JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 37, No. 4, July–August 2000

On-Orbit Shuttle/Mir Mated Reaction Control System and Crew Load Analyses

G. E. Funk* and R. M. Stephenson†
The Boeing Company, Downey, California 90242-2693

The shuttle/Mir joint missions required the development and use of new analytical techniques to ensure the structural integrity of the mated on-orbit vehicles. Normally, the on-orbit loads for a space vehicle are small when compared with the liftoff or landing loads. However, for shuttle payloads that change configuration on orbit or shuttle mated operations with large space structures, reaction control system and crew loads can be significant. For the shuttle/Mir mated configuration, indiscriminate reaction control system thruster firing or crew activity can exceed the structural constraints at the major substructure interfaces. New analysis methodologies were developed to ensure that the proper reaction control system and crew constraints were in place to safeguard the structural integrity of the shuttle and Mir. These methods were utilized in the mated shuttle/Mir structural analyses to define control system and crew operational constraints.

Nomenclature

L = array of load recovery items
Nb = integer number of bipolar pulses, 2 [2 rate limit (RL) + maneuver rate (MR)]/[α_c(0.068 s)], maximum value rounded up
Nu_c = integer number of unipolar pulses, (2RL + MR)/[α_c(0.068 s)], rounded up
n_{jet} = array of (1, 0) for thrusters (on, off)
q_s = array of generalized system (modal) displacements
s_c = attitude hold firing duration, smaller of $T/2$ and 2RL/α_c
T = modal period
T_d = multiple of T, dependent on delay time
T_{df} = multiple of $T/2$, dependent on delay time and sign of generalized force
T_f = T or $T/2$ dependent on sign of generalized force
t_c = maneuver firing duration, smaller of $T/2$ and (2RL + MR)/α_c
α_c = angular acceleration, deg/s
ζ_i = damping coefficient for the ith mode
$\Phi_j^T F_j$ = generalized thruster force matrix
$\Phi_p^T F_p$ = generalized plume force matrix
ω_i = frequency for the ith mode, rad/s

Subscript

c = 1 or 2, complementary jet thruster sets

Introduction

THE shuttle has three major on-orbit propulsion systems, the orbital maneuvering system (OMS), the primary reaction control system (PRCS), and the vernier reaction control system (VRCS). The two OMS engines each produce 6000 lb of thrust, and their use with the mated shuttle/Mir configuration[1] (Fig. 1) would violate the structural constraints in less than 1 s. There are 38 PRCS thrusters that produce 870 lb of thrust each. Standard PRCS control options allow up to six PRCS thrusters to fire simultaneously. The thrust of a single PRCS jet can violate the shuttle/Mir structural constraints in less than 2 s. Therefore, the mated shuttle/Mir configuration, when under shuttle attitude control, used the six VRCS thrusters, each of which produces 24 lb of thrust, as the principal control mode. Because the VRCS is not fault tolerant, a backup control system is required.

In the event of a VRCS failure, the alternate (ALT) PRCS control option could be used. This option was designed to reduce the nominal PRCS induced structural responses. Although the analytical techniques developed here are also applicable to the Mir control system and were used in verification analysis, the focus of the current paper is on the shuttle control system induced structural dynamic loads. Nominal PRCS control logic allows the thrusters to remain on until the desired maneuvering rate has been reached. The ALT PRCS mode is a thruster selection scheme that provides the options to specify the maximum number of thrusters allowed to fire simultaneously, the minimum time between firings, and the maximum thruster on time. ALT PRCS also allows the use of certain PRCS thrusters to be prohibited. From a loads perspective, it is generally best to have the fewest number of thrusters on for the minimum time with as much time as possible between firings. However, from a vehicle control/stability perspective, the opposite scenario would be preferred. An interdisciplinary iterative process was, therefore, developed to determine the control parameters that would meet both structural loads and control/stability requirements.

Process Flow

The on-orbit shuttle/Mir mated vehicle reaction control system (RCS) and crew loads analysis process flow is shown in Fig. 2. First, a mated vehicle on-orbit model is developed. The mission specific on-orbit shuttle finite element model is mated to the appropriate Mir finite element model. All other items in the flight manifest are also included in the mated system model. Load constraints for each major interface are defined, and an output transformation matrix (OTM) is developed. Mir plume loading from the shuttle RCS is also included in the analysis. The plume effects are included in the generalized force matrix. Because the loads are recovered via an OTM, a plume impingement static load matrix (PIM) is also used. Once the mated vehicle on-orbit model has been generated, the combined vehicle mass properties are used by the control/stability team to generate mission specific RCS thruster select tables. The tables are generated for VRCS and appropriate ALT PRCS selections. The VRCS digital autopilot (DAP) configuration parameters of rate limit and maneuver rate are then selected and critical VRCS forcing functions identified. These critical forcing functions are then analyzed using a closed form solution to Eqs. (1) and (2) to verify that there are no load constraint violations. VRCS loads are generally low and allow for simultaneous performance of several crew loading activities.

Received 14 May 1997; revision received 30 January 1999; accepted for publication 24 April 2000.

*Principal Engineering Specialist, Vehicle and Systems Analysis, Reusable Space Systems, Boeing North American, Inc.; currently Principal Engineering Specialist, MC H049-E433, Reusable Space Systems, The Boeing Co., 5301 Bolsa Avenue, Huntington Beach, CA 92647-2099. Senior Member AIAA.

†Member Technical Staff, Vehicle and Systems Analysis, Reusable Space Systems, Boeing North American, Inc.; currently Engineer/Scientist Specialist, MC H049-E433, Reusable Space Systems, The Boeing Co., 5301 Bolsa Avenue, Huntington Beach, CA 92647-2099. Member AIAA.

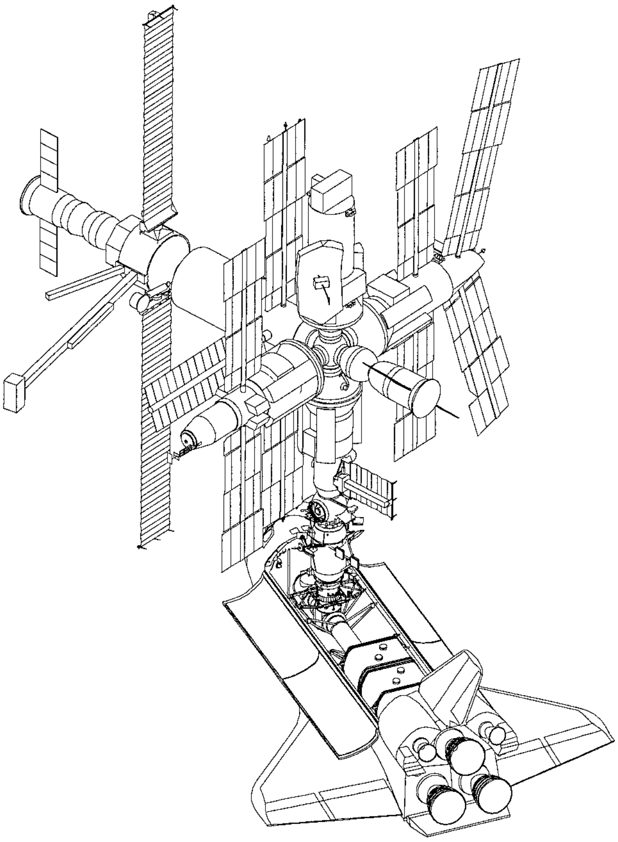

Fig. 1 On-orbit mated shuttle/Mir configuration.

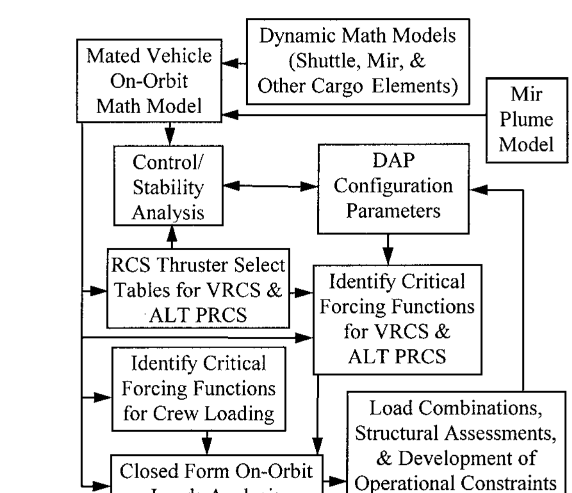

Fig. 2 On-orbit mated vehicle RCS and crew loads analysis process flow chart.

The next step in the analysis is to define an acceptable ALT PRCS configuration. The standard ALT PRCS synthetic forcing function criteria[2] require the input of appropriate DAP configuration parameters. These include a PRCS thruster selection table, maximum thruster on time (typically 80 ms), minimum delay time between thruster firings, rate limit, and maneuver rate. Any or all of these parameters may be varied, within acceptable bounds, when attempting to minimize critical loads cases. Note that the variables just listed also affect mated system control/stability. This selection of acceptable DAP configuration parameters requires a parallel loads and control/stability assessment. For the ALT PRCS control scenario, a maximum thruster on time of 80 ms has been established because it is the minimum duration allowed by the shuttle control system. Skyline plots, which depict critical structural load responses as a function of delay time between 80-ms RCS thruster firings, are

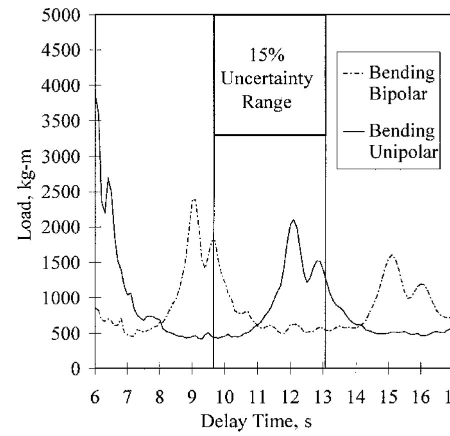

Fig. 3 Skyline plot of shuttle/Mir interface bending moment.

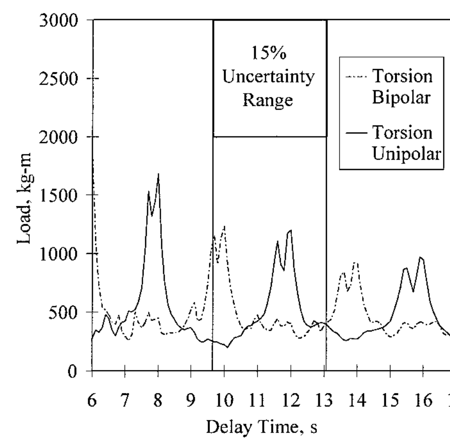

Fig. 4 Skyline plot of shuttle/Mir interface torsional moment.

used to help select a minimum delay time that will reduce certain peak responses. Figures 3 and 4 show examples of the skyline plots used to determine the delay time for shuttle/Mir mission number 5 (Ref. 3) (STS-81). A 15% math model modal frequency uncertainty is also accounted for when selecting a delay time. Any peak load responses that occur within the model frequency uncertainty range must be considered.

Once the ALT PRCS DAP configuration parameters have been selected, critical forcing functions are identified and the case is analyzed using a closed-form solution to Eqs. (1) and (2). For certain cases an iterative process is required to identify DAP configuration parameters that satisfy both the load constraints and control/stability constraints.

Critical crew load forcing functions are also identified for each crew activity and the closed-form modal transient solution is then recovered for each OTM item. Once the OTM responses have been recovered for the RCS and crew loading events, load combinations are analyzed. These load combinations are based on a set of mated shuttle/Mir operational constraints developed over the course of the shuttle/Mir project.[4] If the resultant OTM responses exceed the allowable structural constraints for certain scenarios, additional operational constraints are specified for that scenario. In this manner, operational constraints are developed for each nominal and contingency segment of the mated shuttle/Mir mission.

RCS Loads Analysis Methodology

Analysis of all possible forcing functions would take an enormous amount of time and CPU unless an efficient method could be developed to identify the critical forcing functions. The analysis methodology used to perform an on-orbit shuttle/Mir RCS loads analysis is summarized in three steps. In the first step, the shuttle/Mir mated vehicle modes are calculated by means of modal synthesis. Mated system free–free mode shapes and frequencies up to 25 Hz are retained in assembling the generalized RCS thruster forcing functions and Mir OTM. In the second step of the analysis, a frequency sweep is carried out for each of the VRCS and ALT PRCS load cases to tune the forcing functions to the driving frequencies that maximize the OTM responses, within the model uncertainty, given by the following equations. The modal equation is

$$\{\ddot{q}_s\} + \begin{bmatrix} \ddots & & \\ & 2\zeta_i\omega_i & \\ & & \ddots \end{bmatrix}\{\dot{q}_s\} + \begin{bmatrix} \ddots & & \\ & \omega_i^2 & \\ & & \ddots \end{bmatrix}\{q_s\}$$

$$= \left[\Phi_j^T F_j + \Phi_p^T F_p\right]\{n_{\text{jet}}\} \tag{1}$$

The RCS loads recovery equation is

$$\{L\} = [\text{OTM}]\{\ddot{q}_s\} + [\text{PIM}]\{n_{\text{jet}}\} \tag{2}$$

The driven frequency lists for the various load cases are compared and only the frequencies that maximize the OTM item responses are retained in the final driven frequency list, which is used in the next step to generate the forcing functions. This reduction of the driven frequency list resulted in a 5:1 CPU savings in the transient response analysis. In addition, a screening process is performed to determine all modes, up to 10 Hz, that result in loads that are greater than 1% of the largest load response due to a single jet pulse (80-ms equivalent on time) for any OTM item. Modes meeting this criteria are retained in the solution of Eqs. (1) and (2). Note that, as a minimum, the top 20% of the modes must be retained for each OTM item to maintain solution accuracy. Retaining only these modes when recovering the loads (OTM items) results in an additional 2:1 CPU savings when performing the transient analysis. In the third step, analysis utilizing the closed-form modal transient response for all modes up to 10 Hz, identified in the single pulse mode list for each recovery item, is carried out for each forcing function generated from the frequencies identified in the driven frequency list.

The basics of the synthetic forcing function used in the loads analysis were developed by the control/stability staff at the Charles Stark Draper Laboratory and are described in Ref. 2. The VRCS forcing function consists of four bipolar firings: one attitude hold firing, followed by two maneuver firings representing the beginning and completion of a commanded attitude maneuver, followed by one attitude hold firing. The VRCS forcing function is depicted in Fig. 5. The ALT PRCS forcing functions consist of unipolar and bipolar sequences. The unipolar forcing functions are representative of the beginning and completion of a commanded attitude maneuver.

The bipolar forcing functions are designed to envelope control system responses. Certain modifications to better meet the intent of Ref. 2 based on subsequent control/stability and structural dynamic analysis have resulted in modifications to the forcing function criteria for shuttle/Mir loads analysis. In the case of ALT PRCS, two of these modifications include a 10-pulse limit on single axis forcing functions[5] and a 6-pulse limit on contiguous unipolar pulsing at intervals greater than the ALT delay time. An example of an ALT PRCS unipolar forcing function is shown in Fig. 6 and a

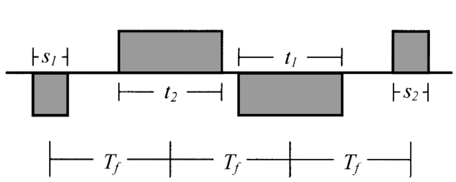

Fig. 5 VRCS forcing function.

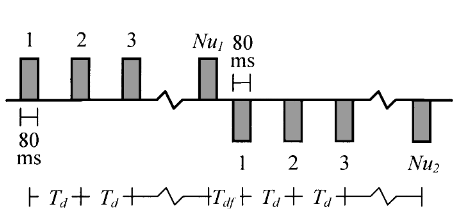

Fig. 6 PRCS ALT DAP unipolar forcing function.

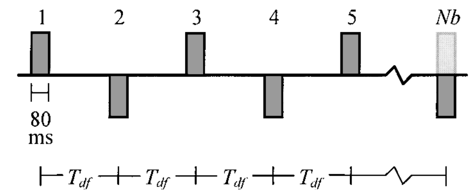

Fig. 7 PRCS ALT DAP bipolar forcing function.

bipolar forcing function is shown in Fig. 7. Once the critical forcing functions were identified, the transient analyses was performed for the VRCS and ALT PRCS load cases. The analysis tools have been validated using a NASTRAN transient response solution with full modal content such that the maximum response error is less than 1%.

To evaluate specific responses, time histories and modal contribution plots may be generated for any recovery item. The tools include automatic frequency selection and creation of RCS forcing functions. Input files are automatically generated. The tools result in significant time and CPU savings. For benchmarking CPU, a comparison has been made between the solution method described in the third step and NASTRAN. For a 5-s check case, the CPU savings was 16 to 1. Standard analysis cycles search many cases and recover much more than 5 s worth of loads. A rough estimate of the CPU savings for a standard analysis cycle using the solution method presented in step three vs NASTRAN is over 3300 to 1. A major factor in this CPU savings is the programs incorporation of a closed-form solution that allows the evaluation of vehicle responses for any particular time slice or window without integrating from time zero. Peak loads in response to a tuned forcing function occur near the end of the forcing function. Recovering loads using a small window near the end of the forcing function results in significant CPU savings.

Crew Loading Analysis Methodology

Crew loading can be divided into two categories: impulsive and cyclic. Impulsive loads are caused by pushing off, translating along, or bumping into objects either inside or outside the spacecraft. They may also be induced when the crew member is attached to a restraining device such as the payload foot restraint. Cyclic crew loading occurs when the crew members exercise on repetitive devices such as treadmills or cycle ergometers.

Impulsive loading is generally represented as a force or as a combined force and a moment. The forces and moments are generally modeled as half-sine forcing functions with varying amplitudes and durations. These forcing functions are applied at various places along the interior and exterior of the mated shuttle/Mir vehicle, as agreed to in Ref. 4.

Cyclic loading generated by the various exercise equipment is modeled as continuous sinusoidal waves. Each exercise has a given frequency range and force amplitude. The treadmill has two exercise options: walking and jogging. To reduce CPU, frequency sweeps are performed to identify exercise equipment critical frequencies, within the equipment's operational frequency range, which tune with structural modes and produce the largest load responses. The critical frequency cases identified are then used as an input to the closed-form modal transient response solution. The frequency sweep can reduce CPU as much as 10 to 1.

Load Combinations and Operational Constraints

Load combinations include shuttle RCS control and crew activities. Cyclic exercise loads were combined with RCS loads as maximum on maximum. The cyclic nature and long duration (usually 30 min) of the exercise loads leads to a high probability of maximum loading events occurring simultaneously. EVA and IVA maximum impulsive loads were usually root sum squared and the results added to the RCS and cyclic exercise combination. Root sum of squares is used to address the low probability of simultaneous peak transient load occurrences. Operational constraints were developed based on peak load responses and load combinations. Typical operational constraints for shuttle/Mir missions included the following:

1) Shuttle treadmill use was prohibited because use of the shuttle treadmill during mated operations could excite the system axial modes and create loads that violate the interface constraints.

2) Jogging in the Mir base module was limited to less than 200 steps per minute to avoid exciting critical frequencies.

3) It was desirable to avoid simultaneous exercise in both shuttle and Mir to protect Mir structural life.

4) During an extravehicular activity (EVA) crew exercise was prohibited.

5) EVA operations were prohibited beyond certain locations to limit the loads at the shuttle/Mir interface.

6) When ALT PRCS was used instead of VRCS control, additional restrictions were placed on crew exercise due to the higher ALT PRCS loads.

Conclusion

To perform the mated shuttle/Mir on-orbit structural loads analysis, new analytical techniques were developed to ensure the structural integrity of the vehicles. Closed-form solutions and frequency search algorithms were developed to greatly reduce the time and computational requirements needed to perform the analysis. These methods were utilized in the mated shuttle/Mir structural analysis to define reaction control system parameters and crew operational constraints.

References

[1] Kochkin, A., Brown, B., Antoshechkin, Y., and Sandars, G., “STS-81 Shuttle–Mir Docking Mission—Shuttle–Mir Physical Characteristics,” NASA WG-3/RSC E/NASA/001/3402-5, Oct. 1996.

[2] Lepanto, J., “Preliminary Definition of Forcing Functions for Orbiter Attached Payloads,” Charles Stark Draper Lab., Memo DI-91-009, EGC-91-231, Cambridge, MA, July 1991.

[3] Funk, G. E., and Stephenson, R. M., “Loads Data Book for STS-81 Verification Loads Analysis,” Rockwell Aerospace, SSD96D0495, Downey, CA, Dec. 1996, Change 2, “Appendix J: On-Orbit Analysis.”

[4] Mezhin, V., Dagen, J., Antoshechkin, Y., and Sandars, G., “Shuttle Mir Docking Mission 5—Structural Loads and Mutual Constraints, STS-81,” NASA WG-3/RSC E/NASA/001/3409-5, Oct. 1996.

[5] Zimpfer, D., “Revised Forcing Functions for Single Axis Commands,” Charles Stark Draper Lab., Letter SSV-93-105, ESC-93-298, Cambridge, MA, Nov. 1993.

G. D. Gamble
Associate Editor