Conference:
Spacecraft and Launch Vehicle Dynamic Environments Workshop

Location:
Los Angeles, California

Date of Conference:
June 9-11, 2009

Draft Title of Paper:
Exploring Modeling Options and Conversion of Average Response to Appropriate Vibration Envelopes for a Typical Cylindrical Vehicle Panel with Rib-stiffened Design

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Abstract

Although applications for Statistical Energy Analysis (SEA) techniques are more widely used in the aerospace industry today, opportunities to anchor the response predictions using measured data from a flight-like launch vehicle structure are still quite valuable. Response and excitation data from a ground acoustic test at the Marshall Space Flight Center permitted the authors to compare and evaluate several modeling techniques available in the SEA module of the commercial code VA One. This paper provides an example of vibration response estimates developed using different modeling approaches to both approximate and bound the response of a flight-like vehicle panel. Since both vibration response and acoustic levels near the panel were available from the ground test, the evaluation provided an opportunity to learn how well the different modeling options can match band-averaged spectra developed from the test data. Additional work was performed to understand the spatial averaging of the measurements across the panel from measured data. Finally an evaluation/comparison of two conversion approaches from the statistical average response results that are output from an SEA analysis to a more useful envelope of response spectra appropriate to specify design and test vibration levels for a new vehicle.

**Exploring Modeling Options and
Conversion of Average Response to Appropriate Vibration Envelopes
for a Typical Cylindrical Vehicle Panel with Rib-stiffened Design**

Presented to
The Spacecraft and Launch Vehicle
Dynamic Environments Workshop

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Bruce LaVerde/ERC
David Teague/Jacobs**

June 2009

Agenda

- Introduce Need and Important Questions
- Show Ground Test Set-up and Measured Sound Pressures
- Show the Test Article and Measured Vibration Response.
- Present Statistical Energy Analysis (SEA) Modeling Cases with Strengths/Weaknesses.
- Relate "Averages From Test Data" to SEA Results
- Show Construction of Design Envelope from SEA using Delta
- Evaluate the SEA Design Envelope using Statistics of Measured Response Data
- Relate Mean of Measured Data to a 95/50 design envelope for Ground Test Case (Appropriate Delta?)
- Present Conclusions & Recommendations
- Emphasize Warning

The Test Article was a flight-like panel of Orthogrid Rib-stiffened construction common to new vehicle designs.

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Introduction/Basic Questions

- SEA techniques are becoming widely used in the aerospace industry today.
- Ground Acoustic Test Data produced at the Marshall Space Flight Center provided a unique opportunity to anchor the response predictions using measured data for a Flight-like Panel.

Compare Average and Average + 4dB Delta to Narrow Band Spectra from 7 Measurment Channels Run-1
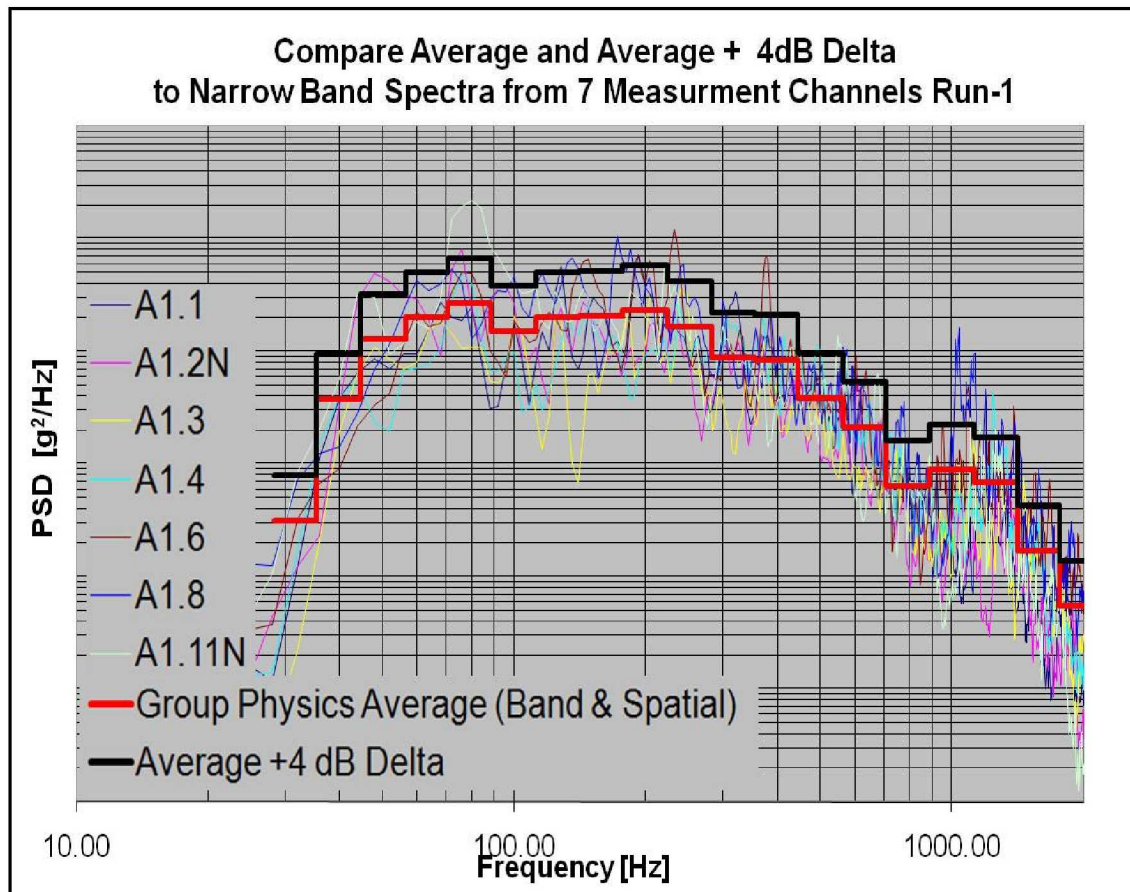
Does this simple trial, The addition of a "4 dB Delta" to a "spatially averaged 1/3 octave band average curve" to guide the construction of an envelope, **make any sense?**

In a more refined approach, would a smaller Delta be required in the high frequency bands?

Presenting the Ground Acoustic Test Set Up

- The tests were conducted in MSFC's East Test Area at the Hot Gas Facility - building 4554.

- Acoustic noise generating equipment from building 4619 was moved to the Hot Gas Facility and setup such that the panel could be located at varying distances from the noise source.

- Testing was completed on December 23, 1994.

- Documented in Reference:

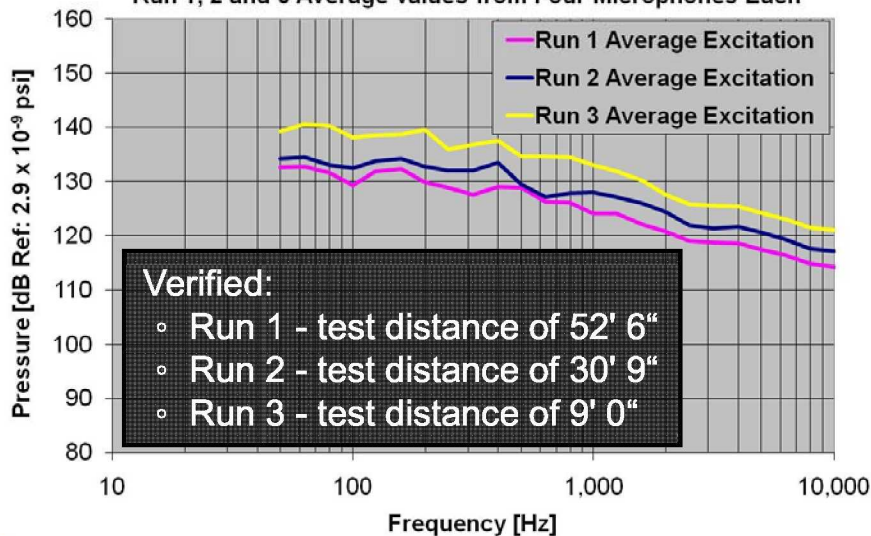"Orthogrid Acoustic Test Report," 809-2087, Lockheed Martin Contract NAS8-36200, April 1997.
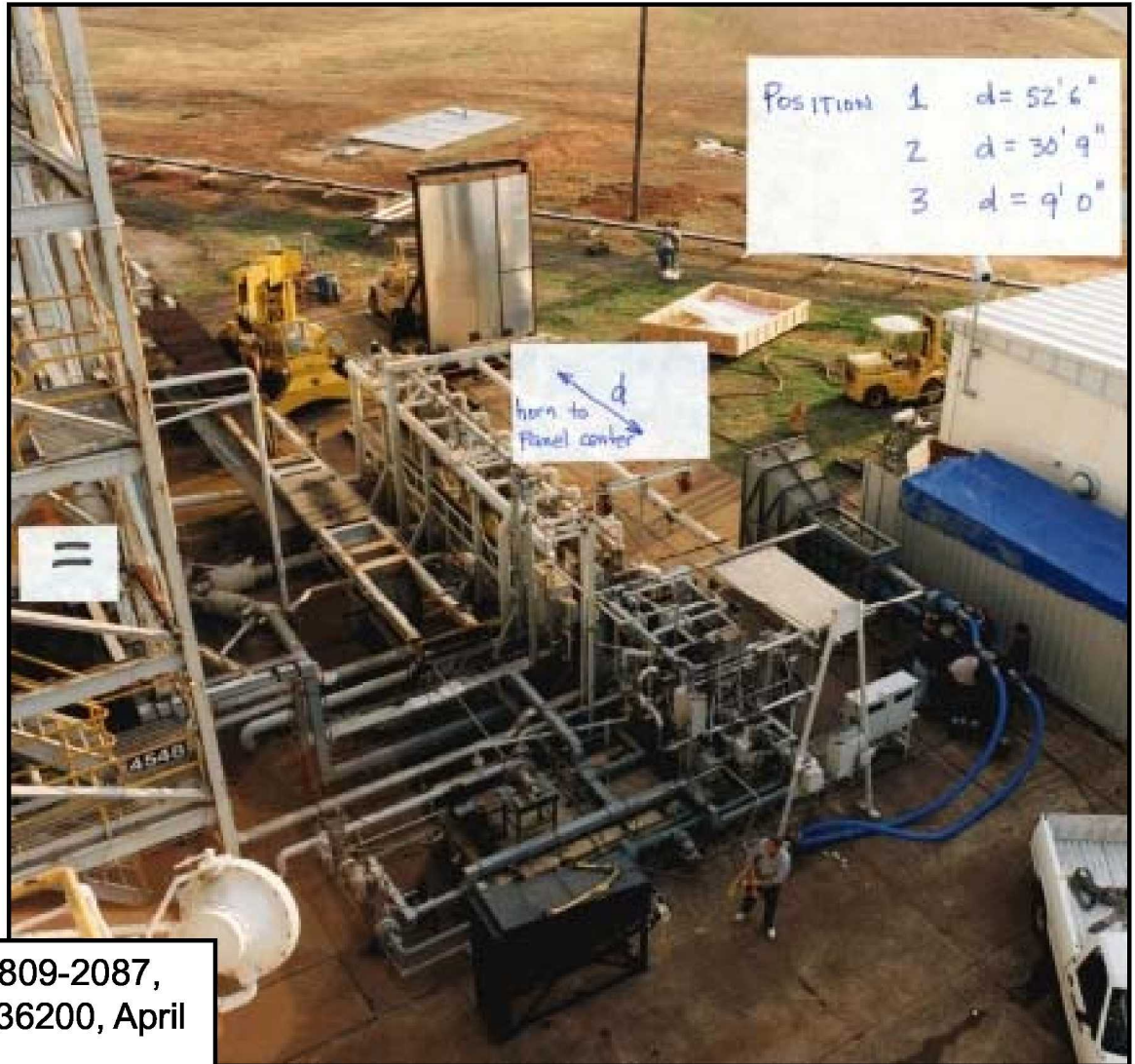
Measured Excitation Data – Pressure Spectra

- ◆ **Location of microphones used during tests are shown at right.**

- ◆ **Microphones mounted on light support structure. Minimum distance in front of panel approximately 37 inches.**
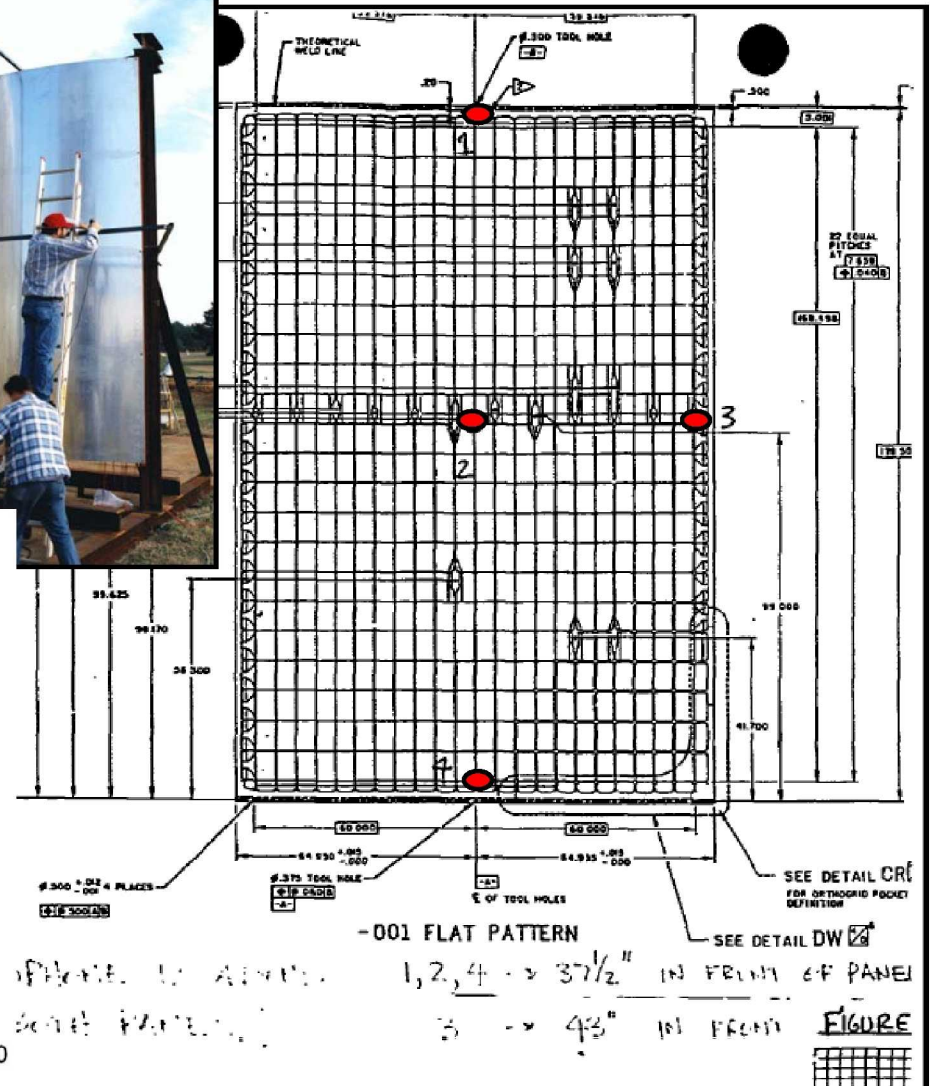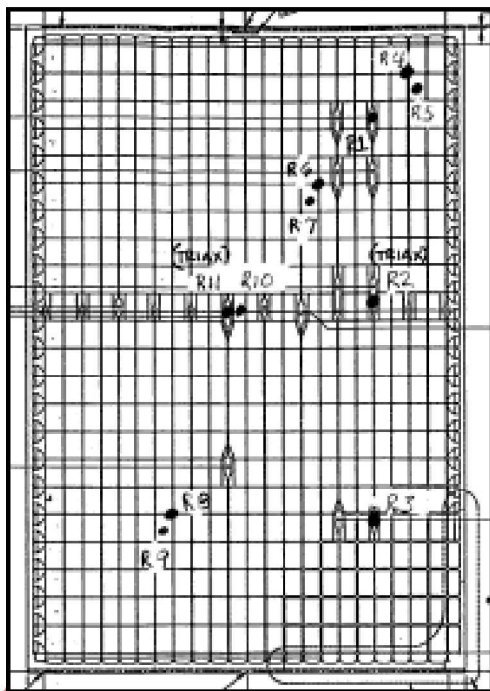

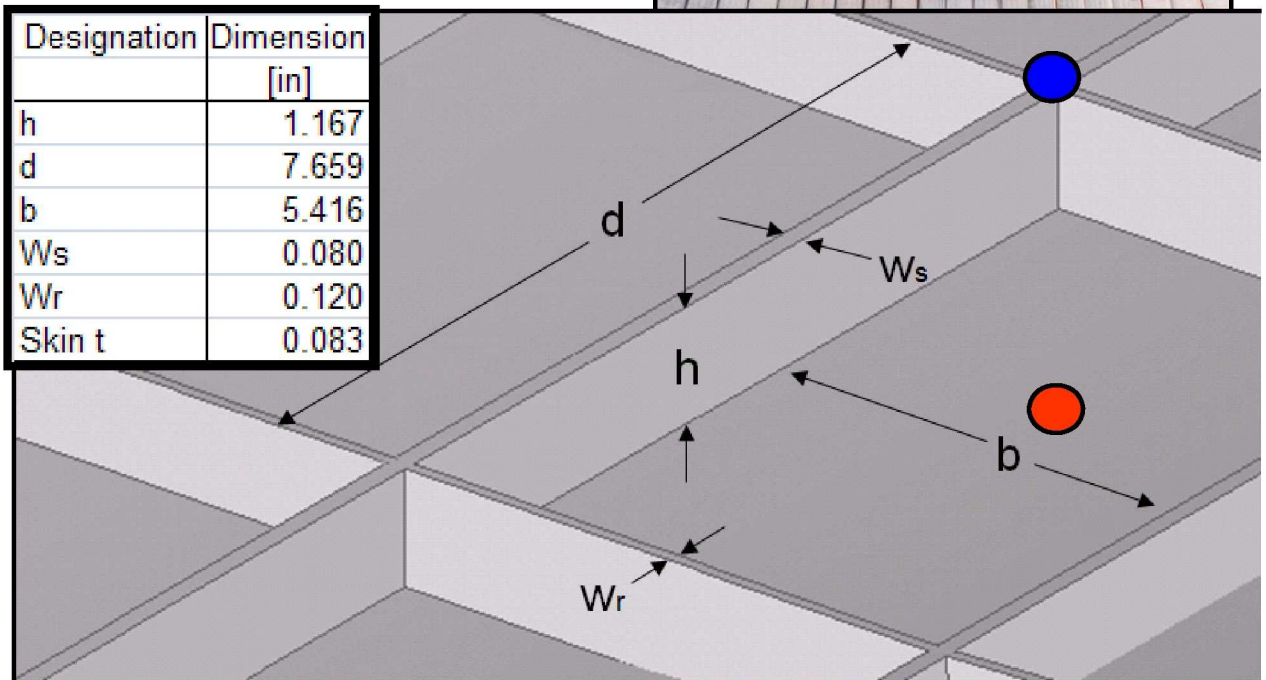**Excitation Spectra from MSFC Test Branch CD, Run 1, 2 and 3 Average Values from Four Microphones Each**

Legend:
- Run 1 Average Excitation
- Run 2 Average Excitation
- Run 3 Average Excitation

Verified:
- ○ Run 1 - test distance of 52' 6"
- ○ Run 2 - test distance of 30' 9"
- ○ Run 3 - test distance of 9' 0"

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Measurement Locations and
Design Details of Flight-Like Test Article

- The upper half of a 10 by 15 ft Orthogrid panel depicted at right. 11 vibration response measurements [4 skin-mounted 🔴 and 7 rib-mounted 🔵 transducer locations].
- An Example of the orthogrid properties used to define subsystem is provided below.
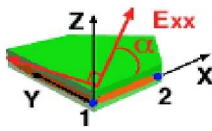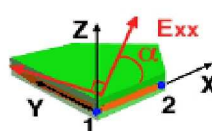
  Each rectangular pocket was 7.659 by 5.416 inches with the following detailed dimensions:
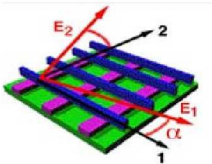

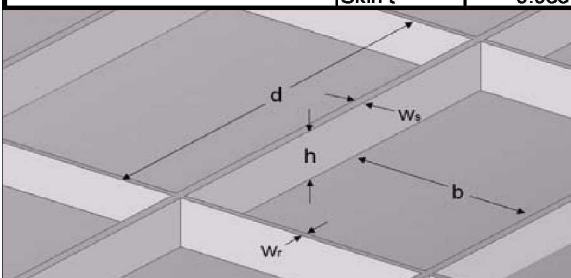| Designation	Dimension [in]
h	1.167
d	7.659
b	5.416
Ws	0.080
Wr	0.120
Skin t	0.083

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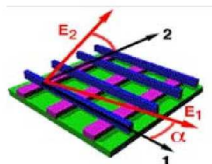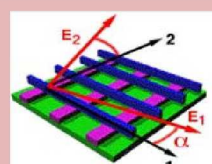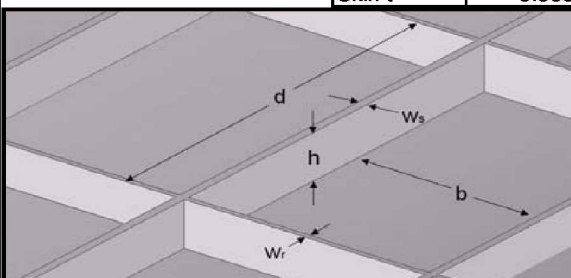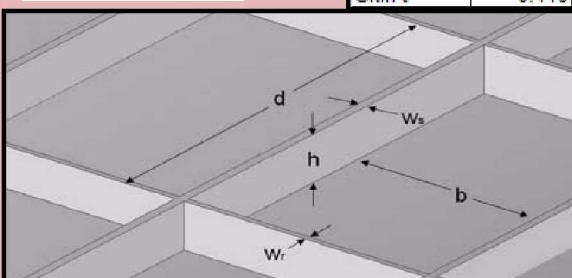
Modeling Case Details Flight-Like Test Article

- Bounding cases have a white background
- Best estimate cases are mass equivalent of the panel & have a pink background
- Monocoque techniques gave consistent peaking at the Ring Frequency
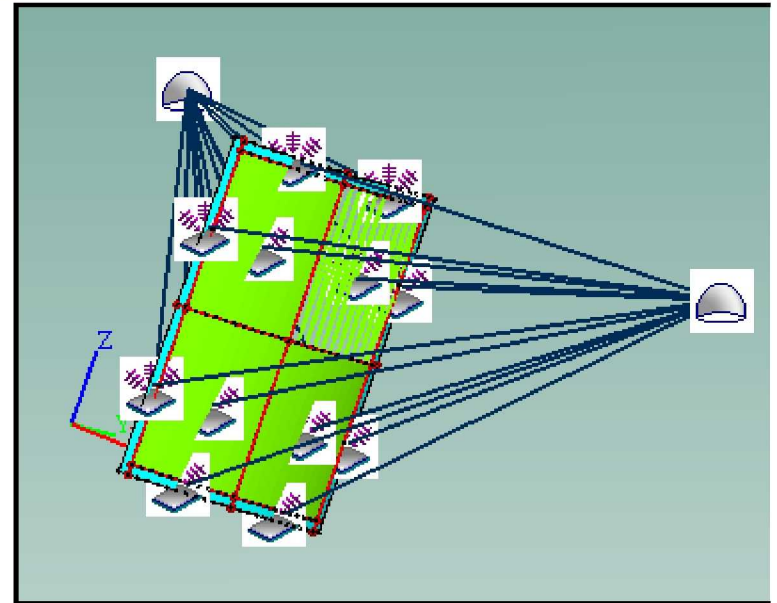- Rib stiffened approach captured pocket mode response effects

Case 1   Skin only Moncoque (0.083 skin)   ★★★

Case 2   Equivalent Mass Moncoque (0.17958 uniform)

***Bounding Cases should overestimate response because they are less massive. But do they bound the problem across the entire frequency range?

Case 3   Rib Stiffened Panel (1/5th rib height)   ★★★

Designation	Dimension [in]
h	0.233
d	7.659
b	5.416
Ws	0.080
Wr	0.120
Skin t	0.083

Case 4   Rib Stiffened Panel (0.083 skin)   ★★★

Designation	Dimension [in]
h	1.167
d	7.659
b	5.416
Ws	0.080
Wr	0.120
Skin t	0.083

Case 5   Rib Stiffened Panel (0.146" skin)

Designation	Dimension [in]
h	1.167
d	7.659
b	5.416
Ws	0.080
Wr	0.120
Skin t	0.146

Assumptions For Calculating Response

♦ **Applied Diffuse Acoustic Field (DAF) Loading:**
  - In order to maximize response
  - Some reflective surfaces along the corridor from the Horn to the test article
  - DAF defined using ambient air fluid properties and average of four microphones for each run.

♦ **Damping Assumptions**
  - In order to maximize response
  - Damping for flexural modes set at 1% of critical damping ratio which results in DLF=0.02
  - Damping for in-plane modes (both extensional and shear) set at 0.33% of critical damping ratio which results in DLF=0.0066

♦ **Radiation Losses**
  - Panel subsystems were permitted to radiate into Semi Infinite Fluid (SIF)
  - SIF defined using ambient air fluid properties
  - Both sides of panel were permitted to radiate

Comparison of Spatial Averages of Run 2 Test Data in 3rd Octave Bandwidths

Below 500 Hz only global modes are present in the ground test data. Contribution of local pocket modes is seen in the skin only and average of all the channels. This is processed test data only.
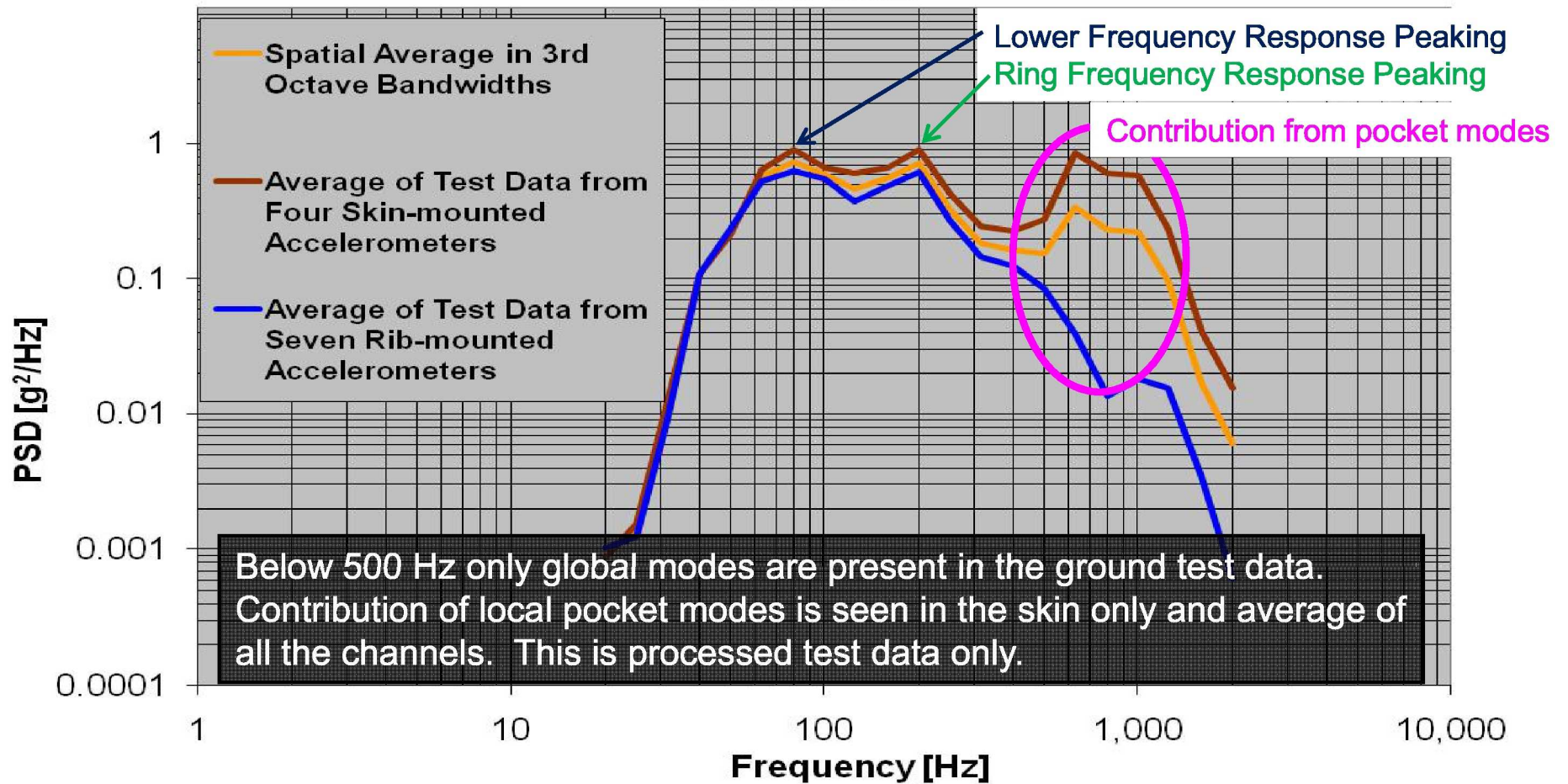
Comparison of Spatial Average of Run 2 Test Data in 3rd Octave Bandwidths to VA One Results
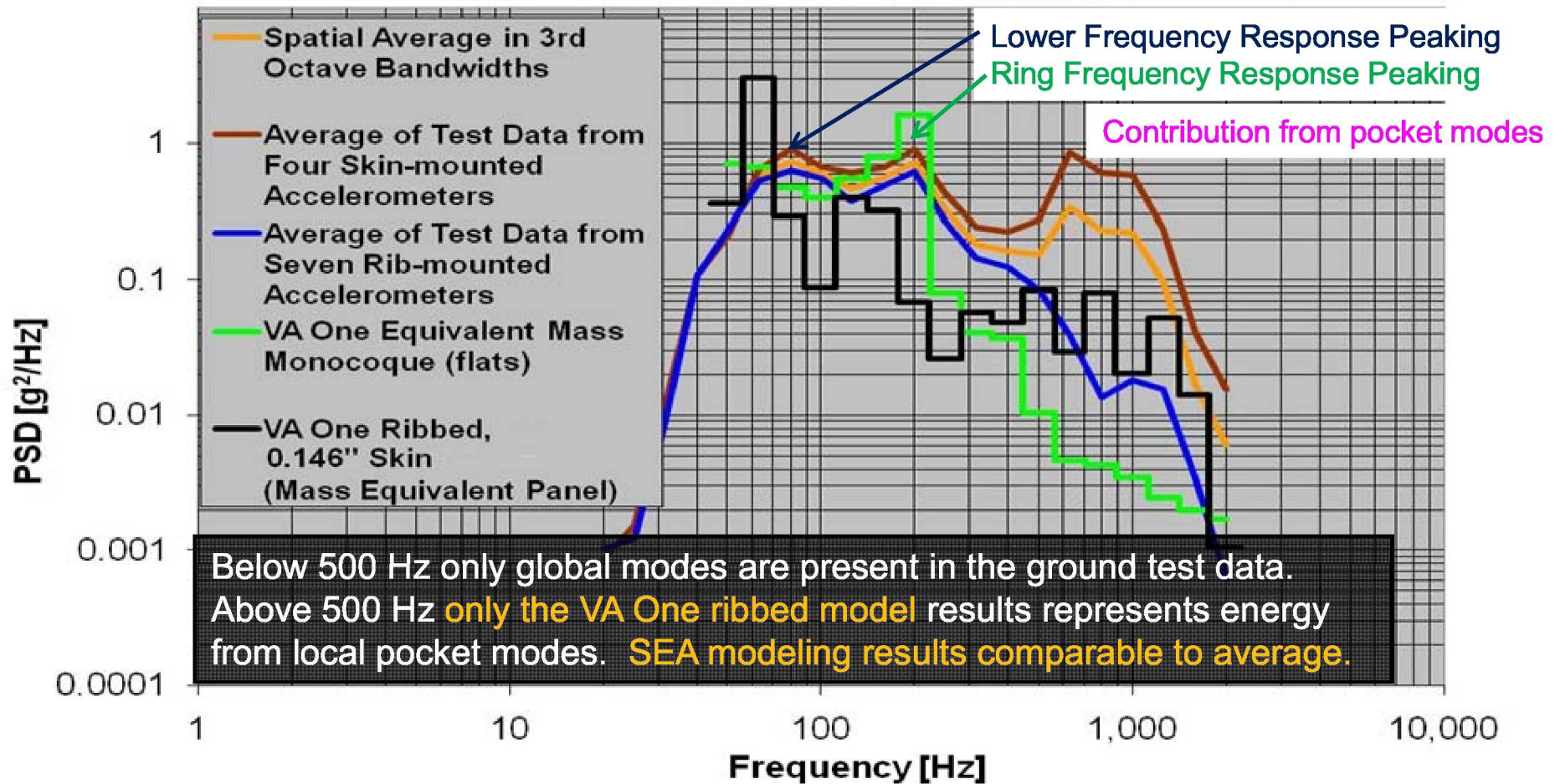
Constructing a Smoothed Vibration Design Envelope from Examination of the Overlay SEA Results from Two Modeling Techniques
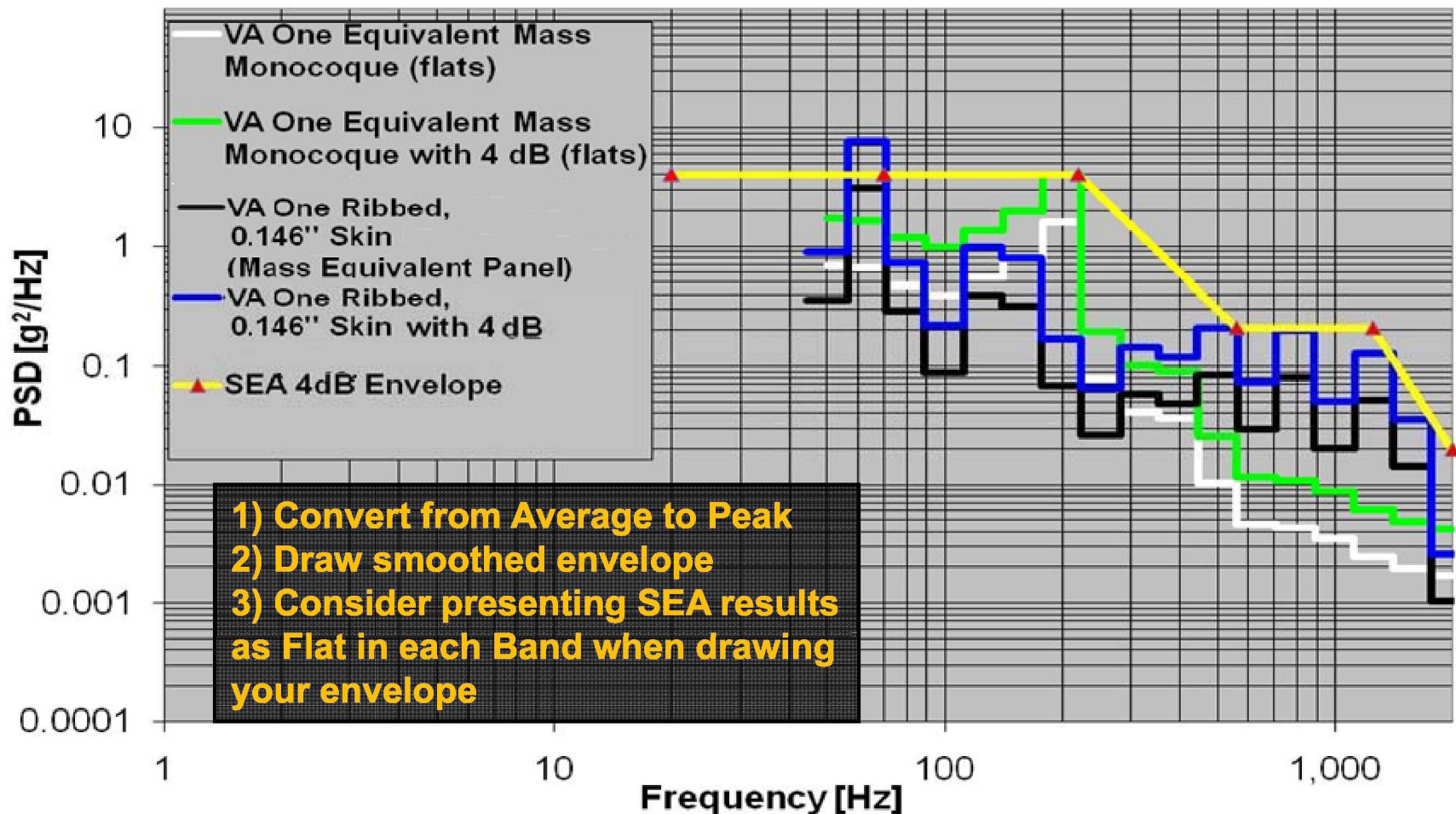
Comparing SEA Envelope with 4 dB
to Different Single SEA Modeling Techniques
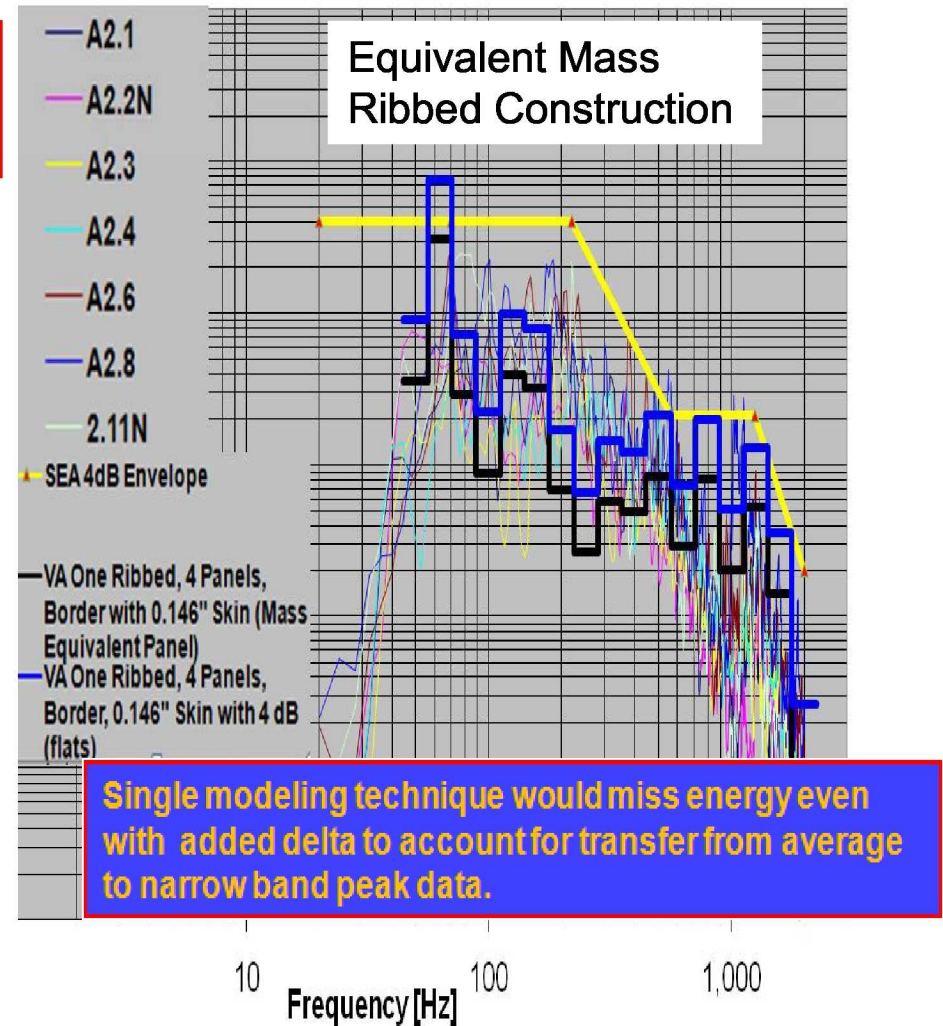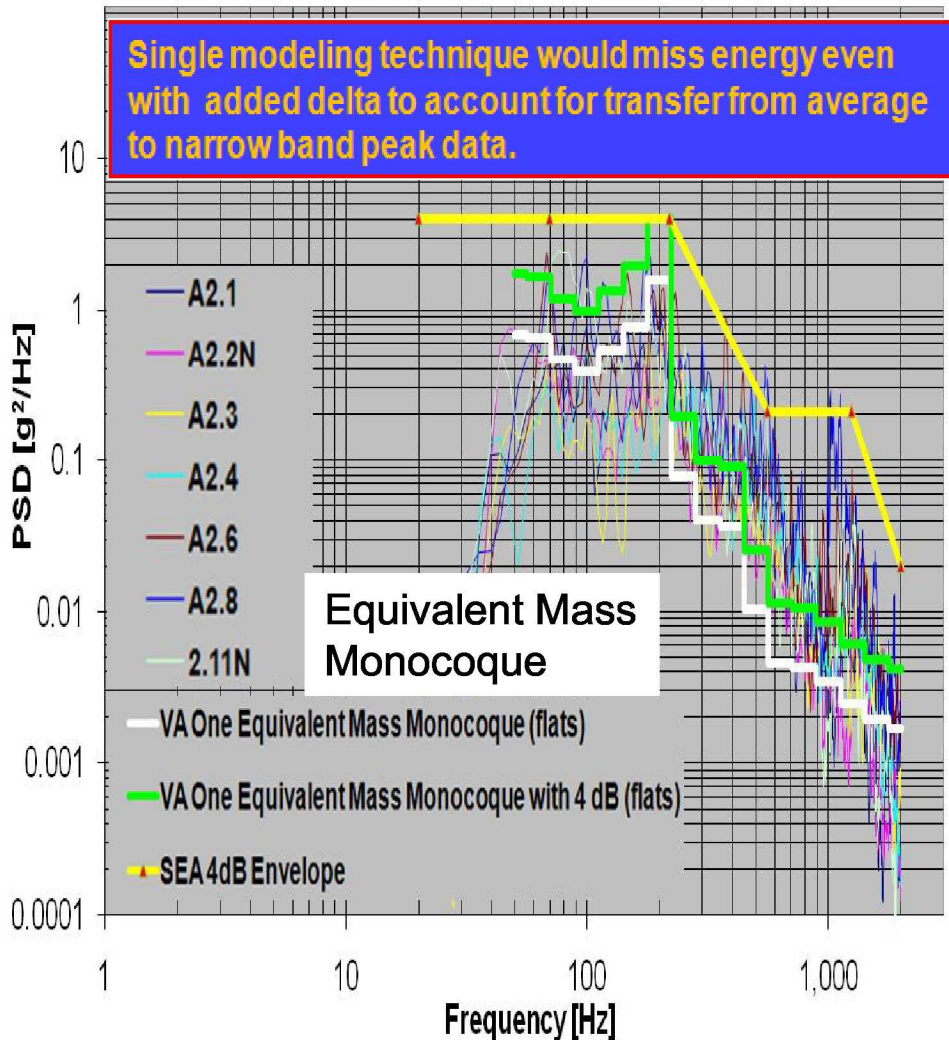
Evaluating the Assumed Delta used to Convert from Average to Design Vibration Levels

- Historically an empirical approach is implemented using judgment to establish smooth envelopes that described vibration energy contained in overlays of narrow band data.

- Later, it became common to establish confidence levels using normal tolerance level statistics.

- Some recommendations from NASA-HDBK-7005 (Reference 5) are quoted below:

    - **"A more definitive way to arrive at a conservative limit for the spectral values of the structural responses in a zone is to compute a normal tolerance limit for the predicted spectra in each frequency resolution bandwidth."**

   - **"Normal tolerance limits apply only to normally distributed random variables. The spatial variation of structural responses to stationary, nonstationary, and transient dynamic loads is generally not normally distributed."**

        - **"However, there is considerable empirical evidence . . . that the logarithm of the spectral values for any motion parameter describing the response of aerospace vehicle structures from one point to another does have an approximately normal distribution, i.e., the spatial distribution for the structural response spectral values in a specific frequency resolution bandwidth approximately fits a lognormal distribution."**

    - **"Using SEA in design requires that a confidence interval be established for the response prediction, so that an upper bound or "worst case" estimate can be compared with design requirements. If the mean response is used for design, half the products produced will fail to meet the design requirements."**

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An Average in Space, A "Spatial Average"

A Spatial Average can be produced from randomized measurements in each sector of a panel.
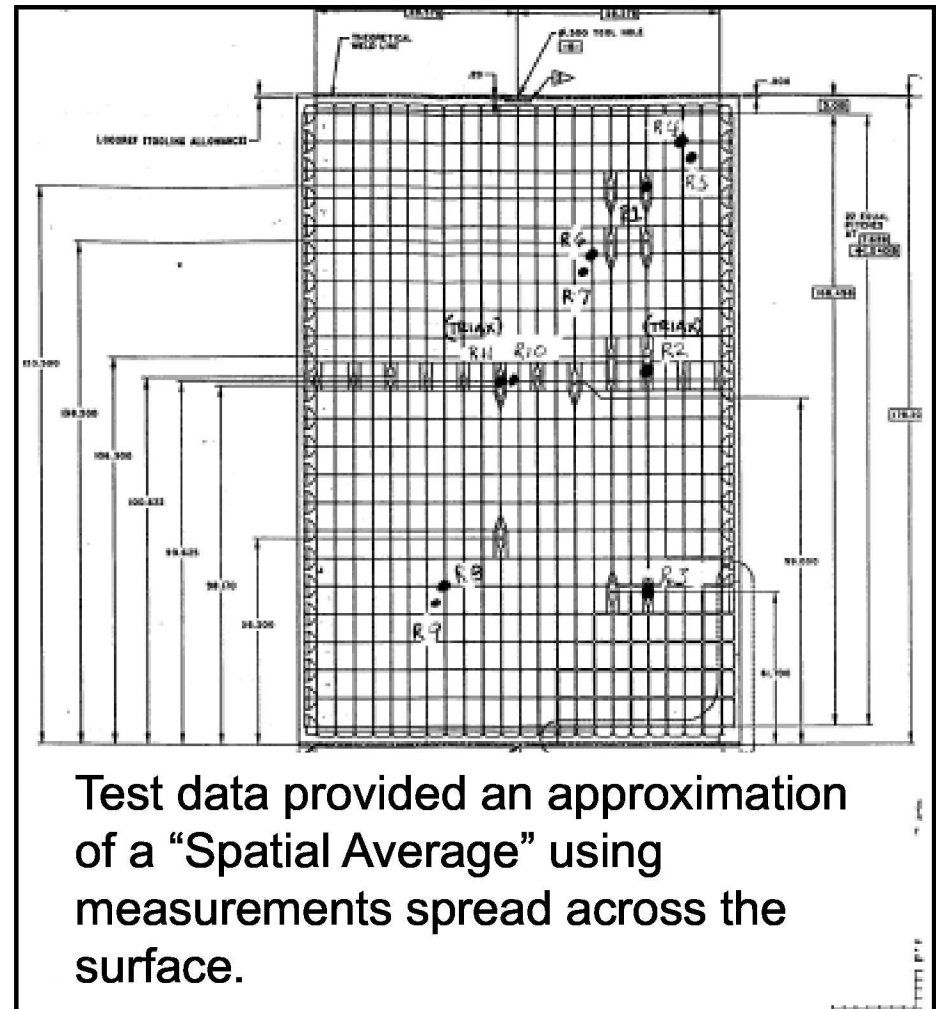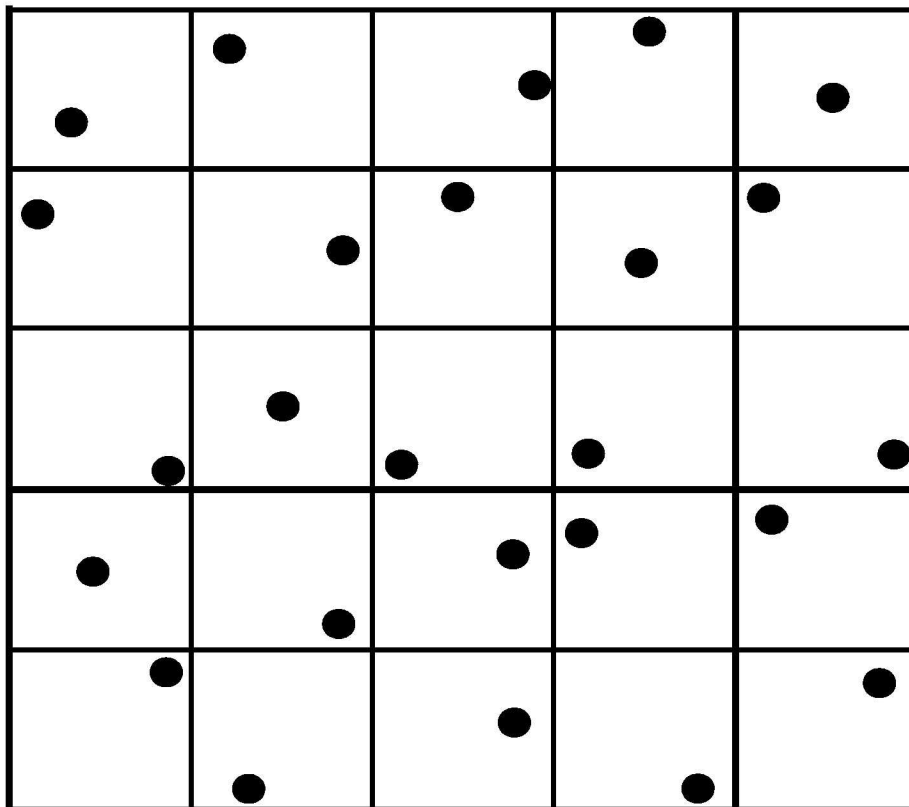
Test data provided an approximation of a "Spatial Average" using measurements spread across the surface.

Processing Steps used in the Evaluation Based on Constructing a Design Envelope from Several Narrow Band Measurements from one Zone

- The spectral values in engineering units are produced by computing root mean square acceleration in each frequency band from the power unit spectra for each measurement location:

$$G_{rms}(f) = [PSD(f) \ x \ BW]^{0.5}$$

- NASA-HDBK-7005 suggests that these spectral values have an approximate Lognormal distribution. The mean and standard deviation, computed in the Log space, are as follows:

$$\overline{Log(G_{rms})} = \frac{\sum Log(G_{rms})}{n}$$

$$STD(Log(G\_rms)) = \sqrt{\frac{\sum \left(\left(Log(G_{rms}) - \overline{Log(G_{rms})} \right) \right)^2}{(n-1)}}$$

G_{rms} = normalized root mean square acceleration
BW = band width
n = number of measurement channels

Processing Steps used in the Evaluation Based on Constructing a Design Envelope from Several Narrow Band Measurements from one Zone (Continued)

- The 95/50 enclosure for the seven measurements is calculated using table look up for normal tolerance limit statics in the Log space (k = 1.73 for 7 measurements).

$$NTL_{95/50} = \overline{Log(G_{rms})} + (k)STD(Log(G\_rms))$$

- Then NTL in Log space is returned to engineering units using a back transform:

$$G_{rms\,95/50} = 10^{\left[\overline{Log(G_{rms})} + (1.73)*STD(Log(G\_rms))\right]}$$

- Finally, the single spectrum is processed back to power units and presented as spectral density:

$$PSD(f)_{95/50} = \frac{\left(G_{rms}(f)_{95/50}\right)^2}{BW}$$

- The measured response data, processed into narrow band spectral densities using several different band widths (10 Hz and 1/6 octave) is presented. Comparison between the $PSD_{95/50}$ spectra calculated from these processed test data to represent Max Predicted Environment (MPE) and the SEA results was then possible.

Run2 Test Data Using Normal Tolerance Limit Statistics on Rib-mounted Sensors to Define MPE Smoothed Envelope (Two "Narrow Band" Treatments)
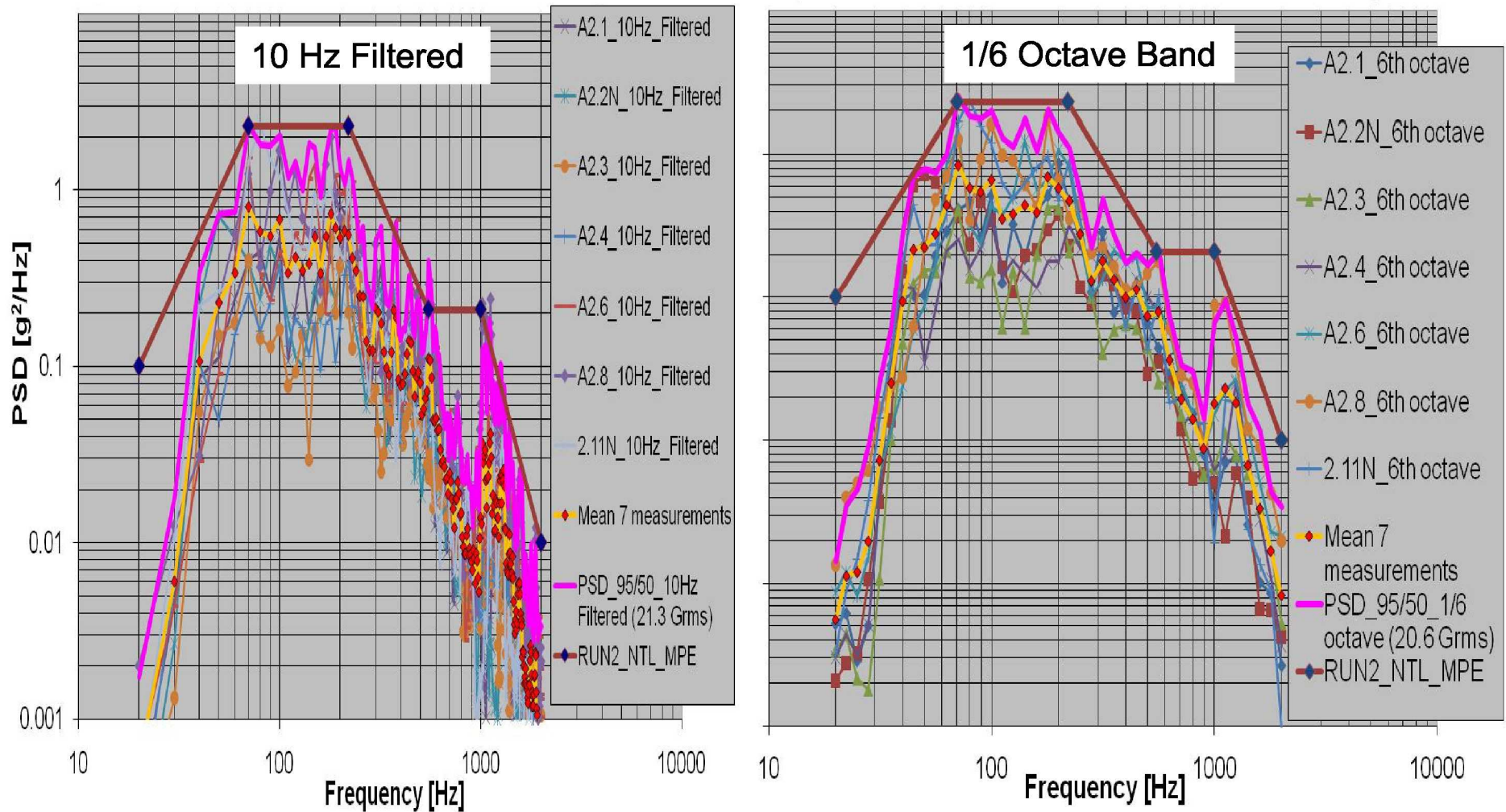
Comparing SEA Envelope (Constructed with 4 dB Delta) to MPE Envelope from Normal Tolerance Limit Statistics of Test Data (Run2 - 10 Hz Filtered Data)
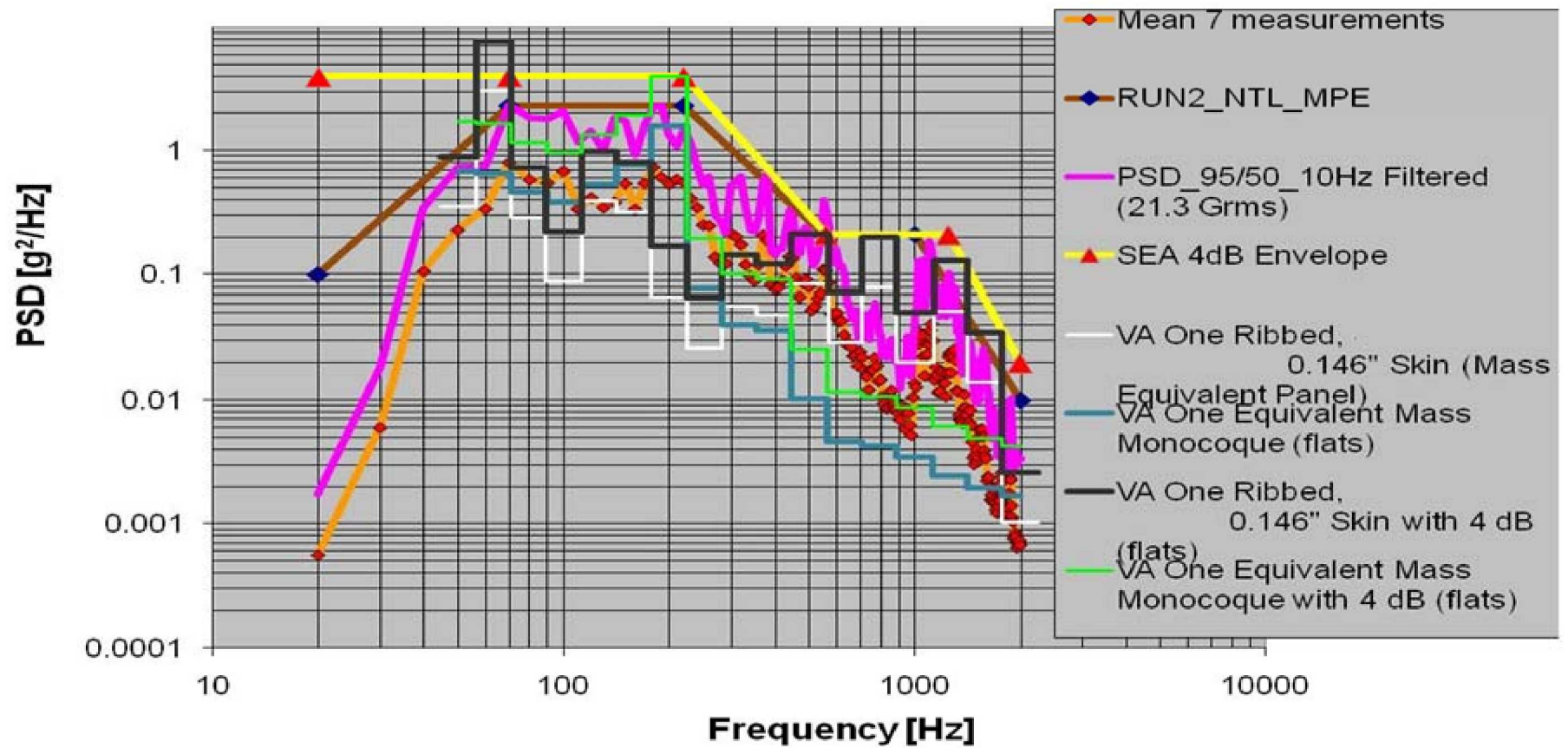
SEA Envelope (Constructed with 4 dB) Compared to the Complete Test Set of 11 channels - Narrow Band Spectra and Similarly to the 7 Rib-Mounted Channels Only
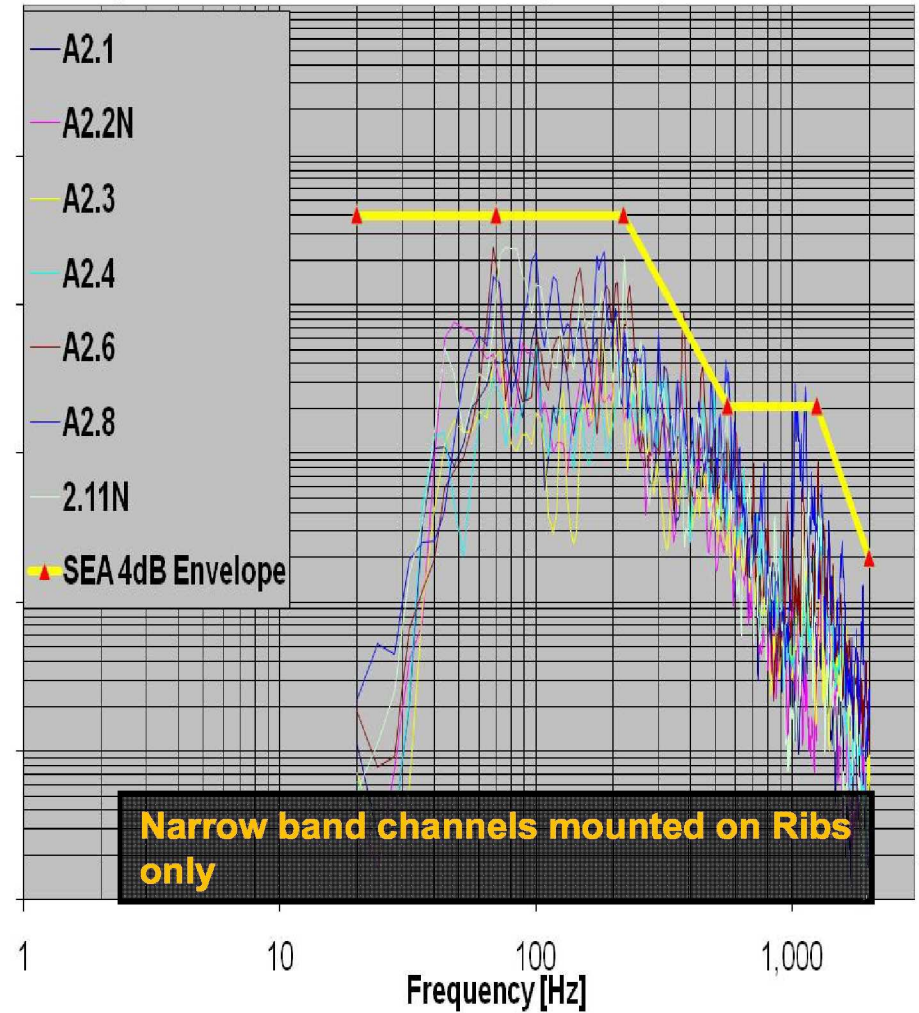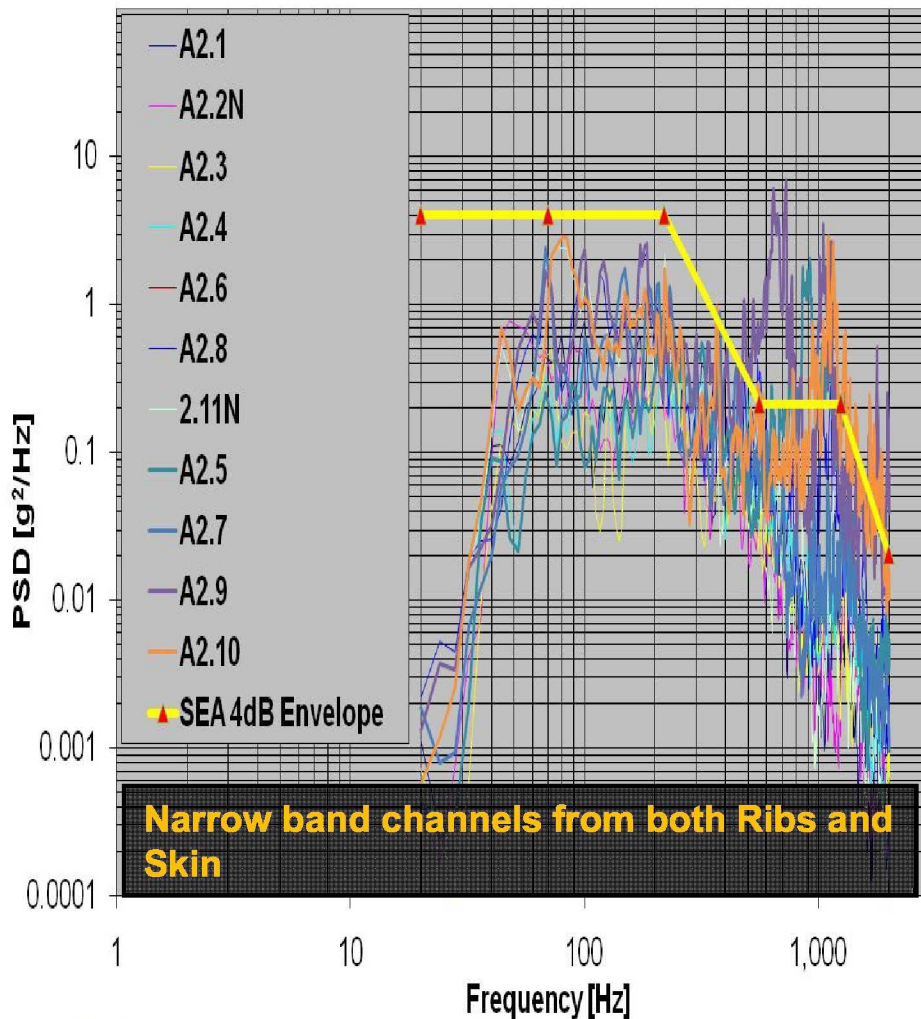
Conversion from 1/3 Octave Mean to
a Design Statistical Envelope from "More Narrow Band" Data
Can be Computed in Different Frequency Bands (Run 2)

Below a 95/50 enclosure developed from 1/6th octave spectra is compared to the mean of 1/3 octave band average of the same 7 Measurements.

$$Delta\ dB = 10Log\left(\frac{PSD(f)_{95/50\left[\frac{1}{6}Oct\right]}}{PSD(f)_{\left[\frac{1}{3}Oct\right]}}\right)$$

Compare PSD(f)$_{95/50[1/6th\ octave]}$ to
The Average Across the Panel from 7 Measurements [1/3 octave]

Legend:
- A2.1 3rd octave
- A2.2N 3rd octave
- A2.3 3rd octave
- A2.4 3rd octave
- A2.6 3rd Octave
- A2.8 3rd Octave
- A2.11N 3rd Octave
- Run2 Average of 7 channels 1/3rd octave
- PSD_95/50_1/6 octave (20.6 Grms)
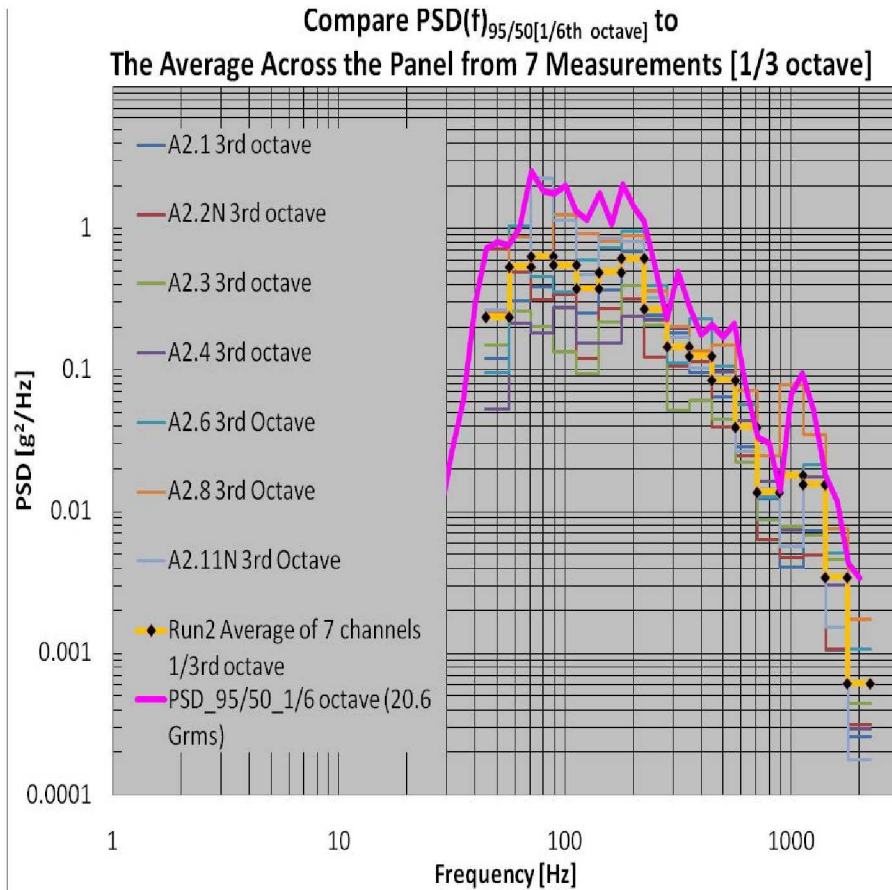
Assessing the Delta to Convert Mean Results to Design Envelope
Delta dB from ratio of 95/50 NTL for 1/6th Octave with
Average from 7 Channels 1/3rd Octave

4 dB Delta Compared well over Large portion of the Broad Band Spectrum.

Legend:
- Delta from Average of 7 channels 1/3 octave to 1/6 octave 95/50
- Assumed 4 dB Delta Conversion this Study
- 3.5 dB -Average Delta 100-1000
- 6.5 dB -Average Delta 1000-2000

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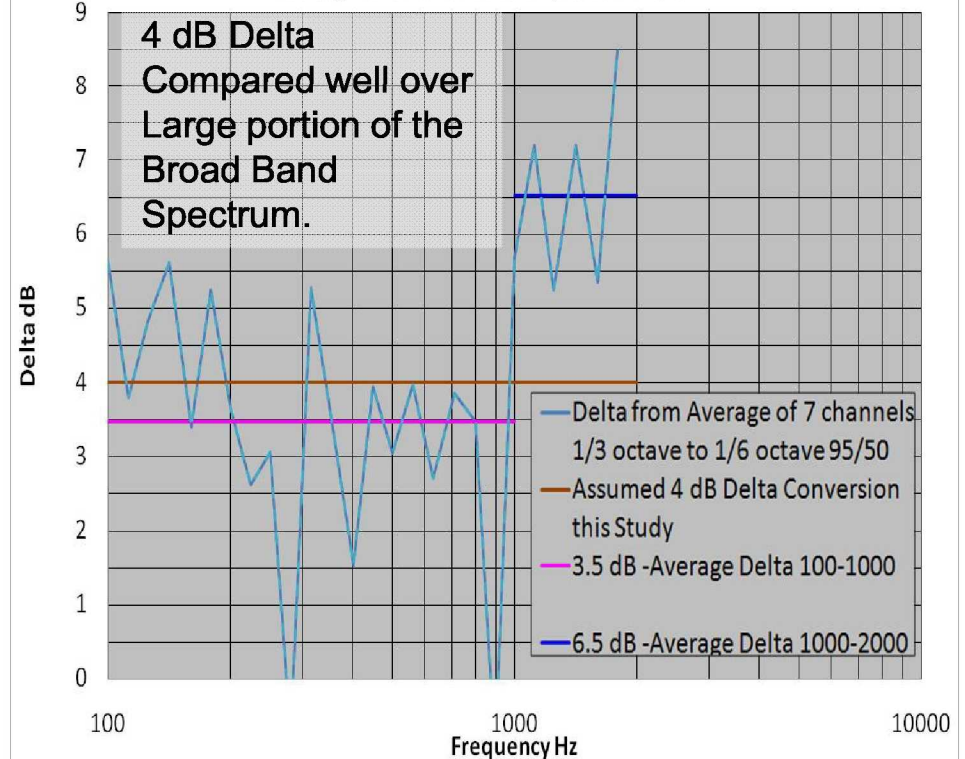
Conclusions and Recommendations

- **The use of Uniform Panel Construction** for Singly Curved Subsystem type models:
  - Produces the expected response peaking at the classical "Ring Frequency."
  - Provides the best estimate for overall structural response of the lower frequency bands up to and including the "Ring Frequency."
  - **Under-predicts the response of a rib-stiffened panel at high frequency.**
- The use of more complicated construction type models, such as the **Rib-stiffened Panel Construction**, results in several significant advantages:
  - Provides a good estimate for the peaking when local panel modes begin to significantly interact with the global panel behavior
  - Serves as the best estimate of response of the overall system for frequency bands above the "Ring Frequency."
  - Provides an estimate for global panel behavior, **but does not capture the response peaking at the classical "Ring Frequency."**
- Recommendations
  - Use modeling types that capture the expected physics.
  - A combination of models might be necessary in order to capture both the "Ring Frequency" and the "Local Panel" peaking.
  - Using both modeling types enabled us to capture the expected physics and to construct a smart envelope.
  - Recommend converting SEA Analytical Results to design envelopes using an approach that is grounded in the process of constructing a design envelope from measured data, since SEA produces average results (expanded on page 23).

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Conclusions and Recommendations

- Observations from Comparison of "SEA + 4 dB" to statistical design envelopes.
  - For this study, a uniform 4 dB increase in the SEA analytical average values provided an adequate Delta to construct a design envelope.
    - SEA with 4 dB Delta "conservatively estimated" the 95/50 enclosure for low frequency level from 80-200 Hz for the Ring frequency and below.
    - SEA with 4 dB Delta "very closely approximated" the 95/50 enclosure for the higher frequency level from 500-2000 Hz.
- Critically assessed the adequacy of using a simple Delta conversion by examining ground test measured data only (No SEA Results) and using normal tolerance limit (NTL) statistics.
  - Test data from Run1 suggested the use of a simple Delta conversion:
    - Run1 test data (7 measurements processed into 1/3 octave band spectral density functions) was used to calculate a location to location mean across the panel.
    - This 1/3 octave band mean spectral density was then compared to the narrow band spectra from the same channels.
    - A function representing the "1/3 octave band mean + 4 dB Delta" was also plotted.
  - Test data from Run2 was assessed with more rigor using NTL statistics:
    - The mean and standard deviation for the 7 measurements were used to produce a 95/50 enclosure of the data using normal tolerance limit statistics using the procedure outlined in NASA-HDBK-7005.
    - This 95/50 enclosure design envelope of 1/6th octave band test data was compared to the 1/3 octave mean across the measurements from 7 locations on the same panel and used to compute a Delta in dB for each center frequency.
    - This derived Delta was compared to the proposed simple Delta used in this study with favorable results (for response of a flight-like orthogrid panel).

Conclusions and Recommendations

- Producing Design Envelopes from SEA Vibration Response Predictions:
  - Strongly recommend using experience/knowledge base from the typical measured response of a representative structure when converting any SEA results to design envelopes.
    - Develop a realistic conversion strategy using available data that is appropriate for each design type.
    - If possible, convert multiple measured narrow band spectra to both octave band averages and spatial averages and make observations on how these compare to an adequate enclosure or envelope of the more narrow band data.
    - The data from this study suggests that the uniform Delta may be a better strategy than an approach based on the **"modal overlap"** assumption. The **"modal overlap"** approach tends to converge toward the band average at high frequency.
    - Acknowledge that this study was limited to the response of an **orthogrid panel**.
- **Warning For Constructing Design Envelopes From SEA Response Averages:**
  - Avoid the use of the modal overlap assumption to convert 1/3 octave SEA vibration response results to design envelopes **without first verifying that the conversion is applicable.** [Suggest a comparison of narrow band spectra from test data with a spatially averaged 1/3 octave processing of the same data on a similar structural design.]
  - The modal overlap expectation that the average results would more closely approximate the design envelope at high frequency **could not be verified for this study of a Flight-like Orthogrid Panel.**
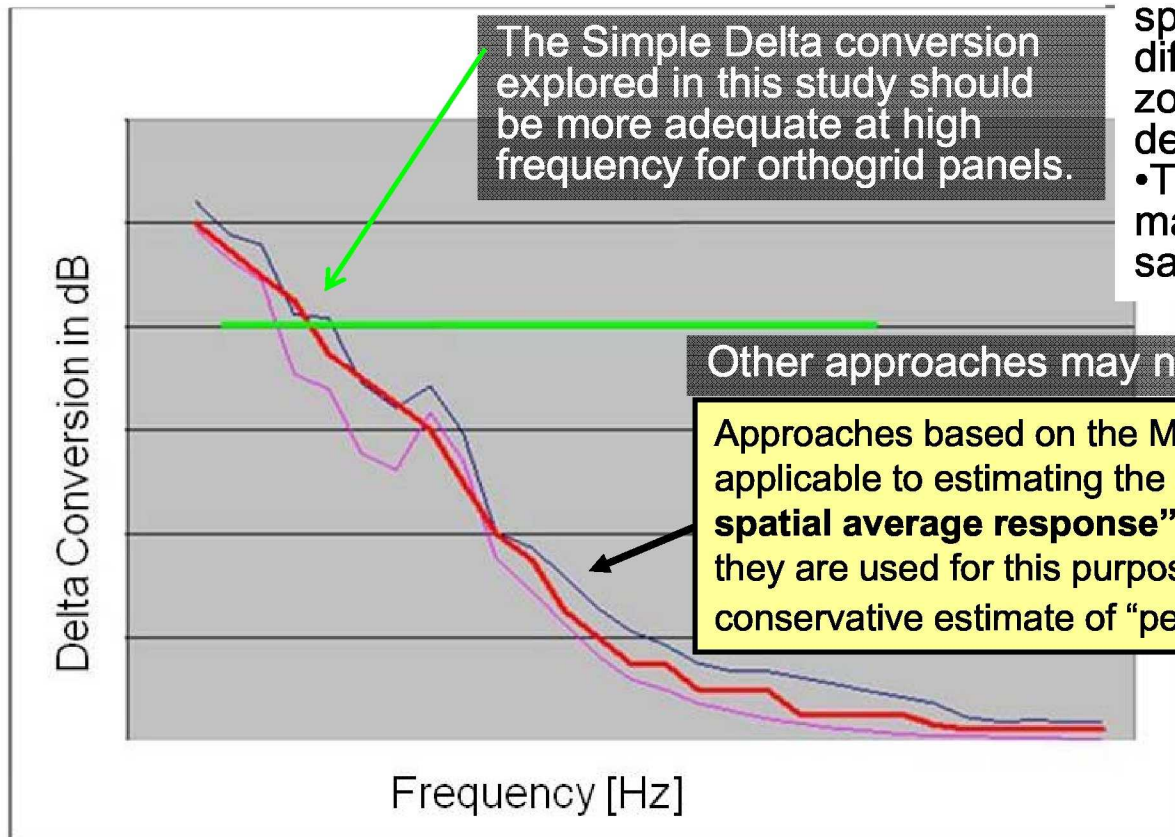
References

1. 809-2087, "Orthogrid Acoustic Test Report," Lockheed Martin Contract NAS8-36200, April 1997.
2. 809-2087 [Reconstituted],"Orthogrid Acoustic Test Report, Lockheed Martin," [Reconstituted from eight separate sources].
3. Unpublished MSFC Test Branch Records, Orthogrid Acoustic Test , 1994.
4. Engineering drawings of the tested panels from the Lockheed Martin library at the Michoud Assembly Facility.
5. ESTSG-FY09-00139, "A Comparison of Statistical Energy Analysis (SEA) Predictions to Acoustic Test Response Results for an External Tank (ET) Panel," David Teague, Jacobs Engineering, April 2009.
6. NASA-HDBK-7005, "Dynamic Environmental Criteria," National Aeronautics and Space Administration, March 13, 2001.
7. "VA One –SEA (Statistical Energy Analysis) Training Class Notes - Basic SEA Training Class," ESI Group, San Diego, CA, August 2007.
8. "Vibro-Acoustic Analysis of Aerospace Structures," ATA Engineering, San Diego, CA, & Cambridge Collaborative, Cambridge, MA, October 2007.
9. "Ensemble Variance of the Response of Uncertain Structures in SEA," ESI Group, August 2007.
10. NASA/TM—2008-215168, "Vibroacoustic Response of the NASA ACTS, Spacecraft Antenna to Launch Acoustic Excitation," Jeffrey M. Larko-Glenn Research Center & Vincent Cotoni-ESI Group, December 2008.

Backup Warning

- Consider trials where you measure the response from many as built units to the same excitation at the same measurement point on each unit.
- The variance of response measurements becomes small at high frequency.

- Estimating the design level across a zone requires comparison of measurements at different locations in the zone.
- Spatial sampling of narrow band spectra from measurements at different locations across the same zone is used to construct vibration design envelopes.
- The convergence described at left may not be applicable for spatially sampled measurements.

The Simple Delta conversion explored in this study should be more adequate at high frequency for orthogrid panels.

Other approaches may not be as conservative.

Approaches based on the Modal Overlap Principle may not be applicable to estimating the **difference between "1/3 octave spatial average response" and more narrow band results**. If they are used for this purpose, then they may yield a non-conservative estimate of "peak" results in higher frequency bands.

Delta Conversion in dB

Frequency [Hz]

Mass Distribution Regions Across The Test Article

- **Orthogrid cells with a similar weight per unit area are shown by the colored zones at right.**

- **The cells transition from a lower weight per unit area on the upper left of the panel to higher values in the lower right corner. Approximate orthogrid cell thickness dimensions are listed for the horizontal rib, the vertical rib and the pocket:**
  - 0.080", 0.120", 0.080"
  - 0.164", 0.120", 0.083"
  - 0.277", 0.210", 0.093"
  - 0.277", 0.210", 0.115"
  - 0.375", 0.375", 0.110"
  - 0.375", 0.375", 0.490"

  Small difference over most of panel area

- **Lower skin thickness/mass covers a large region of the test article. Equipment mounts to the reinforced structure.**

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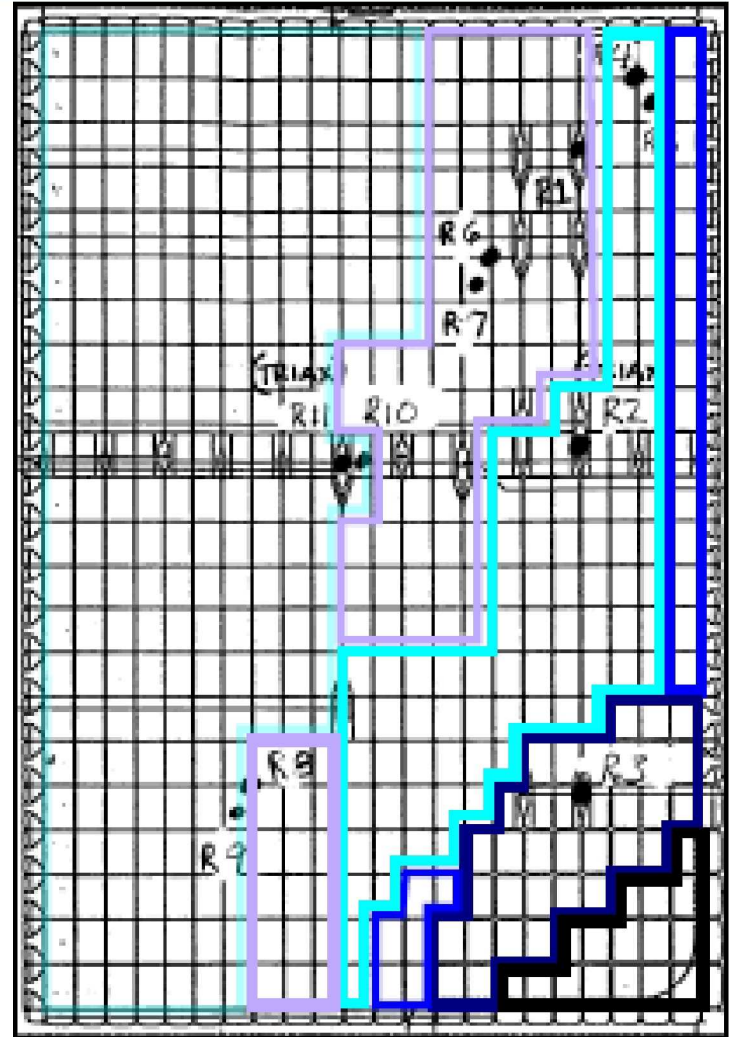
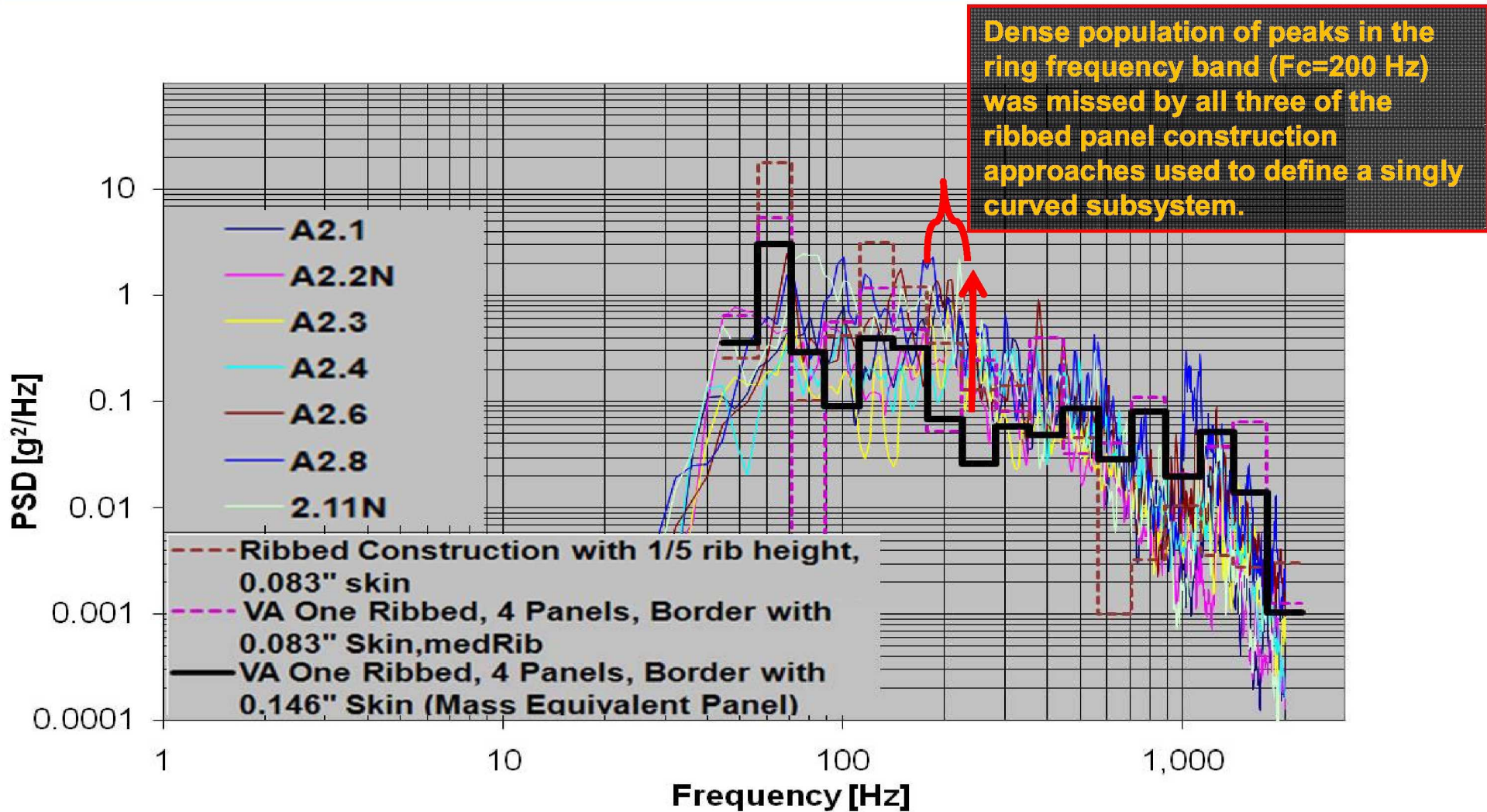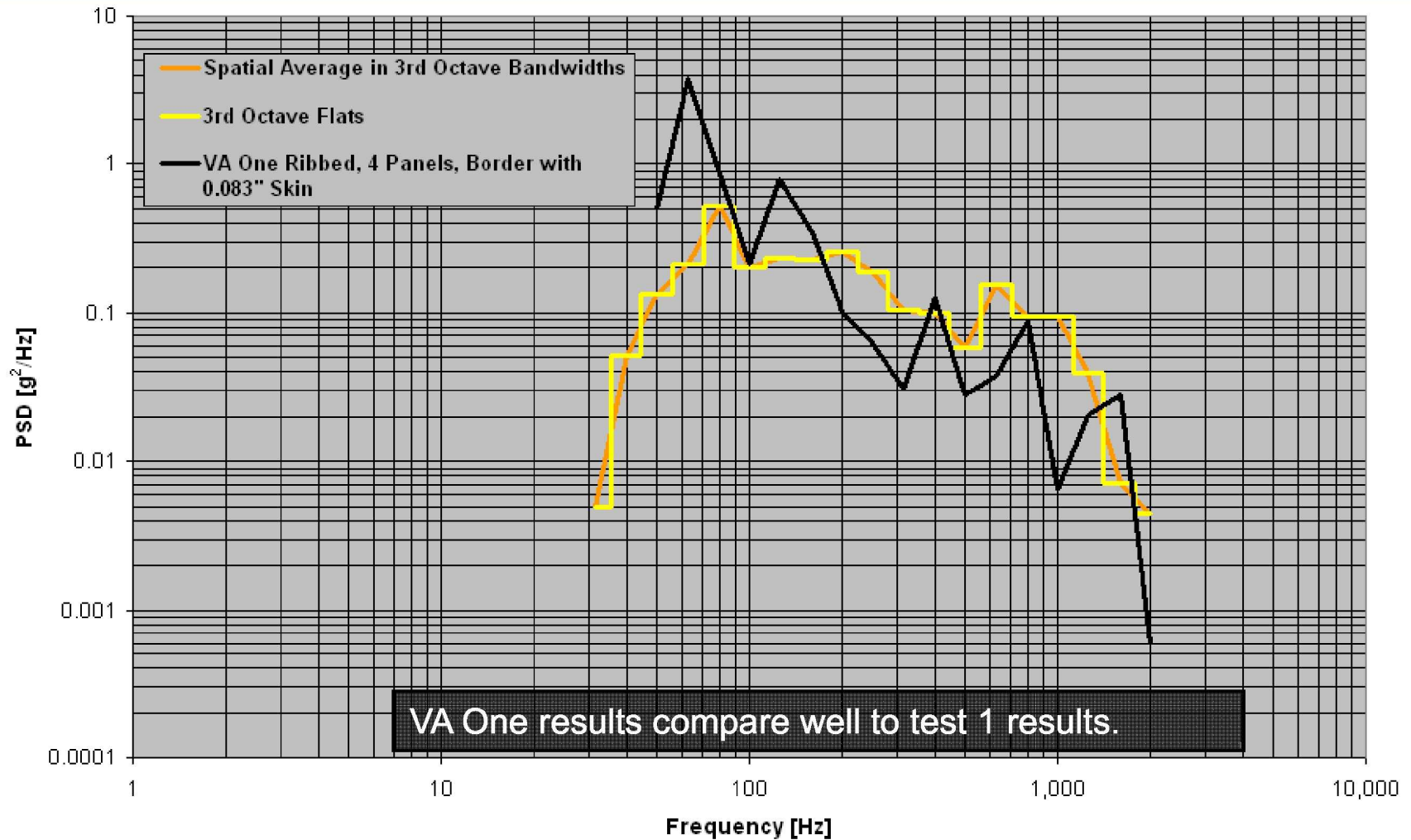# The Run2 Measured Vibration Response Spectra
Narrow Band Spectra from 11 Measurements
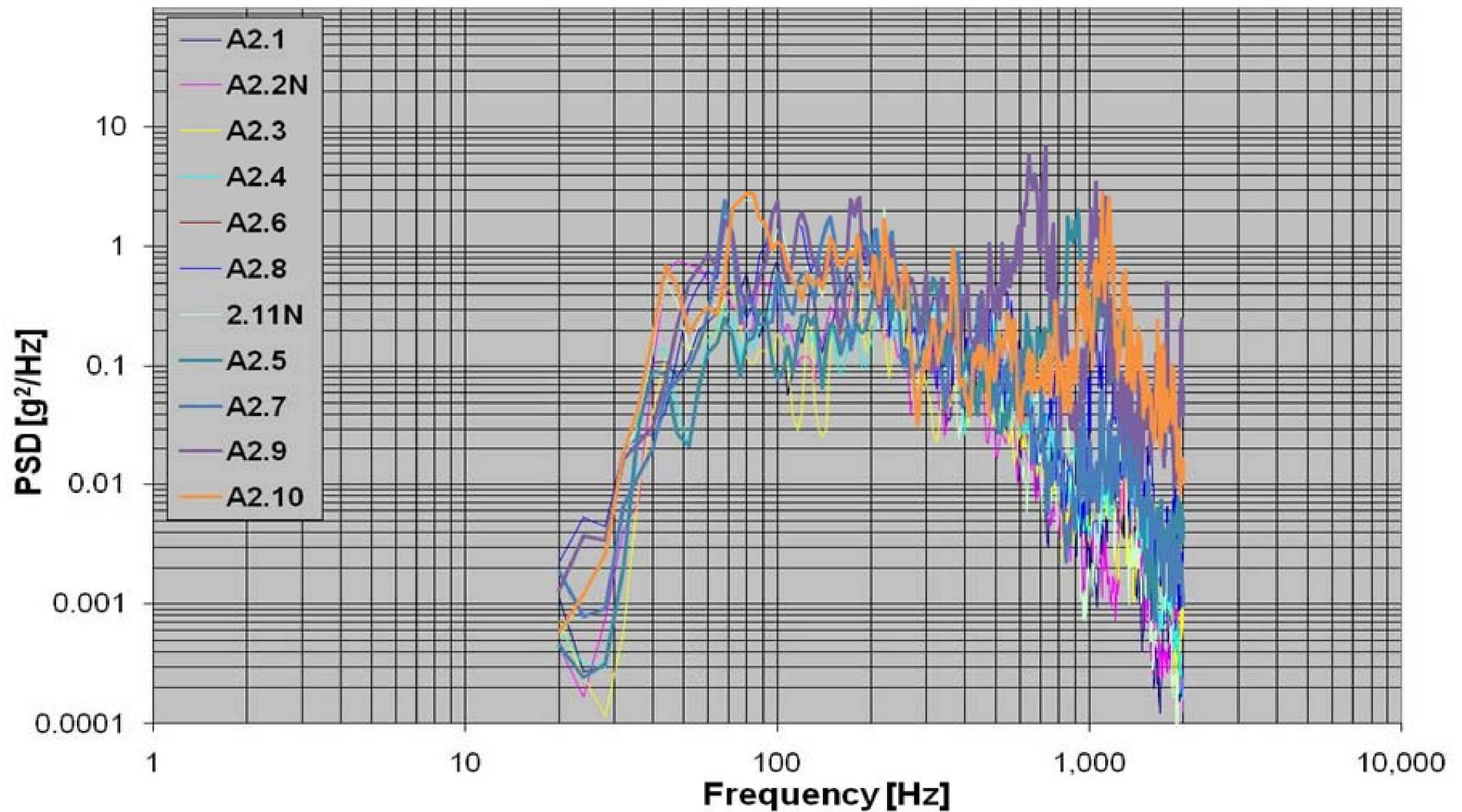
Compare Cases (3, 4, & 5) of Ribbed Panel SEA Results to Narrow Band Channels Located on Ribs

Comparison of Spatial Average of Run 1 Test Data in 3rd Octave Bandwidths to the Most Detailed VA One Model Results

Comparison of Spatial Average of Run 3 Test Data in 3rd Octave Bandwidths to the Most Detailed VA One Model Results