NSTF SHAKER COMMISSIONING USING RESONANT MASS DUMMY

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ABSTRACT

A new vibration facility has been built as part of the newly built National Satellite Testing Faculty at RAL Space. A resonant mass dummy was designed to commission shakers and verify their overturning moments to ensure they function as specified when the purchase was made.

When developing the commissioning plan for the newly installed shakers, it was determined that some form of dummy object was needed that was a robust and repeatable tool for the commission and shaker calibration. This object would be a means to prove the shaker worked as intended at high overturning moments. As development continued, it also became a tool to verify RAL Space's force measurement device.

1. INTRODUCTION

The National Satellite Testing Facility (NSTF) will be completed later this year. The NSTF has been built to address a facility gap in the UK, as there was no single location for full satellite testing [1]. The NSTF will allow thermal vacuum testing, electromagnetic compatibility, vibration and acoustic testing, as well as having two large clean rooms for assembly.

The NSTF represents a significant increase in the scale of spacecraft testing that RAL Space STFC can perform to ensure that the facility is ready for customers (both the hardware and personnel). Extensive commissioning work that goes beyond the Site Acceptance Test (SAT) for the different pieces of hardware will be done.

This paper describes the work that has gone into planning the commissioning for the vibration facility of the NSTF. This commissioning includes the design of a resonant mass dummy (RMD) to allow for dynamic verification of the shakers and the force measurement device (FMD) designed for the facility.

Commissioning is two-sided – the first is to ensure the hardware functions as expected and achieves the design goals (crucially, the overturning moments). The second is to provide the personnel are suitably trained in operating all systems.

The vibration facility of the NSTF is made up of two shakers, each capable of producing 222kN of thrust. Both shakers are set into the floor of the Dynamics Hall so that the interface surface is flush with the floor. The vertical rig has a shaker set deep in a pit with a large head expander on top and is designed to have an overturning moment of 160kNm, as shown in Figure 1.

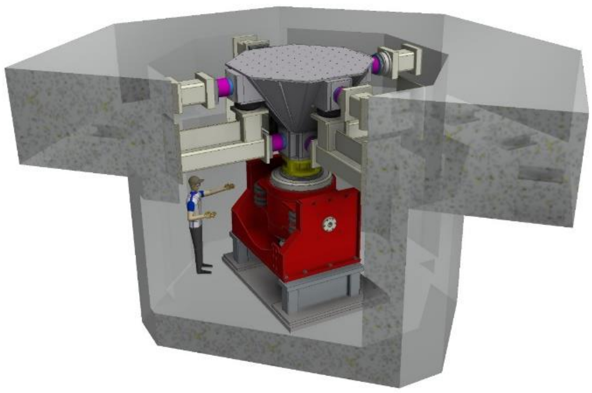

Figure 1: Cross Section of the Vertical Shaker System

The second shaker is the horizontal rig. It can accommodate two sizes of slip tables, and with the larger slip table (approximately 2m x 2m working area) is designed to have an overturning moment of 400kNm, as shown in Figure 2. In addition to the horizontal configurations, this shaker can be turned to operate as an unguided vertical shaker.

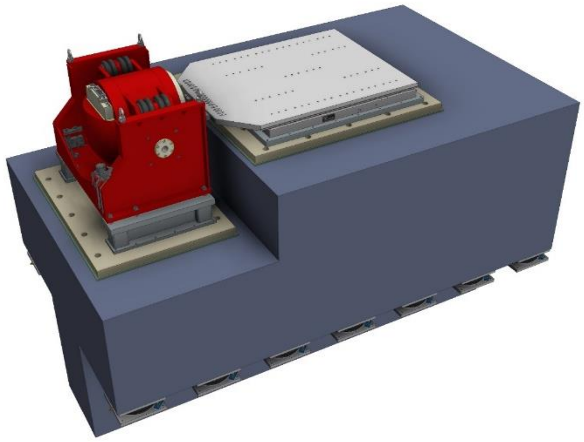

Figure 2: Horizontal Shaker System

The capacities for each system are shown in Figure 3, showing the broad range of sizes and acceleration levels the NSTF vibration facility can achieve. The key value is that the two primary systems can test up to 7 tonne satellites to levels over 2g.

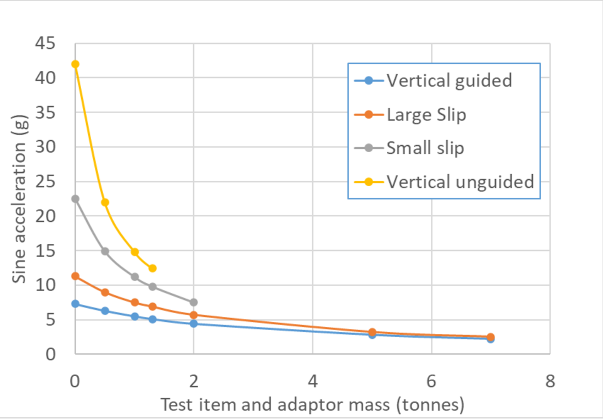

Figure 3: Maximum Sine acceleration, in g, versus mass for each shaker system

2. DESIGN OF RESONANT MASS DUMMY

The RMD was developed to aid the commissioning of the vibration facility. The use of mass dummies to test and verify shakers has considerable heritage [2] [3] as well as for validating FMDs [4].

At the start of the design process, the RMD had to achieve numerous requirements. Key among them was that the RMD should mimic a full-sized satellite with respect to size, mass and first two modes. Additionally, it needed to be able to achieve close to the shakers' specified overturning moments during a sine sweep test. Finally, there were practical requirements regards to transportation and storage.

Satellite manufacturers were contacted to provide typical resonant properties of large satellites. This review led to the design criteria regarding the RMD 'mimicking' a satellite. The mass was required to be at least 4000kg. The first lateral mode should be between 12-20Hz, and the first longitudinal mode should be above 27Hz.

The shaker overturning moments were set as part of the purchase of those systems, with the values set based on projected large satellite mass properties. The maximum required moment on the horizontal system (slip table) is 400kNm in both pitch (about the Y axis) and roll (about the X axis). The maximum required moment for the vertical system (head expander) is 160kNm in both pitch and roll.

A tube design mimics the central tube found in many commercial satellites. This design was divided into four segments to allow for ease of storage and multiple configurations. The second was crucial as only two segments are needed for the slip table commissioning. The whole four segment setup is shown in Figure 4.

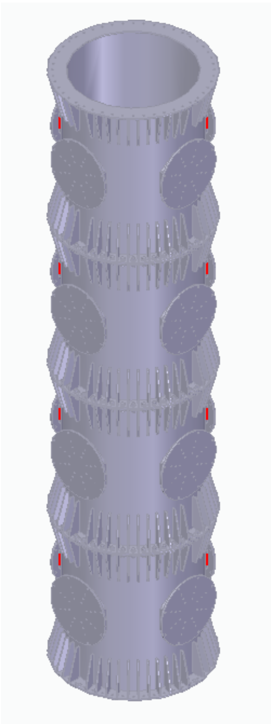

Figure 4: RMD Design made up of four segments

The RMD has been manufactured out of stainless steel 316 to ensure adequate stiffness and mass. Figure 5 shows one of the manufactured segments. Each segment of the RMD has a height of 1.395m, a diameter of 1.34m, and a mass of 669kg. When all four segments are connected, RMD has a total mass of 2676kg and a height of 5.58m. Additionally, each segment has attachment points on it for facility dead masses (432kg each). When all four dead masses are attached, the RMD has a total mass of 4404kg.

Figure 5: Manufactured RMD Segment

The first lateral mode of the entirely constructed RMD, without added masses, is 21.8Hz, and the first longitudinal mode is 91.2Hz. The first mode is just out of the desired range, but it was decided to accept the compromise as the design fits the other criteria. Figure 6 shows the first mode shape of the RMD.

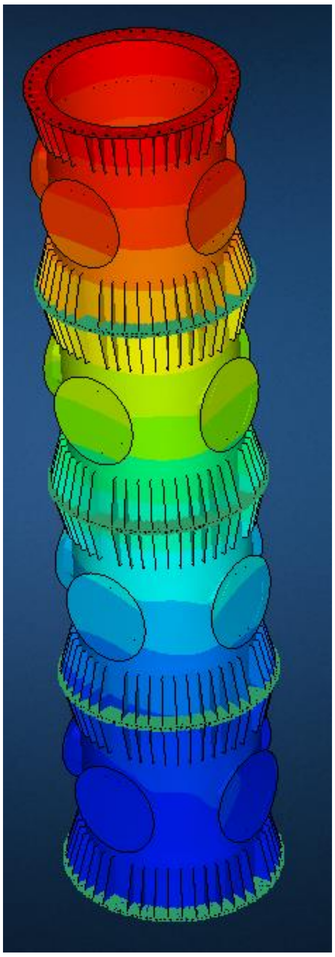

Figure 6: First Mode (Lateral bending) of RMD at 21Hz

3. DESIGN OF FORCE MEASUREMENT DEVICE

Another critical system that is part of the NSTF dynamics facility is the force measurement device (FMD). This FMD will allow force vibration limiting testing (FVLT) to occur. FVLT is where the vibration test is limited, i.e. the acceleration input levels are reduced due to the forces at the base of the test item [5]. This limiting ensures that the test item is not excessively stressed during the vibration test [6]. The potential for this excessive testing comes from the mismatch between the test item's connection with the shaker (an extremely stiff structure) and the connection with the launcher or higher-level assembly [7].

The FMD is comprised of a series of force links (FL) which are a specialist type of force sensor (Kistler Type 9377). To measure the imputed force, transducers use slices of a quartz crystal to translate the force into a signal in terms of charge, measured in pico-coulombs (pC). A charge amplifier can then transform the pC/N signal to a V/N signal that data acquisition (DAQ) equipment can read. As a triaxial signal is commonly needed, the quartz slices must be put under a high preload to counter the effect of slipping and shunting. This preload is usually achieved by a preload assembly of the adapter. However, purchasing the force sensors as FLs, which come preloaded between two attachment blocks, is often more convenient.

Due to the size of expected test items in the NSFT, the FMD comprises 12 FLs to ensure that none of the individual FLs are overloaded. In addition to the FLs, two ring plates keep the alignment of the FLs. This assembly is shown in Figure 7.

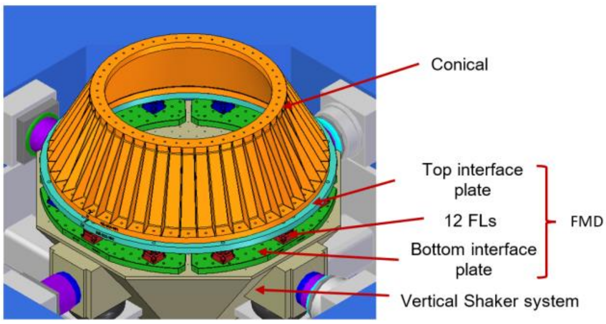

Figure 7: 12 FL FMD on the NSTF Vertical system

With this increase in FLs, the ability to derive moments from the interface plain becomes possible. Using the positions of each FL and the loads in x, y and z directions, moments can be derived by subtracting one side from the other around each axis.

The orientation of the FL around the FMD is critical as they directly influence the moment equations;

therefore, appropriate care must be taken in numbering the FL. Figure 8 shows a diagram of the FMD setup along with the directions of the forces and moments. The total forces are calculated by summing the individual components, as shown in Eqs. 1-3, and the total moments are calculated as follows in Eqs. 4-6.

$$F_{x_T} = \sum_{i=1}^{12} F_{x_i} \quad (1)$$

$$F_{y_T} = \sum_{i=1}^{12} F_{y_i} \quad (2)$$

$$F_{z_T} = \sum_{i=1}^{12} F_{z_i} \quad (3)$$

$$M_x = \sum_{i=1}^{12} R sin(\alpha_i) F_{z_i} \quad (4)$$

$$M_y = \sum_{i=1}^{12} R cos(\alpha_i) F_{z_i} \quad (5)$$

$$M_z = \sum_{i=1}^{12} R(\sin(\alpha_i) F_{x_i} + \cos(\alpha_i) F_{y_i}) \quad (6)$$

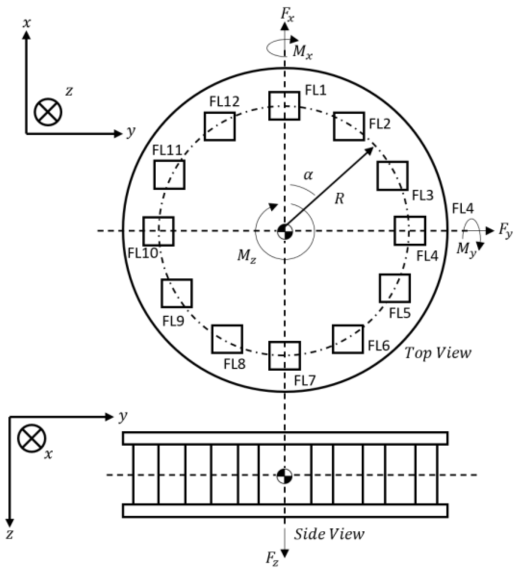

Figure 8: FMD setup with the FLs coordinate system

The coordinate of the FLs has Z pointing down because that is the direction in which it sees the Z force. It is a relatively simple matter to adjust the coordinate system in the software to ensure the outputs from the FMD align with the test item's coordinate system.

4. COMMISSIONING PLAN

The commissioning of the NSFT shakers has been broken up into four stages. The first is to verify the finite element model of the RMD by performing a modal analysis using a force hammer. The second stage is to repeat the tests that made up the shaker manufacturer's site acceptance tests (SAT). The third stage is the verification of the FMD. The fourth and final stage is to use the FMD and RMD to dynamically check the overturning moments of the shakers. As there are two shakers, these four stages will be performed first using the horizontal (slip table) shaker before stages two through four are repeated on the horizontal shaker.

4.1. Modal Analysis of RMD

The first stage in the commissioning plan is to verify the modal of the RMD. This will be done using an impact hammer. It is crucial to ensure the FEM of the RMD is correct before running the sine sweeps to check the overturning moments. Therefore, rather than running a LLS, an impact hammer is used to perform the modal analysis concurrent to the shaker manufacturer's performing the final checks and SAT.

The RMD will be instrumented with numerous accelerometers before being subjected to various strikes of the impact hammer. Once all the tests have been performed, the data will be analysed and compared to the FEA. The FEM of the RMD will then be adjusted to produce results that match as closely as possible the test data.

4.2. Repeat Shaker SAT

The next stage is to re-run the shaker manufacturer's site acceptance test (SAT). These are a series of sine and random test runs with just the bare table before adding the four dead masses. These tests are not expected to be complex regarding setup and results and are being run to ensure NSTF personnel get the same results at the shaker manufacturer. This stage is primarily a test of the training received than a test of the shakers.

4.3. Verification of FMD

The following stage is the verification of the FMD. This stage starts with installing the bottom interface plate before installing the 12 FLs. Once installed and connected to the DAQ and the shaker control accelerometers, a low level sine (LLS) test of 0.1g is performed between 5-50Hz. This LLS checks that all FLs are set up correctly, both mechanically and within the software.

Next, the top interface plate is attached to the FLs. Another LLS of 0.1g from 5-50Hz is performed to verify the FMD has been correctly assembled. Checks will also be done to ensure that the forces are distributed as evenly between the FLs as possible.

The final step is to attach the conical adapter before running a final LLS of 0.1g from 5-50Hz. Then, a last check will be performed to ensure the FLs are set up correctly both mechanically and in the software and check the distribution of the forces, which should be more evenly distributed with the added mass.

4.4. Dynamic Check of Overturning Moment

The final stage will be to verify that the shakers can withstand the specified overturning moment. The specification of the overturning moment capacity of the shakers was specified over a 5-2000Hz sine sweep. For the horizontal shaker, this was specified with a flat 1g input, while for the vertical shaker, it was specified with a flat 1.41g input.

Figure 9 shows the coordinate system of the RMD FEM and the shakers. The horizontal shaker vibrates along the X axis, while the vertical shaker vibrates along the Z axis.

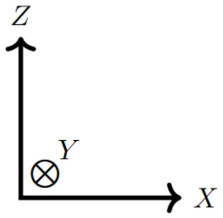

Figure 9: Shaker and RMD coordinate system

For the horizontal shaker, this check will be done using just two segments of the RMD on the slip table. This sine sweep should reach a maximum moment of 365kNm, as shown in Figure 10. The moment is about the Y axis of the shaker and RMD.

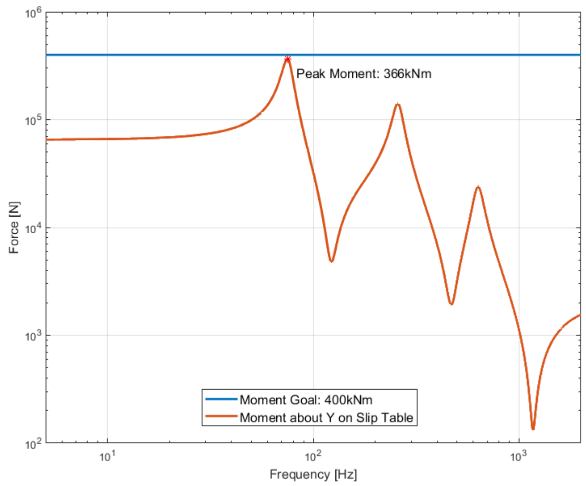

Figure 10: Moment about Y created by RMD during Slip Table Shaker Test in X direction

The vertical shaker will use the four segments along with two dead masses. For the overturning moment about X, the dead masses will be attached to the bottom segment on the -Y side and +Y side of the top segment. Then on -X side on the bottom segment and +X on the top segment for overturning moment about the Y axis. Both tests should achieve a maximum moment of 133kNm, as shown in Figure 11, for the moment about the X axis. Then Figure 12 shows the moment about the Y axis for the vertical test.

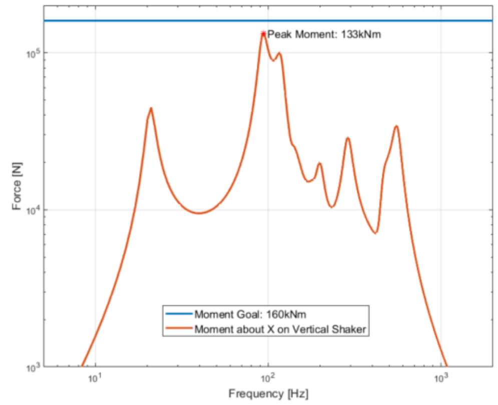

Figure 11: Moment about X created by RMD during Vertical Shaker Test in Z direction

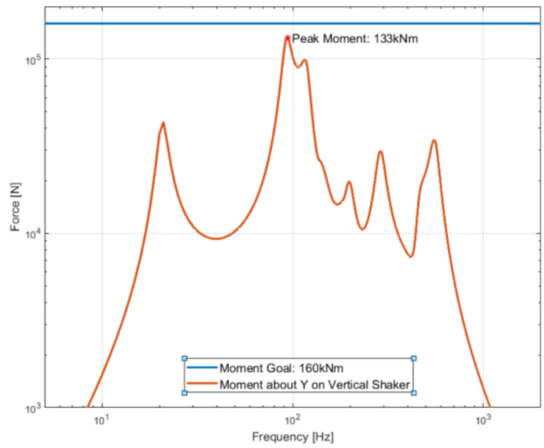

Figure 12: Moment about Y created by RMD during Vertical Shaker Test in Z direction

The maximum moment will not be reached in any of the tests, and a limit of 90% will be set using the FMD to ensure that even if the FEA is incorrect, the test does not hit the shaker's limit. This limitation is because 400kNm and 160kNm are the limits for both these shakers (horizontal and vertical, respectively). If these commissioning tests were to push to the limits, it could break the essential bearings that are part of the shakers, which is not the purpose of these tests.

Instead, the purpose of these tests is twofold: first, to push near the limits of the shakers to ensure they are as specified and second, to ensure the personnel running the NSFT vibration facility are comfortable with running tests at these sizes.

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