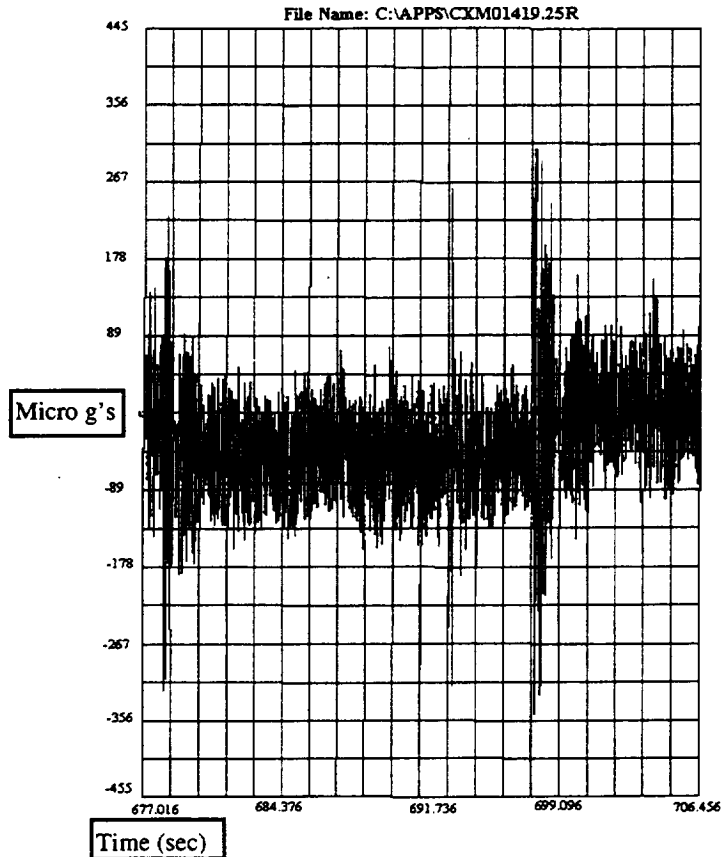sample of the SAMS viewer data from STS-73 is presented in Figure 4.

Figure 4 STS-73 SAMS Data from SAMS Viewer
X-axis Acceleration, R5D+L5D

The desired thruster acceleration data was initially difficult to extract due to the
frequency of the accelerometer data and the low level of acceleration from the VRCS
thruster(s). To aid in data extraction, the accelerometer data was normalized to remove
acceleration biases due to on-board activities and vehicle attitude, then filtered using a
filter with a 0.2 Hz cutoff frequency to eliminate the high frequency content which made
the plots difficult to read. Figure 5 presents the data from Figure 4 after processing
through the MATLAB tools. After determination of the sensed acceleration, the
accelerations were transformed into the Orbiter structural reference frame at the orbiter
CG, rather than in the accelerometer frame at the accelerometer location. Preliminary
force and moment models were then developed using the acceleration data derived
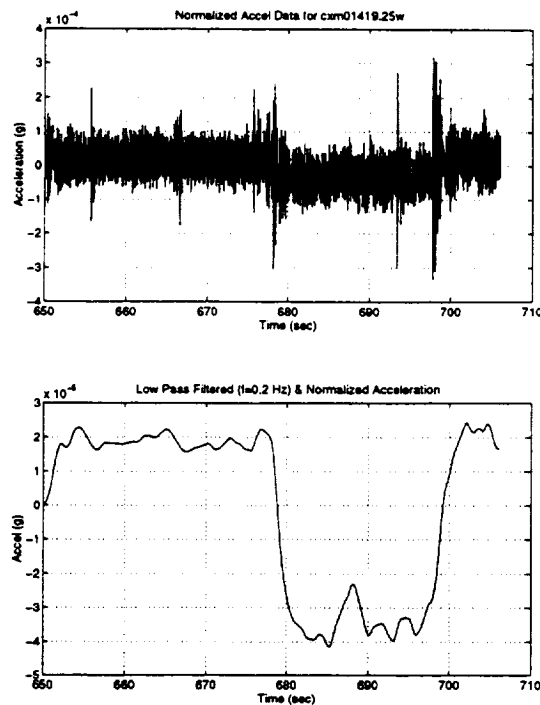from the accelerometer measurements.

Figure 5- STS-73 SAMS Data, Normalized and Filtered
X-axis Acceleration, R5D+L5D

To perform a check on the reasonableness of the accelerations determined via reading the plots from the flight data, a MATLAB tool was developed using the System Identification Toolbox. The tool attempts to simultaneously solve for both forces and moments through repetitive iterations, searching for a local minimum of a specified function using a Gauss-Newton minimization procedure, subject to some criteria. In this case, the specified criteria was a minimum error between the SAMS acceleration data and the tool results. Optimal solutions for the X force value, as determined by the MATLAB tool using STS-73 and STS-78 SAMS data, ranged from 3.8lb$_f$ to 5.3lb$_f$. This bracketed the value of 3.9lb$_f$ determined from reading the plots. The large range in values is a result of two problems encountered with the System Identification toolbox.

The first problem encountered was that the MATLAB system Identification toolbox requires that the equations of motion be represented by a linear model, and this is not accurate due to Euler cross-axis coupling. Euler coupling has a significant effect on shuttle vehicle dynamics while in orbit when using vernier thrusters and may not be ignored in this case. The second problem was numerical precision related. Accelerations measured were in the 1×10^{-5} to 4×10^{-5} range and consequently were near the precision limits of the tools. Because of these problems the results from this tool were refined using a high fidelity six degree of freedom simulation with non-linear equations of motion.

The various candidate force and moment models were input to the high fidelity simulation as both environment and autopilot software values. Initial simulation runs were performed and compared against flight data from STS-73 and STS-71. The revised force and moment models all came closer to matching mated flight data than the original model but the match for orbiter alone cases was adversely affected. When using the models which contained the larger forces in the Orbiter X axis ($F_x > 4$ lb), large under-predictions in rate change (rather than over-predictions seen with the old model) were seen for the mated flight data. The models with lower values of F_x all matched flight data closely, but universally the new models adversely affected results from single jet and two jet cases when compared to the orbiter alone results. A small trade study was performed which resulted in the determination that, for orbiter alone cases, the moment values for M_y and M_z had greater effect on system response than the forces F_x and F_y. The opposite was true for orbiter/Mir mated cases due to the large difference between the system reference and the actual vehicle center-of-gravity, where the moment generated by the revised plume forces is significantly large when compared to the generated control moment. This result led to the conclusion that the original model, created after STS-1, closely approximated the moments generated by the vernier thrusters, but did not accurately represent the forces generated. In creation of the final model, a decision was made to create a hybrid model consisting of new forces and the old moments, since the original model had matched orbiter alone cases well. The final impingement model, and the associated K-load jet model is shown in Tables 2 and 3, with the old model for comparison.

Table 2
IMPINGEMENT MODELS: NEW VS. OLD FORCES AND MOMENTS

Thruster	New Model		Old Model	
	R5D	L5D	R5D	L5D
F_{Ix} (lb)	3.91	3.91	0.403	0.403
F_{Iy} (lb)	-4.35	4.35	-4.293	4.293
F_{Iz} (lb)	10.93	10.93	10.906	10.906
M_{Ix} (ft-lb)	92.6	-92.6	92.64	-92.64
M_{Iy} (ft-lb)	435.3	435.3	435.29	435.29
M_{Iz} (ft-lb)	170.4	-170.4	170.4	-170.4

Table 3
ONBOARD SOFTWARE MODEL- NEW VS. OLD FORCES AND MOMENTS

Thruster	New Model		Old Model	
	R5D	L5D	R5D	L5D
F_{Ix} (lb)	3.91	3.91	0.403	0.403
F_{Iy} (lb)	-4.35	4.35	-4.293	4.293
F_{Iz} (lb)	-13.07	-13.07	-13.09	-13.09
M_{Ix} (ft-lb)	-143.3	143.3	-143.32	143.32
M_{Iy} (ft-lb)	-541.4	-541.4	-541.39	-541.39
M_{Iz} (ft-lb)	170.4	-170.4	170.4	-170.4

RESULTS

The new model was evaluated against flight data from twelve cases spanning five shuttle missions. The evaluations included both orbiter alone and Orbiter/Mir configurations, and four different elevon positions. The new models were first used in an open loop jet selection program to determine raw vehicle rotational acceleration differences for cases where L5D, R5D, or both L5D and R5D were selected. The percentage differences in rotational accelerations between the old and the new models and flight data for the twelve cases are presented in Table 4.

Table 4
ROTATIONAL ACCELERATION DIFFERENCES: FLIGHT VS. OLD AND NEW MODELS

Mission	Condition	Elevon Position (deg)	Thruster	Absolute Difference- Flight vs. Open Loop (%)					
				Flight to Old Model			Flight to New Model		
				Roll	Pitch	Yaw	Roll	Pitch	Yaw
STS-71	Docked	0.0	L5D + R5D	96.83	21.84	103.5	97.37	0.073	102.7
STS-71	Docked	+21.6	L5D + R5D	97.16	31.22	93.43	97.64	7.61	94.88
STS-71	Docked	-7.5	L5D + R5D	31.61	18.07	124.7	42.28	1.46	119.6
STS-71	Orbiter	-7.5	L5D + R5D	75.47	5.44	66.20	74.67	2.56	113.3
STS-73	Orbiter	-7.5	L5D	0.098	7.89	14.10	4.06	0.91	12.15
STS-73	Orbiter	-7.5	L5D + R5D	88.94	12.31	101.4	87.74	3.94	101.7
STS-74	Docked	-7.5	L5D + R5D	6.91	22.16	19.27	14.79	3.10	16.14
STS-78	Orbiter	-7.5	L5D + R5D	116.91	15.19	99.91	119.7	7.18	102.4
STS-78	Orbiter	-7.5	R5D	0.13	18.50	30.08	4.04	10.80	31.73
STS-78	Orbiter	-25.3	L5D + R5D	115.74	16.17	99.82	127.0	8.34	48.97
STS-78	Orbiter	-25.3	R5D	4.69	16.11	19.15	0.73	7.96	18.21
STS-79	Orbiter	-7.5	L5D + R5D	41.65	42.4	99.98	66.67	2.16	99.89

From examination of the tabular data, it is apparent that the new model produces, on the whole, smaller differences between simulation and flight measured accelerations in the axis of interest. All the percentage errors in the table greater than 10% are due to small differences between very small numbers. For example, the Yaw axis 101% error for the STS-73 2 jet case results from the difference between an open loop predicted rotational acceleration of ~2.6E-06 deg/sec^2 and an actual acceleration of 1.4E-04 deg/sec^2. Figures 6 and 7 show the filtered STS-73 SAMS flight measured accelerations (in Orbiter Body Axis) cross plotted with the output of a closed loop simulation for the L5D+R5D -Pitch case. Evaluation of the open loop acceleration comparisons also showed that the plume force and moments vary with elevon position, as might be expected. Due to the sparseness of data points an accurate correlation between elevon position and plume force variation was not possible. Since the variations in rotational acceleration were within the autopilot feed-forward loop angular acceleration increment (angular acceleration over autopilot step time) design criteria of 10% it was determined that the VRCS plume model need not be elevon position dependent as the PRCS models are.
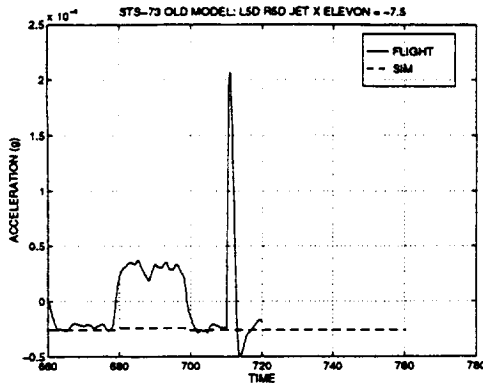
Figure 6 Old Model X Axis Accelerations v. Flight
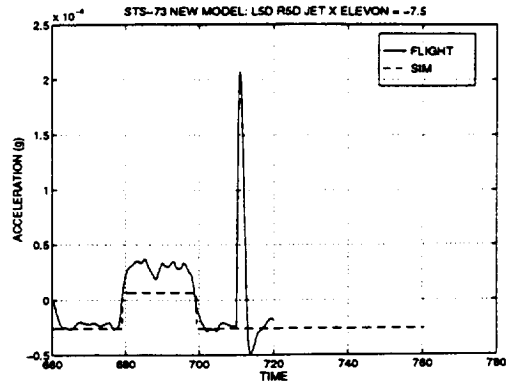L5D+R5D -Pitch Firing, δₑ= -7.5 deg

Figure 7 New Model X Axis Accelerations v. Flight
L5D+R5D -Pitch Firing, δₑ= -7.5 deg

Following the open loop comparisons, closed loop cases were run using both the old and new models for comparison against flight data from five missions: STS-71, STS-73, STS-74, STS-78, and STS-79. Simulation results were plotted against orbiter downlisted flight data obtained from the shuttle downlist. Figure 6 shows the system comparison to STS-73 flight data using the old models, while Figure 7 shows the results using the new models. Both figures represent an L5D thruster firing for 19.6 seconds. Figures 10 and 11 display the results of a 19.6 second firing of L5D and R5D in response to a -Pitch command. As can be seen, there is little difference between the new and old models for an Orbiter alone case. Very small improvements in comparison to the STS-73 flight data for the single jet case were noted. No change was visible in the 2 jet cases shown in Figures 8 and 9. As an item of interest, it was noted that, in the orbiter alone cases examined for STS-71 and -73, both the new and the old models slightly overpredicted the vehicle rate change due to a thruster firing, while in the STS-78 cases the rate change was slightly underpredicted compared to flight. These differences were attributed to mass property variations between the missions.
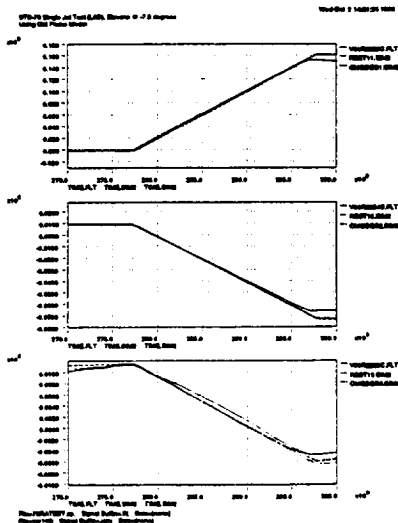

Figure 8 STS-73- Flight vs. Simulation, Old Plume Model, Roll, Pitch & Yaw Rate from L5D Firing, δₑ= -7.5 deg

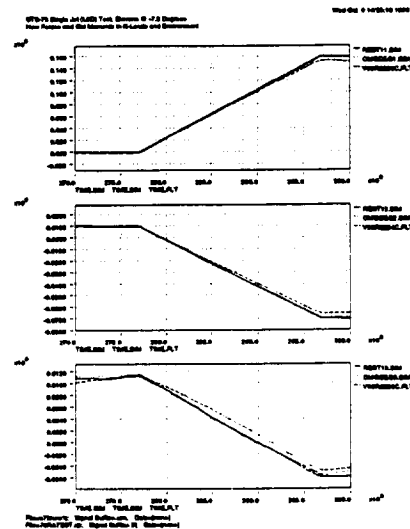
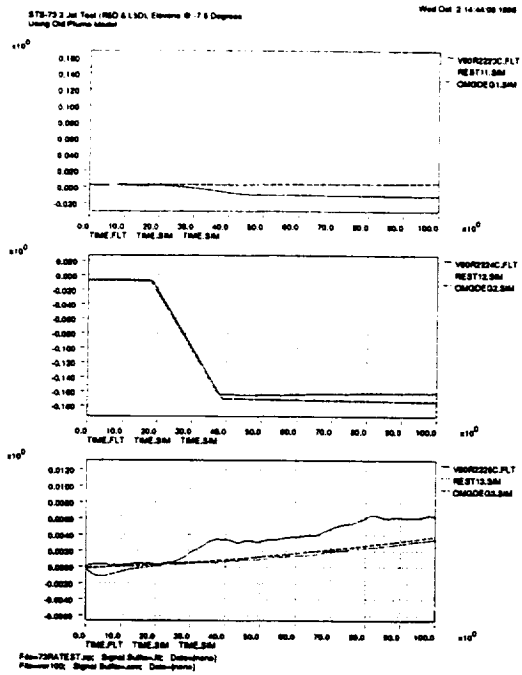Figure 9 STS-73 Flight vs. Simulation, New Plume Model, Roll, Pitch & Yaw Rate from L5D Firing, δₑ= -7.5 deg

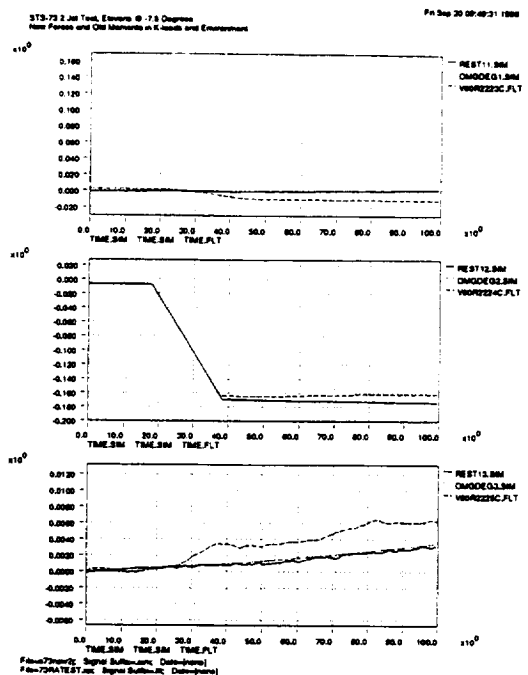Figure 10 STS-73- Flight vs. Simulation, Old Plume Model, Vehicle Rates from -Pitch Firing (L5D+R5D), δₑ= -7.5 deg

Figure 11 STS-73 Flight vs. Simulation, New Plume Model, Vehicle Rates from -Pitch Firing (L5D+R5D), δₑ= -7.5 deg

Although the differences between the orbiter alone configurations examined were minimal, in the orbiter/Mir mated cases, differences were much more evident. Simulations were run for STS-71, STS-74 and STS-79. Since STS-71 flight data was available for several elevon positions (0.0 degrees, +21.6 degrees, and -7.5 degrees) each was individually examined. A single case was performed for STS-74 since the elevons were fixed at -7.5 degrees, and two cases were examined for STS-79 since data was available for both L5D and R5D together, and R5D alone.

The STS-71 simulations were performed using the flight initialization load (I-load) software parameters with the DAP acceleration filter enabled. The STS-74 and STS-79 cases used the defined flight I-loads with the acceleration filter disabled during thruster firings. The acceleration filter was disabled for these missions to mask the plume impingement effects of each thruster firing from the orbiter autopilot, since the onboard software models had not been updated to account for the plume forces. Figures 12 and 13 illustrate the system response for the STS-71 mated case with the elevons at their full down position of +21.6 degrees. Discontinuities visible on the plots are due to data dropouts in the flight data. Figures 14 and 15 are comparisons between old and new plume models and STS-79 flight data, while Figure 16 compares the single jet system response using the new model to STS-79 flight data. As is apparent from examining Figures 12 through 16, the new model compares much more closely to flight results than the previous model.
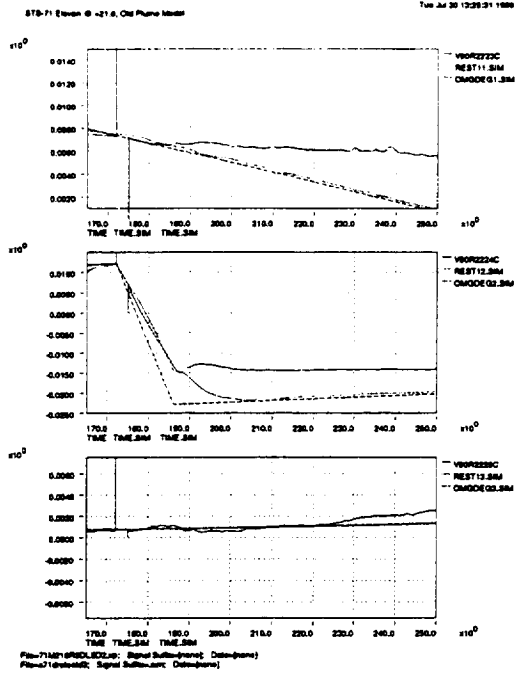
Figure 12 STS-71- Flight vs. Simulation, Old Plume Model, Vehicle Rates from -Pitch Firing (δ_e = +21.6deg)
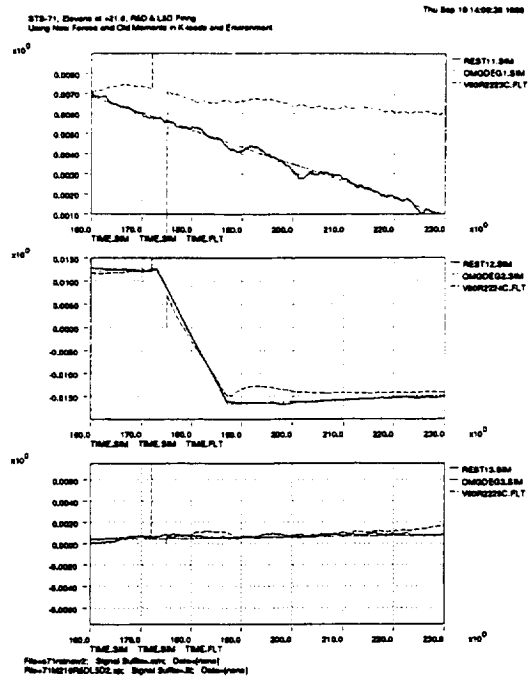
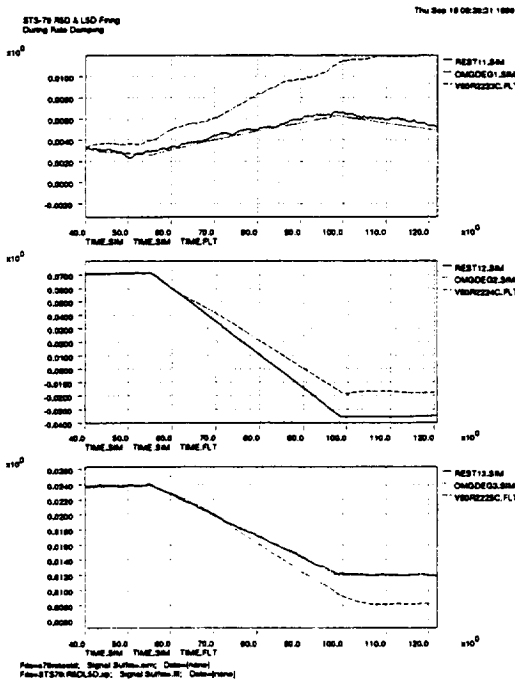Figure 13 STS-71 Flight vs. Simulation, New Plume Model, Vehicle Rates from -Pitch Firing (δ_e = +21.6 deg)

Figure 14 STS-79- Flight vs. Simulation, Old Plume Model, Vehicle Rates from -Pitch Firing (L5D+R5D), δ_e= -7.5 deg
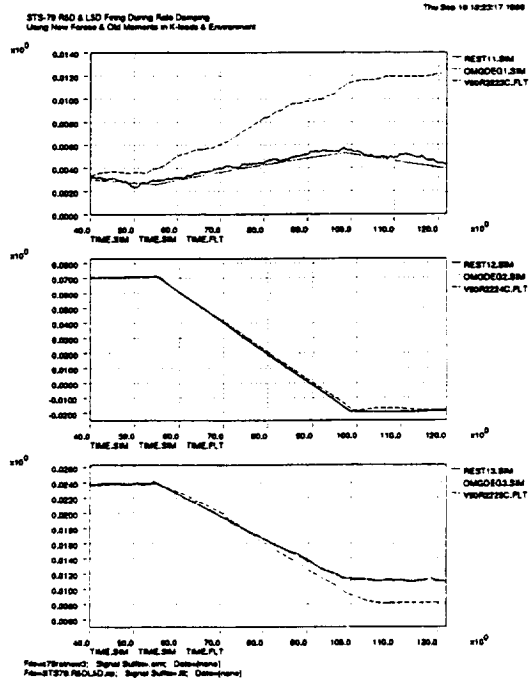
Figure 15 STS-79 Flight vs. Simulation, New Plume Model, Vehicle Rates from -Pitch Firing (L5D+R5D), δ_e= -7.5 deg
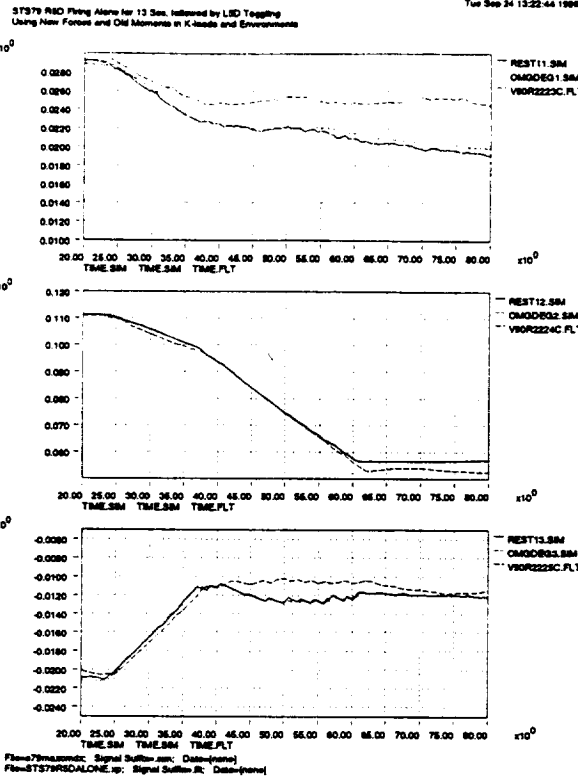
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Figure 16 STS-79- Flight vs. Simulation, New Plume Model,
Vehicle Rates from firing R5D, with some pulsing from L5D, δ_e= -7.5 deg

CONCLUSIONS

It was apparent, from STS-71 flight data, that the vernier RCS plume model created after STS-1 did not represent the actual vehicle self-impingement forces accurately. An investigation to more accurately define plume impingement effects of the aft down-firing vernier thrusters was completed, resulting in a new model of VRCS self impingement forces. The new model has been verified against multiple Shuttle missions and on-orbit configurations. From comparison of the flight data with simulation results using the new plume model, it is evident that much closer matches between simulation and flight signatures may be obtained for both orbiter alone scenarios and scenarios with the Orbiter mated to a large structure. The new model is in use by analysts and mission planners on the shuttle program. Its incorporation into flight design and stability and control analyses results in more accurate estimation of propellant consumption and vehicle performance, both extremely important parameters in the pending Space Station assembly missions requiring Orbiter control of the mated Orbiter/ISS configuration.

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ACKNOWLEDGEMENTS

NOTATIONS

PRCS- Primary Reaction Control System, each thruster develops 870 lb_f thrust
VRCS- Vernier Reaction Control System, each thruster develops 25 lb_f thrust
DAP- Shuttle Digital Autopilot
OARE- Orbital Acceleration Research Experiment
SAMS- Shuttle Acceleration Measurement System
CG- Center-of-Gravity
DTO- Developmental Test Objective
DOF- Degree-of-Freedom
I-Load- Initialization Load, a shuttle software parameter that may change each flight
K-load- Constant Load, a shuttle parameter that is hard coded into the software
F_x- Force acting in the Orbiter X axis
M_x- Moment about the Orbiter X axis
CFD- Computational Fluid Dynamics
δ_e- Delta Elevon position, with - sign denoting upward deflection, and + denoting downward
ω_e- Attitude rate error, the differenced between desired and sensed vehicle rate
θ_e- Attitude error, the difference between desired and actual position

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