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TECHNIQUES FOR IMPROVING THE PERFORMANCE OF FUTURE EVA MANEUVERING SYSTEMS

NAG9-799

Final Report

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Abstract

The Simplified Aid for EVA Rescue (SAFER) is a small propulsive backpack that was developed as an in-house effort at Johnson Space Center; it is a lightweight system which attaches to the underside of the Primary Life Support Subsystem (PLSS) backpack of the Extravehicular Mobility Unit (EMU). SAFER provides full six-axis control, as well as Automatic Attitude Hold (AAH), by means of a set of cold-gas nitrogen thrusters and a rate sensor-based control system. For compactness, a single hand controller is used, together with mode switching, to command all six axes. SAFER was successfully test-flown on the STS-64 mission in September 1994 as a Development Test Objective (DTO); development of an operational version is now proceeding. This version will be available for EVA self-rescue on the International Space Station and Mir, starting with the STS-86/Mir-7 mission in September 1997.

The DTO SAFER was heavily instrumented, and produced in-flight data that was stored in a 12 MB computer memory on-board. This has allowed post-flight analysis to yield good estimates for the actual mass properties (moments and products of inertia and center of mass location) encountered on-orbit. By contrast, Manned Maneuvering Unit (MMU) post-flight results were generated mainly from analysis of video images, and so were not very accurate. The main goal of the research reported here was to use the detailed SAFER on-orbit mass properties data to optimize the design of future EVA maneuvering systems, with the aim being to improve flying qualities and/or reduce propellant consumption. The Automation, Robotics and Simulation Division Virtual Reality (VR) Laboratory proved to be a valuable research tool for such studies. A second objective of the grant was to generate an accurate dynamics model in support of the reflight of the DTO SAFER on STS-76/Mir-3. One complicating factor was the fact that a hand controller stowage box was added to the underside of SAFER on this flight; the position of this box was such that two of the SAFER jets plume it. A second complication was that the EVA astronaut will sometimes be transporting a massive experiment package. This will not only alter the overall mass properties significantly, but can itself also be plumed.

TABLE OF CONTENTS

1. Introduction

The research reported here follows on from the work carried out by the Principal Investigator under two previous grants with the Automation, Robotics and Simulation Division. These projects covered many dynamics questions associated with the SAFER astronaut maneuvering unit[1]. The first grant involved calculating predicted values for the mass properties of the crewmember/EMU/SAFER system for various crewmember sizes and leg positions[2,3]. These mass properties were incorporated into the Virtual Reality (VR) Laboratory (formerly IGOAL) simulator, which is the primary means of crew training for SAFER flight operations. The second grant was then concerned with determining the actual mass properties from on-orbit data, so as to validate the pre-flight predictions[4-6]. The work described here makes use of these experimentally determined mass properties to derive design refinements which should improve either the flying qualities or the propellant efficiency, or both, of future EVA maneuvering systems.

In addition to the previous work just outlined, the Principal Investigator also carried out detailed pre-flight analyses of the flying qualities expected for SAFER, both with AAH on[7] and off[8]. This analysis, which has many implications for the proposed research, predicted that the two major types of cross-coupling encountered would be yaw resulting from a roll input, and yaw resulting from a y translation command. This behavior was actually observed on-orbit: see Figures 1.1 and 1.2 for the angular body rates produced by a roll and y input command, respectively. The comparatively large yaw cross-coupling in both cases can clearly be seen. In addition, it can be seen from Figure 1.1 that pitch is essentially decoupled from roll/yaw, with only a slow "second-order" negative build-up after an appreciable coast time; this again was as predicted[8].

This type of dynamics analysis also served to quantify the propellant consumption and control authority penalties incurred when flying with AAH engaged, as a result of having to counteract the inherent cross-coupling of the system. Furthermore, it described how this penalty varies as a function of crewmember size and posture. One illustration of this variation is given by comparing Figures 1.3 and 1.4. These are both plots of the angular rates resulting from an x translation maneuver on-orbit, but Figure 1.3 is for STS-64 EV1 (Mark Lee) and Figure 1.4 for EV2 (Carl Meade). As EV2 is smaller than EV1, the overall CG of the astronaut/EMU/SAFER system is nearer that of the EMU, i.e. higher, in his case. Thus, a +x translation thrust induces a pitch-up moment for EV2 but not for EV1. If AAH were engaged during this maneuver, it would compensate for the pitching moment by periodically turning the lower x jets off. Consequently, AAH would have to perform more such thruster modulation for a smaller crewmember than for a larger one, so reducing control authority for this type of maneuver. The effects of a stuck-on or failed-off thruster were also analyzed in a similar manner. In particular, it was shown that the control authority of translation maneuvers executed under AAH can become quite severely degraded (down to 25-50% of nominal) as a result of a single failed-off jet. In the worst-case jet failure, roll can become essentially uncontrollable when carrying out a y or z translation. Of course, this problem is unlikely ever to actually arise in practice, but it is important to know that the potential exists and to prepare for it.

The task of deriving the actual on-orbit mass properties made use of data from all maneuvers executed by the two astronauts with AAH off. The Engineering Evaluation maneuvers were expressly designed to generate mass properties data: these consisted of a one-second single-axis input followed by a five-second coast. Each crewmember executed nine of these, one along each translation axis and one in either direction about each rotational axis. During these maneuvers, rotation rate and linear accelerometer data was sampled at 50 Hz and stored in a 12 Mb on-board memory for subsequent analysis. Various other maneuvers were also executed with AAH off, providing useful mass properties information. These included the five Rescue Demo tumbles performed by each crewmember, plus the two Optional Familiarization rotations carried out by EV1. Rotation rate data was stored at 50 Hz for these maneuvers, but accelerometer data was only sampled at 1 Hz. Figures 1.1 - 1.4 are representative angular rate plots for Engineering Evaluation maneuvers, Figures 1.5 and 1.6 show the rates for the EV1 Optional Familiarization yaw and multi-axis Rescue Demo, respectively, and Figures 1.7 - 1.9 give accelerometer data for certain of the Engineering Evaluations. The mass properties computed from this on-orbit data were quite close to those calculated pre-flight. The main points of difference were that the actual yaw inertia was somewhat larger than predicted, and the overall CG was somewhat farther forward than expected. The effect of both of these differences is to increase the amount of yaw cross-coupling obtained for roll or y translation inputs. These were expected before the flight to be the main cross-coupling mechanisms; the flight data shows that they indeed are so, but are even somewhat larger than anticipated.

It can be seen from the above discussion that the DTO SAFER was, of necessity, designed without reliable mass properties data for the astronaut/EMU combination. Any future EVA maneuvering systems can now make use of the data collected during the STS-64 EVA to allow a more fully optimized design. In particular, it may be possible, by changing jet layout, to reduce propellant consumption and improve flying qualities. The research reported here included a description and analysis of several such modifications. This work must not only make use of the on-orbit data collected, but also factor in planned changes to the EMU that are being made for International Space Station operations. Of these, introduction of the planar Hard Upper Torso (HUT) is not likely to alter the mass properties appreciably, due to the central location of the HUT. On the other hand, replacement of the current lithium hydroxide CO_2 removal cartridge by the new, more massive, regenerative cartridge will tend to shift the overall CG rearwards; so too will introducing the new larger battery. Both of these changes will alter cross-coupling effects appreciably, and so must be taken into account when analyzing the dynamics of future EVA maneuvering systems. Similarly, changes to the mass properties of SAFER itself, in going from the DTO to the production version, must also be factored into this work.

The analysis conducted to date on the on-orbit data suggests several possible approaches to improving the original SAFER configuration. These are aimed at combating the yaw that results from both roll and y inputs, as this is the main form of cross-coupling present in the DTO version of SAFER. Thus, if AAH is not engaged, this cross-coupling degrades the flying qualities as experienced by the pilot; if AAH is on, the coupling reduces propellant efficiency and/or control authority. One possible way of overcoming these effects would be to shift the lower side-facing (y) jets somewhat forward. This would move the geometric center of the y jets forward, and so closer to the CG, thus reducing the yaw induced by a y command. Furthermore, moving these jets forward while leaving the upper y jets in their original location can also reduce the yaw that results from a roll input. The reason for this is that the torque generated by a positive roll command is now no longer a pure torque about the positive body roll axis, but rather a combination of positive roll and negative yaw torques. This therefore reduces the resulting yaw cross-coupling.

In fact, there are three distinct approaches that can be taken with this jet-shifting technique:

(1) Leave the jets as they are. A roll command then causes a pure roll torque, resulting in a combination of roll and yaw angular rates.

(2) Shift the jets so as to create a combined roll and yaw torque in such proportions that the resulting output is a pure roll rate.

(3) Shift the jets so as to create a combined roll and yaw torque which is aligned along the principal "roll" axis of the system. The resulting angular rate vector will then also be aligned with this principal axis.

The third of these options does not appear to be of great practical utility, as the principal "roll" axis has no natural interpretation in the frame of reference of the EVA crewmember. We shall therefore concentrate on comparing the first two options. In particular, the central questions are as follows. To what extent can simply shifting jets improve the propellant efficiency of a modified SAFER over that of the DTO version? If significant improvements can be achieved, what is the optimum shift distance to use? Finally, is this shift feasible, given the other constraints that serve to determine the configuration of SAFER? Validation of these comparisons in the VR Laboratory would not only be valuable in its own right, but would also serve to illustrate the great potential of this facility, which was developed (as IGOAL) for SAFER crew training, as a research and development tool for future EVA maneuvering system work.

As a first step in this analysis, it is important to quantify the effects of the predicted differences in mass properties between the production version of SAFER and the original DTO unit. This is the subject of the next section.

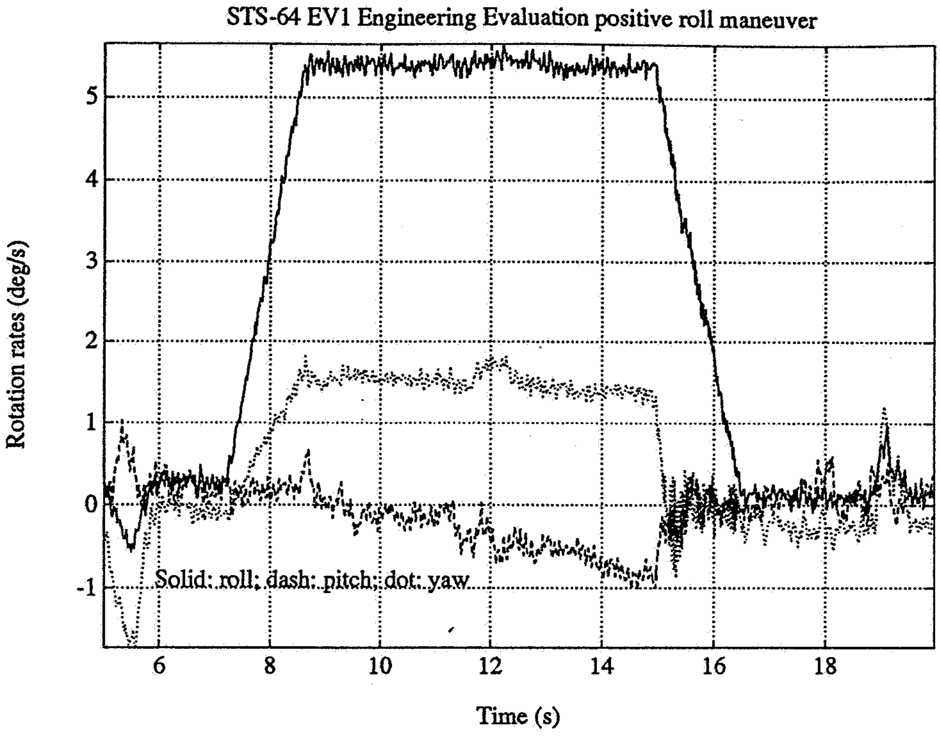


Figure 1.1

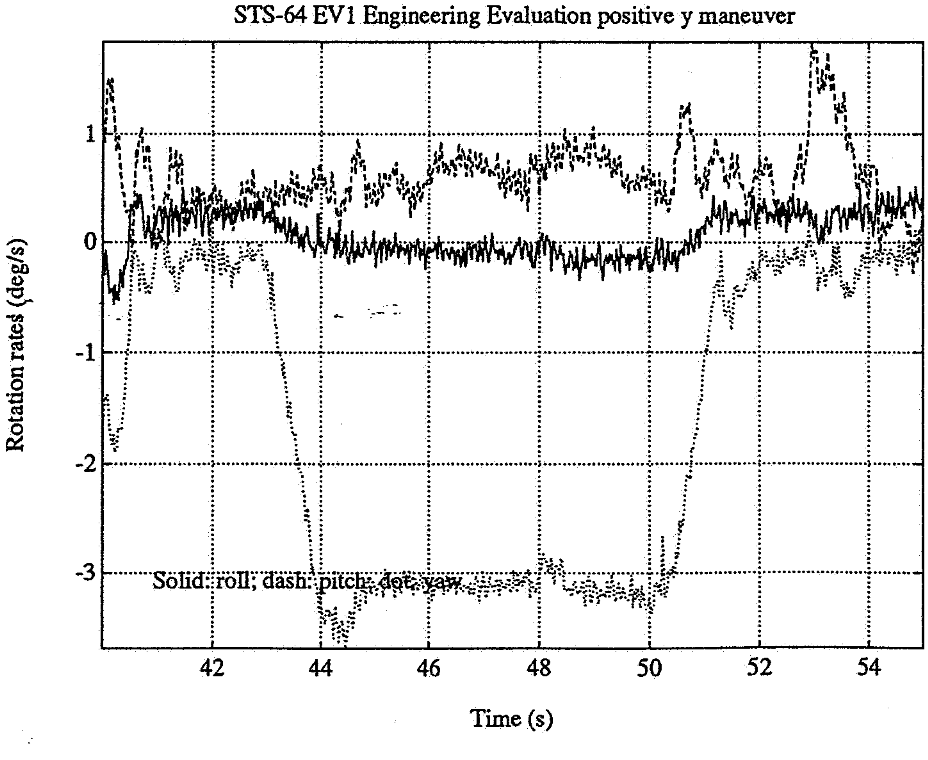


Figure 1.2

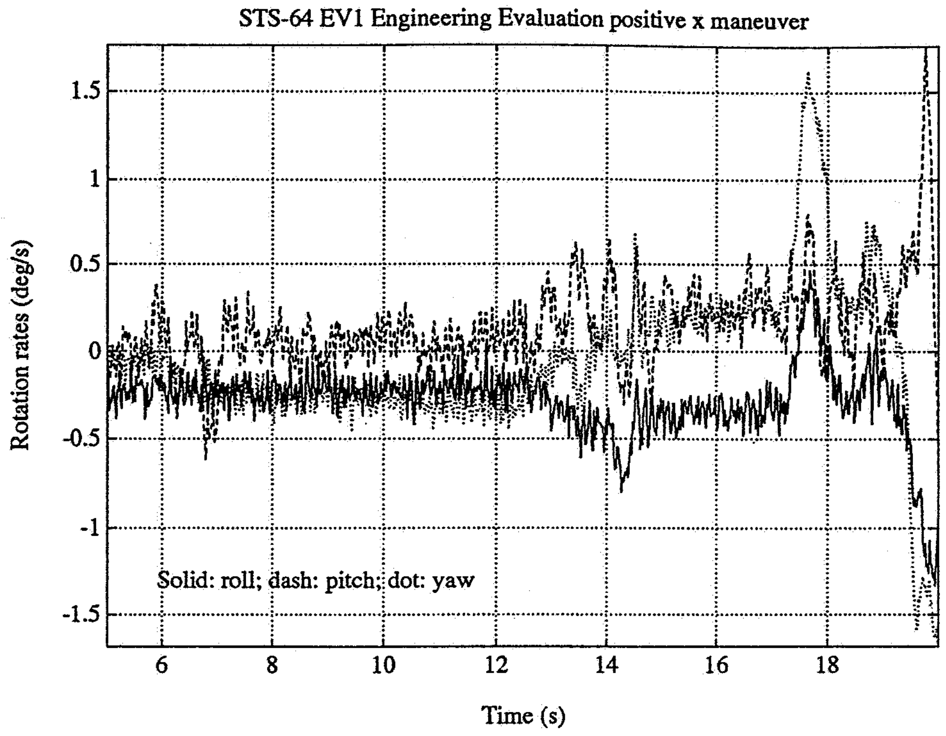

STS-64 EV1 Engineering Evaluation positive x maneuver

Figure 1.3

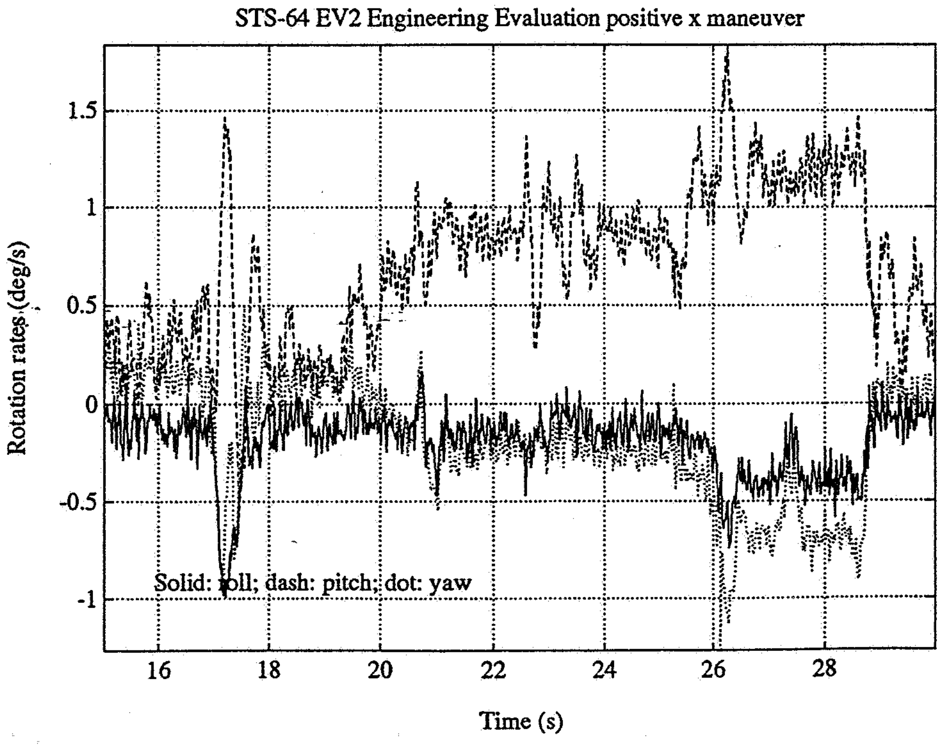

STS-64 EV2 Engineering Evaluation positive x maneuver

Figure 1.4

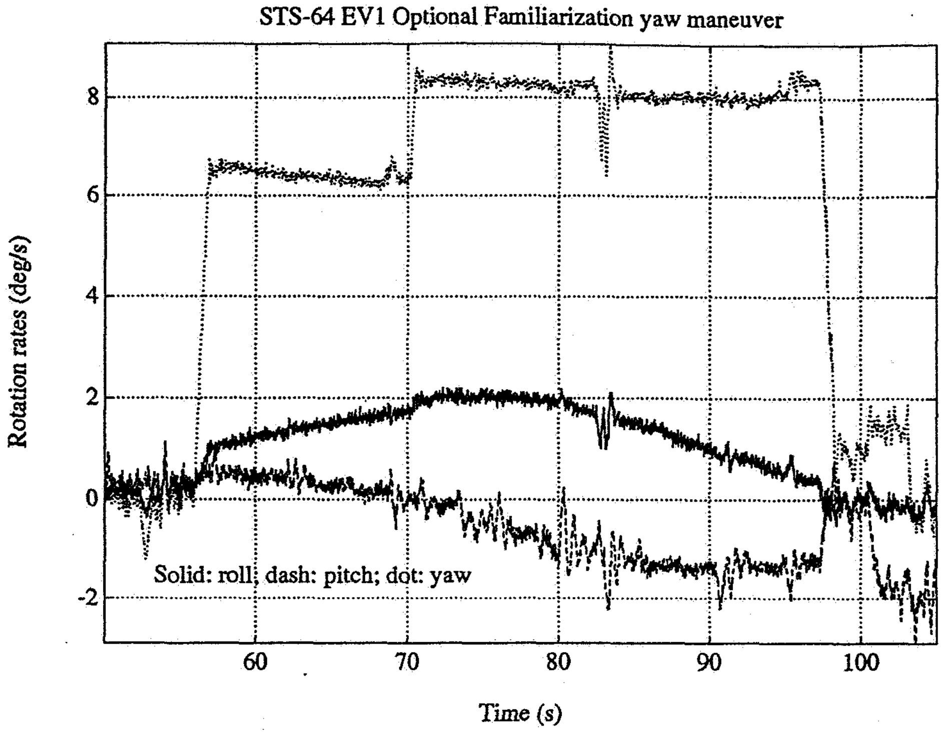


Figure 1.5

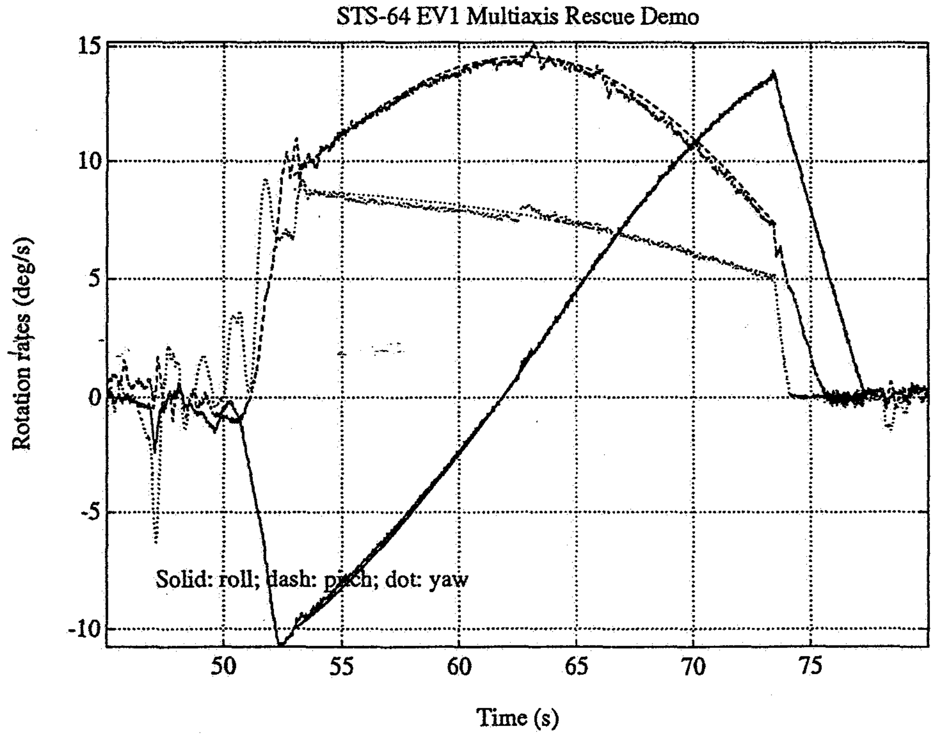


Figure 1.6

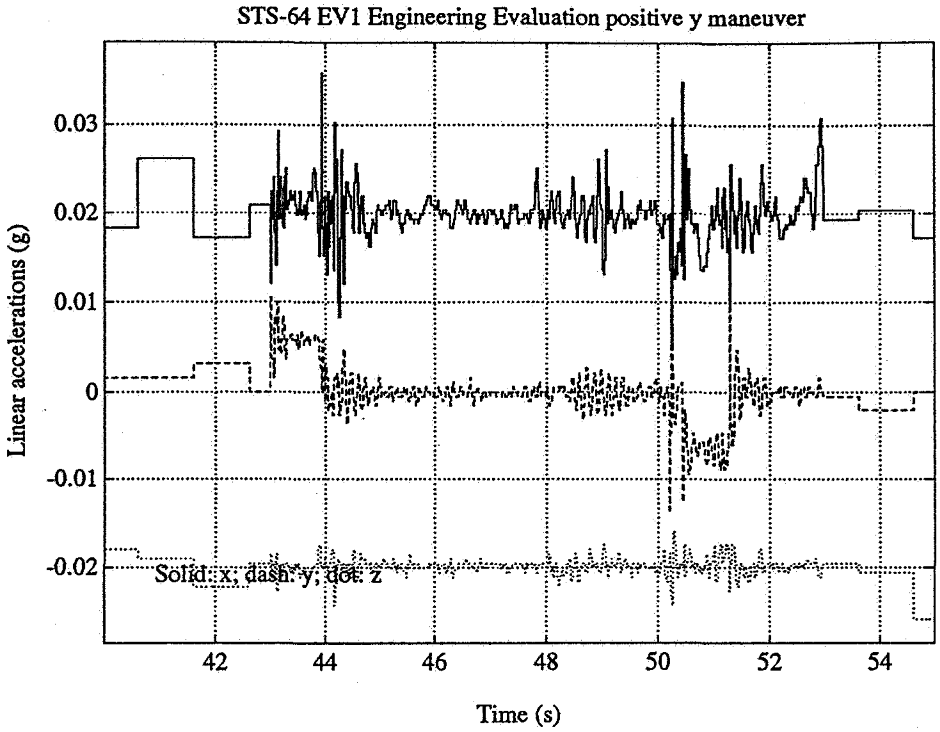


Figure 1.7

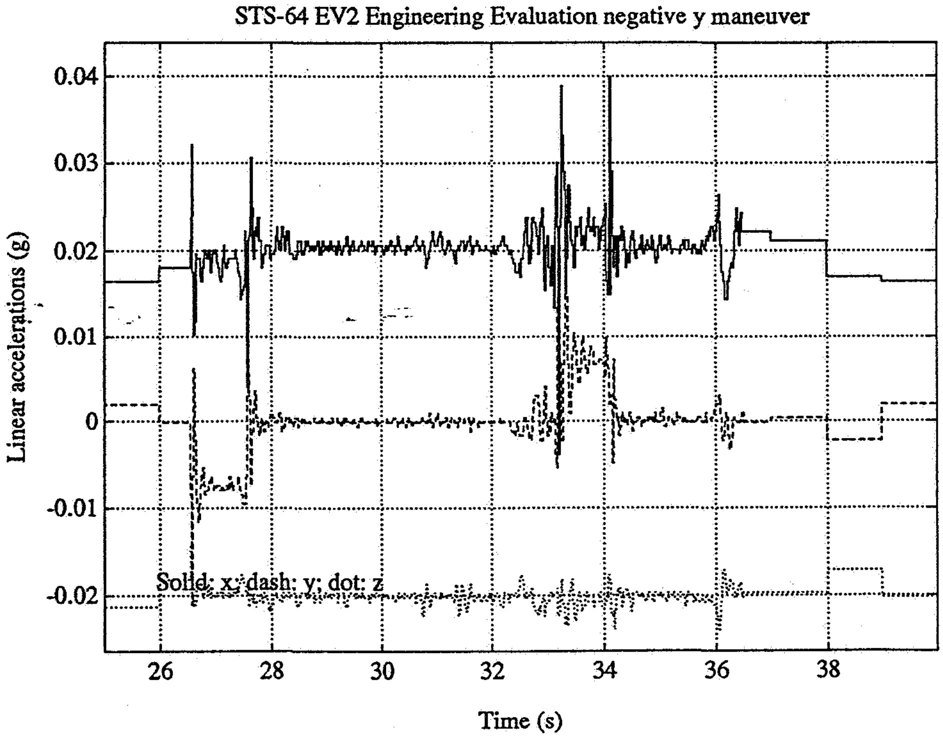


Figure 1.8

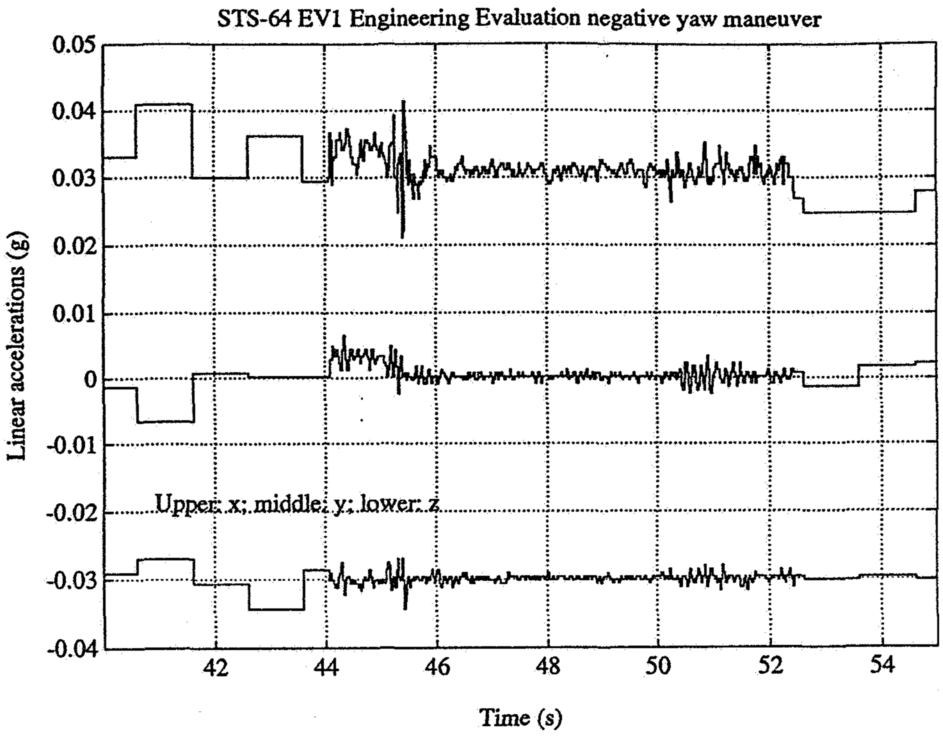

STS-64 EV1 Engineering Evaluation negative yaw maneuver
Linear accelerations (g)
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
Upper: x; middle: y; lower: z
42
44
46
48
50
52
54
Time (s)

Figure 1.9

2. Effects of Production SAFER Mass Reduction on Cross-Coupling

The mass of the production version of SAFER is predicted to be about 10 to 15 lbm less than that of the DTO unit, largely due to the use of lighter tankage. This reduction will cause the CG of the astronaut/EMU/SAFER system to shift forward and the roll/yaw product of inertia to become larger. These changes will now be shown to cause the most significant cross-coupling effects experienced with SAFER, namely the yaw induced by a roll input or a y translation, to increase by about 10%, if no adjustment in the placement of thrusters is made. This will lead to a corresponding increase in the propellant overhead required for yaw-nulling when performing these maneuvers with AAH engaged. Consequently, the improved propellant efficiency that would be expected to result from the reduction in total mass will not actually be achieved for maneuvers about these axes if thrusters are left unshifted.

2.1 SAFER Mass Properties Modeling Approach

This analysis uses as baseline the mass properties derived from the STS-64 on-orbit Engineering Evaluation maneuvers, as summarized in Ref. 6. (The small and uncertain pitch/roll and pitch/yaw products of inertia are taken to be zero in what follows.) Note that the mass properties for EV1 are broadly representative of the Extra Large astronaut case and EV2 of the Large, so these two crewmembers provide a reasonably wide data spread.

It is clear that the production version of SAFER is likely to be considerably lighter than the DTO model. However, the mass distribution of the production model, or indeed its total mass, have not yet been determined precisely. Consequently, the associated mass reduction has been modeled here as the removal of a point mass of 0 - 20 lbm from the CG of the DTO SAFER. While simplified, this model is certainly sufficient for a first-order analysis.

2.2 Results of SAFER Mass Changes

The dynamical effects of this mass reduction are twofold. Firstly, the overall CG of the astronaut/EMU/SAFER system will shift forward, taking it even farther in front of the geometric center of the SAFER thrusters. This will increase the already significant yaw induced by a y translation command. Secondly, the large roll/yaw product of inertia of the system will also become larger, so leading to increased induced yaw in reaction to a roll command. The reason for this increase in the roll/yaw product is that SAFER, positioned below and behind the overall CG, partially compensates for the asymmetry introduced by the mass of the legs of the crewmember below and in front of the CG. If the mass of SAFER is reduced, less of this asymmetry is canceled, so leading to more skewed principal axes and a larger product of inertia. These mass property changes will also cause two other cross-coupling effects of smaller magnitude, namely the pitch induced by a z translation and the roll induced by a yaw command, to increase by around 10%.

The following graphs quantify the most significant dynamical effects of a reduction in SAFER mass. Figure 2.1 shows the forward and upward shift in overall CG that results from mass decreases in the possible range. To the level of reliability of the data, the y component can be seen to be unaffected by such reductions. In this graph, as in all those that follow, the EV2 variations are greater than those for EV1. This is due to the fact that EV2 has a smaller total mass, so a mass reduction of given magnitude makes up a larger relative change for this crewmember. Figure 2.2 then shows the resulting relative increases in induced yaw that are obtained for "standard" Engineering Evaluation roll or y maneuvers (1 sec acceleration burn, 5 sec coast, 1 sec braking) with AAH disengaged. It can be seen that increases on the order of 10% are expected for a mass reduction in the probable range. The corresponding roll maneuver time histories for a mass reduction of 0, 10 or 20 lbm are then given in Figures 2.3 and 2.4 for EV1 and EV2, respectively. In all cases, the roll rate (solid curve), which is the desired outcome of the maneuver, as well as the undesired yaw (dotted) both increase as mass is reduced.

However, it can be seen that the relative increase in the yaw rate is significantly greater than that in roll. Figures 2.5 and 2.6 then give the equivalent time histories for Engineering Evaluation y maneuvers. In this case, all rotation rates are undesired; the large yaw rate results from the forward CG offset, and in turn induces a roll as a consequence of the large roll/yaw product of inertia.

Finally, Figure 2.7 shows the relative increase in the propellant "overhead" required to null the induced yaw when inputting a roll or y command with AAH engaged. (This overhead was computed using the first-order analysis presented in Ref. 7.) It can be seen that this quantity is also expected to increase by around 5 - 10% as a result of the probable SAFER production version mass reduction. It should be noted that this increase does not actually lead to an increase in the propellant required for roll or y maneuvers with AAH engaged; propellant consumption appears to be almost independent of mass. Rather, the increased overhead means that no improvement in propellant usage is obtained as a result of the decrease in total mass, contrary to what might be expected to occur.

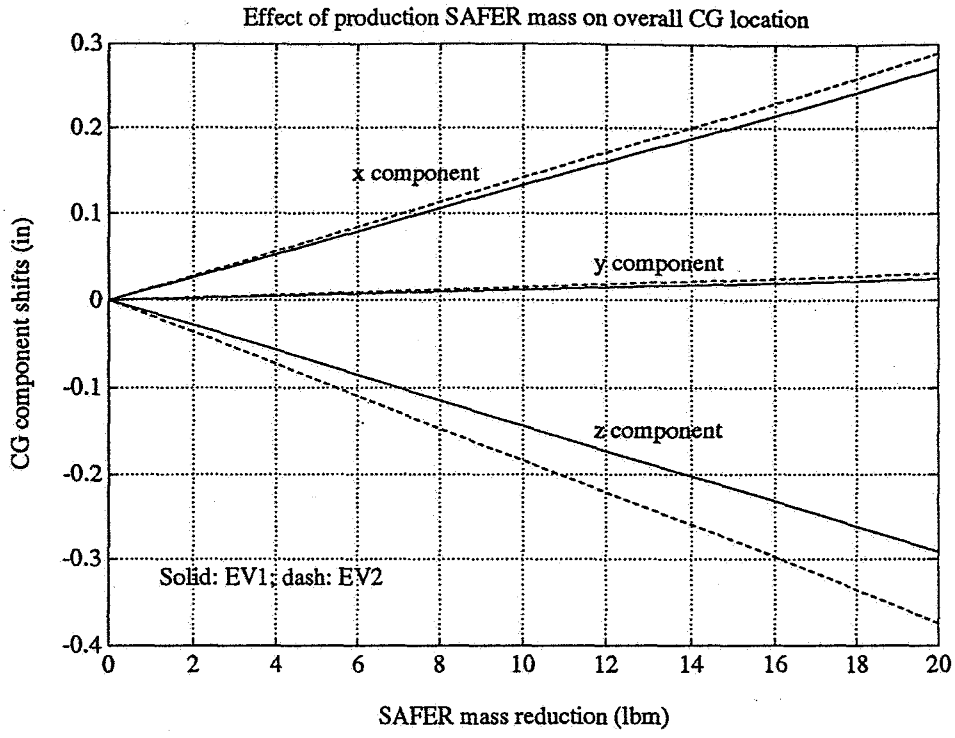


Figure 2.1

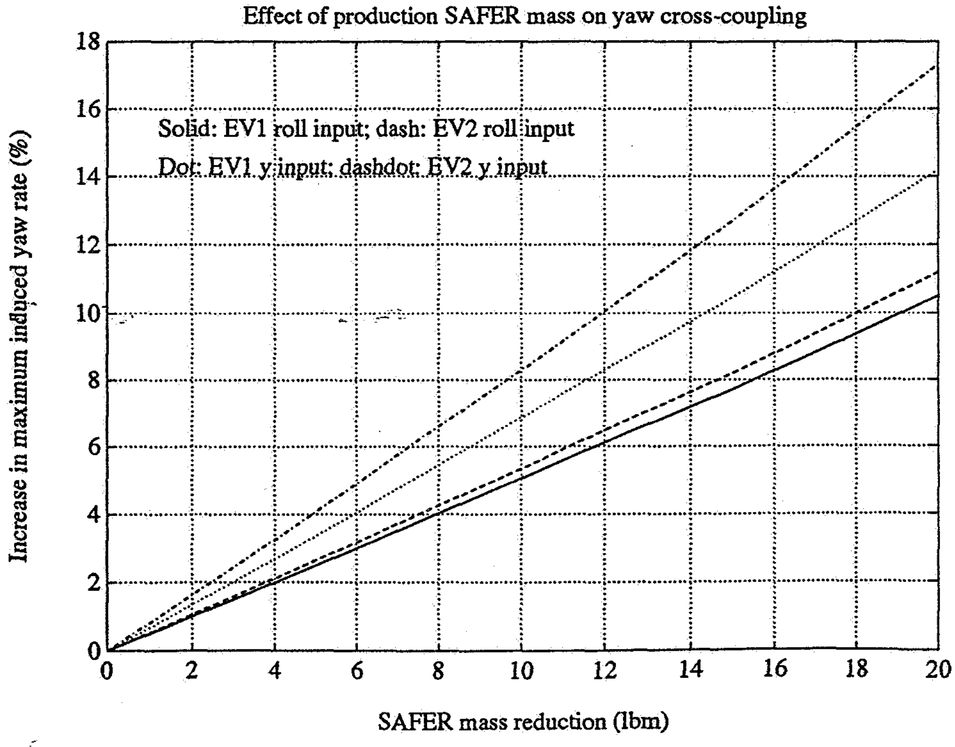


Figure 2.2

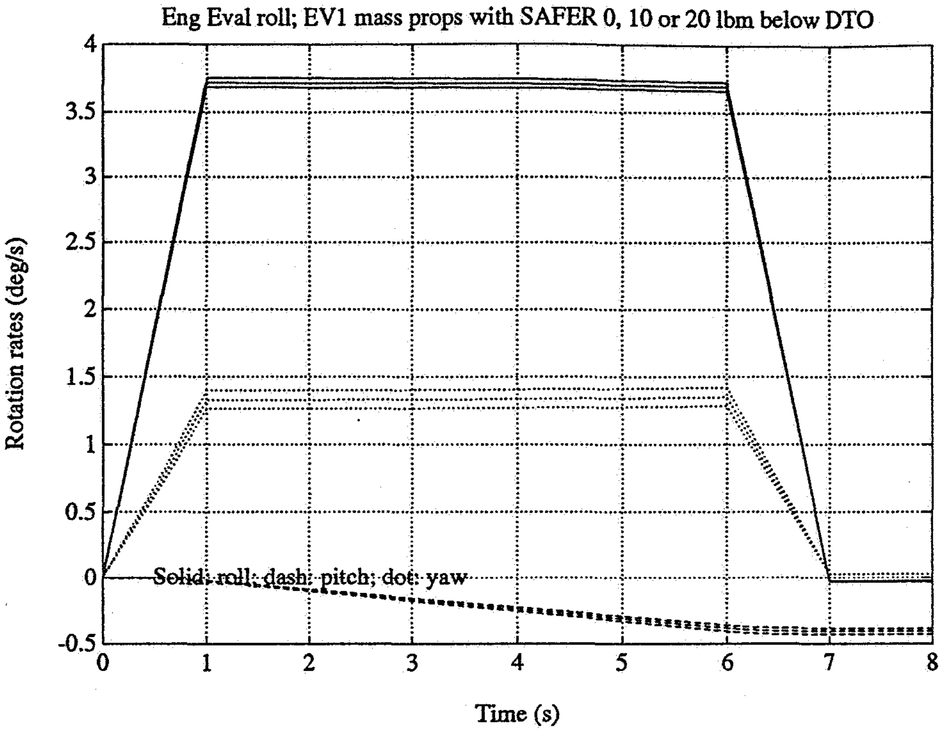
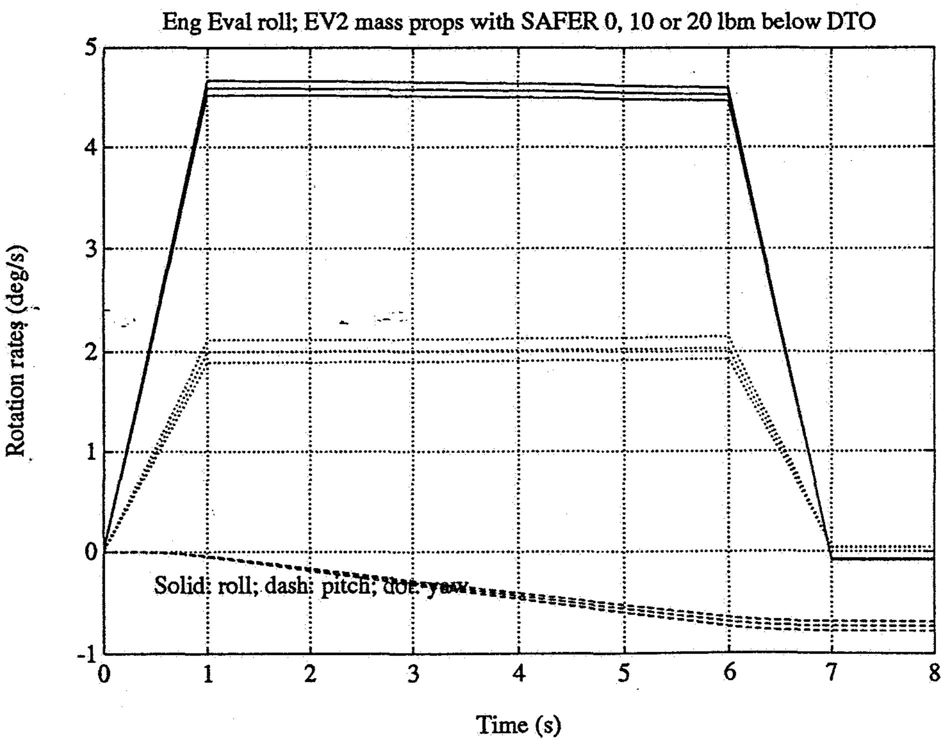


Figure 2.3



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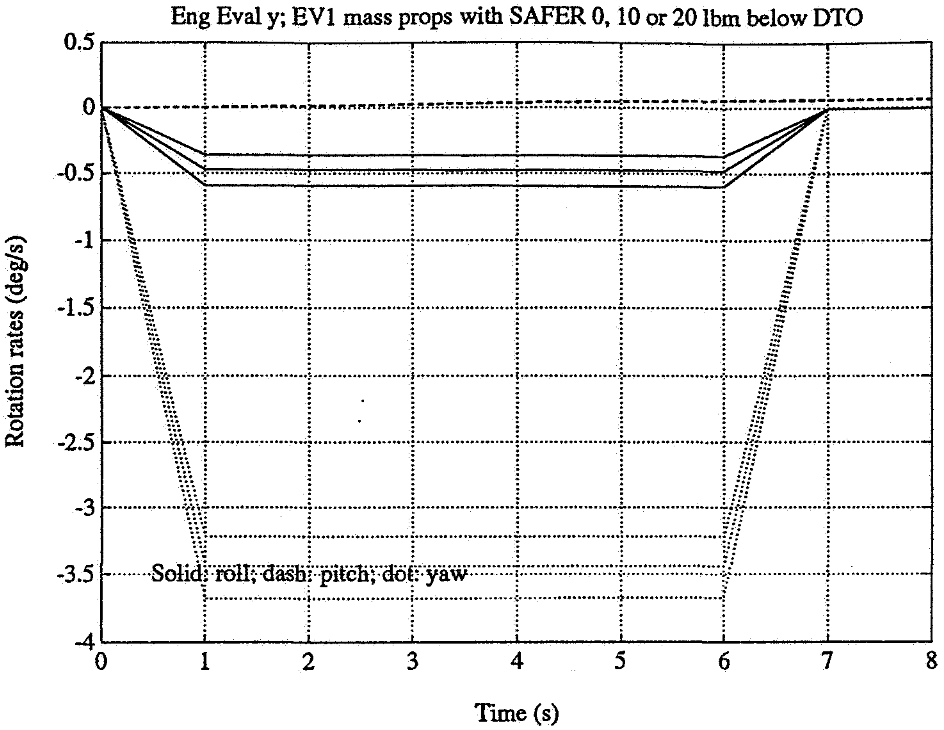

Figure 2.5

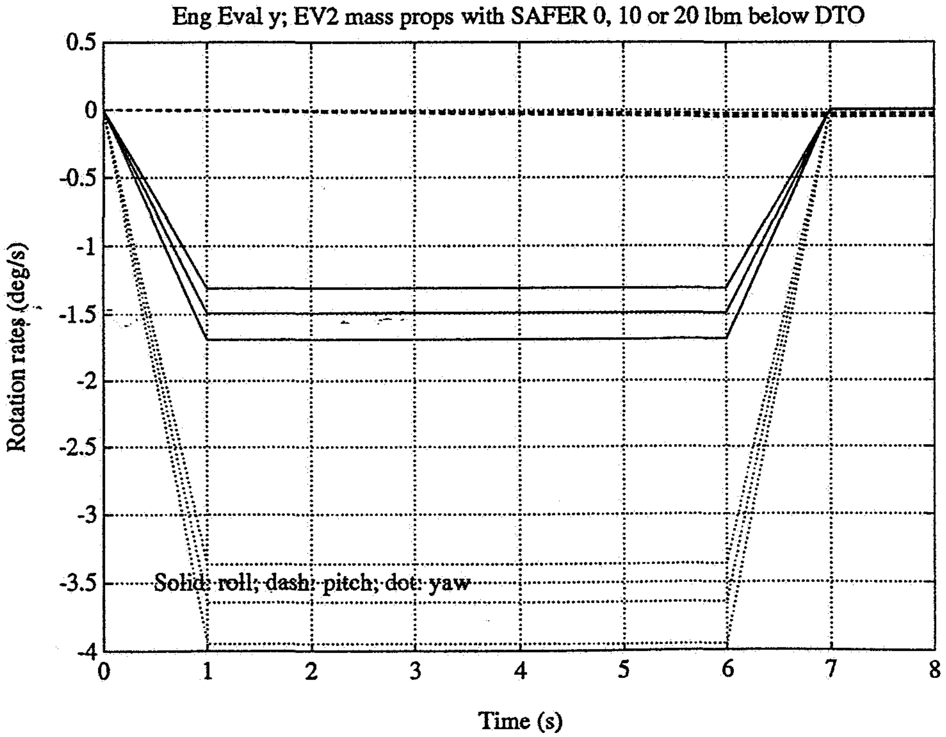

Figure 2.6

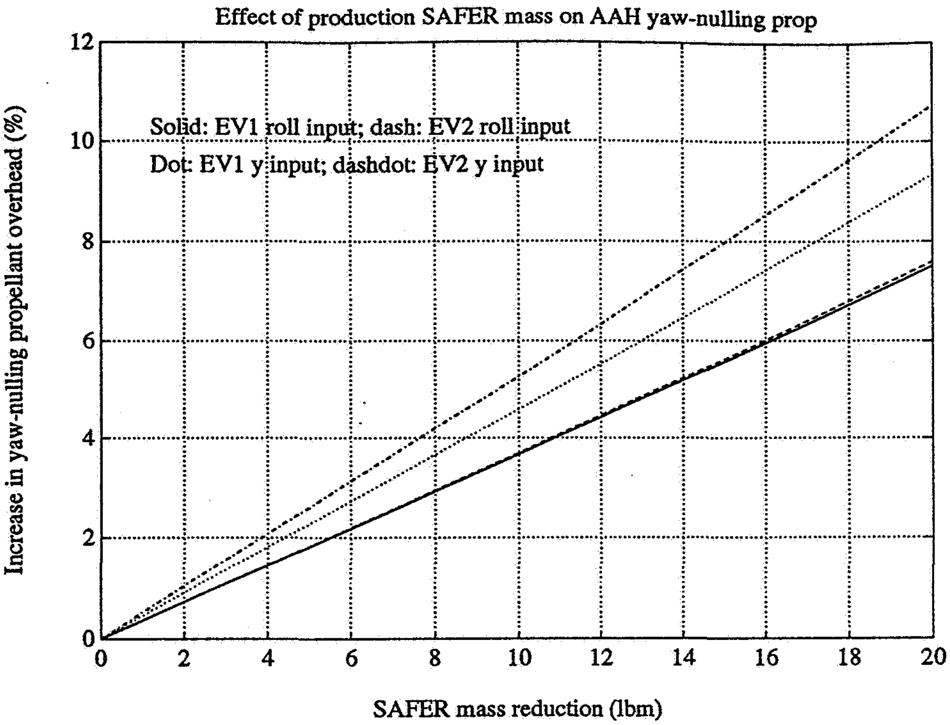
Effect of production SAFER mass on AAH yaw-nulling prop
Solid: EV1 roll input; dash: EV2 roll input
Dot: EV1 y input; dashdot: EV2 y input
Increase in yaw-nulling propellant overhead (%)
SAFER mass reduction (lbm)
0
2
4
6
8
10
12
0
2
4
6
8
10
12
14
16
18
20

Figure 2.7

3. Predicted Beneficial Cross-Coupling Effects of Shifting SAFER Jets

Shifting the lower side-facing jets forward on the production version of SAFER reduces the two major cross-coupling effects experienced with the DTO model, namely the yaw induced by a roll input or a y translation. A shift of 0.5 - 1.0 inches is sufficient to compensate for the increased yaw coupling caused by the new production version mass properties, while a shift of about 5 inches virtually eliminates yaw cross-coupling entirely. On the other hand, shifting the downward-firing jets forward by more than about 3 inches leads to an asymmetric condition under which both positive and negative z inputs give rise to a pitch-up moment. Thus, shifting all lower front jets forward by around 2 inches gives a significant (30 - 45%) reduction in yaw cross-coupling, and hence improved AAH propellant efficiency, without introducing excessive pitch asymmetry.

3.1 Yaw Cross-Coupling and y Jet Shifts

Two different mechanisms lead to the large amounts of yaw cross-coupling experienced with the DTO SAFER. Firstly, the CG of the astronaut/EMU/SAFER system is several inches in front of the geometric center of the SAFER thrusters, giving rise to considerable opposite yaw in response to a y command. Secondly, the forward slant of the legs of the crewmember introduces asymmetry into the mass properties of the system, rotating the "roll" principal axis upwards and the "yaw" axis forwards. An input torque along the positive body roll axis can consequently be shown to give rise to motion consisting of a combination of positive roll and positive yaw. Conversely, in order to obtain rotation which is purely about the positive roll axis, a specific combination of positive roll and negative yaw torques must be applied.

Both of these coupling mechanisms can be reduced by shifting the lower side-facing jets forward while leaving the upper jets fixed. This shift clearly moves the geometric center of the y jets forward, by half the distance over which the lower jets have been moved. Furthermore, the moment arm between the two jets that are used to apply a roll input (one upper y, one lower y) is now rotated counter-clockwise about the positive y axis. Inputting a positive roll command thus automatically gives rise to a combination of a positive roll and negative yaw torque. This reduces the amount of yaw motion induced by a roll command, and similarly lowers the propellant required to cancel this yaw when carrying out a roll under AAH. (It should perhaps be pointed out that shifting these jets will not affect the significantly smaller amount of roll induced by a yaw input, since yaw commands use the fore-and-aft-facing thrusters.)

These effects are quantified by the following graphs. Figure 3.1 shows the relative decreases in induced yaw that are obtained for "standard" Engineering Evaluation roll or y maneuvers (1 sec acceleration burn, 5 sec coast, 1 sec braking), performed with AAH disengaged, as a function of jet shift distance. The mass properties used are those identified from STS-64 on-orbit data for EV1 and EV2 and described in Ref. 6. Comparing this graph with Figure 2.2 shows that a jet shift of between 0.5 and 1.0 inches is sufficient to recapture the AAH-off yaw cross-coupling properties of the SAFER DTO version; a shift of 5 inches essentially eliminates all yaw coupling.

Figure 3.2 then shows the relative decrease in the propellant "overhead" required to null the induced yaw when inputting a roll or y command with AAH engaged, as computed using the first-order analysis of Ref. 7. Comparison of this plot with Figure 2.7 shows that a jet shift of 0.5 - 1.0 inches similarly recaptures the DTO AAH-on yaw coupling properties, and one of about 5 inches eliminates nearly all yaw overhead.

It seems likely that the greatest jet shift that is actually feasible for the production SAFER is around 2 inches. For the mass properties used in this analysis, it can be seen from Figures 3.1 and 3.2 that this shift will lead to a reduction of about 35% in yaw coupling from a y input, and around 30 - 45% for the yaw resulting from a roll command. This reduction appears to be well worthwhile.

Figures 3.3 and 3.4 give the time histories for Engineering Evaluation roll maneuvers for EV1 and EV2, respectively, and jet shifts of 0, 2 and 4 inches. In all cases, the desired roll rate (solid) is reduced only slightly as jet shift increases; by contrast, the undesired yaw rate (dotted) decreases substantially. Figures 3.5 and 3.6 then give the equivalent time histories for Engineering Evaluation y maneuvers. In this case, all rotation rates are undesired; the large yaw rate results from the forward CG offset, and in turn induces a roll as a consequence of the large roll/yaw product of inertia. Both of these rates are reduced considerably as the jets are moved forward, shifting their geometric center closer to the CG.

3.2 Pitch Cross-Coupling and z Jet Shifts

In practice, shifting the lower side-facing jets would be accomplished by moving the entire two lower forward jet groups, each of which contains 5 thrusters. Thus, jets 3, 4, 13 - 16 and 21 - 24 would all actually be shifted forward. This will have no dynamical consequences for the two forward-facing jets (3 and 4), and the effect of moving the side-facing thrusters (13 - 16) has already been described. This leaves only the downward-firing jets (numbers 21 - 24) to be analyzed. These thrusters are used to input negative z impulses; on the DTO version, such inputs gave rise to a pitch-down moment, as a result of the forward CG location. If these jets were to be shifted forward to the CG, a distance of 2.7 - 2.9 inches, a negative z input would no longer induce any pitch; a shift of greater than this distance would cause it to induce a pitch up.

Thus, a jet movement of around 3 inches is optimum in terms of the AAH pitch propellant overhead associated with z commands. However, a related effect must also be considered. This is the fact that a positive z command is executed using the upward-firing jets; these are clearly not affected by shifts of the lower forward thruster groups. There is therefore now an asymmetry in the pitch induced by positive and negative z inputs, with this imbalance increasing with increasing jet shift distance. Figures 3.7 and 3.8 illustrate this for EV1 and EV2, respectively. In each plot, the only significant rate is in pitch, which is shown for jet shifts of 0, 2 or 4 inches. The rate remaining at the end of the maneuver can be seen to grow from zero as the jets are moved farther forward. A jet shift of 2 inches appears to give a good compromise between reduction of the AAH pitch overhead associated with z maneuvers and retaining dynamical symmetry. Indeed, it appears unlikely that a crewmember flying SAFER, particularly with AAH engaged, will be able to detect the z/pitch asymmetry that results from a jet shift of this size.

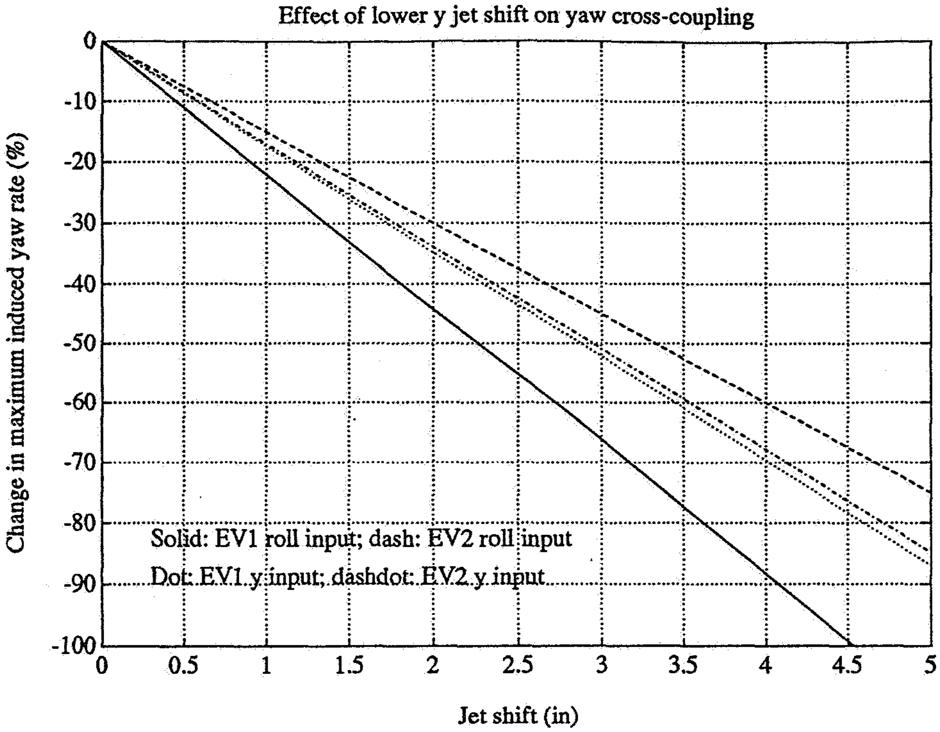

Figure 3.1

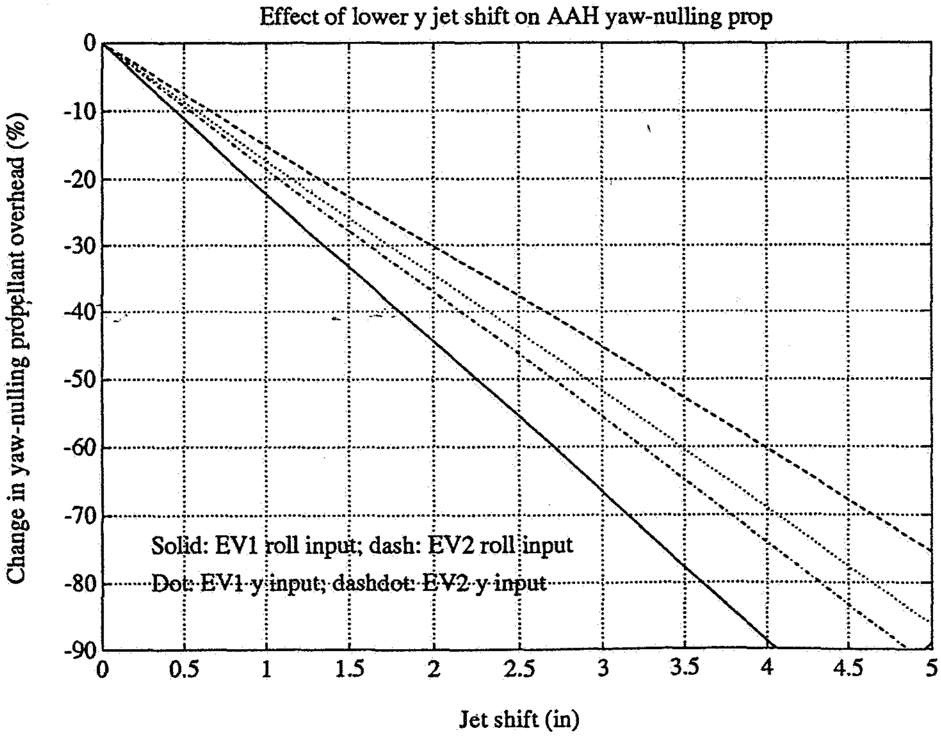

Figure 3.2

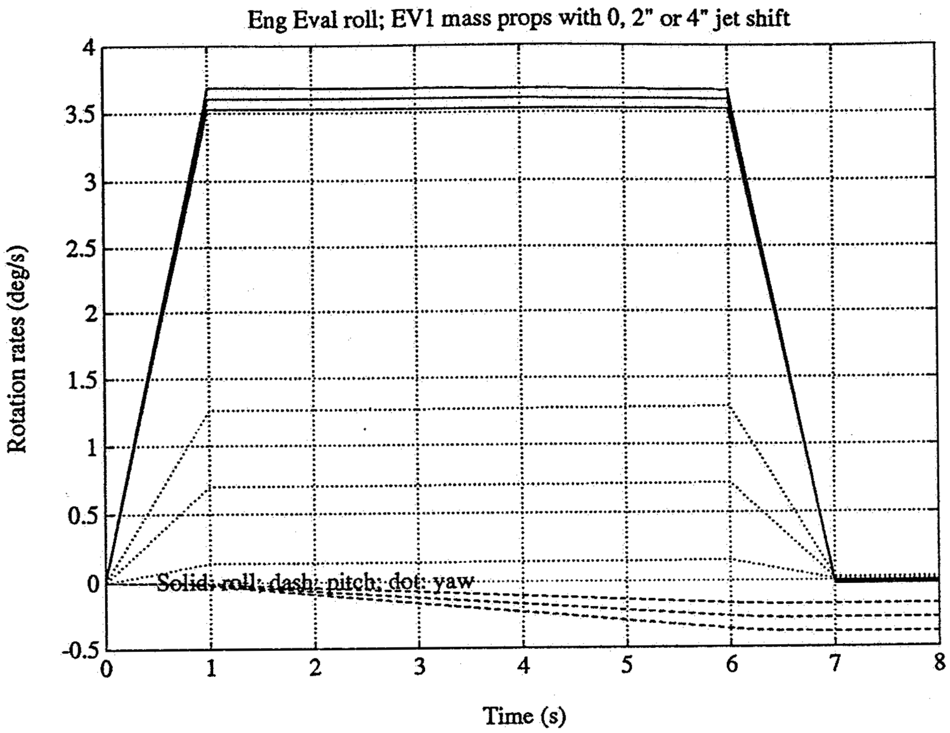

Figure 3.3

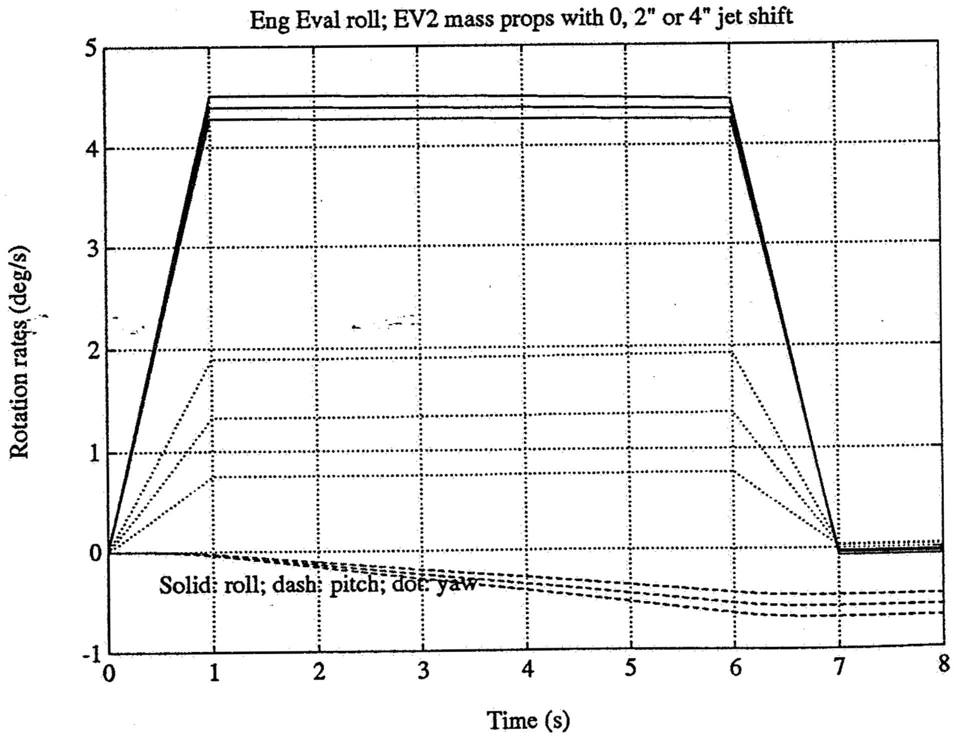

Figure 3.4

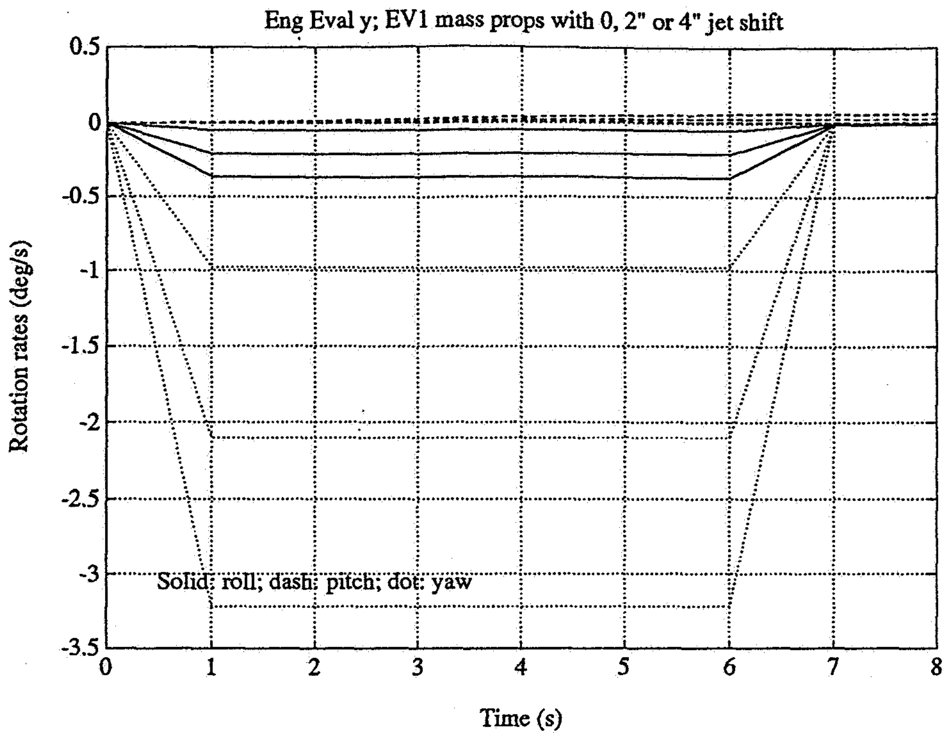

Figure 3.5

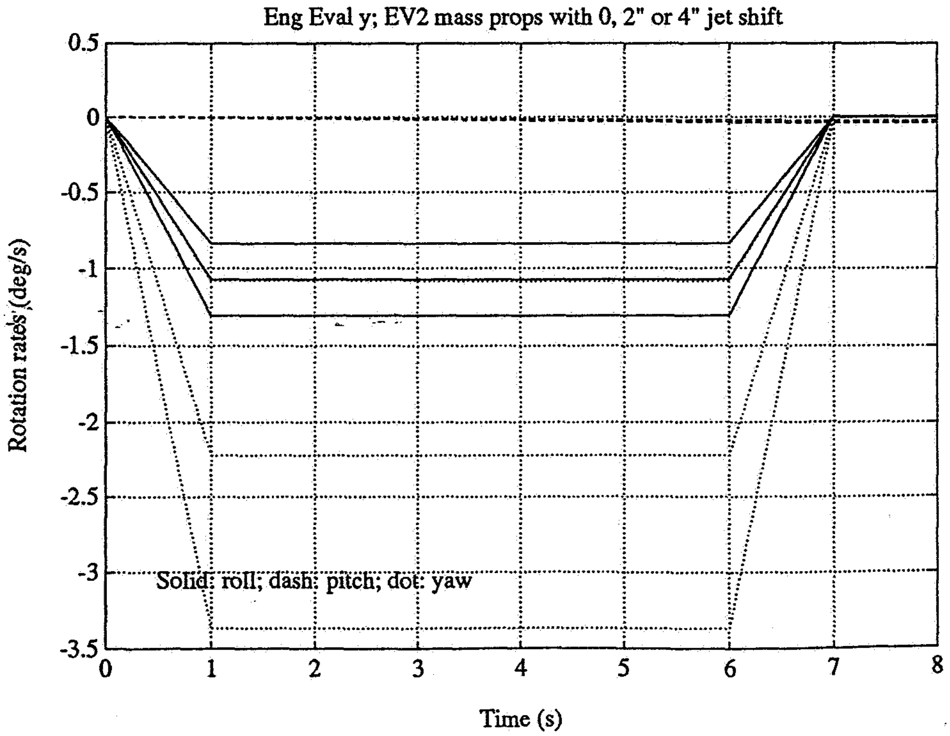

Figure 3.6

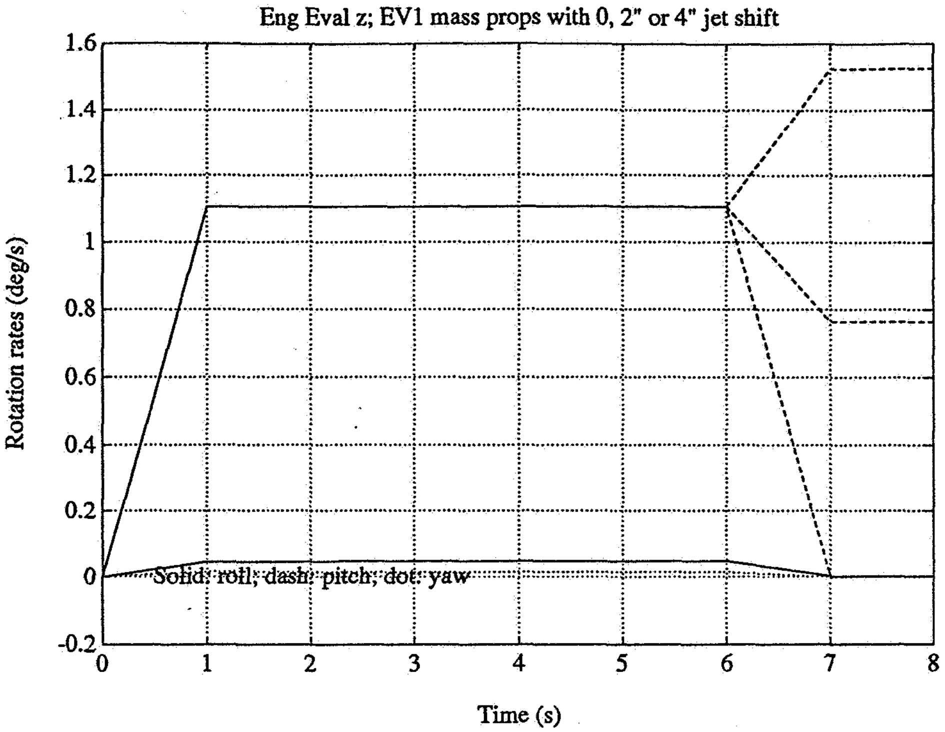

Figure 3.7

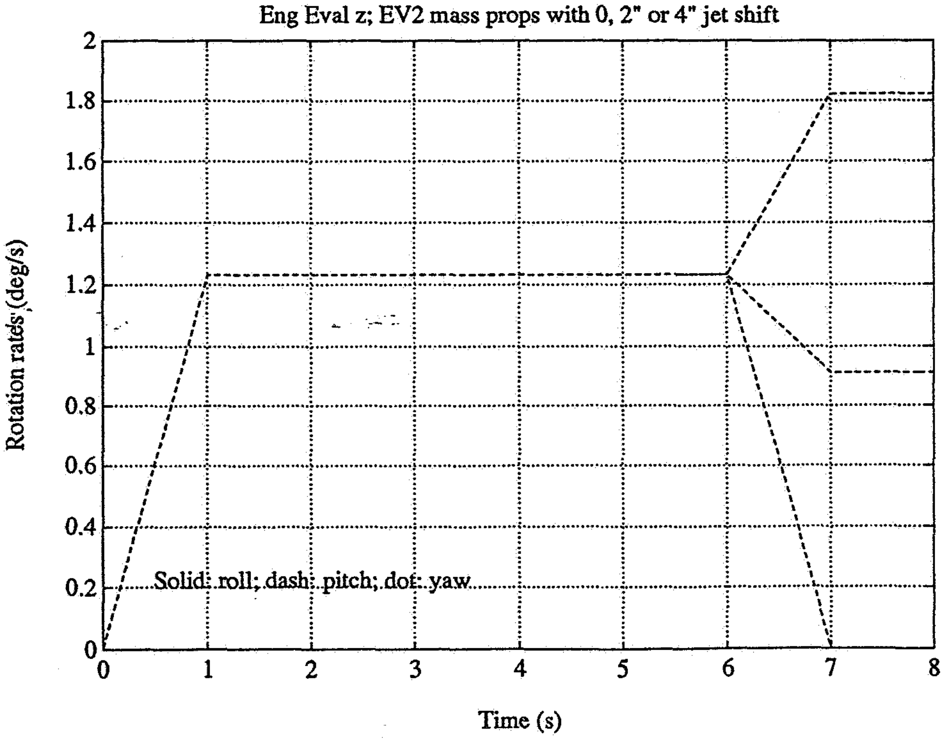

Figure 3.8

4. Results of VR Laboratory Tests on SAFER Jet Shifts

In order to ensure that this analysis did not missed any significant effects, preliminary comparisons of SAFER flying qualities with and without a 2 inch forward shift of the lower front jet groups were conducted in the VR Laboratory simulator. The results obtained were, to the accuracy of the measurements made, in agreement with predictions, and confirmed the cross-coupling benefits of shifting the jets. Also, no unexpected behavior resulting from subtleties of the jet select logic was detected. Furthermore, the asymmetry between positive and negative z commands was not felt to be objectionable. In fact, discussions with an experienced SAFER pilot (Carl Meade) indicated that such a degree of asymmetry would almost certainly not even be detectable in practice.

The VR Laboratory tests that were conducted consisted of manual maneuvers of all the types that are affected by a shift in jet position. The mass properties used were those identified for EV1 from STS-64 on-orbit data[6]. As a consequence of the manual control inputs used, the results obtained were only approximate. They nonetheless provide valid rough data, as can be summarized as follows.

Roll, AAH off: The jet shift led to a detectable reduction in the amount of yaw cross-coupling. For a roll input of about 2 sec, the unshifted case gave about 2.4 deg/sec induced yaw; for a 2 inch jet shift, this was reduced to about 1.5 deg/sec. This reduction of 37.5% is at the midpoint of the predicted range of 30 - 45%.

Roll, AAH on: No detectable problems. (Measurements were not made of the reduction in yaw-nulling AAH "overhead", due to the lack of repeatability of the applied inputs.)

y, AAH off: For unshifted jets, a 2 sec input led to about 6.0 deg/sec induced yaw. Shifting the jets reduced this to about 3.9 deg/sec, a decrease of 35%; this is precisely as predicted.

y, AAH on: No detectable problems, for instance due to jet select logic subtleties.

z, AAH off: The pitch-down resulting from a negative z input with shifted jets should be smaller than the pitch-up induced by a positive z, since the down-firing jets are now closer to the CG than the up-firing ones. This asymmetry was detectable for long inputs conducted with AAH off: a 2 sec negative z burn gave rise to about -0.4 deg/sec pitch, as opposed to +2.2 deg/sec for a 2 sec positive z command. However, this did not appear to be objectionable. In any case, such long inputs are unlikely to be applied without AAH in practice.

z, AAH on: AAH has to fire x-facing jets more often, in order to cancel induced pitch, for a positive z input than for a negative z. When it does so, two of the z-firing jets are modulated off. Consequently, the control authority for positive z is slightly less than that for negative z. (According to the first-order analysis used[7], the difference in authority should be about 10%.) This was again detectable for long z inputs, but did not appear to be objectionable.

Further tests that would be desirable include more quantitative measures, particularly of the propellant "overhead" required for AAH nulling of cross-coupling. These measurements would have to be based on batch control input sequences, for repeatability. It would also be beneficial to carry out tests for the Small crewmember case, in order to ensure that extreme mass property variations do not cause any difficulties. Finally, it is recommended that an experienced SAFER pilot fly the VR Laboratory simulator with and without jet shifts, in order to be absolutely certain that no factors have been overlooked.

5. Mass Properties for Mir-3 SAFER Crew Training

The on-orbit data collected during the STS-64 SAFER test flight was used to generate mass properties to be used for SAFER crew training in the VR Laboratory for STS-76/Mir-3. Modifications to this data were required in order to account for the various equipment configurations to be carried by the EVA crew. In addition, the thrust level identified from STS-64 on-orbit data (0.72 lbf) was used for training for this mission. Finally, a question that will be addressed in the next section is the dynamical effect of possible plume impingement on the SAFER flying qualities with the Mir Environmental Effects Payload (MEEP) experiment package attached.

5.1 EVA Configurations Considered

Four basic configurations will be flown during the STS-76/Mir-3 EVA, and so needed to be modeled in the VR Laboratory for crew training. These are:

(1) Standard crewmember/EMU/SAFER.

(2) Standard crewmember/EMU/SAFER and one MEEP clamp, which has a mass of about 10 lbm, mounted on the Modified Mini-Workstation (MMWS). (See Figure 5.1 for the MEEP clamp layout, and Figure 5.2 for dimensions in inches.) This represents the configuration after one of the clamps has been installed on the Mir Docking Module handrails (see next case). Which of the two clamps is to be installed first was not clearly defined before flight; in any case, the difference in dynamics between the two possibilities is likely to be insignificant.

(3) Standard crewmember/EMU/SAFER and two MEEP clamps mounted on the MMWS. This is the configuration upon initial translation up the Docking Module. As the MMWS must be rotated forward before activating SAFER, the resulting CG will be farther forward than standard, so leading to even more yaw cross-coupling for a y input, and more pitch for a z command.

(4) Standard crewmember/EMU/SAFER and one MEEP experiment package, attached to either the Rigid Tether (RT) or the new Multi-Use Tether (MUT) in the configuration shown in Figure 5.3. There are four MEEP packages, with masses between 70 and 75 lbm; all have dimensions (together with their Sidewall Carrier in the Payload Bay) as shown in Figure 5.4, and are essentially uniform rectangular solids. The two EVA crewmembers will install these packages, one at a time, on the Docking Module (Figure 5.5) by means of the previously-mounted MEEP clamps. It should be adequate for SAFER training to model the worst-case package, i.e. a mass of 75 lbm. The main dynamical effects are expected to be significant shifts in all components of the overall CG, leading to appreciable rotational cross-coupling in response to all translation commands, and major increases in all moments of inertia.

5.2 Mass Properties Obtained

The mass properties for these four cases (inertia matrix about the overall CG; CG position relative to the geometric center of the SAFER jets) were generated, for both the generic Medium and Large crewmember sizes, in time for the start of STS-76/Mir-3 crew training in the VR Laboratory. These mass properties can be tabulated as follows.

Medium astronaut, case 1:

Total mass $m_{med\_1} = 528\,lbm$; inertia matrix $I_{med\_1} = \begin{pmatrix} 35.6 & 0.1 & -6.9 \\ 0.1 & 40.1 & -0.4 \\ -6.9 & -0.4 & 17.9 \end{pmatrix} kg\,m^2$ relative to CG;

CG position $\bar{\mathbf{r}}_{med\_1} = (2.5 \quad 0.1 \quad -1.3)\,in$ relative to geometric center of SAFER jets.

Medium astronaut, case 2:

Total mass $m_{med\_2} = 538\,lbm$; inertia matrix $I_{med\_2} = \begin{pmatrix} 35.7 & -0.1 & -6.8 \\ -0.1 & 41.1 & -0.3 \\ -6.8 & -0.3 & 18.9 \end{pmatrix} kg\,m^2$ relative to CG;

CG position $\bar{\mathbf{r}}_{med\_2} = (2.9 \quad 0.2 \quad -1.3)\,in$ relative to geometric center of SAFER jets. (These values correspond to a MEEP clamp carried on the right-hand side of the MMWS; the results for a left-hand clamp are very similar, but with a small shift in CG to the left.)

<u>Medium astronaut, case 3:</u>

Total mass $m_{med\_3} = 548\,lbm$; inertia matrix $I_{med\_3} = \begin{pmatrix} 35.8 & 0.1 & -6.6 \\ 0.1 & 42.0 & -0.4 \\ -6.6 & -0.4 & 19.8 \end{pmatrix} kg\,m^2$ relative to CG;

CG position $\bar{\mathbf{r}}_{med\_3} = (3.2 \quad 0.1 \quad -1.4)\,in$ relative to geometric center of SAFER jets.

<u>Medium astronaut, case 4:</u>

Total mass $m_{med\_4} = 617\,lbm$; inertia matrix $I_{med\_4} = \begin{pmatrix} 64.2 & -4.8 & 1.5 \\ -4.8 & 66.3 & 11.6 \\ 1.5 & 11.6 & 29.6 \end{pmatrix} kg\,m^2$ relative to CG;

CG position $\bar{\mathbf{r}}_{med\_4} = (0.9 \quad -2.3 \quad 2.8)\,in$ relative to geometric center of SAFER jets.

<u>Large astronaut, case 1:</u>

Total mass $m_{lar\_1} = 564\,lbm$; inertia matrix $I_{lar\_1} = \begin{pmatrix} 41.8 & 0.1 & -7.9 \\ 0.1 & 46.1 & -0.3 \\ -7.9 & -0.3 & 18.7 \end{pmatrix} kg\,m^2$ relative to CG; CG position $\bar{\mathbf{r}}_{lar\_1} = (2.8 \quad 0.1 \quad -0.3)\,in$ relative to geometric center of SAFER jets.

<u>Large astronaut, case 2:</u>

Total mass $m_{lar\_2} = 574\,lbm$; inertia matrix $I_{lar\_2} = \begin{pmatrix} 41.9 & -0.1 & -7.7 \\ -0.1 & 47.0 & -0.3 \\ -7.7 & -0.3 & 19.6 \end{pmatrix} kg\,m^2$ relative to CG;

CG position $\bar{\mathbf{r}}_{lar\_2} = (3.1 \quad 0.2 \quad -0.4)\,in$ relative to geometric center of SAFER jets. (These values again are for a MEEP clamp carried on the right-hand side of the MMWS.)

<u>Large astronaut, case 3:</u>

Total mass $m_{lar\_3} = 584\, lbm$; inertia matrix $I_{lar\_3} = \begin{pmatrix} 42.0 & 0.1 & -7.5 \\ 0.1 & 47.9 & -0.3 \\ -7.5 & -0.3 & 20.6 \end{pmatrix} kg\, m^2$ relative to CG; CG position $\bar{r}_{lar\_3} = (3.4 \quad 0.1 \quad -0.5)\, in$ relative to geometric center of SAFER jets.

<u>Large astronaut, case 4:</u>

Total mass $m_{lar\_4} = 653\, lbm$; inertia matrix $I_{lar\_4} = \begin{pmatrix} 69.4 & -5.0 & 0.6 \\ -5.0 & 71.4 & 11.3 \\ 0.6 & 11.3 & 30.6 \end{pmatrix} kg\, m^2$ relative to CG; CG position $\bar{r}_{lar\_4} = (1.2 \quad -2.2 \quad 3.4)\, in$ relative to geometric center of SAFER jets.

In addition, on-orbit data from STS-64 showed that SAFER thrust was about 10% lower than the nominal value of 0.80 lbf. After discussions with W. Studak, it was agreed to use the value of 0.72 lbf for Mir-3 training as being more representative of the thrust level that is likely to actually be seen on-orbit.

Finally, two questions should be investigated in connection with Case *(4)* above. Firstly, to what extent will flexibility or slop in the MUT, or in the gimbal joint and jaws of the RT, lead to undesirable dynamics analogous to that experienced with the MMU/"stinger" combination on the STS 51-A capture of Westar VI? Secondly, to what extent will the MEEP be impinged upon by plumes from one or more of the jets positioned in the lower left quadrant of SAFER? It may be that this experiment package will affect positive y, negative z and/or negative roll inputs to some degree, depending on its precise location. These considerations must be taken into account fully in any analysis of self-rescue while carrying the MEEP package. A plume impingement analysis of the MEEP package is given in the next section; the tether flexibility question is left for a future research effort.

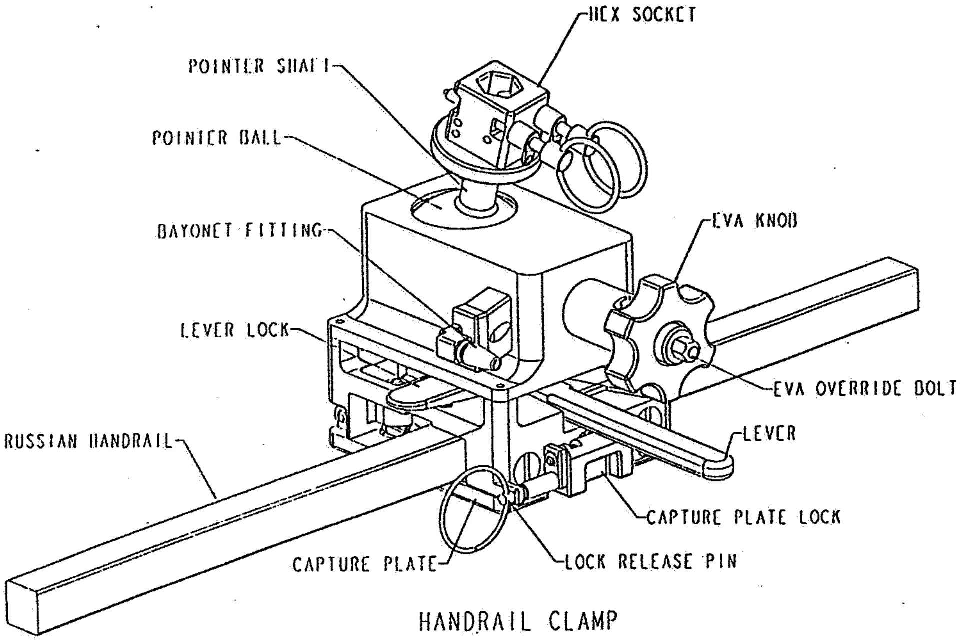

Figure 5.1

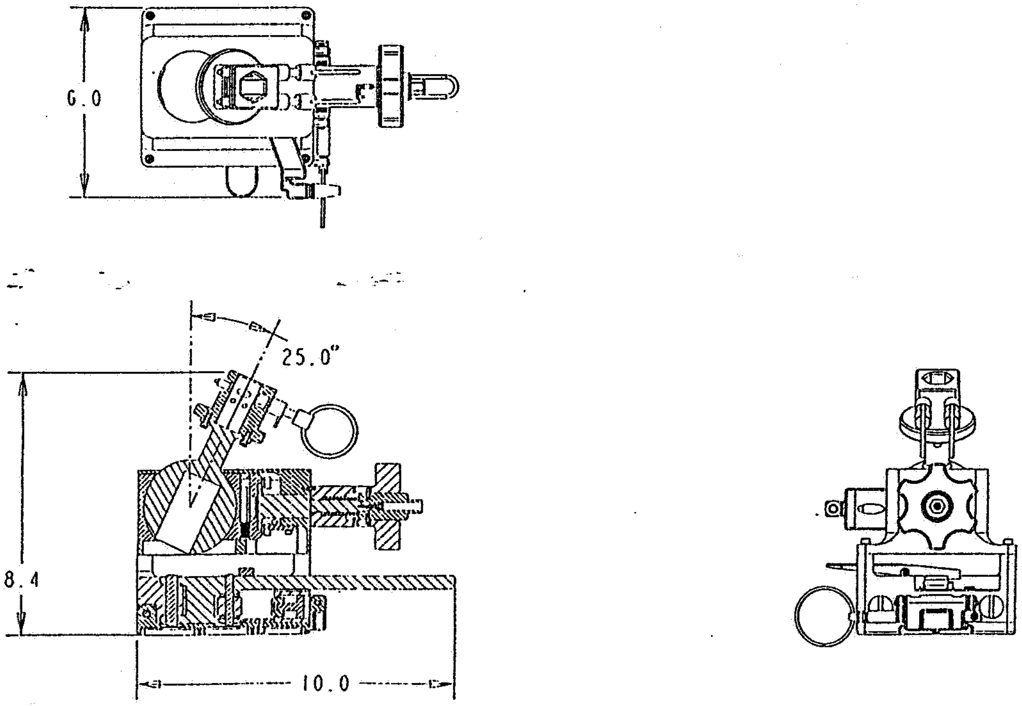

Figure 5.2

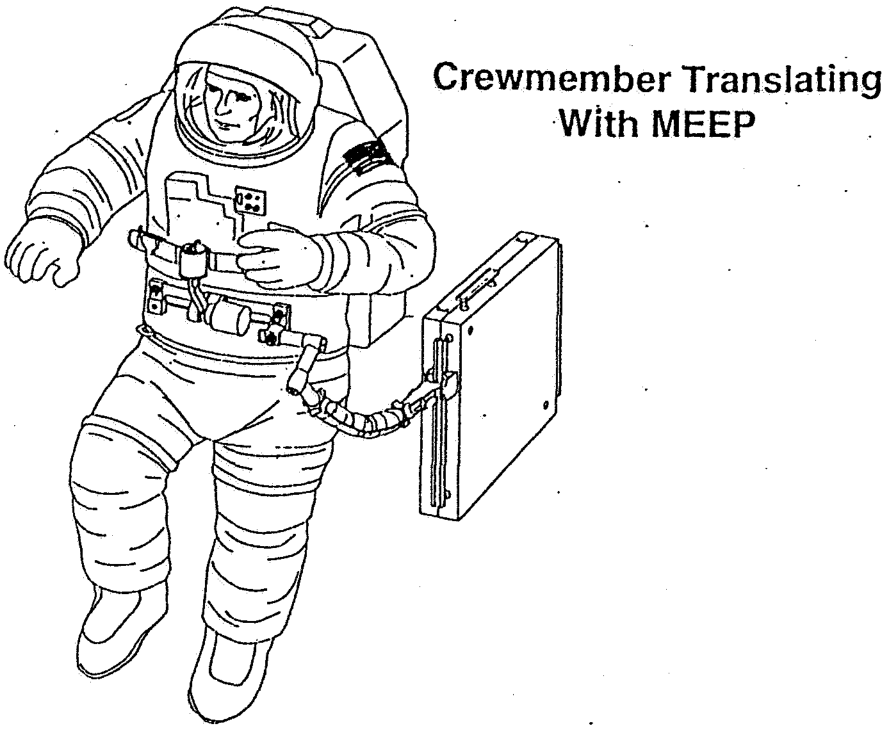

Figure 5.3

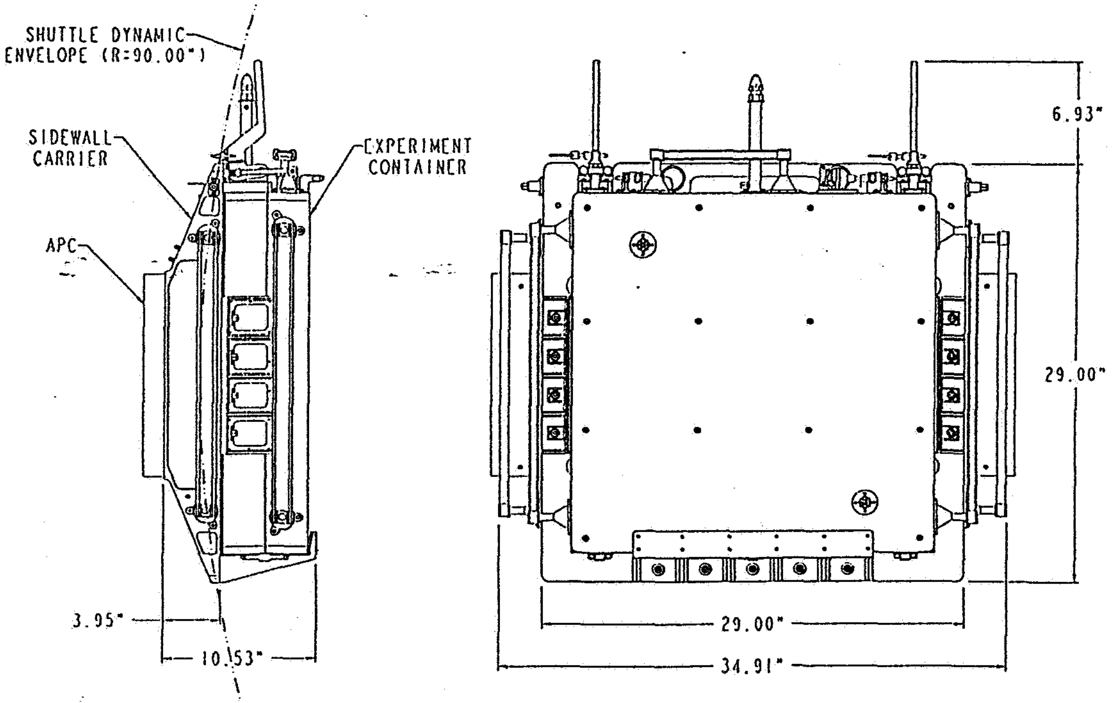

Figure 5.4

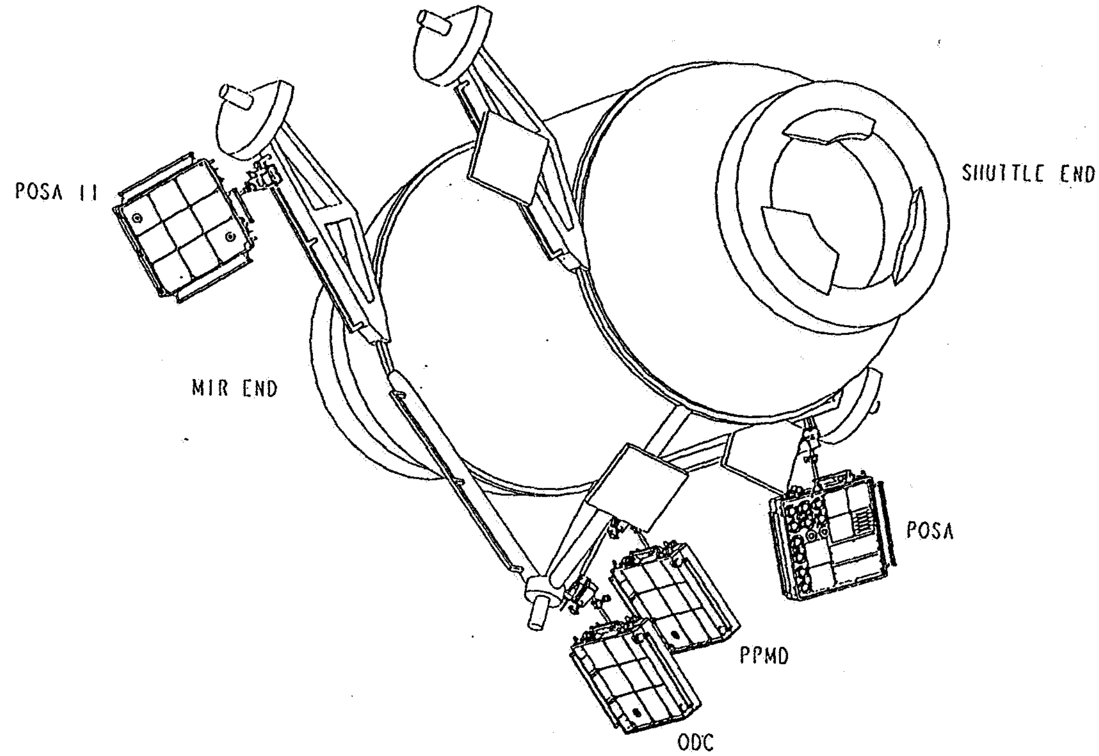

Figure 5.5

6. Plume Impingement Analysis

The approach taken here to model the plume field of the SAFER cold-gas nitrogen thrusters was based on the modified Newtonian formulation described in Ref. 10. This analysis was developed for work involving MMU thruster pluming; the model used in Ref. 11 for impingement studies of the Space Shuttle Primary RCS jets is very similar. The basic approach is to break the plumed hardware down into a set of small planar surfaces. The distance of each of these surface elements from the thruster considered, and its angular separation from the boresight of the nozzle, are then computed, as is the orientation of the surface relative to the jet. These parameters allow the dynamic pressure of the plume at the location of the area element, as well as the normal pressure coefficient C_{PN}, to be obtained. (It is this coefficient that makes the procedure a *modified* Newtonian formulation, reflecting the fact that we are dealing with gas molecules. C_{PN} varies with the incident angle of the plume on the surface element, never exceeding a value of 2. For a standard Newtonian formulation, i.e. involving inelastic collisions of particles, $C_{PN} = 2$ for all incidences.)

Two plume impingement sources must be considered for the STS-76/Mir-3 mission: pluming of the MEEP experiment package when this is being transported, and pluming of the Hand Controller Module (HCM) stowage box on the underside of the SAFER Propulsion Module. Both of these present their own difficulties. Firstly, the position of the MEEP package is not well defined: it depends on whether the Rigid Tether or the MUT is used to attach it, and on the way in which the EVA crewmember choses to orient this. Fortunately though, the MEEP is of simple geometry, with planar sides. The HCM stowage box, on the other hand, is in a well-defined position, but its internal geometry is quite complicated. Furthermore, it is initially closed by a multi-layer insulation flap on its front face. If SAFER were to be activated, this flap would be hinged open and would lie directly in line with the two downward-firing jets that impinge upon the HCM box. In this work, it is assumed that the low mass of the flap implies that it would merely be rotated away from the thrusters, essentially instantaneously, when these fire.

Consequently, the plume impingement analysis performed here for the HCM stowage system involves the box itself and not the flap.

As a result of the difficulties described above, the plume impingement results obtained here are only first-order approximations to the true effects. However, they serve to provide valuable insight into the significance of these effects on the flying qualities of SAFER. The Appendix contains the Matlab code used to generate the HCM pluming results; the MEEP pluming code is very similar. The dynamical results obtained can be summarized as follows: pluming, for both the HCM box and the MEEP package in a worst-case position (as near as possible to a SAFER jet) can give rise to disturbance forces and torques on the order of 10% as large as the nominal jet outputs.

In the case of the HCM box, a negative z (upwards) translation command would give rise to an uncommanded negative x (rearwards) translation, regardless of whether AAH were engaged or not. If AAH were disengaged, positive roll and yaw disturbances would also be expected to occur. Note that the HCM box was originally designed to be in a more upright position, farther back from the downward-firing SAFER jets. However, in order to ensure reliable HCM deployment, this box had to be rotated forward about 15°. It is interesting to note that this change in geometry increased the predicted plume loads by about a factor of 4.

For the MEEP in the position assumed for the mass properties analysis of the last section, the lower left rear-firing SAFER thruster plumes it at a glancing angle. The result is that, if this jet fires to provide a positive x translation, there will be a small uncommanded negative y (leftwards) translation, as well as a positive yaw disturbance torque. This torque may actually, to some extent, serve to compensate for the yaw induced by an x translation as a result of the CG offset caused by the MEEP. It should again be emphasized, though, that these results are very sensitive to the exact position of the MEEP. Changes in position on the order of inches can affect the magnitude of the resulting plume forces and torques, while gross changes in position can cause different jet(s) to plume the package, so leading to entirely different results.

7. Mir-3 SAFER Flying Qualities

This section first summarizes the main points concerning the dynamics of the basic astronaut/EMU/SAFER system as flown on STS-64. A brief description is then given of the dynamics expected when transporting the MEEP experiment package during part of the STS-76/Mir-3 EVA.

7.1 Flying Qualitites without MEEP Package

(1) *Linear acceleration:* The linear acceleration of the basic astronaut/EMU/SAFER system is 0.17 ft/sec^2 for the STS-64 EV2 total mass of 538 lbm, which lies between the generic Medium and Large cases.. This assumes a thrust value for each SAFER jet of 0.72 lbf, as was identified from STS-64 on-orbit data.

(2) *Angular accelerations:* The angular accelerations obtained for the three axes, again assuming STS-64 EV2 mass properties, are:

Roll: 4.5 deg/sec^2;
Pitch: 3.8 deg/sec^2;
Yaw: 7.1 deg/sec^2.

The higher yaw acceleration results from the yaw moment of inertia being considerably smaller than the other two. Consequently, maneuvering in yaw is more efficient than maneuvering in the other two axes.

(3) *CG forward offset:* The astronaut/EMU/SAFER CG is 2.7 - 2.9 inches in front of the geometric center of the SAFER thrusters; the vertical and horizontal CG offsets are approximately zero (but see *(6)* below). As a result, the major cross-coupling effects of

translation maneuvers are the opposite yaw induced by a y (lateral) translation, and the pitch-up induced by a +z (downwards) command. These amount to about a -3.4 deg/sec yaw rate for a 1 sec +y burn executed with AAH disengaged, and a pitch rate of about 1.3 deg/sec for a 1 sec +z burn. The fact that this yaw rate is larger than the roll rate is another consequence of the small yaw moment of inertia.

(4) *Roll/yaw coupling:* The forward slant of the crewmember's legs introduces an asymmetry into the dynamics of the system, which leads to significant coupling between roll and yaw. This roll/yaw coupling occurs because the legs will tend to resist, or lag, a roll or yaw rotation. Imagining the feet as being fixed in space, it can be seen that a positive roll will pivot the body about them, so giving rise to a positive yaw coupling, and *vice versa.* As the yaw moment is considerably smaller than that for roll, the yaw induced by a roll command will be larger than the roll induced by a yaw command. The approximate decoupling of pitch from this roll/yaw motion is due to the fact that the vertical *xz*-plane is roughly a plane of symmetry of the EVA system. These effects were observed by astronaut Van Hoften during his on-orbit checkout of the MMU on STS-41C[9].

(5) *Effect of leg angles:* If the legs of the astronaut drift farther forward, this clearly increases the roll/yaw coupling just discussed. Furthermore, it also causes the CG to move even more forward, so increasing the yaw induced by a y translation and the pitch induced by a z input.

(6) *Effect of crewmember size:* The main effect of an increase in crewmember size is to shift the CG downward, as a result of the greater leg/LTA mass. On STS-64, EV1 (Mark Lee) had a CG about 1 inch below that of EV2 (Carl Meade); this put EV1's CG at roughly the height of the geometric center of the SAFER jets. Consequently, while EV1 experienced essentially no cross-coupling from an x translation, EV2 experienced a small amount of induced pitch (about 0.5 deg/s pitch-up for a 1 sec +x input).

(7) *Cross-coupling summary, AAH off:* The response obtained with the basic astronaut/EMU/SAFER for inputs with AAH disengaged can therefore be summarized as follows:

x command: small pitch-up in response to positive x input for smaller crewmembers; essentially no cross-coupling for larger crewmembers.
y command: large negative yaw in response to positive y input. Also small negative roll for positive y for smaller crewmembers.
z command: moderate pitch-up in response to positive z input.

Roll command: large positive yaw in response to positive roll.
Pitch command: essentially decoupled from the other axes.
Yaw command: moderately large positive roll in response to positive yaw.

(8) *Cross-coupling summary, AAH on:* When maneuvers are executed with AAH engaged (as is likely to be the case in any self-rescue application), the effects of CG offset and roll/yaw coupling will not be observed directly in the form of induced rotations. Instead, the coupling inherent in the system will give rise to a reduction in control authority and/or an increase in the propellant required to carry out a given maneuver. The specific effects depend on the details of the SAFER jet select logic, which is based in part on the fact that no more than four SAFER jets can ever be activated at one time, and can be summarized as follows:

x command: x jets are modulated off as required to counter any pitch or yaw induced by the small y and z CG offsets. This reduces control authority slightly, but does not increase propellant consumption.
y command: a pair of yaw jets must be fired periodically to counter the significant induced yaw resulting from the forward CG; this requires simultaneously switching two of the four y jets off. The result is reduced control authority and increased propellant consumption.

z command: requires periodic firing of a pair of pitch jets to counter the induced pitch, while switching two of the z jets off. This leads to reduced control authority and increased propellant consumption.

Roll command: requires firing a pair of yaw jets periodically, while the two roll jets are still firing, to counter the roll/yaw coupling of the system. This leads to increased propellant consumption, but no reduction in control authority.

Pitch command: essentially decoupled from other axes. No degradation in control authority or propellant consumption.

Yaw command: requires firing a pair of roll jets periodically, while the two yaw jets continue to fire. This leads to significantly increased propellant consumption, but no reduction in control authority.

Consequently, x is the most efficient axis for translation maneuvers with AAH engaged, and yaw (despite the propellant overhead required for roll-nulling) remains the most efficient axis for rotations. Finally, note that all of the major AAH cross-coupling effects listed above become larger as the forward angle of the legs is increased.

7.2 Flying Qualities with MEEP Package

1) *Linear acceleration:* The added mass of the MEEP, together with the hardware (RT or MUT) used to attach it, reduces the linear acceleration achieved by SAFER by approximately 14%, to around 0.15 ft/sec^2.

(2) *Angular accelerations:* The MEEP package gives rise to very significant increases in all three overall moments of inertia; these increases lie in the range 65 - 80%. Consequently, the angular accelerations obtained for the three axes are greatly reduced over the nominal values quoted above. The new values are:

Roll: 2.5 deg/sec^2;

Pitch: 2.3 deg/sec^2;

Yaw: 4.3 deg/sec^2.

It can be noted that maneuvering in yaw is still more efficient than maneuvering in the other two axes. However, all axes are considerably more sluggish than when flying without the MEEP. This decrease in rotational control authority is likely to be readily apparent to the SAFER pilot.

(3) *CG offset:* The presence of the MEEP package will shift the overall CG to between 2.0 and 2.5 inches to the left of the geometric center of the SAFER thrusters. Consequently, a +x translation will now give rise to a significant induced negative yaw rotation, and a +z command will induce negative roll. This contrasts sharply with the nominal case, where the CG lies essentially in the xz-plane. The particular MEEP position analyzed in the last two sections also leads to a significant rearward and downward shift in overall CG, with similar consequences for rotational cross-coupling about other axes. However, it should be noted that the precise position in which the MEEP will actually be carried is somewhat uncertain; it will clearly be to the left of the astronaut/EMU/SAFER, but any details beyond that are not reliable. For this reason, a detailed analysis of the effects of the x and z CG shifts that are predicted to result from carriage of the MEEP will not be given here. Nor, for similar reasons, will details be given of the predicted cross-coupling behavior with AAH off or on.

The most significant dynamical effect of the addition of the MEEP can be seen to be that all self-rescue maneuvers, both translation (e.g. fly-back) and especially rotation (e.g. detumble), will require more propellant to achieve than if they were conducted for the nominal astronaut/EMU/SAFER system. This will make carrying out a successful self-rescue without MEEP jettison a somewhat challenging task. Furthermore, no flexibility effects were considered here. It is possible that any significant relative motion between the astronaut/EMU/SAFER and the MEEP could lead to additional propellant consumption, due to a chattering-type bahavior, if operating with AAH engaged.

8. Conclusions

The main goal of the research reported here was to use the detailed SAFER mass properties data generated from the on-orbit test maneuvers carried out during the STS-64 mission to optimize the design of future EVA maneuvering systems, with the aim being to improve flying qualities and/or reduce propellant consumption. The Automation, Robotics and Simulation Division Virtual Reality (VR) Laboratory proved to be a valuable research tool for such studies. A second objective of the grant was to generate an accurate dynamics model in support of the reflight of the DTO SAFER on STS-76/Mir-3. One complicating factor was the fact that a hand controller stowage box was added to the underside of SAFER on this flight; the position of this box was such that two of the SAFER jets plume it. A second complication was that the EVA astronaut will sometimes be transporting a massive experiment package. This will not only alter the overall mass properties significantly, but also can be plumed by certain SAFER thrusters.

Acknowledgements

Larry Merkel and Jeff Hoblit at NASA Johnson Space Center, and Sergei Tanygin at the University of Cincinnati, assisted with this research. Their help is gratefully acknowledged.

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Appendix: Matlab Plume Impingement Code

```
% An M-file to calculate the total force and torque
% produced by SAFER jets 21 and 22 impinging on the
% Mir-3 HCM stowage box

% Mean location of jets 21,22 (xj,yj,zj) rel to overall CG (in),
% found from jet and CG positions relative to geometric center
%
xj2122gc=0.000; yj2122gc=11.734; zj2122gc=17.470;
xcmgc= 0.9;  ycmgc= -2.3;  zcmgc= 3.0;
xj=xj2122gc-xcmgc; yj=yj2122gc-ycmgc; zj=zj2122gc-zcmgc;
%
% Distance of effective plumed HCM box face behind jets
% at level of lower surface of SAFER Prop Module (inches)
%
x0=4.9;
%
% Maximum left and right limits of plumed HCM face relative
% to jets
%
yleft=5.25; yright=0.75;
%
% Maximum lower limit of plumed HCM face rel to jets
%
zlo=7.9;
%
% Length increment (inches) used to divide up plumed surface
%
dl=0.10; % (May give small over-estimate on plume force and torque)
da=dl*dl;
%
% Set up vector normal to plumed HCM box front face
%
degrad=pi/180;
al=degrad*(15);
sa=sin(al);
ca=cos(al);
ta=tan(al);
%
nhat=[-ca 0 sa]';
nmat=[  0    sa    0
       -sa    0   -ca
        0    ca    0  ];        % Used for vector product calculation
%
% Main loop over area elements making up plumed HCM box face
%
mtotal=[0 0 0]'; ftotal=[0 0 0]';
for z=0:dl:zlo    % Horizontal strips
    for y=-yleft:dl:yright    % Proceed along this strip
%
%       Find position of this area element relative to jet,
%       in standard SAFER coordinates
%
```

```
        xrel=-x0+(z*ta);
        yrel=y;
        zrel=z;
%
%       Hence, find position of area element relative to CG
%
        xel=xj+xrel;
        yel=yj+yrel;
        zel=zj+zrel;
%
%       Polar position of area element relative to thruster
%
        delvect=[xrel yrel zrel]';
        r=norm(delvect);  % inches
        theta=acos(zrel/r);
%
%       Modified Newtonian plume impingement formulation:
%       q plume dynamic pressure at area element (lbf/sq in)
%       cps stagnation pressure coefficient (dimensionless)
%       beta angle between LOS from area element to jet and element surface
%       cpn normal pressure coefficient (dimensionless)
%
        cth=cos(1.353*theta); if cth < 0 cth=0; end;
        q=0.774*(cth^4.762)/r^2;
        cps=1.833;
        beta=asin((nhat'*delvect)/r);
        betadeg=beta/degrad;
        cpn=cps*(0.814+(6.88/betadeg^0.8))*(sin(beta))^2;
%
%       Resulting force increment
%
        df=cpn*q*da;  % lbf
        ftotal=ftotal+df*nhat;
%
%       Resulting moment increment about overall CG
%
        dm=df*nmat*[xel yel zel]';  % lbf in
        mtotal=mtotal+dm;
%
        end;
    end;
%
fnorm=norm(ftotal);
mnorm=norm(mtotal);
[x0 fnorm mnorm]
```