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Flight Test, Modal Analysis, and Model Refinement of the Mir Space Station

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The results and lessons learned from a space-flight experiment, the Mir Structural Dynamics Experiment, are summarized. One of the main objectives for the experiment was to demonstrate the feasibility of performing on-orbit modal testing on large space structures to extract modal parameters that will be used to correlate mathematical models. On-orbit tests were performed in the Mir-alone and Shuttle–Mir mated configurations, and test data were recorded with a variety of existing and new instrumentation systems. Modal analysis was performed on the collected test data to extract modal parameters, that is, frequencies, damping factors, and mode shapes. Model refinements were performed on the Mir-alone and Shuttle–Mir mated configurations. The design sensitivity approach was used for refinement, which adjusts structural properties to match analytical and test modal parameters. Test and analytical responses were compared to evaluate the model verification process. The results demonstrated that on-orbit modal testing and model refinement for large space structures are feasible within operational constraints.

Introduction

THE on-orbit construction of the International Space Station (ISS) began in 1998 and will be completed in 91 incremental assembly stages using the U.S. Space Shuttle and Russian launch vehicles. It is planned to operate the ISS for at least 15 years to conduct science and engineering projects. However there has been little experience to-date regarding how this complex, football-field-size structure will behave in space. In designing the structure and mission operations, numerical analyses with dynamic mathematical models and estimated input forces are primarily used to predict structural loads.[1]

On-orbit dynamic mathematical models of the ISS are generated by combining component mathematical models that are correlated with ground-test results. However, there will be modeling errors, even with ground tests, due to different boundary conditions, mass distributions, and gravity fields, as well as test measurement noise. In addition to mathematical model inaccuracies, load prediction errors also arise from forcing function estimation and dynamic analysis methodology, which may also be called modeling errors in a broader definition.

When on-orbit structural dynamic loads for the ISS are analyzed and predicted, uncertainty factors are used to compensate for the load prediction errors. The later ISS stage configurations will have greater uncertainties due to an accumulation of component model inaccuracies. On-orbit testing of earlier ISS configurations, with ground testing of new hardware components, will lead to the verification of later, more complex configurations. This "phased verification" allows use of the same uncertainty factors in predicting structural dynamic loads for all configurations.[2]

The Russian Mir Space Station is a permanently inhabited spacecraft that evolved from the previous Salyut Program. It consists of several modules, the first of which was launched in 1986.[3] One of the main objectives of the Mir Structural Dynamics Experiment (MiSDE) was to determine the feasibility of correlating and refining mathematical models of large space structures by on-orbit modal testing. The MiSDE recorded structural responses on the Mir from docking, jet firings, crew activities, and quiet periods, which were performed on both the Mir-alone and the Shuttle–Mir mated configurations.

Successful completion of the MiSDE project is expected to minimize risk to the ISS by allowing the verification of integrated loads and dynamic models for the earlier configurations. This paper summarizes on-orbit dynamic tests, modal analysis, and model refinement studies performed as part of the MiSDE. Lessons learned from the MiSDE are also provided. More comprehensive information may be found in Refs. 4–7.

Instrumentation

The Mir auxiliary sensor unit (MASU) was developed, as part of the MiSDE, to measure structural accelerations with wide dynamic and frequency ranges of 3.6 μg–120 mg and 0–250 Hz, respectively.[4] This system provides four levels of gain selection and 16-bit simultaneous sampling. The MASU consists primarily of an experiment support module, a distribution box, accelerometer heads, and associated cables. Data are stored on removable 260-MB Personal Computer Memory Card International Association hard discs.

MASU has five triaxial (three accelerometers aligned in orthogonal directions) and four uniaxial portable sensor units, which contain a total of 19 accelerometers. They were installed throughout Mir on the primary structure. Figure 1 shows the Shuttle–Mir mated configuration. A triaxial sensor is located in the core, Kvant-1, Priroda, Krystall, and Kvant-2. A uniaxial sensor is located in the core, Kvant-1, Krystall, and Spektr (Table 1). These sensors are high-fidelity, electromechanical servoaccelerometers and also provide temperature output.

The crew spent over 40 h of scheduled time plus personal time to setup the MASU, primarily routing over 900 ft (294 m) of sensor cables behind the panels. The crew recommended to preintegrate the hardware as much as possible. The MiSDE provided three options for sensor attachment. All sensors (except one) were attached using a mounting bracket and gray tape option. The crew stated that it is critical to provide flexibility by including more than one mounting option because it is difficult to predict which method will actually work onboard.

The crew stated that the MiSDE hardware and software worked well, were straightforward, and were virtually flawless. Initially, some of the sensors were not properly oriented and/or their orientations were not documented correctly, which required additional crew efforts for sensor inspection and reorientation. It is recommended

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Table 1 MASU sensor locations

Sensor name	Module name	Sensor direction	Sensor location,[a] m		
			X	Y	Z
Triaxial 1	Priroda	X, Y, Z	−12.988	0.000	9.670
Triaxial 2	Krystall	X, Y, Z	−10.738	0.400	−6.925
Triaxial 3	Kvant-2	X, Y, Z	11.738	6.225	−0.790
Triaxial 4	Core	X, Y, Z	−2.265	−0.250	1.350
Triaxial 5	Kvant-1	X, Y, Z	5.195	0.500	0.750
Uniaxial 1	Krystall	Y	−12.638	−0.400	−6.925
Uniaxial 2	Spektr	Z	13.018	−9.380	0.000
Uniaxial 3	Core	Y	−2.265	0.200	−1.600
Uniaxial 4	Kvant-1	Y	4.895	0.150	−0.900

[a]Measured by the Mir coordinate system that has the origin in the core module.

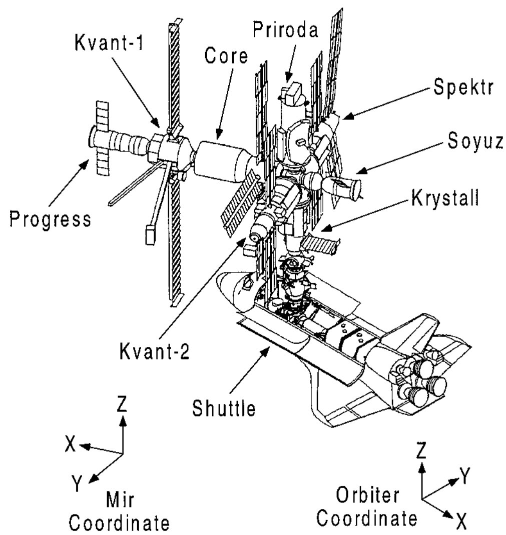

Fig. 1 Shuttle–Mir mated configuration.

to produce the crew instructions using physical descriptions instead of mathematical coordinate systems.

Test data were also obtained by other instrumentation systems.[5] The space acceleration measurement system was developed to measure the microgravity environments of the Mir. The Mir structural dynamic measurement system, also known as BT-751, is a Russian instrumentation system that includes 25 piezoelectric accelerometers. Both the Mir and Shuttle inertial measurement units have sensors that collect angular displacements and velocities with respect to three orthogonal axes. Four Shuttle payload bay video cameras are used to obtain three-dimensional photogrammetric data of the Mir photovoltaic arrays.

Flight Test

The MiSDE testing was performed over a one-year time span including four missions: missions A, B, C, and D.[‡] After each MiSDE mission, data were processed and examined to better plan test sessions for the subsequent mission and also to select data sets for detail analysis.

The MASU data were obtained from a total of 45 test sessions: 25 with the Mir-alone configuration and 20 with the Shuttle–Mir mated configuration. For some sessions, test data were also obtained by other instrumentation systems. Test sessions included Shuttle and Mir thruster firings, Shuttle–Mir and Progress–Mir dockings, crew exercise and pushoffs, and ambient noise during night-to-day and day-to-night orbital transitions. They were designed to provide a wide range of load paths, input force levels, and frequency contents.

[‡]Missions A, B, C, and D are used for convenience, and official mission names are NASA-3/STS-81, NASA-4/STS-84, NASA-5/STS-86, and NASA-6.[5] The Long Duration Mission is identified as NASA-# (National Aeronautics and Space Administration-#) in which a U.S. astronaut serves as a Mir crewmember for a flight duration of four to five months. A given Shuttle mission is identified as STS-# (Space Transportation System-Mission #) and begins with a Shuttle launch and ends with landing.

Table 2 Typical jet firing sequences for Shuttle thruster firing sessions

Jet command	Jet identification	Jet no.	Jet on time, s	Duration, s
Mission A, +unipolar yaw				
+Yaw	F5L, R5D, L5D	40, 43, 44	0.00	5.04
Mission A, bipolar yaw				
−Yaw	F5R, L5L	39, 42	0.00	2.00
+Yaw	F5L, R5R	40, 41	2.00	2.00
−Yaw	F5R, L5L	39,42	4.00	1.84
+Yaw	F5L, R5R	40, 41	5.84	1.84
Mission A, unipolar pitch				
−Pitch	R5D, L5D	43, 44	0.00	3.04
−Pitch	R5D, L5D	43, 44	6.08	3.04
−Pitch	R5D, L5D	43, 44	11.92	3.04
−Pitch	R5D, L5D	43, 44	18.08	3.04
−Pitch	R5D, L5D	43, 44	23.92	3.04
Mission A, bipolar pitch				
+Pitch	F5R, F5L	39, 40	0.00	3.04
−Pitch	R5D, L5D	43, 44	3.52	2.64
+Pitch	F5R, F5L	39, 40	6.16	2.64
−Pitch	R5D, L5D	43, 44	8.96	3.04
Mission A, −unipolar roll				
−Roll	F5L, L5L, R5D	40, 42, 43	0.00	2.00
−Roll	F5L, L5L, R5D	40, 42, 43	4.16	2.00
−Roll	F5L, L5L, R5D	40, 42, 43	8.16	2.00
Mission C, bipolar roll				
−Roll	F5L, L5L, R5D	40, 42, 43	0.00	3.92
+Roll	F5R, R5R, L5D	39, 41, 44	3.92	3.92
−Roll	F5L, L5L, R5D	40, 42, 43	8.08	4.00

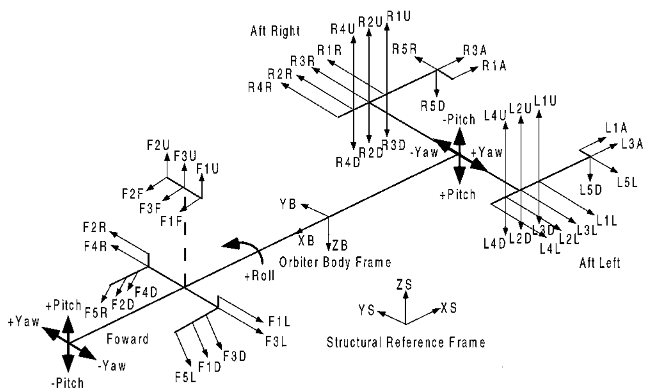

Fig. 2 Space Shuttle Orbiter jet locations and thrust directions.

Shuttle thruster firing test sessions include intentional thruster firing cases used to excite different vibrational modes using different combinations of 25-lbf (111 N) vernier reaction control system jets, number of pulses, pulse on times, and delay times between pulses. Although these sessions produced the best responses for modal analysis among all MiSDE test sessions, they are marginally acceptable for damping identification and primarily excite Shuttle–Mir stack modes. Figure 2 shows the jet locations and thruster directions for the Space Shuttle Orbiter. Table 2 represents the typical jet firing sequences for the Shuttle thruster firing sessions.

Mir thruster firing test sessions include Mir maneuver firing, thruster firing to maintain the inertial orientation attitude, reboost firing to reach the appropriate attitude, and desaturation firings for control moment gyros. All jets produce 30 lbf (133 N) each, except for the reboost jets, which produce 660 lbf (2936 N). Propellant concerns prevented the intentional use of jet firings for the Mir thruster firing sessions. It is believed that the intentional Mir thruster firings for the Mir-alone configuration would have provided the best extracted modes for Mir finite element model (FEM) refinement.

Structural responses were measured during Shuttle and Progress dockings to the Mir. The Progress is a Russian cargo space vehicle. Note that a complete capture of the Shuttle–Mir docking vehicle is not achieved instantaneously and results in a structure that is changing in nature with time.

Table 3 Typical maximum response levels measured by MASU

Test session	Mission	Test date	Absolute maximum accelerations registered, m*g*					
			Core	Kvant-1	Priroda	Krystall	Kvant-2	Spektr
Mir-alone configuration								
Crew pushoffs	A	20 Dec. 1996	12.32	3.73	2.83	1.82	3.56	0.72
Mir thruster firing	A	30 Dec. 1996	15.79	5.80	2.84	8.44	3.34	3.15
Day-to-night transition	B	31 March 1997	15.68	3.53	3.22	1.61	2.49	n.a.
Crew exercise (treadmill)	C	6 June 1997	18.31	3.88	2.38	10.31	4.46	1.89
Progress–Mir docking	D	8 Oct. 1997	12.32	11.60	8.12	6.92	8.78	n.a.
Shuttle–Mir mated configuration								
Shuttle thruster firing	A	17 Jan. 1997	3.74	1.51	1.14	5.35	0.73	0.84
Crew exercise (treadmill)	A	17 Jan. 1997	13.51	5.93	1.83	3.38	2.94	1.01
Crew pushoffs	A	17 Jan. 1997	12.47	4.41	1.35	3.85	4.13	0.50
Shuttle–Mir docking	B	17 May 1997	7.19	6.41	7.64	11.93	7.64	n.a.
Mir thruster firing	C	28 Sept. 1997	8.46	2.90	3.65	3.00	8.29	n.a.
Day-to-night transition	C	2 Oct. 1997	7.44	0.83	1.98	3.53	0.38	n.a.

Data were recorded during intravehicular activities that involve intentional crew activities such as pushoff and push–pull. The push–off test event requires a crew member to push off from one side of a wall to the other side inside the spacecraft. Repeated crew push–pull actions during Mission B mated operations generated unexpectedly high responses. The crew stated that the flexible motion of the Mir modules was observed during this session.

Structural responses were also recorded for the quiescent and nonquiescent ambient noise test events. Quiescent events include orbital day-to-night and night-to-day transitions. Data from these events provide the information needed to study not only the dynamic thermal impact on the structure, but also the microgravity environment. Nonquiescent events include crew treadmill or ergometer exercise. The crew stated that the nonmotorized treadmill provided better excitation to the Mir structure as well as better exercise for the crew.

Table 3 represents the typical maximum response levels measured by MASU. In general, response levels are higher with a higher sampling rate due to the influence from high-frequency forces generated by vibrating machinery such as fans and pumps. Response levels in the core module are generally much higher than those in other modules due to noise interference generated by the majority of vibrating machinery housed in the module. As expected, for similar excitations, sessions with the Mir-alone configuration produced generally higher responses than those with the Shuttle–Mir mated configuration.

It was difficult to identify the precise segment of the test data corresponding to the specific excitation for data analysis. It would be also difficult to use simultaneously the data obtained by other instrumentation systems. The main reason is that there was no system-wide universal time management and synchronization.

Modal Analysis

Test data from the MASU and other instrumentation systems were prepared for analysis. Time history data were calibrated, converted, filtered, and plotted. The power spectrum density for these data was also calculated and plotted. Based on visual inspection of data plots, along with the information about the sensitivity of data acquisition systems and excitation sources, a few test events were selected for modal analysis (Table 4). They include Shuttle and Mir thruster firing sessions, Progress reboost and docking sessions, and crew pushoffs sessions.

A special modal identification method[8] was used, which was developed for applications to large space structures. It is a time-domain free-decay method based on the eigensystem realization algorithm (ERA)[9] and a time-domain zooming technique. This new method does not require input force measurements and characterizes nonlinearities with a series of linearized modal parameters during the free-decay period.

Modal analysis was performed on the MASU data, for a total of 35 transient events obtained from the 14 selected test sessions, to determine frequencies, damping factors, and mode shapes. Test data from six different instrumentation systems were also analyzed to compare their capabilities.[5]

Table 4 Test sessions selected for the modal analysis study

Selected test session	Test date	Total no. of events	No. of events studied
Mission A, Mir-along configuration			
Mir thruster firing (attitude hold)	26 Dec. 1996	3	1
Mission A, Shuttle–Mir mated configuration			
Mir thruster firing (attitude hold)	17 Jan. 1997	6	3
Shuttle thruster firing	17 Jan. 1997	5	5
Mission B, Mir-alone configuration			
Mir thruster firing (maneuver)	8 April 1997	3	2
Progress–Mir docking	8 April 1997	1	1
Mir thruster firing (Progress reboost)	15 April 1997	3	2
Mission B, Shuttle–Mir mated configuration			
Shuttle thruster firing	20 May 1997	4	2
Crew pushoffs	20 May 1997	2	2
Mission C, Shuttle–Mir mated configuration			
Shuttle thruster firing	28 Sept. 1997	7	4
Mir thruster firing	28 Sept. 1997	6	3
Crew pushoffs	2 Oct. 1997	4	4
Mission D, Mir-alone configuration			
Progress–Mir docking	8 Oct. 1997	1	1
Mir thruster firing	8 Oct. 1997	4	2
Crew pushoffs	10 Dec. 1997	4	3

Because of the limited space, only the common modes for the Mir-alone configuration and Shuttle–Mir mated configuration, obtained from the MASU data, are listed in Tables 5 and 6, respectively. They were determined by calculating the modal assurance criterion (MAC) among all modes identified from all missions. The common (identical or coincident) modes were selected if their corresponding MAC values are greater than 80%. Tables 5 and 6 also include the extended modal amplitude coherence (EMAC), which is an accuracy indicator for the ERA modal identification method. Tables 5 and 6 provide information on the variation of their modal parameters between different missions and test configurations.

Nine and seven common modes were determined from comparing all extracted modes for the Mir-alone and Shuttle–Mir mated configurations, respectively. Seven of the nine common Mir-alone configuration modes are under 2.0 Hz; most were extracted with high confidence. All common Shuttle–Mir mated configuration modes are under 1.5 Hz; most were extracted with high confidence. As expected, more confidence is placed in the extraction of the frequencies followed by the extraction of the mode shapes. The identified damping values generally vary considerably, and the variation in the damping factors for some common modes do not even intersect.

From the modal analysis study, the following conclusions can be drawn. Most of the modes identified with high confidence and appeared in more than one analysis are lower frequency modes under 1.5 Hz. Mode shapes were extracted with higher confidence than damping factors but with less confidence than natural frequencies.

Table 5 Common modes for all Mir-alone configuration missions

Test mode no.	Frequency, Hz	Damping factor, %	Damping variation, %	Mission	Test session	EMAC, %
1	0.336	2.69	2.1 ~ 2.7	A	Mir thruster firing (attitude hold)	89.2[a]
2	0.354	2.53	2.0 ~ 2.7	B	Mir thruster firing (maneuver)	92.7[a]
3	0.392	1.37	1.2 ~ 2.1	D	Mir thruster firing	91.3[a]
4	0.615	1.57	1.5 ~ 1.8	B	Mir thruster firing (maneuver)	92.2[a]
5	0.615	5.29	5.1 ~ 5.5	D	Progress–Mir docking	90.4[b]
6	0.884	2.29	1.6 ~ 2.7	B	Progress–Mir docking	91.3[a]
7	0.885	2.81	2.7 ~ 3.1	D	Progress–Mir docking	91.8[a]
8	1.138	2.34	1.2 ~ 3.5	B	Progress–Mir docking	90.3[a]
9	1.087	1.36	1.1 ~ 1.9	D	Crew pushoffs	95.6[a]
10	1.342	2.84	3.5 ~ 3.6	B	Progress–Mir docking	92.5[a]
11	1.320	1.51	1.3 ~ 1.8	D	Progress–Mir docking	90.9[b]
12	1.423	1.82	1.3 ~ 1.8	A	Mir thruster firing (attitude hold)	91.6[a]
13	1.399	1.32	0.6 ~ 1.4	B	Mir thruster firing (Progress reboost)	90.8[a]
14	1.396	0.99	0.4 ~ 1.4	D	Mir thruster firing	87.3[a]
15	1.742	0.88	0.4 ~ 1.3	B	Mir thruster firing (maneuver)	83.0[a]
16	1.750	2.26	1.6 ~ 2.6	D	Progress–Mir docking	81.6[b]
17	2.618	1.01	0.5 ~ 1.7	B	Progress–Mir docking	86.9[b]
18	2.659	0.66	−0.3 ~ 3.6	D	Progress–Mir docking	89.1[b]
19	4.202	4.60	4.4 ~ 5.5	B	Progress–Mir docking	88.3[b]
20	4.146	0.54	−2.3 ~ 1.8	D	Progress–Mir docking	81.9[b]

[a]Modes extracted with high confidence and/or consistently appear in more than one analysis.
[b]Modes extracted with less confidence and/or did not consistently appear in more than one analysis.

Table 6 Common modes for all Shuttle–Mir mated configuration missions

Test mode no.	Frequency, Hz	Damping factor, %	Damping variation, %	Mission	Test session	EMAC, %
1	0.122	5.89	5.8 ~ 7.2	A	Shuttle thruster firing (bipolar pitch)	94.7[a]
2	0.121	13.68	8.9 ~ 15.0	B	Shuttle thruster firing (bipolar pitch)	74.1[a]
3	0.264	4.03	4.0 ~ 4.1	A	Shuttle thruster firing (bipolar yaw)	91.1[b]
4	0.257	2.57	2.5 ~ 3.4	B	Shuttle thruster firing (bipolar yaw)	87.3[c]
5	0.274	3.05	2.7 ~ 3.8	C	Mir thruster firing	85.7[b]
6	0.428	3.13	1.7 ~ 3.5	B	Shuttle thruster firing (bipolar pitch)	75.2[c]
7	0.442	3.88	3.4 ~ 4.0	C	Mir thruster firing	83.2[b]
8	0.778	1.12	1.1 ~ 1.8	A	Shuttle thruster firing (bipolar yaw)	92.7[b]
9	0.792	0.36	0.3 ~ 1.1	C	Crew pushoffs	90.3[b]
10	0.822	0.29	−0.3 ~ 0.5	A	Shuttle thruster firing (unipolar yaw)	86.4[b]
11	0.811	2.53	2.4 ~ 2.9	B	Crew pushoffs	96.8[b]
12	0.836	1.00	0.9 ~ 1.4	C	Shuttle thruster firing (bipolar yaw)	88.4[b]
13	1.069	1.85	1.8 ~ 2.6	B	Shuttle thruster firing (bipolar yaw)	71.3[c]
14	1.058	2.66	2.4 ~ 3.7	C	Crew pushoffs	85.6[b]
15	1.375	1.42	0.9 ~ 1.4	A	Mir thruster firing (attitude hold)	89.4[b]
16	1.334	2.25	1.7 ~ 2.8	B	Shuttle thruster firing (bipolar yaw)	69.6[c]
17	1.378	1.41	0.9 ~ 1.7	C	Crew pushoffs	87.1[c]

[a]Modes extracted with high confidence but show nonlinear characteristics.
[b]Modes extracted with high confidence and/or consistently appear in more than one analysis.
[c]Modes extracted with less confidence and/or did not consistently appear in more than one analysis.

In general, damping factors identified from the test data are greater than the damping values of 1.0% used in the analysis. The damping factors vary considerably for some of the identified modes and, in general, this variation is more pronounced for modes identified with less confidence.

To produce good structural responses for modal analysis, both the appropriate level and frequency contents of the excitation forces are required. Shuttle thruster (jet) firings primarily excited Shuttle–Mir stack modes. Predesigned intentional Mir thruster firings could have produced better modal analysis results. Crew intravehicular activity (and possibly treadmill exercise) could be easily tailored to generate large responses with specific frequency contents.

To obtain good response data for modal analysis and evaluation of the results, both the appropriate instrumentation quality and number of sensors are required. The quality of instrumentation and resulting data affect damping factors more than frequencies, followed by mode shapes. As expected, the space acceleration measurement system provided the best quality data. However, the MASU produced the best modal analysis results because it included high instrumentation quality and, especially, a wide spatial distribution of its sensors.

Model Refinement

The original mathematical models of the Mir Space Station and the Space Shuttle Orbiter were developed using simple beam-element FEMs and comprise 2544 and 114 degrees of freedom, respectively.[10] The masses of the Mir and Space Shuttle Orbiter are 301,370 and 233,220 lb (136,699 and 105,787 kg), respectively. An FEM of the Shuttle–Mir mated configuration is shown in Fig. 3. The FEM for the Mir-alone configuration differs only by the absence of the Space Shuttle Orbiter.

In this study, model refinement using the design sensitivity method is applied due to a small number of potentially mismodeled components. The design variables are the physical properties, which may contain modeling errors, to be adjusted. It was assumed that modeling errors primarily exist in major interfaces, which are modeled in the FEM by six linear spring connections in the three translation and rotation orthogonal directions. Figure 3 shows the locations of those selected interfaces.

Model refinements were performed on a total of six configurations, three Mir-alone and three Shuttle–Mir mated configurations Table 7 summarizes the frequencies and mode shapes from the test

Table 7 FEM changes from refinement process

Test frequency, Hz	Original FEM				Refined FEM			
	Frequency, Hz	Frequency difference, %	Diagonal of MAC	Diagonal of XOR	Frequency, Hz	Frequency difference, %	Diagonal of MAC	Diagonal of XOR
Mission A, Shuttle–Mir mated configuration								
0.264	0.261	−1.14	0.93	0.96	0.263	−0.38	0.98	0.97
0.301	0.294	−2.33	0.91	0.86	0.293	−2.66	0.94	0.86
0.778	0.786	1.03	0.91	0.81	0.774	−0.51	0.91	0.78
1.185	1.148	−3.12	0.81	0.92	1.169	−1.35	0.88	0.94
Mission A, Mir-alone configuration								
1.423	1.298	−8.78	0.74	0.81	1.411	−0.84	0.89	0.88
Mission B, Shuttle–Mir mated configuration								
0.428	0.484	13.1	0.86	0.90	0.441	3.04	0.87	0.81
1.360	1.269	−6.69	0.91	0.98	1.269	−6.69	0.91	0.98
Mission B, Mir-alone configuration								
0.528	0.508	−3.79	0.96	0.98	0.518	−1.89	0.97	0.96
0.884	0.875	−1.02	0.87	0.85	0.879	−0.57	0.90	0.86
1.399	1.298	−7.22	0.93	0.95	1.374	−1.79	0.93	0.96
Mission C, Shuttle–Mir mated configuration								
0.292	0.294	0.68	0.75	0.17	0.292	0.00	0.70	0.29
0.442	0.484	9.50	0.91	0.85	0.452	2.26	0.82	0.65
0.792	0.786	−0.76	0.95	0.91	0.789	−0.38	0.95	0.91
1.085	1.020	−5.99	0.96	0.87	1.021	−5.90	0.96	0.88
1.862	1.648	−11.5	0.88	0.79	1.783	−4.24	0.91	0.82
Mission D, Mir-alone configuration								
0.789	0.778	−1.39	0.79	0.93	0.783	−0.76	0.81	0.94
0.885	0.875	−1.13	0.84	0.81	0.873	−1.36	0.91	0.86
1.087	1.028	−5.43	0.98	0.98	1.083	−0.37	0.97	0.96
1.396	1.298	−7.02	0.89	0.87	1.360	−2.58	0.93	0.93

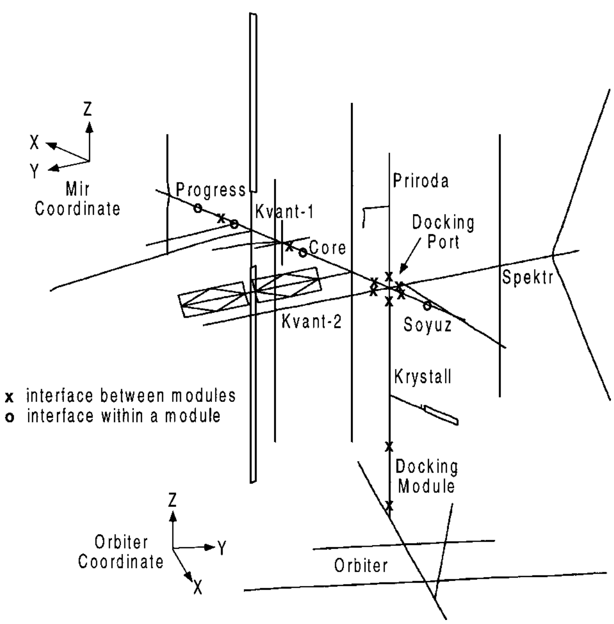

Fig. 3 FEM for the Shuttle–Mir mated configuration.

data, original FEM, and refined FEM. Table 7 includes frequency differences in percentage as well as diagonal values of the MAC and cross-orthogonality (XOR) matrices. The modes selected for refinement were extracted with a high level of confidence (generally an EMAC greater than 80%) and matched well with FEM modes (generally a MAC greater than 0.7).

From the model refinement study, the following conclusions can be drawn. All cases resulted in refined FEMs that better correlate with test frequencies and mode shapes than original FEMs. Accuracy of model refinement depends on both the number of measurements (instrumentation) and the number of modes extracted (testing). Comparisons between test extracted modes and their corresponding original FEM modes generally indicate good correlation. The Mir Space Station had already been tested and operated successfully over the past 10 years.

It is difficult to predict the damping factors in space by ground tests. Therefore, the updated damping factors, which were obtained directly from modal analysis, may have more significance for Mir than the updated stiffness. Refinements with both frequencies and mode shapes produced better overall results than those with frequencies only. Refinements with frequencies only produced slightly better frequency correlation, but significantly worse mode shape correlation.

Refinements did not result in changes to the interface between the Shuttle and Mir docking module due primarily to lack of measurements from the Shuttle. It is highly recommended to include few measurements from the Shuttle in future testing. Test extracted modes for Mir-alone configurations would produce better refinement for Mir itself. For MiSDE, however, those modes from Mir-alone configurations were extracted with less confidence because tests were not conducted with intentional, well-designed excitations.

The current test and analysis approaches, with limited instrumentation, are effective only in correlating global dynamics of the structure. To refine local components, they require additional number of measurements in the target area. All refinement cases produced design variable (spring) changes to the rotational degrees of freedom only. One of the reasons is that the rotational stiffness is generally more difficult to model than the translational stiffness. Another reason is that the majority of the selected modes are bending modes and rotational springs have higher strain energy for those modes.

Test data and analytical responses with original and refined FEMs, for the Shuttle–Mir docking and Shuttle thruster firing sessions, were compared to evaluate the model verification process.[7] For Shuttle–Mir docking cases, there is good correlation between test and analytical responses. The refined FEM with updated structural properties and/or test extracted damping values did not significantly improve the correlation between test and analytical responses. For Shuttle thruster firing cases, refined FEMs with both updated structural properties and damping values produced significant improvements over the original FEM. Figure 4 represents the typical comparisons between test and analytical responses, which is the bipolar yaw firing case from the mission A Shuttle thruster firing session.

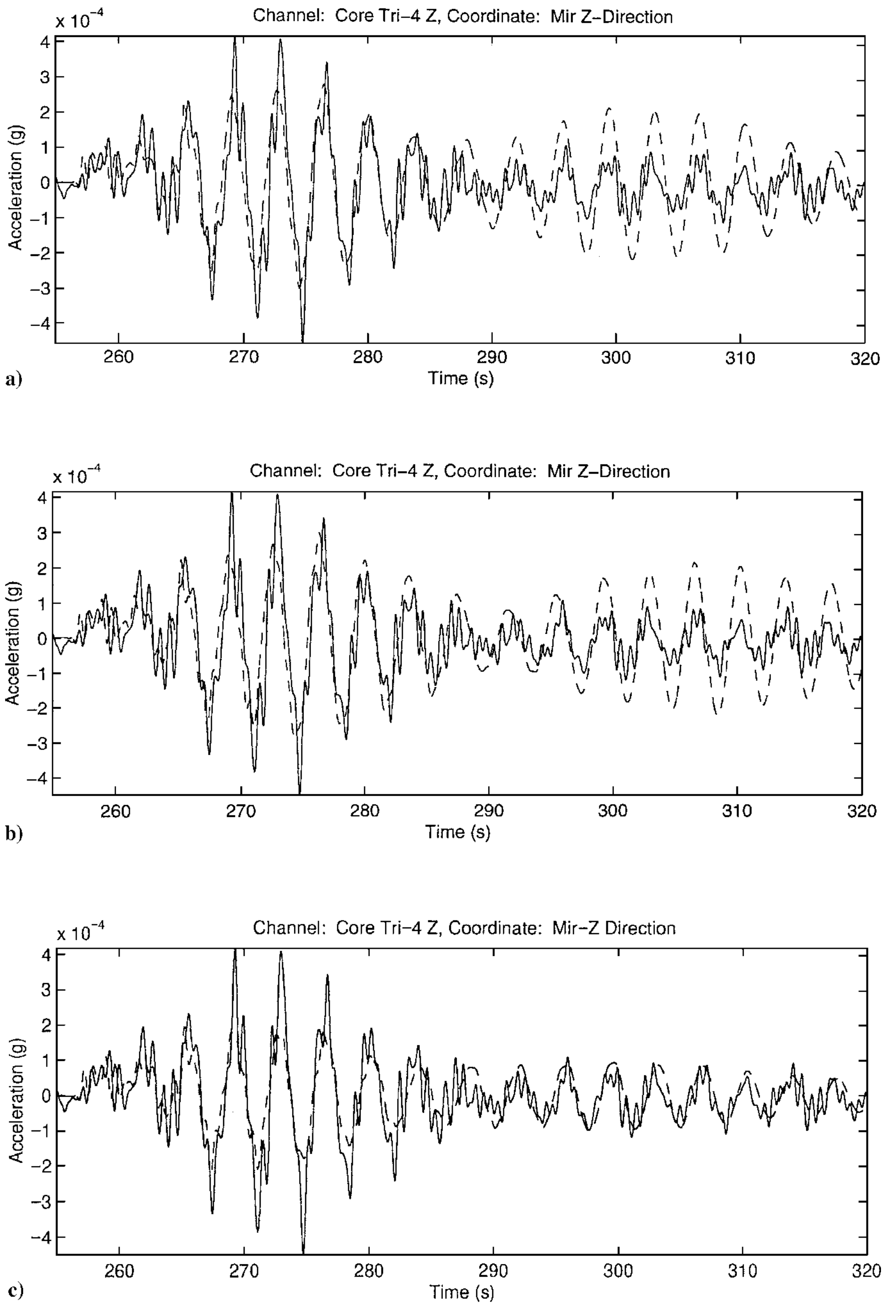

Fig. 4 Typical comparisons between test and analytical responses, where solid and dashed lines represent test and analytical responses, respectively: a) original FEM with 1.0% damping, b) refined FEM with 1.0% damping, and c) refined FEM with test damping cases.

Conclusions

The Mir Structural Dynamics Experiment has been performed and completed successfully. On-orbit testing included a total of 25 test sessions performed on the Mir-alone configuration and a total of 20 test sessions on the Shuttle–Mir mated configuration. Time-domain responses from these test sessions were recorded by the Mir auxiliary sensor unit and other existing instrumentation. Modal analysis was performed using a special free-decay modal identification methodology on a total of 12 selected transient events for the Mir-alone configuration and a total of 23 selected transient events for the Shuttle–Mir mated configuration. The results demonstrated that on-orbit testing and modal analysis of large space structures is feasible within operational constraints. Furthermore, the MASU instrumentation system provided the most suitable data for identification of modal parameters. Model refinements were performed on a total of six configurations, three Mir-alone and three Shuttle–Mir mated, using test extracted frequencies only and both frequencies and mode shapes. Test data and analytical responses with original and refined FEMs were compared to evaluate the model verification process. Refined FEMs with both updated structural properties and damping values produced significant improvements over the original model. The test and analysis results have provided the information and experience on test design, flight testing, and data analysis for the ISS and other future spacecraft, which are critical to the verification of analytical models and structural loads.

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