Acoustic and Aeroacoustic Inverstigation of a Generic Rotor Model

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Introduction

The simulation of flow induced sound for low Mach number applications, it is in many cases possible to neglect compressible effects on the flow field. Thereby, it is possible to compute the aerodynamic field by the incompressible Navier Stokes equations and use an aeroacoustic analogy to obtain the compressible, acoustic field in a subsequent computation. Approaches which rely on this basic idea are referred to as hybrid schemes. They are valid when no sound induced effects occur in the flow simulation. When it comes to aeroacoustic fields induced by moving structures as they occur in rotors, fans and turbines, the application of hybrid computational schemes is much more challenging. Nevertheless, due to several advantages including lower computational complexity and increased robustness compared to the numerical solution of the compressible Navier stokes equations, it is still desirable.

In contrast to the commonly utilized Ffowcs-Williams Hawkings (FWH) aeroacoustic analogy, we will give a hybrid scheme for a volume discretization method, coupling a finite volume flow solver (OpenFOAM) with a finite element acoustic solver (CFS++). Thereby, it is possible to include all refraction effects on the wave propagation due to moving and quiescent structures which is not possible with the standard FWH model. For an investigation of the solution procedure in rotating domains we choose a two dimensional setup, related to the investigations given in [1]. As depicted in Fig. 1, the setup contains two round cylinders rotating around a shaft in the middle of the domain. The computational setup is decomposed in two domains: a quiescent and a rotating domain, which are coupled by a sliding mesh interface. Due to vortex shedding at the moving structures, acoustic waves are generated which propagate through the otherwise quiescent domain. Thereby, we can include characteristics like the Doppler effect in the computation and are able to verify the sliding mesh approach for fan noise in hybrid computational schemes.

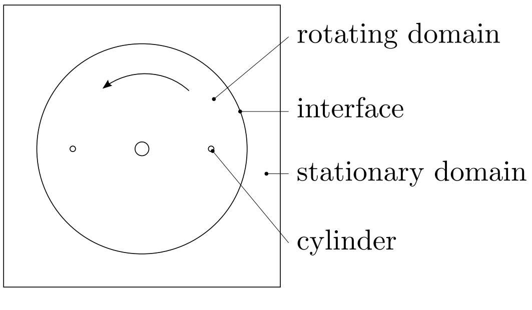

Figure 1: Sketch of the rotating geometry in a square stationary domain.

Acoustic Analogy

An approach to compute the acoustics out of existing flow results are the Acoustic Perturbation Aquations (APE) [2] which separates the flow quantities pressure and velocity in a mean value $(p_0, \boldsymbol{u}_0)$, an incompressible fluctuating part $(p_\mathrm{ic}, \boldsymbol{u}_\mathrm{ic})$ and an acoustic part $(p_\mathrm{a}, \boldsymbol{u}_\mathrm{a})$. For incompressible flow, the following reform of APE can be used [3]:

$$\frac{\partial p_\mathrm{a}}{\partial t} + \boldsymbol{u}_0 \cdot \nabla p_\mathrm{a} + \rho_0 c^2 \nabla \cdot \boldsymbol{u}_\mathrm{a} = -\frac{\partial p_\mathrm{ic}}{\partial t} - \boldsymbol{u}_0 \cdot \nabla p_\mathrm{ic} \quad (1)$$

$$\rho_0 \frac{\partial \boldsymbol{u}_\mathrm{a}}{\partial t} + \rho_0 \nabla \left(\boldsymbol{u}_0 \cdot \boldsymbol{u}_\mathrm{a} \right) + \nabla p_\mathrm{a} = 0 \,, \quad (2)$$

in which ρ_0 denotes the density and c the speed of sound. This set of equations can already be solved , for example with a finite element method (FEM), but in this form the source term on the right hand side contains the time derivative of the incompressible pressure, which is very sensitive to numerically induced pressure fluctuations in the aerodynamic solution. Equation (2) can be rewritten with the acoustic scalar potential ψ as [3]

$$\nabla \left(\rho_0 \frac{\partial \psi}{\partial t} + \rho_0 \boldsymbol{u}_0 \cdot \nabla \psi - p_\mathrm{a} \right) = 0 \text{ and } \boldsymbol{u}_\mathrm{a} = -\nabla \psi \,. \quad (3)$$

The acoustic pressure can be obtained from ψ by

$$p_\mathrm{a} = \rho_0 \frac{\partial \psi}{\partial t} + \rho_0 \boldsymbol{u}_0 \cdot \nabla \psi \,. \quad (4)$$

If we use (4) to substitute p_a in (1) and use the substantial derivative

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \boldsymbol{u}_0 \cdot \nabla \,, \quad (5)$$

we achieve at

$$\frac{1}{c^2} \frac{D^2 \psi}{Dt^2} - \Delta \psi = -\frac{1}{\rho_0 c^2} \frac{D p_\mathrm{ic}}{Dt} \,. \quad (6)$$

By using (4) we obtain

$$\frac{1}{\rho_0 c^2} \frac{D p_\mathrm{a}}{Dt} - \Delta \psi = -\frac{1}{\rho_0 c^2} \frac{D p_\mathrm{ic}}{Dt} \,. \quad (7)$$

Taking the substantial derivative of (7) yields

$$\frac{1}{c^2} \frac{D^2 p_\mathrm{a}}{Dt^2} - \Delta p_\mathrm{a} = -\frac{1}{c^2} \frac{D^2 p_\mathrm{ic}}{Dt^2} \,. \quad (8)$$

Recombination of acoustic and incompressible pressure to a total fluctuating pressure $p' = p_\mathrm{ic} + p_\mathrm{a}$, (8) can be written as

$$\frac{1}{c^2} \frac{D^2 p'}{Dt^2} - \Delta p' = -\Delta p_\mathrm{ic} \,. \quad (9)$$

The left hand side of (9) describes the wave propagation including convective effects, whereas the right hand side corresponds to the source term of Lighthill's aeroacoustic analogy, rewritten for incompressible flows. Thereby, the separation of flow and acoustic pressures is no longer maintained but we obtain a spatial derivative as acoustic source rather than a time derivative. As flow pressures fields, obtained from the numerical solution of the incompressible Navier Stokes equations tend to be sensitive against numerical errors with respect to the time derivative, this formulation can be utilized to circumvent the problem.

To solve (9) with the rotating and stationary domains are to be connected. In this case a sliding mesh interface with a Nitsche type mortaring was used [4].

Two-dimensional Application

The two-dimensional setup consists of a rotating domain that includes two cylinders aligned with a shaft in the center of rotation. The diameter of the cylinders is $d = 2\,\mathrm{mm}$, the diameter of the shaft is $25\,\mathrm{mm}$, the radius to the axis is $r = 95\,\mathrm{mm}$ and the rotation velocity of the cylinder is $\boldsymbol{u}_\mathrm{r} = 20\,\mathrm{m/s}$. Hence the Reynolds number results in 2666 and the flow is considered laminar. The surrounding stationary domain contains quiescent fluid. For the acoustic simulation, the outside was surrounded by a perfectly matched layer (PML) to prevent acoustic reflections at the outer domain boundary. The sound producing mechanisms in this setup are the vortex shedding at the cylinders as well as the interaction of the cylinders with the wake of the former one.

The fluctuating pressure is shown in Fig. 2. It can be seen that in the center high pressure fluctuations occur containing aerodynamic components. Outside the source region influence of the flow decreases and the fluctuating pressure approximates the acoustic pressure. No unphysical reflections or refractions can be seen at the mesh interface. In Fig. 3, the sound pressure level (SPL) for a monitoring point, $6 \cdot r$ away from the center is shown. The peak at $67\,\mathrm{Hz}$ corresponds exactly to the cylinder passing frequency. At $1.8\,\mathrm{kHz}$, a rise in the amplitude can be seen, that represents the vortex shedding. Compared to a single cylinder in a cross flow the shedding frequency is off by $200\,\mathrm{Hz}$ due to the interaction of the cylinders with the wake.

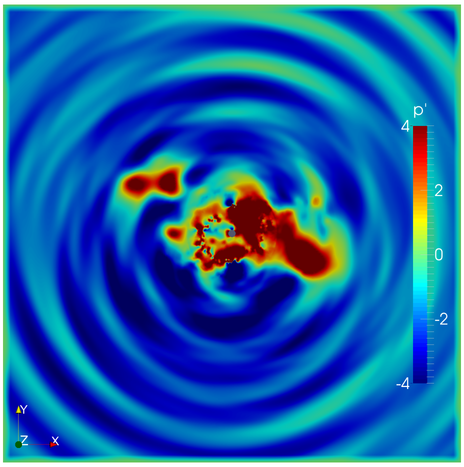

Figure 2: Wave propagation computed with the source term Δp_ic.

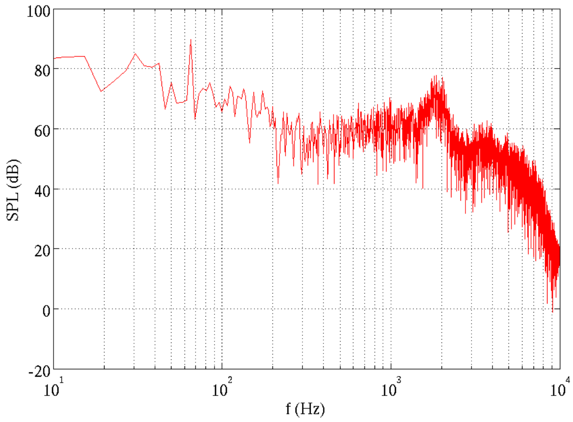

Figure 3: SPL computed with the source term Δp_ic.

Conclusion

It was shown that it is possible to use the second spatial derivative of the incompressible pressure as a source term for hybrid acoustic schemes. This formulation has an improvement of robustness against unphysical pressure fluctuations in the aerodynamic computation. A two-dimensional computation with rotation and a sliding mesh interface shows good results. The rotating geometry is optimized to cover the requirements as a benchmark in terms of applicability and computational effort.

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