HIGH-FREQUENCY STRUCTURE- AND AIR-BORNE SOUND TRANSMISSION FOR A TRACTOR MODEL USING DYNAMICAL ENERGY ANALYSIS

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ABSTRACT

Dynamical Energy Analysis (DEA) is a mesh-based high frequency method modelling structure borne sound for complex built-up structures. Vibro-acoustic simulations are done directly on finite element meshes circumventing re-modelling strategies. DEA provides detailed spatial information about the vibrational energy distribution within a complex structure in the mid-to-high frequency range. We will present here progress in the development of the DEA method towards handling complex FEM-meshes including Rigid Body Elements and sound radiation. The results for simulations are compared to measurements on a tractor model provided by Yanmar Co, Ltd both for structure borne vibrations and sound pressure levels (SPL) inside the cabin. For the latter, a combined DEA/SEA analysis has been developed. The simulation results compare favourably with measurement results both for vibration levels measured across the structure and SPLs inside the cabin.

1 INTRODUCTION

A major difficulty in modelling structure-borne sound lies in the complex geometry of the structures. The Finite Element Method (FEM) can describe geometric details with sufficient accuracy in the low frequency region, but requires extremely fine meshes at high frequencies to capture the shorter wavelengths. Statistical representations such as the *Statistical Energy Analysis* (SEA) [1] have been developed leading to relatively small and simple models in comparison with FEM. A range of methods have been proposed to extend the range of SEA such as the hybrid FEM/SEA method [2–4]. An alternative to SEA is ray-tracing in terms of integral equations leading to linear flow equations for the mean vibrational energy density; this forms the basis of the *Dynamical Energy Analysis* (DEA) method introduced in [5]. DEA includes SEA as special case via a low order representation of the transfer operator. Higher order implementations enrich the DEA model with information from the underlying ray dynamics, leading to a relaxation of SEA assumptions. In particular, DEA allows for more freedom in sub-structuring the total system and variations of the energy density across sub-structures can be modelled [6]. An efficient implementation of DEA on meshes has been presented in [6, 7]. Vibro-acoustic energy densities including multi-modal propagation and energy transport over curved surfaces is computed and coupling at material interfaces is described in terms of reflection/transmission matrices. Thus, DEA resolves the full geometrical complexity of the structure.

In this paper, we apply the DEA method to modelling a tractor model (cabin including windows and doors mounted on a chassis) as well as the SPL inside the cabin and compare with detailed measurements done across the structure. We focus here in particular on how to implement DEA in the presence of *Rigid Body Elements* (RBEs) or similar FE coupling methods. We will furthermore introduce a DEA/SEA method for determining the acoustical response inside the cabin.

2 THE TRACTOR MODEL AND THE SET-UP FOR VIBRO-ACOUSTIC MEASUREMENTS

The tractor model under consideration has been provided by Yanmar Co, Ltd and is a stripped down version of a tractor of the EG400 series. The tractor body consists of a chassis frame and a cabin - the latter includes doors and windows - often referred to as a 'body-in-blue' (BiB). The chassis frame consists of the gear casing and a front frame. The cabin is mounted onto the chassis by four rubber mounts; the actual structure together with an FEM model is depicted in Fig. 1. In the FE model, the rubber mounts are treated as spring elements - so-called CELAS1 elements. Rubber material and glue (such as for describing the fixture of windows, doors and the roof) are modelled with rigid body elements (RBE), mostly of the RBE3 type. The coupling

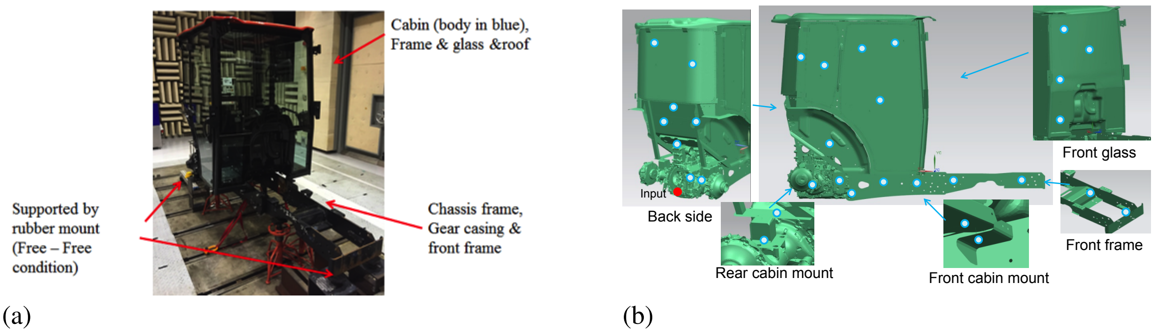

Figure 1: (a) the tractor parts under consideration and (b) the corresponding FEM model of the tractor including the accelerometer positions across the structure (blue dots, 44 points in total).

elements provide a connection over which energy can be transferred. The chassis frame is supported by rubber mounts as free-free condition. The excitation is at the rear side of the gear casing. Excitation is applied using a modal shaker in a frequency range between 400Hz to 4000Hz. The sound pressure at the operator's ear location is measured with a microphone. In addition, the acceleration of the structure is measured at 29 points on the cabin and at 13 points on the chassis frame using an accelerometer. The acceleration on the upper and lower sides of each cabin mount are also measured giving valuable information about the coupling via the rubber mounts. Fig. 1b shows the location of the measurement points (blue dots).

3 DEA ON COMPLEX MESHES AND A DEA/SEA HYBRID TREATMENT

In the following we will focus on DEA on 2D meshes [7] and describe the modelling of connections between different meshes via RBE's such as used in the tractor model. DEA is a technique for determining the flow of (vibrational) energy through a structure in terms of a transfer operator defined on boundaries of subsystems of the structure, here the boundaries of the mesh elements. Mode conversion between in-plane and flexural waves at boundaries are included in the treatment, the reflection/transmission coefficients are obtained from wave scattering theory [8]. Shell effects leading to curved rays [9] are included by treating the meshed structure as a set of plate-like elements, see [6, 7] for details. Once the ray density ρ has been computed, the energy density at any location inside the structure may be obtained in a post-processing step as described below.

The FE model of the tractor structure shown in Fig. 1b is made up of different sub-meshes; these sub-meshes are connected via special FE elements, RBEs, at, for example, glass-metal interfaces, at the sidewall-roof interfaces or for connecting the doors to the cabin frame. We treat RBEs as DEA coupling elements directly. To describe the energy transfer across non-compatible meshes we introduce coupling between edges connected to the mesh cells next to the RBEs both in the 'upper' and 'lower' sheet connected by the RBE. Incoming ray-densities at one side of the RBE-interface are now mapped onto the other side of the interface via a probability density function in phase space (position on each edge and ray directions).

The sound pressure level (SPL) inside the cabin and in particular at the position of the driver's ear can be computed from the vibration levels obtained in the DEA computation. To do so, we identify the main panels of the cabin, determine the mean velocity v_i on each panel i with mass M_i from the DEA analysis and determine the input power P_i radiated off each plate

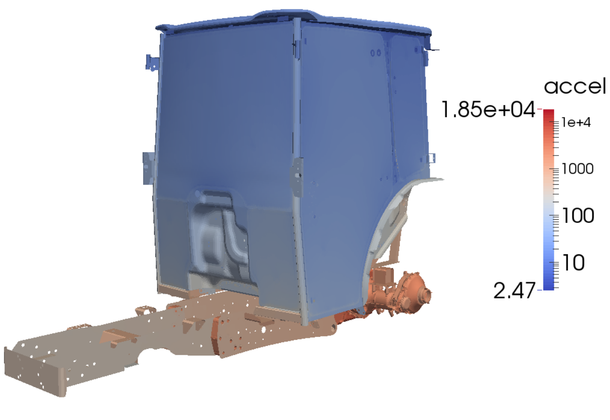

Figure 2: DEA results for the acceleration (given here in mm/s^2) at a frequency of 1000 Hz.

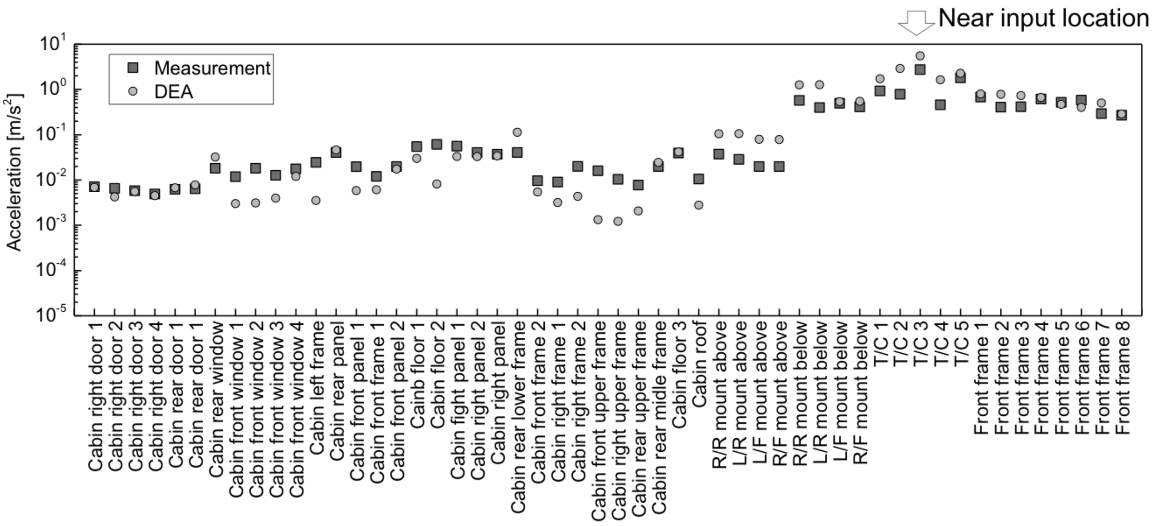

Figure 3: Comparison of Simulation and Measurement results at 1000 Hz.

using the relation

$$P_i = \omega(\eta_i + \eta_i^d) M_i < v_i^2 >, \quad \eta_i = \frac{Z_0 A_i \sigma_{rad}}{\omega M_i} \tag{1}$$

Here, A_i is the area of plate i, η_i is the coupling loss factor between panel i and the interior volume and η_i^d is the loss factor due to dissipation in panel i. (We assume $\eta_i^d = 0.5\%$ and $\eta_V^d = 1.5\%$ for the interior volume). Furthermore Z_0 is the acoustic impedance and σ_{rad} is the radiation efficiency, here for rectangular plates in the approximation derived in [10]. The DEA result enters through the mean velocity $< v_i^2 >$ averaged over each of the panels.

4 RESULTS

We performed DEA calculations for the full structure shown in Fig. 1b in the frequency range 400 Hz – 10 kHz. The results are compared to experimental data obtained from measurements done by Yanmar for the input powers specified. In all calculations, a hysteretic damping level of 0.005 is assumed. The acceleration of surface points are measured in mm/s^2. Fig. 2 shows the outcome of the DEA calculation on the FEM mesh at 1000 Hz. Most of the vibrational energy remains near the source (rear end of the chassis) and in the chassis itself. The cabin shows less excitation which in addition decreases with the distance to the source. A point-by-point comparison with the measurement results can be found in Fig. 3. Overall, the simulation captures the energy distribution across the whole structure remarkably well despite the simplifying assumptions for the RBE coupling and the cabin mounts. We have also conducted SPL calculations at the driver's ear position following the approach sketched in Sec. 3. The results are summarised in Fig. 4. We note large variations in both the experimental data and the simulations, but the overall range (between 45 and 55 dB) is captured well by the simulation.

5 CONCLUSIONS

We demonstrate in this paper that the DEA method can compute structure borne sound across a complex structure – here a BiB substructure of a full tractor. The results presented in this paper emphasise the level of detail provided by the DEA method and its flexibility in handling RBE elements. Results over the full frequency range from 400 Hz to 4 kHz have been presented.

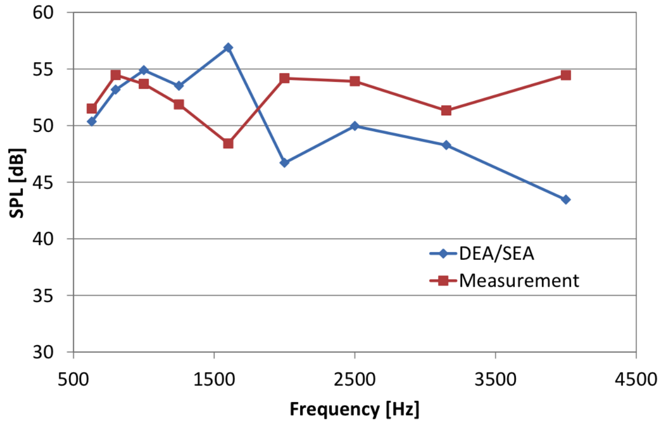

Figure 4: SPL at the driver's ear position: experiment (red); SEA/DEA simulations (blue).

ACKNOWLEDGEMENTS

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