Acoustic Test and Analysis

*Heliospheric Imager on STEREO*

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Outline

• STEREO Mission
• Description of HI instrument
• Test Flow
  – Qualifying HI-A and HI-B
    • Random vibration
    • Acoustic
• Acoustic Prediction
  – Matlab implementation of low frequency acoustic reverberant field
STEREO Mission

- STEREO (Solar TErrestrial RElations Observatory)
- Mission will employ two nearly identical space-based observatories to provide stereoscopic measurements to study the Sun and the nature of its coronal mass ejections.
- Launched October 25, 2006 on a Delta II 7925 rocket.
- Johns Hopkins University Applied Physics Lab (JHUAPL) responsible for STEREO spacecraft design and fabrication, observatory integration, testing, and mission operations
- Naval Research Lab (NRL) responsible for SECCHI instrument suite
- University of Birmingham (UB) in England responsible for Heliospheric Imager (HI) instrument with Centre Spatial de Liege, Belgium
Spacecraft Configuration

- Four instrument suites on each spacecraft
  - SECCHI (includes HI)
  - IMPACT
  - PLASTIC
  - SWAVES
- Composite high gain antenna dish
- Two sets of solar arrays on each spacecraft
Heliospheric Imager

- The HI is a wide-angle imaging system for the detection of coronal mass ejection (CME) events in space between the Sun and the Earth.

- HI consists of two small telescope systems mounted on the side of each STEREO spacecraft, sheltered from the glare of the Sun by a series of baffles.
Test Flow

- Qualifying HI Units
  - Sine/Random at the instrument level
  - Acoustic at the spacecraft level
- HIB integration delayed
  - Does HI-B require a standalone acoustic test?
  - Compare test data from the HI-A unit
Accelerometer Locations

- Key locations discussed
  - CG, door
Finite Element Model

- Finite Element Model
  - 58,000 nodes, 107,000 elements
  - Facesheets (M55J and T300 Fabric)
  - Honeycomb panels
  - Bonded panel connections
Vibration Test Setup

- Cleanroom shaker environment at CSL in Liege, Belgium
- Minor differences (thermal blanket)

X Direction Shake

Z Direction Shake

HIA

HIB
Sine Survey Comparisons

- HIA and HIB have similar responses
- Good match to FEM
- Determine damping
HI-B RV and HI-A Acoustic

- All HI responses are enveloped by random response
  - Except the door
- Increasing random vibe level would overtest the instrument

HI-B standalone acoustic test needed to see expected flight loads

S/C Acoustic Test

HIA on S/C

HI-A spacecraft acoustic test

Door Center

HI-B random vibe

HI-B standalone acoustic test needed to see expected flight loads
HI-B Acoustic Test

- HI-B successfully qualified with standalone acoustic test
  - HI-B door responses almost perfectly match HI-A on S/C
  - Free-free and mounted instrument door responses identical
HI-B Responses
Random and Acoustic

- HI-B qualification requires
  - Random vibe for telescopes and baffles
  - Acoustic for door

- Random vibe Grms on telescopes and baffles ~ 2x’s acoustic Grms
- Acoustic Grms on door ~ 2x’s random vibe Grms

<table>
<thead>
<tr>
<th>Channel No.</th>
<th>Accel No./Dir.</th>
<th>Accelerometer Description</th>
<th>Acoustic Test Response Grms</th>
<th>Max Grms HI-B response</th>
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<td>Random Vibe Highest Grms</td>
<td>Driven Axis</td>
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<td>CEB</td>
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<td>Oval</td>
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Acoustic Analysis Methods

- Use test data to compare to analysis
- Several different analysis methods available based on frequency range of interest
- Interested in Low Frequency FEM
Motivation for Low Frequency

- Structural damage occurs at low frequency
  - Frequency cutoff for Grms: Limit PSD integration under 300 Hz
  - Based off of strain gage data

  - Displacement (and stress) rolls off with acceleration/(freq)^2

\[
x = e^{j\omega t} \quad \ddot{x} = -\omega^2 e^{j\omega t}
\]

\[
x = -\frac{1}{\omega^2} \ddot{x}
\]
FE Analysis outside of Nastran

- External programs can include functionality/insight beyond Nastran
  - Typical solutions easily done in Matlab
    - Frequency response
    - Transient response, including jitter
    - Base Shake
    - Random Analysis
      - Acoustic Analysis: include correlation coefficient matrices which are not easily incorporated in Nastran, such as for a reverberant acoustic field
- Use Nastran as eigensolver only
  - Eigenvalues (natural frequencies)
  - Eigenvectors (mode shapes)
Acoustic Analysis Prediction

• Purpose of analysis
  – Use Stereo test data to compare to Matlab approach for low frequency acoustic response

• Low frequency acoustic analysis
  – FEM method only
  – Area of interest is hinge and latch stress

• Approach
  – Extract eigenvalues and eigenvectors from Nastran
  – Extract nodal forces from unit pressure from Nastran
  – Use Matlab to solve SDOF modal equation for each loaded node
  – Obtain transfer functions between each loaded node and response node
  – Solve random solution with specified PSD
  – Include sin(kx)/kx spatial correlation matrix for reverberant field
  – Include surface correction factor
Acoustic Analysis Prediction

Matlab Script

- Damping (modal)
- Driving frequency, \( \{\omega_d\} \)
- Response node

Nastran FEM

- Eigenvalues, \( \{\omega_n\} \)
- Eigenvectors, \( [\phi] \)
- Nodes #’s
- Node locations, (x,y,z)
- Node #’s with load
- Nodal forces from unit pressure, \( \{F\} \)

• Determine transfer function \( \{H\} \) between each loaded node \( \{F_i\} \) and the response point, for each driving frequency, \( W_d \)
  - Use SDOF solution in generalized coordinates to simplify calculations
• Solve random solution as transfer function squared
  - Multiply by input PSD to obtain response PSD
  - Include spatial correlation coefficient matrix, \( \sin(kx)/kx \)
  - Include surface correlation correction factor, maximum of 3.0
Theory (1/2)

Dynamic equation

\[ M\ddot{x} + C\dot{x} + Kx = F \]

Eigenvector transformation

\[ x = \phi q, \quad \dot{x} = \Phi \ddot{q} \]

Dynamic equation in mass normalized modal coordinates

\[ \ddot{q} + 2\zeta \omega \dot{q} + \omega^2 q = \phi^T F \]

SDOF system solution

\[ \ddot{q} = h\phi^T F \quad \dot{h} = \frac{-\omega^2}{(1 - \omega^2) + 2i\zeta\omega\omega_n} \]

Physical coordinates

Solve for each \( F \) (nodal force from unit pressure)

\[ \ddot{x} = \phi \ddot{q} = H \]

Transfer function

From unit pressure
Random solution at each driving frequency

\[ \{PSD_{resp}\} = \{H\}[\rho]\{H\}^T \times \{PSD_{in}\} \times surfcorr \]

Vector size:
1xpg, pgxpg, pgx1

Correlation coefficient matrix, \([\rho]\), is symmetric matrix of \(\sin(kx)/kx\), where \(k\) is wavenumber and \(x\) is distance between any two loaded points.

Including \([\rho]\) is difficult in Nastran – default is a matrix of ones for all frequencies (perfectly correlated pressure field).
Reverberant field on HI Door
\[ \frac{\sin(kx)}{kx} \]

Door Center

200 Hz

300 Hz

500 Hz

Door Corner
HI Door Results

- Door Center
- Door Corner
Additional Acoustic Results

- Extract side panel of STEREO FEM
  - High Gain Antenna
  - Compare reverberant to perfectly correlated pressure field
- Apply normal pressure to colored surfaces
High Gain Antenna Acoustic Response

- High Gain Antenna – Feed
  - Reverberant field more accurate
  - Can give larger or smaller response to perfectly correlated pressure
  - Surprisingly accurate to 400 Hz
High Gain Antenna Acoustic Response

- High Gain Antenna – Top Edge
  - Reverberant field more accurate
  - Accurate to 200 Hz
  - Model frequencies slightly low
HI Door Opening Movie

- Movie of HI Door opening (conceptual)
HI1-B 1st Data Movie

Conclusions

• Successful test program
  – HI-B required both random and acoustic test for qualification
• Fully operational flight units
• Matlab acoustic analysis
  – Low frequency response
  – Include spatial correlation matrix
  – Compared well to test data
    • More accurate than perfectly correlated pressure field
  – Only as good as the FEM

Coronal Mass Ejection from HI
http://www.stereo.rl.ac.uk/STEREO_Gallery.html