International Space Station Future Correlation Analysis Improvements

Michael R. Laible
Murthy Pinnamaneni
Sujatha Sugavanam
Boeing, International Space Station, Loads and Dynamics
13100 Space Center Blvd
Houston, TX 77059

Ongoing modal analyses and model correlation are performed on different configurations of the International Space Station (ISS). These analyses utilize on-orbit dynamic measurements collected using four main ISS instrumentation systems: External Wireless Instrumentation System (EWIS), Internal Wireless Instrumentation System (IWIS), Space Acceleration Measurement System (SAMS), and Structural Dynamic Measurement System (SDMS). Remote Sensor Units (RSUs) are network relay stations that acquire flight data from sensors. Measured data is stored in the Remote Sensor Unit (RSU) until it receives a command to download data via RF to the Network Control Unit (NCU). Since each RSU has its own clock, it is necessary to synchronize measurements before analysis. Imprecise synchronization impacts analysis results. A study was performed to evaluate three different synchronization techniques: (i) measurements visually aligned to analytical time-response data using model comparison, (ii) Frequency Domain Decomposition (FDD), and (iii) lag from cross-correlation to align measurements. This paper presents the results of this study.
International Space Station
Future Correlation Analysis Improvements

Boeing ISS Loads and Dynamics
Michael R. Laible, Murthy Pinnamaneni, Sujatha Sugavanam

NASA Johnson Spaceflight Center
Michael Grygier

February 2018
Agenda

- Introduction
- F2 Model to Model Correlation and expanded Response Locations
- Synchronization Techniques
  - Graphical using FEM
  - Time Delay from Correlation Lag
  - Frequency Domain Decomposition
- Summary and Recommendation
The International Space Station (ISS) correlation effort uses four accelerometer groups with distinct clocks and sample rates

- All clocks get initial condition from main ISS clock
  - Time sync not consistent
- Some accelerometer groups are wireless and some are hardwired

Not all accelerometers are placed in optimal positions

- Repositioning accelerometers entails crew time, which is expensive
- Owing to its construction over a decade, pre-positioned accelerometers on the ISS are 15+ years old

It is cumbersome to time synchronize over 104 DOF graphically.

This investigation seeks an efficient and accurate method to synchronize accelerometer data across the ISS
Program verification plan requires model correlation

- Necessary to validate critical interface loads and improve fatigue life prediction
- Correlation goals:
  - frequency within 5%
  - Modal Assurance Criteria (MAC) of 0.9

- Internal Wireless Instrumentation System (IWIS): 7 triaxial accels
- External Wireless Instrumentation System (EWIS): 10 triaxial accels
- Structural Dynamics Measurement System (SDMS): 33 accel channels
- Internal Wireless Instrumentation System (IWIS): 8 strain gage channels
- Space Acceleration Measurement System (SAMS): 6 triaxial accels
- IMU-C: 1 triaxial accel
- Ascertain what the best MAC that can be expected with perfectly synchronized data and compare to a case where additional accelerometers are included.
- Use the analytical system model to compute the time-response to Yaw Firing #2 (F2)
  - NASTRAN modal transient response
  - F2 Yaw: 6 thrusters, 0.6 seconds duration
- **Two time simulations are performed:**
  - Baseline accelerometers = 104 DOF (Red)
  - Baseline + additional response points = 185 DOF (Red + Green)
- Extract modes using the Eigensystem Realization Algorithm (ERA) from time histories
- Compute MAC between FEM mode shapes and extracted mode shapes.
- Compare results
### Analytical Results Comparison

- Results show MAC between extracted mode shapes and simulated mode shapes for: 104 DOF & 185 DOF
- Modes are down-selected based on high kinetic energy & modal cost
- Red boxes highlight newly captured modes using additional response points
- The existing number & location of accelerometers, limit modal correlation

<table>
<thead>
<tr>
<th>Mode# - Freq.</th>
<th>DOF</th>
<th>104</th>
<th>185</th>
<th>Mode# - Freq.</th>
<th>DOF</th>
<th>104</th>
<th>185</th>
</tr>
</thead>
<tbody>
<tr>
<td>220 - 0.394</td>
<td>Freq</td>
<td>0.395</td>
<td>0.395</td>
<td>366 - 0.884</td>
<td>Freq</td>
<td>0.830</td>
<td>0.831</td>
</tr>
<tr>
<td></td>
<td>MAC</td>
<td>0.952</td>
<td>0.996</td>
<td></td>
<td>MAC</td>
<td>0.926</td>
<td>0.955</td>
</tr>
<tr>
<td>223 - 0.409</td>
<td>Freq</td>
<td>0.408</td>
<td>0.408</td>
<td>376 - 0.934</td>
<td>Freq</td>
<td>-</td>
<td>0.934</td>
</tr>
<tr>
<td></td>
<td>MAC</td>
<td>0.982</td>
<td>0.994</td>
<td></td>
<td>MAC</td>
<td>-</td>
<td>0.979</td>
</tr>
<tr>
<td>256 - 0.46</td>
<td>Freq</td>
<td>0.460</td>
<td>0.464</td>
<td>394 - 1.007</td>
<td>Freq</td>
<td>-</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>MAC</td>
<td>0.959</td>
<td>0.976</td>
<td></td>
<td>MAC</td>
<td>-</td>
<td>0.853</td>
</tr>
<tr>
<td>257 - 0.465</td>
<td>Freq</td>
<td>0.469</td>
<td>0.470</td>
<td>407 - 1.085</td>
<td>Freq</td>
<td>-</td>
<td>1.085</td>
</tr>
<tr>
<td></td>
<td>MAC</td>
<td>0.704</td>
<td>0.963</td>
<td></td>
<td>MAC</td>
<td>-</td>
<td>0.911</td>
</tr>
<tr>
<td>287 - 0.542</td>
<td>Freq</td>
<td>-</td>
<td>0.535</td>
<td>443 - 1.145</td>
<td>Freq</td>
<td>1.151</td>
<td>1.149</td>
</tr>
<tr>
<td></td>
<td>MAC</td>
<td>-</td>
<td>0.884</td>
<td></td>
<td>MAC</td>
<td>0.909</td>
<td>0.812</td>
</tr>
<tr>
<td>289 - 0.557</td>
<td>Freq</td>
<td>0.553</td>
<td>0.557</td>
<td>539 - 1.47</td>
<td>Freq</td>
<td>-</td>
<td>1.466</td>
</tr>
<tr>
<td></td>
<td>MAC</td>
<td>0.838</td>
<td>0.961</td>
<td></td>
<td>MAC</td>
<td>-</td>
<td>0.807</td>
</tr>
<tr>
<td>304 - 0.598</td>
<td>Freq</td>
<td>0.602</td>
<td>0.598</td>
<td>581 - 1.624</td>
<td>Freq</td>
<td>1.616</td>
<td>1.621</td>
</tr>
<tr>
<td></td>
<td>MAC</td>
<td>0.945</td>
<td>0.994</td>
<td></td>
<td>MAC</td>
<td>0.987</td>
<td>0.991</td>
</tr>
<tr>
<td>315 - 0.641</td>
<td>Freq</td>
<td>-</td>
<td>0.641</td>
<td>675 - 1.875</td>
<td>Freq</td>
<td>1.874</td>
<td>1.874</td>
</tr>
<tr>
<td></td>
<td>MAC</td>
<td>-</td>
<td>0.941</td>
<td></td>
<td>MAC</td>
<td>0.990</td>
<td>0.991</td>
</tr>
<tr>
<td>352 - 0.774</td>
<td>Freq</td>
<td>-</td>
<td>0.780</td>
<td>690 - 1.938</td>
<td>Freq</td>
<td>1.934</td>
<td>1.938</td>
</tr>
<tr>
<td></td>
<td>MAC</td>
<td>-</td>
<td>0.867</td>
<td></td>
<td>MAC</td>
<td>0.967</td>
<td>0.973</td>
</tr>
</tbody>
</table>

Copyright © 2016 Boeing. All rights reserved.
Time Domain Synchronization
Original method to perform time synchronization consisted of co-plotting accelerometer time histories from different locations.

Typically one sensor was chosen as a “reference” to line all others up to.
- Service Module (SM), the output response proximal to thrusters were used for synchronization
- Raw and filtered data used to time shift

Since all three axes of a triaxial accelerometer are regulated by a single clock, a single DOF was used for synchronization

Time-shifts varied between 0-.5 seconds
- Analytical time-response simulation was used to synchronize accelerometers
- Yaw Firing #2 (F2) along ISS-Y (0.35 s to reach 90% thrust) was used to simulate the time-response
- Service Module (SM)-Y, the output response proximal to F2 was used for synchronization
- Accelerometer data was time-shifted to match the analytical response
- Since all three axes of a triaxial accelerometer are regulated by a single clock, a single DOF was used for synchronization
- Time-shifts varied between 0.06 – 1.2 seconds
• IWIS, SAMS, and EWIS synchronization

IWIS FGB

EWIS S5

IWIS N3
Let $x(t)$ denote the acceleration time-history obtained from the analytical model.

Let $y(t)$ denote, the corresponding accelerometer measurement with time delay $\tau_0$, mixed with statistically independent noise $n(t)$

$$y(t) = x(t - \tau_0) + n(t)$$

The cross-correlation function is given by:

$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} x(t)[x(t + \tau - \tau_0) + n(t + \tau)] \, dt = R_{xx}(\tau - \tau_0)$$

The time delay between the analytical response $x(t)$, and the measurement $y(t)$ is given by the correlation lag $\tau_0$.

The correlation lag can be computed using the MATLAB functions $xcorr$ or $finddelay$.

The correlation lag can then be used to align the measurements from various accelerometers, prior to model correlation.
The time delay obtained from correlation lag is not always consistent: e.g. the time delays corresponding to a triaxial accelerometer may vary from one axis to another (despite all three axes of the accelerometer being synchronized to the same clock).

Such inconsistencies are resolved by reasoning/judgment/pattern recognition, and sometimes intuition ...

Correlation lag is a good index of time delay, but the method is not readily automated.
- EWIS and IWIS synchronization using correlation lag

**IWIS FGB**

- GRA.ACCE.E181056.DOF4 vs. AC1009Y.txt

**IWIS N3**

- GRA.ACCE.E161167.DOF4 vs. AC1012Y.txt

**EWIS S5**

- GRA.ACCE.E400043.DOF4 vs. RSU 4006 TAA2-Y (0/4)
Objective:
- Demonstrate the application of FDD to synchronize ISS accelerometers

Background
- FDD is the frequency domain analogue of time-delay from correlation lag
- Here the correlation lag \( \tau_0 \), appears as the linear phase angle of the cross-spectrum:

\[
\theta_{xy}(f) = 2\pi f \tau_0
\]

- Where the cross-spectrum is:

\[
G_{xy}(f) = 2 \int_{-\infty}^{\infty} R_{xy}(\tau) e^{j2\pi f \tau} \, d\tau = |G_{xy}(f)| e^{-j\theta_{xy}(f)}
\]

Frequency Domain Decomposition:
- Compute the power spectral density (PSD) of accelerometer measurements
- Perform a singular value decomposition (SVD) of the PSD matrix
- Plot the first singular value as a function of frequency
- Modes correspond to those frequencies, where the first singular value peaks
- Mode shapes correspond to the first singular vector associated with the first singular value, at those peaks
- The first singular vector is used to compute the phase angle (\( \equiv \) time-lag)
- **Service Module (SM) Module Relative Phase Angles vs. Modal Frequencies**

- **SM Module Relative Phase Angles vs. Modal Frequencies**
  - With time delay estimations included in the measured time histories after two iterations
JEM Module Relative Phase Angles vs. Modal Frequencies

- With time delay estimations included in the measured time histories after two iterations
Results
### Results

<table>
<thead>
<tr>
<th>Model</th>
<th>DOF</th>
<th>104 Original</th>
<th>104 Graphical</th>
<th>104 FDD</th>
<th>86 Correlation</th>
<th>185 anal</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 - 0.12</td>
<td>Freq</td>
<td>0.084</td>
<td>0.087</td>
<td>0.088</td>
<td>0.088</td>
<td>-</td>
</tr>
<tr>
<td>MAC</td>
<td>0.931</td>
<td>0.938</td>
<td>0.937</td>
<td>0.943</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>83 - 0.176</td>
<td>Freq</td>
<td>0.176</td>
<td>-</td>
<td>0.178</td>
<td>0.172</td>
<td>0.176</td>
</tr>
<tr>
<td>MAC</td>
<td>0.887</td>
<td>-</td>
<td>0.881</td>
<td>0.848</td>
<td>0.995</td>
<td></td>
</tr>
<tr>
<td>102 - 0.219</td>
<td>Freq</td>
<td>0.219</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.217</td>
</tr>
<tr>
<td>MAC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.985</td>
<td></td>
</tr>
<tr>
<td>128 - 0.264</td>
<td>Freq</td>
<td>0.258</td>
<td>0.261</td>
<td>0.259</td>
<td>0.256</td>
<td>0.267</td>
</tr>
<tr>
<td>MAC</td>
<td>0.892</td>
<td>0.912</td>
<td>0.902</td>
<td>0.897</td>
<td>0.998</td>
<td></td>
</tr>
<tr>
<td>145 - 0.285</td>
<td>Freq</td>
<td>0.288</td>
<td>0.297</td>
<td>0.290</td>
<td>0.295</td>
<td>-</td>
</tr>
<tr>
<td>MAC</td>
<td>0.904</td>
<td>0.898</td>
<td>0.897</td>
<td>0.870</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>177 - 0.343</td>
<td>Freq</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MAC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>215 - 0.375</td>
<td>Freq</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MAC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.967</td>
<td></td>
</tr>
<tr>
<td>220 - 0.394</td>
<td>Freq</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MAC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.996</td>
<td></td>
</tr>
<tr>
<td>223 - 0.409</td>
<td>Freq</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MAC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>256 - 0.46</td>
<td>Freq</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MAC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.976</td>
<td></td>
</tr>
<tr>
<td>257 - 0.465</td>
<td>Freq</td>
<td>0.465</td>
<td>0.486</td>
<td>0.488</td>
<td>0.472</td>
<td>0.470</td>
</tr>
<tr>
<td>MAC</td>
<td>0.797</td>
<td>0.881</td>
<td>0.770</td>
<td>0.856</td>
<td>0.963</td>
<td></td>
</tr>
</tbody>
</table>

**Red text denotes new mode extracted from untimed 104 DOF correlation**
Summary
Summary

- The ISS is the largest space structure ever built
- It has been constructed over a period of 10 years
- Some accelerometers on the ISS were pre-positioned and others added after assembly
- The four distinct accelerometer groups have individual clocks, and dedicated data acquisition networks
- Current compliment of accelerometers limits the quality of modal correlation and number of modes that can be correlated.

- Time synchronizing accelerometer data improves MAC and provides better correlation of higher order modes
  - Graphical and time-based correlation function methods when used relative to FEM-predicted time histories provided best correlation.
  - More work is planned to improve automation of these techniques.