AERO-VIBRO-ACOUSTIC NOISE PREDICTION FOR HIGH SPEED ELEVATORS

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Abstract

Noise inside the car is an important aspect of the elevator user experience. Accurate prediction of the in-car noise and the aspects affecting it are important for further reducing the noise levels. The present paper describes the use of simulations for predicting and reducing the in-car noise levels.

As aero-acoustic (wind) noise sources have larger speed dependence than structural sources, their relative contribution increases with elevator speed. At high speeds, the effect of wind noise becomes dominating. The wind noise sources are predicted with transient scale-resolving CFD (computational fluid dynamics) simulations. Noise propagation in the elevator hoistway is modeled with BEM (boundary element method) while the transmission into the car is studied with SEA (statistical energy analysis).

Differences between elevator and automotive aero-acoustic simulations are discussed. A major difference is that due to the lower speed of the elevator, the Strouhal number is much higher at the same frequency. This leads to increased need of computational power.

The results of the simulations are validated with measurements in the elevator car. Data from the simulation models and measurements is used for creating a light statistical prediction model for the in-car noise of high speed elevators.

1 INTRODUCTION

The noise level and characteristics are an important part of the ride comfort for the users of the elevators. As the buildings are getting higher and hence the time of the travel in elevator is longer, the increased speed of the elevator is one solution to reduce the travelling time. Hence as the speed increases, the sound pressure levels inside the elevator car rises [1]. The strength of aero-acoustic noise sources increase more rapidly than the strength of structure-borne sources as a function of speed. This means that at high speeds, the effect of the aero-acoustic sources is dominating. For this reason, the main emphasis in the current analysis is on the aero-acoustic sources and their transmission into the elevator car.

The use of aero-vibro-acoustic simulations in the industry is becoming more and more popular. There is an abundance of examples of aero-vibro-acoustic simulations being applied to the automotive (e.g. [2]) and several other industries (e.g. [3]). However, there exist very few publications in the field related to the elevator industry.

2 WORKFLOW FOR DETAIL LEVEL SIMULATIONS

The principle of the workflow used in the detail level simulations is shown in Figure 1.

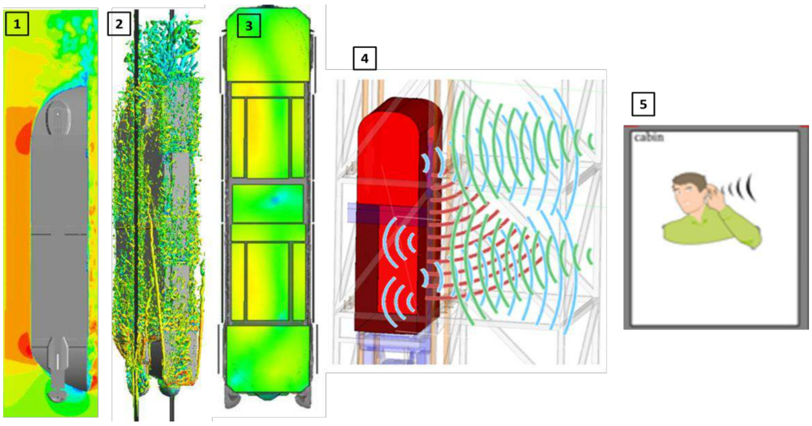

Figure 1: Workflow for detail level simulations

The workflow consists of the following phases:

1) Large scale flow field prediction

The first step in the analysis is determining the large scale flow field in the elevator hoistway. The relative wind speed, V_{rel}, experienced by the elevator depends on: elevator speed V_{car}; elevator and hoistway cross sectional areas (A_{car}, A_h); hoistway leaks, such as ventilation holes and the leaks of the landing doors; elevator drag coefficient; vertical location of the elevator in the hoistway; how many elevators share the same hoistway: whether there is a possibility for a parallel and/or opposite run of the elevators

In the simplest case, assuming a single elevator in an airtight hoistway, the relative speed can be calculated with:

$$V_{rel} = \frac{V}{1 - \frac{A_{car}}{A_h}} \tag{1}$$

In the general case, however, a more complex analysis is required, taking into account each individual leak in the hoistway. In airtight, narrow hoistway, the relative wind speed can be more than double the speed of the elevator. This has a huge effect on the aero-acoustic noise generation.

2) Detail level aero-acoustic CFD and source prediction

The next step is a detailed simulation of a specific elevator geometry using 3D transient CFD models. The simulations are scale-resolving, meaning that the large and medium size turbulent vortices are solved explicitly instead of Reynolds averaging. In particular, the Detached Eddy Simulation (DES) turbulence model is used [4]. 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.

3) Propagation of the sources in the hoistway

While the CFD simulations are performed in the time domain, the results are transformed into the frequency domain for the propagation analysis. The fluctuating air pressure at the elevator surfaces is obtained from the CFD simulations. It is further used as a source for the BEM simulations, which predict the acoustic pressure field in the hoistway.

The BEM model takes into account the reflections from the walls of the hoistway. This has a rather large effect on the SPL level in the hoistway.

4) Transmission of acoustic energy into elevator

The next step in the analysis is predicting the transmission of acoustic energy into the elevator car. The predictions are done using SEA models, with a rather detailed model for the elevator. Number of subsystems in a SEA-model of an elevator car is 100...150.

The transmission paths e.g. through the wall panels, roof, floor and the seals of the doors are included in the model. In addition, the effects of the car interior decorations are also considered.

5) Elevator interior noise analysis

The final step in the analysis is to predict the car interior noise based on the flow of acoustic energy into the car. This is done using statistical methods, without taking into account the individual room mode shapes. When SEA models are used, this step is performed simultaneously with step 4.

Sometimes the steps 4 and 5 are applied in series. This approach effectively neglects the outflow of the acoustic energy from the car back to the hoistway. The latter approach introduces a slight approximation, but allows a more modular calculation process.

3 COMPARISON TO AUTOMOTIVE SIMULATIONS

As there is plenty of experience from successful use of aero-vibro-acoustic simulations in the automotive industry, it is natural to try to adapt the methodology used for the elevator industry.

However, there are several major differences between the cases, from the physics and simulation point of view. All of them together contribute to the fact that the elevator aero-vibro-acoustic simulations are actually in many aspects more challenging than the automotive.

Fully transient nature of the elevators

Automotive cars are quasi-steady from the aero-acoustic point of view. In the simulations, one can always assume that the aero-acoustic sources remain constant as a function of time. The CFD simulations still need to be performed as transient, due to the turbulence. However, the process is rather straightforward, as the geometry and the boundary conditions remain fixed.

Elevators, on the other hand, have a constantly varying aero-acoustic source field. This transient nature comes from the various discontinuities, such as passing the counterweight, landing doors, divider beams and ventilation holes.

If the discontinuities are taken into account, the CFD solution needs to be performed taking into account the relative motion of the objects. Methods to accomplish this include: sliding mesh method; overset mesh method and automated re-meshing at each time step

Caution is needed, as all of the methods can potentially introduce numerical noise to the solution. The sliding mesh method is the only one, which has been widely used in aero-acoustic simulations. However, in the vast majority of the cases, the method has been applied to rotating machines, such as fans. There is little previous experience of applying the sliding mesh method for aero-acoustics of bodies in translational motion. Special treatment is needed at the bottom and top of the hoistway when applying the method.

Hoistway around the elevator

The automotive cars are simulated either in free space or in wind tunnels with a large cross section. Setting up the boundary conditions is straightforward, as the free stream velocity equals the speed of the vehicle. For elevators in a narrow hoistway with leaks, the free stream velocity is a complex function, as explained in Section 2.

From the acoustic propagation point of view, the hoistway creates significant reflections and buildup of acoustic energy. In the automotive industry, the direct (convective) effect of the fluctuating surface pressure is the dominant source of interior noise of the car at low frequencies. The exterior acoustic field originating from the flow becomes significant only at the higher frequencies. For elevators, the same applies, but the reverberant environment enables much stronger build-up of exterior acoustic field, which becomes dominant at lower frequencies than for automotive cars.

Speed of the vehicle

The speeds of the automotive cars in the aero-acoustic simulations are typically in the range of 120 – 160 km/h, while even the fastest elevators move at around 30 – 40 km/h. Assuming the same turbulent intensity, also the turbulent velocity fluctuations *u'* for automotive cars are about 4 times higher than for elevators.

The CFD mesh spacing Δ, required to resolve the turbulent fluctuations can be approximated with [5]:

$$\Delta = u'/(2f) \quad (2)$$

This means, that in order to resolve the same frequencies, *f*, the mesh sizing needs to be 4 times denser in the elevator compared to the automotive CFD model. In the 3D model, this means 4^3=64 times more cells and computing power for a similar volume and frequency. In order to avoid aliasing effects, dense meshes are also needed in BEM-models when fluctuating surface pressures are used as acoustic sources.

Size of the simulation domain

The sizes of the automotive and the elevator cars are comparable. However, the aero-acoustic simulations of the automotive cars are typically focusing on some rather small details, which dominate the aero-acoustic noise generation. These details are typically the side-view mirror and the pillars. This approach helps to limit the size of the computational domain and/or to concentrate the densest parts of the mesh in the important region.

Elevators are typically in general less aerodynamic than the automotive cars. It is often not possible to determine any single dominating region in advance, from the point of view of noise generation. This means that a relatively large computational domain with a dense mesh needs to be included in the simulation.

For the same frequency, *f,* speed, *V* and characteristic length, *L*, the Strouhal number, Eq (3), of the whole elevator is orders of magnitude larger than that of an automotive side-view mirror. The number of cells required, on the other hand scales approximately as St^3.

$$St = \frac{fL}{V} \quad (3)$$

Combining these factors means that a full industrial aero-vibro-acoustic simulation of an elevator is only possible at somewhat lower frequencies compared to the automotive cars. Fortunately, the important frequencies in an elevator are also lower, largely due to the same physical reasons.

4 STATISTICAL CORRELATION MODEL

The detailed simulation process is needed for accurate predictions and optimizing of the elevator design, however it does not provide fast answers, needed for example, in the early tender or design phase and it requires advanced multi-physics specialists to compute them.

For fast predictions, a Matlab tool based on a database of simulations has been developed. In order to cover the entire KONE offering for high-speed elevators, the database consists in addition to detailed simulations, also one-dimensional and correlation models. All the results are validated with measurements from the sites and KONE research facilities, as soon as the components are available.

5 RESULTS AND MODEL VALIDATION

In order to validate the models, the simulation results were compared against measurements. The SPL spectrum using the detailed simulation method is compared against measurement result on the left hand side of Figure 2. The right hand side shows the comparison of the statistical correlation model against measured total SPL values.

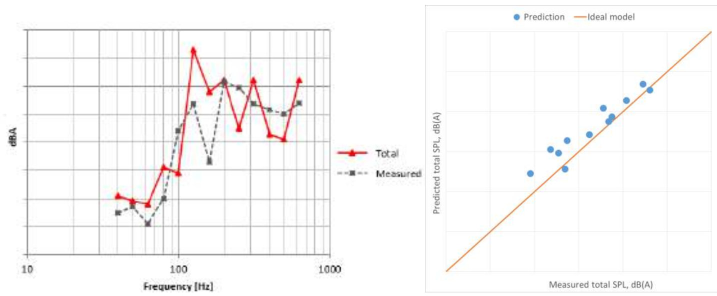

Figure 2: Validation of the model. *Left:* Measured vs simulated SPL spectrum in an elevator car. *Right*: Measured vs predicted total SPL level in several different elevators.

The concept developed in this paper is a powerful tool in predicting in-car noise for elevators 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. Understanding the impact of component selection on in-car noise from the tendering or design phase, contribute to substantial savings for trouble shooting noisy solutions or expensive changes in the last phases of the projects.

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