MSFC-826

INTEGRATED VEHICLE GROUND VIBRATION TESTING IN SUPPORT OF LAUNCH VEHICLE LOADS AND CONTROLS ANALYSIS

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ABSTRACT

All structural systems possess a basic set of physical characteristics unique to that system. These unique physical characteristics include items such as mass distribution and damping. When specified, they allow engineers to understand and predict how a structural system behaves under given loading conditions and different methods of control. These physical properties of launch vehicles may be predicted by analysis or measured by certain types of tests. Generally, these properties are predicted by analysis during the design phase of a launch vehicle and then verified by testing before the vehicle becomes operational.

A ground vibration test (GVT) is intended to measure by test the fundamental dynamic characteristics of launch vehicles during various phases of flight. During the series of tests, properties such as natural frequencies, mode shapes, and transfer functions are measured directly. These data will then be used to calibrate loads and control systems analysis models for verifying analyses of the launch vehicle.

NASA manned launch vehicles have undergone ground vibration testing leading to the development of successful launch vehicles. A GVT was not performed on the inaugural launch of the unmanned Delta III which was lost during launch. Subsequent analyses indicated had a GVT been performed, it would have identified instability issues avoiding loss of the vehicle.

This discussion will address GVT planning, set-up, execution and analyses, for the Saturn and Shuttle programs, and will also focus on the current and on-going planning for the Ares I and V Integrated Vehicle Ground Vibration Test (IVGVT).

INTRODUCTION

Most launch and space vehicles, as well as aircraft, undergo dynamic testing, also known as modal testing or GVT. Such testing is conducted to validate pre-test finite element models (FEMs) for use in verification loads analysis. The testing also determines test-confirmed natural frequencies, mode shapes, and damping for the vehicle under test. GVT supports controls analysis by providing test data to reduce uncertainty in models, which can then carry heavier payloads and provide better vehicle control. Subsystem objectives are also obtained during dynamic testing such as verifying minimum subsystem frequency requirements and confirming flex effects between control sensors and thrust locations.

Without test-calibrated models, the model uncertainty factor (MUF) used in verification loads analysis is not updated and remains at earlier design phase levels. This uncertainty can translate into increased mass if margins are insufficient. Poorly understood vehicle modes also can cause vehicle

instability due to incorrect modeling and boundary conditions. If model uncertainties are too large, guidance, navigation, and control (GN&C) stability requirements, cannot be met.

The Aerospace Corporation conducted a study of 47 launch and space vehicle test programs (65 total modal tests). In all but one program, the analytical models required updating prior to final vehicle deployment. "The author is not aware of a single analytical model of a complex space vehicle, upper stage, or launch vehicle component, that did not require significant adjustments once mode survey test data became available. This implies that a mode survey test is an absolute requirement. Unfortunately, the commercial trend is to eliminate this test to reduce cost and shorten schedule."[1]

Failure to conduct such testing can have catastrophic consequences. The Delta III launch vehicle was destroyed on its maiden launch because the control system software corrected a 4 hertz oscillation that would have smoothed out on its own without correction. Designers had relied on known Delta II vehicle responses even though the Delta III launch vehicle had a significantly different configuration, with an increased-diameter first stage fuel tank, a shorter vehicle, two additional solid rocket motors, and a new second stage engine fueled by liquid oxygen/liquid hydrogen (LOX/LH_2). Based on the heritage Delta II system modes, the Delta III control software corrected a vehicle mode (oscillation) that did not require correction. Had the program conducted dynamic testing on the Delta III, it is likely this mode would have been understood and the control software adjusted to accommodate it.[2]

Similarly, the Ariane 5 was lost on its inaugural flight due to a lack of understanding of the vehicle's new engine nozzle and a decision not to compensate by adding additional safety margins into vehicle design and test. The loss of the satellite payload resulted in Arianespace conducting a demonstration flight with no payload before another paying customer would sign up to use the launch system.[3]

More recently, the commercially developed SpaceX Falcon 1 suffered a partial failure on its second test flight in March 2007. The launch went well until separation of the first and second stages, when the first stage bumped the engine bell of the second stage engine as the Interstage separated. This ultimately produced a vehicle roll that caused the LOX tank to slosh due to the amplified oscillation. This slosh increased the oscillation, which would normally have been compensated for by the thrust vector control (TVC) system, but the increased oscillation caused the TVC to overcompensate the correction, which lead to premature burnout of the second stage engine and a failure to meet mission objectives. That a bump could excite a mode that would persist and ultimately doom the mission indicates that some modal characteristics of the Falcon 1 vehicle were not well understood. This incident is an example of the worst modal attributes coupling together (natural modes, slosh modes) and leading to TVC overcompensation, and perhaps failure of other systems, to respond. More ground testing, including dynamic testing, may have helped identify these modes prior to launch, ensuring better characterization and design of the structural and slosh modes and the vehicle's ability to control them.

The sheer size of NASA launch vehicles, and the need to human rate them, necessitate extensive planning to ensure the vehicle and test facility meet requirements not only for good test results, but for the safety of those setting up and conducting the test. NASA is currently developing the next generation of launch vehicles that will take humans back to the Moon and beyond. These are the Ares I crew launch vehicle, with the Orion crew module, and the Ares V cargo launch vehicle. Both Ares I and Ares V will require a GVT to validate analytical models in support of loads and GN&C.

The Saturn and Space Shuttle programs both performed scale-model dynamic tests in addition to full-scale testing. Saturn used a $1/10^{th}$ scale model. Shuttle used a ¼ scale model. NASA Ares I analysts have challenged the need to conduct scale model testing for Ares I, as the launch vehicle has a simple in-

line configuration and payload. Also, the advanced computational tools in use today are more accurate and process post-test data more quickly. While useful in developing designs for the earlier projects, modern tools allow Ares I to omit the cost and time required to perform scale-model testing.

Planning for the NASA Ares I/Orion Integrated Vehicle GVT (IVGVT) has been ongoing since the Constellation Program's inception. This planning draws heavily on the historic data archived in NASA libraries for Saturn V and Space Shuttle dynamic testing in the dynamic test stand at Marshall Space Flight Center (MSFC). The IVGVT team has already conducted a preliminary Subject Matter Expert (SME) review to obtain the evaluation of experts from both the Saturn and Shuttle GVT projects. This availability of historic records and professional authorities with hands-on GVT experience has been a tremendous aid in IVGVT planning. A second SME review is planned prior to the Ares I Preliminary Design Review (PDR).

While not an objective of dynamic testing per se the dynamic testing of both Saturn V and Shuttle in Test Stand (TS) 4550 represented the first time the entire vehicle was stacked. It will be the same with Ares I/Orion. It is an excellent opportunity to pathfind and learn about the integrated vehicle stack prior to delivery to the Kennedy Space Center (KSC) for launch preparations.

SATURN V

During the Saturn V program, NASA planned and executed the Dynamic Vehicle Test (DVT), also know as a GVT. The test was performed on a full-scale vehicle test article to determine the structural dynamic characteristics for flight control system design and to verify vehicle structural integrity. The test article was built to flight-article specifications. Deviations from these specifications were built to ensure that the overall dynamic response of the vehicle was not changed.[4]

The Saturn V vehicle consisted of three booster stages, the instrument unit (IU) and the payload. Fully fueled, the vehicle weighed approximately 6,000,000 pounds, and measured 365 feet tall with a 33-foot-diameter base. De-ionized dichromate water was used to simulate the propellant, liquid oxygen (LOX) and RP-1, in the first stage. De-ionized dichromate water was used as the simulant for LOX in the second and third stages. Due to the difficulties of adequately simulating liquid Hydrogen (LH_2), the LH_2 tanks were left empty in the second and third stages for lateral testing and were weight simulated with water for longitudinal and roll testing.[5]

Test Stand 4550 (TS 4550) was built at MSFC between 1962 and 1964 to perform dynamic testing for the Saturn program. Due to the very large size of the Saturn V vehicle, TS 4550 is 360 feet high. The 200-ton derrick crane on top of the building adds 64 feet to the overall height. Platforms capable of folding back and away from the test article were built at 24-foot intervals, providing access to full length of the vehicle (Figure 1).[6] The vehicle was handled in the stand by two derrick cranes, one installed on the roof and one about half way up the exterior.[7]

Figure 1 – Saturn V test article and installed in TS 4550

The suspension system required to simulate free-flight conditions was a particular challenge. Suspending the vehicle by cables would not work, as the cables resonate at frequencies similar to that of the vehicle, which might have complicated or invalidated test results.

NASA developed a state-of-the-art suspension system to simulate the free-free boundary conditions of flight. The hydrodynamic support system (HDS) consists of oil bearings and vertical gas springs for lateral and roll stability (Figure 2). Oil under pressure was pumped between flat contacting surfaces to provide a near frictionless support. This system transmits the heavy vehicle load directly to the ground, enabling the support mass to be relatively small.[8] The HDSs were so effective that the entire 6 million pound vehicle could be excited in its low frequency suspension modes by two people pushing the fins on the first stage, deflecting the vehicle as much as two inches.[9]

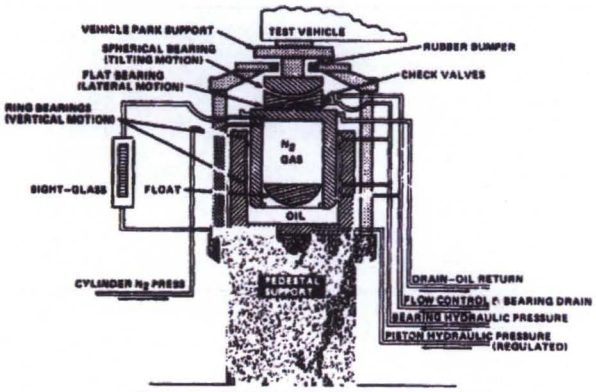

Figure 2. Typical hydraulic dynamic support.

Figure 2 – Hydraulic Support System (HDS)

Lateral support of the vehicle was provided by two sets of lateral stabilizing springs. These springs were located as close to the mean nodal points as possible to minimize their impact on the overall bending modes of the vehicle. An upper stabilizing system of 16 springs was attached tangentially to provide roll restraint and keep the vehicle centered.[10]

The DVT tested three configurations of the Saturn V. Configuration I consisted of the S-IC first stage, S-II second stage, S-IV third stage, IU, Crew Service Module (CSM) and Launch Escape System (LES). Configuration II consisted of the S-II second stage, S-IV third stage, IU, CSM and LES. Configuration III consisted of the S-IVB-D third stage, IU, CSM and LES. All configurations tested both the ignition and burn out conditions of the fuel tanks.

Dynamic testing was conducted on the Saturn V test vehicle between October 1966 and August 1967. A series of test were performed, including force linearity, ring-out damping, and ring mode. The force linearity test excited the vehicle at three different force levels at each resonant frequency to determine nonlinear characteristics of the vehicle. The first four flexible mode resonant frequencies were measured by the ring-out damping test, as was the logarithmic decay of response to determine sensor damping when force was suddenly removed. The ring mode test was an incremental frequency sweep to determine the IU's ring mode activity.[11]

The mathematical model developed during pre-test analysis was verified by the dynamic test and used to analyze the flight vehicle and account for mass and stiffener differences. Generally, the correlation between test results and this model were very good. A major difference, however, was found at the flight gyro cold plate in the IU. The control gyro was located on the upper half of this plate, which had a higher slope than the lower half. This made the analytical flight control parameters marginal. This finding resulted in relocating the control gyro to the lower half of the plate, where it correlated well with analytical predictions.[12]

Table 1 summarizes the major findings from Saturn V's DVT and their likely consequences.[13]

Table 1 – Saturn V DVT Problems and Consequences

Saturn V DVT Problem Discovered	Hardware Impacted	Consequences if Not Discovered
Design deficiency in the SPS tank supports. Unexpectedly high local resonant coupling was detected between SPS and bulkhead support.	The upper support bracket for the SPS tanks was redesigned to eliminate a strong tank cantilever mode.	Hardware failure resulting in loss of mission and possible crew loss.
High LOX and fuel dynamic tank bottom pressures. These pressures were under-predicted by a factor of 2. The significance of these pressures was not understood until after pogo occurred on AS-502.	The higher tank pressures contributed to the S-IC pogo accumulator hardware design.	Potential loss of vehicle and crew due to pogo.

Saturn V DVT Problem Discovered	Hardware Impacted	Consequences if Not Discovered
High 18 Hertz (Hz) S-IC Crossbeam mode gains. DTV data showed that an accumulator should not be used on the inboard engine.	Eliminated a planned inboard engine accumulator.	Potential loss of vehicle and crew due to pogo between the 18 Hz accumulator mode and the 18 Hz crossbeam mode.
Local rotation of the flight gyro support plate. Vehicle dynamic shears and moments deformed the support plate. The math model under-predicted this deformation by 135%.	The gyros were relocated to the bottom of the support plate where the local rotation was much less. This required wire harnesses of new length. The flight control filter network was redesigned.	Flight control instability resulting in loss of vehicle.

SPACE SHUTTLE

NASA authorized the development and manufacturing of the National Space Transportation System, commonly called the Space Shuttle, in 1972. The Space Shuttle launch vehicle consists of the orbiter—a winged vehicle capable re-entry and controlled landing as a reusable craft—an external tank (ET) that supplies the LOX/H2 propellant to the orbiter main engines, and two reusable solid rocket boosters (SRBs) that provide additional power at launch. The launch vehicle assembly, or stack, is 184 feet tall and 122 feet long with a wing span of 78 feet. The launch vehicle weighs 4,500,000 pounds at liftoff (weight may vary depending on payload). On the re-entry runway, the orbiter is 57 feet tall. It can lift a payload of up to 50,000 pounds to orbit and can carry up to seven crew.

The Space Shuttle is the first partially reusable space vehicle, and as such it represented new challenges to design and analysis due to the coupled interaction of the four-body (orbiter, two solid rocket boosters, and external tank) configuration with many joints and local load paths. Also, the viscoelastic effects of the solid rocket boosters (SRBs), together with the unsymmetrical stiffness and mass effects on the orbiter, were an added complexity. A vigorous dynamic test program was planned that included not only the ¼ scale model, but also a horizontal GVT (HGVT) performed on the orbiter by itself and a mated vertical GVT (MVGVT) performed on the four-body full-scale vehicle to validate the mathematical models developed.

The MVGVT was performed between the summers of 1978 and 1979 at MSFC's TS 4550. The vehicle test configuration necessitated modifications to the test stand and the reactivation of HDSs used during Saturn V testing. TS 4550 was designed to test vehicles larger than the Saturn V, specifically a vehicle with a 50-foot diameter and about the same height as Saturn V; thus the interior of the stand was adequately sized to accommodate Shuttle for dynamic testing.[14] Three columns and all horizontal and vertical connectors to them were removed. Five new columns were added and the 200-ton derrick crane was relocated. The door was widened to allow the orbiter to be emplaced in one piece.

The Saturn-era HDSs were used to provide the free-free condition to simulate flight. To save cost, adapter frames were developed for the Saturn-era HDSs. These adapter frames required removing the SRB nozzles, as the weight of these components was compensated by the adapter frames.

The Space Shuttle was tested in five configurations during the MVGVT, two for the four-body vehicle and three for the two-body vehicle. The four-body test configuration consisted of the orbiter, two solid rocket boosters (SRBs) and the external tank (ET). This was tested at lift-off and pre-SRB separation (burn-out) vehicle configurations. The two-body test configuration consisted of the orbiter and ET, which were tested at start of boost, mid-boost, and end-of-boost vehicle configurations.

Results of the MVGVT generally showed mode shapes and frequencies below 10 Hz correlated well, with 5% or less difference between test-measured frequencies and pre-test analytical frequencies. Frequencies between 10 to 20 Hz correlated less well, with differences between the test-measured frequencies and pre-test analytical frequencies greater than 5% and less than 10%. Frequencies greater than 20 Hz correlated poorly (greater than 10% difference between test-measured and pre-test analytical frequencies) with the models. The user frequencies of interest were below 10 Hz, so the structural dynamic models were judged adequate for flight certification.

Major test results identified local resonances in the SRB rate gyros. These resonances corrupted sensor signals. If they had occurred during flight, they would have caused a loss of the sensor. Anomalies were also observed in the orbiter side-mounted rate gyros.

Figure 3 - Orbiter and External Tank in TS 4550

Overall, structural damping data ranged from 0.1 percent to greater than 10 percent. Average modal damping was between 1 percent and 3 percent. This damping data was invaluable in the flight certification stability margins.[15]

The Space Shuttle was the first human-rated NASA spacecraft to fly humans on its inaugural launch. Results of the dynamic testing during the MVGVT were critical to the decision to launch the vehicle without first performing unmanned flight tests. Dynamic testing continued, however, through the first five flights, all crewed. Clearly the verification of vehicle mathematical models was vital to the successful first flight and the eventual assessment to declare the Shuttle operational. Without this test data to verify the models, confidence to launch humans on the first flight of the vehicle would have been greatly reduced.

Table 2 summarizes the major findings from the Space Shuttle MVGVT and likely consequences.[16]

Table 2 – Space Shuttle MVGVT Problems and Consequences

Space Shuttle MVGVT Problems Discovered	Hardware Impacted	Consequences if Not Discovered
SRB-mounted rate gyros exhibited abnormally high transfer functions. The rate gyros mounted on the forward SRB ring frames resonated at local frequencies and high gains, which were critical to flight controls.	Structural redesign was required to stiffen the SRB ring frame, which raised the local resonant frequencies and reduced the gain.	Flight control instability and possible loss of vehicle.
Axial SSME frequencies and mode shapes did not correlate with pre-test analysis. A half-shell dynamic math model using symmetry was used in pre-test analysis.	A new three-dimensional asymmetric math model of the SSME engines and thrust structure was required. No hardware changes necessary.	Pogo stability analyses would have been suspect.
Test rate gyro values showed greater response variations than analysis. Response variations between RGAs were much larger than those used in the analytical studies in determining the Redundancy Management (RM) trip levels.	RM software trip levels and cycle counter levels were increased. The fault isolation routine was modified to inhibit kicking out RGAs and ACCs after first sensor failure.	Flight control instability and possible loss of vehicle.

ARES

In 2005, NASA began work on the Constellation Program with the goal of sending humans to the Moon and building a permanent base there in preparation for missions to other destinations. The Ares project within the Constellation Program is responsible for developing, building, and testing the Ares I and Ares V launch vehicles.

The Ares I crew launch vehicle will lift the Orion crew module to low Earth orbit. It is an in-line, two-stage configuration. The first stage is a five-segment solid rocket booster based on the heritage Space Shuttle SRB design, and, like the Shuttle SRBs, is reusable. The Upper Stage is powered by the J-2X engine, which is derived from the Saturn second-stage J-2 engine and incorporates technologies from other engines. The Orion crew module sits on top of the second stage.

Ares I is 325 feet tall, weighs 2,000,000 pounds at launch and is capable of lifting 56,500 pounds into low Earth orbit. Ares I has two missions: carrying up to six crew (or cargo) to the International Space Station or carry four astronauts to low Earth orbit for rendezvous with Ares V for missions to the Moon.

The Ares V cargo launch vehicle will be a heavy-lift vehicle designed to launch cargo and rendezvous with Ares I in Earth orbit. The core stage will be powered by five RS-68 LOX/LH_2 engines. Two five-segment SRBs, like the first stage of Ares I will also provide launch power. The second stage, or Earth departure stage (EDS), will be powered by a single J-2X engine, the same used for the Ares I second stage. The Altair lunar lander is the payload.

Ares V will be 360 feet tall, weigh 7,400,000 pounds at launch and will be capable of lifting about 316,000 pounds into low Earth orbit and 140,200 pounds to lunar orbit. Its mission is to lift the Earth departure stage, Altair lunar lander, and other mission-related cargo to low Earth orbit for rendezvous with the Orion crew module prior to its journey to the Moon.

Plans to perform the Integrated Vehicle GVT (IVGVT) for Ares I began in early 2006. The models correlated from IVGVT test data will support the Ares I Design Certification Review (DCR) in July 2013. The DCR supports the first crewed launch of the Ares I/Orion vehicle planned for September 2013.

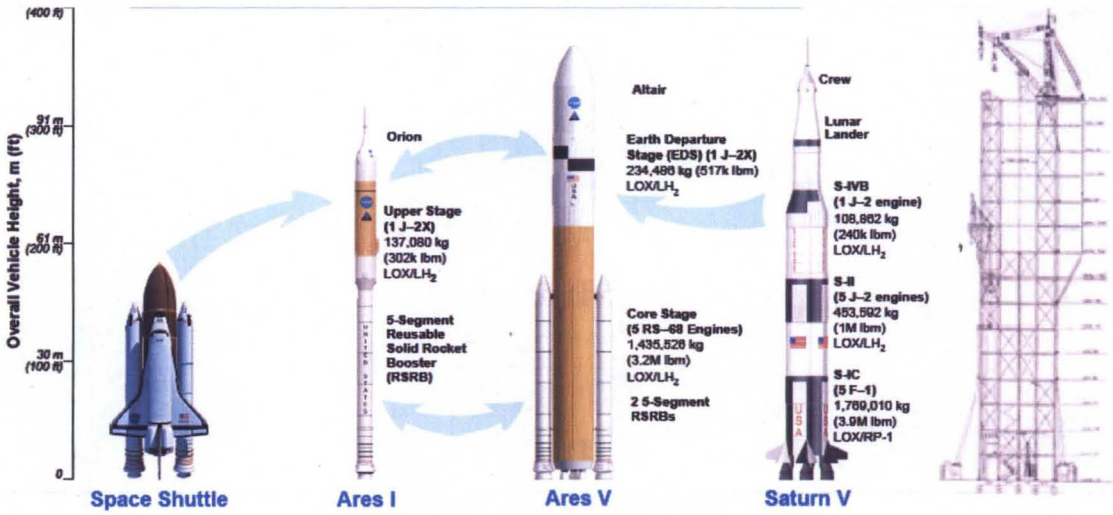

Figure 4 - Launch Vehicle Size Comparison

It has been more than 25 years since the Space Shuttle MVGVT; this TS 4550 is being repaired and modified for reactivation to conduct the Ares I IVGVT. In 1987, the United States Department of the Interior's National Park Service designated TS 4550 a national historic landmark. NASA conducted an historical study of the stand, including a review of the original design and subsequent modifications, which were submitted to the Department of the Interior, Historic American Building Survey. This study ultimately will be part of the Library of Congress collection. As required by Federal law, an environmental impact study was performed and posted for public review. This study was approved by MSFC management in January 2008.

The 200-ton derrick crane on top of the stand has undergone significant repairs, including installation of a new motor. In March 2008, the crane was used to remove the roof panels and lower the door for the first time since the MVGVT. Currently the Shuttle-era platforms are being removed. They will

be replaced with mast climbers (Figure 5) that provide ready access to the test articles and can be moved easily to support different test positions within the test stand. Two new cranes are being procured, a jack/gantry crane and a 100-ton mobile crane, which will be used to aid in moving test articles both at the test stand and at the Redstone Arsenal railhead where first stage segments will be received.

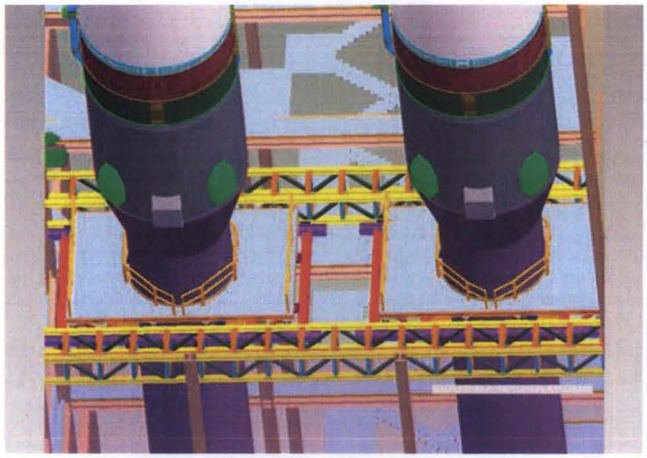

Figure 5 – Mast Climber Concept for TS 4550

The approved design upgrades for TS 4550 include a new electrical system and an additional emergency staircase for improved safety. Work on these modifications will begin in the summer of 2008 and is scheduled to complete in the summer of 2009.

Phase I of test requirements development for the IVGVT was completed in January 2008. This phase consisted mostly of beam model development and exploration of frequency ranges of interest. Phase II is currently underway and will complete prior to the Ares I Preliminary Design Review (PDR) schedule for late summer 2008. The test requirements support development of the IVGVT Test Plan as well as the Special Test Equipment (STE) development and design. A draft Test Plan will be submitted for review at the Ares I PDR. STE design is nearing completion of the preliminary phase in late spring 2008.

The HDSs used for Saturn and Shuttle (Figure 6) are being disassembled and evaluated for use during IVGVT. Progress to date indicates that the 45-year-old HDSs can be refurbished in support of the Ares I IVGT. In parallel with the HDS evaluation, an alternate concept pneumatic system is being explored. A decision on which suspension system to use for IVGVT will be made in late summer 2008.

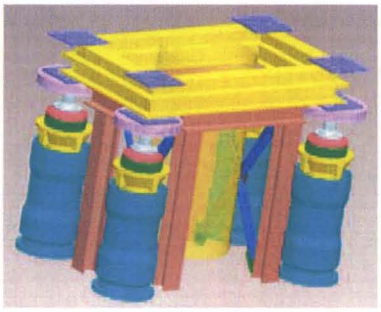

Figure 6 - HDS Concept with New Attach Frame

The current plan is for the Ares I IVGVT to test six configurations in three unique test positions in TS 4550. Position 1 consists of the Upper Stage and Orion crew module. Four test configurations will be tested. These are J-2X ignition, post Launch Abort System (LAS) jettison, critical slosh mass, and J-2X burn-out. Position 2 consists of the full launch stack at first stage burn-out (using empty first stage segments). Position 3 consists of the full launch stack at lift-off (using inert first stage segments). Transfer function measurements will be made during all test configurations (Figure 7).

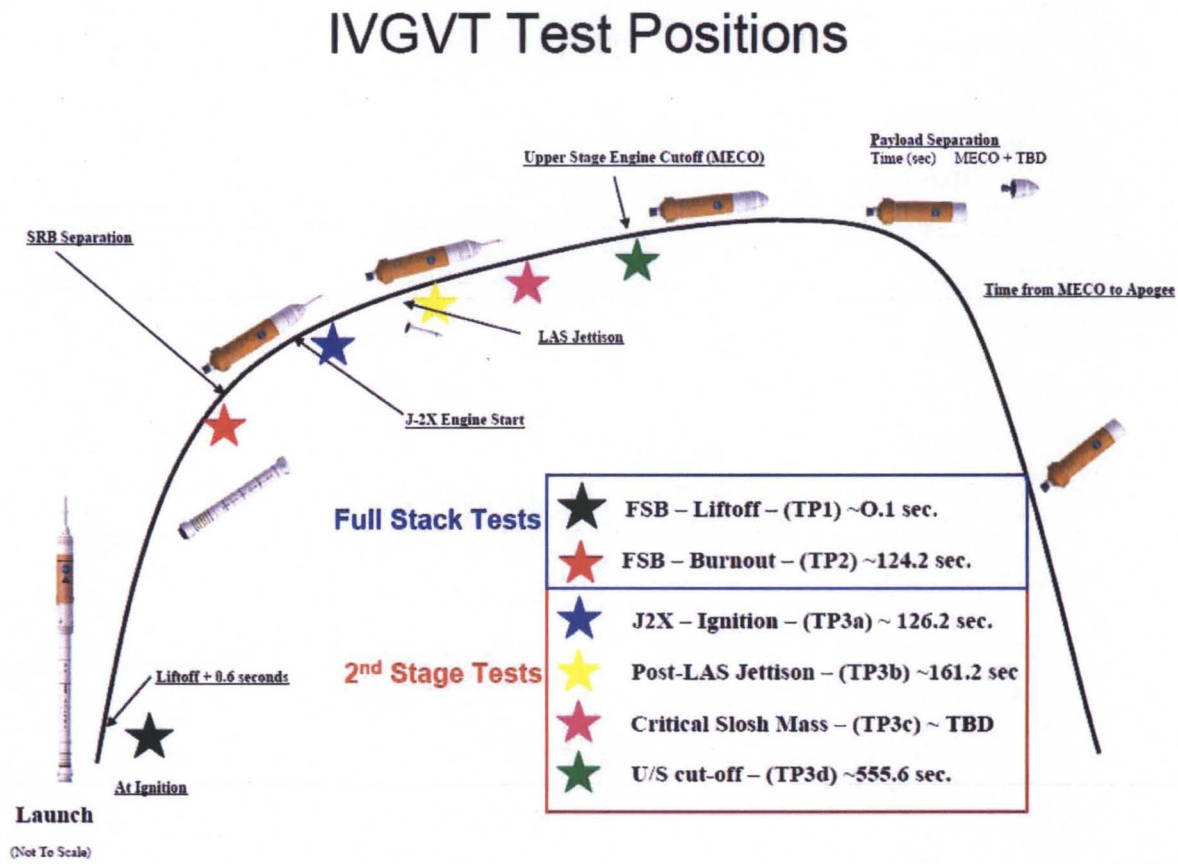

Figure 7 – Ares I IVGVT Test Configurations

The Ares IVGVT will be conducted from mid-2011 to mid-2012. It is intended to measure by test the fundamental dynamic characteristics of Ares I during various phases of operation and flight. The final measured results of the IVGVT are clearly dependent on the vehicle hardware used during the test. A fundamental philosophy of structural dynamic testing is to have as few differences between the test article and the flight article as possible. For accurate testing and model correlation, both the test and flight configurations must be known and differences understood fully, which is sometimes referred to as "test what you fly, fly what you test." To accurately represent the properties of the Ares I flight vehicles, the Ares I IVGVT will be conducted on a test article built to flight-equivalent specifications. Mass simulators of

components may be used for flight-quality components that are not available in the scheduled test timeframe, provided there is sufficient technical rationale to do so.[17]

Test objectives pertaining to flight control objectives are 1) to obtain natural vehicle mode shapes, frequencies, generalized mass and damping characteristics which are used in the stability equations and 2) to obtain the amplitude and phase response of the elastic vehicle from thruster locations to all flight control sensor locations.[18]

Structural dynamic test objectives are 1) to obtain mode shapes, frequencies and damping to be used as the reference for test calibrated CLV configuration models that form the basis of final verification loads and GN&C controls analysis and 2) to obtain experimental non-linear characteristics of vehicle configurations by exciting the test specimen at different force levels.[19]

Ares V planning and early design is in work at this time, but at a very low level of effort as the Constellation program focus at this time is on Ares I/Orion development and launch. However, initial planning for the Ares V IVGVT has been ongoing. This consists primarily of facility studies and a preliminary schedule for long-range budget planning purposes. Ares V efforts are expected to increase in fiscal year 2010.

SUMMARY AND CONCLUSIONS

NASA has conducted dynamic tests on each of its major launch vehicles during the past 45 years. Each test has provided invaluable data to correlate and correct analytical models used to predict structural responses to differing dynamics for these vehicles and for the control of the vehicles. With both Saturn V and Space Shuttle, hardware changes were also required to the flight vehicles to ensure crew and vehicle safety.

The Ares I IVGVT will undoubtedly provide similar valuable test data to support successful flights. The IVGVT will provide test-determined natural frequencies, mode shapes, and damping for the Ares I. This testing will support controls analysis by providing data to reduce uncertainty in the models. The value of this testing has been proven by past launch vehicle successes and failures. Performing dynamic testing on the Ares vehicles will provide confidence that the launch vehicles will be safe and successful in their missions.

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