NASA Dryden: Flight Loads Lab Capabilities and Mass Properties Testing

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Huntington Beach, CA
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Topics

• Flight Loads Lab Capabilities
• Latest Conventional Moment of Inertia (MOI) Tests
  – Bifilar, Simple Pendulum
  – Iron Cross and X-48B Testing
  – Frequency/Amplitude Relationships
    • Phase 1 Testing vs. Phase 2 Testing
• Dynamic Inertia Measurement (DIM) Method
  – Concept Overview
  – Large-Scale DIM Test
  – Lessons Learned
  – Conclusions
NASA Dryden’s Flight Loads Laboratory

- Proof Loading
- Loads Calibration
- Ground Vibration Testing
- Moment of Inertia
- Strain Gage Installation
- Aerodynamic Heating Simulation
- Thermostructural Testing
- High-Temp Instrumentation
Conventional Mass Properties Testing
Conventional MOI Testing

- Conventional MOI Test Techniques include:
  - Bifilar Pendulum: Dual-wire suspension, oscillates about CG in one axis
    - Must accurately know longitudinal CG to evenly balance load across both bifilars
  - Simple Pendulum: Single or multiple suspension, oscillates about a non-CG point in one axis
    - Must use parallel axis theorem to take out transfer inertia
    - Accuracy suffers because inertia about swing point is relatively large
X-48B and Iron Cross MOI Test (Phase 1)

• X-48B MOI Testing was desired to solve discrepancy between aero models and flight data.
  – MOI Errors were identified as a prime cause for this discrepancy.

• Iron cross test article built to quantify accuracy/uncertainty
  – Very simple, easy to analyze inertia values.

• Once conventional methods were analyzed, the same test setup would be used on X-48B.
  – Accuracies/Uncertainties should remain constant due to similarities in test articles.
Iron Cross MOI Testing – Phase 1

Independent MOI testing was performed at Space Electronics

Bifilar Pendulum/Longitudinal CG Test

Simple Pendulum (Roll)

Simple Pendulum (Pitch)
Iron Cross MOI Results – Phase 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>%Error/Abs. Difference</th>
<th>% Error/Abs. Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Article Weight</td>
<td>.04%</td>
<td>Test Article Weight</td>
</tr>
<tr>
<td>Longitudinal CG (A/C CS)</td>
<td>.051 inches</td>
<td>Longitudinal CG (A/C CS)</td>
</tr>
<tr>
<td>Vertical CG (A/C CS)</td>
<td>.116 inches</td>
<td>Vertical CG (A/C CS)</td>
</tr>
<tr>
<td>Yaw Inertia (lzz, lbs*in^2)</td>
<td>1.47%</td>
<td>Yaw Inertia (lzz, lbs*in^2)</td>
</tr>
<tr>
<td>Roll Inertia (lxx, lbs*in^2)</td>
<td>2.99%</td>
<td>Roll Inertia (lxx, lbs*in^2)</td>
</tr>
<tr>
<td>Pitch Inertia (lly, lbs*in^2)</td>
<td>NA</td>
<td>Pitch Inertia (lly, lbs*in^2)</td>
</tr>
</tbody>
</table>

**Summary of Data**

<table>
<thead>
<tr>
<th>Summary of Data</th>
<th>% Error/Abs. Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Article Weight</td>
<td>0.29 %</td>
</tr>
<tr>
<td>Longitudinal CG (A/C CS)</td>
<td>-0.03 inches</td>
</tr>
<tr>
<td>Vertical CG (A/C CS)</td>
<td>-0.009 inches</td>
</tr>
<tr>
<td>Yaw Inertia (lzz, lbs*in^2)</td>
<td>2.13 %</td>
</tr>
<tr>
<td>Roll Inertia (lxx, lbs*in^2)</td>
<td>5.73 %</td>
</tr>
<tr>
<td>Pitch Inertia (lly, lbs*in^2)</td>
<td>2.39%</td>
</tr>
</tbody>
</table>

**Comparison Between Bifilar/ Simple Pendulum Methods and Space Electronics Data**
X-48B MOI Testing – Phase 1

- Using the same setup as on the iron cross, the X-48B underwent Lateral, Longitudinal, and Vertical CG Testing.
- It also underwent Bifilar Pendulum and Simple Pendulum Testing in Yaw and Pitch/Roll.
X-48B MOI Results – Phase 1

- The roll and pitch inertia terms indicated by the experimental results are very different from the predicted results.
- Digging deeper into the frequency data obtained by the onboard IMU (initially a backup system) yields surprising results
  - Initial results obtained from stopwatch data

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<tr>
<th>Variable</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Yaw Inertia ($I_{zz}$, lbs*in^2)</td>
<td>9.28</td>
</tr>
<tr>
<td>Roll Inertia ($I_{xx}$, lbs*in^2)</td>
<td>56.18</td>
</tr>
<tr>
<td>Pitch Inertia ($I_{yy}$, lbs*in^2)</td>
<td>65.01</td>
</tr>
</tbody>
</table>

Comparison between Predicted and Experimental MOI Data
X-48B MOI Results – Phase 1

• It appears as though a frequency shift is occurring as the amplitude of the swing changes.
  – Frequency only varying a small amount (in this case, <.03 hz)
  – Simple pendulum inertia equation is so sensitive that this can result in a shift of as much as 70% in the inertia values.

• Upon further analysis, the pitch data showed even worse frequency shifts.

Time History and Frequency Plot for Roll Swing
Phase 2 MOI Tests

• Why was the frequency shift happening?
  – Many theories, none proven

• Second phase of MOI Testing required to determine:
  – What is causing the frequency shift
  – Can the frequency shift be corrected for

• Attaching an IMU to the iron cross could determine if the results could be “filtered” by removing data where frequency shifts are occurring.
  – It appeared as if smaller amplitude data produced worse results than larger amplitude data, which goes against traditional thinking
  – Frequency analysis would only be performed over data from ~10 degrees maximum oscillation to ~3 degrees maximum oscillation
Phase 2 MOI Tests

• In addition to focusing on larger amplitude swings, a new setup was devised for pitch swings.
  – In the initial tests, the pitch swings showed significant cross coupling of pitch, yaw, and roll.
  – New setup was designed to alleviate cross coupling
Phase 2 MOI Testing

• Other factors investigated were:
  – Length of suspension system: The simple pendulum equations are sensitive to length (due to the mass rotating about a point other than the CG). By shortening the length, theoretically the accuracy of the calculated inertia should increase.
  – If the iron cross saw frequency shifts as well: If so, then aerodynamic effects could be eliminated as the primary source of the shift.

\[ I_{combined} = I_{TA} + I_{rig} + m_{TA}l^2 \]

\[ I_{TA} = I_{combined} - I_{rig} - m_{TA}l^2 \]
Phase 2 MOI Testing Results

- The iron cross did indeed see a frequency shift (same order of magnitude as X-48B)
- Damping ratio was negligible

- Calculated inertia values as a function of amplitude are shown in the figure to the left.
- Inertia values blow past the predicted values (i.e., not asymptotically approaching, etc.)
Phase 2 MOI Testing Results

- A comparison of all the X-48B and Iron Cross pitch and roll swings are shown to the right.
- Nearly identical trends occurring across all test scenarios.
- In theory, using the data where the frequency shift is negligible (flat region) should provide better results.

Flat region is “good data”, where frequency shift is negligible
Phase 2 MOI Test Results

- Iron Cross results are very consistent with original results.
  - This time, roll inertia is more in line with pitch inertia. This seems to point that the original roll inertia swings suffered from the same frequency shift that the X-48B did, while pitch inertia was less affected.

- X-48B results are more in line with the predicted values.

- Unknown cause of frequency shifts at this time

<table>
<thead>
<tr>
<th>Iron Cross Inertia Values</th>
<th>Phase 1 % Error</th>
<th>Phase 2 % Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw Inertia (Izz, lbs*in^2)</td>
<td>2.13 %</td>
<td>2.13</td>
</tr>
<tr>
<td>Roll Inertia (Ixx, lbs*in^2)</td>
<td>5.73 %</td>
<td>-2.2</td>
</tr>
<tr>
<td>Pitch Inertia (Iyy, lbs*in^2)</td>
<td>2.39%</td>
<td>-2.75</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>X-48B Inertia Values</th>
<th>Phase 1 % Error</th>
<th>Phase 2 % Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw Inertia (Izz, lbs*in^2)</td>
<td>9.28</td>
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</tr>
<tr>
<td>Roll Inertia (Ixx, lbs*in^2)</td>
<td>56.18</td>
<td>-4.04</td>
</tr>
<tr>
<td>Pitch Inertia (Iyy, lbs*in^2)</td>
<td>65.01</td>
<td>-2.95</td>
</tr>
</tbody>
</table>
Summary

• Bifilar pendulum, if great care is taken to provide accurate measurements, is very accurate (in this case, ±2.13%).

• Simple pendulum:
  – Same level of care must be taken in setup to ensure accurate measurements
  – IMU must be used to filter out areas of frequency shift
  – Uncertainty can be as low as ± 2%

• Both methods require meticulous measurement of primary variables (length, weight, frequency)

• In order to get all three moments of inertia using these methods, multiple test setups/fxturing must be designed and implemented.
  – Time and cost increase as a result
Dynamic Inertia Measurement (DIM)
DIM Concept

• Use force excitation and measure structural response via accelerations to determine mass properties
  – Similar to Ground Vibration Test (GVT) techniques
  – Focuses on data off-resonance (“mass lines”)

• Possibility of obtaining all mass properties with one set-up
  – Mass
  – Center of Gravity: $X_{CG}$, $Y_{CG}$, $Z_{CG}$
  – Moments of Inertia: $I_{XX}$, $I_{YY}$, $I_{ZZ}$
  – Products of Inertia: $I_{XY}$, $I_{XZ}$, $I_{YZ}$

• Little additional effort required beyond GVT
  – Same test set-up (soft suspension system, shakers, data acquisition equipment, etc.)
  – Similar data processing
DIM Theory

• Based on Newton’s Second Law (F=ma)
  – Expanded to 6 degrees of freedom

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
M_x \\
M_y \\
M_z
\end{bmatrix}_p = \\
\begin{bmatrix}
m & 0 & 0 & 0 & mZ_{CG} & -mY_{CG} \\
0 & m & 0 & -mZ_{CG} & 0 & mX_{CG} \\
0 & 0 & m & mY_{CG} & -mX_{CG} & 0 \\
0 & -mZ_{CG} & mY_{CG} & I_{xx} & -I_{xy} & -I_{xz} \\
mZ_{CG} & 0 & -mX_{CG} & -I_{yx} & I_{yy} & -I_{yz} \\
-mY_{CG} & mX_{CG} & 0 & -I_{xz} & -I_{yz} & I_z
\end{bmatrix} \begin{bmatrix}
\ddot{x} \\
\ddot{y} \\
\ddot{z} \\
\ddot{\theta}_x \\
\ddot{\theta}_y \\
\ddot{\theta}_z
\end{bmatrix}_p
\]

• Must measure all reaction loads
  – Requires 6 degree-of-freedom (6-DOF) load cells at suspension interface points

• Data computed as Frequency Response Functions (FRFs)
  – Mass property values are determined at each spectral line
DIM Analysis Window

Frequency response function

- Phase
- Support Modes
- Mass Line
- Flexible Modes

A/F (in/s^2 / lbf)

NASA DRYDEN FLIGHT RESEARCH CENTER
DIM Testing Background

• Successfully performed on small (desktop size) test articles
• Last attempted on large vehicles on X-38
  – Unexpected flexible modes hindered successful usage of spatial filtering
  – Unexpected suspension system modes also affected spatial filtering
  – Instrumentation issues with 6-dof load cells and excitation
• This attempt aimed at solving issues with large test article
  – Instrumentation required:
    • Seismic accelerometers – for higher sensitivity
    • 6-DOF load cells at soft suspension system interface points
    • Laser tracker to record DIMM instrumentation orientation
  – Preferred excitation methods
DIM Test Overview

• Partnership between NASA Dryden, ATA Engineering Inc., and Dave Brown (University of Cincinnati)
  – Dryden created test article, provided equipment and executed test
  – ATA created the analysis scripts and performed analysis
  – Dave Brown advised on test and analysis techniques

• New 6-DOF load cell created by PCB

• Test article created out of steel I-beams
  – 17,000 lbs
  – Approximate shape of aircraft

• Mass properties measured:
  – Conventionally (bifilar pendulum, $X_{cg}$ and $I_{zz}$)
  – Using DIM method
Conventional Testing

- Test frame was designed and built to suspend DIM test article
- Bifilar method used to measure X-cg and yaw-inertia
- CAD model was updated to match measured values
DIM Test Setup

Test Article on Soft Supports

Seismic Accels

6-DOF Load Cell
DIM Testing

- Evaluated test methods
  - Sensors
    - Seismic accelerometers
    - 6 degree-of-freedom load cells
  - Excitation techniques
    - Impact hammer vs. shaker excitation
    - Force levels
    - Excitation locations
  - Data collection techniques

- Used ATA’s analysis scripts for DIM analysis
Impact Excitation

- Impact hammer used at 13 locations
  - Poor signal-to-noise ratio in lower frequency range
  - Measured first flexible mode at 17 Hz
  - Measured pedestal flexible mode at 6 Hz
- Performed step relaxation/free decay measurement
- Performed long periods of random impact excitation
  - All forces measured through 6-DOF load cells
Shaker Excitation

- Collected data by exciting with shaker at 7 locations
- Initially used burst random shaker excitation
  - Response did not damp out; produced noisy data
- Continuous random excitation improved data quality
  - Used continuous random with window from 0-100 Hz
  - Performed an additional test run at each location for 1-8Hz to concentrate energy at lower frequency range
- Different force levels evaluated
  - Low force levels were adequate for DIM analysis
  - Switched to smaller shaker for easier handling
Seismic Accelerometers

- Seismic accelerometers were able to measure mass line structural response with much lower noise than conventional accelerometers.
DIM Results (continued)
DIM Results

- Analytical Values
  - CAD model update performed to match bifilar values for X-cg and Izz
  - Mass properties of DIM related hardware added analytically

- Reasonable correlation between analytical and DIM values for most properties
  - Details of test configuration reduced certainty of results
  - Anticipating greatly improved accuracy with next iteration of testing

### Comparison of Analytical and DIM Values

<table>
<thead>
<tr>
<th>Property</th>
<th>NASA Estimations</th>
<th>DIM Method</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (lbf)</td>
<td>16882</td>
<td>17331</td>
<td>-2.66%</td>
</tr>
<tr>
<td>Xcg (in)</td>
<td>91.39</td>
<td>91.51</td>
<td>-0.13%</td>
</tr>
<tr>
<td>Ycg (in)</td>
<td>-0.17</td>
<td>-0.43</td>
<td>0.26</td>
</tr>
<tr>
<td>Zcg (in)</td>
<td>23.33</td>
<td>22.01</td>
<td>5.67%</td>
</tr>
<tr>
<td>Ixx (lbm-in^2)</td>
<td>5.68E+07</td>
<td>6.42E+07</td>
<td>-12.98%</td>
</tr>
<tr>
<td>Iyy (lbm-in^2)</td>
<td>4.66E+07</td>
<td>4.52E+07</td>
<td>2.96%</td>
</tr>
<tr>
<td>Izz (lbm-in^2)</td>
<td>9.67E+07</td>
<td>1.08E+08</td>
<td>-11.64%</td>
</tr>
</tbody>
</table>
Lessons Learned

• Several key questions were answered in regards to excitation and instrumentation
  – Shaker excitation with continuous random signal is best for DIM
  – Low excitation force required
  – Seismic accelerometers provided good DIM response
  – Good sensor coverage of lowest flexible modes is a must for successful use of spatial filtering
  – 6-DOF load cell worked well, but design could be improved

• Modes in test support equipment interfered with results
  – Pedestal adapters to isolation system
  – Multiple flexible modes from 6-12 Hz
    • Below first flexible mode of test article (17 Hz)
    • Unable to be filtered out
  – Reduced DIM analysis window
DIM Conclusions

• Some aspects need further consideration for DIM application on large test articles
  – A different 6 degree-of-freedom load cell design should be considered
  – Spatial filtering requires adequate instrumentation to fully measure first flexible modes
  – Care should be taken to anticipate/measure non-structural component modes lower than first flexible mode

• Another large-scale test is planned for 2011