In-Car Noise Computation for a High-Rise Lift

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Abstract. The authors have developed an acoustic model of a lift, using a multi-disciplinary approach. The model enables a full understanding of how the lift design is affected by noise requirements inside the car, and in buildings that are still in planning or construction phase. The approach is based on a hybrid model combining structural finite element (FEM); computational fluid dynamics (CFD); boundary element method (BEM) and statistical energy analysis (SEA); to cover both low and relatively high frequency acoustical domains in a sufficiently detailed model with a reasonable computational time. Special attention has been paid to modelling of the noise sources. Structure-borne sources (point forces) due to roller guide shoes and ropes were applied on the system. Forces were determined on grounds of FEM-computed point mobilities and measured vibration velocity responses at the same excitation points. Airborne sources due to flow-induced noise were computed using an incompressible transient CFD analysis. The resulting time variable air surface pressure was then applied on the car walls. The surface pressure spectra were used both directly (the convective source) and as a source for the acoustic propagation (giving the acoustic source). The reverberant sound field in the hoistway, generated by the flow sources, is a significant contributor. This part was modelled using BEM. The time variable pressure field on the car surface was used as a source distribution for BEM. The end result of the computation was applied as a diffuse acoustic field on the car surfaces. All the sources: structure-borne and airborne, were applied as forces and pressures. They were internally converted to power inputs for solving the SEA model. All transfer paths in the sling, car, doors, fairings and hoistway, including relevant leaks were simulated. After validation, the hybrid model now allows the users to quantify and rank noise contribution of each source and make predictions based on changes in the lift structure, hoistway design and car running parameters.

1 INTRODUCTION

In the recent past, lift ride comfort (noise, vibration, car dynamics, etc.) has been receiving increasing attention by lift users, developers, building owners and leading lift manufacturers. The megatrend of urbanization and the need of building taller buildings, combined with a higher demand for comfort has forced the lift manufacturer to find computational solutions for predicting the dynamic behaviour of the car, in order to ensure that all the ride comfort requirements are fulfilled. Passenger ride comfort covers a broad area of objective (measurable) and subjective properties, representing one of the main aspects of the brand image for lift manufacturers. In this paper, the focus lies on the acoustic performance of high-rise lifts.

The challenge was to create a model for predicting interior sound pressure level in the car for a specific lift architecture, ride parameter and component selection. Then the model had to be validated on a site and ultimately used to rank the noise sources and offer engineering solutions for decreasing them.

2 CHALLENGES AND SELECTION OF THE COMPUTATIONAL STRATEGY

Acoustic models have been developed for many years for automotive and train industries. The challenge to adapt them to lift industry comes from the uniqueness of every lift installation, low speed and tight clearance between lift and hoistway walls.

Although the basic components are similar, the combination of parameters like the height of the building, the dimensions and the cross section of hoistway, the numbers of car sharing the same hoistway, the number and distribution of landing doors and the location of counterweight make each lift different to the next.

Validating cars and trains in wind tunnels are a common practice for understanding the limitations of the CFD results. However, since the lifts are designed to be suspended and move in vertical direction, the validation in a wind tunnel is very challenging. In addition, if the clearance between the road vehicles or trains and the tunnel wall can be one or two meters, in lift industry, the clearances can vary from few centimetres to the landing doors up to half a meter or more for the rest of hoistway. The small clearances combined with low speed result in a lower Mach number, which makes the computation and the testing very challenging.

Regardless these differences, the same methods used for computing and validating the acoustic models can be applied for the lift industry. The basic type of simulation chosen for covering low, middle and relatively high frequencies was Statistical Energy Analysis (SEA). The method was developed within the US Space Program in the early 1960's [1]. Application of SEA in automotive industry was published first time in 1980's [2] and on a lift in 1990's [3].

The basis of SEA is the principle of conservation of energy from which a set of power balance equations can be derived for a given frequency band and subsystem. For every subsystem *i* there is a steady-state power balance; the power injected (P_{in}) equals to the power consumed (P_{out})

$$P_{in,i} = P_{out,i} \tag{1}$$

The power injected and consumed is either dissipated in the subsystem (P_{diss}) or transmitted (P_{trans}) out from the subsystem:

$$P_{out,i} = P_{trans,i} + P_{diss,i} \tag{2}$$

The set of SEA equations for the total system composed of a number of subsystems is

$$\{P_{in}\} = [L]\{E\} \tag{3}$$

Where $\{P_{in}\}$ is the input power vector, $[L]$ is the loss matrix governing the power dissipation and transmission between the subsystems and $\{E\}$ is the subsystem energy vector. Once power inputs for all subsystems and the loss factor matrix are formed, the system of equations is solved for the subsystem energies. The subsystem energies are then converted into engineering units of interest, i.e., sound pressure (acoustic subsystems like ducts and cavities) or vibration velocity (structural subsystems like beams and plates).

SEA works best in case of broadband random excitations and reverberant (lightly damped subsystems with as many resonant modes as possible [4, 5]. The advantages of SEA are very short solve times and that fewer details are needed to calculate reasonable results. The main disadvantages are the limited accuracy at low frequencies, the average character of results, and that parts with complex shapes may be difficult to model with standard SEA subsystems.

For the low frequencies, as well as for stiff subsystems, where the number of modes is low, FEM can be used. Theory of combining FEM and SEA into a coupled hybrid model is available in [6, 7, 8]. This is the method also used in this paper.

3 IDENTIFYING THE SOURCES OF NOISE

The noise sources inside a lift car can be divided based on their excitation and travelling path into structure-borne and airborne sources.

3.1 Structure-borne source

Structure-borne sources are induced by vibrations of lift components that are located close or in contact with the car: roller's guides, ropes, safety gears, car walls, fans, air condition devices, door operator, sling-car interface, etc. The energy of these vibrations is transmitted to the walls of the car, creating pressure fluctuation of the air inside the car that is perceived as noise.

The excitation forces were determined from FEM-computed point mobilities and measured vibration velocity responses at the same excitation points (Fig. 1).

The structure of the sling and the platforms for the cars were modelled using FEM, due to their stiffer structure.

3.2 Airborne sources

The airflow around the car creates two types of pressure fluctuation [9]; turbulent fluctuation due to sudden change in cross section of the hoistway and acoustic fluctuation, due to interaction of eddies travelling within the flow and rigid surfaces. Acoustic waves are also reflected from the hoistway walls. The two types of fluctuation have to be modelled differently because they are coupling in a different way with the car walls and they transmit different types of sound energy that will be radiated inside the car. (Fig. 1).

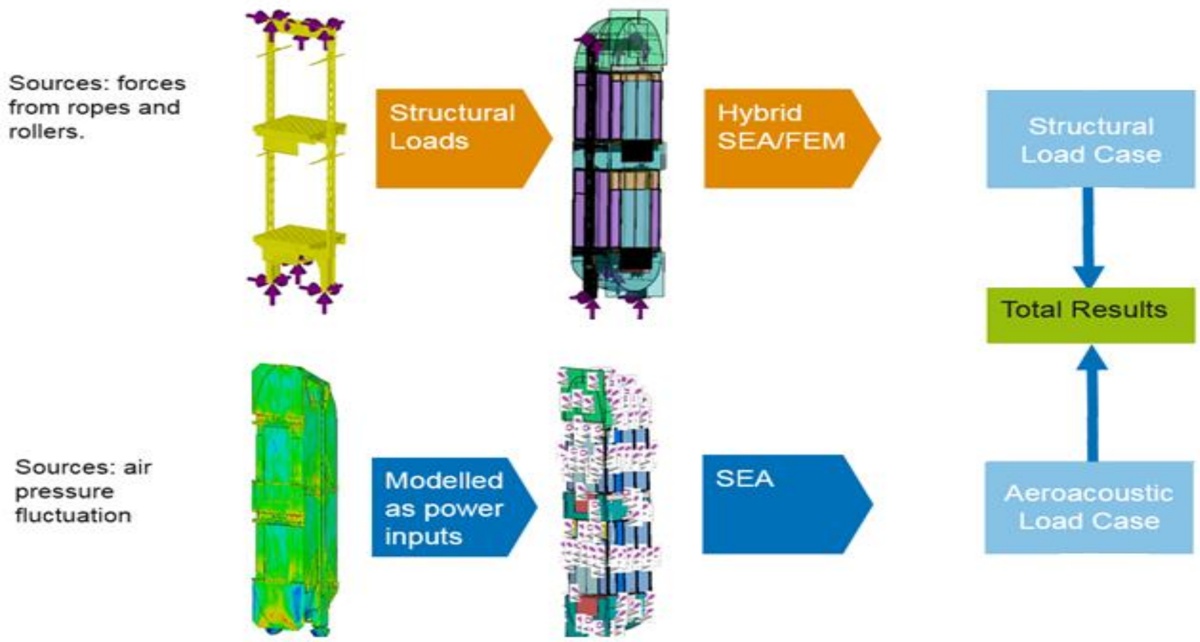

Figure 1 Noise sources in the lift car

The turbulent air sources were computed using a transient CFD with incompressible air, for a section of hoistway that did not include landing doors or the counterweight. The direction of the lift movement was downwards at the speed of 10 m/s (Fig. 2)

The equations solved are the transient, incompressible, filtered Navier-Stokes equations [10]:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (4)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = \frac{\partial}{\partial x_j}\sigma_{ij} - \frac{\partial p}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_i} \quad (5)$$

In Equations (4) – (5) u = velocity vector, x = spatial coordinate, t = time, ρ = density, σ = stress tensor due to molecular viscosity and p = pressure. From the acoustic point of view, the main outcome of the simulation is the fluctuating surface pressure $p(x,t)$, which is further transformed into the frequency domain.

The simulations were scale-resolving, meaning that the large and medium size turbulent vortices were solved explicitly instead of Reynolds averaging. The subgrid-scale stress tensor τ in Equation (5) is modelled with the Detached Eddy Simulation (DES) method [11]. The transient, scale-resolving simulations are significantly more time consuming than steady state simulations, but necessary in order to obtain the turbulent acoustic source terms.

This convective pressure flow source was modelled as a Turbulent Boundary Layer (TBL) type load. The TBL load is defined by a pressure spectrum and a wavenumber (i.e., wavelength) spectrum. This data was computed from the CFD-results at all the main surfaces of the lift and the wind deflectors.

The acoustic component or air source was computed using BEM, (Fig. 3). The fluctuating pressure (FSP) result from CFD at the surface of the car was used to excite the air around the car. The reflective walls of hoistway were modelled by adding absorption properties on the wall and considering the hoistway having anechoic ends.

Several assumptions have been done to compute the acoustic component: in BEM, only the surface pressure terms of Curle analogy were considered; the analysis is time -invariant stationary, which means that the computation is performed for each frequency separately and that additional contribution of standing waves could influence the results. In addition, it is assumed that the flow field and the acoustic field do not influence each other.

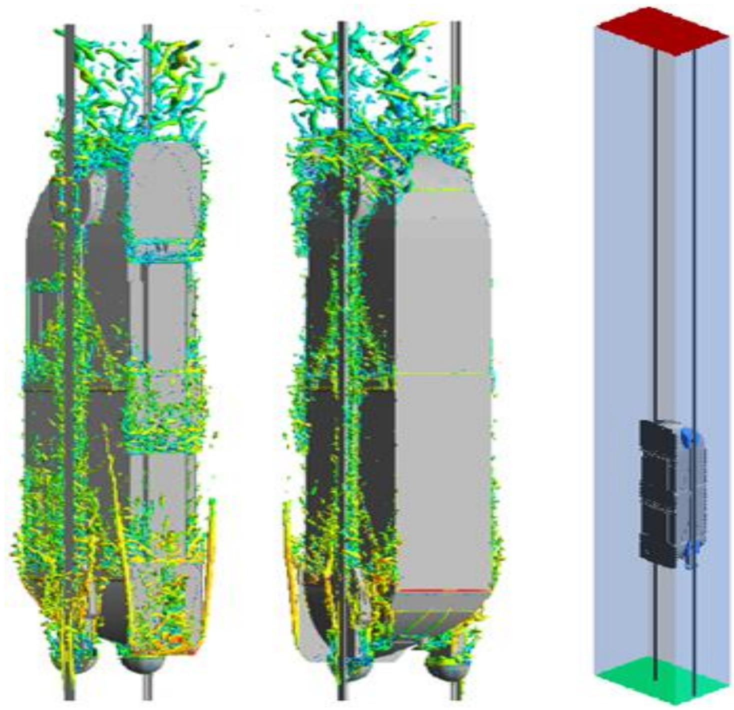

Figure 2 Turbulent air sources and the CFD simulation domain

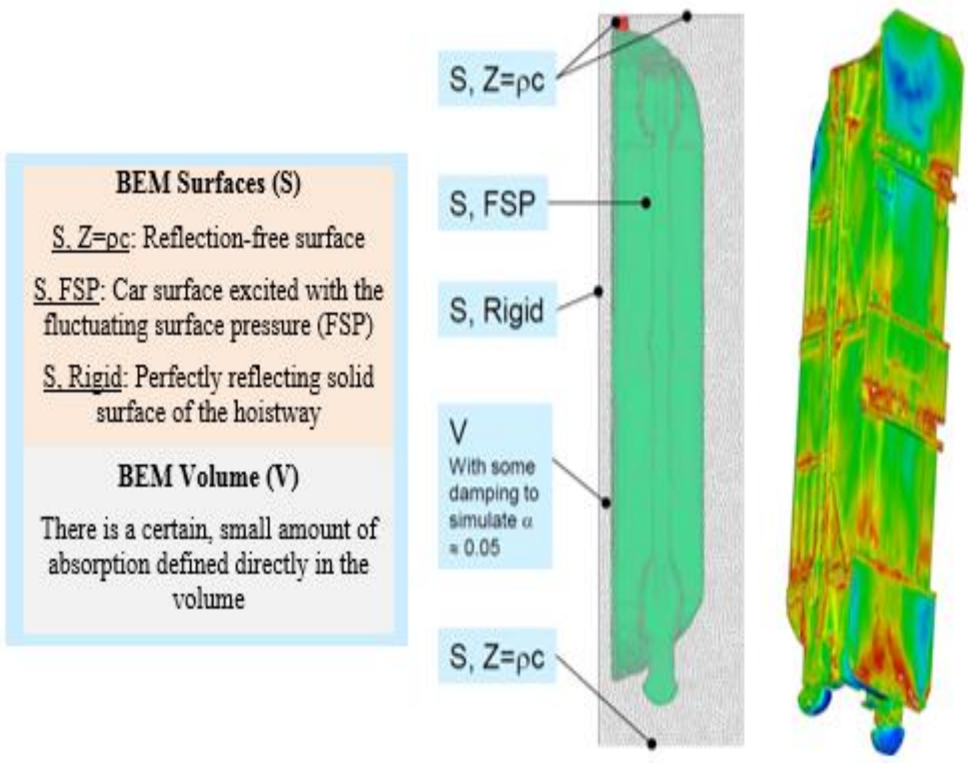

Figure 3 Composition of a BEM-model. FSP distribution shown on the right.

These procedures are described in more detail by Blanchet et al in [12].

4 APPLYING THE SOURCES OF NOISE IN SEA MODEL OF THE CAR

A special attention has been paid in modelling the structure of the car with SEA. The sandwich structure of car panels, the ventilation holes, the roof structure, the fan labyrinth, the air gaps around the panels and doors were included (Fig. 4). The connection between SEA structure and FEM structure has been modelled using hybrid junctions.

The frequency of interest for in car noise was 20 – 500 Hz. The noise was computed for the entire air cavity inside the car with 1/3 octave frequency resolution.

Due to the hybrid junctions, the structure-borne computation for the frequency range of interest was straightforward. The structural loads were applied as forces at relevant points in the sling.

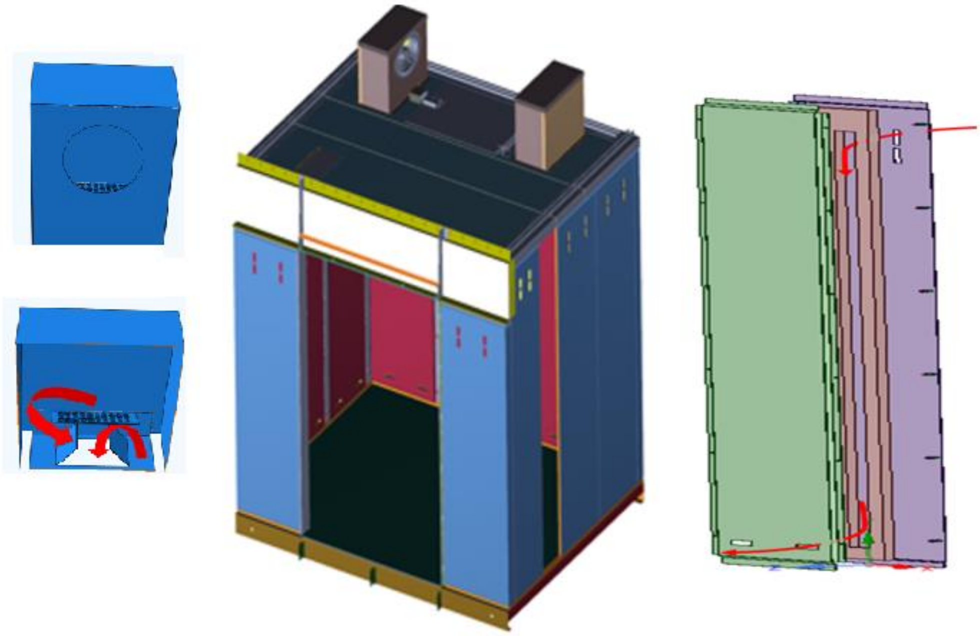

Figure 4 Car structure and details: fans, car, panel structure

The airborne loads were applied as a sum of two different contributions. The Turbulent Boundary Layer (TBL) loads and the Diffuse Acoustic Field (DAF) loads were applied on all lift and wind deflector surfaces as relevant pressures-wavenumber combinations (Fig. 5).

To solve the SEA set of equations, pressures and forces are first converted into power inputs. The equations are then solved for the subsystem energies. Finally, the subsystem energies are converted into engineering units (sound pressures and vibration velocities).

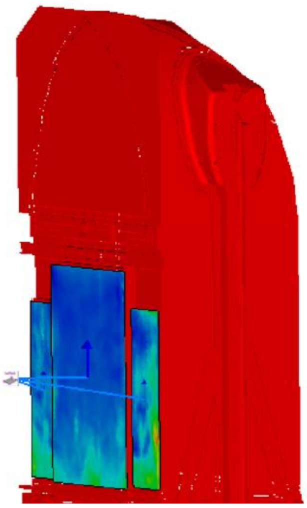

Figure 5 Example of surface pressure fluctuation at lift surface in the frequency domain

5 RESULTS AND DISCUSSIONS

Four different computational methods (Fig. 6) were used to analyse and rank the noise sources inside a lift car for a specific frequency range.

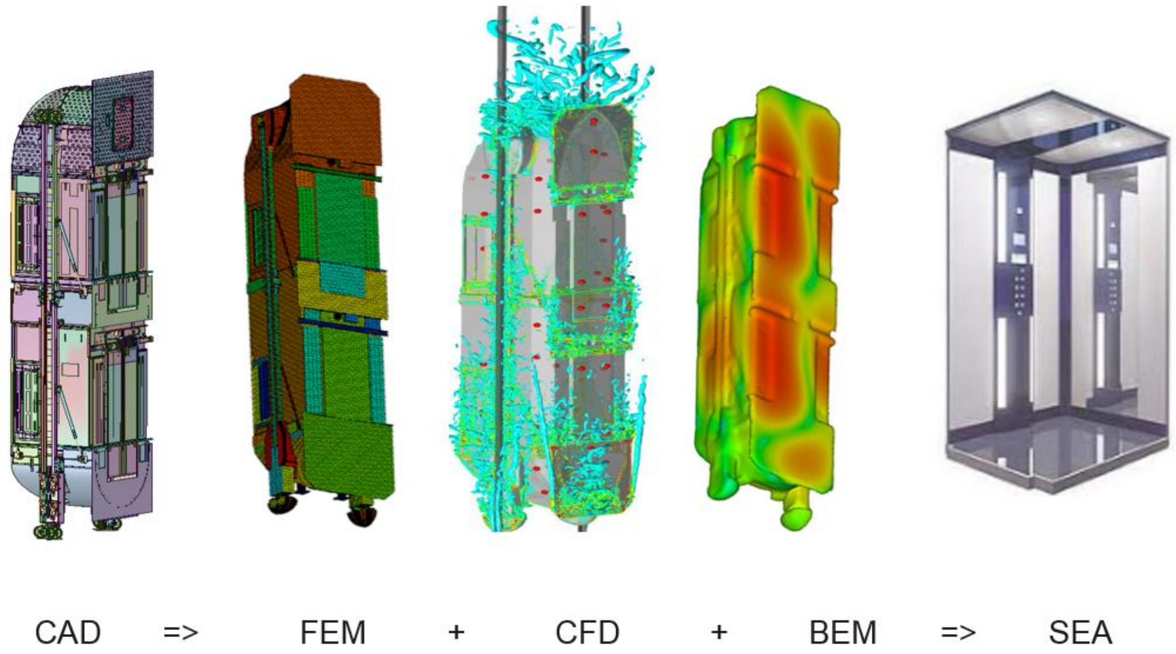

Figure 6 Simulation workflow

The computed result of in-car sound pressure level spectrum is shown in Figure 7. On top of the total sound pressure level, the contributions from the three different kind of sources are shown.

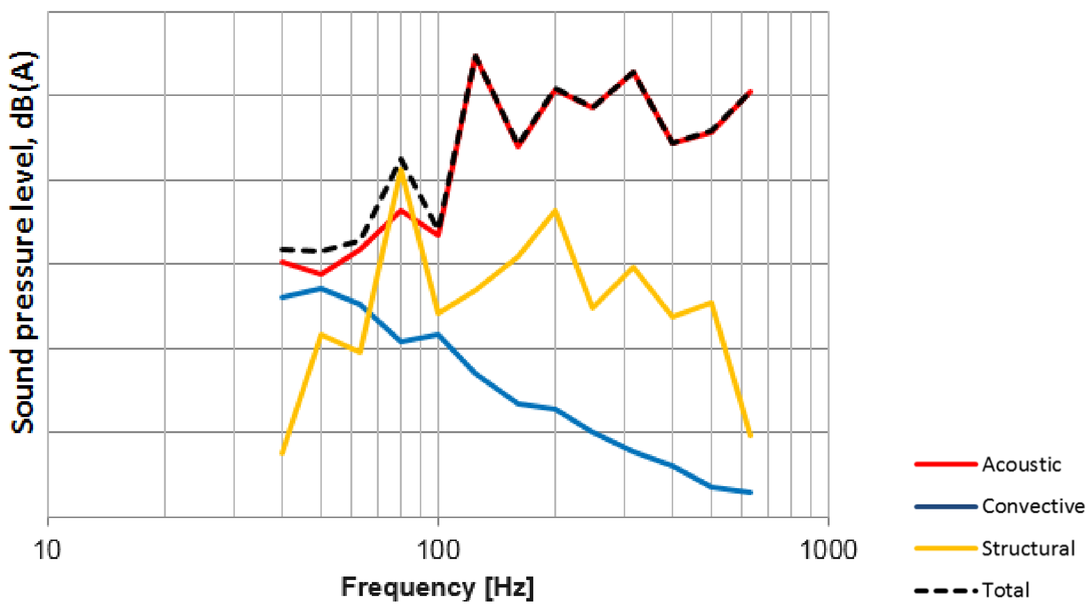

Figure 7 Influence of different sources on in-car noise

The results are providing valuable information regarding each source contribution: for high speed, the acoustic contribution is dominant, excepting the lowest frequency below 100 Hz; which means that any noise reduction should be done starting with reducing the acoustic component: streaming the shape of car, minimizing the changes in the hoistway section, adding absorption structure to the hoistway surfaces. The convective component (TBL) has relevant contribution only at the lowest frequencies. The structural component shows a distinctive peak at 80 Hz but is otherwise non-significant.

There is good agreement between computed and measured data (Fig. 8), with one exception.

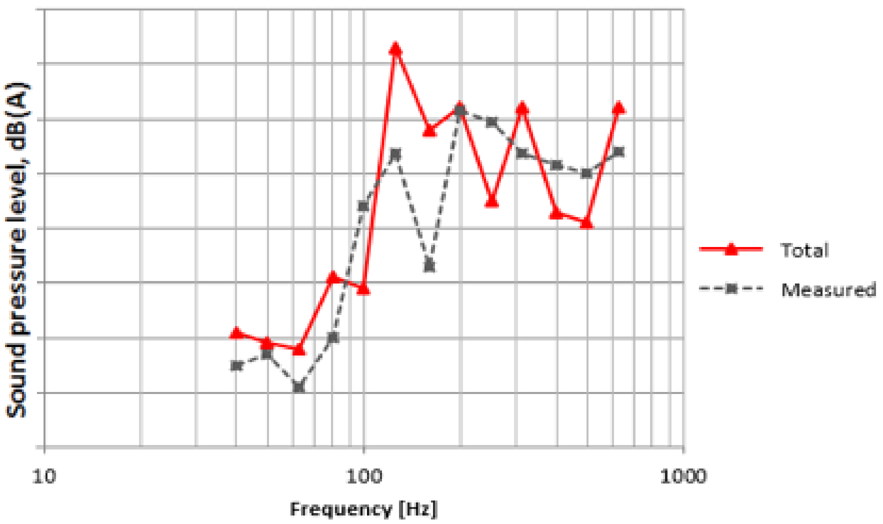

Figure 8 Comparison between simulation and measurements

At frequencies above 100 Hz the predicted spectrum is peakier than the measured spectrum; this difference can be explained because the BEM-based procedure does not take the lift movement into account. Formation of high-pressure standing waves in the hoistway is predicted in the stationary situation. In reality, the relative movement of the lift hoistway does not support formation of strong standing waves. This smooths out the spectrum.

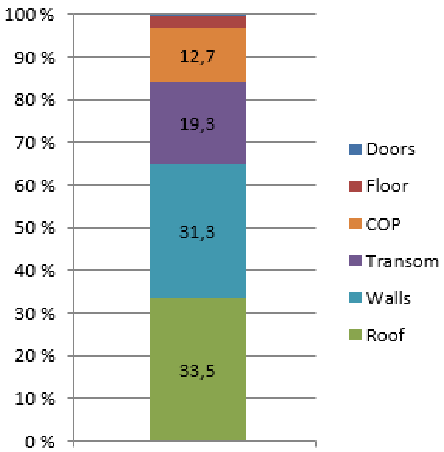

Figure 9 Ranking the noise sources based on components

The method can be used to rank the noise contribution of each component of the car (Fig. 9) and therefore to start optimising the car structure based on the noisiest source.

Apart from imminent technical results and information thereof, development of simulation competence has many short and long term benefits.

Interpretation of measurement results becomes easier. With a good model one is able to study effects of system parameters and gain a deeper understanding on various observations. Models can also be used to conduct virtual measurements and, in that way, they can be extremely useful in planning of real measurements.

Measurements in situ have a limited repeatability and reproducibility. This means that it is challenging to experimentally ascertain noise level changes in order of ± 1 dB, because the level may change more in repeated measurements for unknown and uncontrollable reasons. Simulations do not suffer from that kind of weakness.

The method developed in this paper is a powerful tool in predicting in-car noise for lifts that have not been built and it opens the world of “what if” providing the designers a tool to take controlled risks and the managers a tool to understand the capabilities of their products.

The long term aim and megatrend is frontloading [13]. This concept means the driver of simulation competence development may reach the situation where more simulation effort is directed to the very early design phases. More and more design challenges, difficult and expensive to deal with afterwards, are solved cost-effectively before any physical prototype is built.

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BIOGRAPHICAL DETAILS

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