Performing a Large-Scale Modal Test on the B2 Stand Crane at NASA's Stennis Space Center

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ABSTRACT

A modal test of NASA's Space Launch System (SLS) Core Stage is scheduled to occur prior to propulsion system verification testing at the Stennis Space Center B2 test stand. A derrick crane with a 180-ft long boom, located at the top of the stand, will be used to suspend the Core Stage in order to achieve defined boundary conditions. During this suspended modal test, it is expected that dynamic coupling will occur between the crane and the Core Stage. Therefore, a separate modal test was performed on the B2 crane itself, in order to evaluate the varying dynamic characteristics and correlate math models of the crane. Performing a modal test on such a massive structure was challenging and required creative test setup and procedures, including implementing both AC and DC accelerometers, and performing both classical hammer and operational modal analysis. This paper describes the logistics required to perform this large-scale test, as well as details of the test setup, the modal test methods used, and an overview of the results.

KEYWORDS

NASA, Large-Scale Structure, Derrick Crane, Experimental Modal Analysis, Hammer Impact Testing, Lessons Learned

INTRODUCTION

The National Aeronautics and Space Administration (NASA) is currently producing flight hardware for the new Space Launch System (SLS). The SLS is a heavy launch vehicle capable of launching massive payloads to deep space destinations including Earth's moon, Mars, and beyond. The first vehicle configuration will be capable of launching 77-tons of payload using a center Core Stage with four RS-25 rocket engines, supplemented with two Solid Rocket Boosters [1]. In order to certify the SLS for launch, a hot-fire test of the Flight Core Stage will take place at the B2 test stand located at NASA's Stennis Space Center (SSC), in southwestern Mississippi. The main derrick crane, located on top of the test stand, will be used to move and position the Core Stage for this test.

Prior to Flight Core Stage testing, an experimental modal analysis test is scheduled to take place on the Core Stage while suspended from the B2 stand main derrick crane. During this Core Stage modal test, the crane will dynamically couple with the test article. Therefore, a modal test was performed on the crane by itself—in a loaded and unloaded configuration—with the goal of providing modal data in the frequency bandwidth of 0 Hz to 20 Hz in order to evaluate the varying dynamic characteristics of the crane. Increased confidence in the validity of the crane dynamic models will allow focus to remain on Core Stage model verification and correlation from data acquired during the Core Stage modal tests.

Performing this challenging, experimental modal test on the B2 Stand Crane only (no Core Stage) is the focus of this paper, where both classical hammer impact data as well as operational response data was measured. Instrumenting, exciting, and measuring modal data from such a large outdoor structure is discussed in detail, as well as lessons learned. The results are only briefly discussed, as the data is still under analysis at NASA Marshall Space Flight Center (MSFC).

B2 STAND MAIN DERRICK CRANE

In addition to providing general lifting support for the Stennis Space Center B2 test stand, the main derrick crane is primarily responsible for unloading rockets from ground-level transportation and placing them into the stand for test firings, as will be performed during the SLS Flight Core Stage hot-firing test. The crane, located on top of the 265-ft tall test stand, consists of a 64-ft tall mast with a 180-ft long boom that is capable of lifting almost 400,000-lb when at an 80-degree boom angle. The B2 test stand and main derrick crane (painted red and white) are shown in Figure 1.

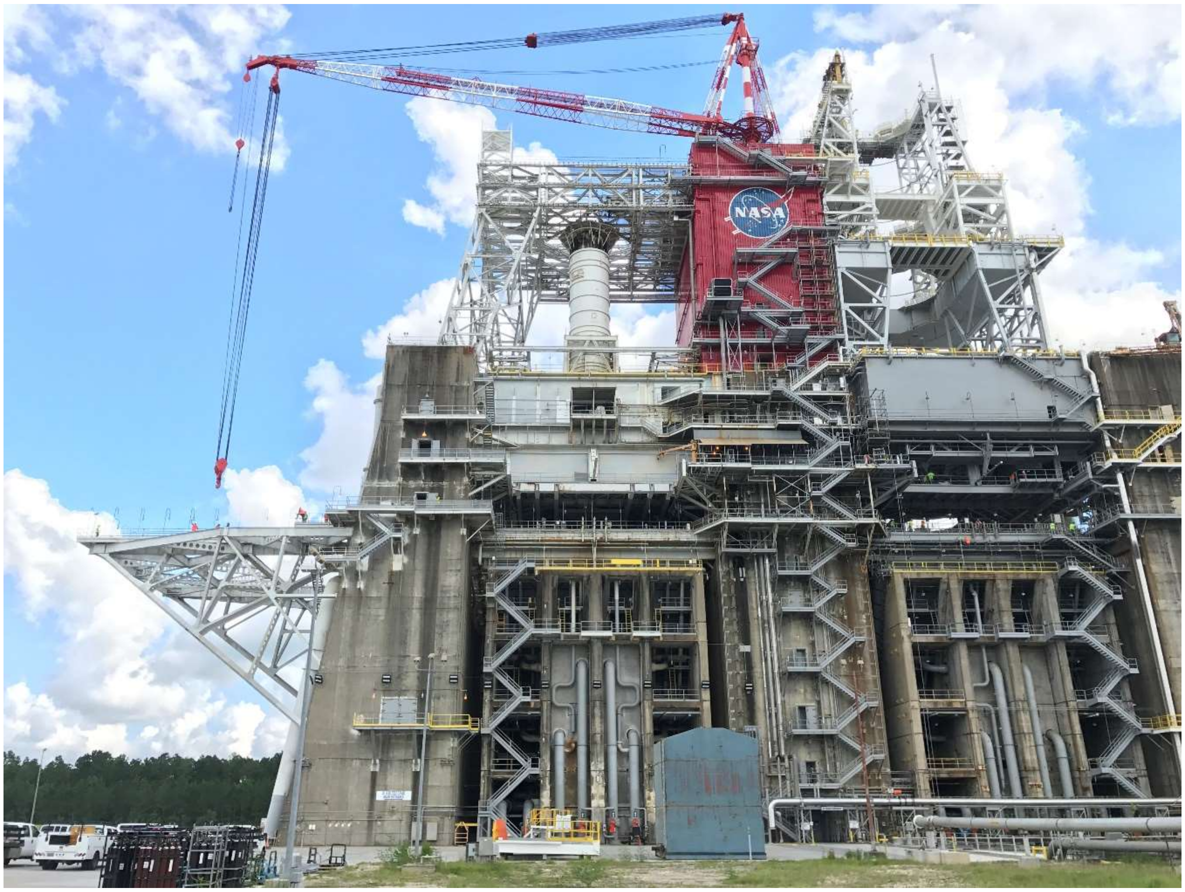
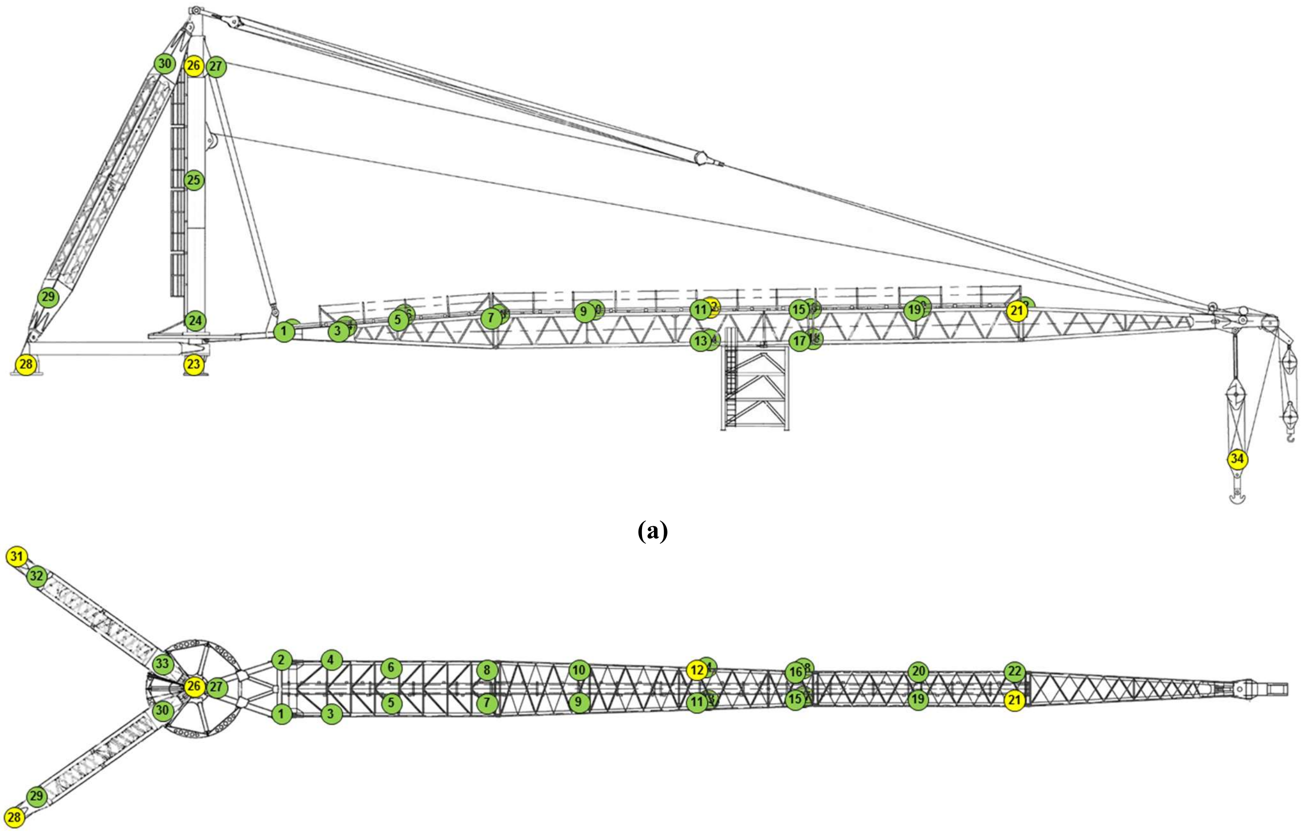


Figure 1: Stennis Space Center B2 Stand and Main Derrick Crane

There were two additional structures of interest measured during the modal testing: the crane hook block and water tank used to load to the crane. While not appearing large in the previous figure, the crane hook block was of substantial size, measuring 6.6-ft wide by 10.3-ft tall (from the top of the block to the bottom of the hook), with a pulley diameter of 3-ft. The water tank, shown placed on the ground transportation pad in front of the crane, is periodically filled with water to proof-test the crane and measured 18-ft square by 20-ft tall and weighed 58,000-lb when empty.

ACCELEROMETER INSTRUMENTATION

To capture the desired modes of interest below 20 Hz, a pre-test analysis was performed and identified 35 measurement locations on the B2 stand main derrick crane. The first 34 locations are shown and labeled in Figure 2, which displays the crane configured over the test stand cradle. Not shown in the figure is Location 35, which was the located on the water tank. To capture all three axes, each location was instrumented with three accelerometers assembled in a tri-axial block, for a total of 105 accelerometers. As will be discussed subsequently, the yellow locations in the figure designate DC accelerometers and the green locations designate AC accelerometers.



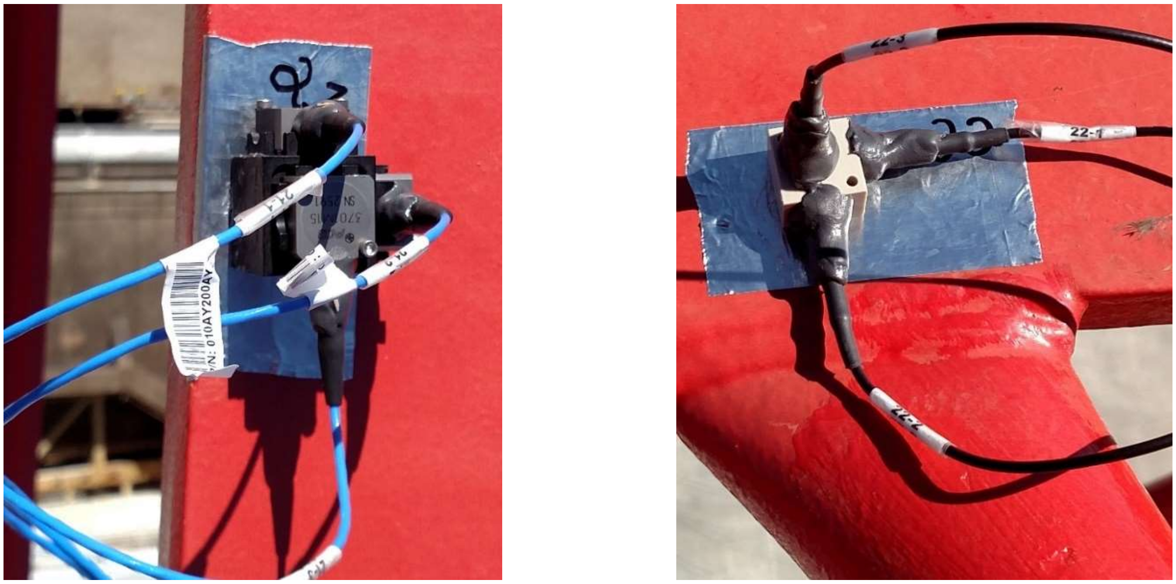
(a)

(b)

Figure 2: DC (yellow) and AC (green) Accelerometer Measurement Locations (a) Side View and (b) Top View

To better capture the low-frequency response of the crane, seven locations were measured with 21 DC accelerometers assembled in tri-axial configurations—the locations were chosen to clearly define the first bending and torsion modes of the crane. These accelerometers, PCB Model 3701M15, were selected as they are capable of measuring low frequencies down to 0 Hz (nominal sensitivity of 1 V/g) and were powered with external signal conditioners that were adjusted prior to each test to remove any DC offset present in the output signal. The remaining twenty-eight locations on the crane were measured with 84 AC accelerometers assembled in tri-axial configurations. These IEPE (Integrated Electronic Piezoelectric) Endevco Model 46A16 accelerometers were capable of measuring down to 1 Hz (nominal sensitivity of 100 mV/g) and were powered with excitation current provided by the data acquisition hardware. An example of DC and AC accelerometers mounted in tri-axial configurations as used for the crane modal test are shown in Figure 3.

Applying the accelerometers to the crane required additional preparations and procedures due to exposure to the hostile summer Mississippi weather. First, aluminum tape was placed at the measurement location to both protect the crane paint and provide a clean work surface. Next, the aluminum tape was scuffed with 320 grit sand paper to provide good surface texture for adhesion. Instant adhesive was then used to glue the tri-axial blocks with accelerometers to the aluminum tape. And finally, the accelerometer/cable interface was sealed and weather-proofed by applying small squares of Tacky Tape, which was easy to apply (as well as remove) and proved to be resilient in the weather that occurred between the test setup in May and the modal test in July. Additionally, in order for test personnel to access the measurement locations on the crane, safety harnesses and fall protection training were required and all equipment was tethered (such as hardhats, safety glass, and rolls of tape).



(a) (b)

Figure 3: Tri-Axial Accelerometer Blocks: (a) DC and (b) AC

Following the logistically and mentally challenging crane instrumentation, as the boom and upper mast were hundreds of feet above the ground, the crane hook block and water tank were fairly easy to instrument. The crane hook block was first lowered to the personnel walkway located on the 7th floor exterior rolling deck (left, white platform shown in Figure 1). A tri-axial DC accelerometer block connected to 200-ft long accelerometer cables was then adhered near the center of the block pulley, as seen in Figure 4(a); strain-relief was provided by wrapping the cables around the hook and taping them to the block. Once installed, the instrumented crane hook block was raised to approximately 28-ft below the end of the boom. The water tank was easiest to instrument, as it was done with the tank lowered on the ground transportation pad with a tri-axial DC accelerometer block and 200-ft long accelerometer cables, adhered at bottom center of the water tank, as seen in Figure 4(b).

(a) (b)

Figure 4: Instrumented (a) Crane Hook Block and (b) Water Tank

IMPACT HAMMER INSTRUMENTATION

Exciting a structure as large as the B2 stand crane for a classical hammer modal test required an impact hammer of significant size. For this reason, a PCB Model 086D50 instrumented sledge hammer with a 12-lb head (nominal 1-mV/lbf sensitivity) was selected as the baseline hammer for this test. This hammer was then modified to better focus the input force to the desired frequencies of 20 Hz and below by both increasing the softness of the hammer tip with 6.5-inch thick packing foam and increasing the mass of the hammer with a 35.25-lb weight. The resulting 47.25-lb hammer is shown resting on the crane cradle platform in Figure 5, with the square packing foam covered in yellow tape and the cylindrical mass secured with a yellow-taped bolt; the red rope shown was used as a safety tether and was tied to the cradle while the hammer was on the platform.

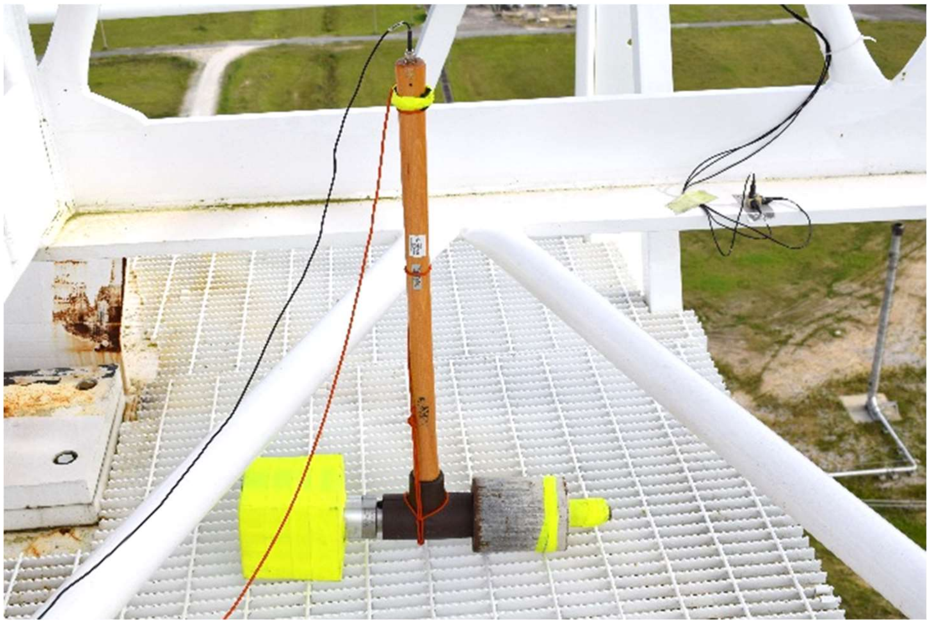


Figure 5: Modified Modal Impact Hammer

INSTRUMENTATION CABLING

Connecting all 99 accelerometers (33 locations) located on the crane to the signal conditioners and data acquisition system located on the 19th floor of the test stand was achieved with 200-ft long lengths of accelerometer connector-to-BNC cable. The length was sufficient for all measurement locations, even with extra slack given to the boom and mast accelerometer cables to allow for boom elevation and rotation without any pulling or damaging the cables. Where possible, the cables were bundled and secured along their lengths to the crane structure with cable ties and tape.

Keeping this amount of cable organized—about 3.75 miles in total length—was accomplished by originating each cable from an individual spool stored in an aluminum frame assembly, as seen in Figure 6. The assembly allowed for easy transportation to, from, and around the test site in a van or on a wagon, and guaranteed few tangles when pulling out the accelerometer-end of the cable for instrumentation on the crane. On the outside of each spool was the BNC connector, which was directly connected to the signal conditioners and main data acquisition chassis, also shown in the figure.

The crane hook block and water tank accelerometer cables were configured differently from the crane cables due to their far distance from the 19th floor. For the impact hammer test, with the crane in the cradle position, the 200-ft long cables from the crane hook block accelerometers were long enough to connect to a DC signal conditioner and modular data acquisition card located on the 7th floor exterior rolling deck walkway. This hardware was powered with a long extension cord running to the interior of the B2 stand. For the operational response test, when the crane lifted the water tank over the transportation pad, there was enough length of both the crane hook block and water tank accelerometer cables to reach the DC signal conditioner and modular data acquisition card, which were moved to the 2nd floor of the B2 stand.

Figure 6: Accelerometer Cable Spools, DC Signal Conditioners, and Data Acquisition Chassis

It must be emphasized that maintaining a neat and organized cable routing scheme during modal testing was crucial for many reasons. Primarily, if a sensor issue was encountered during a test, it was much easier and less time consuming to track down the source of the problem while minimizing the potential to damage other sensors. Thoughtful cable routing also minimized cable damage in high traffic areas around the test article through the use of extra cable protection (cable trays, wire tied bundle, plastic covers, etc.) and managed personnel routes. Finally, well-planned cable management also facilitated in a much quicker test tear-down, which is particularly important for test programs with tight schedules, where tear-down time is often neglected from the schedule.

DATA ACQUISITION SYSTEM

The data acquisition system (DAQ) used to perform the modal test of the B2 stand crane consisted of Bruel and Kjaer (B&K) Pulse Reflex acquisition software running B&K LAN-XI hardware. The 12-channel hardware cards were modular and capable of operating apart from the main 11-card data acquisition chassis through the use of Ethernet cables connected to the DAQ computer via a network hub. The modular card was necessary for the crane hook block and water tank accelerometers, as to avoid using two separate data acquisition systems or running more than 500-ft of instrumentation cable per accelerometer, which would have been expensive and more complex (1 Ethernet vs 6 accelerometer cables). Additionally, the data was acquired with the same time clock using Procession Time Protocol (PTP), avoiding any asynchronous (out of phase) measurements between the DAQ hardware.

Connecting both the main data acquisition chassis and modular data acquisition card to the DAQ computer on the 2nd floor was accomplished through the use of two 300-ft long Cat6 Ethernet cables. For the main data acquisition chassis located on the 19th floor, an instrumentation shaft running the height of the B2 stand provided access to run an Ethernet cable to the data acquisition computer. For the modular data acquisition card located on the 7th floor exterior walkway when performing impact testing, an Ethernet cable was run outside along the exterior walkways and stairs of the B2 stand to the DAQ computer. The modular card was moved to the 2nd floor DAQ computer location for the operational response testing, and connected with a much shorter Ethernet cable. A diagram illustrating the overall instrumentation and cabling setup used for the B2 stand modal test is shown in Figure 7.

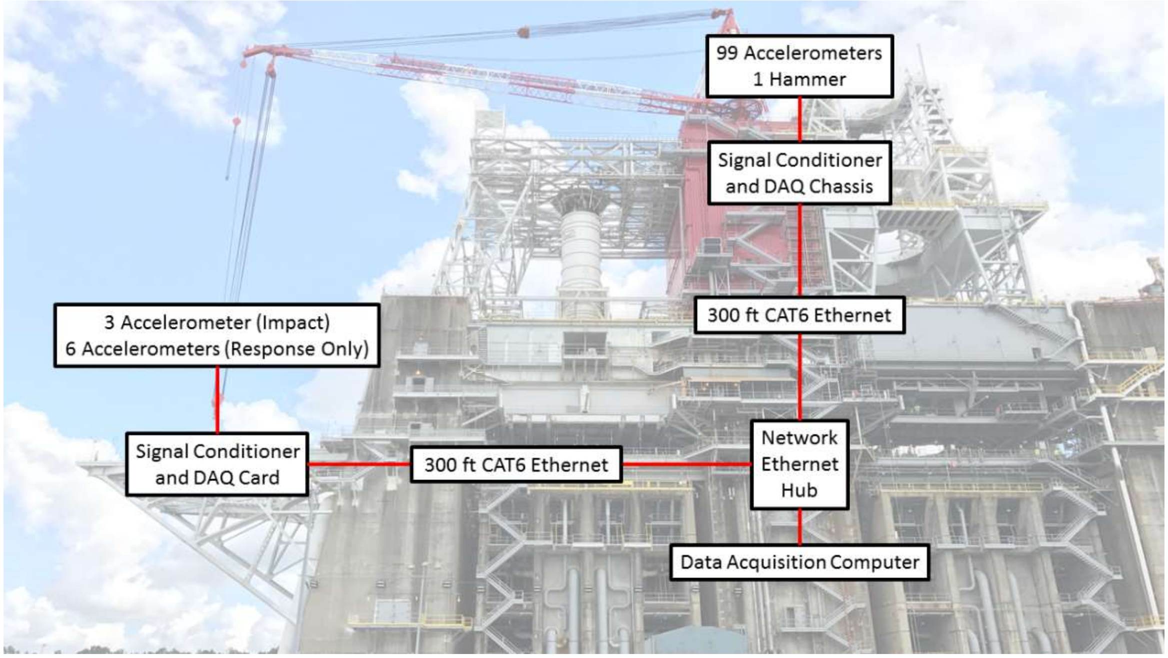


Figure 7: Instrumentation and Data Acquisition (DAQ) Cabling Diagram

An important capability that the data acquisition system provided, and must be emphasized, was the ability to measure spectral data and time history data simultaneously. This was very valuable for the B2 stand crane test, as only two days were available to perform the modal and operational response testing. With pre-determined digital signal processing (DSP) parameters, the spectral data was viewed and curve fit to determine if the desired modes and frequencies were captured very soon after testing. However, having the recorded time history data allowed for further post-processing at a later time with different DSP parameters to remove damaged accelerometer data, clean up accelerometer signals, and calculate more accurate FRFs and therefore extract more accurate modal parameters.

TEST PROCEDURE

For the classic modal hammer impact test, the B2 stand crane was positioned with the boom raised about 6-inches above the cradle platform (where the boom rests when not in operation). Standing on the cradle platform, test personnel used the modified modal hammer to excite the boom at Location 17 (see Figure 2) in the lateral and vertical directions, as seen in Figure 8(a). After viewing data from some pre-test impacts, the DSP parameters used were an analysis frequency of 100 Hz (sample rate = 256 Hz) with 16 second record length, resulting in 1600 spectral lines with a frequency resolution of 0.0625 Hz. With these settings, each direction was impacted ten times with one-minute duration between each impact, with a force/exponential window applied to the data. The one-minute duration was to allow the crane response to sufficiently die down prior to the next impact, and provide extra flexibility in post-processing the time data. The softness of the hammer tip and the weight of the hammer resulted in good rebounds of the hammer and prevented any double-hits.

For the operational response testing, the crane was moved over the transportation pad to a position similar to that of the scheduled SLS Core Stage modal test. With the boom at 72.1-degrees, the crane was attached to the water tank and filled to approximately 281,000-lb to simulate the Core Stage weight. Once filled, time history data was recorded with the same DSP parameters as with the impact hammer tests (100 Hz analysis frequency), while the crane moved the tank to five different positions horizontally in 5-degree increments, then vertically in 1-foot increments, with one minute in between positions. The start/stop motion of the crane provided a pulse-like input into the structure for operational modal analysis. Once complete, the tests were repeated with a reduced water level (weight of 230,000-lb) as well as with an empty tank. There was enough slack in the crane hook block and water tank accelerometer cables to allow this test to be performed at about 25-ft above the concrete pad as seen in Figure 8(b).

Figure 8: Modal Testing (a) Classic Hammer and (b) Operational Response

IMPACT HAMMER MODAL RESULTS

With the modified impact hammer, the measured time histories showed that approximately 500-lbf of peak force input was applied to the B2 stand crane boom in the lateral (Y+) and vertical (Z+) directions. The resulting, averaged auto-spectrum for the force at each location is shown up to the 100 Hz analysis frequency in Figure 9. The plot illustrates that the modification of the hammer was successful, as the force spectrum magnitude can be seen to decrease by a factor of 100 (-20 dB) by 20 Hz—this desired 20 dB drop is common practice in performing impact hammer testing [2]. Even though the impact hammer data was measured up to 100 Hz, and the desired test frequency was up to 20 Hz, the remainder of the results plots will be shown from 0 Hz to 10 Hz, to better illustrate modes present in the crane below 10 Hz.

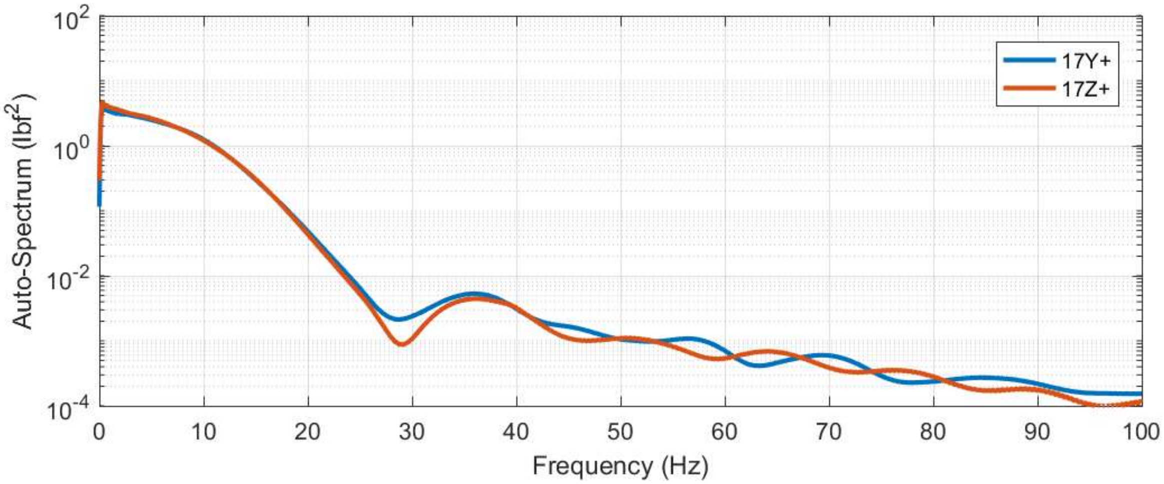


Figure 9: Impact Hammer Auto-Spectrum Results

For the sake of brevity, only the averaged drive point Frequency Response Functions (FRFs) and coherence measured at the test site are shown from 0 Hz to 10 Hz in Figure 10. When viewing the plots, it was concluded that the first realized mode of the B2 stand crane occurred at approximately 1 Hz, due to the FRF peak and the corresponding high coherence value (0.9). Any peaks that occurred in the FRF below this frequency coincided with low coherence values (less than 0.5), which indicated incoherent response. Alternately, peaks above this frequency, such as the small peak at 1.9 Hz, correspond with high coherence values (close to 1), indicating real excited modes. It was also noticeable in the plot that there are a few bands of closely-spaced modes such as those at 2.15 Hz and 2.21 Hz, and 3.43 Hz and 3.50 Hz.

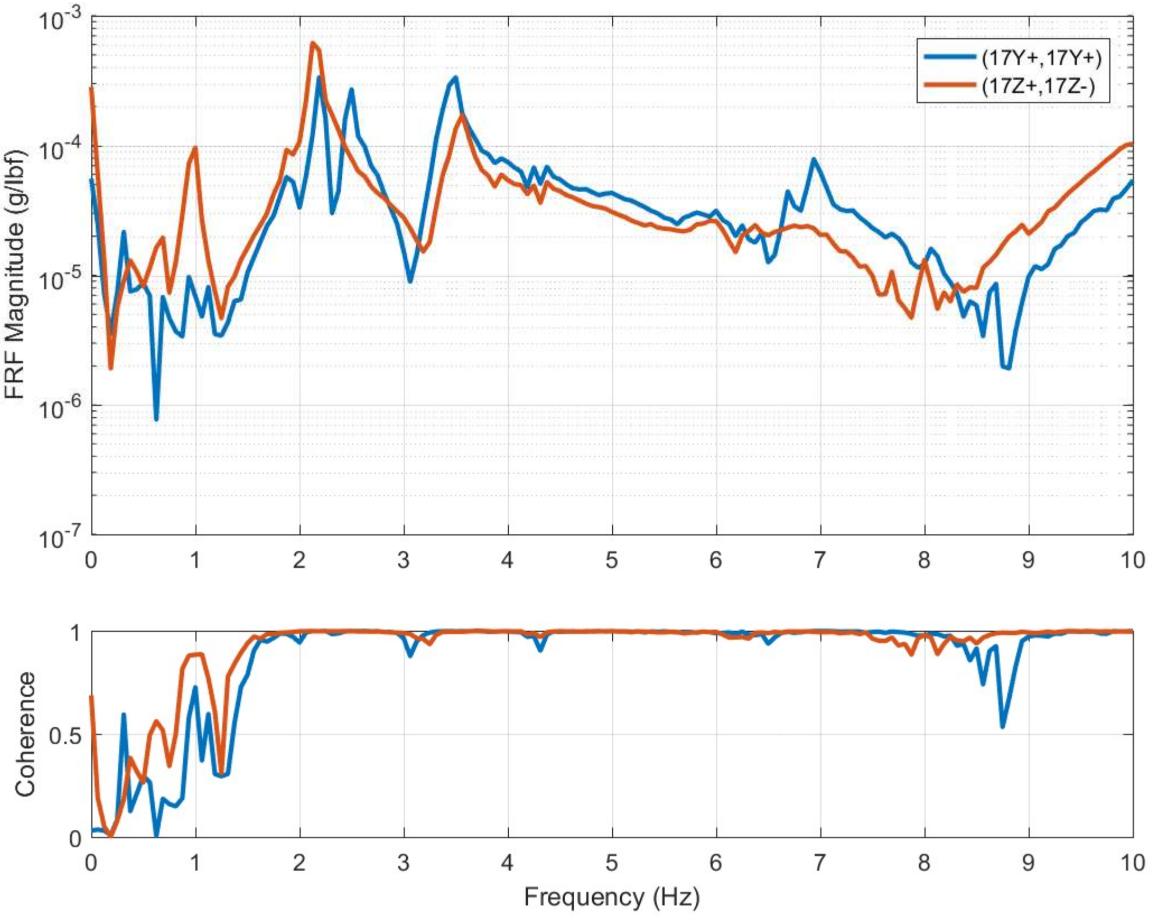
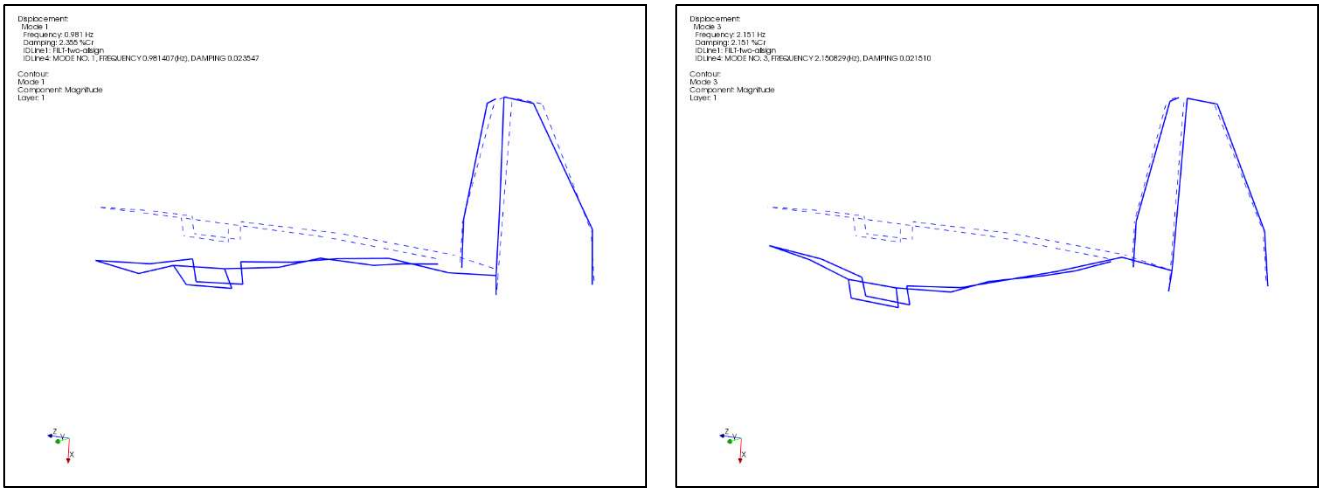


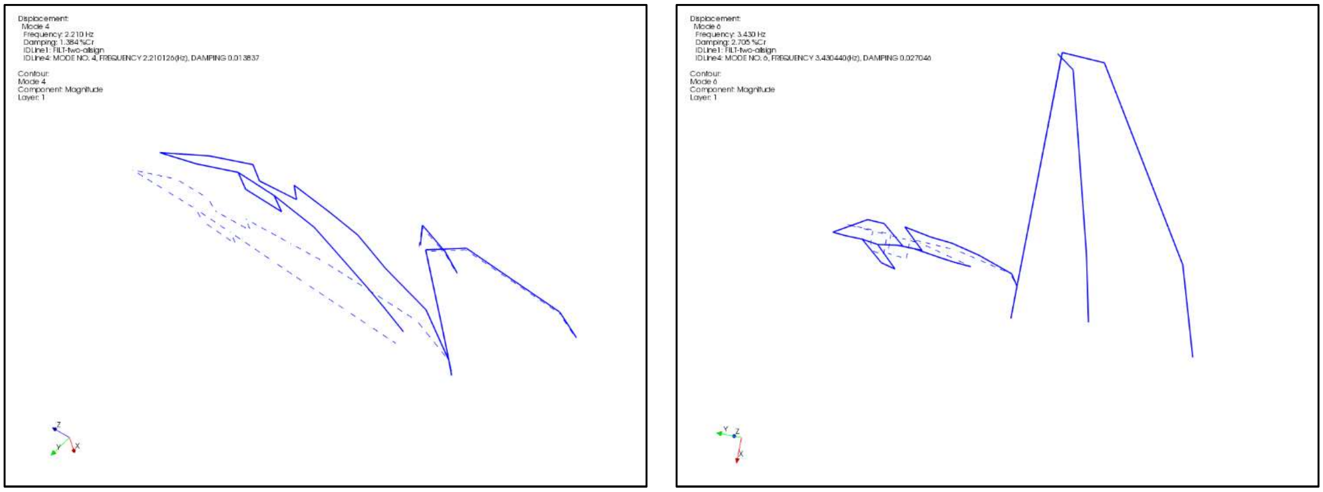
Figure 10: Drive Point Frequency Response Functions and Coherence

The FRFs and coherence data processed in real-time during the impact tests were used immediately after the test to estimate modal parameters to determine if all desired modes were captured. The time histories and power spectral densities were viewed as well to assess data quality. Once back at NASA MSFC, a more thorough study and modal analysis was performed on the time history data. It was discovered that some of the accelerometer measurements indicated a bad accelerometer (such as at Location 21) and that the DC accelerometers exhibited low frequency drift, that when combined with exponential windows, led to incorrect FRF calculations. After removing the bad accelerometer data and applying band pass filters (0.5 Hz to 25 Hz) and new windows to the time history data, modal frequencies, mode shapes, and damping were extracted from the data more accurately than could be done at the test site.

Again for the sake of brevity, not all mode shapes extracted from the modal impact hammer testing will be shown. However, a sample of modes are plotted in Figure 11, corresponding to the large peaks shown in the FRF and coherence plot of Figure 10. These mode shapes include the first vertical bending of the boom with the in-phase first bending of the mast at 0.98 Hz, the first vertical bending of the boom with the out-of-phase first bending of the mast at 2.15 Hz, the very closely-spaced first lateral bending of the boom at 2.21 Hz (mast in-phase), and the first torsion mode of the boom at 3.43 Hz.



(a) Mode 1: 0.98 Hz **(b) Mode 3: 2.15 Hz**



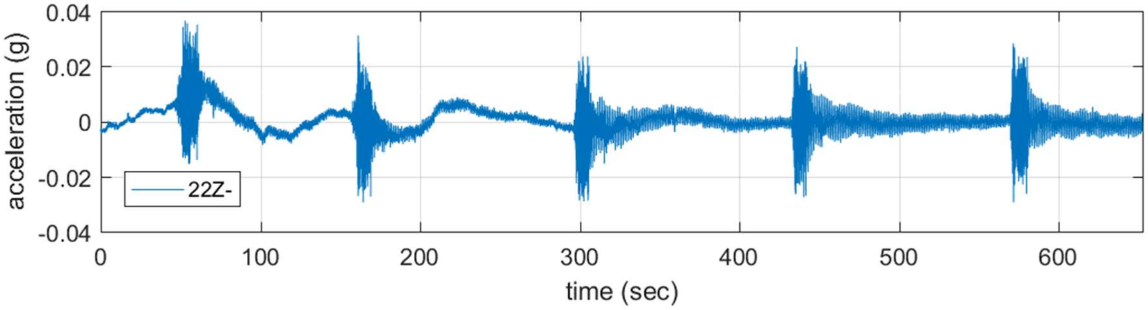
(c) Mode 4: 2.21 Hz **(d) Mode 6: 3.43 Hz**

Figure 11: B2 Stand Crane Mode Shapes from Impact Hammer Testing

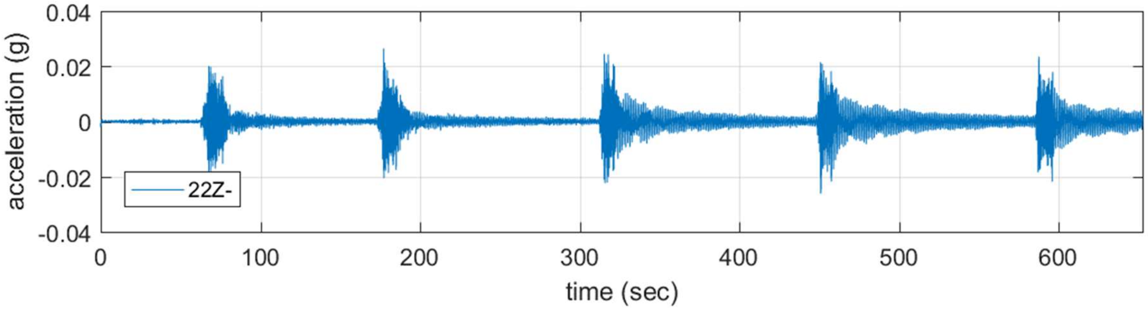
OPERATIONAL RESPONSE RESULTS

An example of operational response time history data, measured at Location 22 in the vertical axis, is shown in Figure 12(a). This was acquired while the crane lifted a full bucket (281,000-lb) vertically five times in one foot increments with at least 60 seconds between lifts. This data illustrates how not-textbook-like measurements can be in the field. In this case very low frequency content caused by accelerometer drift can be seen. For these tests, the data was recorded with the approach that as long as the accelerometers did not overload, the data was considered valid and could be post-processed.

After all testing was complete, the time history data was post-processed with a band pass filter set from 0.5 Hz to 20 Hz to remove the accelerometer drift and focus on the frequency band of interest; the data was truncated as well to simplify analysis. As can be seen in the post-processed time history data in Figure 12(b), the impulses resulting from hard-stopping the crane lift are evident and measure maximum accelerations of approximately 0.02-g. Accelerometers located on the feet of the mast measured even lower acceleration values, at approximately 0.003-g. Even with these low magnitude values, the transient response data following impulse loading was above the noise floor of the measurement system, and operational modal analysis can be applied to determine operational modal deflection shapes. This work is currently ongoing at NASA MSFC.



(a)



(b)

Figure 12: Vertical Bucket Lift Operational Response Measurement (a) As-Measured and (b) Post-Processed

LESSONS LEARNED

The most valuable lesson learned from the B2 stand test is the importance in measuring time histories when running experimental modal tests out in the field. In a lab, there may be time to collect perfect FRF data before breaking down the test setup. However, when obligated to a tight test schedule, having quality and sufficiently sampled time history data allows for fastidious post-processing at a later date (hopefully in an air conditioned room), to apply different filtering, windowing, or longer time frames to calculate better FRFs and resulting modal parameters.

Communication is integral to running a proper modal test as well, particularly when impact hammer personnel or crane operators were located hundreds of feet away from the DAQ computer operator. Initially the plan was to use SSC two-way radios, but the concrete bunker where the DAQ computer was located prevented radio transmission. Therefore, someone had to stand with a radio just outside the test stand/DAQ room door and relay information to the DAQ operator. Cellular phones were eventually used as they worked better, provided the phone used by the DAQ operator had the ability to use the B2 stand Wi-Fi signal to relay phone calls. This emphasizes that no matter how well things are planned, flexibility is usually required to run off-site tests.

In regards to the performing a better test in the future, such as with the scheduled Core Stage modal test, a lesson learned was to allow longer durations between hammer impacts of the boom, to allow for time windows of 64 seconds, resulting in finer frequency resolution of the FRF calculations. This was discovered during post-processing of the time history data, where the time window was increased from 16 seconds to 32 seconds to better resolve the closely spaced modes in the FRFs. An additional lesson learned from the modal identification process was that the crane cables may have contributed to some unidentifiable modes in the data. If there were a way to measure the crane cable responses (such as with a Laser Doppler Vibrometer) in future tests, this may make modes more easily identified, which is under consideration for future testing.

Finally, when modal test data is to be used in modal correlation as with the B2 stand crane, it is very important to work with the analysts conducting the correlation efforts. During the instrumentation process, it is valuable to have the analyst present to assure that the actual location of sensors is suitable to provide proper comparisons between analysis and test, as well as assess excitation locations to assure proper modal response for the sensors chosen. Additionally, when creating the modal test geometry, the analysts can assist in designating a common global coordinate system to be used when transforming modal displacements from the modal coordinate system to the analysis coordinate system. This was particularly useful with the B2 crane, where geometric complexities required many local coordinate systems to keep track of the modal responses—the test results were easily transformed into the global coordinate system and given to the analysis for efficient model validation.

CONCLUSIONS

A large-scale modal test was performed by the NASA Marshall Space Flight Center Structural Dynamics Test Branch on the B2 Stand crane at NASA's Stennis Space Center in preparation of the upcoming SLS Flight Core Stage modal test. Due to concern that the dynamics of the crane would couple with the Core Stage, this crane-only modal test was performed in order to provide data for crane model validation. Both classic impact hammer and operational response modal testing was performed on the instrumented B2 stand crane in an unloaded and loaded configuration. Focusing on frequencies of interest from 0 Hz to 20 Hz, frequency and time history data were successfully measured and analyzed. After post-processing the recorded time histories with band-pass filtering, windowing, and extending the analysis time windows, modal analysis was performed on the resulting data. Modal frequencies, damping, and mode shapes were extracted from the impact hammer data; the operational response data is still under analysis at NASA MSFC.

Performing a modal test on such a large, outdoor structure was a challenge and some of the solutions are worth summarizing. Weatherproofing the accelerometer/cable interface was done with squares of tacky tape, which kept water out of the connection as well as kept the cable tightened to the accelerometer. Each accelerometer cable was stored on a spool, which kept the cables relatively tangle free; the spools were kept together on an aluminum assembly which made cable transportation easy and helped tremendously in identifying each accelerometer/cable when issues arose. Finally, keeping the data acquisition hardware near the test item helped reduce the amount of instrumentation cable; only a single 300-ft Ethernet cable was required to connect each DAQ hardware to the DAQ computer, reducing the complexity of the setup tremendously.

The presented modal test on the B2 Stand crane was successful and valuable in numerous ways. In addition to providing modelers with valuable real-world data, there were lessons learned from performing the actual test as well as from performing the modal analysis on the time history and FRF data. This experience has greatly prepared NASA Marshall Space Flight Center for the upcoming Flight Core Stage modal test as well as for future modal tests required to provide a successful launch of the new Space Launch System.

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