AEROACOUSTIC SIMULATIONS OF AN AXIAL FAN WITH MODELLED TURBULENT INFLOW CONDITIONS

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SUMMARY

In applications the acoustics of fans can differ significantly from measurements of the standalone fan. This is due to disturbed inflow conditions for example caused by a heat exchanger upstream of an axial fan. Resolving the complex geometry and dimensions of typical heat exchangers in aeroacoustic scale-resolving simulations leads to a very high computation effort, which is currently not economically feasible. Turbulence reconstruction tools, such as the FRPM, provide the possibility to model the turbulent inflow conditions, thereby avoiding the representation of the heat exchanger in the aeroacoustic simulations. This approach is tested on a benchmark experiment of a ducted fan with an upstream turbulence grid.

INTRODUCTION

The evaluation and reduction of the acoustics is an important part in the development of new fans. Especially in applications which operate close to humans, such as air conditioning or kitchen hoods, quiet fans are requested. In contrast to the measurements of the standalone fan, typically used in the development process, in applications the acoustics can be significantly influenced by disturbed inflow conditions. As shown by Lucius et al. [1], even a rectangular box in front of the fan drastically increases the emitted sound, whereas the effect on the aerodynamic properties is only minor.

Evaluations of the aerodynamic properties with numerical simulations using CFD (Computational Fluid Dynamics) are commonly used in the development process of new fans. Due to increased computational resources, CAA (Computational Aeroacoustics) methods become more important to predict the emitted sound and identify sound generating mechanisms. As shown by Lucius et al. [1] scale resolving simulations such as LES (Large Eddy Simulation) are able to correctly calculate the acoustics of fans. However, a high computational effort is needed to resolve upstream structures, which influence the inflow conditions. Especially, due to the complex geometry the dimensions of heat exchangers it is currently not economically feasible to resolve all the necessary details.

Turbulent reconstruction tools, such as the FRPM (Fast Random Particle Mesh) method, developed by the DLR in Braunschweig (Ewert et al. [2]), offer the possibility to synthetically recreate the turbulence of disturbed inflow conditions based on the statistic information of precursor RANS (Reynolds Averaged Navier Stokes) simulations. This avoids the necessity to resolve the turbulence generating geometries and allows a prediction of the acoustic properties under disturbed inflow conditions. For the benchmark test case of an airfoil behind a turbulence grid in a wind channel this method was successfully applied (Dietrich et al. [3]).

In this paper the turbulence reconstruction technique using the FRPM for disturbed inflow conditions is applied on a benchmark test case of a ducted axial fan with an upstream turbulence grid investigated at the University of Siegen (Zhu [4]). The same setup was also investigated by Moghadam et al. [5] however the acoustics was only simulated for undisturbed inflow conditions. Varying inflow conditions for this ducted fan in a similar setup were numerically and experimentally investigated by Reese and Carolus [6] who showed the capabilities of different turbulence modelling techniques to capture the relevant sound sources.

EXPERIMENTAL SETUP

The experimental setup and measurement results are published by Zhu [5] and can be consulted for additional information. In the experiment an axial fan with a diameter of 300 mm and a rotational speed of 3 000 rpm is placed in a duct, sucking air from a semi-anechoic chamber over a comparatively coarse turbulence grid. A schematic of the experimental setup is shown in figure 1.

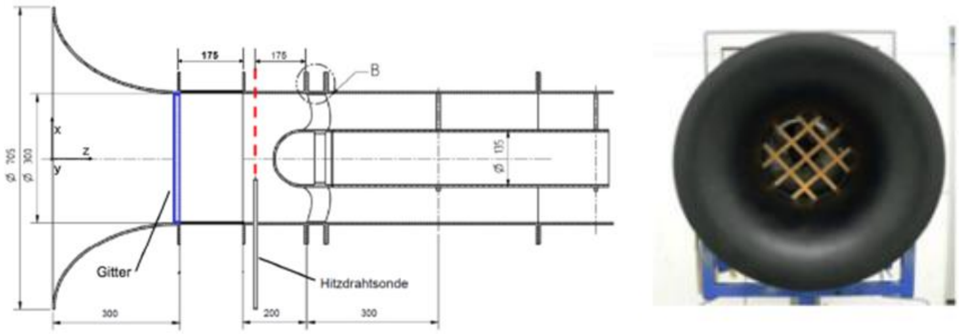

Figure 1: Schematic of the experimental setup (left) and picture of the installation with the turbulence grid (right) [4]

The inflow field for the fan after the nozzle and the turbulence grid is measured by a hot wire probe located 175 mm in front of the leading edge of the fan. In addition, the pressure on the blade surfaces is measured by pressure sensors on the suction and pressure side of the blades.

The acoustics is recorded by 3 upstream microphones placed in the semi anechoic chamber (figure 2) and one microphone in the duct after the fan. For the comparison in this paper only the microphones on the suction side (semi anechoic chamber) are used.

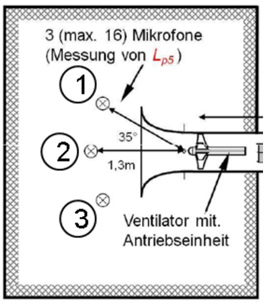

Figure 2: Location of suction side microphones (Schematic based on [7])

SIMULATION SETUP

This experiment was selected for the test because it features a turbulent inflow condition for a fan which can still be resolved with a scale-resolving simulation thereby providing additional reference for the simulation with turbulent reconstruction.

For the full-model simulation a computational grid involving the nozzle, the turbulence grid and the fan was created. The scale resolving simulation was set up as a compressible simulation in StarCCM+ with a frequency resolution up to 3 000 Hz with 20 point per wavelength (PPW). The acoustics in the suction side microphones was calculated using the Ffowcs-Williams and Hawkings (FWH) model directly from the fan blades as well as from a permeable surface in front of the nozzle. For the turbulence resolution the boundary layer was resolved with the dimensionless wall normal distance (N+, Y+) below than 1 and a dimensionless resolution in the tangential direction (T+) below 200 in the entire domain leading to approximately 60 million cells. The used LES typically requires T+ values below 40 for a proper resolution of the boundary layer, however it was shown, that for the acoustics this setup is sufficient [3]. Figure 3 shows a schematic view of the calculation domain.

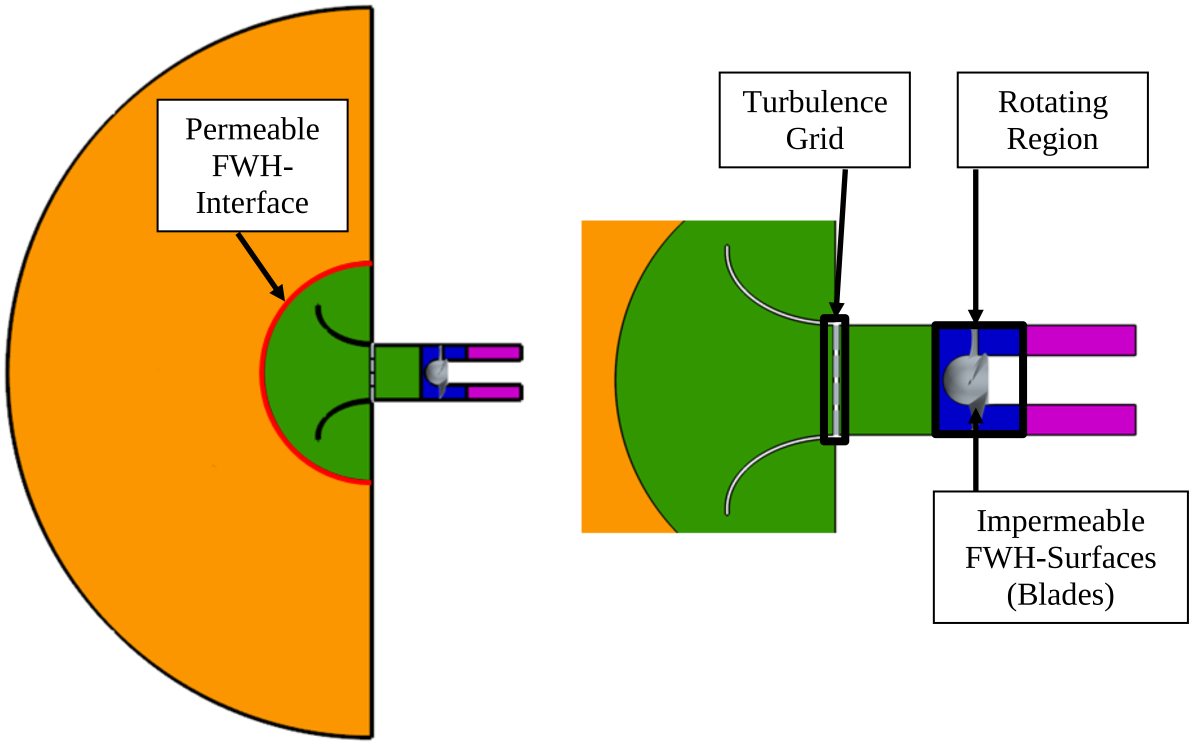

Figure 3: Calculation domain for the full-model simulation of the ducted fan with upstream turbulence grid. Full view (left); detailed view (right)

For the simulation with turbulence reconstruction the simulation model is reduced. It now starts at 175 mm in front of the leading edge (the position of the hot wire measurements in the experiment). In contrast to the geometric setup of the full model, in the simulation with turbulence reconstruction the entire domain is rotating. As basis for the turbulence reconstruction with the FRPM, a RANS simulation of the entire domain is used. For the acoustic evaluation the simulation procedure for both approaches is the same. First 3 revolutions with a comparably coarse timestep are calculated. Afterwards the acoustic evaluation of 2 revolutions of the fan with FWH is started using a smaller timestep (Δt < Period duration divided by 30) ensuring the temporal acoustic resolution up to 3 000 Hz. Due to the reduced setup for the turbulence reconstruction simulation the permeable FWH-Interface is not part of the domain and therefore cannot be evaluated. The reduced model consists of approximately 40 million cells.

To perform the turbulence reconstruction a volumetric section (patch) of the mean flow profile and the statistic turbulence properties is extracted from the precursor RANS simulation and provided as input for the FRPM. The transient turbulent fluctuations reconstructed by the FRPM are then combined with the mean flow profile of the RANS simulation and provided as turbulent boundary condition in the scale resolving simulation. These turbulent boundary conditions can be created prior to the scale resolving simulation or in parallel. Figure 4 shows the process of the turbulence reconstruction for this case.

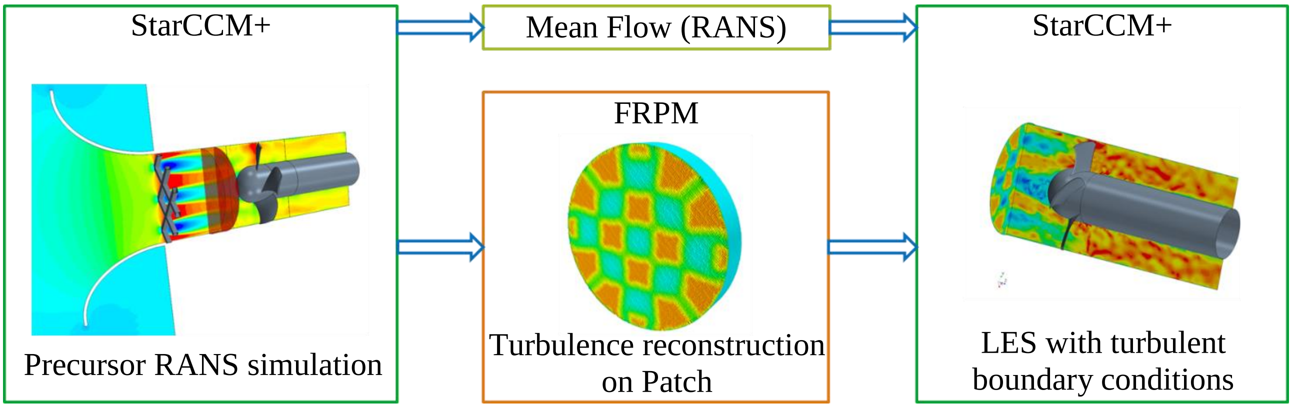

Figure 4: Setup of simulation for turbulence reconstruction using StarCCM+ and FRPM
(The red patch is used to reconstruct the turbulence from RANS)

Both the full model simulation and the simulation with reconstructed turbulence feature LES using the WALE (Wall-Adapting Local Eddy-viscosity) model for the turbulence of the subgrid scales. To avoid reflections at the boundaries, the inlet and outlet section are implemented as non-reflecting “Free-Stream” boundary conditions. In addition, on the outlet an Acoustic Suppression Zone (ASZ) is used. The precursor RANS simulation is simulated with the k-ε realizable model.

AERODYNAMIC RESULTS

The turbulence reconstruction is based on the RANS simulation, which was also used to initialize the scale-resolving simulation of the full-model. As already observed in [3], the flow field of RANS and LES differ in the structure of the wakes. This can also be seen in figure 5.

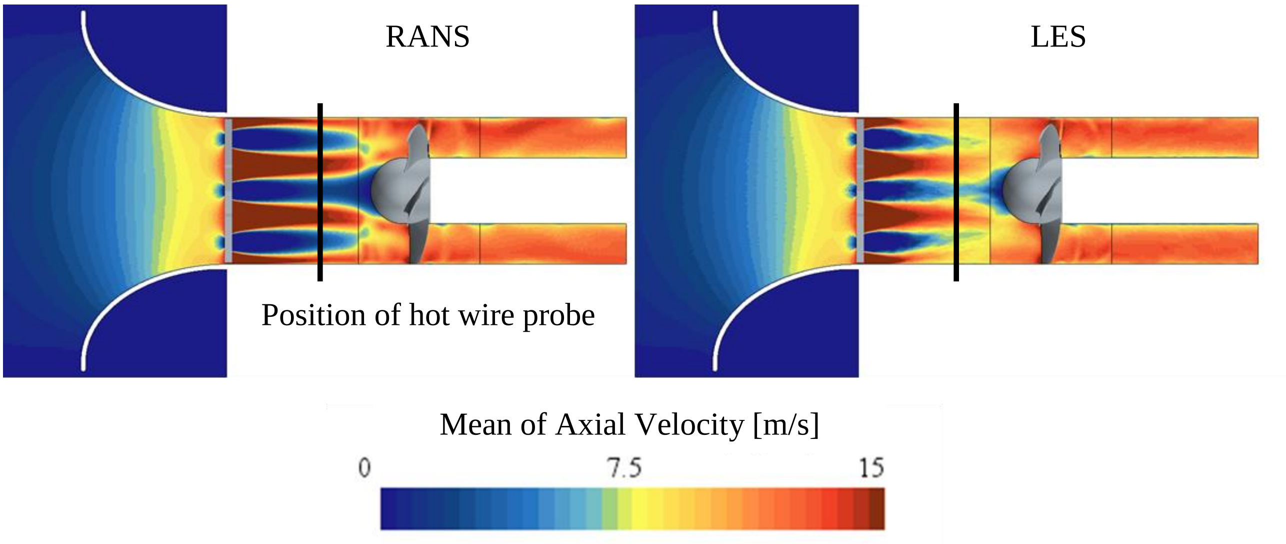

Figure 5: Mean axial velocity in RANS and LES

The different structure of the turbulence can also be seen in the comparison of the measurements with the hot wire probe 175 mm in front of the fan, shown in figure 6.

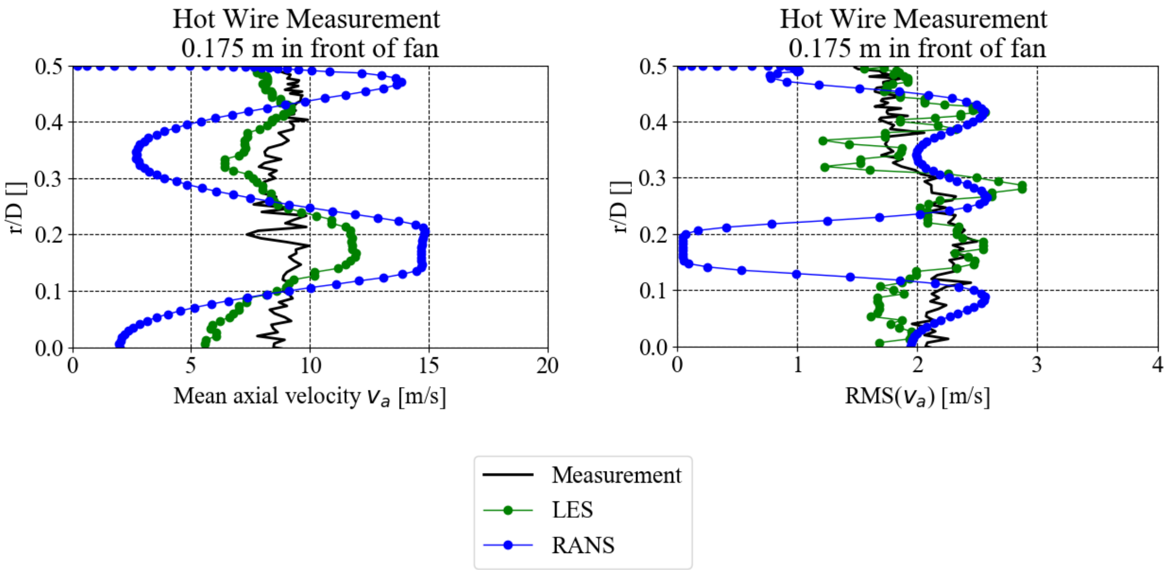

Figure 6: Comparison of RANS and LES (both full model) with hot wire measurements 175 mm in front of the fan [4] (Mean Axial Velocity [left] and RMS-Value of Axial Velocity [right])

In comparison to the measurement the wakes can be seen in the profiles of the axial velocity for both simulations (RANS and LES), however the structure of the wakes is more dominant in the RANS profile. The fluctuations (RMS) of the axial velocity calculated by the LES match the measured values quite well. The fluctuating nature of the profile is probably caused by the limited simulation time. However, significant differences can be seen in the RANS profile. This can be explained by the more dominant wake structures and the modelled isotropic turbulence in the RANS approach, since the RMS value of the RANS was calculated based on the turbulent kinetic energy.

In addition to the hot wire probes the pressure on the blade's surfaces can also be compared to the measurements. In figure 7 the spectra of the measured surface pressure are compared to the full model simulation and the simulation with reconstructed turbulence.

The surface pressure in the full model simulation shows for the most part of the spectrum higher levels compared to the measurement. This can be an effect of the insufficient surface resolution in the presented LES. It can be seen, that especially close to the leading edge on suction and pressure side the pressure profile of the reconstructed turbulence shows a significantly faster decay. Close to the trailing edge the pressure fluctuations of the full model and the reconstructed turbulence are in good agreement up to ~2 500 Hz. For higher frequencies the pressure signal for the reconstructed turbulence shows significantly lower levels. In the FRPM a Gaussian spectrum, calibrated with the turbulent kinetic energy and the turbulent length scale of the RANS simulation, is assumed for the reconstruction of the turbulence. The turbulent length scale is dominated by the large turbulent structures of the flow. Therefore, only the part of the turbulent spectrum, which is located around the turbulent length scale, is reconstructed. Small scale fluctuations at higher frequencies are neglected in the reconstruction leading to an unphysical shape of the energy distribution. This is most likely the reason for the differences found in the pressure spectra.

Previous investigations [3] showed, that by focusing the reconstruction on the large scale turbulence based on the RANS mean flow yields good acoustic results compared to reference simulations and measurements. Therefore, it might be assumed, that, despite the differences seen for the flow field, good acoustic results can be obtained with the turbulence reconstruction method.

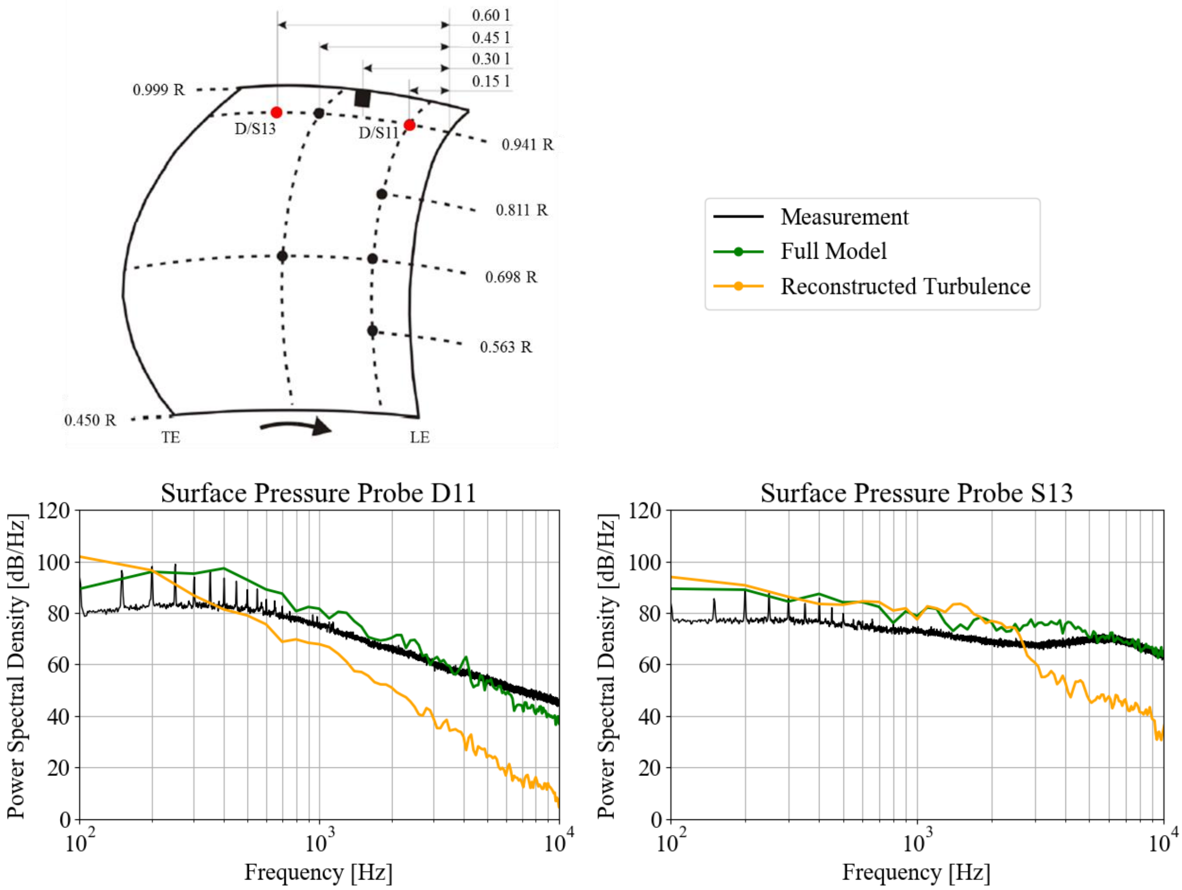

Figure 7: Comparison of surface pressure spectra of full model simulation and simulation with reconstructed turbulence with the measurement (Data and positions based on [4])

AEROACOUSTIC RESULTS

In the full model simulation, the acoustic results in the 3 microphones on the suction side can be obtained by the propagation using FWH either from the permeable surface or the direct propagation from the fan blades (ref. figure 3). In the simulation with reconstructed turbulence due to the reduced simulation domain only the propagation directly from the fan blades is possible. The mean of the acoustic spectra in all 3 suction side microphones (front) and separately the microphone on the axis (microphone 2) can be seen in figure 8.

The result based on the propagation from the permeable surface shows a very good agreement with the experimental values. In comparison to the propagation from the blades the effect of the duct and the nozzle on the acoustic spectrum is clearly visible for frequencies below ~1 000 Hz. For frequencies above 1 000 Hz the shape of the spectrum and the levels are in good agreement between the different propagation methods.

The reference for the simulation with turbulent reconstruction is the propagation from the fan blades in the full model simulation. The shape of the spectrum and the levels are in close comparison. There are slight differences at ~ 1 000 Hz and at higher frequencies. The additional noise at higher frequencies might be an effect of the neglect of small turbulent fluctuations in the Gaussian spectrum in the turbulence reconstruction method.

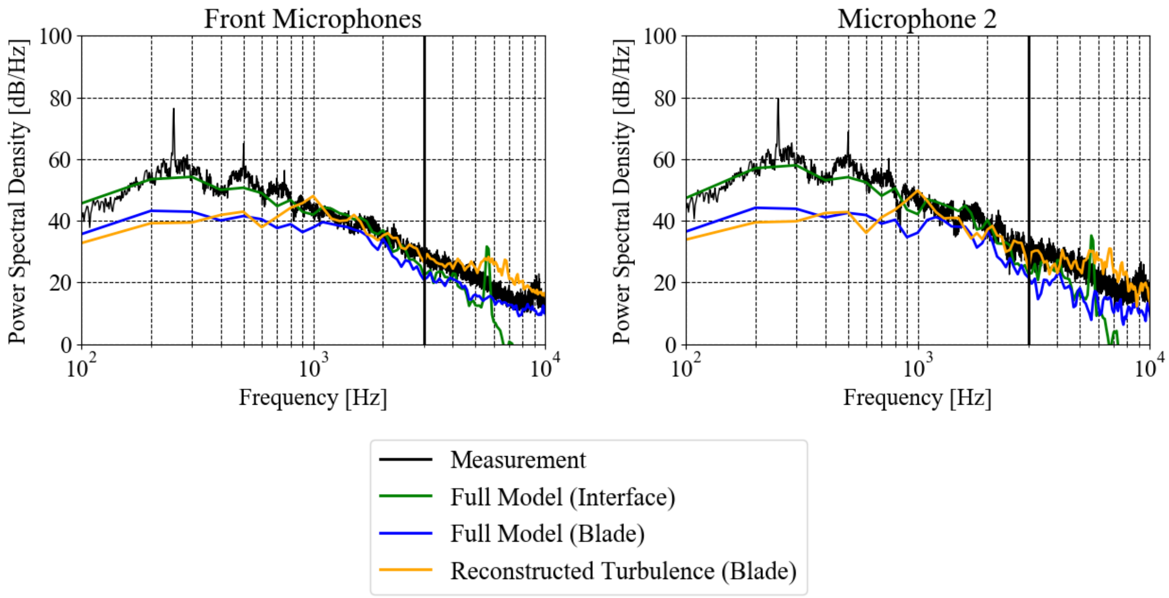

Figure 8: Mean acoustic spectra of all 3 suction side microphones (left) and single microphone spectrum for microphone on the axis (right) (Measurement data based on [4])

Despite the differences in the aerodynamics, shown in the previous section, it is possible to correctly predict the effect of the inflow turbulence on the acoustics of the fan by the presented turbulence reconstruction method. In contrast to a heat-exchanger application the resolution of the turbulence grid in this setup requires a comparably small amount of computational resources.

PERIODIC SIMULATION

To further reduce the computational effort needed to predict the effect of inflow turbulence on the ducted fan, further reduction techniques are investigated. As shown in previous studies [3, 5], it is possible to exploit the periodicity of the fan geometry in the simulation without inflow turbulence. For the full model approach this is not possible since the periodicity of the turbulence grid and the fan are not the same (1/5th periodicity for the fan and 1/4th periodicity of the turbulence grid). In the simulation setup with reconstructed turbulence however, the turbulence grid is no longer part of the simulation domain. Therefore, a new mesh was created, featuring only one blade in a periodic segment. The setup for the full and periodic model for the turbulence reconstruction simulations are displayed in figure 9.

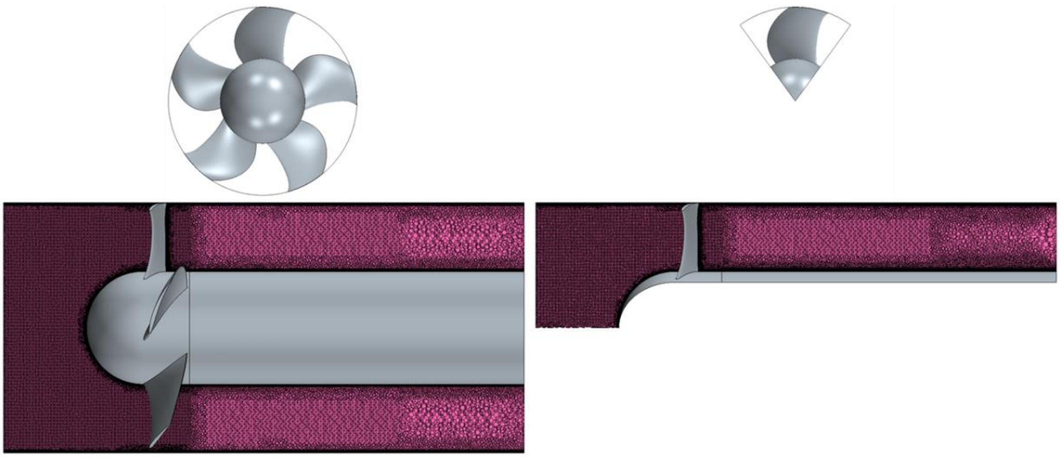

Figure 9: Calculation domain and mesh for turbulence reconstruction simulations. (Full Model [left]; Periodic Model [right])

Due to the exploitation of the periodicity of the fan geometry, a significant reduction in the cell count can be achieved. Starting from ~60 million cells for the full model (fan + turbulence grid) the cell count is reduced to ~8.6 million for the periodic turbulence reconstruction simulation.

For the periodic model however, it is not possible to directly use the mean flow provided by the precursor RANS as specified in figure 4. The mean flow still shows the structure of the grid, which has a 1/4th periodicity. Using this inflow would lead to unphysical fluctuations in the periodic aeroacoustic simulation. Using the circumferential mean of the RANS flow field and the turbulent fluctuations generated based on the original mean flow no unphysical fluctuation could be observed in the frequency region of interest. Since, it is currently not possible to reconstruct the turbulence in a circumferential periodic domain in the FRPM, the same region as for the full model turbulence reconstruction was used. The profiles used for the mean flow and the turbulence reconstruction are shown in figure 10.

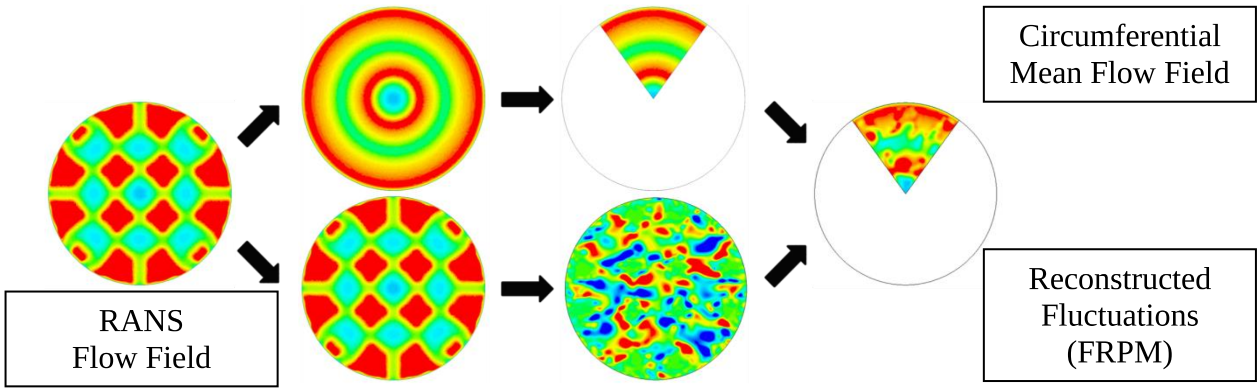

Figure 10: Mean inlet flow field and reconstructed turbulence for periodic simulation

The acoustic results for microphone 2 can be seen in figure 11. The signal for the periodic model is shifted by $\Delta PSD = -10\ log_{10}(5)\ dB$ (5 representing the number of blades of the fan) to account for coherent sound sources on the axis. Here only the microphone on the axis is shown due to the ongoing investigations to account for coherent sound sources for off-axis microphones (Lucius et al. [7]).

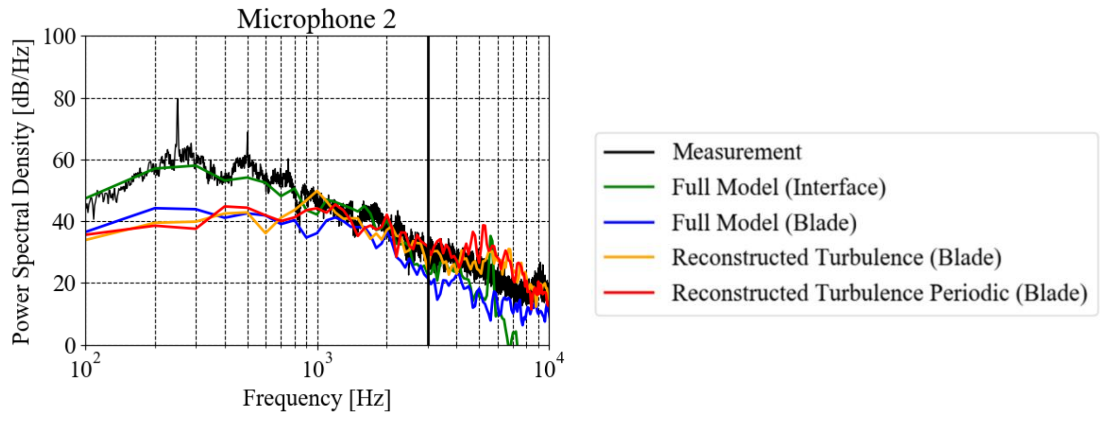

Figure 11: Comparison of the acoustic spectra in microphone 2 for the full model simulation and different turbulence reconstruction approaches (Measurement data based on [4])

The acoustic spectrum from the periodic simulation with reconstructed turbulence matches the reference simulation and is also in good agreement with the full model simulation with reconstructed turbulence. For higher frequencies additional fluctuations can be observed, which can be accounted for the generation of the synthetic turbulence and the periodic model itself. For the spectrum at low frequencies (f < 1 000 Hz) it is important to use the original RANS flow field for the turbulence reconstruction. If the circumferential mean of the flow field is also used for the turbulence reconstruction, significantly lower levels are observed in this frequency region.

CONCLUSION

In this paper an approach to reduce the computational effort for the aeroacoustic simulation of fans by reconstructing the turbulence generated by geometric features upstream of the fan is presented. The approach was applied to a benchmark case of an axial fan in a duct with an upstream turbulence grid.

For this approach the statistical turbulence information from a precursor RANS was reconstructed using the FRPM-Tool, developed at the DLR in Braunschweig, and used as inlet boundary condition of a scale-resolving aeroacoustic simulation of the fan. The results were compared to the experimental finding and an aeroacoustic simulation of the entire setup (fan + turbulence grid). Additionally, an approach was presented to further reduce the computational effort for the acoustic prediction by exploiting the periodicity of the geometry.

The aerodynamic comparison showed that there are differences in the mean flow field and the turbulent properties of the RANS simulation compared to the experiment and the reference LES. Furthermore, the pressure signals on the fan blade surface partially show significant differences between the simulation with reconstructed turbulence and the reference simulation of the entire setup. Despite these differences a good agreement between the acoustic spectra of the simulations with reconstructed turbulence and the reference simulations was found. The reference spectra from the experiments could not be reproduced with the turbulence reconstructing simulations due to the reduced computational domain.

With the turbulence reconstruction and the exploitation of the periodicity of the geometry it is possible to significantly reduce the computational effort of aeroacoustic simulations with inflow turbulence. Especially for applications with complex upstream geometries, such as heat exchangers, this approach enables simulations in an industrial context.

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