Simulation Environment for the Computation of Aeroacoustic Noise Generated by Rotating Systems

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Introduction

The cabin noise of modern ground vehicles is highly affected by flow related noise sources. This is especially the case, when the vehicle is not moving. Thereby, fan and outlet of the air-conditioning system are main acoustic sources and may reduce the comfort significantly. Rotating fans generate a highly turbulent flow field and can be identified as the main noise source in air conditioning units.
This contribution focuses on Computational Fluid Dynamics (CFD) simulations of rotating fans in air conditioning units using the Arbitrary Mesh Interface (AMI) which is implemented in OpenFOAM®. For the computation of the acoustic sources, highly accurate unsteady CFD simulation data is needed. Therefore, the transient simulations are carried out by using a DES (Detached Eddy Simulation) turbulence model to accurately resolve the complex flow field. In addition, CAA (Computational AeroAcoustics) simulations with the Finite-Element (FE) research software CFS++ (Coupled Field Simulation) are performed, which uses a Nitsche type mortaring to couple the acoustic field between rotating and stationary parts.

Aeroacoustic Formulation

The acoustic/viscous splitting technique for the prediction of flow induced sound was first introduced in [1], and afterwards many groups presented alternative and improved formulations for linear and non linear wave propagation [2, 3, 4, 5]. These formulations are all based on the idea, that the flow field quantities are split into compressible and incompressible parts.

We introduce a generic splitting of physical quantities to the Navier-Stokes equations. For this purpose we choose the following ansatz

$$p = \bar{p} + p^{\mathrm{ic}} + p^{\mathrm{c}} = \bar{p} + p^{\mathrm{ic}} + p^{\mathrm{a}} \quad (1)$$

$$\boldsymbol{v} = \bar{\boldsymbol{v}} + \boldsymbol{v}^{\mathrm{ic}} + \boldsymbol{v}^{\mathrm{c}} = \bar{\boldsymbol{v}} + \boldsymbol{v}^{\mathrm{ic}} + \boldsymbol{v}^{\mathrm{a}} \quad (2)$$

$$\rho = \bar{\rho} + \rho_1 + \rho^{\mathrm{a}}\,. \quad (3)$$

Thereby the field variables are split into mean ($\bar{p}$, $\bar{\boldsymbol{v}}$, $\bar{\rho}$) and fluctuating parts just like in the Linearized Euler Equations (LEE). In addition the fluctuating field variables are split into acoustic (p^{a}, $\boldsymbol{v}^{\mathrm{a}}$, ρ^{a}) and flow components (p^{ic}, $\boldsymbol{v}^{\mathrm{ic}}$). Finally, a density correction ρ_1 is build in according to (3). This choice is motivated by the following assumptions:

- The acoustic field is a fluctuating field.
- The acoustic field is irrotational, i.e. $\nabla \times \boldsymbol{v}^{\mathrm{a}} = 0$, and therefore may be expressed by the acoustic scalar potential ψ^{a} via

$$\boldsymbol{v}^{\mathrm{a}} = -\nabla \psi^{\mathrm{a}}\,. \quad (4)$$

- The acoustic field requires compressible media and an incompressible pressure fluctuation is not equivalent to an acoustic pressure fluctuation.

By doing so, we arrive for an incompressible flow at the following perturbed convective wave equation (PCWE) [6]

$$\frac{1}{c^2}\frac{D^2\psi^{\mathrm{a}}}{Dt^2} - \Delta\psi^{\mathrm{a}} = -\frac{1}{c^2}\frac{Dp^{\mathrm{ic}}}{Dt}\,; \quad \frac{D}{Dt} = \frac{\partial}{\partial t} + \bar{\boldsymbol{v}}\cdot\nabla\,. \quad (5)$$

Now, as shown in [7], we may apply an ALE (Arbitrary Langrangian Eulerian) formulation to couple rotating and stationary domains. Thereby, our operator D/Dt changes to

$$\frac{D}{Dt} \rightarrow \frac{\tilde{D}}{\tilde{D}t} = \frac{\partial}{\partial t} + (\bar{\boldsymbol{v}} - \boldsymbol{v}_{\mathrm{r}})\cdot\nabla \quad (6)$$

with $\boldsymbol{v}_{\mathrm{r}}$ the mechanical velocity of rotating parts. Finally, the acoustic pressure p^{a} computes by

$$p^{\mathrm{a}} = \bar{\rho}\frac{\tilde{D}\psi^{\mathrm{a}}}{Dt}\,. \quad (7)$$

Applications

To demonstrate the applicability of our overall computational scheme, we will present CFD and CAA computations of an axial vent used in rail HVAC systems, and a side channel blower as used in automotive air-conditioning systems.

Axial Fan

We investigate the aeroacoustic field of an axial fan in a duct as displayed in Fig. 1. The fan is embedded in a sound hard tube. The inlet and outlet openings on each side lead into a non reverberant chamber to emulate free field sound propagation. The rotational speed

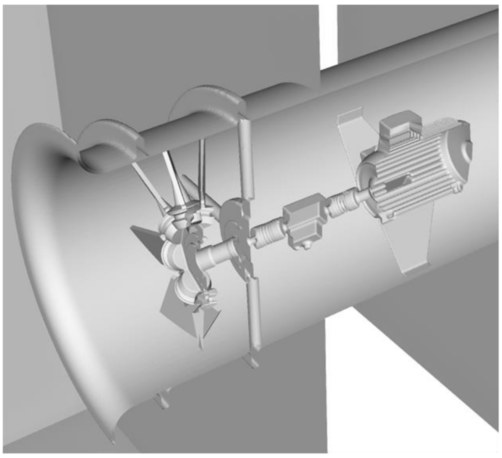

Figure 1: Computational setup.

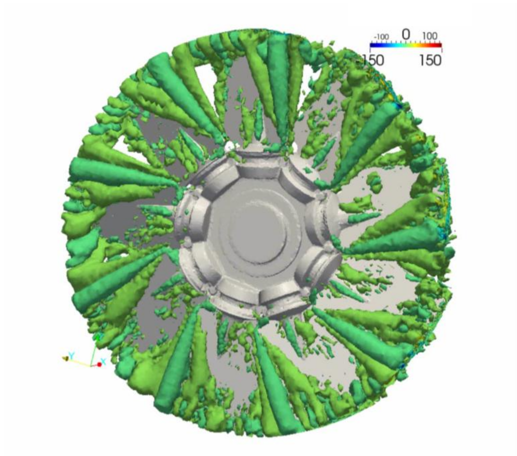

Figure 2: Visualiszation of the acoustic source terms at a characteristic time step.

of the fan is about 1500 rpm, which results in a maximum rotation velocity of 38.89 m/s. We use the OpenFOAM (Open Field Operation and Manipulation) CFD Toolbox version 2.3.0 for performing the flow computations. OpenFOAM is an Open Source library of C++ routines to solve the Navier-Stokes equations based on the finite volume method. Since version 2.1.0 the arbitrary mesh interface (AMI) was implemented based on the algorithm described in [8]. The AMI allows simulation across disconnected, but adjacent mesh domains, which are especially required for rotating geometries.

The flow solution is computed using an adapted version of the pimpleDyMFoam solver implemented in OpenFOAM, which can handle dynamic meshes with a time step size of $\Delta t = 10\,\mu$s. For the CFD computation a hex-dominant finite volume mesh consisting of 29.8 million cells was created by using the automatic mesh generator HEXPRESS$^{\text{TM}}$/Hybrid from Numeca. The transient simulation was carried out by using a detached-eddy simulation based on the Spalart-Allmaras turbulence model to accurately resolve the complex flow field [9]. The calculation was performed on the Vienna Scientific Cluster VSC2 with 256 Cores [10]. In Fig. 2 we display the computed acoustic source terms (substantial time derivative of the incompressibel acoustic pressure, see (6)).

In accordance to the flow computation, the rotating domain is embedded into a quiescent propagation region (see Fig. 3). Furthermore, we add at the inflow and outflow boundaries of the CFD domain two additional regions, on which we apply an advanced *Perfectly-Matched-Layer* technique to effectively approximate acoustic free field conditions [11]. Figure 4 displays the computed power spectral density of the acoustic pressure and compares it to the measured one. Thereby, we display the smoothed measured spectra obtained from the 30 s recodred pressure signals as well as the induvidual spectra by just using measured data of 0.1 s (in gray). The computed spectra based on our numerical simulation is computed out of a real time simulation of 0.06 s.

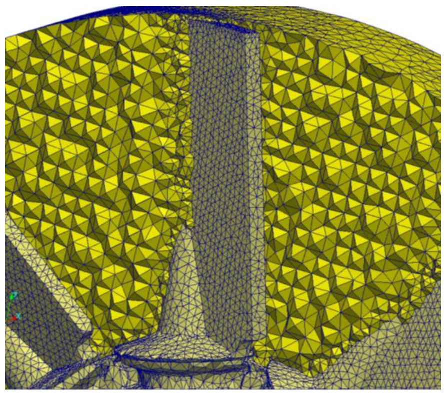

Figure 3: Detail of the computational CFD grid.

Side Channel Blower

The setup of investigation consists of a side channel blower as used in todays automotive air conditioning units [12]. Figure 5 displays the geometry with the stationary and rotating domains. Regarding the computational setup (see Fig. 5), we embed inside the quiescent domain (displayed in grey) a rotating subregion, marked in orange. The boundary of the rotating region is modeled through the AMI. The blower rotates with 1.860 rotations per minute giving a maximum velocity at the rotating interface of about 13 m/s, which corresponds to a Mach number of about 0.038. As the interior of the subregion is rotated around the z-axis, an air stream is generated owing towards the outlet with maximum velocities of about 35 m/s in the whole domain. Thereby, we can safely assume the assumption of incompressible flow to be valid which enables the utilization of the given hybrid approach. The flow solution is computed using an adapted version of the pimpleDyMFoam solver implemented in OpenFOAM, which can handle dynamic meshes with a time step size of $\Delta t = 10\,\mu$s. For the CFD computation a hex-dominant finite volume mesh consisting of 16.4 million cells was created with the automatic mesh generator HEXPRESS$^{\text{TM}}$ / Hybrid from Numeca. The transient simulation was performed, as in the previ-

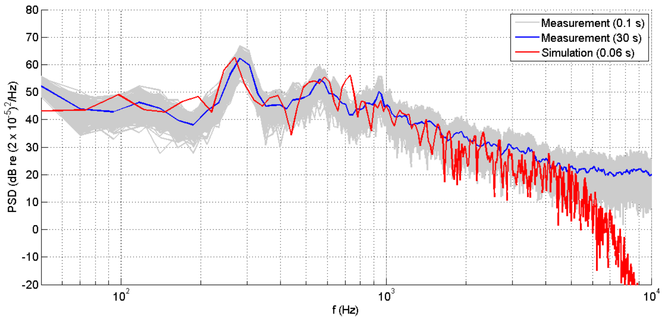

Figure 4: Power spectral density of the acoustic pressure at measurment poistion

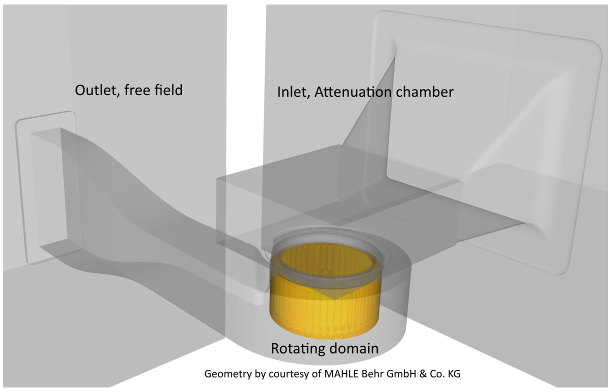

Figure 5: Geometry with rotating domain.

ous case, by using a detached-eddy simulation based on the Spalart-Allmaras turbulence model [9].

For peforming the acoustic calculations, we used the pre-processor ICEM for generating the computational grid. Thereby, we have chosen a maximum element size of $h_{\max} = 2$cm to accurately compute acoustic wave propagation up to a frequency of approximately 3kHz. The resulting computational grid thereby contains 2.3 million elements and 682.952 nodes. A close up of the computational grid is depicted in Fig. 6. It can be seen, that a tetrahedral mesh is utilized around the more complex geometries and a coarser, hexahedra-dominant mesh is defined in the remainder of the domain. Figure 7 dis-

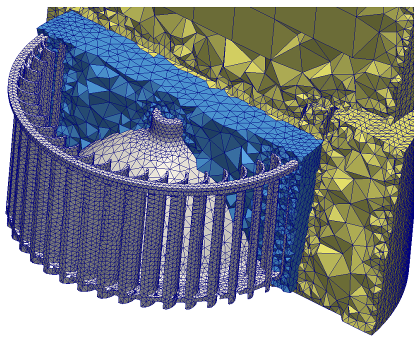

Figure 6: Slice through computational grid for acoustic computations with rotating (blue) and quiescent (yellow) regions.

plays the computed power spectral density of the acoustic pressure and compares it to the measured data.

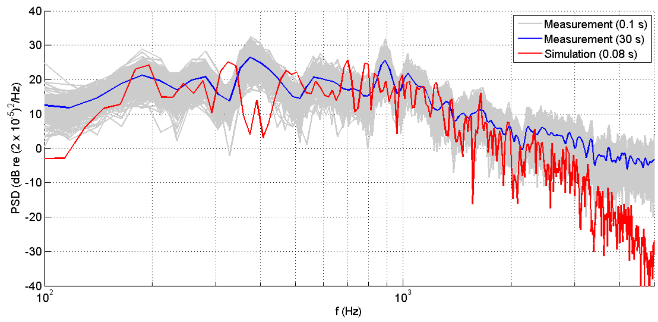

Figure 7: Power spectral density of the acoustic pressure at measurment poistion

Conclusion

A recently developed numerical scheme for computational aeroacoustics has been applied to calculate the noise generated by an axial fan as well as a side channel blower. Thereby, the flow is computed by a DES turbulence model and utilizing an arbitrary mesh interface between rotating and stationary domains. The acoustic field is modeled by a perturbation ansatz to separate flow and acoustic quantities, which results in a convective acoustic wave equation with the substantial derivative of the incompressible flow pressure as a source term. The equation is solved by an FE formulation with a Nitsche type mortaring coupling the acoustic field between the rotating and stationary domains.

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