Chapter 12
A Portable Fixed Base Support for Modal Survey Tests

Peter A. Kerrian, Kevin Napolitano, and Gregory Less

Abstract Fixed base (FB) correction methods (FBCMs) have been increasingly used to transform flexible or dynamically active boundary conditions into fixed boundaries in modal tests. This chapter documents the development of a portable test setup to conduct an FB modal survey test that can be integrated into other environmental testing configurations to accelerate testing schedules. The test article is attached to a T-slot table via an adapter plate that is bolted at multiple locations via T-slot bolts. During testing, inflatable airbags are used to raise the T-slot table off the supports, thus creating a soft boundary condition. Using 11 electrodynamic modal shakers, nine constraint shapes were measured and used to remove the dynamics of the T-slot table via the FBCM. Overall, there was excellent agreement between the FB target modes and the extracted FB modes. With this deployable setup, FB modal tests can easily be integrated into existing testing schedules, providing the ability to correlate FB models of flight hardware.

Keywords Modal testing · Vibrations · Base-shake · Fixed base · Constraint shapes · Boundary condition correction

Nomenclature

ATA	ATA Engineering Inc.
CMIF	Complex mode indicator function
CS	Constraint shape
DOF	Degree of freedom
DP	Drive point
FB	Fixed base
FBCM	Fixed base correction method
FEM	Finite element model
FRF	Frequency response function
IMAT™	Interface between MATLAB Analysis and Test
MSS	Millennium Space Systems
MST	Modal survey test
PODIuM	Portable Dynamically Fixed Mass
PSMIF	Power spectral mode indicator function
RB	Rigid body
SMURF	Structural modification using frequency response functions
SVD	Singular value decomposition
TA	Test article

12.1 Introduction

Modal survey tests (MSTs) are performed on flight hardware to help ground finite element models (FEMs) to measured test data. Doing so increases confidence in the results from subsequent analyses, such as coupled loads analysis. Fixed base (FB)

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mode shapes are the desired boundary condition for a correlation effort for two reasons. First, Hurty/Craig-Bampton analysis models of test articles (TAs) used in coupled loads analysis are fixed at their base interfaces. Second, having a fixed interface eliminates the need to spend time during the correlation updating the boundary conditions. Unfortunately, conducting an FB MST can be very costly to both the program schedule and budget because of the challenges associated with creating a support structure stiff enough to behave as a fixed boundary.

The FB correction method (FBCM) [1–10] was developed to transform flexible or dynamically active boundary conditions into fixed boundaries by using acceleration data or constraint shapes (CSs) as references when calculating frequency response functions (FRFs). By mathematically removing the compliance of the TA interface from the FRFs, FB modes can be extracted and used for subsequent model correlation. Recently, ATA Engineering, Inc., (ATA) developed the Portable Dynamically Fixed Mass (PODIuM) as a portable FBCM test setup to enable high-quality FB MSTs to be performed anywhere. The PODIuM consists of a T-slot table on top of a soft-suspension system to which a TA can be attached via an adapter plate. The advantage of this setup is that it eliminates the need to either ship the TA to a separate testing facility or invest a significant amount of resources developing a separate test fixture.

The primary focus of this chapter is to document the successful deployment of the PODIuM for an MST on the Millennium Space Systems (MSS) Aquila™ bus structure. The MSS Aquila is designed to take Class C/B payloads into orbit. MSS contracted ATA to perform the MST and then perform a model correlation utilizing the FB modes extracted using the FBCM. During the test, nine shakers were used to remove the six rigid body (RB) and first three flexible modes of the T-slot table. Subsequently, the FB modes were used to correlate the MSS Aquila FEM.

12.2 Test Overview

The MSS Aquila consists of a large rectangular bus structure, large solar panels connected at the top of the bus structure on two sides, two triangular antenna booms mounted to opposite corners of the top, and an antenna dish mounting structure connected to the top. For the test configuration, the bus structure was connected to an adapter ring, which was bolted to a second adapter ring to elevate the vehicle to allow for sufficient clearance for the solar panels in the test configuration. The second adapter ring was mounted to a 1 in. thick adapter plate that was mounted to the T-slot table with rings of T-slot bolts on the inside and outside of the footprint of the secondary adapter ring. During testing, the T-slot table was raised off the rigid ground supports using a soft-suspension system that consisted of four air bag isolators. The entire boundary configuration was added to the FEM of the MSS Aquila, as shown in Fig. 12.1.

A traditional pretest analysis was performed to identify sensor placements and create a back-expansion matrix for the MST. In total, 231 acceleration degrees of freedom (DOFs) at 153 separate locations were measured simultaneously using multiple LAN-XI 12-channel 3053 modules. Nine shakers were positioned around the T-slot table for use as references in the FBCM, as shown in Fig. 12.2. Six vertical shakers were positioned to remove the first three out-of-plane RB modes (RB Z, RX, and RY) and the first three flexible T-slot table modes (first bending, first torsion, and second torsion); three lateral shakers were positioned to remove the first three in-plane RB modes (RB X, Y, and RZ).

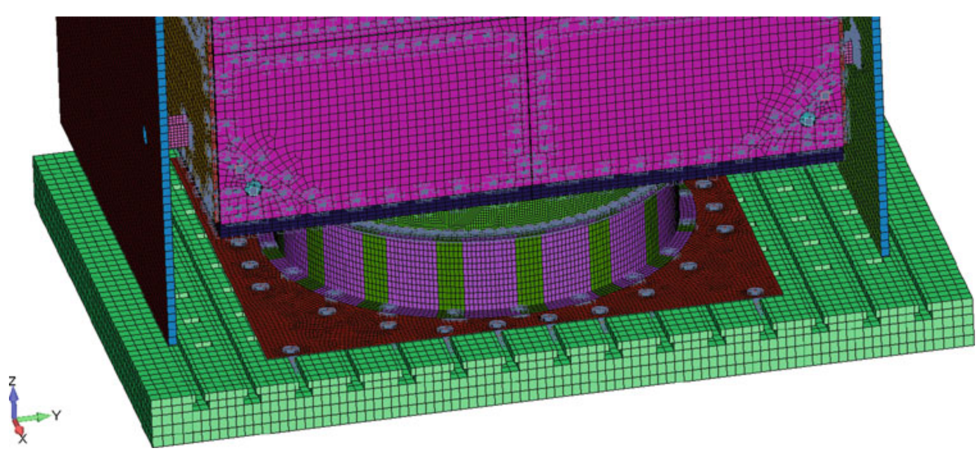


Fig. 12.1 FEM visualization of the base support structure for the MSS Aquila™ MST

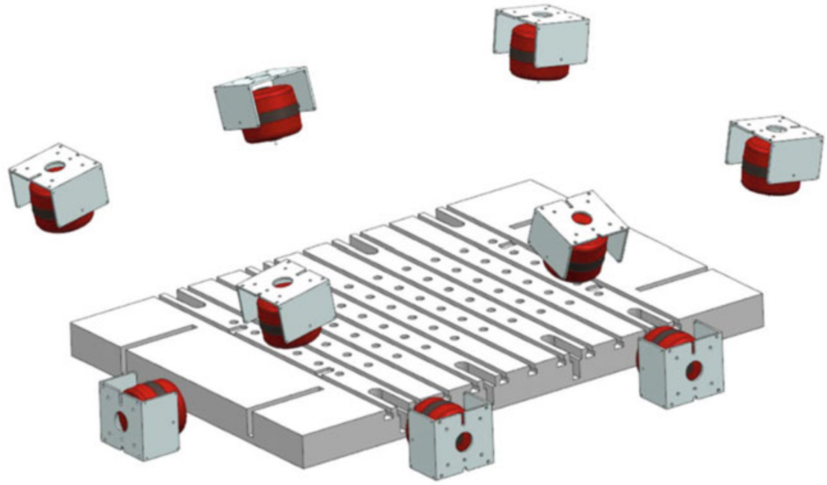


Fig. 12.2 Depiction of the six vertical and three lateral shakers attached to the T-slot table

Two additional shakers were attached to the TA for excitation of the TA modes. The shaker controller used was an EMX-1434 system driven by a custom MATLAB/IMAT™ software application. All 11 shakers were excited with continuous random vibration at three different levels. Impact data were collected at 25 locations on the MSS Aquila and at 9 locations on the T-slot table.

12.3 Shaker Data Analysis

The theory of the FBCM has been previously explained in multiple publications [3, 5, 8, 9]. This section focuses on the implementation of the method using the raw time histories collected from the shaker data. All data processing was performed using ATA's IMAT™ suite of MATLAB-based software applications. Upon completion of each run, FRFs were computed for the free test configuration to evaluate data quality. A complex mode indicator function (CMIF) was computed, shown in Fig. 12.3, to evaluate the overall modal behavior of the test system. In anticipation of utilizing the FBCM, a useful secondary data quality check is examining the antiresonances of the CMIF of the FRF matrix partitioned down to the DOF associated with the drive points (DPs) on the T-slot table, as shown in Fig. 12.4. If structural modification using FRFs (SMURF) [1] was used to calculate FB FRFs directly from the DP accelerations, this subset of the FRF matrix directly shows the matrix inversion that would be performed. The antiresonances oftentimes become the resonances in the FB FRFs. Figure 12.4 provides a good example of the type of data quality needed for the calculation of clean FB FRFs.

Utilizing SMURF to calculate FB modes from the DP forces and accelerations only fixes those individual DOFs. Alternatively, CS can be used as references in the FRF calculation to remove additional dynamics of the T-slot table. Because the T-slot table is isolated from the floor with a soft-suspension system, the six traditional RB modes were used as the first six CSs. Additional CSs are calculated from the measured time histories with a singular value decomposition (SVD). For the MSS Aquila MST, three CSs were extracted from the time histories; these CSs are considered the first three flexible modes of the T-slot table. The FBCM requires one unique reference (excitation source) per CS. Table 12.1 shows the nine CSs extracted from the DOFs on the T-slot table. These CSs allowed for calculation of FB FRFs up to 100 Hz. To extend the analysis to higher frequencies, additional shaker references can be used to calculate higher-order CSs associated with the next flexible modes of the T-slot table. Rather than utilizing SMURF with CS FRFs, the following procedure was used to directly calculate the FB FRFs from the time-history data [7]:

1. Calculate the six RB modes of the T-slot table based on the test display model geometry.
2. Estimate RB time histories based on the response DOF time histories on the T-slot table.
3. Subtract the RB time histories from the original time-history data.
4. Perform an SVD of the remaining signal to obtain three flexible CSs.
5. Calculate CS time histories.
6. Calculate FB FRF utilizing the H_{SVD} method [11] with the following settings:

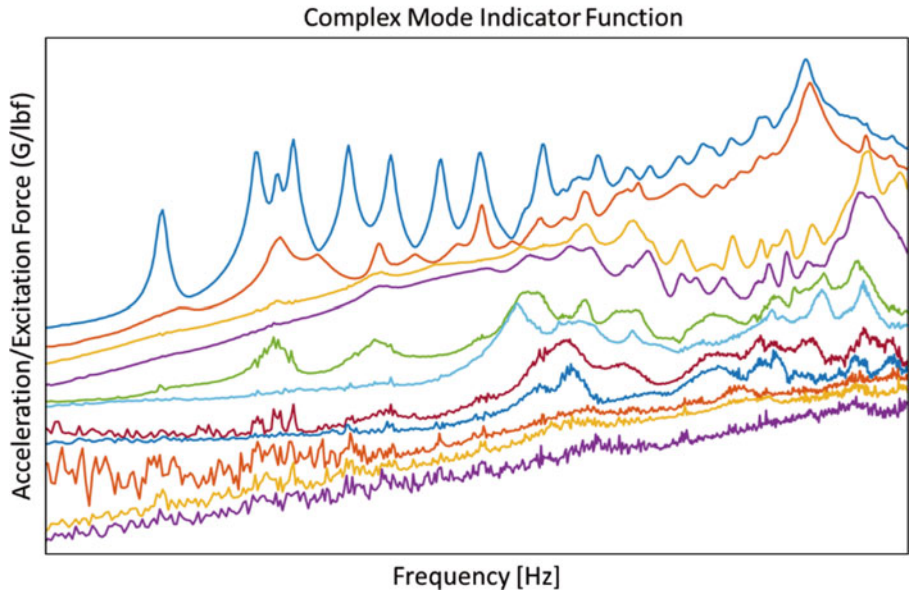


Fig. 12.3 Overall CMIF of free raw test data

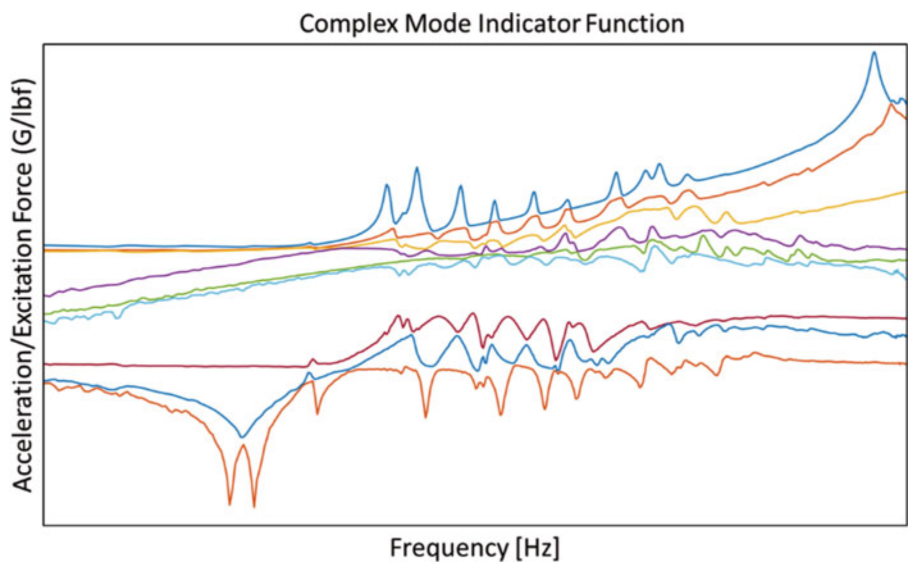


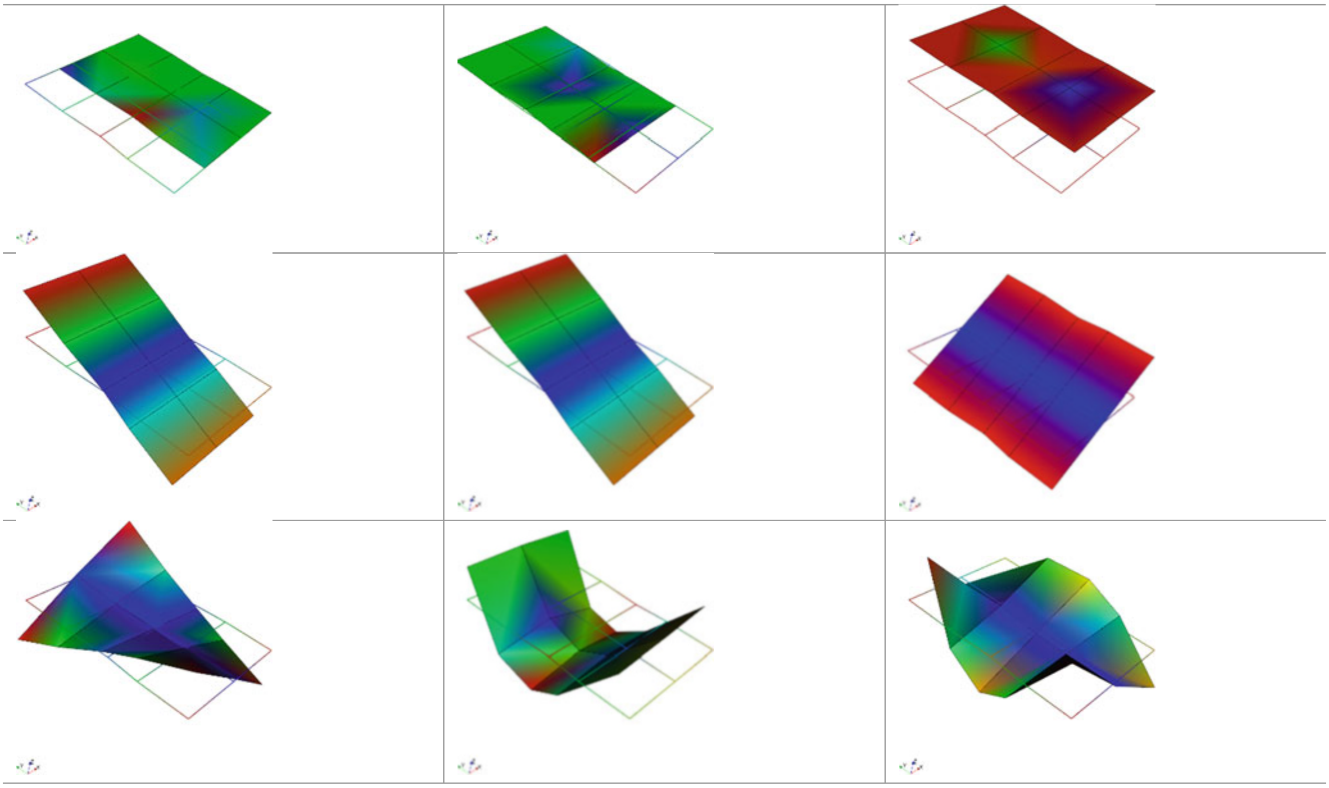
Fig. 12.4 Overall CMIF of FRF matrix inversion

- *References*: Two TA excitation forces and nine CS virtual time histories
- *Basis vectors*: Two TA excitation forces and nine T-slot table excitation forces
- *Responses*: Two TA DP accelerations, all response DOFs, and nine T-slot table excitation forces and accelerations

7. Calculate FB modes utilizing standard parameter estimation software.

Figure 12.5 shows a CMIF of the FB FRFs for the MSS Aquila. As previously mentioned, the antiresonances of the CMIF in Fig. 12.4 correspond to the resonances of the CMIF in Fig. 12.5. Mode shapes were extracted from the FB FRFs using ATA's IMAT modal parameter application OPoly™. Table 12.2 shows the first four extracted modes of the MSS Aquila. Visualization of the mode shapes indicates that the dynamics of the T-slot table have been removed. Although not included in this chapter, standard linearity checks can be made utilizing the FB FRFs for different excitation force levels.

Table 12.1 Summary of T-slot table CSs used for FB FRF calculation



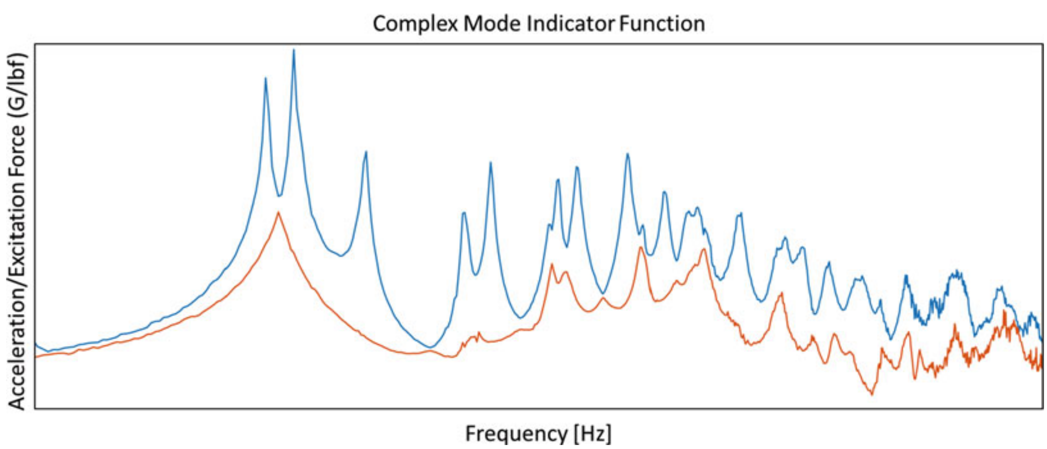
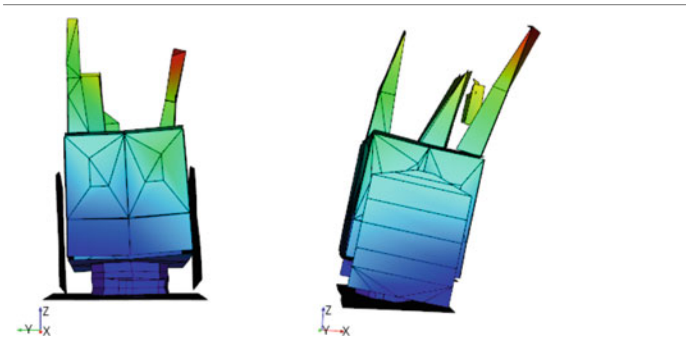
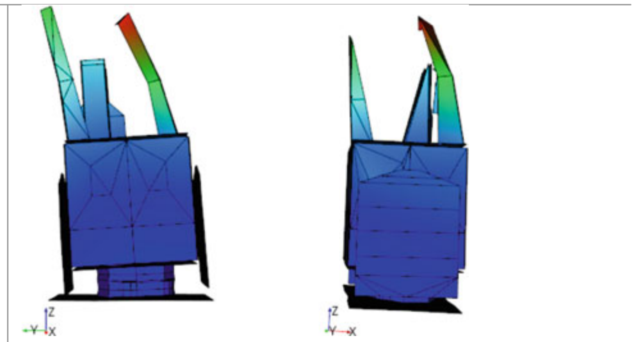
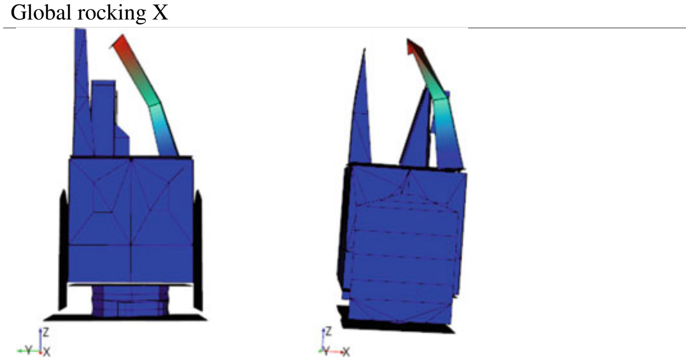
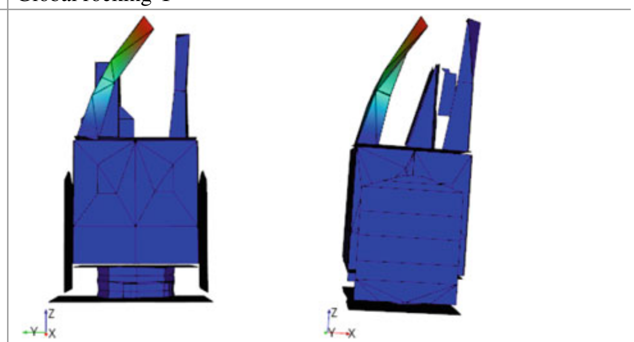


Fig. 12.5 CMIF of FB-corrected FRF matrix

12.4 Impact Data Analysis

For the MSS Aquila MST, the majority of the target modes were extracted from multipoint random shaker excitation, as discussed in the previous section. However, as with most MSTs, impact data were needed to supplement the shaker data to extract higher-order component modes. To illustrate the process of utilizing impacts with the FBCM, data from impacts on one antenna boom of the MSS Aquila are presented with the objective of extracting the second-order bending and torsion modes, which were not well excited with the shaker data. Impacts were made in two orthogonal directions on the boom as well as on the T-slot table in the same locations as the shaker references. The following process was used to compute FB FRFs and extract the component modes. All local component FRFs could be combined into a single matrix for processing.

Table 12.2 First four mode shapes of the MSS Aquila

	
Global rocking X	Global rocking Y
	
Boom 1 first bending	Boom 2 first bending

1. Calculate traditional acceleration/force FRFs for each impact location.
2. Combine all impact data into a single FRF matrix.
3. Use a partial inversion of the FRF matrix to calculate FB FRFs by moving the DP forces to responses and moving either a) the T-slot table DP accelerations or b) the CS DOFs to the references.
4. Extract modes for each component using standard modal parameter software using only the DOF on the component for the curve-fitting process for cleaner pole estimates.

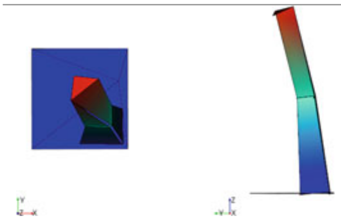
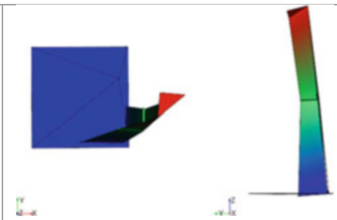
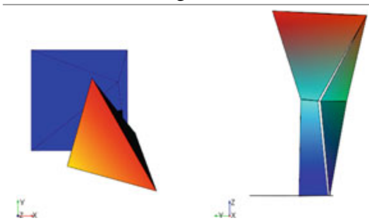
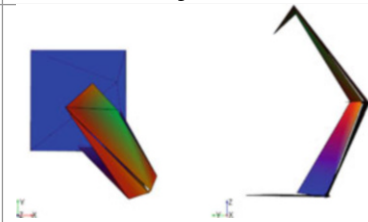
Table 12.3 shows the primary modes of one of the MSS Aquila antenna booms. The torsion and second bending modes were cleanly extracted from the impact data. Figure 12.6 shows the power spectral mode indicator function (PSMIF) for only the DOFs on the boom for both the uncorrected and the FB-corrected FRFs. As indicated by the PSMIF, shifts in the frequency of the first bending modes show the influence of the T-slot table dynamics. However, the higher-order torsion and second bending modes were not affected by the T-slot table dynamics and could have been extracted directly from the measured FRFs. This is typical of most MSTs, where higher-frequency (and low-effective-mass) local component modes are not affected by TA boundary condition.

12.5 Posttest Model Correlation

The final set of mode shapes for the MSS Aquila MST was compiled from a combination of shaker and impact data, as described in the previous sections. In total, 55 FB modes were extracted. Table 12.4 shows the cross-orthogonality matrix and summary table comparison between the FEM and FB test shapes at the conclusion of the test. In general, there is decent agreement with respect to shape orthogonality, but there is a significant frequency discrepancy, which indicates that a significant amount of stiffness was missing from the model.

The model updating process consisted primarily of introducing stiffness to the bolted connections throughout the model and updating simplified meshes of component joints to better represent the as-built component. Adjustments were also made to spring stiffnesses and mass moments of inertia to certain lumped-mass elements. Table 12.5 shows that there was significant improvement to the cross-orthogonality matrix and summary comparison table between the updated FEM and the FB test shapes. Typical correlation standards are for diagonal orthogonality values to be above 90%, for off-diagonal values

Table 12.3 Primary modes of antenna boom

	
First boom bending	First boom bending
	
Boom torsion	Second boom bending

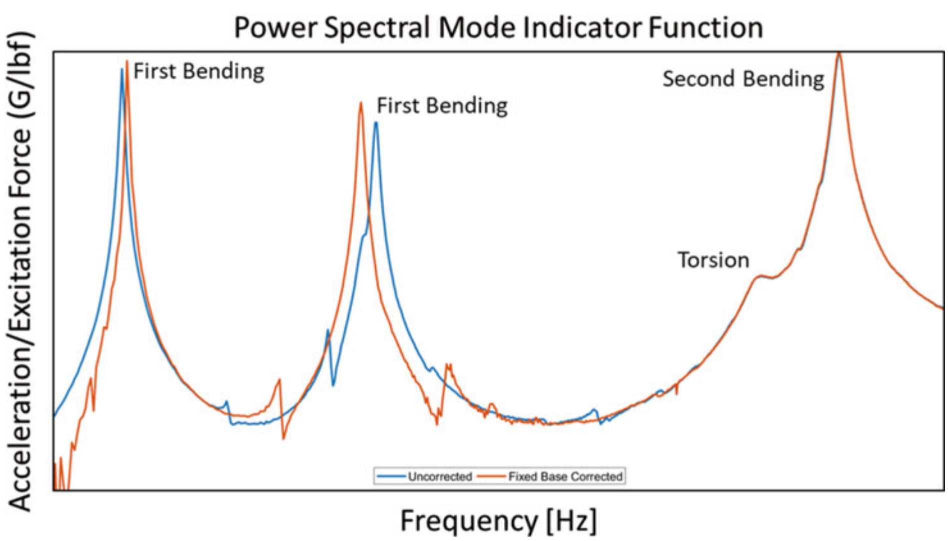


Fig. 12.6 PSMIF of impacts before and after FB correction

Table 12.4 Posttest cross orthogonality

FEM/Test Cross Orthogonality Table

FEM Shapes

Otg	Test S	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	3% CRSS
100	1	97									22									97
95	2		98																	98
90	3		21	98																98
85	4				25	96														99
80	5				93	26														97
75	6							67	63											67
70	7						97													97
65	8							87	44											87
60	9								35	91										91
55	10							24		25	47	91								92
50	11										68	28	49	52	34	35				72
45	12											20	77		43	37				81
40	13													35		69		25		69
35	14										28			42	22	48		50		52
30	15																		53	53
3%	CRSS	97	98	98	93	96	97	87	63	91	68	91	79	52	53	79	81	73	79	

90 - 100
50 - 89

Test Mode No.	FEM Mode No.	Freq Pct Diff	Cross Ortho	CRSS XOrtho 3%
1	1	-16.9	97	97
2	2	-17.2	98	98
3	3	-21.2	98	98
4	5	-22.8	96	99
5	4	-28.9	93	97
6	7	-19.4	67	67
7	6	-26.5	97	97
8	7	-24.2	87	87
9	9	-22.7	91	91
10	11	-17.1	91	92
11	10	-23.3	68	72
12	12	-22.1	77	81
13	15	-15.2	69	69
14	17	-11.1	50	52
15	18	-7.6	53	53

Table 12.5 Post-model-correlation cross orthogonality

		FEM/Test Cross Orthogonality Table																
		FEM															3%	90 - 100
Otg	Test	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	CRSS	50 - 89
100	1	99															99	
95	2		100														100	
90	3			100													100	
85	4				99												99	
80	5					99											99	
75	6						99		37								99	
70	7							98	24								98	
65	8						25		96								98	
60	9									97		20					97	
55	10									20	95						95	
50	11											96					96	
45	12												97				98	
40	13													90	33		97	
35	14													20	93	20	96	
30	15															97	97	
3%	CRSS	99	100	100	99	99	99	98	96	97	95	96	99	98	95	98		

Test Mode No.	FEM Mode No.	Freq Pct Diff	Cross Ortho	CRSS XOrtho 3%
1	1	0.5	99	99
2	2	-0.1	100	100
3	3	1.8	100	100
4	4	-2.7	99	99
5	5	-0.9	99	99
6	6	-1.1	99	99
7	7	1.7	98	98
8	8	0.0	96	98
9	9	0.8	97	97
10	10	2.8	95	95
11	11	1.2	96	96
12	12	0.2	97	98
13	13	1.9	90	97
14	14	0.8	93	96
15	15	0.4	97	97

to be below 10, and for frequencies to match within 5%. The results of the MSS Aquila FEM match all requirements for diagonal values, and frequencies match to within 3% for the first 15 modes of the structure. The remaining high off-diagonal terms in the matrix are associated with limitations on where sensors could be placed because the TA was flight hardware.

12.6 Summary

Overall, two primary conclusions can be drawn from the results of the MSS Aquila™ MST. First, ATA's PODIuM provided the portable FB support test setup, which resulted in a successful MST. Utilizing the PODIuM significantly reduced the schedule and cost compared to a traditional FB MST because it eliminated the need to either build a true FB boundary condition at MSS's facility or move the TA to a remote facility with an adequate boundary condition. Additionally, the correlation effort was focused entirely on the MSS Aquila FEM and not on the boundary condition – leading to improved model results.

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