Coupled FE-SEA vibroacoustic analysis of floating floors for trains

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Introduction

Prediction tools based on Finite Elements Method (FEM) and Statistical Energy Analysis (SEA) methods are frequently used for analyzing and solving vibro-acoustic problems in the industry. However, the use of separate software for different frequency ranges result in loss of time and computational resources. In addition the frequency range for which neither numerical nor statistical models are applicable can be fairly wide and is often critical for practical design issues in vehicles.

A theory allowing coupling of these two methods has recently been presented [1,2] and implemented in commercial software [3]. The aim is to provide a tool for vibro-acoustic study in a wide frequency range. For structural sources effects of changes in the receiving structure can be accounted for, like in standard FE analysis. In comparison with FEM, the coupled method can be used is able to analyze transmission in a wider frequency regime.

Coupling Loss Factors between two plates

In SEA, Coupling Loss Factors (CLFs) determine the energy transferred from one system to another. For two panels separated by a number of equal linear springs, the CLF can be expressed as [4]:

$$\eta_{12} = \frac{m\,\mathrm{Re}\{Y_2\}}{2\pi f \rho_1 \left(\left(\mathrm{Re}\{Y_1\} + \mathrm{Re}\{Y_2\}\right)^2 + \left(\frac{2\pi f}{k}\right)^2 \right)} \qquad (1)$$

where Y_i is the mobility of panel i, m the number of springs per unit area, ρ_1 the surface mass of the source panel, k the stiffness of the isolators and f the frequency. The transition frequency is found by setting the two terms in the denominator equal. At low and high frequencies respectively the CLF can be approximated by:

$$\eta_{12} = \frac{\mathrm{Re}\{Y_2\}}{2\pi\rho_1 f \left(\mathrm{Re}\{Y_1\} + \mathrm{Re}\{Y_2\}\right)^2} \quad \text{and} \quad \eta_{12} = \frac{k^2\,\mathrm{Re}\{Y_2\}}{8\pi^3 \rho_1 f^3} \qquad (2)$$

A simple FE-SEA model was set up with two SEA panels with properties corresponding to the system of Figure 1 separated by one single rubber isolator, typical used in a train floating floor. The panel mobilities were then determined as $Y_{iso} = 4.8.10^{-5}\, m/Ns$ and $Y_{ortho} = 5.85.10^{-4}\, m/Ns$. The isolator was modelled using FE with material properties estimated from the rubber shore quality (45 Sh.). In the figure below numerically determined CLFs are shown for two different rubber stiffness, together with an analytical CLF according to equation (1) applying the lower rubber stiffness. For the analytical CLF, measured isolator stiffness data from low frequency laboratory tests [5] was applied.

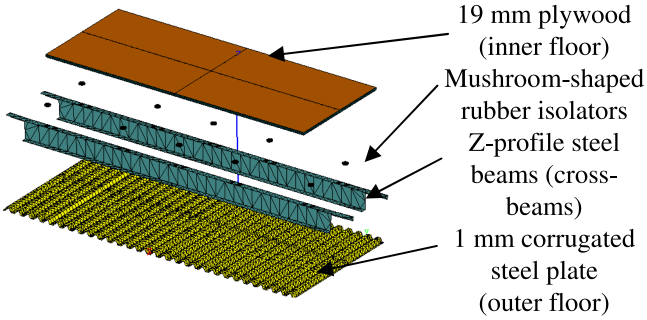

Figure 1: Lay-out of the floating floor studied

From the transition frequency of the numerical CLF, the stiffness of the isolator is $k=2.6.10^5$ *N/m* to be compared to $k_{measured}=3.10^5$ *N/m.* The peaks in the numerical response coincide with frequencies at which the isolator has a mode with pronounced displacements in the vertical direction.

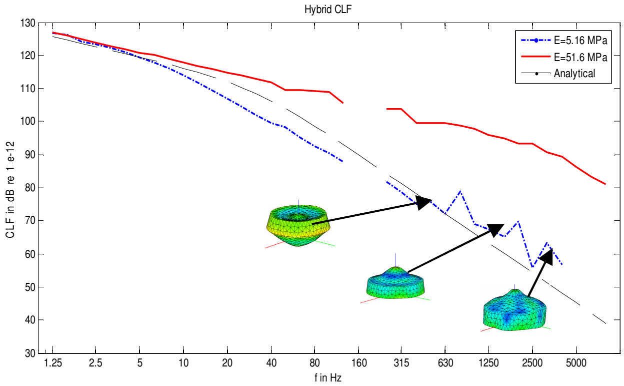

Figure 2: Analytical and numerically computed CLFs

The results illustrate how coupled FE-SEA can be used to determine the CLF of a complex joint, including effects of resonances within the joint.

Floating floor analysis

Floating floors are frequently applied to reduce interior noise and vibration of rail vehicles. Here, the vibration reduction of a floating floor of a metro vehicle has been analysed. The geometry and characteristics of the floor is described in Figure 1: The gap between the inner and outer floors is filled with mineral wool. The objective here is to evaluate how coupled FE-SEA can be used to widen the frequency range that FE analysis offers. In [5] the vibration isolation of the same floor was analysed up till 200 Hz using FE. The airborne transmission has successfully been analysed using commercial a SEA software [6].However, the vibration isolation was not predicted with this model.

Modeling and calculations

The inner and outer floors are fairly large sub-systems (2.2 x 1.5 m) with a high number of modes-in-band. They are therefore modelled as SEA subsystems. The orthotropicity of the corrugated panel was estimated from standard smearing theory [7]. The cross beams and the isolators have lower modal densities and are therefore modelled as FE subsystems. The damping loss factor (DLF) of the metallic subsystems, the plywood inner floors and the rubber isolators are taken as 1%, 4 % [5] and 15 % respectively throughout the frequency range. The DLF of the wool filled cavity was taken as [6]

$$\eta = 0.733 f^{-0.5}, \tag{3}$$

based on empirical data. Calculations are made in two steps. First a standard modal analysis of the FE parts is made using MSC Nastran. The first bending mode of the cross-beams is found at $f = 52\ Hz$. Second, the boundary impedances that the SEA subsystems constitute on the FE subsystems at their common junctions (and vice versa) are calculated. Finally, the coupled response due to a white noise force applied on the frame, as presented on Figure 3, was calculated.

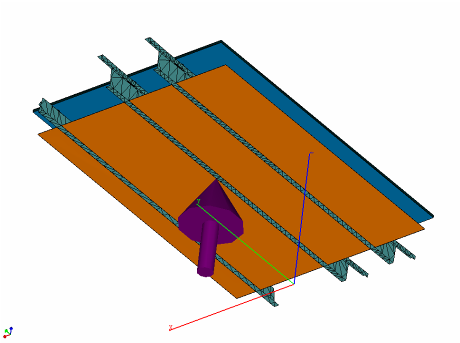

Figure 3: Coupled FE-SEA model

The vibration isolation is computed as

$$\Delta L = 10\log_{10}\left(\left|v_1^2\right| / \left|v_2^2\right|\right)\mathrm{dB}, \tag{4}$$

where $\left\langle\left|v_i^2\right|\right\rangle$ denotes the space and time averaged square velocity of the panels.

Results

The calculated results compare quite well to those measured as shown in Figure 3. Measurements up till 400 Hz are taken from [5] in which 20 accelerometers on the top floor and 6 on the structural floor were used for spatial averaging. Above 400 Hz measurement results from [8] are used. The analytical results are taken from a model by Jutulstad [9]. The reduced vibration isolation at higher frequency is most likely due to resonances in the upper floor. In reference [10] a different train floor design is analysed in which also source impedance results are given.

Conclusion

The coupled FE-SEA analysis offers benefits for acoustic analysis of the floating floor. As compared to standard SEA, the vibration isolation properties can be more accurately predicted and in relation to full FE, a widened frequency range is reached.

The added "cost" of the analysis in relation to SEA is the engineering judgement needed for partitioning the structure into FE and SEA parts and also meshing and solving of the FE sub-systems. For the present model the calculation times are short due to the fairly small FE system. In the present work solely structural transmission was determined. It remains to validate the model for air-borne excitation.

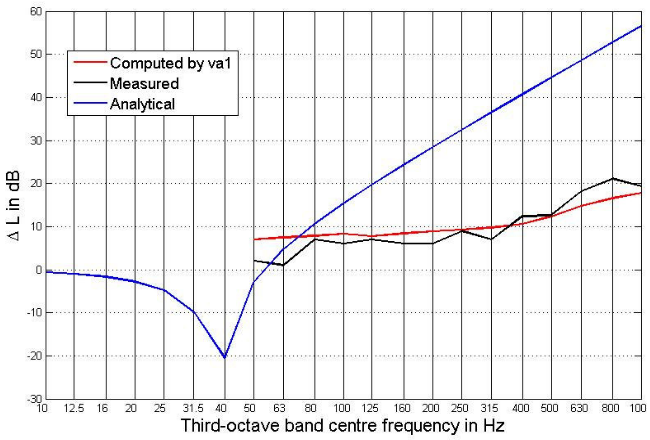

Figure 4: Measured and computed vibration isolation

References

[1] Shorter, P. & Langley, R.S. *On the reciprocity relationship between direct field radiation and diffuse reverberant loading*. Journal of the Acoustical Society of America, 117, pp 85-95. 2005.

[2] Shorter, P. & Langley, R.S. *Vibroacoustic analysis of complex systems*, Journal of Sound and Vibration, Volume 288(3), pp 669-699. 2005.

[3] VA One 2005.1, The ESI Group (2006).

[4] Craik, R. J. M., *Sound Transmission through buildings using Statistical Energy Analysis.* Gower publishers. Aldershot. 1996.

[5] Wollström, M., *Floating floors: models and simulations of vibration characteristics.* TRITA-FKT 2000:13. KTH Stockholm. 2000.

[6] Stegemann, B. *Development and validation of a vibroacoustic model of a metro rail car using Statistical Energy Analysis (SEA).* Master's Thesis Chalmers University of Technology. 2002.

[7] Cremer, L., Heckl, M. and E. E. Ungar *Structure-Borne Sound* (Springer-Verlag, Berlin, New York) (1988).

[8] Nordborg, A. & Stegemann, B. *Vibration transmission measurements on a C20 metro steel carbody.* Technical report 3 EST 7-622. Bombardier Transportation. Västerås 2002.

[9] Jutulstad, H., *Flytende gulv på fjærer – lydreduserende konstruksjon for fartoy*. Universitet i Trondheim, Norges Tekniske Høgskole, Institutet for husbyggnadsteknik, Norway. 1985.

[10] Orrenius, U., Baurès, L. & Cotoni, V. Modelling of structural sound transmission in train structures using hybrid FE-SEA and EFM analysis. *Proceedings of ISMA*. Leuwen 2006.