



National Aeronautics and Space Administration

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Integrated Vehicle Ground Vibration Testing in Support of Launch Vehicle Loads and Controls Analysis



Outline

- ◆ **Background of Ground Vibration Tests (GVTs)**
- ◆ **Failures Attributable to Lack of a GVT**
- ◆ **GVT Experiences on Saturn V**
- ◆ **GVT Experiences on Space Shuttle**
- ◆ **GVT Activities on Ares Launch Vehicles**
- ◆ **Conclusion / Questions**



Background of Ground Vibration Testing (GVT)

- ◆ **Ground vibration tests (GVT) measure fundamental dynamic characteristics of launch vehicles simulated for various phases of flight**
- ◆ **Validates pre-test finite element models (FEMs) for use in verification loads analysis**
- ◆ **Performed before flight**
- ◆ **GVT has led to the development of successful NASA launch vehicles**
- ◆ **Without test-calibrated models, model uncertainty factor (MUF) is not updated**
- ◆ **Uncertainty can translate into increased mass and vehicle instability due to incorrect modeling and boundary conditions**



Failures Attributable to Lack of a GVT



◆ Failure to conduct a GVT can have catastrophic consequences

● Delta III

- Destroyed on maiden launch because control system software corrected 4-hertz oscillation that would have self-corrected
- Designers relied on known Delta II vehicle responses despite being significantly different vehicle

● Ariane 5

- Lost on inaugural flight because of lack of understanding of new engine nozzle and lack of additional safety margins

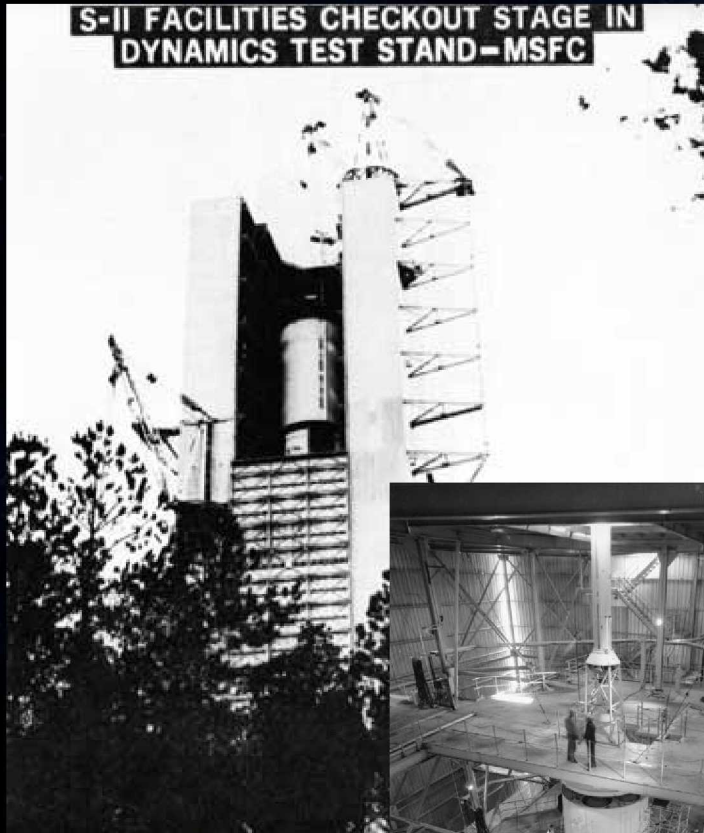
● Falcon 1

- Suffered partial failure on second test flight when first stage bumped second stage engine bell
- Ultimately produced vehicle roll causing LOX tank to slosh from amplified oscillations
- Mission indicates some modal characteristics not well understood



GVT Experiences on Saturn V

S-II FACILITIES CHECKOUT STAGE IN DYNAMICS TEST STAND—MSFC



- ◆ **Dynamic Vibration Testing (DVT) performed on full-scale vehicle test article at Marshall Space Flight Center (MSFC)**
 - Determined structural dynamic characteristics and verified structural integrity
 - Three booster stages, instrument unit (IU), and payload
 - Vehicle weight ~6 million pounds fully fueled
 - 365 feet tall, 33-foot-diameter base
 - De-ionized dichromate water used to simulate first stage propellant and LOX in the second and third stages
 - LH₂ tanks left empty in second and third stages for lateral testing and water simulated weight for longitudinal and roll testing
- ◆ **Test Stand (TS) 4550**
 - 360 feet high
 - 200-ton derrick crane on top of the building
 - Platforms at 24-foot intervals provided access to vehicle



Generating Vibrations for TS 4550

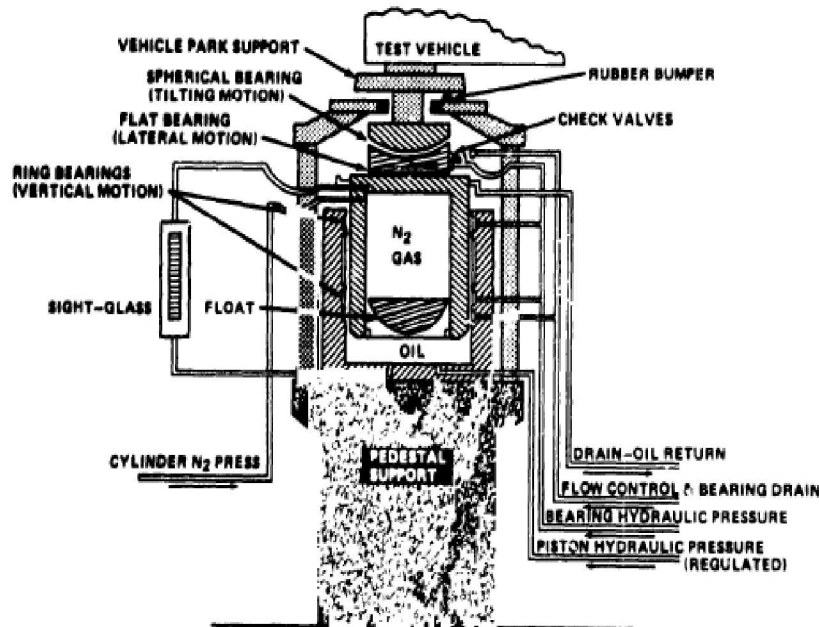


Figure 2. Typical hydraulic dynamic support.

- ◆ **Suspension system required to simulate free-flight conditions**
- ◆ **Soft-support systems used to simulate free-free (unconstrained) boundary conditions vehicle experiences during flight**
- ◆ **Hydrodynamic support system (HDS) uses oil bearings and vertical gas springs for lateral and roll stability**
- ◆ **Lateral support provided by two sets of lateral stabilizing springs**
- ◆ **DVT tested three configurations:**
 - S-IC first stage, S-II second stage, S-IV third stage, IU, Crew Service Module (CSM) and Launch Escape System (LES)
 - S-II second stage, S-IV third stage, IU, CSM and LES
 - S-IVB-D third stage, IU, CSM and LES



Lessons Learned from Saturn V GVT

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.
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.



GVT Experiences on Space Shuttle



◆ Mated Vertical GVT (MVGVT) performed at Marshall Space Flight Center (MSFC) on full-scale vehicle test article

- Included orbiter, external tank, and two solid rocket boosters (SRBs)
- New challenges to design and analysis due to coupled interaction of four-body configuration
- Viscoelastic and mass effects of configuration added complexity
- TS 4550 modified to fit Shuttle, but Saturn-era HDS still used
- Five configurations: two for the four-body vehicle and three for the two-body vehicle
- Results of MVGVT critical to decision to launch vehicle without first performing unmanned flight tests



Lessons Learned from Shuttle MGVVT

Space Shuttle MGVVT Problems Discovered	Hardware Impacted	Consequences if Not Discovered
<p>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.</p>	<p>Structural redesign was required to stiffen the SRB ring frame, which raised the local resonant frequencies and reduced the gain.</p>	<p>Flight control instability and possible loss of vehicle.</p>
<p>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.</p>	<p>A new three-dimensional asymmetric math model of the SSME engines and thrust structure was required. No hardware changes necessary.</p>	<p>Pogo stability analyses would have been suspect.</p>
<p>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.</p>	<p>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.</p>	<p>Flight control instability and possible loss of vehicle.</p>



GVT Activities on Ares Launch Vehicles

◆ Two test vehicles to be delivered and tested at MSFC:

- **Ares I** crew launch vehicle (Launches Orion with 4-6 crew members to LEO for ISS or for lunar missions)
 - 2 SRB first stage sets (inert and empty)
 - 1 flight-like Upper Stage with dynamically simulated USE (J-2X)
 - 1 flight-like Orion
- **Ares V** cargo launch vehicle (Launches Altair to LEO for rendezvous with Orion and missions to Moon or beyond)
 - 2 SRB sets (inert and empty)
 - 5 RS-68 LH2/LOX engines or simulators for core stage
 - 1 J-2X engine or simulator for Earth departure stage
 - Launches Altair to LEO for rendezvous with Orion and missions to Moon or beyond

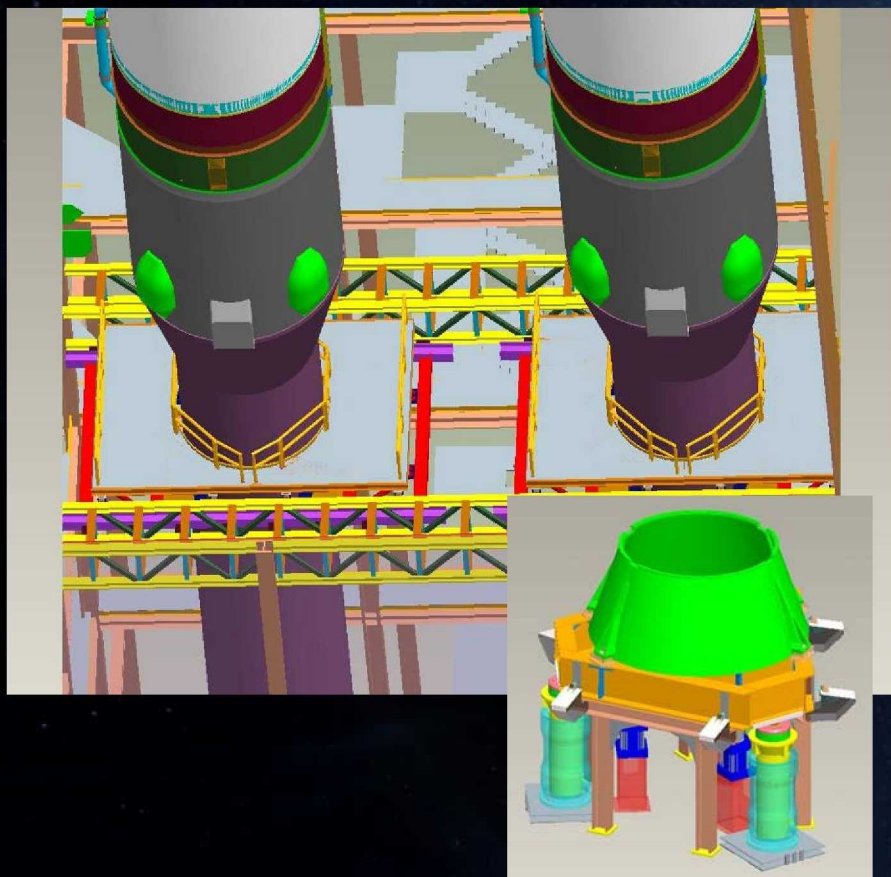


◆ **Ares I** IVGVT 2011 **Ares V** IVGVT 2015



GVT Activities on Ares Launch Vehicles

- ◆ **TS 4550 to be repaired and modified for Ares Integrated Vehicle GVT (IVGVT)**
 - Derrick crane repaired
 - Two new cranes being procured to help with moving test articles
- ◆ **Phase I of developing test requirements for IVGVT completed January 2008.**
- ◆ **HDS used for Saturn and Shuttle being disassembled and evaluated for use in IVGVT**
- ◆ **Decision on hydraulic, pneumatic, or hybrid suspension system in May 2010**
- ◆ **6 test configurations:**
 - 4 2nd Stage tests (Upper Stage and Orion)
 - Full launch stack at first stage burn-out (using empty first stage segments).
 - Full launch stack at lift-off (using inert first stage segments)



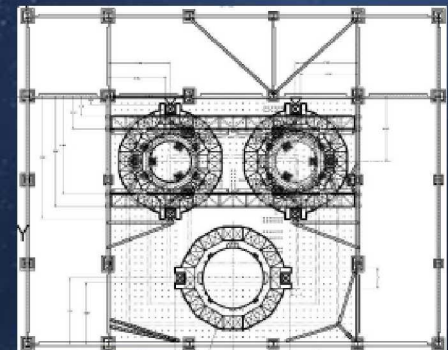
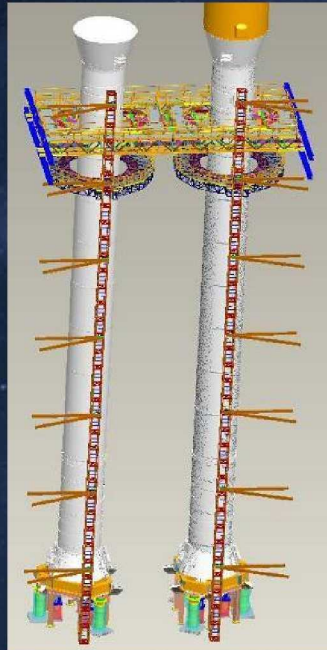


GVT Activities on Ares Launch Vehicles

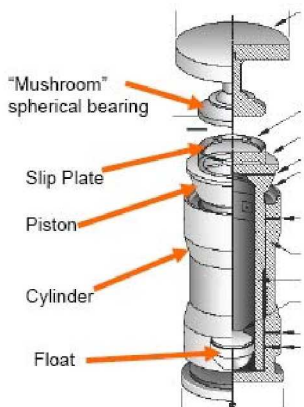
Preparing TS 4550



Designing Mast Climbers



Analyzing HDS Alternatives



"Rocker" spherical bearing prototype



Pneumatic suspension system prototype

Coordinating Test Article Transportation

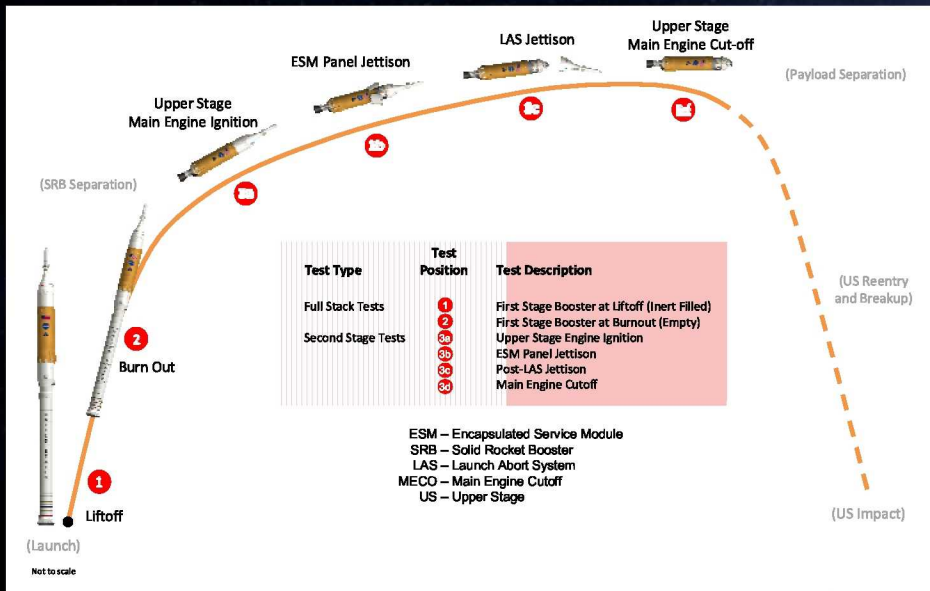


HYDRODYNAMIC SUPPORT (HDS)
 -Used for Saturn & Shuttle Dynamic Tests
 -Primary/Baseline option
 -Investigating "no float" option
 -Only 4 units. Must move between test positions.

PNEUMATIC ALTERNATIVE
 -Designed and Fabricated by Rodney Phillips/ET40
 -Designed as alternative in case HDS's were unusable
 -Continued development for technical & cost comparison
 -Uses pneumatic new slip plate and spherical bearing



IVGVT Objectives



- ◆ **IVGVT will measure fundamental dynamic characteristics of Ares I during various phases of operation and flight**
- ◆ **Minimizing dynamic differences between test article and flight articles**
- ◆ **Flight control test objectives:**
 - Obtain natural vehicle mode shapes, frequencies, generalized mass and damping characteristics
 - Obtain amplitude and phase response of elastic vehicle from thruster locations to all flight control sensor locations
- ◆ **Structural dynamic test objectives:**
 - Obtain mode shapes, frequencies and damping to be used as reference for Ares I models
 - Obtain experimental non-linear characteristics of vehicle configurations
- ◆ **Ares V efforts expected to increase in fiscal year 2010**



Summary

- ◆ **NASA has conducted dynamic tests on each major launch vehicle during the past 45 years**
- ◆ **Each test provided invaluable data to correlate and correct analytical models**
- ◆ **GVTs result in hardware changes to Saturn and Space Shuttle, ensuring crew and vehicle safety**
- ◆ **Ares I IVGVT will provide test data such as natural frequencies, mode shapes, and damping to support successful Ares I flights**
- ◆ **Testing will support controls analysis by providing data to reduce model uncertainty**
- ◆ **Value of testing proven by past launch vehicle successes and failures**
- ◆ **Performing dynamic testing on Ares vehicles will provide confidence that the launch vehicles will be safe and successful in their missions**



Questions?

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