Structural Dynamics Qualification of Space Exploration Rover Prototypes

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Abstract

The Exploration Core program of the Canadian Space Agency (CSA) has developed families of terrestrial prototypes of planetary rovers in view of future space exploration missions. This paper presents results and experience gained in performing modal testing on a JUNO rover. The modal testing consisted of two types of excitation: (i) Random excitation from two portable exciters, and (ii) impact excitation with an instrumented modal hammer. This paper investigates the applicability of impact testing for a complex structure such as the JUNO rover. It is demonstrated that impact testing is not an appropriate excitation approach for such a nonlinear test article. As discussed in the paper, data for the rover from impact testing are noisier than those from dual exciter and processing of the test data of a rover obtained from impact testing can lead to estimation of two closely-spaced modes when there is only one in reality.

1 Introduction

As discussed in the next section, an internal activity was initiated at the CSA under the Exploration Core (ExCo) program to investigate the structural dynamics and methods of structural qualification of a planetary flight rover. One of the tasks of this activity consists of performing modal testing of such a rover in order to extract its structural dynamics or modal parameters (resonance frequencies, damping values and mode shapes). Such test-based parameters can subsequently be used to help understand the rover structural responses in operating conditions and under the various critical dynamic environments that occur during flight. These modal parameters will also be used to validate the finite-element (FE) model of the rover. The test-based validated FE model will then serve for qualification purposes at both system and component levels. At system level, the model will predict the margins within the rover to qualification requirements imposed by the spacecraft organization. At component level, the rover FE model will define the requirements at the component interface to be passed on to organizations responsible for the numerous components of the rover.

Since no Canadian flight rover exists presently, the first modal test campaign was perform on a JUNO rover, one of the families of the CSA terrestrial prototype rover fleet [1]. This type of rover was selected because of (i) its availability (Five rovers compose the JUNO fleet), (ii) its structural characteristics are relatively close to a possible future flight rover and (iii) its relative simplicity as opposed to some other types of rovers within the CSA fleet.

The test results and experience presented in the present paper are complementary to those described in a previous paper [2]. The IMAC paper contains the estimated test-based modal parameters of the rover and mast assembly from modal tests performed using two portable exciters simultaneously at different locations/directions. It also describes the modal tests with an exciter performed on the rover without the mast in order to extract the rover modes; it explains why the estimation of these rover modes were so critical in subsequent extraction of the modes associated with the mast.

This paper first provides an overview of the internal investigation activity on rover qualification and the context in which it was initiated. It also describes the JUNO rover (and its mast) selected for the first modal testing campaign. The paper then presents some details and results of the impact modal testing of the rover and mast assembly. These impact tests were performed right before the portable exciter tests of the same hardware. In particular, it is demonstrated that impact testing of a very nonlinear rover is not an appropriate excitation technique for different reasons discussed. Such conclusion will be useful for future modal testing of rovers.

2 Overview of CSA Rover Qualification Activity

Canada needs to better prepare for future space exploration activities which could see more International collaboration than in the past, taking into account shared exploration goals. Consequently, the CSA established the ExCo program to address the needs for technologies and capabilities in Canada for future planetary exploration missions. One of the major elements of the ExCo program is the Exploration Surface Mobility (ESM) Project, which has delivered families of ground prototypes of planetary rovers and payloads (Figure 1).

To be ready for a planetary exploration mission, a rover hardware qualification methodology and approach needs to be established. Canada has over 50 years of history of developing satellites and payloads and launching them into earth orbits. Over these 50 years, Canada has developed tremendous experience and expertise in qualification and testing of satellites and has no record of major failure. However, there still exist many challenges in how to qualify space hardware for planetary missions due to stringent mass budget requirement, harsh space environments, and complex mission phases. Even though Canada has developed payloads for Phoenix and MSL Mars missions, no Canadian planetary rover has ever been developed and launched.

An internal activity was initiated at the CSA under ExCo program to investigate the structural dynamics and methods of structural qualification of a planetary flight rover at both system level and component level with the ultimate goal of establishing structural qualification requirements for future Canadian rover missions. Within the framework of this activity, a set of tasks has been planned and is being executed, including:

- Rover modal and vibration testing;
- Rover field testing;
- Rover finite element modeling and analysis;
- Rover dynamic loads analysis.

3 Description of Rover and Mast Assembly

Each rover of the JUNO fleet has a rectangular hollow "U"-shaped main body (referred to as MainBody in future sections) that encloses all of the batteries and required operating electronics (avionics). The main body has a length of 124 cm and a width of 87 cm. The main body is composed of three sections: an avionics box at the rear and a battery box on each side. On this main body are mounted the two parallel drive gearboxes on which the electric motors are mounted between the wheels and their respective spindles midway along the extended segments of the "U"-shaped rover. Figure 2 presents an overview of the rover (JUNO-005) that was tested.

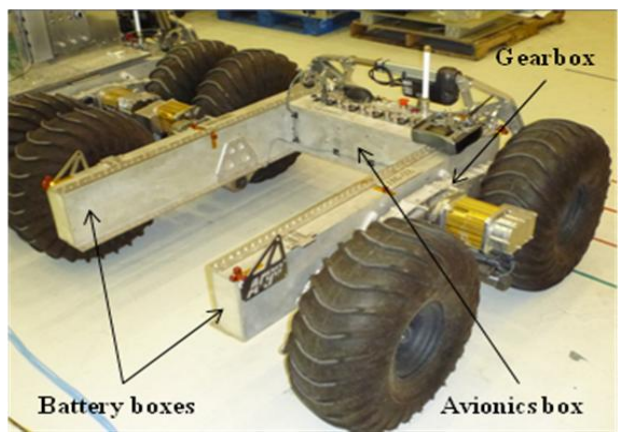

Figure 2. Overview of tested JUNO rover

A mast structure supporting navigational and scientific equipment can be attached to a JUNO rover (Figure 3). The mast is composed of two main components: (i) the "Pi" shaped support beam (PiStrut),

Figure 1. CSA ESM rover fleet

which is a 5.08 cm (2") diameter hollow stainless steel tubular structure leaning forward vertically from the back of the rover, and (ii) the support structure (Struts) made up of two parallel 2.54 cm (1") hollow stainless steel tubes supporting the mass of the PiStrut from the forward extended segments of the “U” to the upper portion of the PiStrut. Figure 3 shows an overview of the rover with its mast without any navigational or scientific payload.

Figure 3. Overview of rover and mast assembly

4 Modal Testing with Impact Hammer

4.1 Test Configuration and Instrumentation

Right before performing the modal testing with portable exciters on the rover and mast assembly for which the results are presented in [2], a series of impact modal tests using an instrumented hammer was performed. Such impact tests are very convenient since the setup time is minimal and the test itself can be performed promptly.

The assembly was instrumented with a total of 56 accelerometers mounted at 21 different locations. A geometric representation of these instrumented points is shown in Figure 4. As can be observed from the figure, only the upper surface of the rover was monitored. Of the total of 56 accelerometers, 21 were mounted on the main body of the rover and the remaining 35 were installed on the mast.

Two reasons explain why the majority of accelerometers were mounted on the mast. First, the impact and shaker modal tests were initially performed to investigate the concern that resonance within the mast was the prime contributor to the observed motion of the top horizontal tube of the mast while the rover was moving. Second, without any FE model available to predict the dynamic behaviour of the rover and mast assembly, it was thought that the mast modes would be among the lowest-frequency modes of the assembly. As discussed in [2], it turned out that the first seven modes of the assembly were rover modes and that only three of the first fifteen modes of the assembly were modes of the mast.

The total number of accelerometers mounted on the rover was selected based on the fact that the data acquisition system is equipped with a 32 channel front-end. Assuming two shakers are exciting the test article simultaneously requiring two channels for force measurement, 30 channels were then available for acceleration measurement for each test run. Consequently, for every excitation point, instrumenting the rover with a maximum of 60 accelerometers allowed the acquisition of all measurement data with only two different test runs.

Impact hammers for modal testing come with an integrated force sensor mounted on the striking end of the hammer head, in order to measure the force imposed on the test article during the impact. Figure 5 shows a picture of the hammer used for the present tests. One can see the force sensor which is the smallest portion of the cylinder hammer head. The tip is the part of the hammer that impacts the test article; the role of the tip is to transfer the force of impact to the sensor. The figure also distinctively shows the black tip which is the dark end of the hammer head; this soft tip is made of plastic. Changing the tip of the hammer (e.g. rubber, plastic, aluminum or steel) modifies the duration of impact (or pulse width) and thus frequency content of the excitation force. The white cable at the end of the handle connects the hammer to its power unit and the unit is connected to the data acquisition system.

Before performing the final runs of impact testing, some preliminary runs were done to define the following:

- Hammer size: Considering the mass of the test article, a much bigger hammer than the one shown in Figure 5 was initially used to excite the rover. These runs showed that the electrical channels of the accelerometers closed to the impact location were overloaded, unless very small impact motion was executed to hit the rover. Such small striking motion was difficult to control and reproduce. Proper hits of the rover without overloading the electronics with more normal amplitude of motion was found to be easier with the smaller impact hammer.

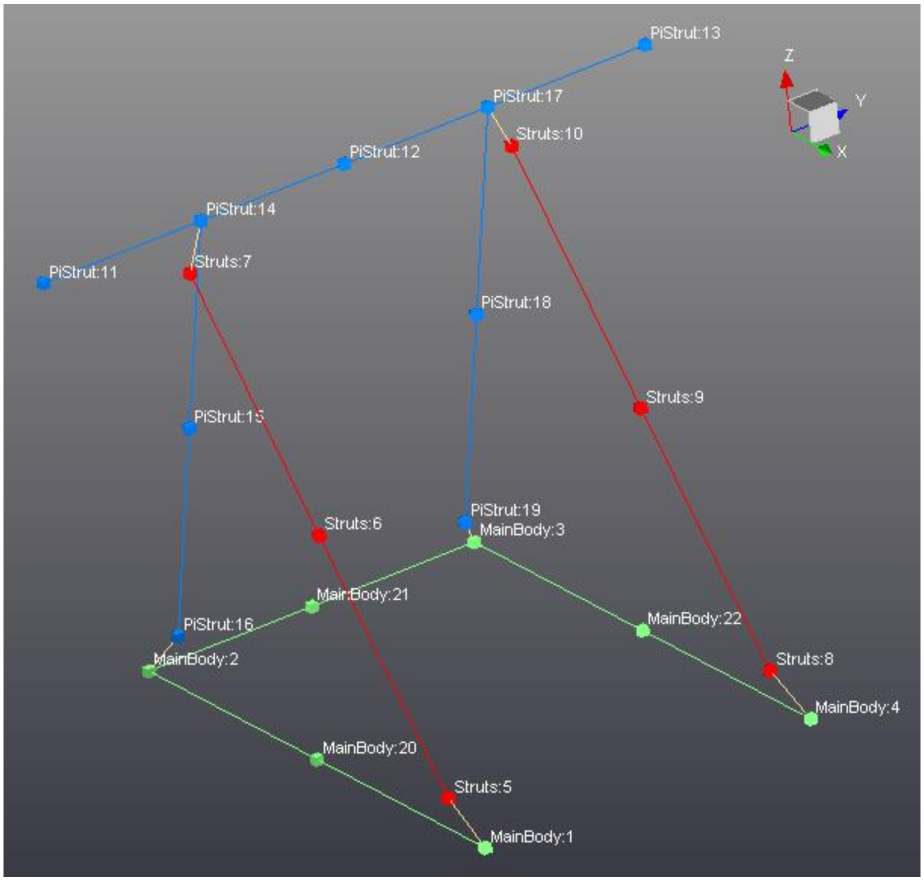

Figure 4. Geometric representation of the instrumented points for assembly testing

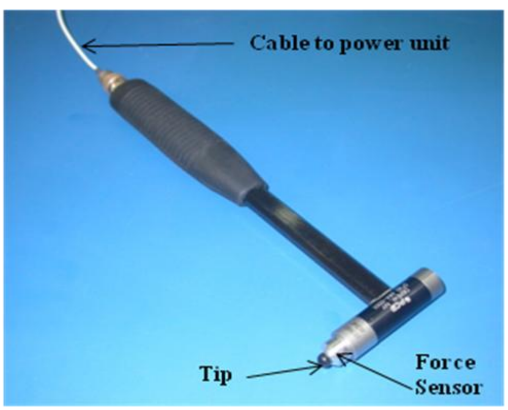

Figure 5. Instrumented modal hammer

- Type of tip: Various tip materials were tested before selecting the one found to be most suitable for the test article and the frequency range of interest. The selected material resulted in the upper limit of the usable frequency bandwidth of impact force to be more than 500 Hz, way above the maximum frequency of interest for the assembly. Harder tips result in higher frequency content of the force.
- Amplitude of striking motion: Proper amplitude of motion for hitting the test article was found by trial and error. One wants the force level to be sufficient for the resulting vibration to excite all accelerometers on the test article, without overloading the electronics. This exercise had to be done for each excitation point, before collecting the final formal data sets.
- Number of averages: For each excitation point, one performs several impacts in order to average out the noise in the measured data. It was defined through testing that five averages, a typical number, was sufficient for the present test situation. This implies that taking more averages did not significantly reduce the noise in the subsequently processed data.

As for any impact testing, the following difficulties had to be overcome while stricking the test article:

- Hit the structure exactly at the same location and with the same orientation to generate consistent data for the averaging process;
- Impact the structure with the same intensity for getting consistent data, especially in light of the rover being a nonlinear structure.

For collecting the final set of data, the rover and mast assembly was impacted at the seven locations/directions shown in Table 1. It should be noted that directions in the table are according to the orientation of local axis systems of the components being hit; these local systems are different than the global axis system presented in Figure 4. Collectively, these different locations/directions were considered to be sufficient to properly excite at least once all the modes of interest of either the rover or the mast. The two closely-spaced points (PiStrut:17 and Struts:10) were selected since it was considered before the tests that the structural joint separating them could dynamically behave in a nonlinear way.

Table 1. Excitation points for impact testing

Excitation number	Location	Direction
1	MainBody:4	X
2	MainBody:4	Y
3	MainBody:4	Z
4	PiStrut:17	X
5	PiStrut:17	Z
6	Struts:10	Y
7	Struts:10	Z

4.2 Measured Data

This section deals with quality of the measured data from impact testing and compare them with those from random excitation with two portable exciters. Only the information required to assess the quality of impact testing data is presented.

Using time-domain measurements from input force and response accelerations at instrumented locations, the data acquisition software computes a Frequency Response Function (FRF) (response acceleration/input force) for all combinations of input and response. Other useful frequency-domain functions are derived in this process, but these are not addressed in this paper.

The main observation that can be made about the derived FRFs from impact testing is that most of these FRFs for the accelerometers on the rover are noisier, when not much noisier, than their counterparts obtained with random excitation with two portable exciters [2].

This fact is illustrated with the data presented in Figure 6. The top portion of the figure shows the FRF from impact testing associated with the acceleration at MainBody:21:X and the impact at MainBody:4:Y. It should be noted that these FRFs are only zoomed portion up to 100 Hz of the measured data. The bottom portion of the figure shows the FRF from dual exciter testing associated with the acceleration at MainBody:4:Y and the exciter at MainBody:21:X. The software algorithm estimates which portion of the response acceleration is attributed to the exciter at 21:X, in order to derive the latter FRF. It should be noted that if these FRFs were coming from the same test and the structure was linear, these two FRFs should overlap according to the Principle of reciprocity, since their input and output points are related [3].

Two observations can be made by comparing these two plots:

- The FRF from impact testing is quite noisier than the FRF from random excitation of exciter testing. This can be partly attributed to the fact that impact testing has a poor peak to RMS ratio, while random excitation has a fair peak to RMS ratio [4].
- The peak portions, corresponding to resonances, of the FRF from impact testing are lower than their counterparts from random excitation. This could be attributed to the fact that deterministic energy from impact testing is more attenuated by the nonlinear portions (e.g. joints and mechanisms of the rover) than random excitation from the exciters. Also, as mentioned in [4], random excitation best averages out nonlinearities (i.e. provide the best linear approximation of non-linear systems) and impact testing can have problems with nonlinearities. In fact, such problems with their implications for the impact data and their derived modal parameters are presented in the next section.

Another explanation to the previous two observations is the relatively large distance between accelerometers on the massive rover (and its components) attenuating the impact pulse. Since the accelerometers had similar sensitivities, the level of impact applied was set by the accelerometers closest to the impact location in order not to overload their electronics. Consequently, accelerometers at more distant locations on the rover were forced to measure lower structural responses. On the other hand, dual portable exciters were generating more uniform vibration field throughout the rover. Consequently, accelerometers at various locations measured more similar levels of response.

FRFs associated with accelerometers mounted on the mast are less noisy than those on the rover. This may be explained by the fact that the mast was less massive and did not have any nonlinear joint or mechanism to attenuate the vibration from the impact. As an example, the top portion of Figure 7 shows the FRF from the accelerometer at the same end of the battery box as where the impact was input, while the bottom portion of the figure presents the FRF for the accelerometer on top of the mast on the opposite side at point PiStrut:14 (Figure 4). Although the peak heights are similar in both FRFs, the FRF of the accelerometer on the mast is surprisingly less noisy, despite the much larger distance separating it from the input.

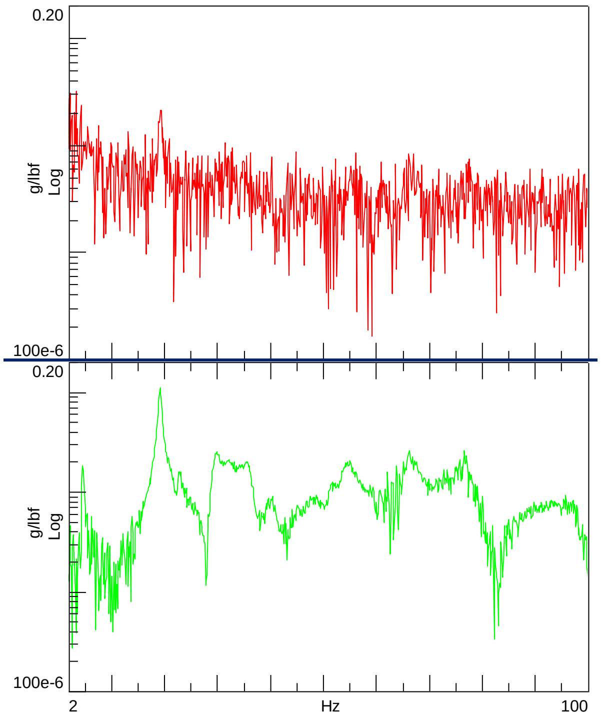

Figure 6. (Top) FRF for impact (21:X / 4Y), (Bottom) FRF for 2 shakers (4Y / 21X)

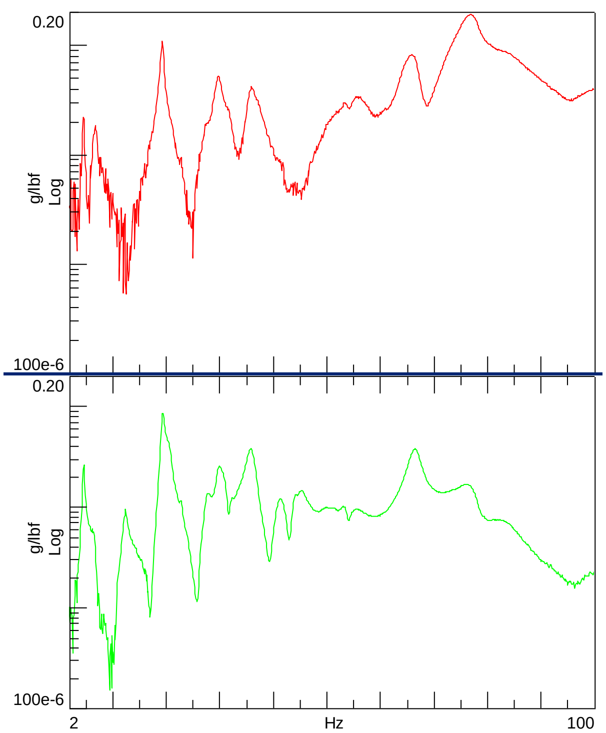

Figure 7. (Top) FRF for impact (4Y / 4Y) (Bottom) FRF for 2 impact (14Y / 4Y)

4.3 Estimation of Modal Parameters

By curve fitting the FRF data obtained from impact testing, the PolyMAX curve fitting algorithm estimated the modal parameters (resonance frequencies, damping values and mode shapes) of the rover and mast assembly. PolyMAX is the most advanced curve fitting algorithm available with the Modal Analysis module of the LMS TestLab program (version 11B).

The PolyMAX algorithm proceeds in two steps for parameter estimation: (i) Estimation of the poles (providing frequency and damping values) of the identified modes and (ii) estimation of the residues proportional to the mode shape coefficients at the instrumented locations of the test article. Because the FRFs of the accelerometers on the main body of the rover were usually so noisy for impact testing, the first step of the curve fitting process for pole identification was only applied on the FRFs of the accelerometers on the mast. It was observed that using these FRFs of the rover accelerometers for pole identification was complicating the process in generating pseudo-modes in the so-called stabilization diagram (a tool used by the user to select the modes) that had no relationship with real structural modes. However, these ignored FRFs were used in the second phase of the processing for the mode shape estimation.

For most of the modes in the frequency bandwidth of interest (up to 45 Hz), the modal parameters extracted from impact testing data were very similar to those obtained with testing the assembly with two exciters. Since the objective of this paper is not to report on the structural characteristics of the assembly, the reader is referred to Reference [2] for details of the identified modes for that frequency bandwidth. In fact, while the IMAC paper presents 14 assembly modes (including three mast modes) in that bandwidth, an additional mode has been extracted after writing that paper. This newly-identified mode of the rover is a torsion mode of the avionics box at 22 Hz.

The focus of this section is to present the type of issues observed in the extraction of modal parameters for the rover and mast assembly. Table 2 provides the frequency and damping values of a single rover mode that was clearly identified by exciter testing of both the rover by itself and the rover/mast assembly. Although the origin of this mode could not be completely identified (because only a few accelerometers were mounted in the vicinity of the deforming region), this mode was attributed to dynamics in the shaft attaching the gear box to the main frame of the rover. The corresponding mode shape of this mode is shown in Figure 8. Although this is much more revealing in the animation, one can still see that both battery boxes are vibrating, with the right one showing more displacement.

Table 2. Mode of assembly providing issues with impact testing at MainBody:4:Y

Single exciter test of rover by itself		Dual exciter test of rover/mast assembly		Impact testing test of rover/mast assembly	
Frequency (Hz)	Damping ratio (%)	Frequency (Hz)	Damping ratio (%)	Frequency (Hz)	Damping ratio (%)
36.1	2.6	35.3	2.0	35.8	2.3
				37.0	1.8

As shown in Table 2, instead of a single mode, PolyMAX extracted two closely-spaced modes in that frequency range when processing FRFs from the impact test with excitation at point MainBody:4:Y. The corresponding mode shapes are presented in Figures 9 and 10. It can be observed that more displacement occurs for the battery box at the right for the mode at 35.8 Hz, while the battery box at the left exhibit more displacement for the mode at 37.0 Hz.

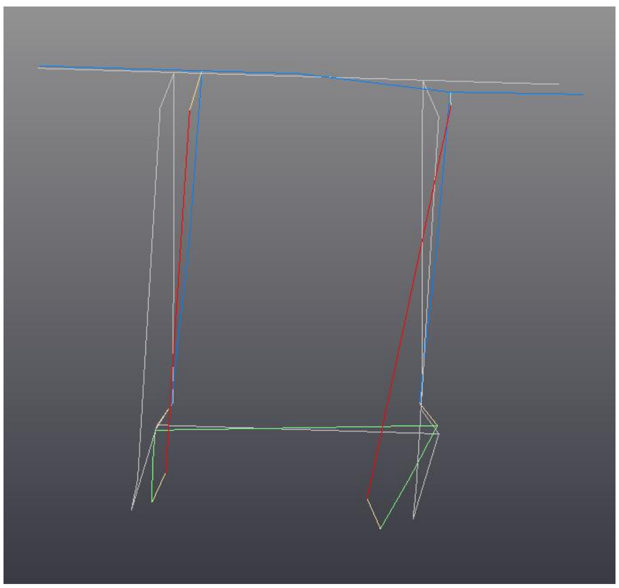

Figure 8. Mode shape for resonance at 35.3 Hz, from dual exciter test of assembly

The appearance of these two modes for what is a single structural mode can be explained by observing the overlap of the zoomed FRFs for locations 1Y and 4Y (Figure 11). As shown, there is a frequency difference of 1.3 Hz between peaks of the same mode for these two points on each side of the rover. This frequency shift from one point to the other is explained by the fact that:

- The resonance frequency of a nonlinear structure such as the rover is dependent of the vibration amplitude.

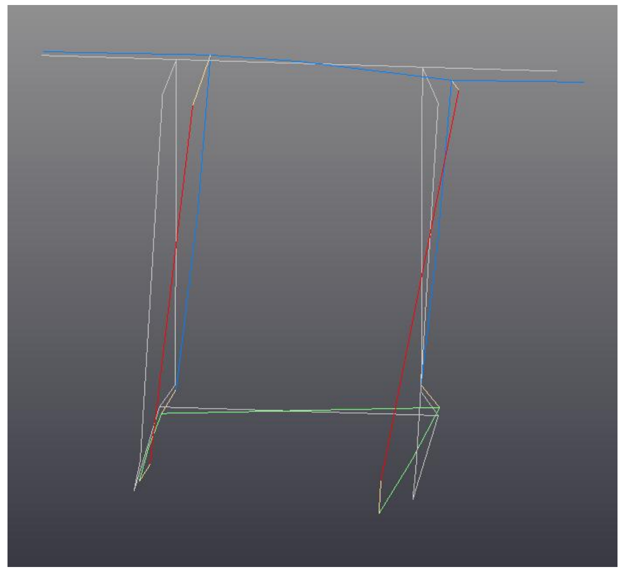

Figure 9. Mode shape for resonance at 35.8 Hz, from impact test at 4Y

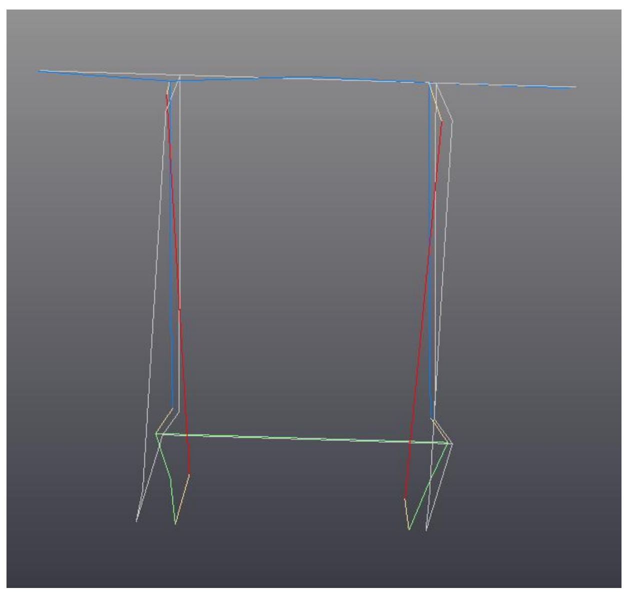

Figure 10. Mode shape for resonance at 37.0 Hz, from impact test at 4Y

- Hitting the rover at a single point on one side of the rover results in lower vibration on the other side, due to vibration attenuation throughout the structure. For the sake of comparison, for the dual-exciter configuration, the frequency separation between these two peaks for these locations is much lower, being only 0.4 Hz; this smaller frequency separation can be attributed to the two exciters generating a more uniform vibration field within the rover.

The same issue of 'resonance splitting' of a single mode for impact testing applied to the nonlinear rover was also observed for processing the FRFs from impact testing at Struts:10:Y and PiStrut:17:X.

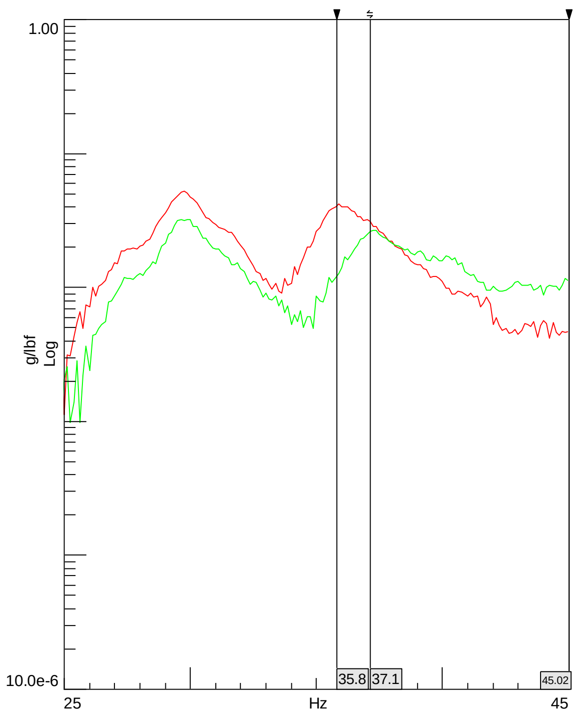

Figure 11. Overlap of zoomed FRFs showing frequency shift

5 Concluding Remarks

It is recommended that future modal testing of rovers be performed using at least two portable exciters simultaneously, instead of the alternative method of applying impact testing. This is especially important when the extracted test-based modal parameters are for validation of a FE model of the rover.

This recommendation is made in light of the two issues observed in performing impact testing on a JUNO rover, one of the families of the CSA terrestrial prototype rover fleet. The issues discussed in details in this paper follows. First, impact excitation at a single point results in noisier data from accelerometers mounted on the rover than data measured from a more uniform vibration field generated by exciting the structure with two portable exciters. Second, for a nonlinear structure such as a rover made up of joints and mechanisms, the less uniformly-distributed vibration from impact testing can result in a mode being measured at significantly different frequencies. As demonstrated in the paper, a large enough frequency shift from point to point can result in the curve fitting algorithm, as advanced as it might be, to extract two modes instead of one. Such a situation could obviously create issues if the purpose of test-based modal parameters is to correlate a FE model of the rover.

This recommendation does not preclude the use of impact testing for preliminary runs to define proper locations for exciter positioning or for troubleshooting.

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References

[1] E. Dupuis and E. Martin, "An Overview of Recent Canadian Space Agency Activities in Space Robotics", Proceedings of the 2012 International Symposium on Artificial Intelligence, Robotics and Automation in Space, Turin, Italy, 4-6 Sept. 2012.

[2] Y. Soucy and F. Brassard, "Modal Testing of Space Exploration Rover Prototypes", Proceedings of the IMAC XXXII Conference, Orlando, Florida, U.S.A., 3-6 Feb. 2014.

[3] D.J. Ewins, "*Modal Testing: Theory, Practice and Application*", Second Edition, Research Studies Press Ltd, Baldock, Hertfordshire, England, 2000.

[4] Anon, "Basic Modal Testing Analysis Seminar", University of Cincinnati Structural Dynamics Research Laboratory, 1984.