Main Challenges in the Application of Hybrid Aeroacoustic Methods to Rotating Systems

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Introduction

Hybrid aeroacoustic methods are a widely used tool to predict the sound of low Mach number flows. These methods are suitable for fan design, as most fans are operated at low Mach numbers and the flow can be considered incompressible. Although these methods yield several advantages, they include main challenges in the applictaion. Hybrid aeroacoustic methods are split in three steps, the Computational Fluid Dynamics (CFD), the computation of acoustic source terms and the Computational Aeroacoustics (CAA), all of which yield their individual challenges. Furthermore, rotating systems contain nonmatching interfaces between rotating and stationary domains that need special treatment.

The application to real geometries is often complex and computationally costly because of the large number of unknowns. To get the correct parameters for numeric simulations, several simulations with different parameters should be done, but this is very demanding. To give an overview of some important parameters and their influence on the acoustic result, we compare acoustic simulations with measurements. In the acoustic simulations, we are investe the influence of the source term interpolation, the truncation of source terms in space and time and the treatment of under resolved acoustic source terms and provide a best practice guide.

The investigated rotor was already presented in [6] and the hybrid aeroacoustic method was also applied successfully to other fans, see [5]. The measurement setup of the rotor is shown in Fig. 1. The rotor consists of 9 flat

Figure 1: Setup of the measurement

blades and is installed in a wall mounted duct. The diameter of the rotor is 0.5 m and the rotational velocity 1500 rpm, which leads to a tip blade velocity of 38.89 m/s (which corresponds to a Mach number of $M = 0.11$ and therefore, the flow can be considered incompressible). The volume flow was 1.3 m^3/s and the measurement time in the experiment 30 s.

Simulation

The hybrid aeroacoustic method consists of three different steps. The first is the computation of aerodynamic quantities from the incompressible Navier-Stokes equations

$$\nabla \cdot \mathbf{u}^{\mathrm{ic}} = 0\,, \tag{1}$$

$$\rho \frac{\partial \mathbf{u}^{\mathrm{ic}}}{\partial t} + \rho(\mathbf{u}^{\mathrm{ic}} \cdot \nabla)\mathbf{u}^{\mathrm{ic}} = -\nabla p^{\mathrm{ic}} + \nabla \cdot [\boldsymbol{\tau}] + \mathbf{f}\,, \tag{2}$$

with the incompressible unknowns velocity $\mathbf{u}^{ic}$ and pressure p^{ic}, the constant density ρ, the time t, the viscous stress tensor $[\boldsymbol{\tau}]$ and a volume force $\mathbf{f}$. The second step is to compute acoustic source terms according to an acoustic analogy. If the mesh contains rotating domains (like a fan does), it is necessary to take the movement into account by using an Arbitrary Lagrangian Eulerian framework [2]. In the formulation of the Perturbed Convective Wave Equation (PCWE) [4], the source term computes as the substantial derivative of the pressure

$$\frac{\mathrm{D}p^{\mathrm{ic}}}{\mathrm{D}t} = \left(\frac{\partial}{\partial t} + (\bar{\mathbf{u}} - \mathbf{u}_{\mathrm{r}}) \cdot \nabla\right) p^{\mathrm{ic}}\,, \tag{3}$$

where $\bar{\mathbf{u}}$ describes the mean velocity and $\mathbf{u}_{\mathrm{r}}$ accounts for the rotational velocity of the rotor. In the third step this source term is used as the right hand side of the PCWE

$$\frac{1}{c_0^2}\frac{\mathrm{D}^2\varphi^{\mathrm{a}}}{\mathrm{D}t^2} - \nabla \cdot \nabla\varphi^{\mathrm{a}} = -\frac{1}{\rho c_0^2}\frac{\mathrm{D}p^{\mathrm{ic}}}{\mathrm{D}t}\,, \tag{4}$$

which is a convective wave equation with the acoustic potential φ^a as the unknown and c_0 describes the speed of sound. To obtain the acoustic pressure from the result of the propagation simulation one has to compute the substantial derivative of the scalar acoustic potential

$$p^a = \rho \frac{\mathrm{D}}{\mathrm{D}t}\varphi^a\,. \tag{5}$$

To solve the Navier-Stokes equations, we used the Finite Volume code OpenFOAM. The computational domain, shown in Fig. 2, with an inflow in the left chamber of the same size as the measurement facility, the rotor in the middle and an outflow from the right chamber. The

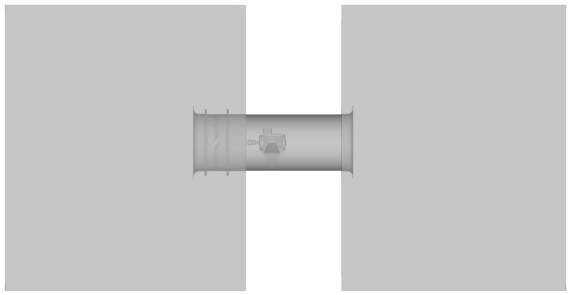

Figure 2: Computational domain of the flow simulation

mesh consists of 29.8 M cells and to resolve the turbulent structures, a Detached Eddy Simulation was used. To reach a steady state in the simulation, not just for the flow quantities from eq. (1) and (2) but also for the acoustic source term in eq. (4), 6.825 revolutions were computed with a time step size of $\Delta t = 10\,\mu$s and 1.5 revolutions were used for the output of the flow quantities.

To compute the acoustic source terms and solve the PCWE, we used our Finite-Element (FE) based multiphysics research code CFS++ [1]. The computational domain is shown in Fig. 3. The mesh consists of 1.92 M

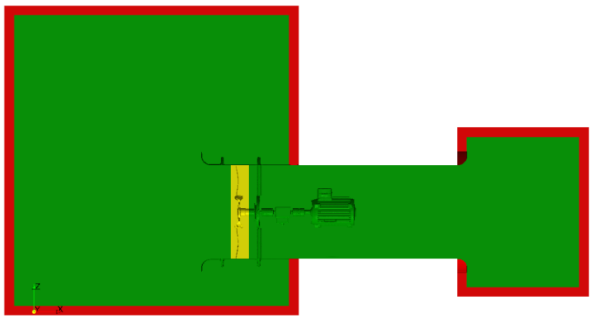

Figure 3: Computational domain of the acoustic simulation

nodes, and a Perfectly Matched Layer (red area) was used to account for the free radiation. All other walls were assumed to be sound hard. The yellow area is the rotating domain and the green domains are stationary. The used time step size was $\Delta t = 20\,\mu$s to account for a resolution of 10 time steps up to a frequency of 5 kHz. The acoustic result was evaluated 1 m in front of the rotor.

Figure 4 shows a comparison of the computed acoustic result the measurements. The black line describes the measurement averaged signal for the whole measurement time. The orange line describes the simulation result and the grey lines is the measurement signal cut into signal lengths equivalent to the simulation. The agreement of simulation and measurement can be seen in the blade passing frequency of 300 Hz and the broad band noise.

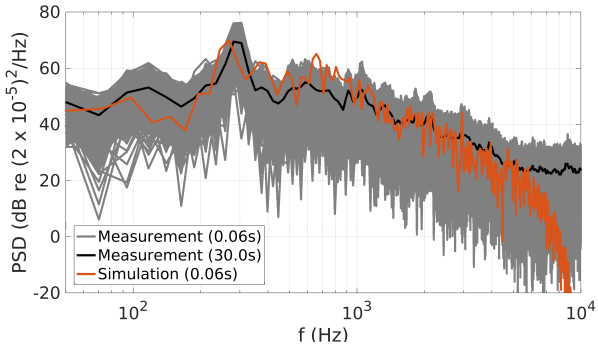

Figure 4: Microphone result 1 m in front of the rotor

The not resolved frequencies above 5 kHz are well filtered. This result was obtained by a specific set of parameters for the time discretization scheme, which will be altered and discussed in the following.

Source term interpolation

Due to the disparity of scales between CFD and CAA, the acoustic mesh can be much coarser. The reduction in the number of unknowns mentioned before lead to a strong reduction in computational time from weeks to days as well as a reduction in storage use from terabyte to several gigabyte. Nevertheless, the transfer of data from the CFD mesh to the CAA mesh is quite challenging. Hüppe [5] showed the importance of an cut-volume-cell approach. Figure 5 shows the interpolated source term of two different interpolation algorithms. The left one is a standard conservative interpolation of nodal results on the acoustic mesh. The right one is the result of the cut-volume-cell interpolation, where the meshes are first intersected and then interpolated. Although both

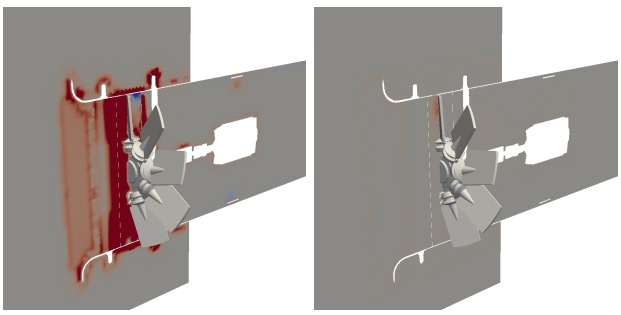

Figure 5: Acoustic source terms on the acoustic mesh with a mesh size dependent interpolation algorithm (left) and a mesh size independent algorithm (right)

interpolation algorithms are conservative, the standard interpolation is dependent on mesh size and especially at stages of mesh refinement unphysical source terms occur. The cut-volume-cell interpolation is mesh size independent and the source terms occur just at the blades, where they are expected. The acoustic results computed with such unphysical source terms lead to large errors. The standard interpolation should be avoided or - if no mesh independent interpolation algorithm is available - only used for two meshes with a constant cell size ratio.

Source term blending

Another challenge in the simulation of acoustics is the boundary conditions in the CFD and CAA but also in the computation of the source terms. The boundary conditions in the CFD are often just pressure or velocity conditions and in CAA either sound hard walls or fully absorbing boundaries (like the PML). In acoustics, the finite computational domain leads to a truncation of the acoustic source terms which can alter the ideal acoustic solution. But sometimes the truncation may be desired to blend out unphysical source terms that result just from numerics, for example in regions in the farfield where no acoustic sources should be, or at interfaces inside the computational domain.

Another type of blending is blending in time, which occurs for every source term with a start value different from zero. The finite time of the source terms can be seen as a function in time with a Heavyside step function multiplied to it. This jump at the beginning of the signal may cause unphysical results.

Blending in time

Figure 6 shows two blending functions used for the acoustic simulation. The green function corresponds to a step function (no blending) and the blue one to a smooth blending function.

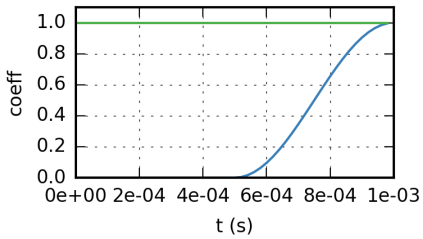

Figure 6: Different functions of blendings in time

The acoustic results at the same microphone position are shown in Fig. 7. The orange curve is the result from the original simulation, which used the blue bending function (see Fig. 6). Besides small differences in the high frequencies, the results are almost the same. This behavior is specific for the free radiation setup that exists in this case. The unphysical disturbances at the beginning of the simulation are radiated in the PML and then absorbed, so that the unphysical beginning of the signal can be observed just for a short time. One has to be careful, if the setup is not dominated by free radiation. When many reflections occur, as in ducts or pipes, the reflected acoustic signal from the beginning can corrupt the acoustic result even after a long time.

Blending in space

The blending in space is more challenging. A smooth blending function has to be chosen to suppress unphysical source terms in the inlet region where the flow is mostly uniform and no sound sources should occur. The

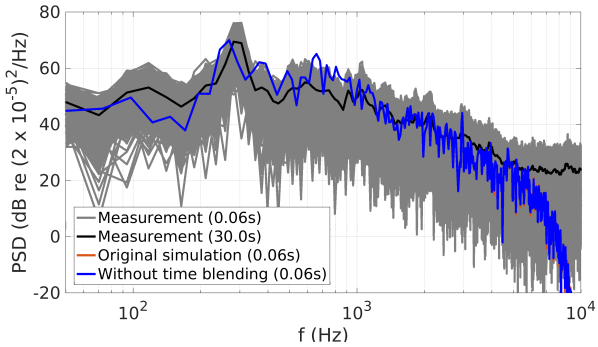

Figure 7: Microphone result for different blendings in time

blending function used in the original simulation is shown in Fig. 8 in blue. The vertical lines show the interfaces between the rotating and the stationary domains. An alternative, more aggressive, approach would be to even blend out the interfaces, where often numerical errors occur. The alternative blending function is shown in green (see Fig. 8).

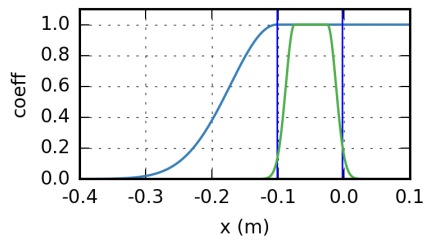

Figure 8: Different functions of blendings in space

The result of the more aggressive blending compared to the original simulation with the slower transition in the blending is shown in Fig. 9. The more aggressive blend-

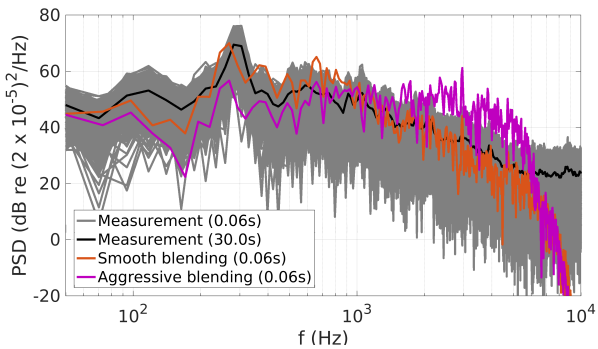

Figure 9: Microphone result for different blendings in x-direction

ing (shown in magenta) is very close to the rotor and reduces the low frequencies including the blade passing frequency, but exaggerates the broad band noise over 1 kHz. So to choose the blending function is a tradeoff between the suppression of unphysical source terms and the influence on the physical source terms.

Treatment of unresolved frequencies

The time step size limits the frequency resolution, so not resolved frequencies should be filtered to avoid aliasing. This can be done by a filtering of the source terms, or by the usage of a time stepping scheme like the Hilbert-Hughes-Taylor method [3]. This so called α-method is a Newmark method, which is unconditionally stable and of second order accuracy for

$$\alpha \in [-1/3, 0] \tag{6}$$

and the original Newmark parameters of

$$\gamma = (1 - 2\alpha)/2\,, \tag{7}$$

$$\beta = (1 - \alpha)^2/4\,. \tag{8}$$

Lower values of α increase the dissipation for not resolved frequencies.

In Fig. 10, the original simulation with $\alpha = -0.20$ is compared to a simulation with a value of $\alpha = -0.05$ in dark green and one with $\alpha = 0.00$ in bright green. It

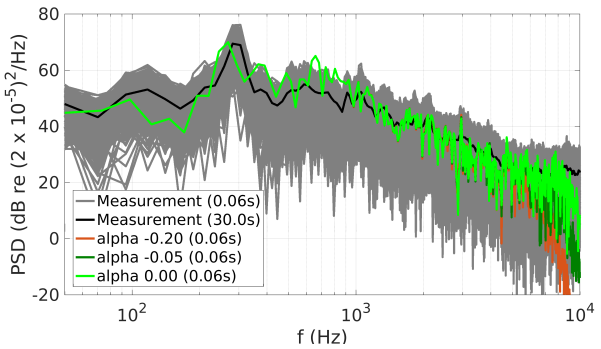

Figure 10: Microphone result for different time step α values

can be seen that in the low frequencies more or less no differences occur. At a frequency of $5\,\mathrm{kHz} = \frac{1}{10 \cdot \Delta t}$ (in other words every wave is at least resolved with ten time steps per period) the acoustic result gets filtered. With smaller values of α the high frequencies are more and more damped. For small enough α values this method provides a sufficient filtering, where a separate source term filtering would mean an additional effort for the actual filtering.

Conclusion

The CFD is a very costly step in hybrid aeroacoustic methods. It needs a very fine grid to resolve turbulent structures and therefore leads to a high computational effort and large amount of data that has to be stored on disc. It is very beneficial to use the disparity of scales between the CFD and CAA and interpolate the acoustic source terms on a separate acoustic mesh. The interpolation should be done with a cut-volume-cell approach to prevent errors due to dependency of mesh size. The source term blending in time is not important if the setup is dominated by free radiation, but the blending in space has to be chosen carefully. A blending too close to physical sources can pollute the physical result, where a blending too far can bring too much numerical noise in the result. The not resolved acoustic waves can easily be filtered using a Hilber-Hughes-Tailor method without doing a separate source term filtering.

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