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COUPLED CFD-CAA APPROACH FOR ROTATING SYSTEMS

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Abstract. We present a recently developed computational scheme for the numerical simulation of flow induced sound for rotating systems. Thereby, the flow is fully resolved in time by utilizing a DES (Detached Eddy Simulation) turbulance model and using an arbitrary mesh interface scheme for connecting rotating and stationary domains. The acoustic field is modeled by a perturbation ansatz resulting in a convective wave equation based on the acoustic scalar potential and the substational time derivative of the incompressible flow pressure as a source term. We use the Finite-Element (FE) method for solving the convective wave equation and apply a Nitsche type mortaring at the interface between rotating and stationary domains. The whole scheme is applied to the numerical computation of a side channel blower.

1 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, the fan-noise 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. Therefore, in addition to the aerodynamic efficiency of the fan, the acoustic signature of the fan is a main design criterion.

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 [1]. By introducing on the interface between moving and quiescent grid an appropriate flux term in combination with a penalization term, the method retains symmetry, consistency and stability of the algebraic system of equations. Furthermore, to precisely approximate the acoustic far field condition, we apply our recently developed PML (Perfectly Matched Layer) technique [2]. To demonstrate the applicability of our overall computational scheme, we will present CFD and CAA computations of a side channel blower, as used in automotive air-conditioning systems.

2 Computational Aeroacoustics

The acoustic/viscous splitting technique for the prediction of flow induced sound was first introduced in [3], and afterwards many groups presented alternative and improved formulations for linear and non linear wave propagation [4, 5, 6, 7]. 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

$$p = \bar{p} + p^{\mathrm{ic}} + p^{\mathrm{c}} = \bar{p} + p^{\mathrm{ic}} + p^{\mathrm{a}} \tag{1}$$
$$\boldsymbol{v} = \bar{\boldsymbol{v}} + \boldsymbol{v}^{\mathrm{ic}} + \boldsymbol{v}^{\mathrm{c}} = \bar{\boldsymbol{v}} + \boldsymbol{v}^{\mathrm{ic}} + \boldsymbol{v}^{\mathrm{a}} \tag{2}$$
$$\rho = \bar{\rho} + \rho_1 + \rho^{\mathrm{a}}\,. \tag{3}$$

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
$$\boldsymbol{v}^{\mathrm{a}} = -\nabla \psi^{\mathrm{a}}\,. \tag{4}$$
- 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 perturbation equations (for a detailed derivation of this perturbation equations we refer to [8])

$$\frac{\partial p^{\mathrm{a}}}{\partial t} + \overline{\boldsymbol{v}} \cdot \nabla p^{\mathrm{a}} + \rho_0 c^2 \nabla \cdot \boldsymbol{v}^{\mathrm{a}} = -\frac{\partial p^{\mathrm{ic}}}{\partial t} - \overline{\boldsymbol{v}} \cdot \nabla p^{\mathrm{ic}} \tag{5}$$

$$\rho_0 \frac{\partial \boldsymbol{v}^{\mathrm{a}}}{\partial t} + \rho_0 \nabla \big(\overline{\boldsymbol{v}} \cdot \boldsymbol{v}^{\mathrm{a}}\big) + \nabla p^{\mathrm{a}} = 0 \tag{6}$$

with the speed of sound c and mean density ρ_0. This system of partial differential equations corresponds to [5]. The source term is the substantial derivative of the incompressible flow pressure p^{ic}.

Using the acoustic scalar potential ψ^{a}, we may rewrite (6) by

$$\nabla \left(\rho_0 \frac{\partial \psi}{\partial t} + \rho_0 \overline{\boldsymbol{v}} \cdot \nabla \psi - p_{\mathrm{a}} \right) = 0\,, \tag{7}$$

and arrive at

$$p^{\mathrm{a}} = \rho_0 \frac{\partial \psi^{\mathrm{a}}}{\partial t} + \rho_0 \overline{\boldsymbol{v}} \cdot \nabla \psi^{\mathrm{a}}\,. \tag{8}$$

Now, as shown in [9], we replace in the convective terms the material (Eulerian) velocity $\overline{\boldsymbol{v}}$ by the convective velocity $\overline{\boldsymbol{v}} - \boldsymbol{v}_{\mathrm{r}}$, where $\boldsymbol{v}_{\mathrm{r}}$ is the mechanical velocity of rotating parts. By doing so, we arrive at an ALE (Arbitrary Langrangian Eulerian) description for the acoustic pressure

$$p^{\mathrm{a}} = \rho_0 \frac{\partial \psi^{\mathrm{a}}}{\partial t} + \rho_0 \big(\overline{\boldsymbol{v}} - \boldsymbol{v}_{\mathrm{r}}\big) \cdot \nabla \psi^{\mathrm{a}} = \rho_0 \frac{D\psi^{\mathrm{a}}}{Dt}\,; \quad \frac{D}{Dt} = \frac{\partial}{\partial t} + \big(\overline{\boldsymbol{v}} - \boldsymbol{v}_{\mathrm{r}}\big) \cdot \nabla\,. \tag{9}$$

Furthermore, we transform (5) to the ALE framework

$$\frac{\partial p^{\mathrm{a}}}{\partial t} + \big(\overline{\boldsymbol{v}} - \boldsymbol{v}_{\mathrm{r}}\big) \cdot \nabla p^{\mathrm{a}} + \rho_0 c^2 \nabla \cdot \boldsymbol{v}^{\mathrm{a}} = -\frac{\partial p^{\mathrm{ic}}}{\partial t} - \big(\overline{\boldsymbol{v}} - \boldsymbol{v}_{\mathrm{r}}\big) \cdot \nabla p^{\mathrm{ic}}\,. \tag{10}$$

Now, we substitute (9) into (10) and arrive at

$$\frac{1}{c^2}\,\frac{D^2 \psi^{\mathrm{a}}}{Dt^2} - \Delta \psi^{\mathrm{a}} = -\frac{1}{c^2}\,\frac{Dp^{\mathrm{ic}}}{Dt}\,. \tag{11}$$

This convective wave equation fully describes acoustic sources generated by incompressible flow structures and its wave propagation through flowing media. In addition, instead of the original unknowns p^{a} and $\boldsymbol{v}^{\mathrm{a}}$ we have know just the scalar unknown ψ^{a}. Furthermore, it allows to perform computations on stationary and rotating domains and results in the acoustic scalar potential, from which the acoustic pressure p^{a} is computed via (9).

3 Application

The setup of investigation consists of a side channel blower as used in todays automotive air conditioning units [10]. Figure 1 displays the geometry with the stationary and rotating domains.

The used work-flow is depicted in Fig. 2, which illustrates the forward coupling of the flow field to the acoustic field.

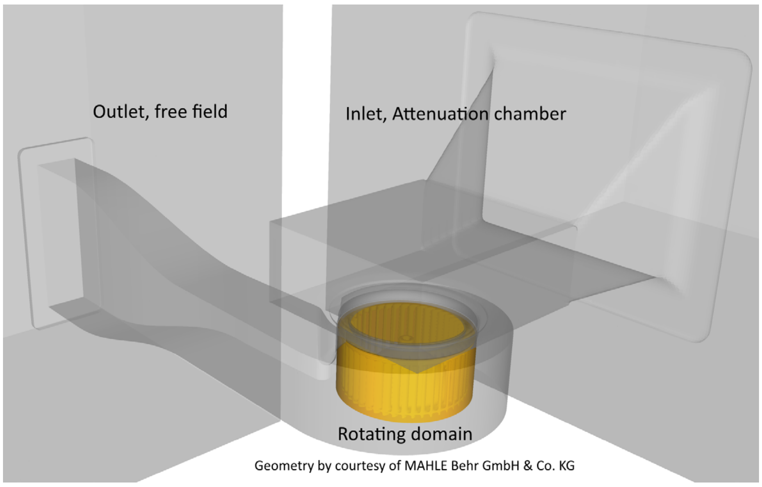


Figure 1: Geometry with rotating domain.

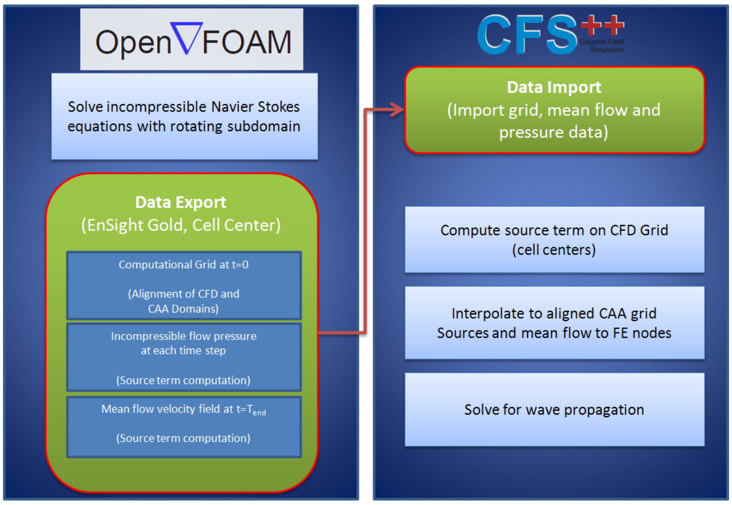


Figure 2: Work-flow for hybrid aeroacoustic computations in OpenFOAM and CFS++.

As discussed in the previous section, we compute the aeroacoustic sources based on the flow field and project them to the acoustic domain using a conservative mapping algorithm.

3.1 CFD

In this contribution the OpenFOAM (Open Field Operation and Manipulation) CFD Toolbox version 2.3.0 is used. 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 [11]. The AMI allows simulation across disconnected, but adjacent mesh domains, which are especially required for rotating geometries.

Regarding the computational setup (see Fig. 1), 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 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$^{\mathrm{TM}}$ / 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 [12]. The calculation was performed on the Vienna Scientific Cluster VSC2 with 144 Cores [13]. Figure 3 illustrates the highly unsteady flow field around the blower.

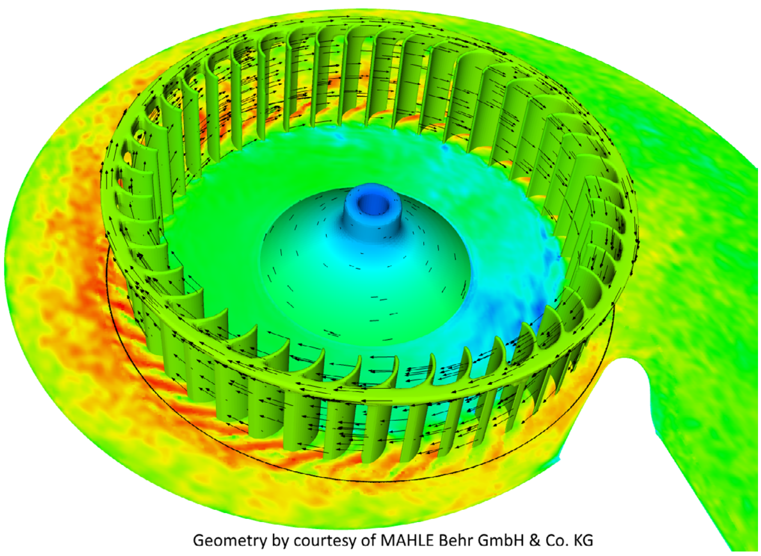
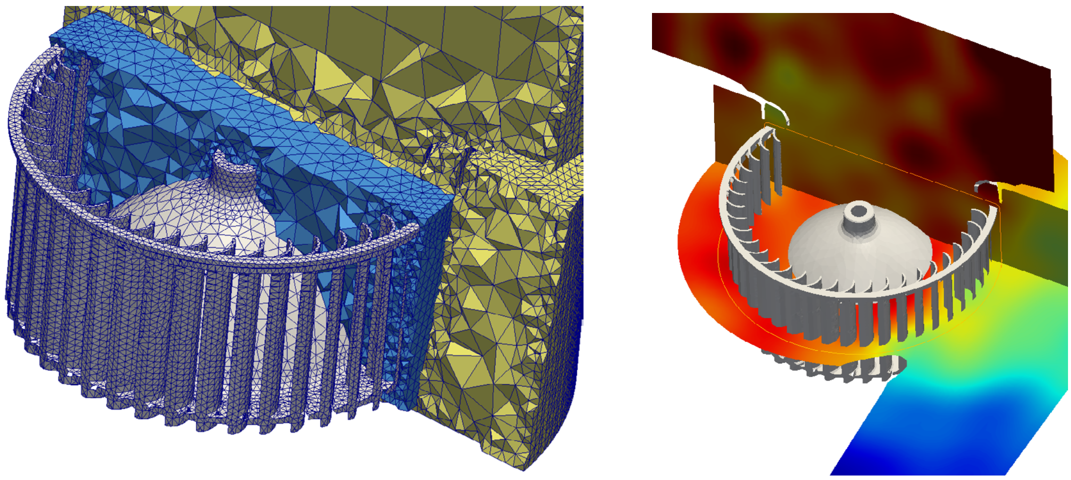


Figure 3: Cut at the z-plane colored by velocity, the black line represents the AMI.

3.2 CAA

In accordance to the flow computation, the rotating domain is embedded into a quiescent propagation region. 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 [2].

A close up of the computational grid is depicted in Fig. 4a. 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. To create the grid, the Preprocessor ICEM is utilized and the maximum element size ($h_{\max} = 2$cm) is chosen 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. To solve the resulting system of equations in each time step, a parallelized GMRES (Generalized Minimal Residual Method) implementation is utilized which converges to a minimum residual of 10^{-10} using an average of 108 iterations per time step. Utilizing a direct solution procedure is not necessarily beneficial in the context of rotating systems as the system matrix is altered in each time step due to the update of the rotating interface.

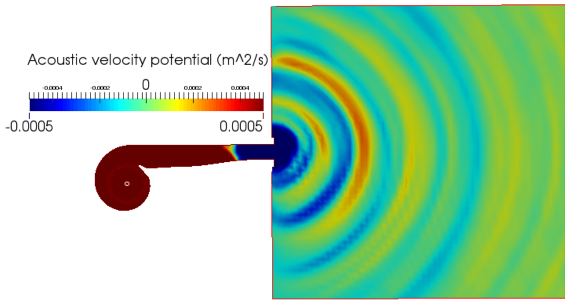


(a) Slice through computational grid for acoustic computations with rotating (blue) and quiescent (yellow) regions.

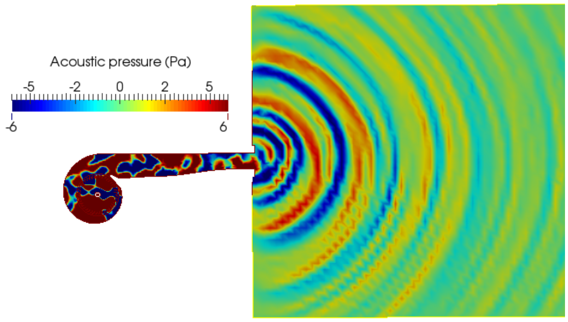
(b) Contours of acoustic velocity potential at the interface between computational regions. No numerical disturbances at the interface are visible.

Figure 4: Computational CAA grid and contours of acoustic velocity potential.

For a characteristic time step, we display in Fig. 4b the acoustic velocity potential at the interface. We can observe no visible numerical disturbances which demonstrates the correct physical computation of the acoustic field. Finally, Fig. 5 provides an impression of the acoustic wave propagation towards the exterior domain.



(a) Contours of velocity potential.



(b) Contours of acoustic pressure.

Figure 5: Acoustic waves in outlet domain.

4 Conclusion

A recently developed numerical scheme for computational aeroacoustics has been applied to calculate the noise generated by a side channel blower as used in automotive air-conditioning systems. 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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