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Space Station On-Orbit Solar Array Loads During Assembly

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This paper is concerned with the closed-loop dynamic analysis of on-orbit maneuvers when the Space Shuttle is fully mated to the Space Station Freedom. A flexible model of the Space Station in the form of component modes is attached to a rigid orbiter and on-orbit maneuvers are performed using the Shuttle Primary Reaction Control System jets. The traditional approach for this type of problems is to perform an open-loop analysis to determine the attitude control system jet profiles based on rigid vehicles and apply the resulting profile to a flexible Space Station. In this study a closed-loop Structure/Control model was developed in the Dynamic Analysis and Design System (DADS) program and the solar array loads were determined for single axis maneuvers with various delay times between jet firings. It is shown that the Digital Auto Pilot jet selection is affected by Space Station flexibility. It is also shown that for obtaining solar array loads the effect of high frequency modes cannot be ignored.

I. Introduction

When the Space Station Freedom (SSF) and the Space Shuttle are mated to each other on orbit, the Shuttle attitude control system will be used to control and maneuver the combined vehicles until control authority is switched over to SSF on Mission Build (MB) flight 5. The Shuttle Reaction Control System (RCS) consists of 6 Vernier RCS (VRCS) jets, each providing 25 lb. of thrust, and 38 Primary RCS (PRCS) jets where each jet provides 875 lb. of thrust. The heavy weight of the SSF structure causes large center of gravity offsets for the Shuttle. This, combined with the non-redundant nature of the VRCS system, causes the PRCS system to be used for attitude control. The standard PRCS system induces large loads on the SSF. Therefore an alternate mode of operation (ALT Mode) in which the number of jets that can be fired simultaneously as well as maximum duration of firing and minimum delay between firings can all be controlled by the crew. The PRCS ALT Mode reduces induced loads on the SSF systems via the following restrictions: using minimum pulse duration (80 milliseconds), a maximum of two simultaneous jet firings, and long delay times. But, at some point the delay times and firing durations can cause controllability problems. Furthermore, since the SSF structure is highly flexible, the effect of structural flexure can affect the jet firing selection by the Digital Auto Pilot (DAP). This paper does not attempt to address the controllability issues of the SSF assembly flights. Extensive studies have been performed at NASA/JSC to study the controllability problems. Results of those studies indicate that when PRCS pulse durations are limited to 80 milliseconds, the delay times between each firing cannot be extended beyond 10 seconds without degrading control performance. From a control point of view smaller delay times are desirable but, internal SSF loads can limit the minimum allowable delay time.

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Normally, the mated Orbiter/SSF loads analysis is performed in an open-loop manner. The controllability studies are performed with rigid vehicles and PRCS jet profiles are generated for a number of cases. Certain profiles are selected for loads analysis based on the frequency of firings and the specific jets that were active. For very stiff payloads this is a proper approach since high frequency modes do not affect the jet firing selection. The SSF structure, however, is a very flexible system with primary bending modes below 1 Hz., and mass properties in the same order of magnitude as that of the Space Shuttle. Therefore it is expected that the attitude control jet firings will be affected due to system flexibility. An open-loop rigid-body approach to determining jet firing sequences does not take this effect into account and can produce unrealistic profiles.

In this study a flexible model of the SSF MB2 in the form of component modes is attached to a rigid Shuttle model using the DADS software. The Shuttle DAP is coupled with the dynamics model of the combined vehicles to obtain a closed-loop model. The DAP is then commanded to perform single axis maneuvers with various time delays. Interface loads between the Shuttle and SSF are recovered. A Load Transformation Matrix (LTM) is also used to recover SSF Solar Array loads as well as desired displacements and accelerations at various internal points. Closed-loop flexible body analysis results are compared with rigid body analysis. A simplified model is also set up to study modal contribution for on-orbit loads analysis. The DADS dynamics model developed has the capability to include multiple flexible articulating/non-articulating payloads and perform on-orbit attitude control or general maneuvers using any of the operational modes of the Shuttle RCS system. The results of this study and the models developed can be used to further study the on-orbit loads and controllability issues for critical SSF assembly flights.

II. Dynamic Model

The dynamic analysis for this study was performed using the DADS software. DADS was selected for its general purpose capability to simulate large angle/displacement multi-body/multi-disciplinary systems. The ability to link the program with existing in-house codes makes it an ideal tool for this type of analysis.

The SSF MB-2 configuration is shown in Figure-1 attached to the Orbiter. It consists of a center truss, an electrical power system radiator, a port-side solar power module and two photovoltaic arrays. The finite element model consists of 1267 grid points and 1825 elements. This model reflects the design as of May 1991. The assumption is that the alpha and beta gimbals that rotate the solar array about its base are locked in the position shown in Figure-1. The truss structure is represented by an equivalent beam model. The total mass of this configuration is 70874 lb. The finite element model was fixed at the interface with the Shuttle and normal modes were generated. Forty two modes with a frequency range of 0.07-4.8 Hz were recovered. An LTM for 130 items was also generated. Details of this work can be found in Ref. 1.

The Shuttle DAP software (Ref. 6) determines jet firing commands for attitude control or general single- or multi-axis on-orbit maneuvers. In a typical scenario the desired Shuttle attitude and/or rates are requested by the crew. The DAP then attempts to achieve and maintain these attitude and rate commands within the crew-specified error margins. The error margins are the attitude dead bands and rate limits. The error is defined as the difference between the DAP commands and estimates of the states derived from Inertial Measuring Unit (IMU) data. Jet firings are commanded whenever the errors exceed the margins. The DAP has two major operational modes; manual and automatic control. When manual control of Shuttle attitude or rate is required, the pilot requests rate changes through the hand controllers, which are converted to jet-firing commands by the DAP. In the automatic mode the DAP determines when jet firings are required. Since PRCS firings induce flexure in the mated vehicles the Shuttle IMU data will include a component due to flexure. The IMU data is then used to generate subsequent jet firing commands. Therefore, a rigid-body simulation may produce inaccurate jet firing histories compared to a flex-body simulation. The Shuttle Flight Control System Simulator (FCSSIM) is a FORTRAN program that simulates all the operational modes of the RCS system. This is an in-house developed program that is used for controllability studies by control analysts.

The Shuttle is modeled as a rigid body in DADS. From the controls standpoint a rigid body assumption is appropriate for this study since it is known that the shuttle flexible modes do not affect the jet firing selection. From a loads point of view since SSF modes are below 5 Hz, it is assumed that there will be no significant coupling between Shuttle and SSF modes. Furthermore, since this study is the first attempt at performing closed-loop on-orbit loads analysis, simplifying the problem facilitates understanding of the system behavior. The SSF MB-2 component modes were translated to DADS format and were coupled to the Shuttle model. In a final modelling step, the FCSSIM program was linked to DADS via a subroutine call. Figure-2. shows a flow-chart of the coupled model. The attitude control system parameters are set in FCSSIM. These parameters include RCS mode of operation, maneuver command, dead bands, rate limits, delay time, initial rates, etc.. The Shuttle attitude and rates are sensed from the DADS model and are passed to FCSSIM. FCSSIM operates on this data and determines which jets are to be fired. The resultant force and moments of the DAP-selected combination of RCS jets is then passed back to the DADS program to be applied to the Shuttle. At every integration step the SSF generalized coordinates response is used to recover desired data from the LTM.

The cases that were studied reflect a subset of the available control options. Automatic single-axis maneuvers were commanded in the Roll, Pitch, and Yaw directions. The maneuver angle was set to 10 degrees. Combined vehicle rates were initialized to 0.1 deg/sec about all axes in order to ensure prompt maneuver initiation. The SSF MB-2 configuration extends forward of the Shuttle when it is mated to it as shown in Figure-1. In this configuration the fourteen Shuttle PRCS jets in the nose cannot be fired because of contamination of the SSF structure and plume impingement on the SSF solar arrays. Therefore DAP was set for Tail-jets-only option. Furthermore a maximum of two jets were allowed to fire simultaneously with a maximum pulse duration of 80 milliseconds to reduce induced loads on the SSF. For each single-axis maneuver the delay times were set to 0, 4, and 10 seconds in separate runs. The delay time represents the minimum wait time between consecutive PRCS firings. A total of nine cases were evaluated in this study. It is important to emphasize that a broader spectrum of conditions must be studied in order to adequately cover the entire envelope of SSF assembly operations. Although this study does not present a complete answer for the on-orbit loads issues with respect to SSF, it represents a set of points within the realm of possible scenarios. The models that were developed in the course of this study and the lessons learned can be used in any future work dealing with on-orbit loads issues. Future simulations should also include manual pulse trains (Ref. 2) designed to excite specific modes.

III. Results

Figure-3. compares the attitude rates of a rigid-body simulation of the SSF/Shuttle combination and a flexible simulation for a 10 degree Pitch maneuver with 4 seconds delay between PRCS firings. Attitude rates for Roll, Pitch, and Yaw are overlayed for the two cases. Curves 1, 2, and 3 are the results of the rigid-body study. The impulsive changes seen in the Orbiter rate are as a result of PRCS jet firings. In the Pitch direction a rate change is seen every 4 seconds. Curves 4, 5, and 6 represent the flexible-body simulation. The oscillations seen on these curves are due to SSF flexure induced by the jet firings. The flex-body and the rigid-body results show the same jet firings until 32 seconds into the maneuver when a Roll jet is fired in the flex-body run. The most significant difference occurs at approximately 37 seconds when a Pitch correction is made which is in the opposite direction as that of the rigid-body simulation. The differences between the rigid-body and flex-body runs become more significant as the maneuver continues. These results show that even for SSF MB-2 configuration the effect of flexibility can be significant with respect to which jets are fired and in what direction. Heavier and more flexible configurations such as MB-5 will only amplify this effect. From a control point of view these differences are not considered significant as long as they do not cause instability but, with respect to loads a different jet profile can cause higher loads.

Figure-4. shows the bending moment at the solar array base for a 10 degree maneuver with 4 seconds delay between jet firings. The peak load is approximately 22000 in-lb at 90 seconds into the maneuver. Load spikes occur every 4 seconds consistent with the jet firings. Highest loads were obtained for the pitch maneuver, as it was expected, since the solar arrays are positioned in the x-y plane. Although maximum solar array bending moment (24,500 in-lb) was obtained for the pitch maneuver with zero delay, it is not likely that PRCS ALT mode will be used with zero delay option during SSF assembly. The other conditions analyzed (4 sec. and 10 sec. delays) also resulted in high bending moments as mentioned earlier. Figure-5. shows the interface pitch moment between SSF and Orbiter in a pitch maneuver. Table-1. summarizes the peak bending moments about for the solar arrays and the Orbiter interface. The Orbiter interface bending moments have to be reacted by the unpressurized berthing adapter. Closer examination of the solar array and Orbiter interface responses revealed that the frequency range used for the SSF may not have been sufficient. Upon further investigation with a simplified model of the SSF it was shown that in problems where impulsive loading is present the contributions of the sixth bending mode of the system is also significant. Similar studies have shown the same results (Ref. 3). It was also shown that insufficient modal representation causes the interface loads to converge from the rigid body solution during the load application. Therefore impulsive changes in the interface response can be seen if higher bending modes are not included. Adding more modes results in a time-shift of the peak loads but, not a significant reduction in their magnitudes. The response amplitude between firings is higher when modal representation is sufficient. This means that the results of the present study are not conservative in spite of insufficient modal representation which usually results in a stiff system. This is because higher response amplitudes between PRCS pulses can result in peak loads greater than what was computed in this study when subsequent pulses occur. Considering the capability of the solar arrays, approximately 31,500 in-lb about their weak axis, and the results of this study which does not even include any uncertainty factors, it is possible to overload the arrays when Orbiter uses its PRCS jets for maneuvering and attitude control. This means that certain limitations have to be imposed on the PRCS ALT mode operations. At least one limitation is obvious; untuning of delay times from dominant bending modes. Other limitations need further studies using closed-loop models, such as the one developed for this study, where the effect of flexibility on jet selection can be accounted for. Future studies can perform parametric studies on different dead bands and rate limits, longer pulse durations and delay times, and notch filters for cases where dominant bending modes are of low-frequency nature and affect jet selection logic significantly. It is important to remember that one of the assumptions in this study is that the Orbiter is rigid. If higher bending modes with frequencies above 5 Hz need to be used in future studies then the potential of interaction with Orbiter modes cannot be neglected. Such studies have to consider using a flexible Orbiter for loads analysis.

IV. Conclusion

A closed-loop dynamic model of the SSF MB2 mated to the Space Shuttle Orbiter was developed in DADS. SSF flexibility was represented by means of forty two component modes with a frequency range of 0.07 - 4.8 Hz.. Orbiter DAP was coupled to the dynamic model and on-orbit single-axis maneuvers were performed. Solar array and Orbiter/SSF interface loads were recovered. The effect of structural flexibility on jet profiles was shown to be significant in some cases, however, from a controllability point of view the differences were not considered to be major. The solar array loads were found to be high for the cases studied. It was found that the frequency range used for the SSF component modes were not sufficient for loads analysis, however, further investigation using a simple beam model of SSF concluded that adding more modes can result in higher loads than what was obtained in this study. Any future work should consider using up to the sixth bending mode of the SSF. If SSF modes above 5 Hz are used then consideration should be given to using Orbiter flexible modes in order to account for any coupling effects. Additional studies should also be performed on the effect of longer pulse durations to compensate for longer delay times, multi-axis maneuvers, variations in dead bands and rate limits.

References

1. Ghosh, T., Vasquez, T.,"*Space Station Freedom Pre-Integrated Truss On-Orbit MB2 Configuration Finite Element Model*", Rockwell Internal letter 91-EPS-8E-067, Rocketdyne Division.

2. Lepanto, J.,"*Preliminary Definition of Forcing Functions for Orbiter Attached Payloads*", The Charles Stark Draper Laboratory, Inc. memo no. DI-91-009, EGC-91-231.

3. Abramson, N.,"*An Introduction to the Dynamics of Airplanes*", pp. 144-146.

4. Biot, M. A., and Bisplinghoff, R. L.,"*Dynamic Loads on Aircraft Structures During Landing*", NACA Wartime report W-92 (ARR 4H10) (1944).

5. "*DADS Theoretical Manual*".

6. "*Space Shuttle Orbiter, Operational, Level C, Functional Subsystem Software Requirements, Guidance/Navigation/Control, Part C, Flight Control, Orbiter DAP*", Rockwell Internal document, SSD.

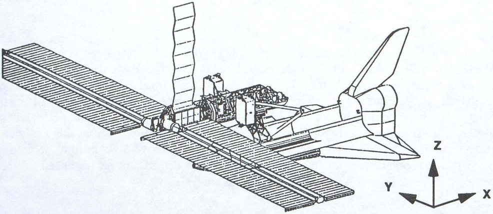

Fig. 1 SSF MB2 mated to the Orbiter.

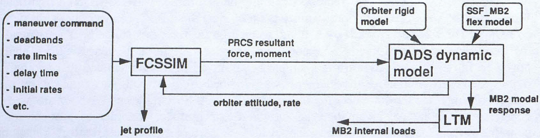

Fig. 2 Closed-Loop Structure/Control model.

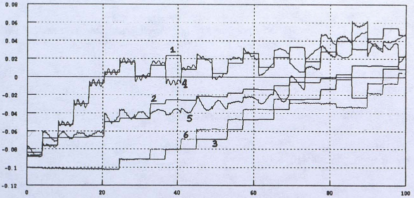

Fig. 3 Comparison of Rigid vs. Flex-body results.
Orbiter attitude rates (deg/sec vs. seconds).
(10 degree pitch maneuver, 4 sec. delay)

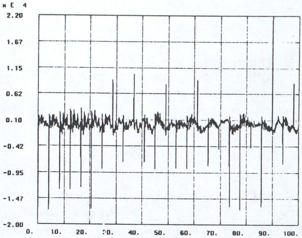

Fig. 4 YZ-plane Bending Moment at the solar array base (lb-in vs. seconds). (10 degree pitch maneuver, 4 sec. delay)

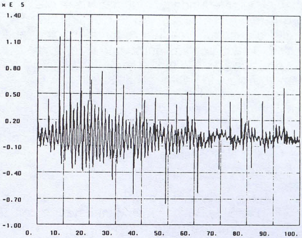

Fig. 5 Interface pitch moment between Orbiter and SSF (lb-in vs. seconds). (10 degree pitch maneuver, 4 sec. delay)

Solar Array Interface		Orbiter/SSF Interface		
My (lb-in)	Mz (lb-in)	Mx (lb-in)	My (lb-in)	Mz (lb-in)
24,500	7,500	85,000	195,000	145,000

Table 1 Maximum bending moments at the solar array and Orbiter interface.