Determining System Response using Uncoupled Transfer Functions - And Advantages Using Response Matching Methods

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Introduction/Agenda

- Introduction Goal
  - Development of a Tool that provides best-in class-accuracy for vibration response assessments of Mass loaded panels.
  - The tool should also place capability in the hands of the end user with less complexity for each assessment.
  - Development of methodology for calculating system vibrations response using uncoupled models (uncoupled transfer function sets) is provided.
- Background - Addressing What need:
  - Validation and refinement of the approaches used to estimate the vibration environments associated with Equipment mass loaded exterior panels of launch vehicles is of major importance to new vehicle programs
  - This Validation has been identified by the NASA Engineering and Safety Center (NESC) as an area of uncertainty that is worthy of on-going study (References 1 and 2).
  - System damping values can increase with greater levels of integration.
  - Important to test validate damping under flight like conditions.
- Validation Test Program Test Conditions
- Methodology:
- Response comparisons
- Conclusions/Future Work

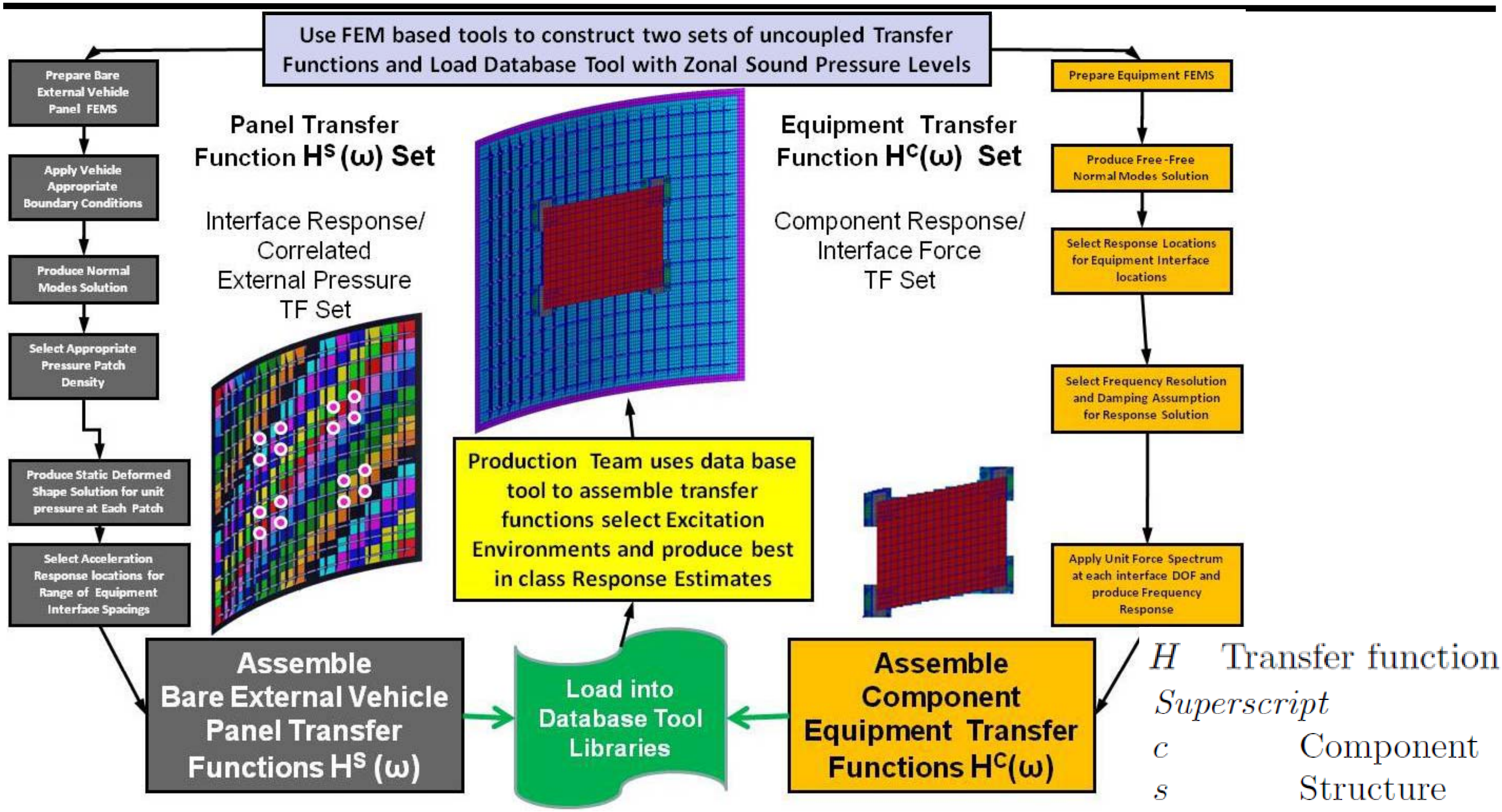
Background

- Background - Addressing What need:
  - In response to the NESC's critical technological need (References 1 and 2), **the authors have presented a pair of validated methodologies** for calculating both vibration response and dynamic loads for equipment mounted to vehicle exterior panels.
  - . RPTF applies a correlated pressure field across the surface of a vehicle panel. This is A direct method calculating response from input excitations. A diffuse acoustic field (DAF) pressure assumption was assumed. Pressure spectra provided as RMS sound pressure levels are first converted to pressure autospectral density. Then cross-spectra associated with the pressure field excitation are calculated according to the best fit for a DAF **(References 4 and 5).**
  - The second method, the Response Matching Method (RMM), provides the basis for much of the theoretical development presented here. It is a indirect method. Response is calculated based on a ratio of Transfer functions and the known response of one of the two systems.
  - **The third method, RPTF – Uncoupled, represents the methodology under development for this technical paper. RPTF – Uncoupled is also a direct approach.**

Method	Transfer Functions	Modal Requirements	Type of Input	Available Output
RPTF	Coupled	Loaded Structure	Pressure Auto Spectral Density	Any Response Auto and Cross Spectral Densities
RMM	Coupled	Unloaded Structure and Loaded Structure	Unloaded Skin Acceleration Auto Spectral Density	Any Response Auto Spectral Density
RPTF	Uncoupled	Unloaded Structure and Component	Pressure Auto Spectral Density	Any Response Auto and Cross Spectral Densities

Database Tool

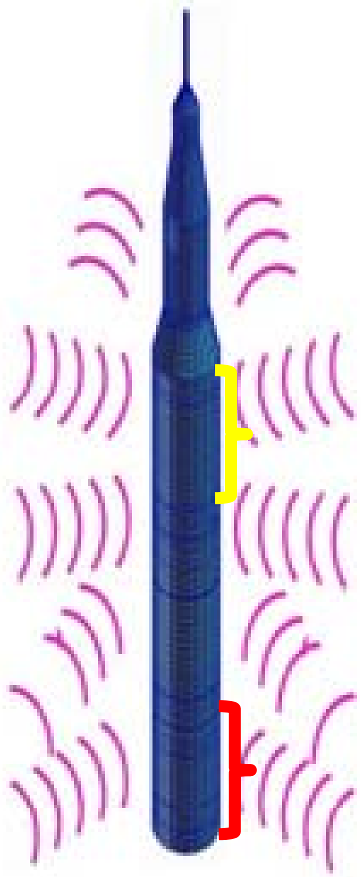
Uncoupled Approach



- Development of a Tool that provides best-in class-accuracy for vibration response assessments of Mass loaded panels.
- The tool should also place **a flexible capability** in the hands of the end user with less complexity for each assessment. **An Uncoupled Approach.**

Database Tool

Uncoupled Approach



Component Designation	Number of Interfaces	Interface DOF	Weight (lb)	Centroid Offset (in)
1-SFP-15-8	4	24	15.00	8.00
2-SFP-30-8	4	24	30.00	8.00
3-SFP-45-8	4	24	45.00	8.00
4-SFP-15-11	4	24	15.00	11.00
5-SFP-30-11	4	24	30.00	11.00
6-MFP-30-8	8	48	30.00	8.00
7-MFP-45-8	8	48	45.00	8.00
8-MFP-60-8	8	48	60.00	8.00
9-MFP-15-11	8	48	15.00	11.00
10-MFP-45-11	8	48	45.00	11.00
11-LFP-45-11	16	96	45.00	11.00
12-LFP-60-11	16	96	60.00	11.00

- Database Library will provide Selectable Primary Structure Panels (Yellow and Green Brackets at left).
- Database Library will provide Selectable Secondary Structure Equipment/Component Examples (Table On Right).
- **An Uncoupled Approach.** Database Library is expandable.

Database Tool

Features

- Tool will be delivered to the customer as a standalone executable.
- Cross-platform compatibility (Windows, OSX, Unix).
- Designed for speed and ease of use.
- Tool consists of two main modules: Database Browser and Analysis/Results.

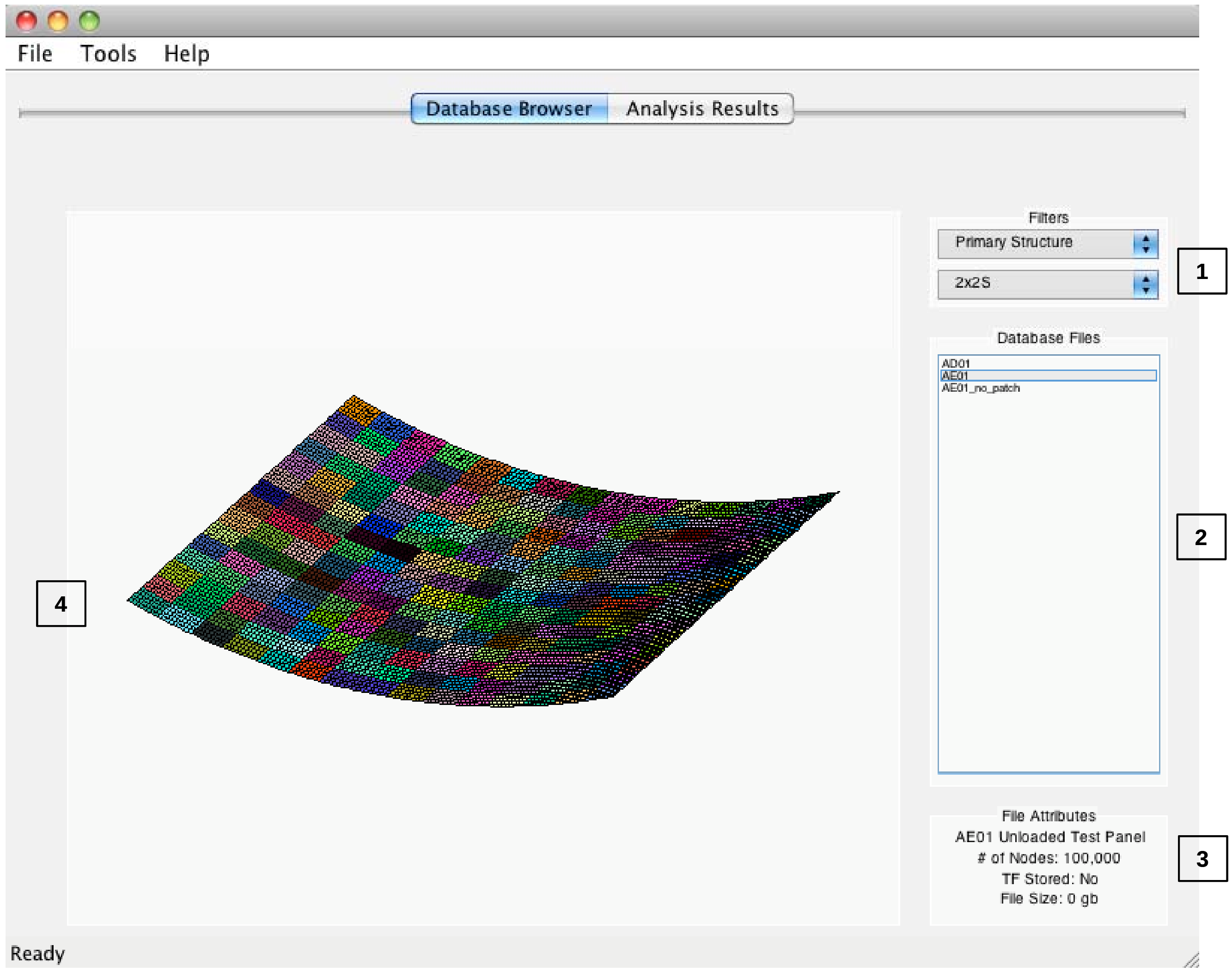
Database Browser Features:

1: Several filters allow for quick access to different file types and interface footprints stored on the database (models, pressure FFs, etc.).

2: Database list allows the user to view all available files stored on the database.

3: File attributes provides quick access to relevant information.

4: Display provides FEM geometry with patch definitions or forcing function plots.



Database Tool
Features

Analysis/Results Features:

1: Footprint filter identifies compatible Primary and Secondary structures via stored interface location definitions.

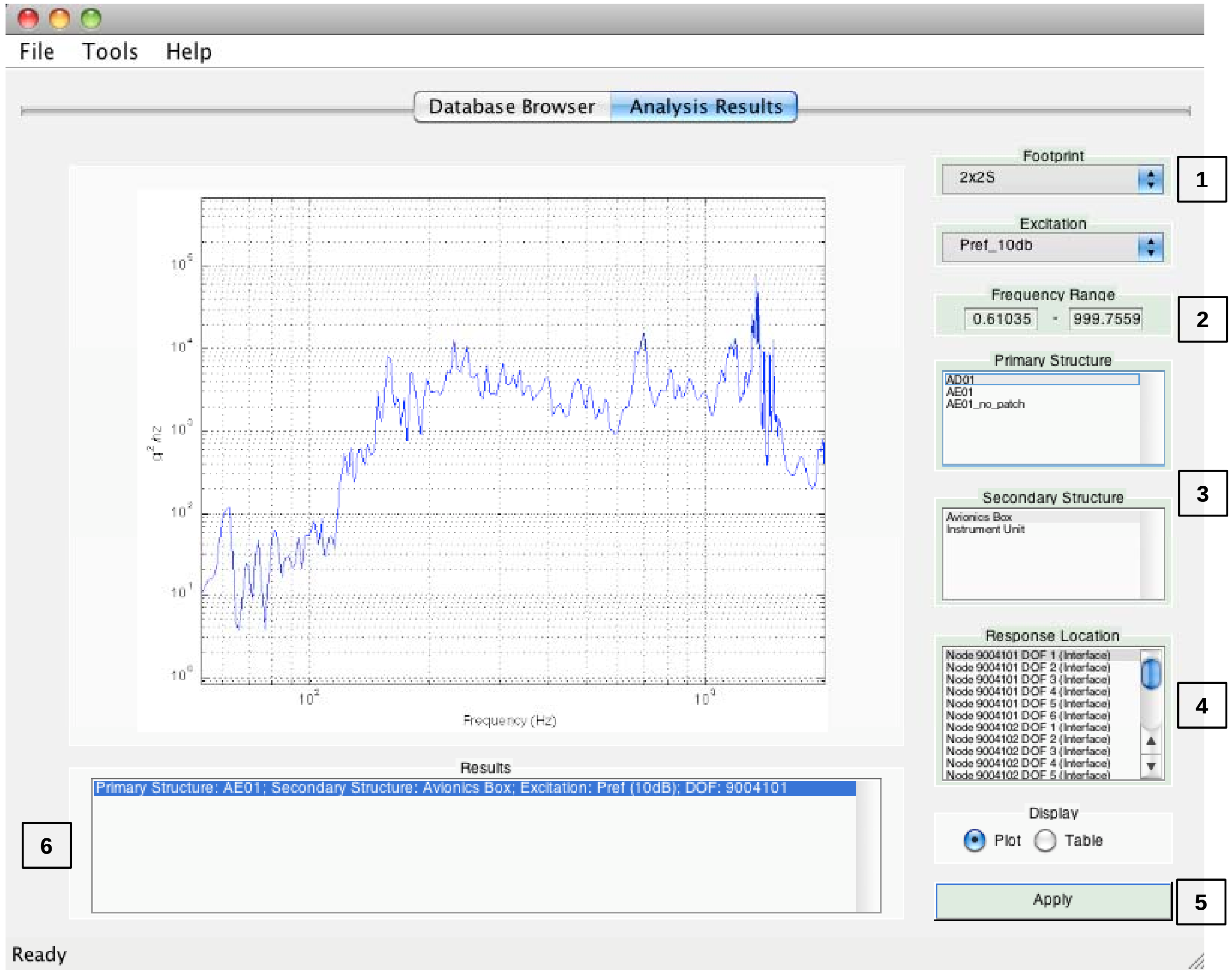
2: Frequency range boxes allow the user to specify the desired evaluation frequencies (with error checking to ensure range is within model and FF limits).

3: Lists allow the user to select a Primary and Secondary structure for coupling.

4: Response location sets the desired DOF or DOFs for response output.

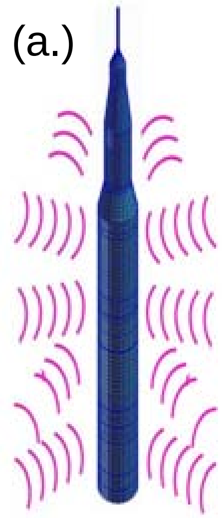
5: Comprehensive error checking ensures all inputs are provided and valid (all panels turn green) before allowing response computation.

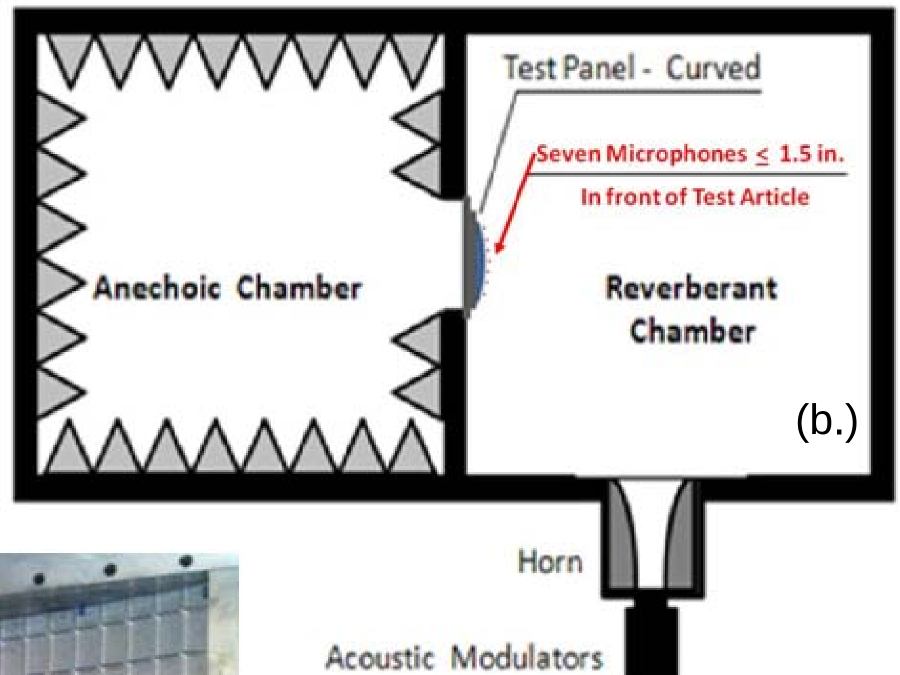
6: Results panel stores all responses calculated and allows for overlay plots.

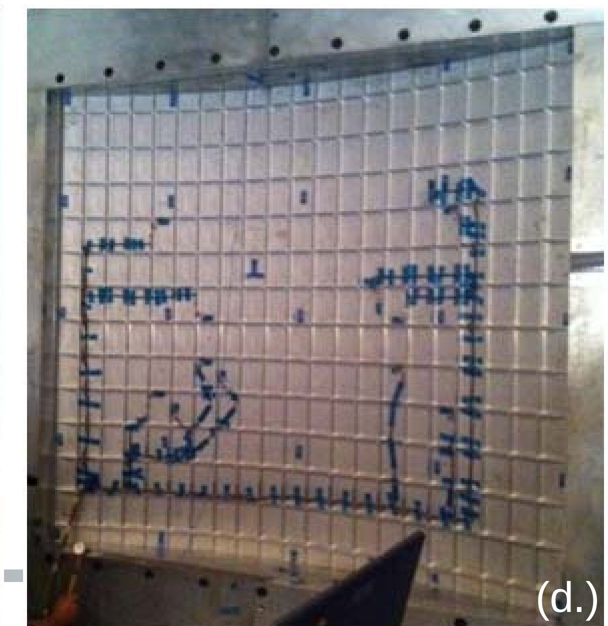


Validation Test Program Test Conditions

(a.) Acoustic or Fluctuating Pressures affect the exterior surface of Vehicle panels.
(b.) Ground test setup.
(c.) Flight like excitation of exterior surface in Baffled panel test setup. (Reverberant)
(c.) View of Flight like test article from Anechoic receiver room.



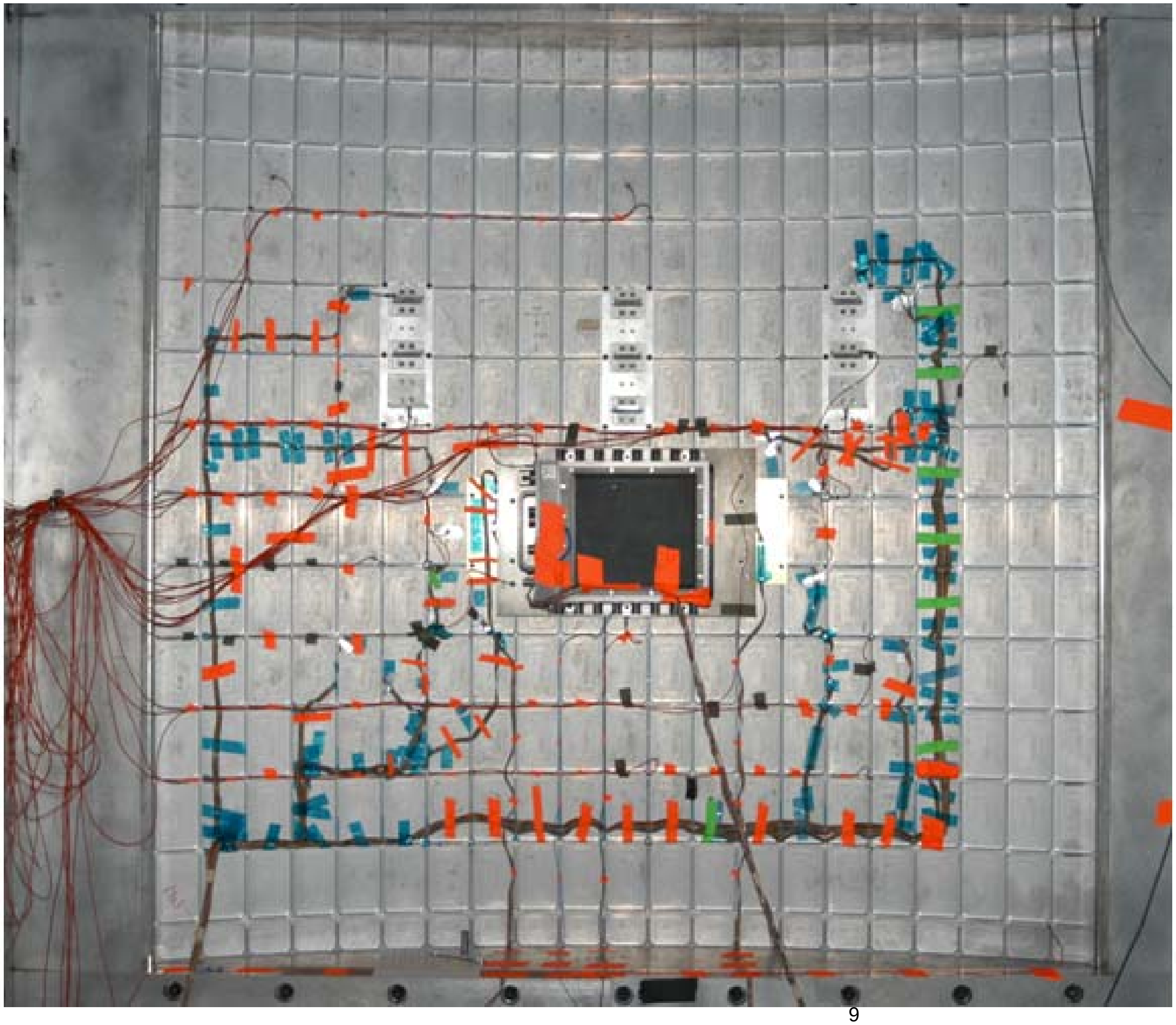




- Note that the Vehicle Panel Test Article can be configured as a bare panel As in (d.)
- or further integrated with equipment/cables.

Validation Test Program Test Conditions

• In figure (a.) at the below the test article is configured with an equipment assembly near the center:

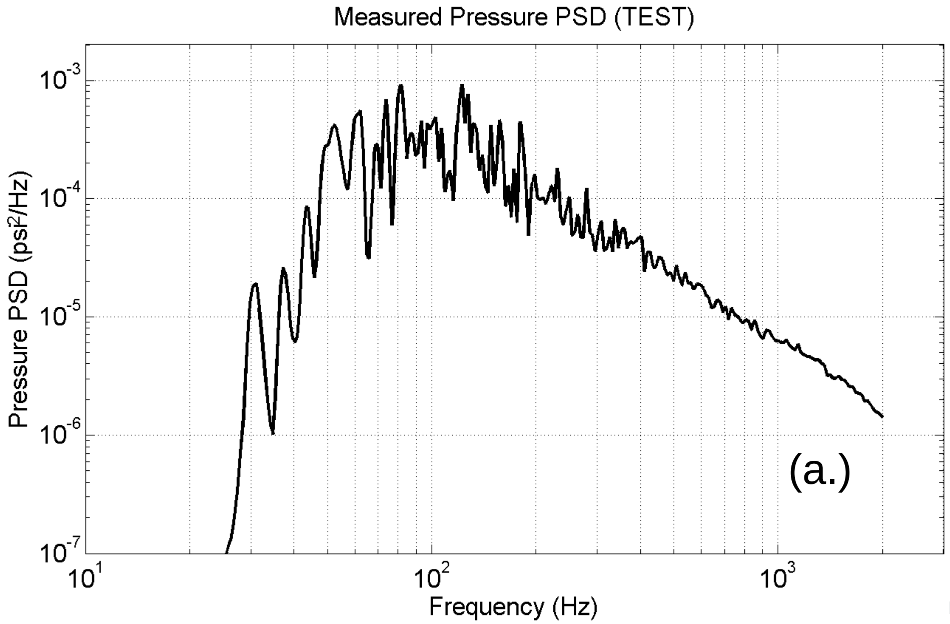


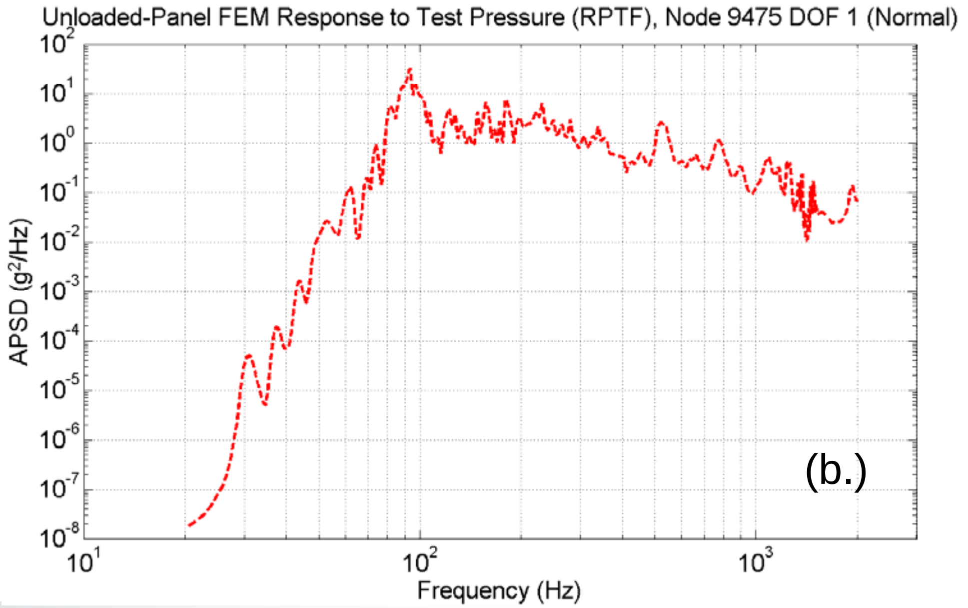
Medium footprint

8 fasteners

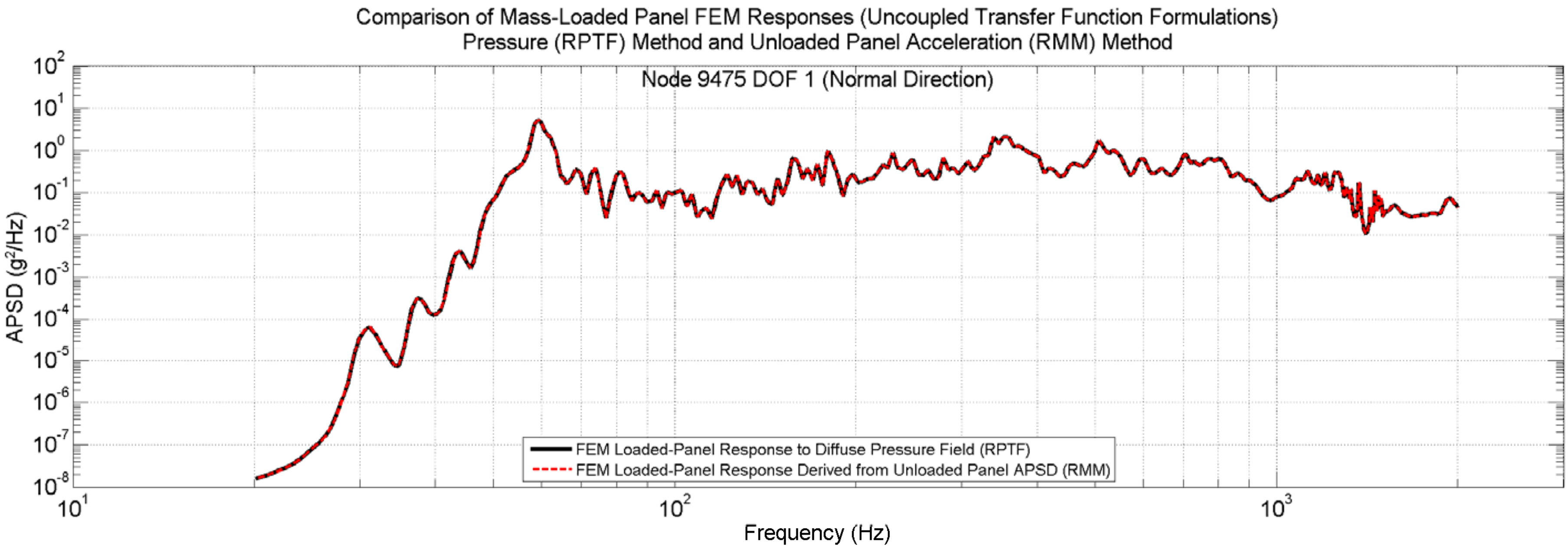
Validation Test Program Test Conditions

- The plots labeled a and b below present response at locations 1 and 2 for configurations with and without cables.
- Both provide evidence of attenuation in the range from 100 to 400 Hz. Note these two responses have nearly identical spectral shapes below 600 Hz. In this frequency range the structural bending wavelengths remain large relative to the orthogrid cell size. Global panel behavior is exhibited.
- Above 600 Hz, the responses shown in diverge from each other:
  - the bending wavelengths are small enough for the response at the center of an orthogrid cell to be different from the response on the perimeter.





Validation Test Program Test Conditions



- The plots labeled a and b below present response at locations 4 and 16 for configurations with and without

Response of Structural Panel with an Attached Component

The Multi Degree of Freedom Frequency Response Equation:

$$\mathbf{a} = [H]\{\mathbf{f}\}, \qquad (1)$$

Consider a Partition where the coupling/boundary DOF are grouped at the top:

$$\mathbf{a} = \left\{ \begin{array}{c} \mathbf{a}_{\mathrm{b}} \\ \cdots \\ \mathbf{a}_{\mathrm{p}} \end{array} \right\} = \left[\begin{array}{ccc} H^s_{be} & \vdots & H^s_{bb} \\ \cdots & \cdots & \cdots \\ H^s_{pe} & \vdots & H^s_{pb} \end{array} \right] \left\{ \begin{array}{c} \mathbf{f}_e \\ \cdots \\ \mathbf{f}_{\mathrm{b}} \end{array} \right\}. \qquad (2)$$

H Transfer function

Superscript

c Component

s Structure

Subscript

b Interface points

e Excitation points

p Non-interface points

Response of Structural Panel with an Attached Component

The Forces at the coupling/boundary dof can be written:

Imposing the Constraint Equation

$$\mathbf{f_b} = -[H^c_{bb}]^{-1}\mathbf{a_b}. \qquad (3)$$

Combining Eqs. (2) and (3) and solving for a_b ,the acceleration at the interface in terms of the interface transfer functions and the external force is :

$$\mathbf{a_b} = \left[[H^s_{bb}]^{-1} + [H^c_{bb}]^{-1}\right]^{-1}[H^s_{bb}]^{-1}[H^s_{be}]\,\mathbf{f_e}. \qquad (4)$$

H	Transfer function		
	Superscript		
	c	Component	
	s	Structure	

Subscript	
b	Interface points
e	Excitation points
p	Non-interface points

Response of Structural Panel with an Attached Component

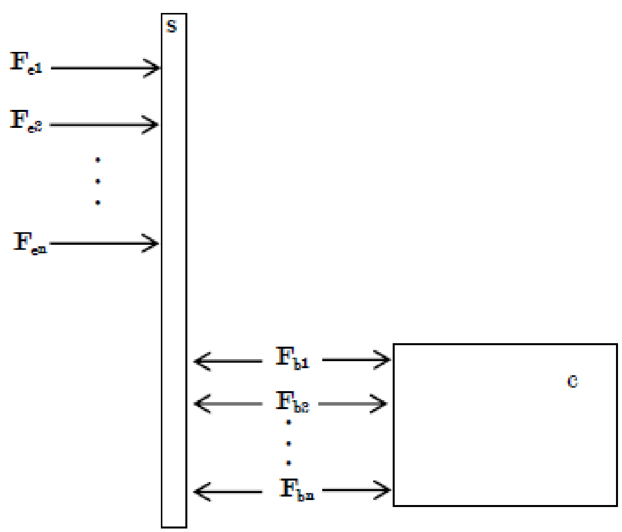
The Forces at the coupling/boundary dof can be written:

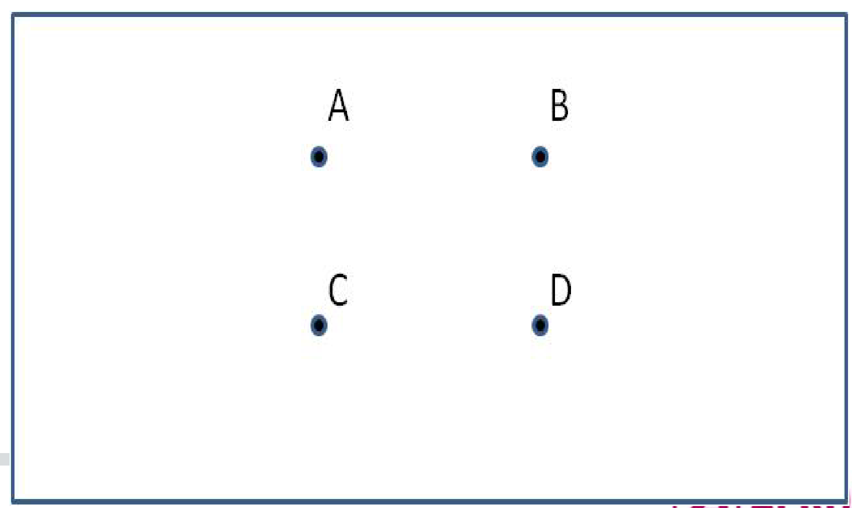
Equal and opposite Forces

$$\mathbf{f_b} = -[H^c_{bb}]^{-1}\mathbf{a_b}. \qquad (3)$$

Combining Eqs. (2) and (3) and solving for a_b ,the acceleration at the interface in terms of the interface transfer functions and the external force is :

$$\boxed{\mathbf{a_b} = \left[[H^s_{bb}]^{-1} + [H^c_{bb}]^{-1}\right]^{-1} [H^s_{bb}]^{-1}\,[H^s_{be}]\,\mathbf{f_e}. \qquad (4)}$$





Response of Structural Panel with an Attached Component

Now consider points p that are located on the panel, but not at interface points. The acceleration response of such points is given by:

$$\mathbf{a_p} = \left[H^s_{pe}\right] \mathbf{f_e} + \left[H^s_{pb}\right] \mathbf{f_b}. \qquad (5)$$

Using Eqs. (3) and (5) as well as acceleration continuity(imposing a constraint condtion), the response at points p is :

$$\boxed{\mathbf{a_p} = \left[\left[H^s_{pe}\right] - \left[H^s_{pb}\right]\left[\left[H^s_{bb}\right] + \left[H^c_{bb}\right]\right]^{-1}\left[H^s_{be}\right]\right] \mathbf{f_e}. \qquad (6)}$$

Since Eqs. (4) and (6) will be used later to find the response of the component loaded panel subject to random pressure excitation, we begin to express these quantities in the modal form of the equations.

Imposing the same Constraint Equation

Response of Structural Panel with an Attached Component

The response at a single point p due to a single force excitation e. For linear structural systems, the complex scalar elements of the force/acceleration TF matrices shown in Eqs. (4) and (6) can be expressed as a summation of natural frequencies and modes:

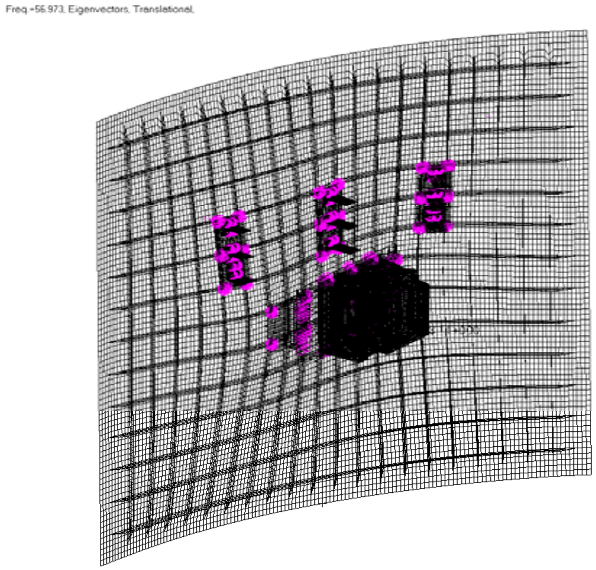
$$H_{pe} = \sum_{m=1}^{M} \frac{-\omega^2 \phi_{pm} \phi_{em}}{(\omega_m^2 - \omega^2 + 2i\varsigma_m \omega_m \omega)}, \qquad (7)$$

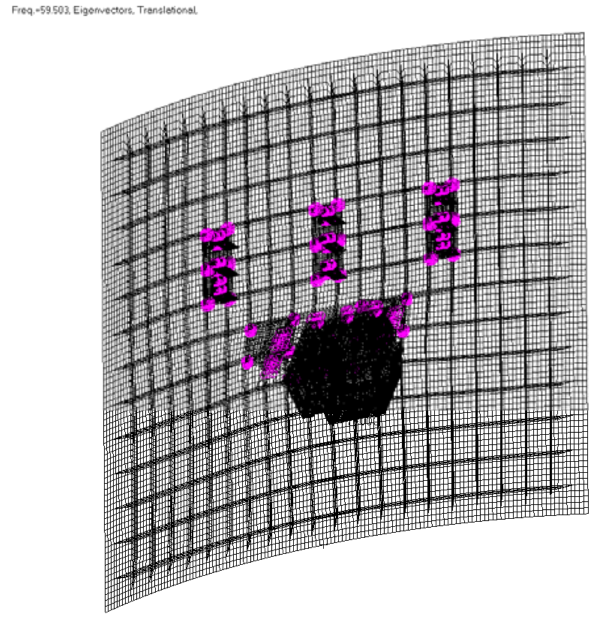
where the TF elements given by Eq. (7) take the same form for responses at interface and non-interface points. This form also applies regardless of whether one is assembling matrices of bare structure TFs or component TFs (provided, of course, that the appropriate structure or component natural frequencies and modes are used). **An Uncoupled use of the Models.**

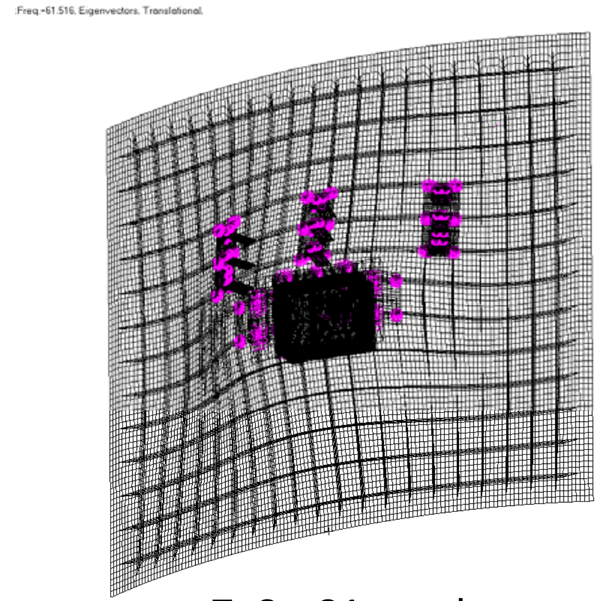
M is the number of modes. Avoid truncation errors by including many modes from the uncoupled models.

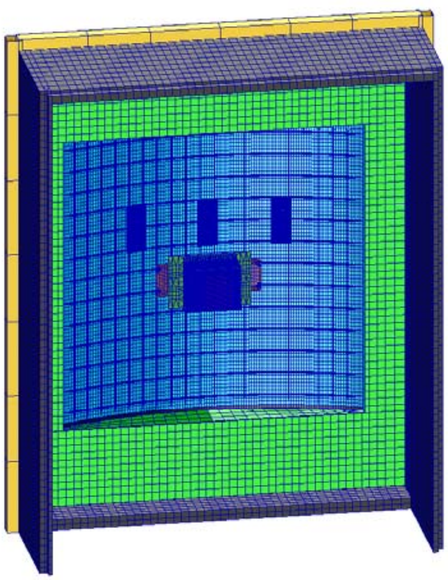
Transition to Patch Method

Vehicle Panel Responding to Fluctuating Acoustic Pressure Excitation





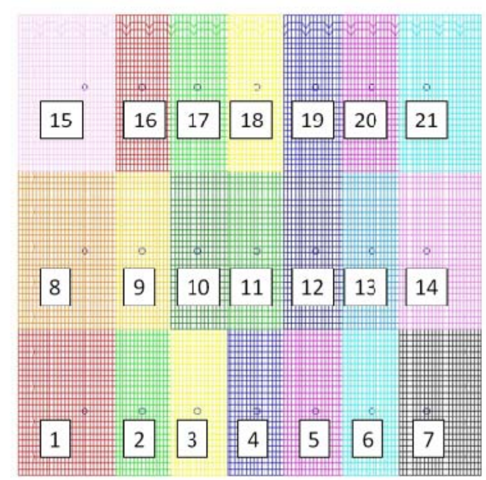




At the top are the first three **system mode shapes** of the test article (57.0, 59.5 and 61.5 Hz respectively) Hundreds of modes are used across the frequency range for Vibroacoustics.

On the left the System model is shown including some facility structures that represent the boundary conditions at the perimeter of the test article.

7x3 =21 patches

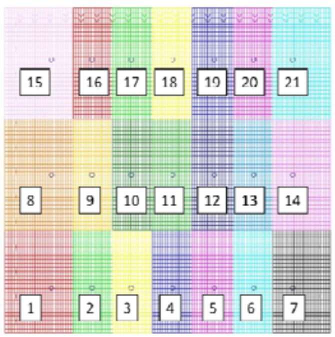


Methodology Development

Vehicle Panel Responding to Fluctuating Acoustic Pressure Excitation

Pressure Excitation of Panel (The Patch Method)

Cross correlation may be calculated between the pressures any pair of patches (exhibiting a non-zero cross-spectral density between them). The random pressure field is represented as a Hermitian matrix of spectral densities of dimension N_p, the total number of pressure patches. The pressure autospectra occur on the diagonal of the matrix. The cross-spectra appear off diagonal:



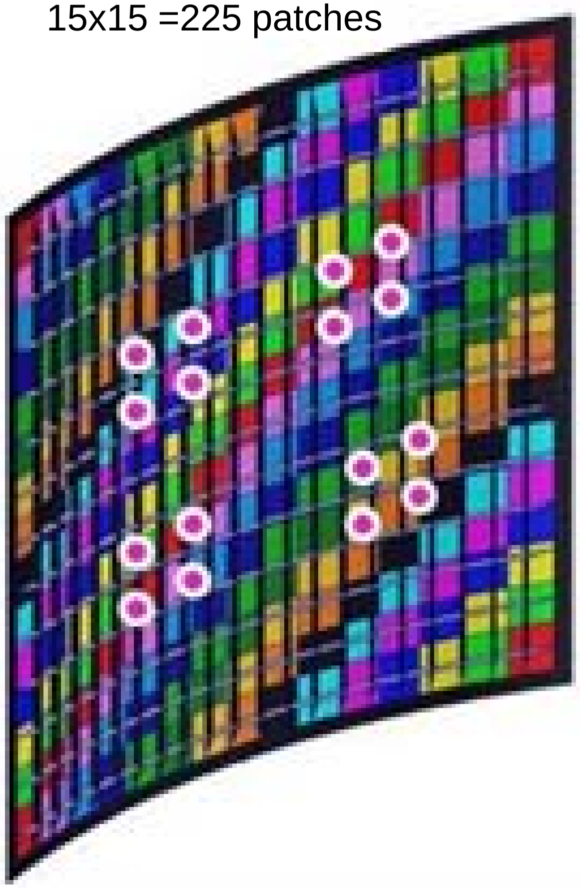
$$P(\omega) = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1N_p} \\ P_{21} & P_{22} & \cdots & P_{2N_p} \\ \vdots & \vdots & \ddots & \vdots \\ P_{N_p1} & P_{N_p2} & \cdots & P_{N_pN_p} \end{bmatrix}, \qquad (8)$$

where $P_{jk} = P_{kj}^*$. If spatial functions $\gamma(\omega, r)$ are defined to relate the autospectra to the cross-spectra, Eq. (8) may be written as :

$$P(\omega) = \begin{bmatrix} \gamma_{11}\hat{P}_{11} & \gamma_{12}\hat{P}_{12} & \cdots & \gamma_{1N_p}\hat{P}_{1N_p} \\ \gamma_{21}\hat{P}_{12} & \gamma_{22}\hat{P}_{22} & \cdots & \gamma_{2N_p}\hat{P}_{2N_p} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{N_p1}\hat{P}_{1N_p} & \gamma_{N_p2}\hat{P}_{2N_p} & \cdots & \gamma_{N_pN_p}\hat{P}_{N_pN_p} \end{bmatrix}, \qquad (9)$$

Pressure Excitation of Panel (The Patch Method)

15x15 =225 patches



When j = k the spatial functions coincide with the patch autospectra and the gamma approaches unity by L'Hopital's Rule.

where $\hat{P}_{jk} = \sqrt{P_{jj}P_{kk}}$. As will be discussed shortly, in the case of a DAF,

$\gamma_{jk}(\omega, r_{jk}) = 1$ along the diagonals;

however, the γ terms have been included in the diagonal terms in Eq. (9) for generalization. The expression for $\hat{P}_{jk}$ satisfies an inequality requirement on the coherence which states that

$$0 \le \frac{|P_{jk}(\omega)|^2}{P_{jj}(\omega)P_{kk}(\omega)} \le 1.0. \qquad (10)$$

For a DAF, the spatial functions may be expressed as:

$$\gamma_{jk}(\omega, r_{jk}) = \frac{\sin(kr_{jk})}{kr_{jk}}, \qquad (11)$$

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Pressure Excitation of Panel (The Patch Method)

Finally, the components of the pressure matrix may be expressed as products of frequency-dependent scaling functions, W_{jk} and an arbitrary reference autospectrum pressure, P_{ref} :

$$P_{jk}(\omega) = \gamma_{jk} W_{jk}(\omega) P_{ref}(\omega) \qquad (12)$$

and:

$$P(\omega) = \begin{bmatrix} W_{11} & \gamma_{12} W_{12} & \cdots & \gamma_{1N_p} W_{1N_p} \\ \gamma_{12} W_{12} & W_{22} & \cdots & \gamma_{2N_p} W_{2N_p} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{1N_p} W_{1N_p} & \gamma_{2N_p} W_{2N_p} & \cdots & W_{N_p N_p} \end{bmatrix} P_{ref}, \qquad (13)$$

or more compactly:

$$\boxed{P(\omega) = [W]^{\frac{1}{2}} \, [\Gamma] \, [W]^{\frac{1}{2}} P_{ref}, \qquad (14)}$$

and for a DAF:

$$\Gamma(\omega) = \begin{bmatrix} 1 & \frac{\sin(kr_{12})}{kr_{12}} & \cdots & \frac{\sin(kr_{1N_p})}{kr_{1N_p}} \\ & 1 & \cdots & \frac{\sin(kr_{2N_p})}{kr_{2N_p}} \\ & \text{SYM} & \ddots & \vdots \\ & & & 1 \end{bmatrix}. \qquad (15)$$

Mass Loaded Panel System Response from DAF Excitation

The acceleration response of a panel at non-interface points p due to a vector of patch pressures, p_ε is :

$$\mathbf{a}_\mathbf{p} = \left[H_{p\varepsilon}^{s+c}\right]\{\mathbf{p}_\varepsilon\}. \qquad (16)$$

where $H_{p\varepsilon}^{s+c}$ denotes the acceleration/pressure TF of the component loaded panel.

From Eq. (6), it follows that $H_{p\varepsilon}^{s+c}$ can be written in terms of acceleration/pressure TFs for the bare structure and component as : **System Response from Uncoupled TF sets**

$$\boxed{\left[H_{p\varepsilon}^{s+c}\right] = \left[H_{p\varepsilon}^{s}\right] - \left[H_{pb}^{s}\right]\left[\left[H_{bb}^{s}\right] + \left[H_{bb}^{c}\right]\right]^{-1}\left[H_{b\varepsilon}^{s}\right]. \qquad (17)}$$

In terms of patches

Acceleration/pressure TFs can be related to acceleration/force TFs by considering the pressure on a patch as an array of distributed point forces. Using this TF conversion and Eq. (7), it is possible to write the individual elements of $[H_{p\varepsilon}]$ corresponding to response point p and patch ε:

$$H_{p\varepsilon} = \sum_{m=1}^{M} \phi_{pm} \frac{-\omega^2\{\phi_{lm}\}^T\{\alpha_l\}}{(\omega_m^2 - \omega^2 + 2i\varsigma_m\omega_m\omega)}, \qquad (18)$$

Where $\{\phi_{lm}\}$ is a partial eigenvector containing the elements corresponding to the degrees of freedom associated with a single patch ε and $\{\alpha_l\}$ is the vector of areas associated with those degrees of freedom.

Methodology Development

Vehicle Panel Responding to Fluctuating Acoustic Pressure Excitation

Mass Loaded Panel System Response from DAF Excitation

Turning attention to the acceleration PSD response of a panel, the total response at a single point p includes the autospectra from the pressures on all of the patches and also from non-zero cross-spectra between any two patches, or :

$$A_p = \sum_{j}^{N_p} \sum_{k}^{N_p} H^*_{p\varepsilon_j} H_{p\varepsilon_k} P_{jk}. \qquad (19)$$

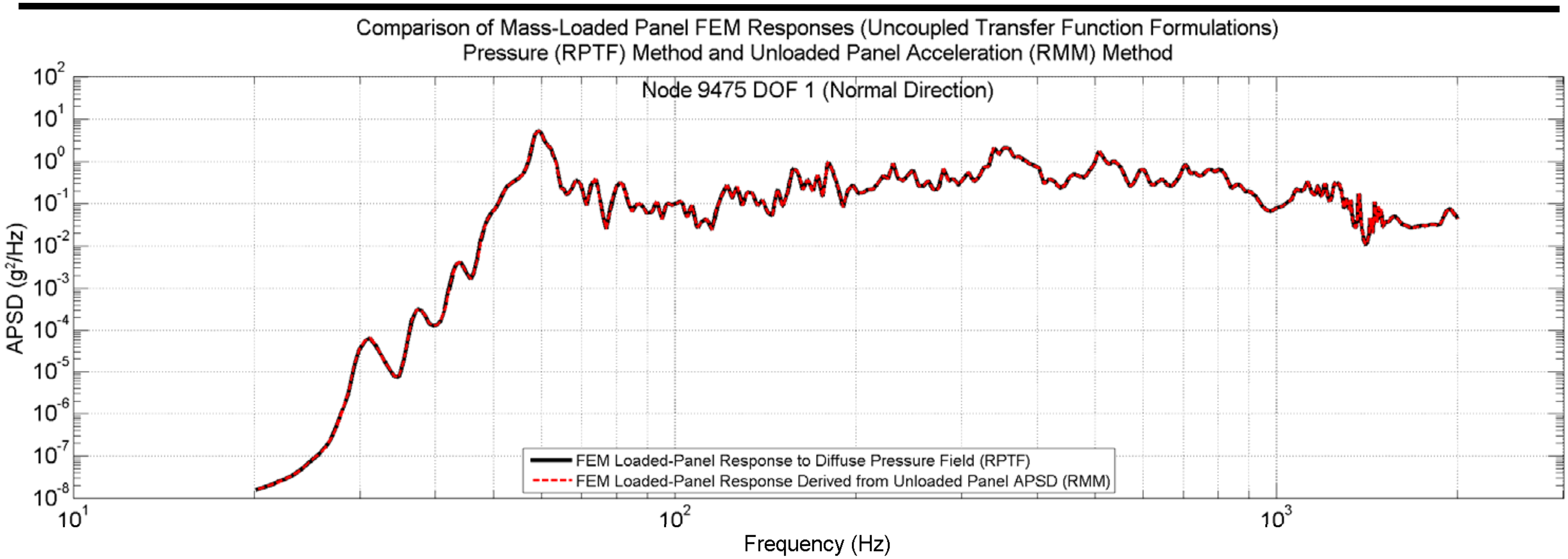
Using Eqs. (14) and (19), the PSD response of a component loaded panel at point p can be expressed in matrix-vector form for computational efficiency as:

$$A_p^{s+c} = \{H_{p\varepsilon}^{s+c}\} [W]^{\frac{1}{2}} [\Gamma] [W]^{\frac{1}{2}} \{H_{p\varepsilon}^{s+c}\}^{\dagger} P_{ref}, \qquad (20)$$

Where $\{H_{p\varepsilon}^{s+c}\}$ is a $1 \times N_p$ vector and N_p is the number of pressure patches. The individual elements of $\{H_{p\varepsilon}^{s+c}\}$ are given by Eq. (18). Similarly, the PSD response of the bare structure is:

$$A_p^s = \{H_{p\varepsilon}^s\} [W]^{\frac{1}{2}} [\Gamma] [W]^{\frac{1}{2}} \{H_{p\varepsilon}^s\}^{\dagger} P_{ref}. \qquad (21)$$

Validation of Methodology and Critique

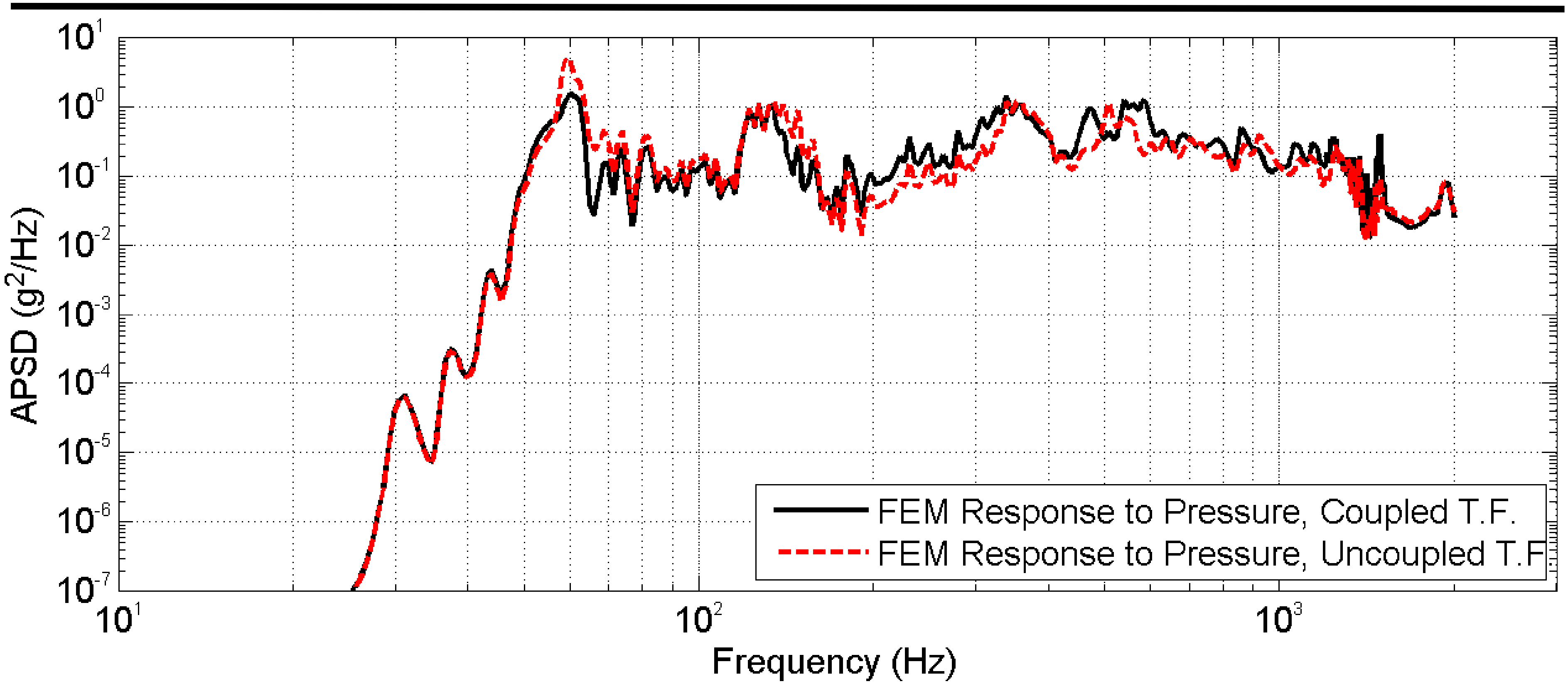


If the acceleration PSD response of the bare structure to the same excitation is known, it is possible to combine Eqs. (20) and (21) to obtain a relation that is independent of pressure:

$$A_p^{s+c} = A_p^s \frac{\left\{H_{p\varepsilon}^{s+c}\right\}[W]^{\frac{1}{2}}[\Gamma][W]^{\frac{1}{2}}\left\{H_{p\varepsilon}^{s+c}\right\}^{\dagger}}{\left\{H_{p\varepsilon}^{s}\right\}[W]^{\frac{1}{2}}[\Gamma][W]^{\frac{1}{2}}\left\{H_{p\varepsilon}^{s}\right\}^{\dagger}}. \qquad (22)$$

Note from the figure above that the result from the direct RPTF Coupled and RMM Coupled response compare as **an exact match**.

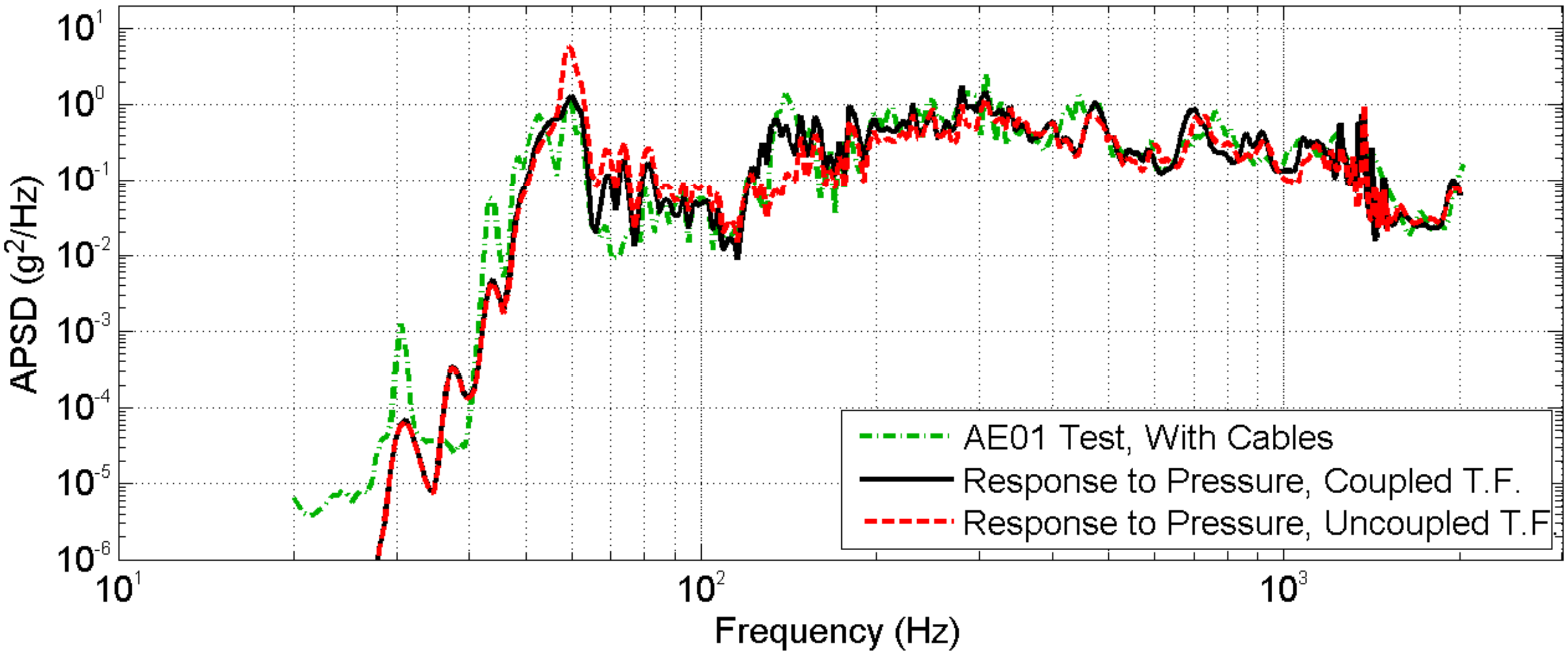
Validation of Methodology and Critique



The response of a mass-loaded panel at an interface point calculated using the coupled TF and uncoupled TF formulations of the RPTF method. Not yet an exact match.

Note the interface locations were not a measurement location during the ground test.

Validation of Methodology and Critique



Acceleration response spectra from uncoupled RPTF formulation and the coupled RPTF formulation compared with test data at one measurement location.

Improvements based upon Component Modes synthesis as described by Craig-Bampton and others are contemplated. Modal truncation has already been explored as a reason for slight mismatch.

Next improvement trial will be including static interface displacement shapes so that more strain energy is represented at the interfaces.

Conclusions and Future Work

- The uncoupled Transfer Function formulations were presnted and validated for the uncoupled RPTF and system RMM methods.
- A simple, but powerful, database analysis tool for the MSFC vibroacoustics team is under development to estimate vibration responses at equipment mounting locations.
- This useful estimating tool will supplement he heritage processes that typically required:
  - the development of detailed system analysis models>
  - and/or the collection and processing of substantial ground and flight test data.
- This puts powerful capability into the hands of the propulsion and vehicle system departments to provide input vibration environment requirements for a new launch vehicle program.

Status:

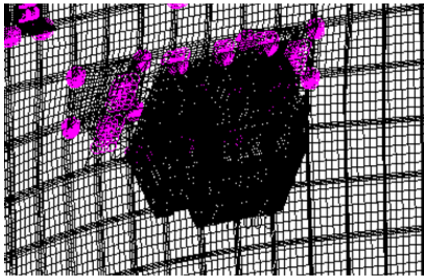
- “RPTF Coupled” and “RMM Coupled” have been fully vetted for use within the Database Tool.
- “RPTF Uncoupled” methodology was described and demonstrated.
- A few improvements to The “RPTF Uncoupled” are planned before the tool is complete.

Conclusions and Future Work

Future Work:

Approach methodology for producing system transfer functions appropriate for vibroacoustics proof of concept trials from uncoupled models will be improved using several standard approaches was also verified in part.

- For instance truncation of modes does result some inaccuracy, the team demonstrating that keeping significantly greater number of modes from the uncoupled models improved the results (already demonstrated).
- It is well known that the free-free modes of subsystems may not demonstrate as much strain in the elastic elements near coupling degrees of freedom as they may after coupling. **Therefore it is expected that further improvement is possible by including some static fixed interface shapes.**



Future work may also involve expanding the methods to accept other types of source environments as input. For instance, the aero-fluctuating pressure environment associated with vehicle ascent is often modeled with what is known as a Corcos model. This would provide even greater capability for predicting environments across all flight regimes.

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