ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

# USING THE HYBRID FE-SEA METHOD TO PREDICT STRUCTURE-BORNE NOISE TRANSMISSION IN A TRIMMED AUTOMOTIVE VEHICLE

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**Abstract**

A Hybrid method that rigorously couples Statistical Energy Analysis (SEA) and Finite Element Analysis (FEA) has been used to predict interior noise levels in a trimmed vehicle due to broadband structure-borne excitation from 200Hz to 1000Hz. This paper illustrates how the Hybrid FE-SEA technique was applied to successfully predict the car response by partitioning the body-in-white into stiff components described with FE and modally dense components described with SEA. Additionally, it is demonstrated how detailed local FE models can be used to improve SEA descriptions of car panels and couplings. The vibration response of the bare car floor and dash is validated against experiments. Next, the radiation efficiency and vibration response of bare and trimmed vehicle panels are compared against reference numerical results. Finally, interior noise levels in bare and trimmed configurations are predicted and results from a noise path contribution analysis are presented.

## 1. INTRODUCTION

The air-borne noise transmission in cars is one of the areas where Statistical Energy Analysis (SEA) is routinely applied with great success [1]. While SEA has been successfully applied to numerous structure-borne noise problems, complex geometry can be difficult to model using the library of subsystems and junctions found in a traditional SEA code. This paper discusses how SEA models of structure-borne noise transmission in cars can be improved through the addition of Finite Elements (FE).

The Hybrid FE-SEA method [2] enables modelling of complex structural-acoustic systems by rigorously coupling FE and SEA descriptions of the various subsystems in a single analysis. While SEA is well suited for regions of the system with short wavelength behaviour, stiff components (exhibiting long wavelength behaviour over a wide frequency range) are best described with FE. The approach is computationally efficient and can be used over a broad frequency range. The Hybrid FE-SEA method was successfully used to predict the vibration response of a car body-in-white to structural excitation from 200 to 1000Hz. This paper describes the process to create the Hybrid model. Predictions are compared against reference numerical results and tests. Finally, predictions of noise radiated by a bare and trimmed body-in-white using the Hybrid method are presented along with a noise path contribution analysis.

## 2. MODEL BUILDING

These instructions are written in a form that satisfies all of the formatting requirements for your manuscript. Please use them as a template in preparing your manuscript. Authors must take special care to follow these instructions concerning margins. The basic instructions are A Hybrid FE-SEA model of a car body-in-white (BIW) was created using the software package VA One [3], starting from a detailed Nastran FE model of the BIW. The details of the model building process are provided in the following sections.

### 2.1 Partitioning of the Floor in Subsystems

The starting point for the Hybrid modeling effort is to determine how the structure should be split into deterministically and statistically described regions. A BIW typically exhibits both long and short wavelength behaviors in the mid-frequency range (200-1000Hz for this problem). While stiff frame members will generally be modeled with FE, regions made of thin sheet metal may be modally dense and thus good candidates for SEA subsystems.
An original partitioning is decided based upon inspection of the geometry and physical properties. For instance, components with homogeneous properties may exhibit a homogeneous response at high frequency, and thus be best described by SEA. However, the decision making process is difficult due to the complex geometry encountered in modern BIW. A more rigorous process is recommended. The partitioning scheme is thus refined based on 1) global modal analysis of the floor (localized modes indicate potential SEA regions), 2) local modal analysis of floor regions which were identified as potential SEA subsystems (the deformation wavelength, the modes in band, the spatial uniformity of the response, the sensitivity to boundary conditions), 3) forced response analysis of the floor (SEA regions will have homogenous response).
The process is illustrated in Figure 1 for the tunnel region. From the global modal analysis on the BIW FE model, localized modes across the tunnel illustrate a potential SEA subsystem. A local modal analysis shows that the tunnel exhibits short wavelength behavior starting from 300Hz. The forced response analysis shows a relatively homogenous response over the tunnel surface as well as reinforcement sheet metal on top. This region may thus be modeled as a single SEA subsystem. This process is repeated over the floor and dash regions of the BIW, and leads to adequate partitioning into SEA and FE subsystems for a simplified energy flow model. Additional considerations such as the need to accurately describe the vicinity of a loading point can also be considered in the partitioning process.

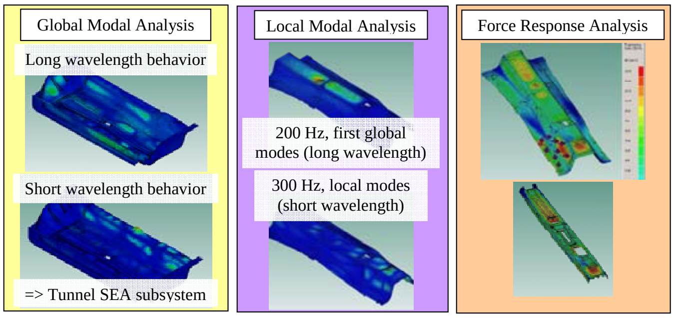


Figure 1. Verification of the subsystem partitioning: tunnel region.

### 2.2 Characterization of the SEA Subsystems

The SEA subsystems need to have a high modal density, and the main intrinsic SEA parameters (i.e. not considering any structural or acoustic coupling) that have to be estimated are 1) the mass, 2) the modal density (or alternatively the modes in band), and 3) the damping loss factor. The SEA properties could be computed using the wide library of standard SEA subsystems formulations (flat plate, singly-curved shell, doubly-curved shell) for which dispersion curves can be computed from subsystem geometry and physical properties. However, the subsystems in a car floor exhibit fairly complex geometries, with corrugation, presence of local stiffeners, changing curvature and such. These complex geometries yield difficulties in assessing the properties of the equivalent SEA subsystems. It was decided here to extract the intrinsic properties of each SEA subsystem based on detailed analysis with a local FE model [4].

The process is illustrated in Figure 2 for the toeboard subsystem. First, the toeboard model is extracted from the full BIW FE model. Modal analysis is performed on the local FE model for varied sets of boundary conditions applied to the edge of the subsystem. This is done to confirm that the dynamic properties (such as number of modes in band) of the components to be described with SEA are insensitive to changes in boundary conditions. Additionally, a region is generally considered to be adequately modeled with SEA if it contains more than 3 modes in band. The local FE analysis helps verify these assumptions.

From the local FE model, one is able to extract the mass of the subsystem, which is in turn used to define the density of the material for the equivalent SEA subsystem (this step is required only when the subsystem is made out of several materials, thicknesses…). The stiffness of the material for the SEA subsystem is updated so that the modes in band computed from the local FE model match the SEA calculation. In some instances, the equivalent subsystem for the region was modeled as a singly curved shell for which the radius of curvature is adjusted to fit the FE modal density. This standard process is referred to as finding the stiffness multipliers [5], and is needed when the component is too complex to be directly characterized by one of the standard SEA subsystem formulations. As can be observed in Figure 2, the toeboard region constitutes a good SEA subsystem above 250Hz. Note that the damping loss factor which is a critical parameter in SEA can not be obtained from the process above, and has to be postulated based on previous experience or measurements.

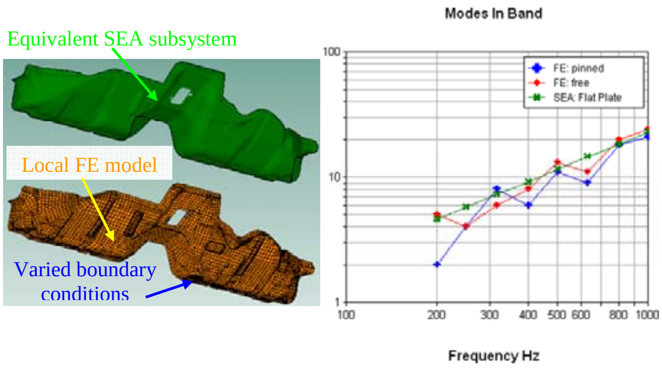


Figure 2. Characterization of subsystems for SEA – toeboard.

### 2.3 Coupling Loss Factor Calculations

The quantities describing the coupling between two SEA subsystems are the coupling loss factors (CLF). For simple structural junctions such as welds and bolted connections, CLFs can be accurately estimated using standard algorithms [6,7] for idealized junctions. However, in the case of complicated floor components with complex spot-welded connections and presence of stiff rails at the interface between subsystems, the local FE models can be used to derive the CLFs. Two advanced approaches are available in VA One to refine the SEA model: i) the Hybrid FE-SEA formulation allows the introduction of extra detail with an FE model for the connection between two SEA subsystems; ii) local FE models of both the connection and the SEA regions can be post-processed using the Energy Flow Method to compute the

related CLFs. The first approach is used in the complete model of car floor for connections explicitly described with FE in the model. In the case of other connections, it was chosen to account for their complexity through CLFs computed with EFM, rather than by including some additional FE parts in the Hybrid model.
The EFM process is illustrated in Figure 3 for the calculation of the CLF between the floor side and side rail SEA subsystems. The detailed local FE model includes both SEA regions as well as the stiff frame around them (represented in yellow color in the FE model). The coupling loss factor between regions identified as SEA is computed using the global modes of the local FE model and rigorous EFM post-processing [8]. The CLFs are then applied in the Hybrid model as user-defined CLF between the two relevant SEA subsystems.
Note that, thanks to the local behavior of the transmission dynamics at high frequency, the calculation above needs only to be performed with local FE models of portions of the floor, making it computationally efficient.

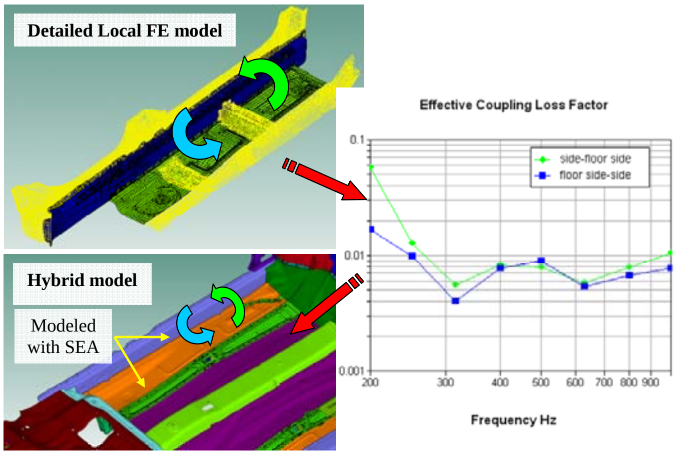


Figure 3. Characterization of SEA coupling loss factors through local EFM models – floor side/rail.

## 2.4 Hybrid Model Creation

Once the SEA subsystems and their coupling have been defined in the Hybrid model, the only missing elements are the Hybrid junctions (not considering the loading to be used to drive the model). Those Hybrid junctions are automatically calculated based on properties of the SEA subsystem and FE structure at the interface between them.
The Hybrid FE-SEA model of the car BIW is shown in Figure 4. Out of the 315,000 elements from the original BIW FE model, less than 100,000 elements were kept in the FE portion of the Hybrid model. Most of this includes the car frame forward of the dash as the structural excitation will be applied near the engine mounts and front shock towers. From the floor region that includes the frame, rockers and pillars, only the mains rails are explicitly modeled as FE in the Hybrid model (note that the dynamics of some of the rails is taken into account through SEA CLFs calculated by EFM). Eleven SEA subsystems represent most of the thin sheet metal constituting the car floor and dash sub-assemblies.
Note that the reference FE model of the BIW was already truncated from the original version. In particular, most of the green house components (pillars, doors, and roof) were removed in order to facilitate FE calculations up to 1000Hz. It was verified that truncation of the green house *did not have a significant impact on the dynamics of the BIW region under study (floor / dash / car front)* in the frequency range of interest.

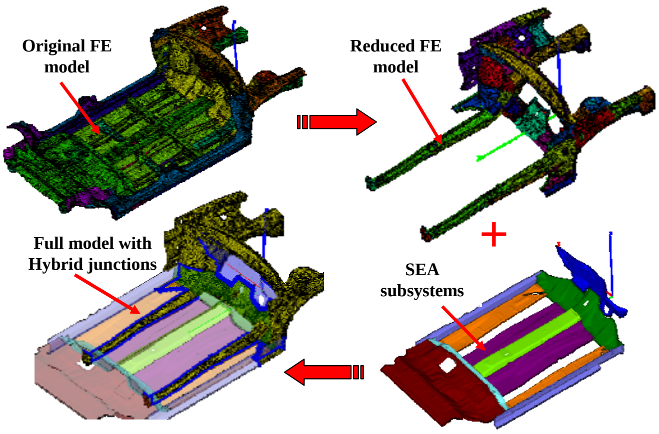


Figure 4. Hybrid FE-SEA model of car BIW.

## 3. NUMERICAL VALIDATION

The FE model from Nissan that constitutes the baseline of the Hybrid model was used for validation. The numerical validation effort consists in comparing prediction results from the Hybrid model to those from the original FE model. The main objective is thus to verify that the Hybrid model replicates the dynamics of the baseline FE model. In particular, the Hybrid model of the BIW should predict similar vibration levels for the floor and dash sub-assemblies when subject to the same structural loading.
A secondary objective of this numerical validation work is to investigate the validity of the reference FE model used. For instance, as was explained earlier, the reference FE model of the BIW was truncated to manage solve times and memory requirements. Varying the boundary conditions at the “cut” sections of the BIW (such as the pillars) would help verify if the partial FE model is representative of the floor dynamics of the full BIW.

### 3.1 Reference FE Model

The FE model used to create the Hybrid model contains over 600,000 elements and is routinely used by Nissan for analysis up to 200Hz. In order to manage memory and solve time, part of the FE geometry deemed irrelevant to the structure borne noise transmission in the floor and dash was discarded. The resulting FE model contained less than 300,000 elements as illustrated in Figure 5. Sensors were placed on the structure to recover vibration response to various point force loadings.

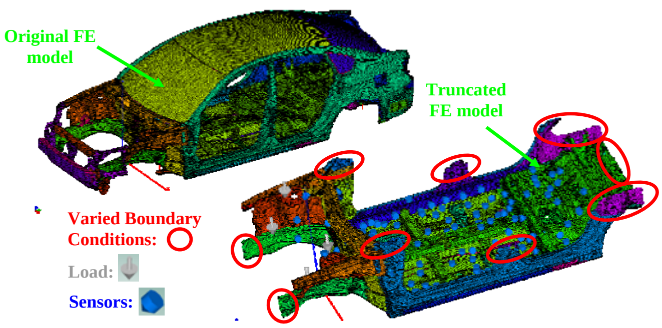


Figure 5. Initial FE model of BIW car and truncated model used for numerical validation of the Hybrid model.

### 3.2 Validation Results

The solve times below are for a PC Workstation with PIV 3.6GHz processor and 2GB RAM:

- For the reference FE model, approximately 1800 modes were extracted up to 1000Hz for both sets of boundary conditions (free and clamped). For each boundary condition set, the modes extraction took approximately 4 days (100 hours).
- For the Hybrid model, approximately 850 modes were extracted up to 1300Hz (free boundary conditions). The modes extraction took approximately 5 hours on a PIV 3.6GHz with 2GB of RAM.
- After the modes were obtained, the solution of the forced response took approximately 45 min for the reference FE model and slightly over one hour for the Hybrid model. The Hybrid solve is more time consuming due to Hybrid junctions calculations as opposed to a simple inversion of a diagonal stiffness matrix for the solve of the reference FE model (with no acoustics). Results were calculated in 1/24 octave bands between 177Hz and 1122Hz, then averaged to 1/3 octave band.

For each load case, validations consisted in comparing 1) the power injected in the structure, 2) the driven subsystem response, and 3) the remote subsystems response. Fifteen load cases were studied, of which four consisted in a single drive point at key locations (shock towers, engine mounts). The other eleven load cases consisted in rain-on-the-roof excitation over each SEA subsystem region.

Example results presented in Figure 6 demonstrate that 1) the truncation of the green house does not have a major impact on the floor dynamics, 2) the Hybrid model properly predicts input power and subsystem response to point force excitation. The error brackets for reference FE results correspond to the min/max response recorded over the subsystem (typically 10 "virtual" sensors used per subsystem).

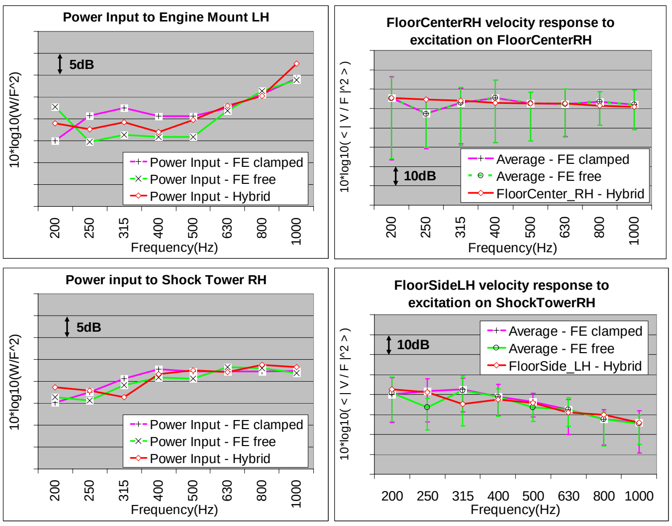


Figure 6. Example numerical validation results – Left: Power Input, Right: average velocity response in some SEA regions.

## 4. EXPERIMENTAL VALIDATION

An actual vehicle corresponding to the BIW under study was instrumented with over 135 accelerometers and the response to the fifteen load cases described earlier was recorded. Example validation results presented in Figure 7 demonstrate that the Hybrid model can accurately predict the input power and subsystem response to point force excitation at the shock tower or engine mount locations. For rain on the roof excitation on any SEA region, the

Hybrid model also predicts the correct energy distribution over the whole floor / dash, which validates the coupling loss factors and subsystems properties. Here again, the error brackets for test results correspond to min/max response recorded over the subsystem (typically 10 sensors used per SEA subsystem).

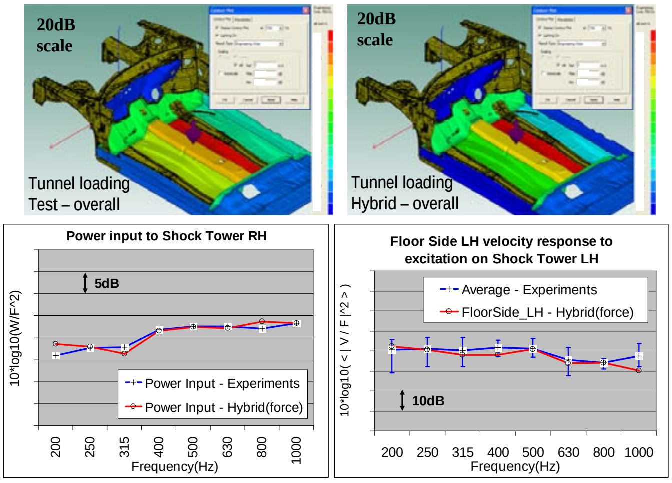


Figure 7. Experimental validations results. Top: measured and predicted contour maps of velocity response to rain-on-the-roof loading of the tunnel region. Bottom: power input and velocity response to point force loading on the shock tower.

## 5. ACOUSTIC PREDICTIONS

The validated Hybrid model was used to predict noise radiated by a bare or trimmed BIW. The radiation efficiency of SEA subsystems was predicted using the same local FE models employed to characterize the subsystems intrinsic properties (modal density and mass): a SEA semi-infinite fluid was created and coupled to the structure through a Hybrid area junction. This models acoustic radiation into a free field. The Hybrid area junction yields a result approximately equivalent to a boundary element approach, with a computational gain of 5 to 10, and with the capacity of quickly adding noise control treatment [9].
The total sound power radiated for a given structural load was then predicted by the Hybrid model (assuming no reflection from the fluid) in both bare and trimmed configurations as illustrated with the contour maps presented in Figure 8.

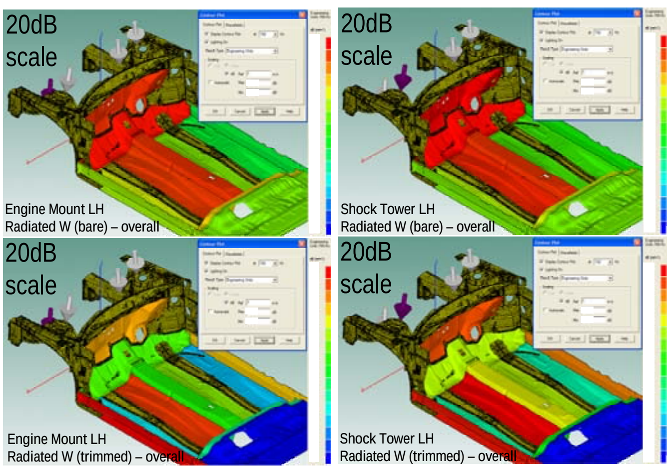


Figure 8. Noise contribution analysis, Top/bottom: bare/trimmed floor, Left/right: engine mount LHS / shock tower LH loading.

## 6. CONCLUSIONS

A Hybrid model of a BIW with focus on the floor and dash sub-assemblies was created. By combining FE and SEA, this model is capable of predicting structure-borne noise transmission over the range [200-1000] Hz. A process to analyse the dynamics of a complex structure and define the most appropriate model partitioning was established. Based on this partitioning, the regions of the structure that exhibit short wavelength behaviour were described with SEA. Only the stiff regions were left as FE, making the resulting Hybrid model computationally efficient. It was shown how detailed local FE models of the BIW components could be used to efficiently calculate the SEA subsystem properties and SEA couplings loss factors across complex junctions. The SEA subsystems were coupled to the rest of the structure which was modelled as FE through Hybrid point and line junctions.

The structure-borne dynamics of the Hybrid model were validated both numerically and experimentally. The Hybrid model predictions compared well with the predictions of the original FE model. The Hybrid model is capable of predicting power inputs due to point force excitation at the engine mounts and shock tower locations within 3dB of tests for most frequency bands. Additionally, the Hybrid model is capable of predicting the velocity distribution on the floor and dash, not only for point force excitation on the front frame (shock towers and engine mounts), but also for spatially delta-correlated excitation ("rain on the roof") of any component of the floor.

Key components for the propagation of structure-borne vibration in the floor and dash were identified. In particular, the main rails supporting the engine sub-frame carry a large portion of the energy to all floor subsystems. Additionally, predictions were made to identify the contribution of the various subsystems to interior noise based on their respective radiated sound power. These predictions were performed in both bare and trimmed configurations over the mid-frequency range [200-1000] Hz.

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