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A hybrid FE-SEA model reduction method to obtain detailed responses at chosen locations from a large launch vehicle model

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Abstract

Innovative Hybrid FE- SEA modeling methods allow stiff structures modeled with finite elements to be coupled directly to more flexible SEA (Statistical Energy Analysis) structures in a combined model.
This allows for a reduction of overall model computational time while preserving detail in areas where it is most needed. This case study presents a launch vehicle where a very stiff section was modeled with FE to preserve the critical response information in this section.
A method to reduce the SEA structure in the model to just the locally connected structures was implemented, taking advantage of high-frequency responses being highly localized.
With this reduced modeling method, comparisons to the full vehicle model show that the result retains its accuracy with only a small part of the total vehicle being modeled.

1. Introduction

Finite Elements (FE) and Statistical Energy Analysis (SEA) are two classical methods heavily used for the dynamic analysis of launch vehicle structures. On a launch vehicle, the finite element method is typically used in the low-frequency range for Coupled Load Analysis (CLA) models. Due to the structure's size, this type of analysis is often limited in frequency and therefore requires the usage of an alternative method such as SEA to predict the response at higher frequencies.
However, due to the nature of the method, SEA does not allow one to obtain a detailed response at a given locations nor accurately predict the response of stiff structures with low modal density. Hybrid models, i.e. coupling FE subsystems and SEA is an established solution commonly used in the aerospace industry allowing one to perform a dynamic analysis on a wide frequency range while meeting the accuracy expectations. As part of an engineering service contract, ESI was contracted to model the Interim Cryogenic Propulsion Stage (ICPS) of NASA's Space Launch System (SLS) on a broad frequency range (200 Hz to 2,000 Hz).

The main objective of this study was to predict the response on critical panels placed at the interstage (shown in Figure 1) between liquid oxygen and liquid hydrogen tanks. The complete interstage structure is stiff and cannot be subdivided into multiple SEA subsystems to obtain a localized response. The hybrid FE-SEA technique is, therefore, adequate as most of the SLS can be modeled using SEA, and the interstage can be modeled using FE giving the expected results.

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VA One being the chosen solution for vibroacoustic analysis of the SLS, SEA models of both the Crew Module and the LVSA (Launch Vehicle Stage Adaptor) were available. The complete hybrid model contains about 2,200 wavefields and the finite element part about 6,000 structural modes. The memory requirements to solve such model were prohibitive and led to the development of a reduced hybrid method.
The following presents a two-step method developed to overcome these limitations and look at the gains for both memory usage and solve time. Accuracy discussed as results of the original model are compared to the reduced models.

Figure 1: ICPS picture showing the location of the interstage structure. Image credit: ULA

2. Proposed method

The Hybrid FE-SEA method allows the coupling of components with high modal density (SEA subsystems) to components with low modal density that can be considered deterministic (FE subsystems). The method is widely used in the automotive sector in the mid-frequency range to obtain a good representation of a vibroacoustic system where some subsystems show large wavelengths compared with their dimensions and others show small wavelengths compared with their dimensions.
The method is based on the concept of a "direct field" and "reverberant field", where, taking the example of a thin plate excited at the boundaries, the direct field is the contribution from the initially generated waves, prior to any boundary reflections and the reverberant field is the contribution from waves produced from the first and all subsequent reflections [1-3].

2.1 Memory usage of hybrid models

The equation solved in each hybrid model is as follows:

$$\langle \mathbf{S}_{qq} \rangle = \mathbf{D}_{tot}^{-1} \left(\mathbf{S}_{ff}^{ext} + \sum_m \frac{4E_m}{\pi \omega n_m} \mathbf{Im}\left\{ \mathbf{D}_{dir}^{(m)} \right\} \right) \mathbf{D}_{tot}^{-H} \qquad \mathbf{(1)}$$

Where:

- $\mathbf{S}_{qq}$ is the cross-spectral response of the deterministic degrees of freedom
- $\mathbf{S}_{ff}^{ext}$ is the cross-spectral force matrix for external excitation applied to the deterministic degrees of freedom
- $\mathbf{D}_{dir}^{(m)}$ is the contribution to the dynamic stiffness arising from the direct field(s) of the m'th SEA wavefield
- E_m and n_m are the energy and modal density of the reverberant field of the m'th SEA wavefield

To compute the direct field contribution of the SEA subsystems to the FE subsystems, the matrices $\mathbf{D}_{dir}^{(m)}$ must be computed and stored in memory. Therefore, the memory usage is directly proportional to the number of wavefield and the square of number of modes [2]. The amount of memory required is low for most models, however, in this case the SEA part of the model contains several thousand modes therefore the memory consumption can be quite extensive.

2.2 Traditional memory management methods

Two memory management methods are implemented in the VA One software:

- The *Modes To Include In Analysis* controls the use of the enabled modes in a coupled solve. If resonant, mass-controlled or both are selected the VA One solutions times will decrease, and less memory will be used. However, the computed solution is approximate, and one must perform a convergence study to verify the solution accuracy. Most of the times the *Resonant modes* option is the one used for hybrid models. This specifies that X resonant structural and acoustic modes will be included in the analysis, where X is specified in the Number of resonant modes around center frequency field. This is equivalent to enabling only the X structural modes around the computed frequency at each frequency step and the X acoustic modes of all the cavity groups around the computed frequency.
- The *banded modal matrices* option specifies the Semi-bandwidth of the matrices describing the impedance that SEA subsystems present to the modes at hybrid junctions ($\mathbf{D}_{dir}^{(m)}$ matrix). For many problems, the modes of the FE subsystems are weakly coupled by the SEA subsystems (i.e. the off-diagonal terms in the modal impedance matrix are small). VA ONE gives the user the option to store these impedance matrices as banded matrices (and neglect some of the off-diagonal terms). The accuracy of this approach depends on the number of terms that are kept for a given problem (i.e. the semi-bandwidth).

These two methods can efficiently limit the memory usage while solving. However, both are committing an approximation regarding the number of modes used for the analysis. For the project described in this paper, the usage of these methods was excluded as the number of modes to include in the analysis was very large and the approximation had to be limited as much as possible.

2.3 Proposed two model method

Based on the model's characteristics, the modal density of the interstage is low, if one chose to replace the interstage by a set of beam subsystems, the overall energy transfer between all the SEA subsystems is not altered. Multiple verifications have been performed for a limited frequency range (and therefore a limited set of modes), the analysis showed that the energy levels on the SEA subsystems were very similar whether the interstage was modeled as an FE subsystem or a set of SEA subsystems.

Therefore, if one can calculate the energy levels on all the SEA subsystems neighboring the interstage using a SEA only model, detailed responses can be calculated on the FE subsystem of the interstage by creating a reduced model only containing the interstage (modeled as FE) and the neighboring SEA subsystems for which their energy level is constrained with the results of the SEA only model.

The second reduced model contains only a very limited number of wavefields, reducing the memory usage of the model drastically.

3. Models construction and process

The project objective is to calculate the response at the intertank of the ICPS. Therefore, it was decided to include SEA models of the Crew Module, the LVSA, and the top part of the core stage. The justification for this choice was to provide the correct junctions and power input to the modeled stage.

Both the Crew Module and the LVSA SEA model were already available from the supplier. The Crew Module SEA model was very detailed and contained many wavefields (over 2,100). The choice was made not to alter this model and integrate it directly into the vehicle model.

The incompatibility between the nodes of each stage was solved by creating manual line junctions while cavities present at the interface were created using slim temporary faces.

As the two-step process was used, in a first step, the interstage was modeled as SEA, and the levels on all SEA subsystems were calculated. In a second step, all SEA subsystem not having a direct junction with the interstage were removed, the SEA interstage was replaced by its finite element model, energy constraints were created on the

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neighboring SEA subsystems, and the response levels on the critical panels were calculated. Note that the time cost of creating this second model is minimal as most of the subsystems are taken from the initial model.
The modeling process is also described in the diagram presented in Figure 2 showing each step of the model creation. Using this technique, the number of SEA wavefield went from about 2,200 to 25. As the memory requirements vary linearly with the number of wavefields, the total memory consumption for the model was divided by 88, allowing more modes to be used for the calculation and therefore doubling the maximum frequency range for the calculation from 1,000 Hz to 2,000 Hz.

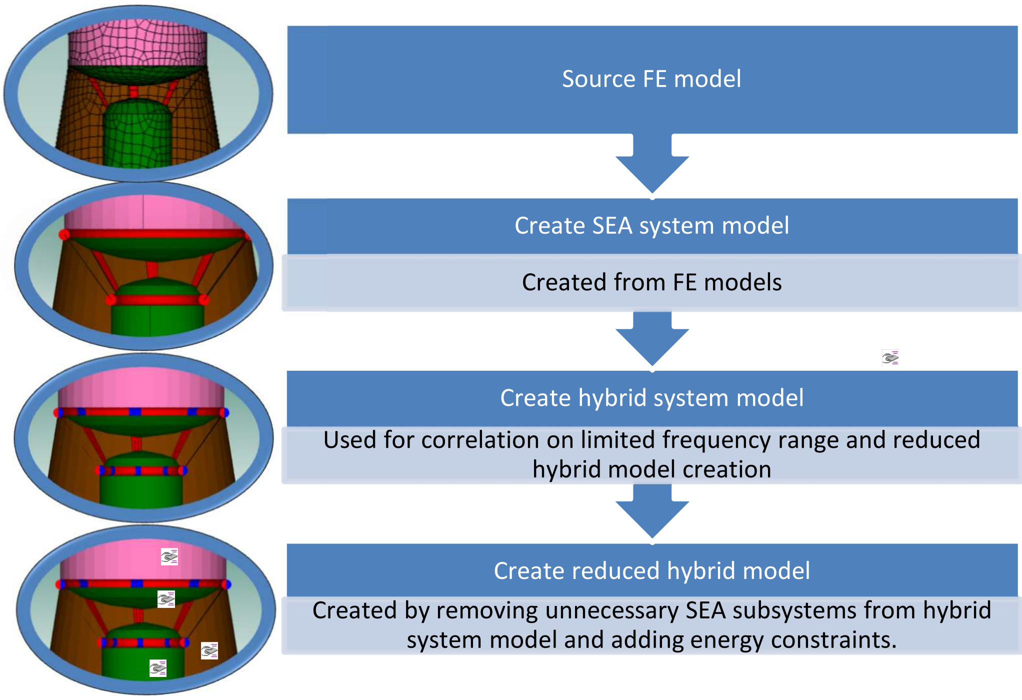

Figure 2: Model creation process. (screenshots are taken from a dummy model created for the purpose of this paper)

4. Validation

Validation of the technique was performed by comparing results from the full hybrid model to the reduced hybrid model for a limited frequency range (200 – 1,000 Hz). In order to illustrate this, a dummy model was created for this paper as illustrated in Figure 3.

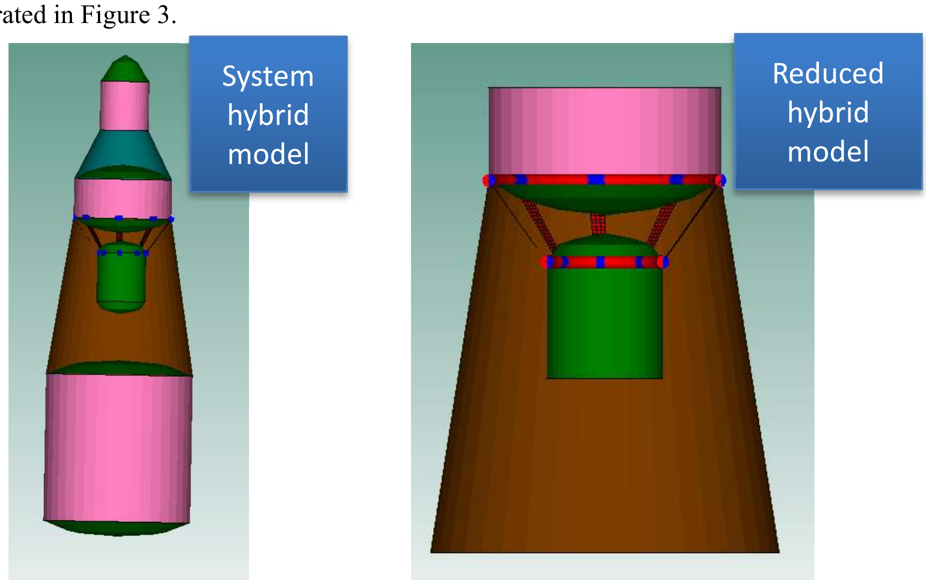

Figure 3: Dummy illustrative model

Dummy loads were placed on the model and results can be comped at given sensor locations (described in Figure 4). As this illustrative model is small, the comparison was performed for the complete frequency range (up to 2,000 Hz).

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Results are presented in Figure 5 and show a good match between the full hybrid model and the reduced hybrid model. The same conclusions were obtained with the actual model.

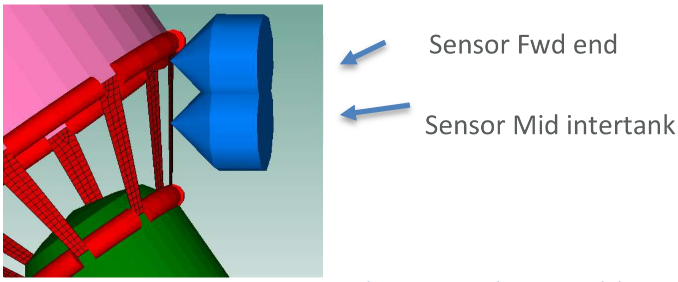

Figure 4: Sensor locations on dummy model

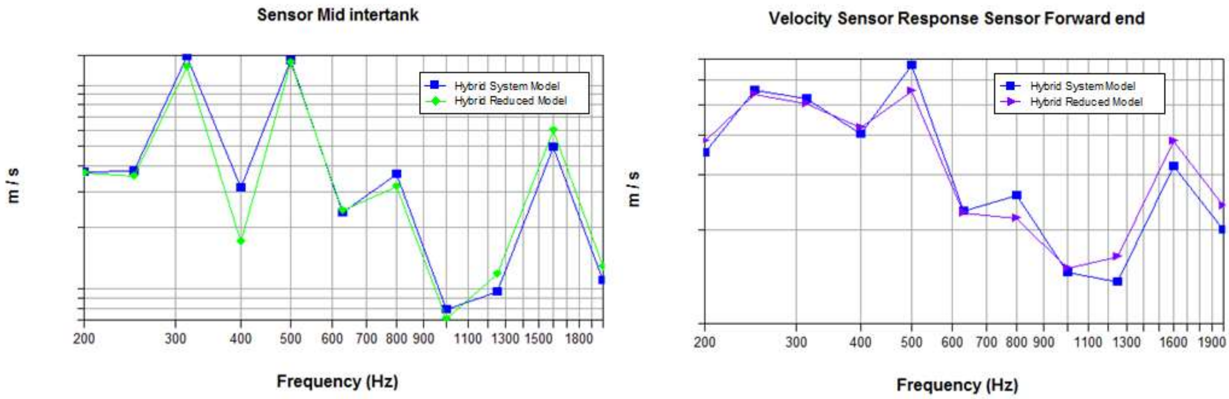

Figure 5: Results comparison for the dummy model sensors

5. Conclusions

The development of a two-step process to calculated responses at the detailed location of a hybrid model allowed a considerable memory requirement reduction and therefore allowed to reach maximum frequency twice as high as the one in the original model. Contrarily to classical memory reduction methods, this process does not have a convergence issue and can be considered accurate.

In doing so, one must keep in mind when replacing the FE subsystem by a SEA subsystem, the modal density must allow for this replacement. Standard SEA recommendations require having at least 3 resonant modes per frequency band. However, this could be lower if it found that the subsystem is not part of the critical path. When in doubt, a comparison between the two models could be performed for a limited frequency range to confirm the validity of the approach.

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