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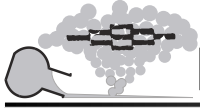
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Prospectives to tractor cabin design with computational acoustics tools

Abstract

Computational acoustical models allow automated optimization of tractor design with respect to acoustic properties, which could speed up significantly the design process of tractor cabin prototypes. This article gives insightful prospectives to the tractor design process by considering modern computational acoustics technology. Mathematical formulation for a system consisting of vibrating elastic tractor structure and air-filled acoustic enclosure are given and a related numerical solution technique with finite element method (FEM) is presented. Simulation results produced with commercially available software are reviewed.

Introduction

The demands of tractor industry customers have been changing greatly over time. Only a few decades ago, the focus was mainly in making powerful and strong enough vehicles for everyday use. Today, one of the key values in product development is to improve comfortability of the product. The engineers have to concentrate on providing better solutions to fulfill modern expectations and to survive strict competition between producers. To improve end user comfort, acoustical properties of the vehicle cabin are of major importance.

Acoustical waves are vibrations that propagate, for instance, in air, soil, water, and mechanical structures. Applications of computational acoustics exist in several fields of technology from medical measuring equipments to design of machinery. The sound can be modelled and simulated with numerical calculations of acoustic pressure fields. In more realistic models arising from real-life applications, coupled systems of several media, e.g., air and structure are needed. Further, acoustical phenomena often interact with other physical phenomena, such as, heat or electromagnetics. As acoustical problems are often considered in rather large and complex geometries, solving acoustic problem may demand a considerable amount of time and memory. This motivates the development of efficient simulation methods, that we have reported, e.g., in [2, 3, 4, 8, 14].

This study is concentrated on the numerical simulation of air-structure interaction problems. Earlier work in the field of noise reduction applications includes, to name a few, elevator, vehicle, and work machine cabins, airplanes as well as propagation of noise from engines or machines and environmental noise attenuation (see, e.g., [1, 5, 7, 9, 15, 18]). Closely related topic is also evaluation of sound propagation into the human head (see, e.g., [16]). Although the basic principles of these applications are the same, there is a wide variation, e.g., in modelling approaches including the geometry approximation as well as in simulation methods.

This paper focuses on presenting several promising prospectives on utilizing computational acoustics tools in order to improve the acoustical properties of the design. We consider utilizing advanced tools for mathematical acoustical analysis of tractor cabin. A natural motivation for computer simulations is to study and optimize devices without time-consuming and expensive experiments. Computer simulations also allows investigations in the places where normal measurement tools cannot archieve.

Computational modelling of tractor cabin

The computational model of the tractor cabin acoustics is formulated by coupling the sound propagation in the interior and the elastic vibrations of the cabin structure. These are governed by two partial differential equations. First, time-harmonic acoustic wave propagation of the air-filled interior, denoted by Ω_f, of the tractor cabin is described by Helmholtz equation

$$-\frac{\kappa^2}{\rho_f}p - \nabla \cdot \left(\frac{1}{\rho_f}\nabla p\right) = 0, \qquad \text{in } \Omega_f, \qquad (2)$$

where p is the sound pressure, $\kappa = 2\pi/\lambda$ is the wavenumber depending on the wavelength λ, and ρ_f is the density of the fluid. The wavelength λ is related to the frequency f and to the speed of sound c by the formula $f = c/\lambda$. Secondly, the wave propagation in elastic cabin structure, denoted by Ω_s, is represented by Navier equation

$$-\rho_s\omega^2\mathbf{u} - \nabla \cdot \sigma(\mathbf{u}) = \mathbf{0}, \qquad \text{in } \Omega_s, \qquad (3)$$

where $\mathbf{u}$ is the displacement vector in the structure, $\sigma(\mathbf{u})$ is the linearized stress tensor ω is the angular frequency related to the frequency f such that $\omega = 2\pi f$, and ρ_s is the density of the solid material.

The ceiling of the cabin is modelled by the conventional first order impedance boundary condition for acoustic waves

$$-i\kappa\beta p + \frac{\partial p}{\partial \mathbf{n}_f} = 0, \qquad \text{on } \Gamma_{fa}, \qquad (4)$$

with the imaginary unit $i = \sqrt{-1}$ and absorption coefficient β. When $\beta = 1$, this local operator approximates the waves propagating out of the domain without reflections and with $\beta = 0$, the equation corresponds to sound-hard boundary condition (Neumann condition).

The data exchange at the interface $\Gamma_i = \Omega_f \cap \Omega_s$ between fluid and structure domains is an important feature of the model. To get the continuity accross the interface, the key issue is that the normal components of displacements and forces need to be balanced such that

$$\rho_f\omega^2\mathbf{u}\cdot\mathbf{n}_s + \frac{\partial p}{\partial \mathbf{n}_f} = 0, \qquad \text{on } \Gamma_i, \qquad (5)$$

$$\sigma(\mathbf{u})\mathbf{n}_s - p\mathbf{n}_f = \mathbf{0}, \qquad \text{on } \Gamma_i, \qquad (6)$$

where $\mathbf{n}_s$ and $\mathbf{n}_f$ are the unit normal vectors pointing outward from the solid and the fluid domain, respectively. Models related to Eqs. (2)–(6) can be used in modelling various applications such as concert halls, loudspeakers, noise barriers, mobile phones, and acoustic materials. For existence and uniqueness of the solution for structural-acoustic problems we refer to [11].

Simulation software tools

Another significant subject, alongside with mathematical modelling and method development, is to test and tailor the existing simulation methods and software to get rid of the time-consuming handwork between the simulation steps from geometry modelling to optimization results.

A typical method to reduce the size of the computational problem in three-dimensional vibro-acoustical simulations is to use combinations of boundary and finite elements. There, finite elements are used to model elastic vibrations in the cabin structure, which is coupled to the boundary element method solution of the air volume acoustic pressure field inside the cabin. In [9], this was done to a tractor cabin by using Sysnoise software. In [5], acoustical optimization of construction machinery cabin is considered with combination of ModeFrontier, ANSYS, and Sysnoise software packages. There, ANSYS is used for the structural, Sysnoise for acoustical simulations, respectively and ModeFrontier is used as an optimization backend which communicates with other software.

Recently, the pure FEM approach is used with the ANSYS program in [19] for simulating the noise in a bus passenger compartments. In [17], the finite elements simulations were carried out with the direct inversion method in ANSYS. The results were compared to the solutions obtained by structural-acoustic problems by Krylov-based model order reduction techniques discretized with FEM. Passive noise control optimization was discussed in [12].

Numerical results

In this paper, we present one choice for using commercially available software tools. The basic setting is similar to the approach introduced in [9], but we have chosen to use a different software. The motivation for the choice of the software was to make the data transfer between CAD software and simulation and optimization tools easier. The intention is to make a step towards better automatization in digital product development including design for manufacturing processes and numerical optimization for improving the product properties.

The 3D geometry that we used in numerical experiments was based on a tractor CAD model by Valtra Inc. The original CAD model was simplified by removing small details from the original model with CATIA V5 CAD software. Further preprocessing was done in ANSYS DesignModeler 12.1.

Meshing and computing was done in ANSYS Mechanical 12.1. Triangular shell elements were used in the elastic structure of the cabin (see Fig. 1). The interior of the tractor cabin, presented in Fig. 2, was meshed using tetrahedral finite elements. (see, e.g., [6, 20]). The parts were connected together with bonded connections. The two-way fluid-structure interaction works so that the fluid nodes at the interface have translational degrees of freedom and are bonded to the struc-
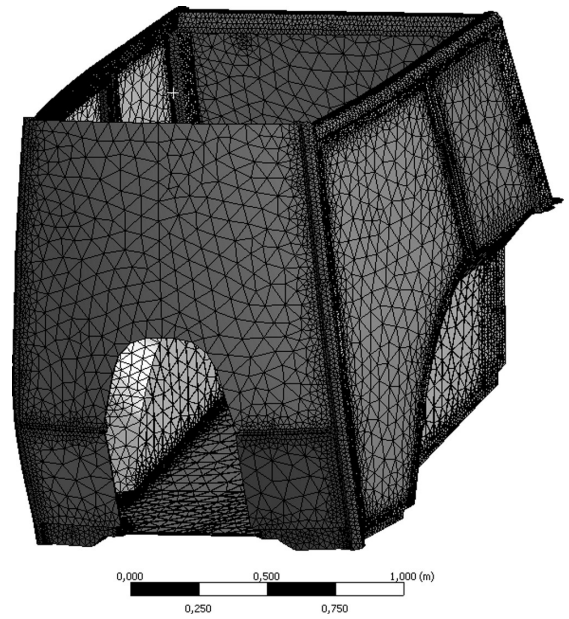
ture.

Figure 1: *Triangular shell element mesh that is used to model the elastic vibrations in the cabin structure.*
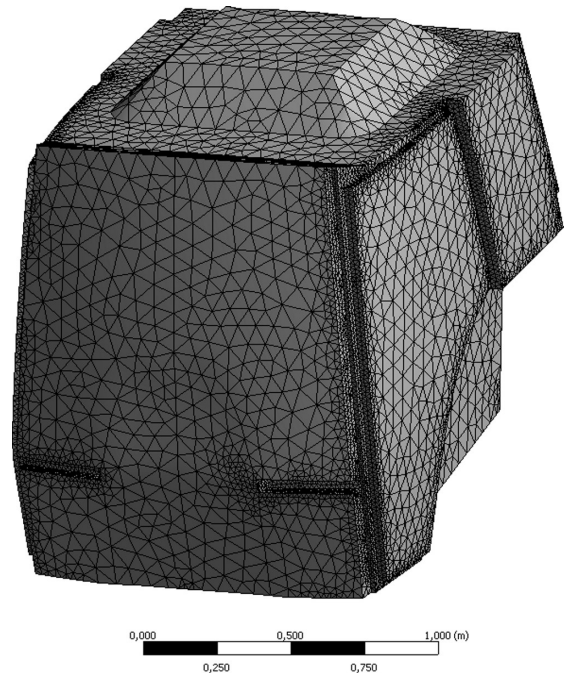

Figure 2: *Tetrahedral mesh used to model the acoustics in tractor cabin interior.*

The cabin structure was mostly steel but the windows are glass and the acoustic domain consists of air. The solid domain Ω_s was modelled to be composed of two parts, i.e., metallic skeleton and glass windows. The skeleton part was assumed to consist of steel with Young's Modulus $E = 2 \cdot 10^{11}$ Pa, Poisson's ratio $\nu = 0.3$, and density $\rho_s = 7850$ kgm^{-3}. The material parameters for the windows are $E = 6.5 \cdot 10^{10}$ Pa, $\nu = 0.161$, and $\rho_s = 2190$ kgm^{-3}. The structure is supported rigidly at the lower corners. The inside of the cabin Ω_f is modelled as air having sonic velocity $c = 343$ m/s and density $\rho = 1.2$ kgm^{-3} implying the wavelegth $\lambda = 3.18$ m. The ceiling is modelled as an absorbing boundary with the value of absorption coefficient $\beta = 0.04$.
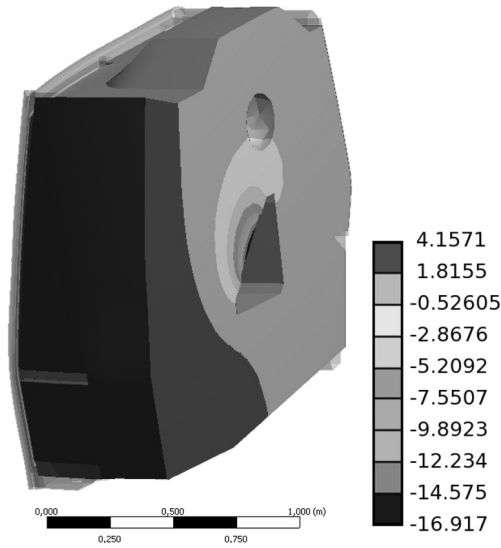
Figure 3: *Cross-section of the cabin shows the pressure field inside the cabin and the positions of the sound source and the driver's head.*

In this model a simple speaker, modelled as a cavity inside the acoustic domain, excites vibrations. The sound source is due to a forced displacement with amplitude 28 mm on the speaker membrane having area 70686 mm^2 (see Fig. 3). The angle between the membrane surface and the horizontal plane is $45°$. The other parts of the speaker are assumed to be rigid surfaces. An acoustically rigid sphere, presented in Fig. 3, acts as a driver's head. The values of the acoustic pressure field can be observed around the head. The head may cause scattering but it was considered negligible at the interesting frequencies.

Penalty method provided by ANSYS is used for transferring the data between the structure and the air-filled domain. The built-in sparce matrix direct solver is used for solving the linear system arising from the discretization of the equations. The simulation results are illustrated in Figs. 4–5. The deformations are described as displacement amplitudes in Fig. 4. The pressure field in the air-filled interior of the tractor cabin is presented in Fig. 5.
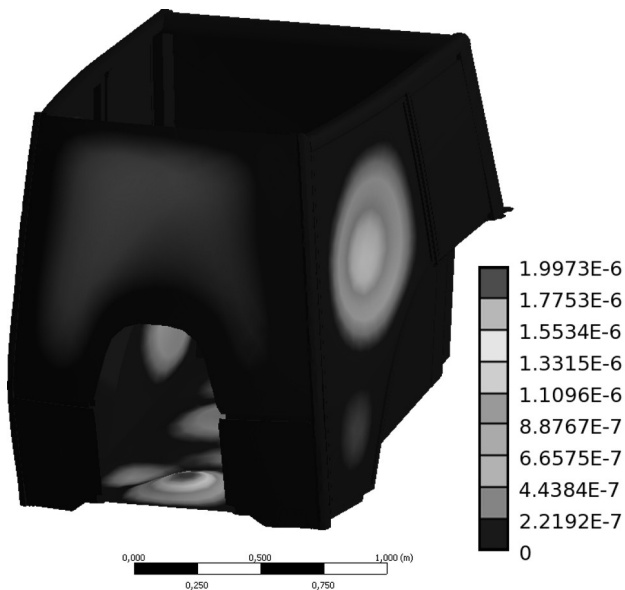

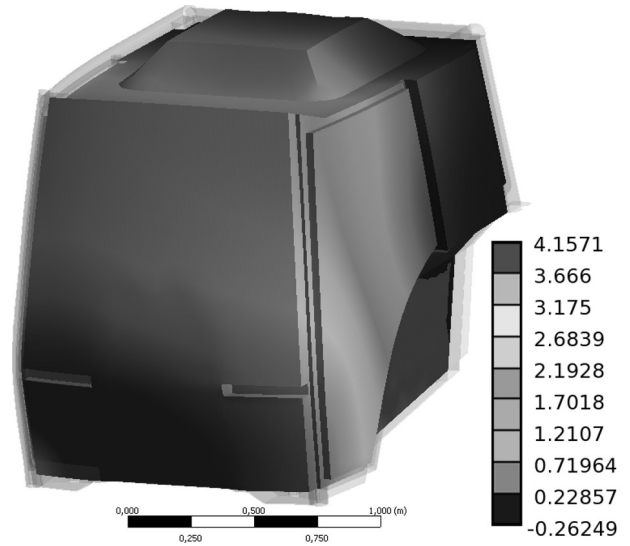**Figure 4:** *Displacement amplitude field in the cabin structure.*

Figure 5: *Pressure field in the air-filled interior of the tractor cabin.*

Conclusions and prospectives

We have defined mathematical models and combined the existing software components for tractor cabin acoustical design. Interaction between elastic materials and acoustic waves is observed and solved by computer simulations. Defining material parameters was found to be a challenging task in the modelling process, since the acoustical properties of some materials is not well-known.

When seeking the shape of the cabin that minimizes the distracting noise, the simulations based only on trial and error methodology may be inefficient and lead to inadequate results. If there are several design parameters which affect the final outcome of a simulation model, it is often very difficult, even for an expert, to find the optimal set of parameters just by intuition. Thus, the process will be further developed by employing numerical optimization tools for exploring the design candidate that minimizes the distracting noise inside the cabin. Proceeding this way, the design process – as well as research and development – can be improved and the development cycle shortened with the computer aided design.

At this stage, the CAD geometry of the cabin is defined for product process, not for numerical simulation purposes. Consequently, the pre-processing step for modifying the cabin geometry to a computational mesh has been time-consuming. Thus, we will further test and demonstrate the automatization of this step by, e.g., using 3D camera for deforming the mesh from the cabin geometry.

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