Dynamic Characterisation as a Tool for Avoiding Vibration Related Problems

Ajay Kumar Panda, Asir Nesa Dass N, R. Balaji Srinivas, Arunkumar R, and M. Vasudevan Unni

Abstract In aerospace applications, mathematical models used for the dynamic analysis of launch vehicles are validated through dynamic characterization tests for better confidence in the models. The models are being used for flight critical studies; hence, the accuracy of the models in predicting the behavior of the system correctly is essential. This paper describes the dynamic characterization tests used for validating the mathematical model of the system from a dynamics point of view. In the paper, tests on three different test specimens with different requirements and different modes of testing are presented. The objective of the tests is to mainly obtain the frequency, mode shapes of the specimen, and get an estimate of the damping of the system, if required. The test methodologies are dependent on the test article configuration, which includes its material, overall layout, attachment points, etc. In the three test cases presented, the first test was an impact hammer excitation test carried out with the test specimen suspended with slings. In the second test case, the test was carried out by mounting it over the slip table of a high capacity shaker, and provided sine & random excitation through the shaker. For the third case, the specimen was fixed rigidly at the base, and excitation was carried out with small capacity shakers to estimate frequency response functions (FRFs) at various points.

Keywords Dynamic characterization · Mode shape · Modal analysis

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A. K. Panda (✉) · A. N. D. N · R. B. Srinivas · A. R · M. V. Unni
ISDTF/SDMG/STR, VSSC/ISRO, Trivandrum 695022, India
e-mail: ajaykpanda@gmail.com

A. N. D. N
e-mail: n_asirnesadass@vssc.gov.in

R. B. Srinivas
e-mail: r_balajisrinivas@vssc.gov.in

A. R
e-mail: r_arunkumar@vssc.gov.in

M. V. Unni
e-mail: m_vasudevanunni@vssc.gov.in

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1 Introduction

In aerospace and other critical applications, any new design or major modifications in the existing design of parts or assemblies has to be qualified through tests. The qualification tests include static, dynamic, acoustic tests, etc. In aerospace applications, dynamic test plays a major role in determining the flight worthiness of the test assembly. For airborne structures, the estimation of dynamic characteristics is necessary for updating the mathematical model, which can be used for response studies and digital autopilot design with full confidence. The present paper describes three test cases with different test objectives, different specimen configuration and material, and hence different test setup and procedures were adopted for extracting the dynamic characteristics of the specimens.

2 Test Case I

This section describes the dynamic characterization testing of a composite thin cylindrical structure that has undergone a modification in design. The objectives of the tests were (1) to obtain the dynamic characteristics like frequency, mode shape, and damping of the structure to be used for finite element model updating and (2) to verify the health of the structure after the static test to confirm structural integrity. Hence, tests were carried out prior to the structural test to obtain the pre-static test response and the same set of tests were repeated after the structural test for structural health monitoring.

2.1 Test Setup

The test article was a thin cylindrical structure made of composite material. The overall diameter of the structure is about 3000 mm and the height is about 1200 mm. Total mass of the test article was about 175 kg. On the aft end of the test article, a metallic ring was provided for additional stiffening.

Tests were carried out with free-free boundary conditions by suspending the article from crane through elastic chords. The free-free condition was preferred to eliminate the uncertainty of support stiffness. Figure 1 shows the test article in a free-free condition, with 4 elastic chords.

Impact excitation was used wherein the test article was excited using an instrumented hammer. Tests were carried out with the excitation at four locations, two on Fore End side and two on Aft End ring. The transfer function for all the response locations was determined with each of these impact locations as reference. The objective of multiple reference points is to have redundant measurements to enhance the confidence in the test results. After the tests, the Frequency Response Function

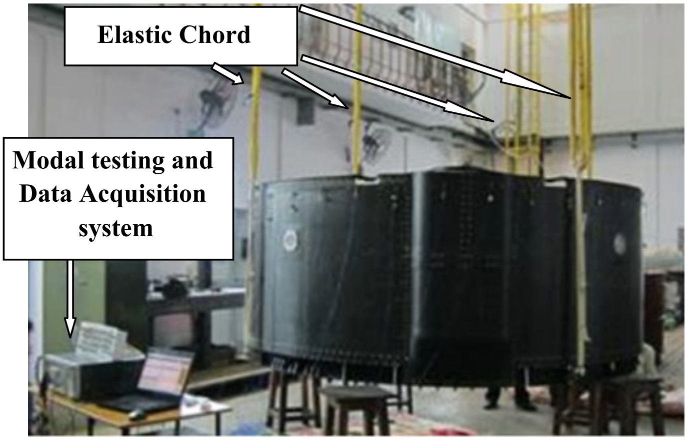

Fig. 1 Test article with suspension

(FRF) data obtained from all the reference locations were compared and the best FRFs were selected using the Modal Assurance Criterion (MAC). These FRFs were used for estimating the resonant frequencies and corresponding mode shapes. The bold dots in Fig. 2, show the four excitation locations. The arrows show the 4 planes along the height of the test article, where measurements were taken.

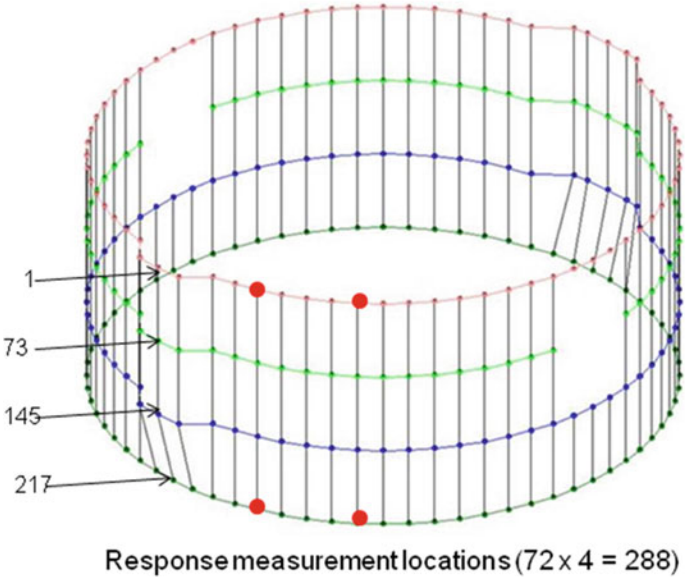

Fig. 2 Response measurement Locations and modal model [Case 1]

To effectively capture shell modes of such a large structure, response measurements were carried out using high sensitivity ICP type accelerometers having TEDS support. Figure 2 shows the response locations as grid points. Radial measurements were taken at four planes, with 72 measurements in each plane at 5° interval (Total 288 measurements).

From the measured input (force) and output (response), FRFs were computed. With 4 reference locations (impact excitation points) and 288 response measurements, $4 \times 288 = 1152$ FRFs were obtained. The FRFs corresponding to each reference location were separately analyzed using Modal Analysis Software for determination of the dynamic parameters, i.e., frequencies, associated mode shapes, and damping ratios.

2.2 Test Procedure

The tests were carried out in 2 phases to verify the structural integrity of the article. (i) Pre-static test dynamic characterization and (ii) Post-static test dynamic characterization. The test setup is shown in Fig. 1. The excitation was provided with an instrumented hammer with rubber tip and the transfer function for 288 channels with respect to each excitation location was recorded from 0 to 100 Hz, in each test. (these data were generated from 8 sets of tests with a 32 channel acquisition system).

The same procedure was repeated for the post-static test dynamic characterization and transfer functions with respect to the same 4 reference locations were obtained.

2.3 Data Analysis and Results

In data analysis, the first task was to select the best set of transfer functions to interpret the dynamic characteristics of the test article correctly. With more detailed analysis, the transfer functions with respect to location 9 were selected to be the best ones from satisfying MAC [1]. PolyMAX method of Frequency Domain Parameter Identification method was used for the analysis and frequency band of 1–100 Hz with a model size of 120 [1]. The stabilized poles were selected from the stabilization diagram which corresponds to the resonant frequency of the structure. The mode shapes and the damping were estimated for all the selected frequencies. The same method of analysis was followed for dynamic characterization after the static structural test, for FRFs with all 4 reference locations. The dominant and global modes were selected for comparison with the post-structural test results.

The pretest and posttest FRFs at location 40 were compared in Fig. 3. It shows a close match indicating no deviation in dynamic characteristics of the structure due to static load test.

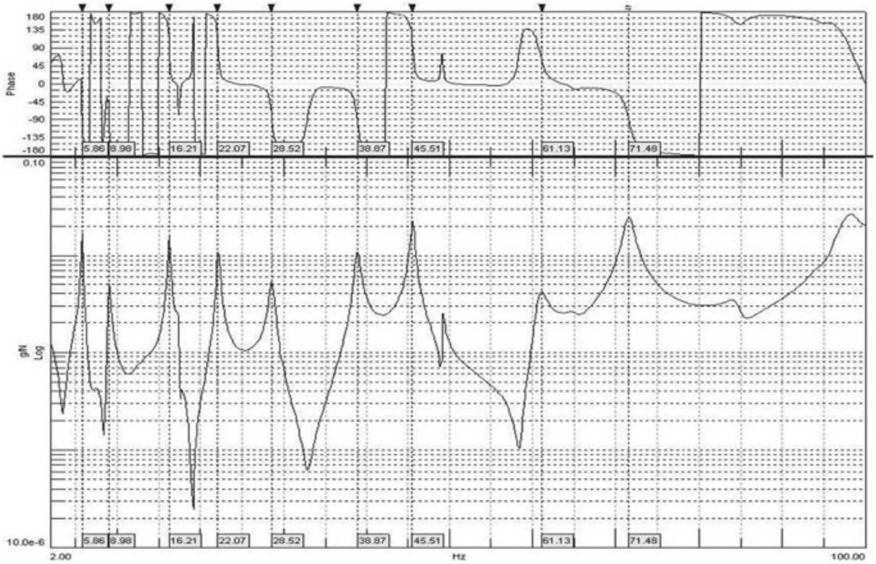

Fig. 3 Comparison of FRFs for pre-static and post-static test case (Location 40)

3 Test Case II

For multiple satellite missions, different configurations of adaptors were designed to accommodate and ensure the safe deployment of each satellite in their respective orbits without any collision. The mathematical model of the new adaptor was validated through dynamic characterization tests. The adaptor was made of the honeycomb structure. The main objective was to estimate the frequencies and mode shapes of the satellite simulator and masses mounted on the adaptor. Due to the honeycomb structure, impact excitation was not suitable for this specimen; hence the test was carried out by mounting it on a shaker and provide base excitation.

3.1 Test Setup

The test article was mounted on the slip table of an electro-dynamic shaker using a conical fixture (Fig. 4). Three triaxial accelerometers were mounted on each of the heavy masses, as well as satellite simulators. One accelerometer each is mounted at the base of these balancing masses and satellite simulators. Three accelerometers were mounted on the cylindrical portion in two perpendicular directions to identify both bending and torsion modes of the cylinder.

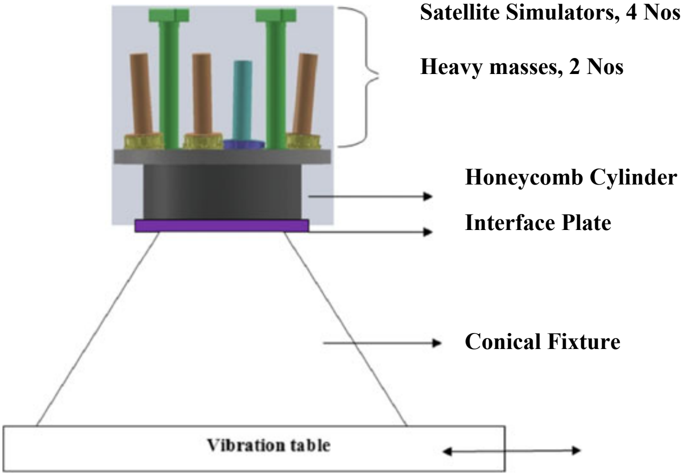

Fig. 4 Test setup (lateral axis)

Table 1 Test matrix for case II

Sine	5–200 Hz	0.1 g, 0.25 g
Random	10–2000 Hz	0.5 grms

3.2 Test Procedure

Low-level Sine and Random Tests were carried out in two lateral axes. The details of the tests were provided in the Table 1.

The data were acquired in a data acquisition system. Time and frequency domain data were acquired.

3.3 Test Analysis and Results

The results were analyzed and the modal properties were extracted from the test data and validated using modal validation methods. Control channel (input) was used as the reference for generating Frequency Response Functions, which were used to identify the modes. Typical FRFs were shown in Figs. 5 and 6, where a number of closely spaced modes can be seen. To distinctly identify each mode, mode shapes were generated using coordinates of the location and the FRF data. All the mode shapes were compared with finite element analysis results (a typical comparison of Mode shape as shown in Fig. 7). The difference clearly shows the importance of tests to validate and update the model if necessary.

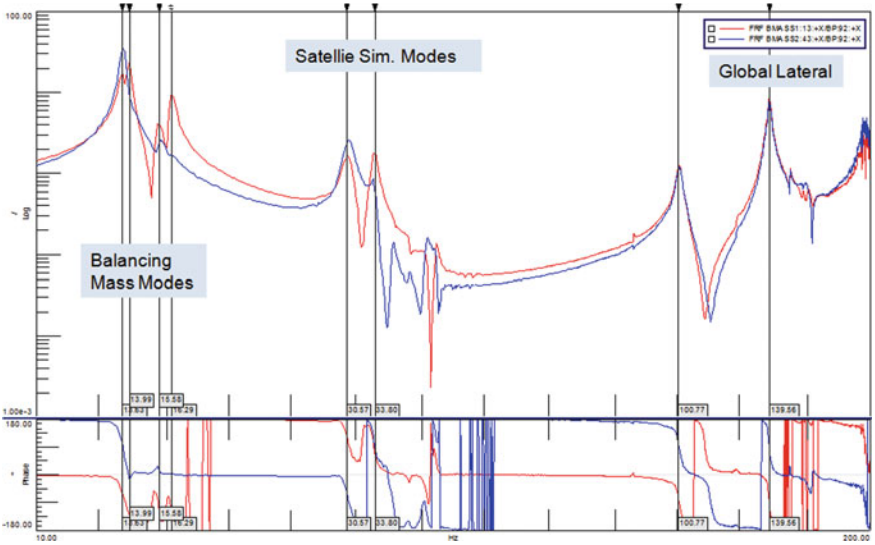

Fig. 5 FRF at a typical location (Tangential measurements)

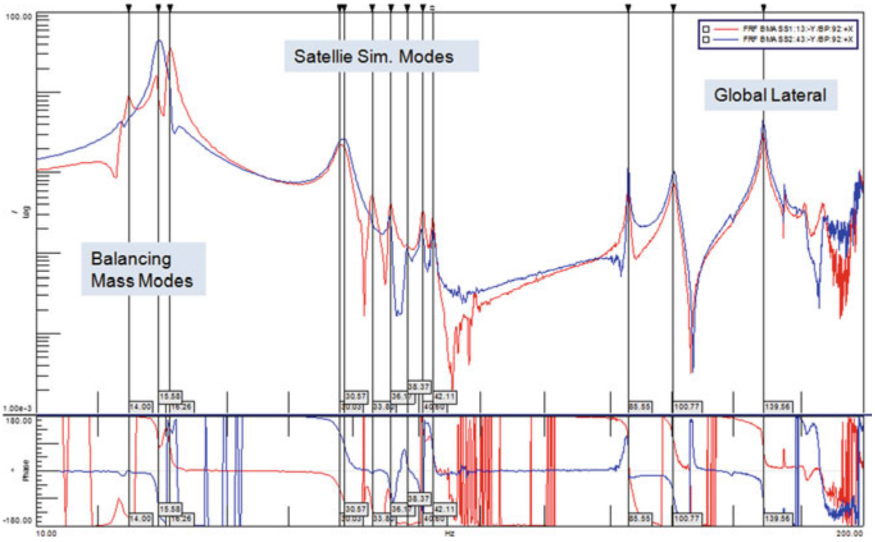

Fig. 6 FRF at a typical location (Radial measurements)

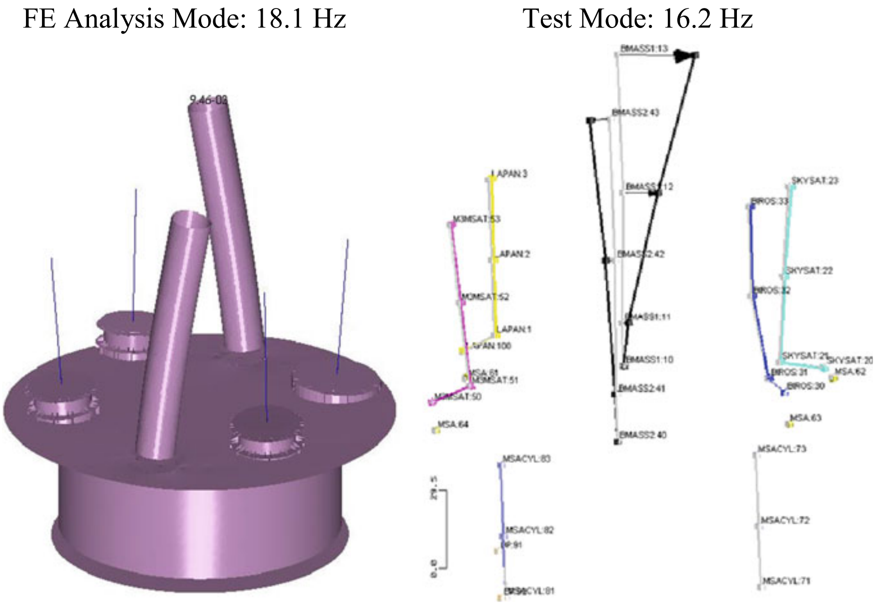

Fig. 7 Typical mode shape from finite element analysis and test

4 Test Case III

In this test case, the test article was a large structure that was designed as a gridded structure of honeycomb to keep the weight minimum. It was attached at the bottom to an adaptor which attaches this structure to the vehicle during flight. On top of it, the main satellite was attached through an adaptor. On the gridded specimen, three small satellites were mounted. Hence, the structure was critical for the flight point of view, and hence it's FE model has to be validated through dynamic characterization tests. The different options for excitation included either mounting on a shaker or using impact excitation through a hammer or exciting with small shaker while fixing it rigidly at the base. Impact excitation was not a good choice as the size of the subassembly was too large. Due to the lack of interfaces in large slip tables at smaller diameters, it cannot be mounted on large shaker systems. Also, due to heavier mass, small shakers cannot be used, and thus this option of using a shaker has been ruled out. Hence, it was decided to fix the subassembly at the base and excite it using small portable shakers for exciting all the required modes.

4.1 Test Setup

The specimen was mounted rigidly on a fixture to ensure minimum flexibility at the base. The base flexibility adds an uncertainty while matching the analysis results with the test results. On the top of the specimen, a satellite simulator with the same mass and moment of inertia as the satellite was attached to get a flight equivalent configuration. This was important to ensure that both the test and analysis represent the same configuration. The instrumentation locations were numbered as shown in Fig. 7. The measurements were carried out on two perpendicular directions to find lateral, as well as torsion modes. Triaxial measurements were also placed near the satellite simulators for each small satellite. ICP type accelerometers were used for the measurements. Three Small Shakers (200 N force rating) were used for exciting the specimen in axial, lateral, and torsion modes. The input force was measured using force gage connected between the rod connecting the shaker to the specimen (Fig. 8).

4.2 Test Procedure

Band -imited random excitation was used for the specimen from 5 to 100 Hz for the lateral modes and from 5 to 300 Hz for torsion modes estimation (Fig. 9).

4.3 Test Analysis and Results

The test results were analyzed and modal parameters were extracted using the good data. The frequency and mode shapes were compared with Finite element analysis and a good match was observed (Figs. 10, 11).

5 Conclusions

This paper provides details of the dynamic characterization of three different test specimens. In the first test case, a composite thin cylindrical structure was tested in a free-free condition. The pre- and post-static test results were compared and a good match in frequency and mode shapes was observed. This confirmed the structural integrity of the test article, which was later confirmed by NDT techniques also. In the second test case, a satellite adaptor was tested by mounting on a vibration table. By taking FRFs with respect to the shaker input (control channel) the frequency and mode shapes were obtained and compared with the Finite element results. The FE model was then updated to match the test results. In the third case, a gridded assembly of honeycomb structure was subjected to dynamic characterization tests using small

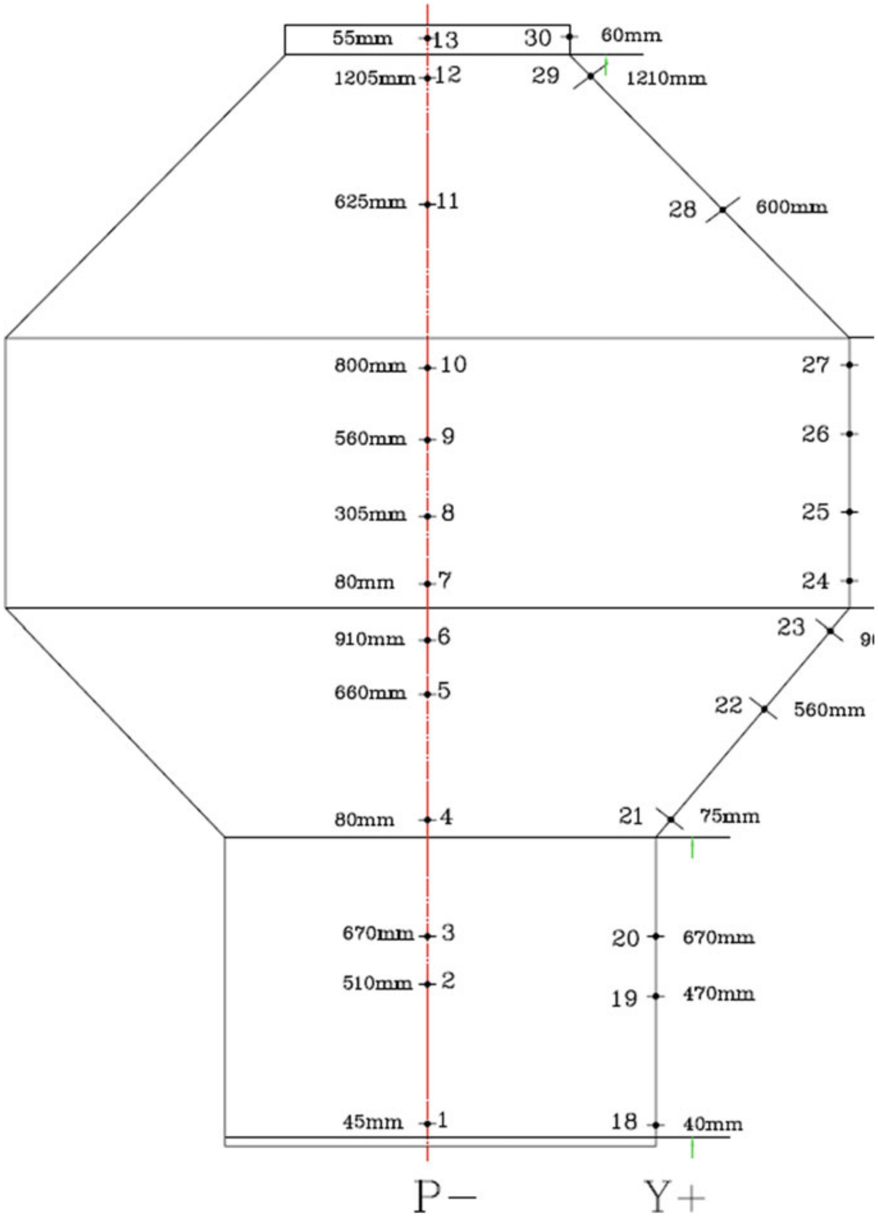

Fig. 8 Instrumentation for test case III

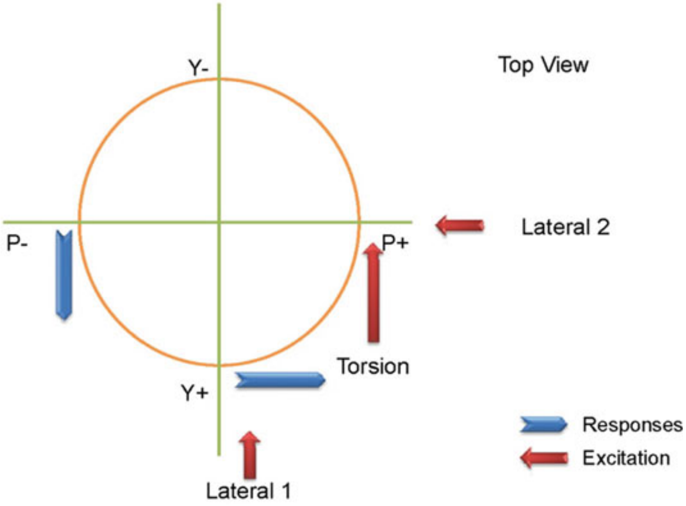

Fig. 9 Excitation for test case III

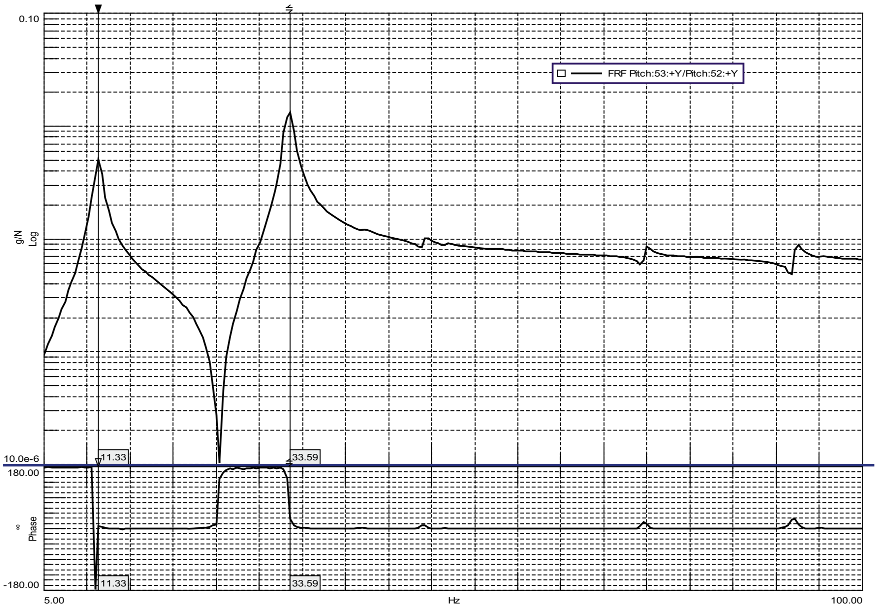

Fig. 10 Typical FRF for lateral excitation

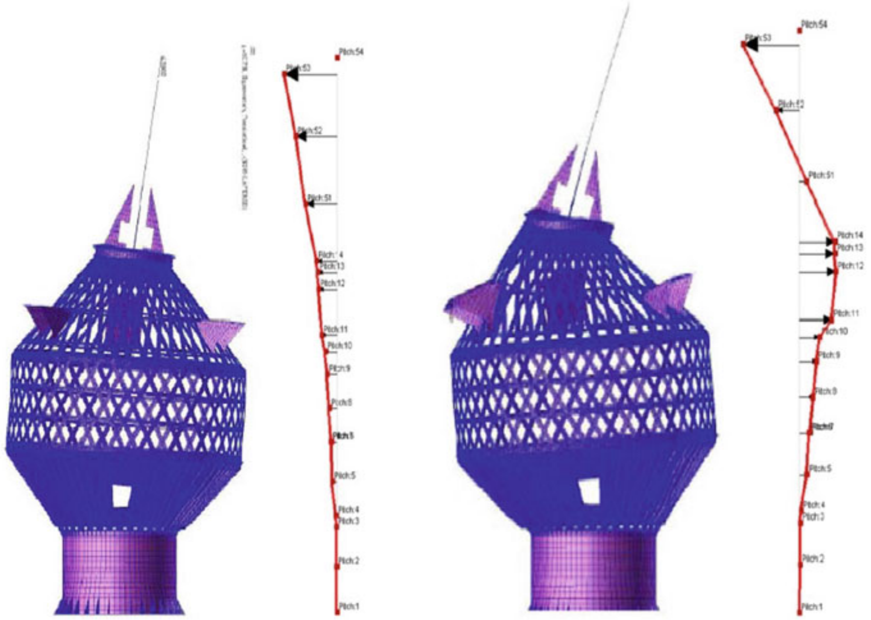

Fig. 11 Comparison of first and second bending modes (Finite Element and Test Mode shapes)

shakers suspended with cranes. The global frequencies, as well as frequencies of each small satellite branch mounting, were also estimated accurately. The test data was matching with the FE analysis after modifications.

As we have seen from the above three test cases, dynamic characterization tests can be effectively used to validate mathematical models, and these models can be used for all critical studies with confidence to avoid problems to the systems and assemblies by proper management before the actual flight/ground use.

Reference

1. LMS user manual, LMS international, 2010