Combining Finite Element and SEA approach in Vibroacoustic Analysis

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The SEA predictive scheme

SEA is based on power balanced equations between parts of a dynamical system, called subsystems. For a set of subsystems, the equilibrium between their frequency band-integrated energy **E** and the input power, Π, generated by external forces is expressed in matrix form as $\boldsymbol{E} = \boldsymbol{L}^{-1}\Pi / \omega$ where **L** is the Loss factor matrix and $\omega = 2\pi f$ with f, central frequency of analyzed band, wide enough to include several eigen-frequencies.

The L-matrix is real, well conditioned and most of the time small. Computation is fast and does not require any powerful computer.

SEA has been originally developed [1] to provide close-formed formulations to random vibration problems and has always made extensive use of analytical theory for calculating all required parameters over broad frequency band. SEA has been widely applied to the prediction of random vibrations of rockets [2] as they are made of large simple cylinder-shaped structures of which response can be predicted with good accuracy from analytical formulations.

The analytical SEA limitations

Nevertheless, applying SEA to more complex-shaped industrial systems such as car bodies, small spacecrafts and train mainframes can be a more difficult engineering exercise as expertise is required to build consistent SEA models. A major limitation is the call to analytical libraries, mainly designed for homogeneous and simple-shaped subsystems.

It is why SEA is mainly a diagnosis tool. A SEA network is used as an interactive book of formulas that helps the expert in his understanding process. To get predictive, SEA needs to be complemented by test data to reduce the information entropy of the model.

The experimental SEA approach

Experimental SEA is the inverse approach of 'direct' SEA. The L-matrix is the inverse of the transfer energy matrix Eij. Each term, e_{ij}, of this matrix represents the energy of the subsystem i when a subsystem j is excited by unit power, and is called energy influence coefficient. All e_{ij} can be experimentally determined by recording frequency response functions (FRF) at various observation points within the system. Nick Lalor developed this technology and has proposed various algorithms to compute L from Eij [3]. InterAC has improved inverse SEA in various ways in its SEA-XP software product dedicated to the creation of experimental SEA models [4]. The recording process is very similar to the modal analysis technique, except it targets high frequency domain. Experimental SEA provides a compressed 'picture' of the dynamics as shown in Figure 1. When this picture is compared to the analytical SEA one, it provides an estimate of model quality and variance leading to faster analytical model tuning. Figure 2 shows an example of absolute error between experimental and analytical model of a full car body. For this large complex structure, the distribution of errors is roughly Gaussian. Even after tuning, rather high incompressible residual variance is found for large SEA models of car bodies.

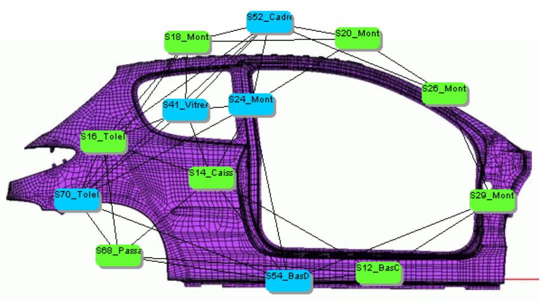
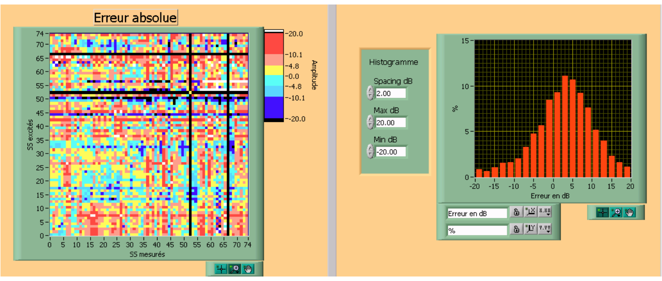


Figure 1: This is an example of industrial experimental SEA model of the right side of a white car body created with SEA-XP



Spacing dB 2.00
Max dB 20.00
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Figure 2: Comparing the FRF of analytical and experimental SEA model of a car using SEA-XP. Left, absolute error in dB scale between analytical and experimental SEA model (black lines are obtained when no measurement is available for comparison). Right, histogram of error distribution in $\mathbf{e}_{\mathbf{ij}}$ set

The Virtual SEA approach

Variance in analytical SEA models is mainly due to

- **Non suitable-user's choice of subsystems,**
- **Analytical formulations themselves or their numerical implementation in software especially when dealing with structural complexity.**

FE modelling is naturally taking into account structural complexity. It is then attractive to try performing experimental SEA on FE-computed FRF. This numerical experimental SEA was called virtual SEA and test cases were performed with Peugeot-Citroën using the SEA-XP solver [5]. The SEA-XP solver was improved to automatically detect the most suitable subsystem portioning from a grid of FE-observation nodes in a targeted frequency band (Figure 4). The generated virtual SEA models were proved to be far more reliable (up to 2 kHz) than corresponding analytical prediction as shown in Figure 5.

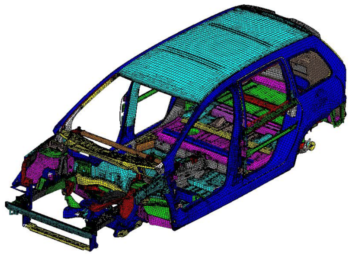

Figure 3: PSA model of a 806 vehicle used to create a virtual FRF data set analyzed by Virtual SEA

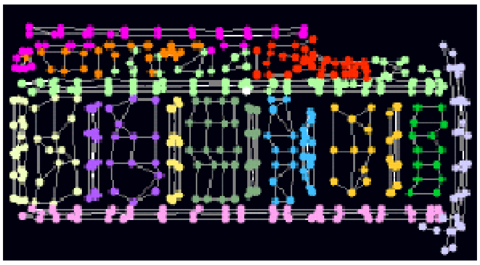

Figure 4: Floor SEA subsystem decomposition automatically generated by virtual SEA at 500 Hz

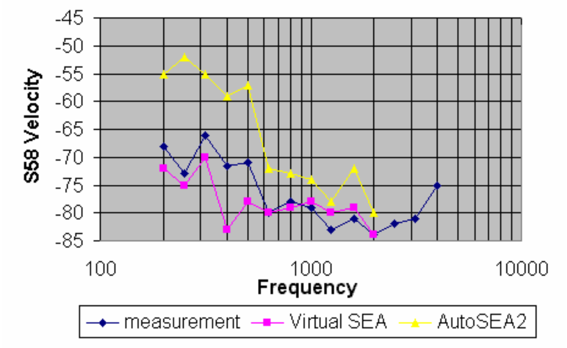

Figure 5: Comparing transfer velocity of a floor subsystem far away from excitation between virtual and analytical model

Virtual SEA data can be hybridized in already existing ‘classical’ SEA models and can improve the resolution of all existing SEA networks. Nevertheless the FE model needs to be fully solved with many load cases prior to apply the technique. As FE-solver speed increases following Moore’s law, it is already faster to use computing power in place of engineering expertise in SEA model creation. The dynamics of complex FE models is compressed into simple power-balanced equations and the final SEA model reliability is increased. More requests for accuracy are coming also from aerospace industry. Vibrations induced on equipment by pyrotechnical shocks have very large frequency content (up to 100 kHz). SEA techniques are useful to extend the FE computation frequency range [6]. In the FE-SEA overlapping frequency domain, the sub-structuration can dramatically change, leading to difficulty in correlating SEA and FE results. In Figure 6, the shock separation is performed via the fairing adaptor cylindrical structure that connects the SPELDA (2d payload compartment) and the fairing of Ariane 4 launcher. The ring frequency of the fairing adaptor strongly signs the shock response spectrum and is thus a critical subsystem in the SEA network. Computing the virtual SEA coupling loss factor (from the SPELDA to the adaptor) clearly shows that around its ring frequency (500 Hz) the dynamics is dramatically changed. Below 500 Hz, the adaptor is a part of the SPELDA cylinder and can hardly be dissociated from it. Above, it progressively becomes a diffuse SEA subsystem but due to the small height (8 cm), the frequency convergence with analytical SEA, assuming the adaptor as a weakly-coupled subsystem, is slow. Reduced data coming out from virtual SEA can quickly point to critical behaviour, not so easy to detect directly from thousand FE-output.

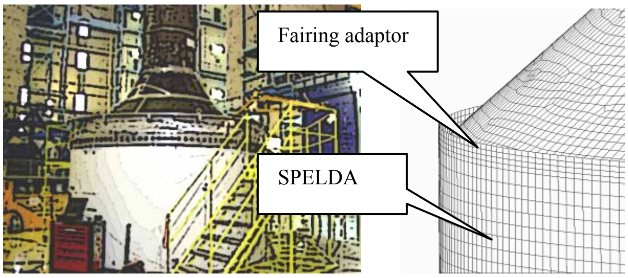

Figure 6: Upper part of Ariane 4 launcher in shock separation tests and related FE mesh for shock simulation

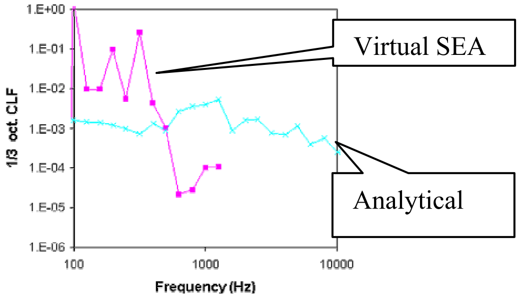

Figure 7: Coupling loss factor (CLF) of fairing adaptor to SPELDA computed from analytical SEA and from virtual SEA

Conclusions

SEA models can be generated automatically from finite element results. Thus, the essential features of the physics are preserved into a small SEA network for better understanding of the system dynamics. The virtual SEA model can be used for faster parametric optimization as it is more accurate than corresponding analytical representation.

References

[1] Richard H. Lyon - "Statistical Energy Analysis of dynamical systems: Theory and applications" The MIT. Press, Cambridge MA., 1975

[2] G.Borello (CNES), J.N.Pinder (ISVR), I.U. Borchers (DORNIER), “Interior Noise Control of Spacecraft Launch Vehicles” 40th IAF congress, 7-12 Oct.1989, Malaga, Spain

[3] N. Lalor - "The measurement of S.E.A loss factors on fully assembled structure" ISVR, Technical Memorandum N° 150

[4] SEA-XP User’s Guide version 2.5 February 2004, InterAC software for experimental SEA

[5] L. Gagliardini & col. (PSA), G.Borello (InterAC) – “Virtual SEA: Mid-Frequency Structure-Borne Noise Modeling Based on Finite Element Analysis”, SAE conference, 2003, Traverse City, USA

[6] G. Borello (InterAC), V. Cipolla (CNES), "Prediction of high frequency shock response of a satellite using SEA" European Conference on Spacecraft Structures, Materials & Mechanical Testing, 11-13 Dec. 2002, Toulouse France