Modal Analysis with the Mobile Modal Testing Unit

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Abstract

Recently, National Aeronautics and Space Administration's (NASA's) White Sands Test Facility (WSTF) has tested rocket engines with high pulse frequencies. This has resulted in the use of some of WSTF's existing thrust stands, which were designed for static loading, in tests with large dynamic forces. In order to ensure that the thrust stands can withstand the dynamic loading of high pulse frequency engines while still accurately reporting the test data, their vibrational modes must be characterized. If it is found that they have vibrational modes with frequencies near the pulsing frequency of the test, then they must be modified to withstand the dynamic forces from the pulsing rocket engines. To make this determination the Mobile Modal Testing Unit (MMTU), a system capable of determining the resonant frequencies and mode shapes of a structure, was used on the test stands at WSTF. Once the resonant frequency has been determined for a test stand, it can be compared to the pulse frequency of a test engine to determine whether or not that stand can avoid resonance and reliably test that engine. After analysis of test stand 406 at White Sands Test Facility, it was determined that natural frequencies for the structure are located around 75, 125, and 240 Hz, and thus should be avoided during testing.

Nomenclature

f_s	=	Sampling frequency
f_c	=	Highest frequency within a signal

I. Introduction

NASA's White Sands Test Facility is a branch of NASA's Johnson Space Center whose primary function is testing. One of WSTF's core capabilities is the testing of a wide range of propulsion systems. In certain scenarios variable thrust levels are required by a rocket engine to accomplish various mission objectives such as controlling the attitude of a space craft. However, in some instances, a rocket engine is limited in its ability to control thrust by throttling the engine valves to control the flow of propellant into the system. In these instances rapid pulsation of the engine can be performed to control thrust instead. This high frequency pulsing is used in hypergolic engines, where fuel and an oxidizer combust on contact, eliminating the need for an ignition source. As such, WSTF needs to be able to reliably test engines with this type of mission duty cycle. In rocket engine testing, WSTF uses test stands to hold engines and measure their thrust. These test stands must therefore be able to withstand rapid pulsation from the engines. Some of the stands being used for this testing were designed for sustained bursts or relatively low pulse frequencies, and thus their dynamic response must be characterized to determine how they will handle higher frequencies. The primary issue arises in finding the resonant, or natural, frequencies of the test stands. The natural frequency of a structure is a frequency at which the structure tends to oscillate with greater amplitude. While testing, if one of the test stands is oscillating at its natural frequency the strong vibrations can obscure the thrust data that WSTF provides to its customers, or worse, cause damage to the stand or test article.

To capture the natural frequency of a test stand, a physical modal analysis was conducted on the test stand structure using the Mobile Modal Test Unit (MMTU). The MMTU uses accelerometers placed on a structure to measure vibrations when the structure is excited with an impact hammer. This system will provide experimental results for the natural frequencies of a given test stand.

If any of these natural frequencies are within expected testing frequencies, the structure must be altered, or tuned, to shift the natural frequency away from the testing frequency. The MMTU software is capable of modeling and animating the mode shapes of specific vibrational modes. This tool can be applied to vibration modes found within the testing range, and used in the tuning process to strategically add and/or remove material and supports.

II. Theory

The MMTU, along with the ModalView software it uses, is a robust tool allowing its users to determine the resonant frequencies of a wide variety of structures. To do this effectively, however, it must be used properly. There are several factors to take into consideration while testing with the MMTU, many of which will be examined here.

First, the MMTU has five accelerometers, each able to measure movement along three different axes, and an impact hammer, which is used to excite the structure. The accelerometers measure the minute accelerations that occur at the various locations on the structure when it is excited with the hammer. The ModalView software twice differentiates this value to determine the displacement of the accelerometer and the time taken to reach this translation. A Fast Fourier Transform, a mathematical method for transforming a function of time into a function of frequency, is then applied to the data to determine frequencies at which these displacements occurred. (Nave)

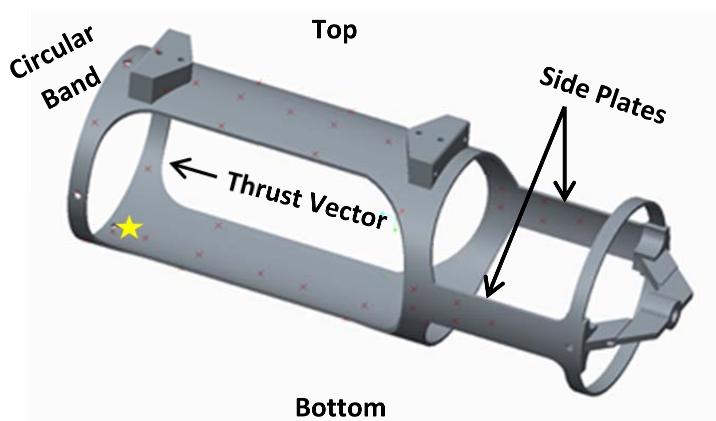

Figure 1 Accelerometer Placement on a Test Stand (Accelerometers denoted by points on model)

To optimize the results of a test, the accelerometers must be placed in clusters at several different locations throughout the structure, as seen in Figure 1. Placing all five accelerometers in a cluster allows them to work together to build a clear picture of the vibrations occurring in that portion of the structure. Once one set is completed, all five accelerometers must be moved to a different location on the structure. These different locations are very important, as sufficient data points must be selected to obtain a clear picture of the mode shapes of the entire structure. Depending on the geometry and size of the structure being tested, many locations may need to be chosen for accurate results.

Just as important as accelerometer placement is the use of the impact hammer. There are various tips available for the impact hammer, ranging from soft rubber to hard metal. A tip must be selected which will excite the structure sufficiently to obtain vibrational readings from the accelerometers, yet it must not cause excessive excitement, as the noise within the signal will make acquiring accurate readings very difficult. This decision can be made by looking at the material and design of the structure. In the case of the test stand, a metal tip was selected to excite the structure. Also, in order to get consistent readings between sets, the impact hammer must strike the same location every time. A location must be preselected which will excite the entire structure on impact. The location selected for the test stand is indicated by the star in Figure 1.

Another important aspect to any kind of frequency testing, and therefore important when using the MMTU, is the sampling rate at which the data is acquired while testing is occurring. The Nyquist Sampling Theorem states that

“*The sampling frequency should be at least twice the highest frequency contained in the signal,”* (Olshausen)

or, as shown in equation 1:

$$f_s \geq 2f_c \tag{1}$$

Following this rule prevents data from being misinterpreted due to aliasing. Aliasing occurs not enough data is collected to define the peaks and troughs of the signal being measured. To insure this does not happen during MMTU testing, a sampling rate of over 1000 Hz was selected. Current rocket engine testing frequencies are well below 500 Hz, a 1024 Hz sampling frequency is more than enough to capture any natural frequencies in the testing range.

III. Results

Using the system and guidelines described above a tap test, or modal test, was performed with the MMTU on the Test Stand 406 thrust stand at White Sands Test Facility. The test was done at a sampling frequency of 1024 Hz to ensure accuracy within our desired testing range.

To set up the test, the accelerometers were placed in eight sets of five, with three readings taken and averaged for each set. By averaging three readings for each set, the outliers and noise within the data sets was reduced. To achieve an optimal covering of the structure, two sets were placed on the top plate of the test stand, two on the bottom, two on the circular front band of the structure, and one on each side plate. Figure 1 can be referenced for exact placement of accelerometers on the test stand, and Figure 2 shows how the

Figure 2
Accelerometer placement for the top plate of the test stand

accelerometers are placed on the stand (they are physically attached using beeswax on the contacting surface). Once the accelerometers within a set were placed, the impact hammer was used to excite the structure and obtain the desired readings. This process was completed for each set. With the testing completed, the results from all of the accelerometers were able to be combined into Figure 3, which shows the Frequency Response Function (the amplitude of

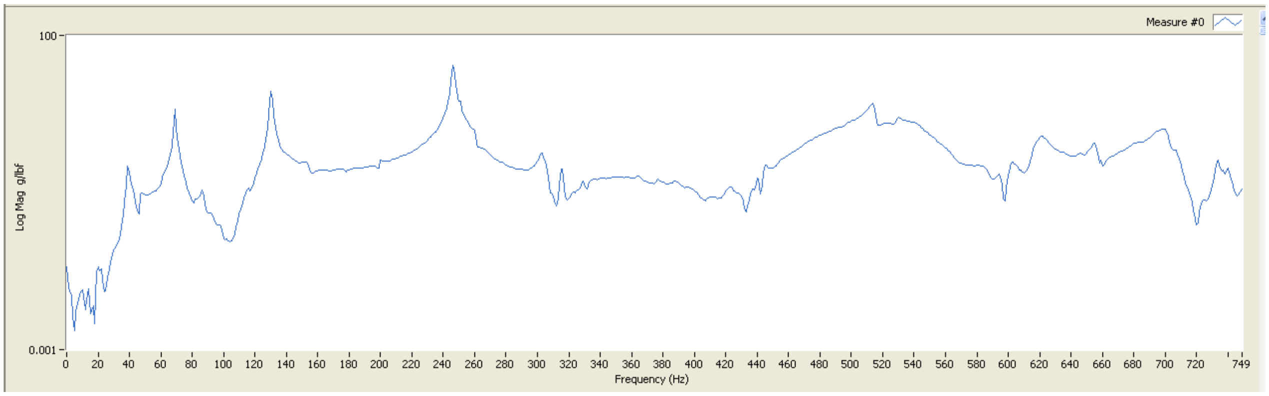

Figure 3 Frequency Response Function results of the test done on Test Stand 406

vibrations against the frequency at which they occured) of the accelerometer data once the Fourier Transform has been applied. The frequency and amplitude are along the x and y axes, respectively.

The MMTU is also capable of estimating natural frequencies based on the FRF data which is provided in Figure 3. The peaks in the graph represent the natural frequencies of the test stand. Table 1 shows the natural frequencies estimated for the data set in Figure 3. The estimation is only applied between 0 and 500 Hz, as anything above 500 Hz is out of the sampling rate frequency range. Looking at the graph, it is easy to see that several of the estimated frequencies are very close to each other, and are actually located within the same large peak. This occurs because along the graph, there are minute peaks within the larger peaks where the test has recorded small deviations within the data, illustrated in Figure 3. These deviations occur for several reasons. Three readings at eight locations analyzing three directions led to 24 sets of vibrational data. This data is

Frequency (Hz)
68.886
84.135
118.385
123.991
124.015
129.596
154.559
231.901
232.207
236.378
302.360
341.654
466.493
467.649

Table 1
Natural Frequencies Estimated by MMTU Software

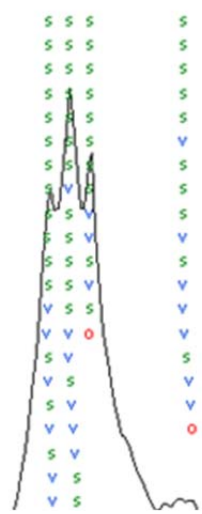

Figure 4
Zoomed in View of the Peak at 125 Hz

condensed into the graph in Figure 3. With this large amount of data, some variation is to be expected as testing conditions do not remain the exact same for every test set. There may also be a small error associated with the newly calibrated accelerometers used in the testing process. Regardless of the reasons for the deviations, however, the estimation software is looking for peaks. Rather than picking one large peak it will select all of the high amplitude peaks. Combining this knowledge with the graph in Figure 3, Table 1 can be narrowed down to a list of three major natural frequency estimations that are shown by the major peaks in the graph. Table 2 shows these major natural frequencies, which are the frequencies which must be taken into consideration while performing rocket engine tests on this particular test stand.

Frequency (Hz)
75
125
240

Table 2
Refined Natural Frequency List

IV. Discussion

With the analysis of the test results completed, it can be seen that there is a natural frequency within this test stand in the range of 240 Hz. This is a frequency that must be avoided when testing rocket engines on this stand. There are other natural frequencies located around 125 and 75 Hz whose amplitudes are not as extreme as the one located at 240 Hz, however these should be avoided as well when testing. The reason for having several of these natural frequencies at relatively low frequency lies in the design of the structure itself. The test stand is a very thin structure – only 1/8 of an inch thick- that is essentially a hollow cylinder with large sections cut out. The thinner a structure is, the more susceptible it is to low frequency vibrations. Thin structures oscillate much more freely with much lower forces required. The test stand, therefore, begins to oscillate at its natural frequencies very easily once dynamic forces are applied to the structure. In order to test at the natural frequencies listed above on this stand, the test stand must be altered in such a way to adjust these natural frequencies. This can be accomplished by adding mass to the test stand. Adding mass to a structure can serve to stiffen the structure. This will raise the frequency at which resonance occurs. To determine how to place the mass on the structure, knowing the mode shape for the natural frequency is required. The mode shape is how the structure vibrates at that natural frequency. If it is known, then mass can be placed in such a way to suppress the vibration and thus alter the frequency that it occurs at. Initially, mode shape analysis was a part of this project, however at the time this paper was written technical difficulties with the ModalView software prevented the mode shapes from being obtained. That is the next step that will be required in order for WSTF to make modifications to the test stand.

V. Conclusion

After analysis of test stand 406, it was determined that natural frequencies for the structure are approximately 75, 125, and 240 Hz. Because natural frequencies can lead to inaccurate data or even damage to the test stand or test article during testing, these frequencies must be avoided when testing high pulse frequency rocket engines on this test stand. If a customer requires a rocket engine to be tested at these frequencies on this stand, then further analysis must be performed to determine the mode shape. The mode shape will allow the structure to be strategically altered in order to shift the natural frequencies of the structure. Doing so will allow testing to be performed at the desired frequencies.

Acknowledgements

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Resources

[1]Bruggeman, Jeremy, NASA White Sands Test Facility, private communication, November 2013.

[2]Nave, C.R., *Fast Fourier Transforms* [online database] URL: http://hyperphysics.phy-astr.gsu.edu/hbase/math/fft.html [cited November 27, 2013]

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