IAC-02-1.2.06

INTERNATIONAL SPACE STATION, A DEPLOYMENT AND MODAL TEST FACILITY

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ABSTRACT

The International Space Station (ISS) present opportunities for testing of lightweight deployable structures whose successful deployment presents large programmatic risk. One such structure is the NGST sunshield. Its deployment is the critical parameter, but its modal properties will have significant operational impact. The concept of experimental effective modal mass measurement may provide a 'low-cost' instrumentation approach by using the capabilities already present on ISS as part of the station robot. Early results on the experimental effective modal mass determination from reaction force measurement during a driven base test are presented. The station robot has a 6 degree of freedom force sensor capable of making such measurements. The driven base excitation of the structure can be applied by the station robot.

Nomenclature

a	absolute displacement
[C]	physical damping matrix
[K]	stiffness matrix
m	modal mass
[M]	physical mass matrix
s	laPlace variable
ξ	modal damping
ω_i	modal frequency

Introduction

One issue of key importance in deployable space structures is their proven ability to deploy. This is generally one of the hardest conditions to verify with ground testing, because the terrestrial friction levels which result from off-loading the 1-G effects are large compared to the forces required for deployment. Significant cost and effort goes to qualifying the successful deployment of solar arrays, large synthetic aperture radar (SAR) antennas or sunshields (such as needed for NGST).

For cases where it is deemed either mission critical, impossible to adequately test the deployment or impractical to overdesign the deployment, the ISS offers an alternative. The robotic capability that is provided externally on ISS provides a technology test bed.

The particular robotic capability on ISS also offers the ability to measure the forces a candidate test structure experiences during the deployment. This facility will provide the data necessary to understand the deployment sequence, in the unfortunate event that there are flaws. The force time history provided can be compared with the deployment simulations done prior to manufacturing the test article.

After a successful deployment of candidate test structure, the SSRMS can then provide a driven base input to the deployed structure to excite it as for a modal test. This form of testing, driven base testing is the configuration that space structures traditionally undergo for launch vibration qualification.

The presence of a force moment sensor (FMS) on the SSRMS allows a means of extracting modal data, with no additional instrumentation beyond an accelerometer at the sunshield/SSRMS interface.

Modal Test Driven Base Theory

The modal effective mass concept is used in FE modeling, particularly for large aerospace subsystems, such as solar arrays to determine if modal truncation of a model sufficiently represents the structure. [1,2]

The use of driven base testing to obtain a complete set of modal parameters requires that reaction forces be measured. These reaction forces can then be used to obtain modal frequencies, damping and effective masses. The equation of motion for driven base testing is:

$$[M]\ddot{a}+[C]\dot{a}+[K]a=0 \text{..........................(1)}$$

where the vector **a** represents the absolute motion of the structure (i.e. includes rigid body component $\mathbf{a}_0$ and the elastic motion **z**)

$$a=a_0+z$$

Transforming equation (1) into elastic and rigid body components:

$$[M](\ddot{a}_0+z)+[C]\dot{z}+[K]z=0 \text{.....................(2)}$$

And then reorganizing the equation back to the conventional forced vibration equation:

$$[M](\ddot{z})+[C]\dot{z}+[K]z=-[M]\ddot{a}_0 \text{..................(3)}$$

Thus the product of the mass matrix and the rigid body motion has become the forcing function. Converting equation (3) into modal domain

$${}^{2}[M]+s[C]+[K])Z=-s^{2}[M]A_0 \text{..............(4)}$$

$\mathbf{A_0}$ is the rigid body motion of the structure, where each point on the structure is represented by a 6x6 matrix.

The flexible and rigid body motion terms are split into frequency and spatial components where:

$$Z=\phi_E\times\eta(f)$$
$$A_o=\phi_R\times\delta(f)$$

equation (4) becomes:

$$s^{2}[M]+s[C]+[K])\phi_E\times\eta=-s^{2}[M]\phi_R\times\delta \text{..(5}$$

pre multiplying both sides of (5) by the transposed eigenvectors

$$(s^{2}[I]+s\phi_E^T[C]\phi_E+\phi_E^T[K]\phi_E)\eta=-s^{2}[\mathcal{L}]\delta$$
$$\text{...(6)}$$

where the participation factor term for driven base is:

$$[\mathscr{L}] = \phi_E^T [M] \phi_R \text{..............................(7)}$$

and where the eigenvectors are normalized for unity modal mass, i.e.

$$\phi_E^T [M] \phi_E = [I]$$
$$\phi_E^T [M] = \phi_E^{-1} \text{.....(8)}$$

Now consider the participation factors product:

$$\mathscr{L}^T \mathscr{L} = [\phi_E^T M \phi_R]^T \times [\phi_E^T M \phi_R]$$
$$= \phi_R^T M^T \phi_E \phi_E^T M \phi_R \text{........................(9)}$$

Substituting (8) into (9)

$$\mathscr{L}^T \mathscr{L} = \phi_R^T M^T \phi_E \phi_E^{-1} \phi_R$$
$$= \phi_R^T M \phi_R \text{...................(10)}$$

which is the mass moment of inertia of the structure.

Reaction Force Measurement

Modal testing

Reaction force measurements of driven base modal test have the potential to provide a means of measuring effective modal mass terms.[3,4]

The attempts so far have concentrated on linear driven base excitation - largely because this is easiest to implement with existing hydrodynamic shakers. If testing is to be done in space, it seems possible that rotational driven base should be considered.

Both linear and rotational inputs provide a form of rigid body excitation which should be considered as input to a candidate test structure from SSRMS . Though the SSRMS can be commanded to input a particular motion form, the actual input motion applied should be independently measured (by installing an accelerometer).

The conventional measured acceleration (output) is the absolute response acceleration, which is equal to the elastic component and the rigid body one, as shown below in equation (11).

Acceleration at degree of freedom corresponding to coordinate j is given by:

$$\ddot{a}_j = (\sum_i \eta_i \phi_{E_{ij}} \times s^2) + \ddot{a}_o$$
$$= (\sum_i \frac{-s^2 \phi_{E_{ij}} \mathscr{L}_i s^2 \delta}{m_i (s^2 + 2\zeta \omega_i s + \omega_i^2)}) + s^2 \times \delta \text{.....(11)}$$

where the physical (i.e. M& K) quantities have been converted to modal domain and η has been taken from equation (6).

A useful FRF is generated by considering the measured acceleration less the rigid body component, divided by the rigid body acceleration:

$$\frac{\ddot{Z}}{\ddot{a}_o} = \sum_i \frac{-s^2 \mathscr{L}_i \phi_{E_{ij}}}{m_i (s^2 + 2\zeta_i \omega_i s + \omega_i^2)} \text{........(12)}$$

In practice the FRF of equation (12) is obtained by subtracting rigid body motion from the measured acceleration FRF (1 for linear acceleration motion, 1 x distance for rotation acceleration motion). This has a small effect in the curve fitting process.

A similar reaction force FRF is generated by dividing the measured reaction force by the rigid body acceleration.

The reaction force equals the product of structural mass times rigid body motion plus the sum of the product of elastic responses and local masses:

$$\begin{aligned}\sum f &= [\phi_R]^T \times f \\ &= \ddot{a}_o[\phi_R]^T[M][\phi_R] + [\phi_R]^T[M]\ddot{z} \text{...........(13)}\end{aligned}$$

The 2nd term of equation (13) is the component of the measured reaction force needed to obtain effective mass. Considering it in the frequency domain:

$$\begin{aligned}&[\phi_R]^T[M]\ddot{z} \\ &= [\phi_R]^T[M]s^2 Z \\ &= [\phi_R]^T[M]s^2\sum_i \eta_i\phi_{E_i} \\ &= s^2\mathcal{L}^T\eta \text{........................(14)}\end{aligned}$$

When the ratio of measured reaction force to a single degree of freedom input acceleration is considered:

$$\begin{aligned}&\frac{s^2\mathcal{L}^T\eta}{s^2\delta} \\ &= \frac{\mathcal{L}^T\eta}{\delta} = \sum_i \frac{-s^2\mathcal{L}_i\mathcal{L}_i}{m_i(s^2+2\zeta_i\omega_i s+\omega_i^2)} \text{......(15)}\end{aligned}$$

For the case of rotational acceleration as the input, equation (15) is multiplied by the distance from the centre of rotation, to the point of the response accelerometer being evaluated.

Thus to solve for the participation factor terms of each mode, the measured reaction force FRF is treated as a driving point acceleration term.

Preliminary Effective Mass Test Results

The concept of extracting effective mass parameters from reaction force measurements of driven base testing are being explored by the David Florida Lab (DFL) at the Canadian Space Agency (CSA).

Preliminary results are very encouraging. A communications antenna is being used as a demonstration structure. A finite element (FEM) model of the structure is shown in figure 1.

The antennae reflector used for the analysis was provided courtesy of Spar Aerospace (now EMS). It is a single honeycomb shell, with an outer ring and a reinforcing rib structure. The shell diameter is 60 inches..

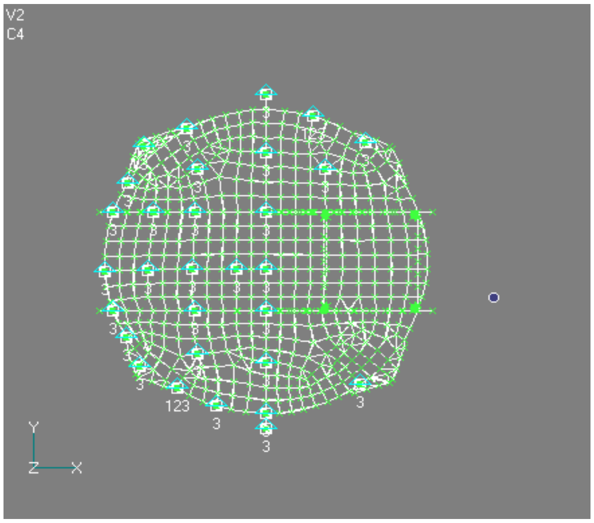

Figure 1: Antenna FEM

Four tie-down brackets are bonded onto the reinforcing rib structure. The reflector honeycomb shell, outer ring and reinforcing rib structure are constructed with Kevlar honeycomb core material faced on both sides with Kevlar prepreg cloth. The total weight of the reflector is 6 lb.

The structure mass properties were measured at DFL and confirmed to be within 10% of the FEM values.

The finite element model is a 6600 dof UAI Nastran Model with 2079 elements, predominantly plates. It was originally modeled by SPAR Aerospace in MSC Nastran.

The 30 accelerometers were installed with identical locations and coordinate systems as those of the reduced modal model (ASET) for the finite element model , expect for 2 locations where z and x were transposed. This results in a small error on effective masses calculated from accelerometer data.

There were four Kistler 9251A4 3 dof component force sensors used. For this initial test series, one of the 12 channels (400Y) of the force channels was not working.

The antenna driven base test (Z axis) is shown in Figure 2. The shaker is a 40,000 lb force rated, Unholz-Dickie UD-4000 shaker. It is isolated from ground through a reaction mass/suspension system.

The excitation input used was 0.2 GRMS burst random, 50% duty cycle.

Figure 2: Z-Axis Driven Base Modal Test - Antenna

The testing is to be repeated to correct the instrumentation problems, and as a result, only the first 3 modes have been processed. The modes were processed with LMS CADA-X software and the effective mass properties were calculated in MATLAB routines. The effective mass has been calculated for the first 3 modes based on three methods:

1. FEM mass matrix and FEM mode shapes
2. FEM mass matrix experimental mode shapes
3. Experimental reactions forces

Table 1 presents the preliminary results of the z-axis driven base excitation, along with the mass properties of the complete structure, as taken from the full FEM.

Table 1: Effective Mass Results

Total FEM	DOF	(1)-3 modes **FEM**	(2) - 3 modes **accel.**	(3) -3 modes, **reaction force**
0.017	X	0	0	0
0.017	Y	0	0	0
0.017	Z	0	0	0
8.01	Rx	1.58	1.73	0.301
15.19	Ry	11.9	11.5	10.98
16.67	Rz	0.82	0.41	0.127

These initial results do not validate the reaction force method - there are errors in all three methods of calculating the mass properties. The comparison between FEM and experimental resonances for the first three modes showed errors in the range of 10-15%.

They do suggest that measurement of reaction forces provides the potential to measure effective mass experimentally.

Reaction Force vs time history for deployment

The deployment dynamics of a large flexible structure are simulated in advance using a variety of computer tools. The reaction force between the flexible appendage and its support are normally calculated to check that the spacecraft is not given excessive perturbation.

The measurement of these reaction forces during deployment can be used to validate the simulation to correct any significant modeling errors. The main importance of measuring the reaction forces is in diagnosing any problems that occur during the qualification deployment test. If the deployment test is without incidence, the result is just increased confidence that the structure will be deploy properly in service.

Candidate Demo NGST sunshield/solar array

The NGST sunshield presents one of the most interesting challenges for lightweight deployable structures. Figure 3 shows one of the two NGST concepts. The sunshield clearly dominates the spacecraft for a dynamics point of view.

Figure 3:
NGST Concept

It is not hard to accept that the sunshield deployment is mission critical. With a planned orbit at L2, there will be no opportunity for a repair mission if the deployment is not successful.

The derived data presented in this paper are based on early sunshield design requirements. The first resonant frequency of the deployed NGST sunshield is likely to be in the range of 0.1 Hz. It is expected to have a weight of about 200 lb and a surface area of 2000 sq ft. The maximum operational quasi-static torque level (due to slew maneuvers) at the s/c to sunshield interface should be in the range of 80 ft-lb. Any on-orbit modal testing would in a similar force regime. The 80 ft-lb estimate is based on slew rate of 1 °/sec, a 30 ft boom and a boom stiffness of 3000 ft-lb/rad.

The maximum expected deployment forces will be very dependent on the particular sunshield design selected. In particular, the stiffness of the partially deployed structure could have a much lower resonant frequencies than the fully deployed structure, if the deployed structure relies on differential stiffening effects.

ISS/SSRMS Configuration

The SSRMS initial mode for the unloaded, maximum extension, is approximately 0.2 Hz. Figure 4 presents a non verified, version of the Nastran UAI finite element model. The model was developed with a series of coordinate systems to allow for quick reconfiguration of the grids to implement rotation of the robotic joint angles. There are a total of 7 joints: 3 degrees of freedom at shoulder location, one at elbow and 3 at wrist location. The FE model is a beam model, with 90 grids and 112 elements.

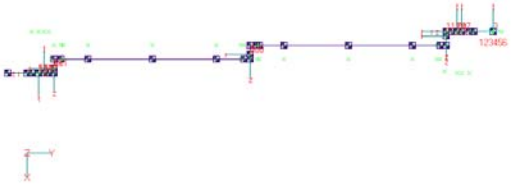

Figure 4: SSRMS FE model

Table 2 presents the frequencies of the first five modes of the unloaded SSRMS in three configurations. The third configuration includes a prop to represent the SPDM mass and stiffness.

The SSRMS has been designed to be maintained by the SPDM robot, which means that SPDM has the capability to brace the SSRMS, at a point not far from the tip.

Table 2
Unloaded SSRMS Modes

Mode	Straight	Elbow 90 deg	Elbow 90 deg + SPDM prop
1	0.22 Hz	0.27 Hz	0.58
2	0.22 Hz	0.30 Hz	1
3	2.3 Hz	0.97 Hz	1.2
4	2.3 Hz	1.0 Hz	6.1
5	4.6 Hz	6.4 Hz	7.2

The requirements of the 6 dof force moments sensors provided as part of the ISS robotic capability are presented in Table 3.

Table 3: Space Robotic FMS Requirements

.	SSRMS	SPDM
Stiffness	3.2e6 Nm/rad	6.8e4 Nm/rad
Resolution: Linear Moment	 5 N 2 Nm	 1.34N 0.45Nm
Max. Load:	4100 Nm	542 Nm

The SSRMS force sensor is undergoing qualification in situ.

Outstanding Technical Issues

The list of technical studies that need to be done before such a test could be undertaken include:

- simulations of the deployment forces and dynamics of the sunshield deployment. This could be done with the robotic package MDSF (multi-body dynamic simulation facility)
- review of SSRMS operational procedures and special control modes
- ground tests to implement rotation driven base modal testing on a conventional structure
- ground tests to validate reaction force measurement for use in extracting effective mass properties
- disposal of deployed sunshield after testing is complete

There are two special hardware requirements:

1. construction of a qualification package (e.g. NGST sunshield), suitable for transport to ISS
2. installation of a accelerometer on the supporting structure (e.g. SSRMS end effector), to measure the input accelerations.

References

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(6) "Space Station Remote Manipulator System (SSRMS) Specification, Part 1 Technical Requirements", SPAR-SS-SG-0379, Issue E. August 1992.

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Acknowledgements

I would like to thank Mark O'Grady, Dr. Raj Singhal, and Dr. Yvan Soucy of the Canadian Space Agency for providing the preliminary reaction force driven base test data.