Application of Virtual SEA for the Prediction of Acoustic Performance of Cockpit

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Key Words: SEA (Statistical Energy Analysis), Experimental SEA (Experimental SEA), Coupling loss factor (Coupling loss factor), CLF, Cockpit (Cockpit)

ABSTRACT

One of the crucial factors which determine the quality and the accuracy of SEA model is how subsystems are defined. Experimental SEA technique had been a unique way to divide entire systems accurately for mid-frequency range, until FEA based virtual FRF response technique, virtual SEA method presented. Virtual SEA has been developed for predictive SEA tool in early design process.

In this study, Modal analysis results from modified crash FE model is used for Statistical transfer matrix. Observation nodes on the cockpit are grouped by attractive substructuring method based on point to point transfer and correlation matrix. Complex cockpit structure is divided into subsystems by automatic substructuring. Comparison with experimental SEA results validates the application of Virtual SEA to cockpit.

1. INTRODUCTION

Not only for the carmakers but also for the automotive parts suppliers, cost reduction and shorter development cycle are strongly required to survive in highly competitive market. The simulation models predicting acoustic performance of cockpit module at early design stage could be a part of time-saving and cost-effective solution for those demands.

The design of noise insulation of the cockpit is connected to relative importance of the various propagations paths of acoustic vibrations through the cockpit. The statistical energy analysis (hereafter, SEA) analysis could be used to provide the decomposition of acoustic transmission through the cockpit into the various airborne and structure borne paths with the help of an SEA model based on analytical description of subsystems.

One of the crucial factors which determine the quality and the accuracy of SEA model is how subsystems are defined. Experimental SEA technique had been a unique way to divide entire systems accurately, until FEA based virtual FRF response technique, virtual SEA method appeared. Recently proposed virtual SEA using FE models from crash analysis are useful to reduce the ambiguity of SEA modeling which could make a big difference in the result.

It is proved that SEA is a very convenient tool for the design stage of a project. SEA is widely used for air-borne transmission of sound, but some unexpected difficulties are arising with structure-borne sound. For example, most car body parts do not look like conventional structures such as flat plates, cylinders or beams. Moreover, when a candidate subsystem appears, its limits are difficult to draw, due to complicated 3D-geometries. For additional reasons, experimental SEA and analytical SEA cannot currently produce a robust car body SEA model in the target frequency range of 200-1000 Hz. Experimental SEA is limited by a lack of consistency in the measured data, but also because the sub-structuring is not controlled, which can lead to contradictory behaviors between points of the same subsystem. This sub-structuring problem is also encountered while building analytical SEA models. With analytical models, the user also has to tune the model to account for heterogeneity (e.g., corrugations, small hollow bodies, variable beam cross-sections, etc.). Overcoming these difficulties would require an impractically high level of expertise among all design engineers.

Virtual SEA is developed to provide reliable and robust sub-structuring for SEA. It uses results of modal analysis to build virtual averaged FRF signal pairs of the model. Using the virtual averaged FRF, parts of the system is grouped by their energy levels and correlations. Virtual SEA is proved to be useful for a car-body, wind turbine cases.

In this study, Theory of SEA will be addressed briefly, followed by application and validation of the virtual SEA on cockpit module. FE model converted from crash analysis is used to find a reliable set of subsystems. Experimental SEA results are compared to validate usefulness of virtual SEA. Analytical SEA results which covers the optimal acoustic treatment configuration has not dealt in this paper.

2. Theory of SEA

2.1 Experimental SEA

The SEA analysis is describing the behavior of a dynamical
Figure 1. SEA experiments for 4 subsystems with interaction system by a reduced set of energy equilibrium equations (the power balanced equations in steady-state).

The first problem to be solved consists in determining the number of necessary equations, i.e. the number of subsystems to be created for a suitable representation of the exchanges. It is necessary that each subsystem includes several local modes of resonance so that it can constitute an independent element. If we have formulas of modal density and wave number, we can quickly determine the scale of substructuring when the system exhibits simple topology. Many dynamical systems can thus be reduced to sets of inter-connected simple elements from which simple calculations yield robust results. If the junctions are also simple: welded joints, fluid-structure interfaces without dissipation, analytical formulas are available to approach the physical reality of the junction behavior. Nevertheless, many systems or more generally some parts of them cannot be reduced to asymptotically simple behaviors. These systems obey nevertheless the energy equilibrium equations.

Experimental approach SEA was born from this need for characterizing complex structures and is also used for the validation of "analytical" SEA models. The tests are carried out on the built-up structure in order to extract the coupling and dissipative parameters.

With experimental SEA tests, an inverse problem has to be solved. If, by measuring, we get an access to vibratory transfer energy between subsystems and to injected power using a set of calibrated excitations, it can be possible to identify the matrix of loss parameters (coupling and damping loss factors) that connects energies and powers. To achieve this task, it is required to first subdivide the system into parts (subsystems) then to collect enough information for solving the inverse problem. Let us assume to have split a system into N subsystems. We thus need to identify N intrinsic damping loss factors (DLF) and N(N-1) coupling loss factors (CLF), if the reciprocity of CLF is not used.

The data related to the analyzed system is generated by exciting at a turn by a calibrated force each of the subsystems and by collecting the vibratory velocity or acoustic pressure on a grid of points (transducers) for all of the subsystems. In the sketch here below, one excite at a turn each of the 4 subsystem that are part of the analyzed system.

For each test, one can write a power balanced set of 4 equations that describes the energetic equilibrium between the various subsystems. These equations are depending upon the transfer energy $E_{ij}$ between the excited subsystem $j$, the measured subsystem $i$ and the power which is injected by the force $P_i$.

One has at disposal a total of 16 equations relating $E_{ij}$ and $P_i$ (input data). The unknown are the DLF and CLF connecting the subsystems. In most cases, it is preferable to identify separately the DLF and CLF.

Indeed, if on assumes junctions to be non dissipative, the injected power into a given subsystem is always equal to the sum of dissipated powers in all subsystems. That can be written as:

$$P_i = \sum_j \eta_{ij} E_{ij}$$

Thus, this leads to the following system of equations:

$$
\begin{bmatrix}
P_1 \\
P_2 \\
P_3 \\
P_4
\end{bmatrix}
= \omega
\begin{bmatrix}
E_{11} & E_{21} & E_{31} & E_{41} \\
E_{12} & E_{22} & E_{32} & E_{42} \\
E_{13} & E_{23} & E_{33} & E_{43} \\
E_{14} & E_{24} & E_{34} & E_{44}
\end{bmatrix}
\begin{bmatrix}
\eta_1 \\
\eta_2 \\
\eta_3 \\
\eta_4
\end{bmatrix}
\tag{1}
$$

The DLF vector is obtained by inversion of the $E_{ij}$ matrix as:

$$
\begin{bmatrix}
\eta_1 \\
\eta_2 \\
\eta_3 \\
\eta_4
\end{bmatrix}
= \frac{1}{\omega}
\begin{bmatrix}
E_{11} & E_{21} & E_{31} & E_{41} \\
E_{12} & E_{22} & E_{32} & E_{42} \\
E_{13} & E_{23} & E_{33} & E_{43} \\
E_{14} & E_{24} & E_{34} & E_{44}
\end{bmatrix}^{-1}
\begin{bmatrix}
P_1 \\
P_2 \\
P_3 \\
P_4
\end{bmatrix}
\tag{2}
$$

These previous equations can be subtracted of the general system of equations. We can then derive a solution for CLF identification using the next compact formulation:
These equations are only connecting subsystems \( j \) to a particular \( I \) subsystem and \( N \) systems of this kind need to be solved to obtain all CLF.

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According to SEA fundamentals, the excitation is not deterministic. The force location is random over the subsystem domain \( SS_i \). The velocity descriptor for subsystem \( SS_j \) is the spaced and frequency averaged velocity over \( \omega \Delta \omega \) and over domain \( SS_j \). This transfer function will be denoted as \( V_j^2(\omega, \Delta \omega) \).

It is approximated from the deterministic point-to-point transfer as:

\[
\langle V_j^2(\omega, \Delta \omega) \rangle = \frac{1}{\Delta \omega} \int \sum_{k,k \neq SS_i, j \in SS_j} \sum_{l} V_{kl}^2(\omega) \cdot d\omega
\]
Deterministic transfer

Statistical transfer

\[ F_i \rightarrow M_i \rightarrow V_i \]

\[ (F_{\text{tot}})_{\text{i}, \text{SSi}} \rightarrow \text{SSi} \rightarrow \text{SSj} \rightarrow V_j \]

Figure 2. Comparison between deterministic and statistical transfer

\[ N_k \text{ and } N_j \text{ are the number of discretized loads and velocity points in both domain SSi and SSj.} \]

The statistical transfer is the main descriptor of the vibrational field in a SEA model. It assumes equiprobable load distribution as well as velocity responses among the subsystem.

Once a partition of the dynamical system is decided, the statistical transfer is the descriptor of the vibrational state which is used by SEA in its predictive scheme.

As Virtual SEA is derived from FE representation, more deterministic transfer descriptor can be chosen, for example by localizing the excitation force within the subsystem. Force distribution for statistical transfer derivation must be thus a free variable of which value can be selected by the user with default option based on force location randomization.

When the response point is also an excitation point, the transfer is called input mobility.

When input mobility is averaged over location and frequency, the corresponding descriptor is called statistical input mobility. The real part of this statistical input mobility corresponds to the active power per unit of force injected in the related subsystem.

\[ Y = 4Ym \]

(6)

2.2.2 Energy Analysis and power flows

Virtual SEA provides a statistical model of power flows within a dynamical system from a real-valued matrix of loss factors. To built this matrix from the FE deterministic point-to-point transfers, statistical transfers need to be converted into energy.

This conversion is performed provided that:

1) a division of the system into subsystems in which energy can be computed (the SEA substructurization),
2) a frequency band of integration,
3) an equivalent mass allows the expression of total energy from kinetic energy that can be computed in various ways. Transfer velocity is thus converted into transfer energy.

When the system is homogeneous, the mass is constant with frequency and the conversion is done using the following expression:

\[ e_{ij} = m_j \left \{ V_j^2 \left( \omega_c, \Delta \omega \right) \right \} \]

(7)

If the system is non homogeneous, the equivalent mass is frequency-dependant and must be determined using specific protocols. In virtual SEA, the internal damping of the structure is an input and is perfectly known. Equivalent mass can be thus calculated with accuracy solving the power balanced equations with a known damping loss factor value.

If only a fraction of the full FE model is used to derive a local SEA model, the modeled SEA subsystems will loose some energy in un-modeled part of the FE model and the local damping of these subsystems will become again an unknown. Technique based on time decay identification inside these subsystems will provide extra-equations to solve these extra-unknowns. Regarding FE database, no extra FE response is required as complex FE transfer functions can be converted into time domain to identify time decay after pas-band filtering and decay slope estimate. This technique is exactly the same that is used to process experimental data in experimental SEA software. Nevertheless this will lead to increase in CPU time and it is not sure that the frequency sampling of FRF will be suitable for a time-domain reconstruction. Adaptation of the FE model to the selected substructurization is thus recommended in all situations.

The SEA model is derived from the energy equilibrium between subsystems that states the injected power within a subsystem is equal to the power dissipated into this subsystem augmented from the net power coming in and out from the connected subsystems.

In SEA theory the net power flow between \( i \) and \( j \) subsystems can be expressed as:

\[ P = \omega_c \left \{ \eta_{ii} E_i - \eta_{ij} E_j \right \} \]

(8)

where \( \omega_c \) is the central angular frequency of the integrated band, \( E_i, E_j \) the related subsystem energies and \( \eta_{ii}, \eta_{ij} \) the related coupling loss factors (CLF).
2.2.3 Solving a virtual SEA problem

Virtual SEA analysis implies several tasks to transform a FE model into a SEA network.

1) Solving the FE model with well-defined load cases and store a matrix of narrow band responses on a selected grid of observation/excitation points (nodes).

2) Portioning the matrix set into several groups of nodes in order to create “weakly coupled” geometrical regions that will be used to define SEA subsystems for a particular targeted frequency band of analysis (Auto substructurization).

3) Compressing the narrow band point-to-point FE matrix into a spaced and frequency averaged matrix, the dimension of which is the number of SEA subsystems, output of the previous step. This matrix is the spaced and frequency averaged transfer velocity matrix.

4) Solving an inverse problem: to determine the SEA loss matrix from the previous transfer velocity matrix.

5) Using the reduced-sized SEA model to perform parametric studies or to export a subset of the loss matrix into a standard “analytical” SEA model.

This dataflow is straightforward and the main interest is it can be fully automated; especially the model creation is becoming independent of the user as SEA subsystems are generated by pure numerical routines.

3. Application and validation of virtual SEA

3.1. Virtual SEA of Cockpit model

A Finite Element model of the cockpit has been transformed from crash analysis model. The database of FRF is then created by solving the FE model up to 1000 Hz. The model of the cockpit is shown in Figure 13. The FE model includes air conditioning unit and air bag descriptions. The FE mesh includes around 150000 finite elements and can be considered as usable up to 1000 Hz.

Eigenfrequencies and modal amplitudes on a grid of 423 randomly selected nodes are extracted by NASTRAN (Lanczos solver) up to 1200 Hz and stored in a PUNCH file. 2300 modes are thus identified up to 1200 Hz to cover the 1000 Hz 1/3rd octave band.

The grid of 423 observation and excitation nodes is selected to synthesize all cross FRF between nodes. The model is loaded by a unit-point forces applied at a turn at the location of each of the 423 nodes in the 3 axis x, y, z. For each load case, the FRF at all node locations are synthesized in the 3 axis directions. The FRF that are saved in the database are the response in the direction of maximum output mobility of the observation point, the excitation being applied in the direction of maximum input mobility.

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The transfer functions between excitation nodes and observations are computed with the dedicated SEAVirt modal solver. The analytical SEAVirt solver is used here to compute the 423 x 423 required FRF as 1/3rd octave band-averaged FRF.

The analytical solver uses the exact solution for the integral over frequency of the modal transfer function and then performs modal summation of all modal and cross-modal transfers to synthesize the physical FRF between two nodes. In parallel, for each node, the software determines the real part of the complex input mobility that corresponds to the physical active power injected in each node by a load case.

At the end, the database is made of a 2D FRF matrix, depending upon frequency representing the transfer between two nodes and a 1D vector representing the real part of input mobility at each node, also depending upon frequency.

This FRF matrix is then packaged to obtain a decomposition.
of nodes into groups that can be considered as SEA subsystems. To derive this grouping, a dedicated sort algorithm called peripheral attraction which performs the grouping operation is used.

At the end, the different groups of nodes can be visualized with different colors as shown in Figure 4(a). The grouping is optimized to give SEA substructurization in the band 400-800 Hz.

On output 17 subsystems are identified of which names are listed below. A detailed view of subsystems including energy flow is shown in Figure 4(b).

<table>
<thead>
<tr>
<th>#</th>
<th>SS</th>
<th>Subsystem names</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>(air cond casing No EXP)</td>
<td></td>
</tr>
<tr>
<td>S02</td>
<td>(left Htr Blower EXP 12)</td>
<td></td>
</tr>
<tr>
<td>S03</td>
<td>(right Htr Blower EXP 12)</td>
<td></td>
</tr>
<tr>
<td>S04</td>
<td>(Ganish Defrost EXP 2)</td>
<td></td>
</tr>
<tr>
<td>S05</td>
<td>(Right crashpad EXP 5 &amp; 7)</td>
<td></td>
</tr>
<tr>
<td>S06</td>
<td>(Front centre console)</td>
<td></td>
</tr>
<tr>
<td>S07</td>
<td>(back centre console EXP 15)</td>
<td></td>
</tr>
<tr>
<td>S08</td>
<td>(air cond unit rear panel No EXP)</td>
<td></td>
</tr>
<tr>
<td>S09</td>
<td>(glove box front EXP10)</td>
<td></td>
</tr>
<tr>
<td>S10</td>
<td>(Crashpad doubly curved EXP 1)</td>
<td></td>
</tr>
<tr>
<td>S11</td>
<td>(left small panel behind EXP 8)</td>
<td></td>
</tr>
<tr>
<td>S12</td>
<td>(air cond fan box)</td>
<td></td>
</tr>
<tr>
<td>S13</td>
<td>(glove box int EXP 16)</td>
<td></td>
</tr>
<tr>
<td>S14</td>
<td>(Cowl cross EXP 14)</td>
<td></td>
</tr>
<tr>
<td>S15</td>
<td>(Lower panel EXP 8)</td>
<td></td>
</tr>
<tr>
<td>S16</td>
<td>(air bag casing EXP 4)</td>
<td></td>
</tr>
<tr>
<td>S17</td>
<td>(steering column No EXP)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 17 subsystems from Virtual SEA at 400-800Hz

The subsystems 14, 16 and 17 have been found with a low number of modes par frequency bands. They are removed from previous model and with this new model, the equivalent masses can be computed over the whole 200-1000 Hz spectrum without any hole in the spectrum. The performance index of the reconstruction of velocity field is also increased and now is nearly 92%. This latter model is exported in AutoSEA1 environment for comparison with the experimental SEA model.

### 3.2. ESEA Test for cockpit analysis

#### 3.2.1. The experimental SEA model of the cockpit

The cockpit test specimen to be tested is shown in Figure 5. The cockpit is split into 16 subsystems and the choice of subsystems has been influenced by virtual SEA prediction. Nevertheless, due to differences in the virtual model that includes the air conditioning unit and the tested specimen where the air conditioning unit is removed and to difficulty in accessing some subsystems, the two substructurizations can only be partially compared. The names of the ESEA subsystems are referring also with PID numbers included in FE model. In Table 1, the virtual SEA subsystems are tagged with the number of related ESEA or EXP subsystem.

The subsystems are either soft (plastic structure or pipes) or hard (cowl cross). Due to accessibility problems, some impacts have been given on the trimmed face of Crashpad covered by sloshed material. Other impacts can be considered as representative of mean input mobility of subsystems.

Figure 4. (a) Grouped nodes of cockpit, subsystem 5, (b) Power flow between subsystems
3.2.2. Input mobility measurement

The goal is to provide vibration data related to local behavior of the cockpit subsystems. The theoretical modeling of the cockpit material properties can then further be validated by comparing measured input mobility’s to the predicted ones.

Due to high non-homogeneity of cockpit construction (change in thickness and curvature), several points have been selected on the cockpit subsystems to perform input mobility measurement using two different hammers as excitation.

Statistical velocity transfers measurement between various parts of the cockpit

The cockpit is divided into areas considered as subsystems following virtual SEA results. One accelerometer is fixed in each area. All areas are excited at a turn at various randomly selected points by the hammer and the related frequency response function (FRF), ratio of acceleration over force in the frequency domain is recorded simultaneously.

3.2.3. Test apparatus and transducers

The data acquisition was performed with the following equipment: InterAC 8 channels SEA-XP system (version 2.53) made of a National Instruments DAQCARD 4472 driven by the SEA-XP software. Signals are recorded in synchronous mode with sampling frequency of 30 kHz. The DAQCARD includes anti-aliasing filters and on-board ICP power supply for transducers.

Transducers were a set of 5 Faurecia B&K ICP accelerometers for vibration (1000 mV/g), and 2 InterAC PCB accelerometers (10 mV/g). Considering frequency and damping Two hammers are selectively used:

- A mid-size Kistler hammer with force cell delivering around 500 N (sensitivity 11 mV/N).
- A small-size PCB hammer with force cell delivering around 50 N (sensitivity 22 mV/N).

3.2.4. Analysis of cockpit input mobility

The experimental SEA data set for the cockpit is a collection of frequency response functions describing the transfer response between the 16 structural areas previously defined. Between 10 to 20 impacts par area were performed, leading to around 3000 transfer functions to describe the statistical transfer velocity.

The input mobility has also been recorded with 10

Figure 5. 16 Subsystems of Experimental SEA.
records per impact at reference transducer location. The values of input mobility range between 0.2 and 1e-4 W/N². The lowest values are found on subsystem 14 (cowl cross) which is the stiffer subsystem. With the mid hammer the bandwidth is not very high of soft subsystems (less than 1000 Hz for subsystem 13 for example). This is due to width of force peak in the time domain that acts as a low pass filter on injected power measurement. The injected power is measured again using the small hammer. Differences could be explained between the two sets of measurement: the mid-sized hammer reduces the bandwidth of the measurement while differences in levels can be seen mainly due to spatial phase difference between the accelerometer and the hammer tip much smaller with small hammer and small accelerometer. The injected power on this structure is difficult to measure with accuracy and it will be assumed that the standard deviation is around 2 dB.

3.2.5. Loss Factors Matrix Identification

The Coupling and Damping Loss Factors (CLF and DLF) are computed from previous database of squared...
transfer velocity and injected power in third-octave frequency bands. The solution is using the pseudo-inverse process (SVD) to estimate a least-mean-squared solution for DLF and the Standard Inverse solver for CLF estimates. Around 100000 random inversions are required here to get a consistent statistical set of all positive DLF and CLF.

The set of identified intrinsic subsystem DLF is compared with the related apparent DLF obtained from reverberation time measurement. It can be seen that except for subsystem 15, the intrinsic DLF are always lower that the apparent DLF. The subsystem 15 at low frequency is in fact not a subsystem (no local mode) thus a very low mass and high DLF value is identified for this subsystem in frequency band where the subsystem is showing anti-resonant behavior.

To take into account the non homogeneity of the cockpit, a Monte-Carlo algorithm is used, it introduces some randomness into the measured dataset within the measurement Standard Deviation bounds.

After a first solve, the DLF and CLF that are identified can be used to calculate power flow between subsystems. At this stage, junctions that are not seeing any large power flow are removed from the analysis to simplify the coupling scheme and to reduce the number of parameters as shown in Figure 6.

The two models are cross-checked by applying a unit-power to virtual subsystem 10 and ESEA subsystem 1 and looking at velocity computed by both models in virtual subsystems 2 & 3 that correspond to ESEA subsystem 12. The energy in subsystems is given in Figure 7(a). One can see that energy levels in the excited virtual and ESEA subsystems are similar (curves X1 against S10V_X10). The energies in indirectly excited subsystems are also in good agreement below 800 Hz. X12 is nevertheless exhibiting much more energy in the upper frequency bands but this is easily explainable as the air conditioning unit is not present in the ESEA test and has a strong influence on the connecting pipe X12.

Another example is found in Figure 7(b). The excited subsystems are the same than previously but the receivers are virtual subsystem 13 (glove-box) related to ESEA subsystem X16. The trend of the transfer energy agrees quite well in the low frequency range but it overpredicts the transfer energy in the upper bands. The FE model seems then to exhibit too much rigid connection of RBE2 type to describe accurately the drop of energy above 600 Hz. Nevertheless, due to different configurations between virtual and ESEA, a more rigorous validation is not possible. Due to the fact that no

Figure 7. Comparison of energy between experimental and virtual SEA.
modification has been performed to the FE, this first cross-check shows the great potential of the virtual SEA approach to describe highly inhomogeneous structures by a reduced set of SEA parameters.

4. Conclusions

The Virtual SEA enables building a SEA model based on FEA results. A large, energetic transfer matrix is computed, providing a wide observation of the vibratory behavior of the studied structure. This matrix is then processed similarly to experimental SEA, in order to produce an ‘optimized’ SEA model of the studied structure. Such an SEA model allows some understanding of the medium/high frequency vibrations in terms of vibratory power flows between subsystems.

The main advantage of Virtual SEA is the quasi-automatic generation of SEA subsystems and Coupling Loss Factors. Virtual SEA does not require the a priori knowledge of the substructuring, which considerably reduces the required expertise and the associated manpower.

Application of virtual SEA on cockpit module has been tested by Experimental SEA, in this study. Considering the agreements in energy level, it is proved that virtual SEA is quite useful for highly inhomogeneous systems such as cockpit. The constitution of subsystems acquired from virtual SEA was used to probe acoustic material performance of cockpit module in succeeding study. It is expected that virtual SEA would be enormously useful, if we turn our focus on other car parts related with high frequency structural vibration, which could not be covered by finite element approach for its complex and inhomogeneous nature.

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