Lessons from the James Webb Space Telescope Vibration Test Prep

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Agenda

JWST/OTIS Overview
Facility Commissioning Challenges
Operational Constraints
Control System
Data Acquisition
Pre/Post Test Signatures
Mission Objective

- Study the origin and history of galaxies, stars and planetary systems
  - Optimized for infrared observations (0.6 – 28 µm)

Organization

- Mission Lead: Goddard Space Flight Center
- International collaboration with ESA & CSA
- Prime Contractor: Northrop Grumman Space Technology
- Instruments:
  - Near Infrared Camera (NIRCam) – Univ. of Arizona
  - Near Infrared Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA
  - Fine Guidance Sensor (FGS) – CSA

Description

- Deployable telescope w/ 6.5m diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
- Launch on an ESA-supplied Ariane 5 ECA rocket to Sun-Earth L2
Facility Requirements

• Test article size
  • OTIS envelope: 8’-5” x 7’-10” x 28’-3”
  • OTIS mass: 8,686 lbs
  • Fixture mass: 6,200 lbs

• Cross-axis motion
  • Bare Table: <10%
  • OTIS Payload: <40%

• Overturning moment capacity
  • Must react moments simultaneously

• No test aborts <400ms

<table>
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<th>Axis</th>
<th>Frequency (Hz)</th>
<th>Test Level (zero to peak)</th>
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</tr>
<tr>
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Pitch: 3.50e6 in-lbf
Roll: 180,000 in-lbf
Yaw: 50,000 in-lbf
Vertical: 1.30e6 in-lbf
1.40,000 in-lbf
300,000 in-lbf
Dual Shaker Systems

- Horizontal system
  - T-film slip table system
  - Single ED shaker
  - Excite V1 & V2 axis

- Vertical System
  - Patented inertial mass guidance
  - Dual ED shakers
  - MIMO control
  - Excite V3
Horizontal System

• Design Concept: T-Film slip table with high rotary inertia reaction base
  – Expansion of standard Team T-Film Table to accommodate extremely large overturning moments

• Design Components:
  – Electrodynamic Shaker
    • Single 50,000 lbf shaker
    • Air isolated trunnion mount
  – T-Film Table
    • Hydrostatic Bearings
    • Couples overturning moments into reaction base
  – Reaction Base
    • High rotary inertia
    • Air isolated
    • High density concrete masses
Horizontal System – Hydrostatic Bearings

- **T-Film Bearings**
  - Fundamental element in Team slip tables
  - Reacts roll and pitch moments
  - Placed in load path from OTIS to reaction base

- **Yaw Bearings**
  - Reacts yaw moment
  - Guides slip plate in shaker axial direction

- **Filler Elements**
  - Static load support
  - Do not react moments

- **5-degrees of control**
Vertical System

- **Design Components:**
  - Electrodynamic Excitation
    - Dual 50,000 lb shakers
  - Guided Head Expander
    - Transmits energy from shaker to test article
  - Inertial Masses
    - React moments generated by test article
  - Hydrostatic bearings
    - Provides short, stiff load path into masses
  - Air Isolated Supports
    - Isolates vibration system from building
Vertical System
Soft Shutdown

• The soft shutdown requirement was integral to the system design

• Shutdowns are controlled by the furnished Data Physics control system
  • Abacus hardware
  • SignalStar Vector/Matrix software

• Shutdown time is software programmable

• The Abacus generates an enable signal that is passed to all hardware required to enable test (stop switch, THC, amplifier, TAPS)

• Each piece of equipment must command a relay closed to return the enable signal

• Removal of the enable signal triggers a controlled shutdown
Facility Commissioning Challenges

• Poor Coherence on Shaker#2:
  
  – Determined to be caused by poor connection between copper current lead and aluminum lead block on shaker
  
  – The likely root cause of the poor connection is a combination of dimensional discrepancy and galvanic corrosion

Arcing caused by the poor electrical connection.

A good electrode on the top
The bad electrode on the bottom
Facility Commissioning Challenges

- Opening the shaker up to investigate the coherence problem uncovered cracks in the copper compensating bands
  - Cracks formed in weld areas joining copper plates
  - Cracks formed in the plug welds joining the copper plate to the steel body
- Further investigation showed these cracks in all 3 DP shakers
- DP return the 2 vertical shakers to Corona for repair
- Horizontal shaker remained installed at GSFC
Facility Commissioning Challenges

• The shaker tear down also revealed some possible wear on the upper armature bearing
  – Initially thought the coherence problem could be stiction in bearing or armature rubbing
  – Raised concerns that shaker armature is over constrained

• Possible solutions
  – Redesign shaker driver adapter, adding compliance
  – Increase armature gap in shaker body
  – Compute lateral armature deflections from test data

• DP offers that the copper bands can be removed
  – Acts as a transformer but only at high frequencies (>500Hz)
  – Eliminates troublesome cracked components
  – Increases gap around armature

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Shaker Rework

• Decision to remove compensating bands
• Factory acceptance test without compensating bands
  • Without cooling integral to the compensating bands, shaker body gets hot and stays hot (250F on body and center pole)
  • Peak force degradation begins at 70Hz
• DP reconsiders and recommends reinstalling compensating bands/cooling, but first turning down the shaker body to retain gap
• JWST agrees and shaker #1 is expedited on the new plan with shaker #2 to follow
Shaker #1 Returns to GSFC

• Shaker #1 completes factory acceptance test and is shipped to GSFC
• During on site acceptance testing, at 27 min into a 30 min random test at 80% force, the amplifier aborted on a peak current fault
• The armature had ruptured and gallons of armature cooling water erupted into the shaker body.
Shaker #1 Compensating Band
Shaker #1 Hot Spots and Rupture

Blow out area between steel cladding
Shaker #1 Failure

• Poor process control resulted in a poor installation of the compensating band
  • Copper was not in sufficiently in contact with the steel
  • Welding process not well controlled, resulted in poor heat conduction
  • The final machining of the band (following welding) resulted in very thin sections of the band

• The armature in shaker #1 was the armature exposed to “no copper” testing
  • Overheating of the fiberglass insulation resulted in compromised mechanical and dielectric properties resulting in catastrophic arcing
Shaker #2

• Following the failure of shaker #1, DP step up efforts to complete shaker #2 rework, perform factory acceptance testing, and deliver to GSFC

• Hot spots on shaker #1 were discovered while shaker #2 was in the midst of factory acceptance test, prompting disassembly of shaker #2 for inspection

• Some hot spots were found on shaker #2, but to a lesser extent than shaker #1
Operational Constraints

• Limit heating of the shaker internals
  • Limit amplifier current to 1750A, ~70% of capability
    • Reduces shaker force to ~35,000 lbf
    • Implemented as limit channel on controller
  • Measure hot spot temp directly with thermocouple
    • Record TC as response channel during test
    • Applied abort limit to TC at 100C

• Monitor voltage coherence for any deviation

• Monitor head expander/slip table/vibe fixture temps
  • Required average temp of 24C +/-3C to perform any test runs
Control System

• Data Physics Abacus/SignalStar

• Integral to satisfying soft shutdown requirement

• During the facility commissioning phase a hard shutdown was experienced while testing on the slip table
  • “Urgency Stop” error message was reported in the software
  • Shaker stopped abruptly
  • DP determined that the software had called for a stop in zero seconds by executing an unexpected code path due to a communication error

• NASA GSFC Flight Software Division was brought in to help
Control System

• Identified that the communication error is a vulnerability when using more than one Abacus chassis (>32 channels)
  • Communication over Ethernet in a ‘realtime’ control system is not robust
  • Ethernet protocol ensures that the data packets with get there eventually
  • Eventually resolved to limit control system to 32 channels

• Hard code 400ms shutdown is such a way that “stop” cannot be called with any other value

• Several other important, but less critical issues were identified
  • Software lockup
  • Lack of a global scale factor for limits
  • Overwrite of test data
  • Improper channel labeling
  • Painfully slow parameter file generation
Control System

• It took several months to get the bugs fixed, properly tested, and the new version delivered

• The fixes implemented seemed to reveal more bugs
  • Faulty start up logic when limits predicted to engaged at start frequency
  • Faulty startup logic when limits predicted to engage as stop frequency.
  • Failure to generate COLA running multiple test runs

• DP went through several iterations and provided several software releases to us

• Settled on a release that was stable and the known risks could be mitigated
Data Acquisition

• Initial requirement ~500 channels
• Existing DSPCon DataFlex 1000 Hardware 320 channels
• Supplemented by purchasing m+p VibRunner

• Final configuration: 544 channels of response + 64 channels for facility
  • 288 channels of DataFlex for response
  • 256 channels of VibRunner for response
  • Additional 64 channels of DataFlex backing Abacus and recording facility channels (reaction base accels, amp current, amp voltage, bearing pressures, etc.)
Data Acquisition

- After adding the VibRunner hardware we approached m+p about their ability to interact with our soft shutdown circuit.

- VibRunner is capable of commanding relays with digital I/O to trigger shutdown when abort limits are exceeded.

- In our configuration VibRunner controls two relays in series:
  - A normally open relay is commanded closed to enable the controller.
  - A normally closed relay is commanded open when an abort limit is exceeded.
Data Acquisition

• The resulting system can trigger an abort on any of the 256 channels

• Limitations:
  • COLA must be present to function, due to our use of the sine reduction package to drive data acquisition
  • Only configured to abort on time domain peak acceleration
    • Other options should be possible, but have not been tested yet
Completion of Facility Commissioning

• Dynamic test mass
• Final software
• Enforcing operational constrains
• Performing OTIS test specification
Pre/Post Signature

- Sine control at requested levels (0.025 to 0.05g) difficult to control with lightly damped test article
Pre/Post Signature

Pretest transfer function from same control accels

Slopes of 400 to 500 dB/oct
Pre/Post Signature

• Implemented method using open-loop pretest random for signatures
  - Computed transfer functions
    • Flat random drive signal does not result in uniform excitation, but transfer functions normalize the results
    • In axis input monitor accel as reference
  - SignalStar gives the user control over the pretest drive signal
    • Number of averages (indirectly controls duration)
    • Shaped pretest
      • Define breakpoints to set relative amplitudes
      • Burst random – need to experiment with this one

• This technique has the benefit of a built in signature in every test run
Example Response Signature Overlay

Fsum 300V3 F300V3

Notes:
1. MP\_v1Swp90.mat
   - Channel: 52
   - Run: MP\_v1Swp90 - PreTest Only
   - Analysis: PreTest Transfer Fcn

Project: JWST
Test Item: OTIS
DDAS Channel: 52
Location: Fsum 300V3 F300V3
Low Pass Filter: 3686.4

Data Source
1. MP\_v1Swp90.mat
2. MP\_v1Swp88.mat

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<th>Min Amp / Freq</th>
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<td>1b</td>
<td>1.47e+05 / 10.63</td>
<td>145 / 55.63</td>
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• The pretest results were also used to verify facility and test article health in a more limited fashion after the execution of every pretest.

• For the 32 channels on the controller, transfer functions relative to the drive are already computed in SignalStar.

• This data was copied to an excel file and pasted into its own sheet.

• A macro was written to generate a new sheet with a chart for each channel overlaying data for all the runs stored in the current file.

• In this way all channels can be check for trends against the previous 5 to 10 runs.

• The process is fast enough that it can be completed for every run prior to executing the sweep.

• Sensitive to changes in the gain knob setting
Example Controller Pretest Overlay