Broadband flow noise prediction of an unducted low speed axial fan using a Zonal LES – FWH approach

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Introduction

Zonal LES coupled with the Ffowcs Williams-Hawkings (FWH) acoustic analogy can provide reliable predictions of the broadband noise emitted by an unducted low speed fan in reasonable computational time, as shown by the authors in previous works [1,2,3]. The proposed approach consists of a fully resolved LES, which embeds the acoustic generation region, merged with a RANS solution in the outer flow domain. However, the complexity of the phenomena involved requires a careful setup of the numerical simulation. The latest developments, presented here, focus on the impact of the mesh topology and the accurate control of inflow turbulence on the far field noise prediction. Computational results are in good agreement with aerodynamic and acoustic measurements taken by the authors [4].

Numerical models

The Zonal LES approach is designed to overcome the high computational burden of LES. It consists of a fully resolved LES in a sub-domain region interfaced with a RANS solution in the outer domain. In this work the LES WALE subgrid turbulence model is applied, which is designed to give the correct asymptotic behavior for wall bounded turbulent flows and zero turbulent viscosity for laminar shear flows [5]. The grid requirements of WALE-LES are those typical of LES ($\Delta x^+ \sim \Delta z^+ \sim 20$ and $y^+ \sim 1$). In the RANS domain the k-ω SST turbulence model is adopted. The RANS-LES interfaces are treated with the random vortex method approach [5] to convert turbulence between the RANS and the LES regions of the domain. The effect of the rotation of the fan is introduced by transforming the flow equations from the fixed to a moving reference frame.
The acoustic propagation is performed by applying the FWH acoustic analogy in the Farassat & Brentner [6] formulation, but neglecting quadrupole sources (first r.h.s. term) which only weakly radiate in low Mach number flows.

The unsteady calculations are performed in ANSYS Fluent 14.5 with a time step of $2.85 \cdot 10^{-5}$ s, i.e. 1500 time steps per revolution. The blade surface is selected as FWH integration surface. The sampling frequency is 35 kHz with a resolution of approximately 3 Hz, corresponding to 8 revolutions.

Test case and computational meshes

The test geometry is a 5-bladed axial fan, with tip and root diameters of 350 mm and 102 mm, respectively. The blade profile is based on F-Series aerofoils, with a chord length ranging from 85 to 95 mm. The blade Reynolds number, at the nominal working condition of 1400 rpm, ranges from 0.06 million at the root to 0.16 million at the tip.

Two meshing strategies with different topologies are compared. Both consist of an inner domain, that includes the LES box with the finest resolution, and a coarser large outer flow domain, as depicted in Figure 1.

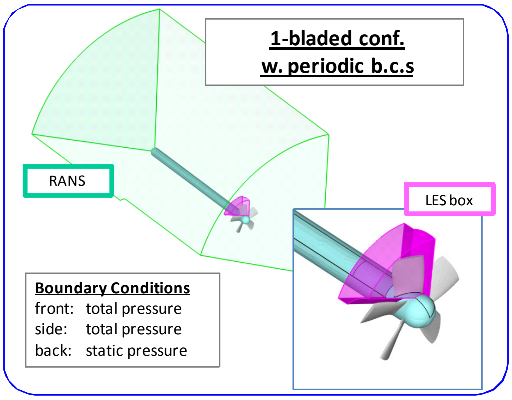

Figure 1: Computational model and domains

The *unstructured-hybrid mesh* is composed of a prismatic region on the blade generated by extruding 20 layers of prisms from the surface triangular mesh. The bulk domain is filled by polyhedral cells. Two different computational meshes are generated: Mid (2.6M cells, see Figure 2, left) and Fine (5.2M cells). As shown in [3], already the Mid mesh is able to provide good results, however, in this work, the Fine mesh was taken for comparison since it has a cell number close to the structured-hybrid mesh.

The *structured-hybrid mesh* is composed by a structured mesh in a region enclosing the blade and part of the wake (see Figure 2, right). The remaining volume is filled by polyhedral cells with a conformal interface established by a layer of pyramid cells. In the upper boundary of the structured mesh (above the blade tip) a non-conformal interface is adopted. This mesh counts 5.2M cells in total.

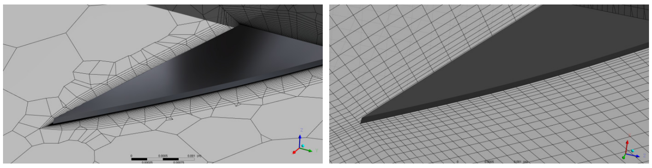

Figure 2: Projection of the unstructured-hybrid (left) and structured-hybrid mesh (right) at the isoradial (r=0.175m) surface. Detail of the blade tip.

Two cases of inflow turbulence level are considered: "Low inflow turbulence" with an intensity of 0.01%, in order to remove uncertainties connected to freestream turbulence (value, spectra, eddy size, numerical diffusion); and "High inflow turbulence" with a more realistic value (i.e. 5%).

Results and Conclusions

In both inflow turbulence cases, the structured-hybrid mesh predicts the volume flow rate with higher accuracy (relative error about 2-4%, compared to measurements) than the unstructured-hybrid mesh (rel. error of 6-10%). This is mainly due to the higher resolution of the tip vortex and the near wake region.

Noise spectra are calculated for a microphone located at an in-axis position, 1 m upstream the fan. As the simulation setup is rotational periodic, the FWH solver clones the sources from one simulated blade to the virtual positions of the other blades. The acoustic pressure at the microphone location then is the sum of 5 coherent source regions which should be incoherent in reality. For comparison with experimental data, the FWH results are corrected by $10\log_{10}(5p^2/(5p)^2) \approx -7$ dB.

The unstructured-hybrid mesh yields a realistic prediction of the broadband noise level. At low inflow turbulence (Figure 3) the noise level is well below the experimental data. At high inflow turbulence (Figure 4) it reproduces well the experimental results with the characteristic bump around 2 kHz, showing a slight underprediction of the level. In contrast, the structured-hybrid mesh shows a large overprediction of the sound pressure level in the mid frequency range, exceeding the experimental data in both cases.

The inspection the surface pressure fluctuations on the blade suction side, see Figure 5, reveals that structures and levels are highly similar over a large part of the suction side for both mesh topologies, whereas a major difference is found at the trailing edge close to and at the blade tip, where the structured-hybrid mesh shows high intensity fluctuations due to tip vortex – blade surface interaction. Presumably, there the near surface hexahedral mesh is still too coarse to resolve adequately the breakdown of the tip vortex to smaller turbulent scales. This might result in artificially coherent flow structures in the tip vortex which in turn induce high pressure fluctuations at the trailing edge that mask the broadband noise. On the other hand, the unstructured-hybrid mesh highly dissipates the tip vortex due to cell-coarsening outside the prism layer but retains well the turbulent boundary layer fluctuations.

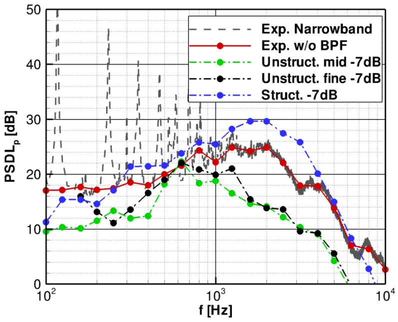

Figure 3: Comparison of the numerical sound pressure *PSDL* (1/3 octave band averaged) at 1400 rpm with low far field turbulence. Experimental data as indicative value.

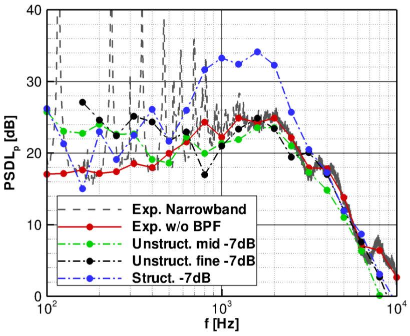

Figure 4: Comparison of the experimental and numerical sound pressure *PSDL* (1/3 octave band averaged) at 1400 rpm with high freestream turbulence intensity in the numerical simulations.

Further investigations shall clarify the impact of the mesh resolution on the tip vortex formation and break-down to improve the acoustic prediction capabilities of the structured-hybrid methodology.

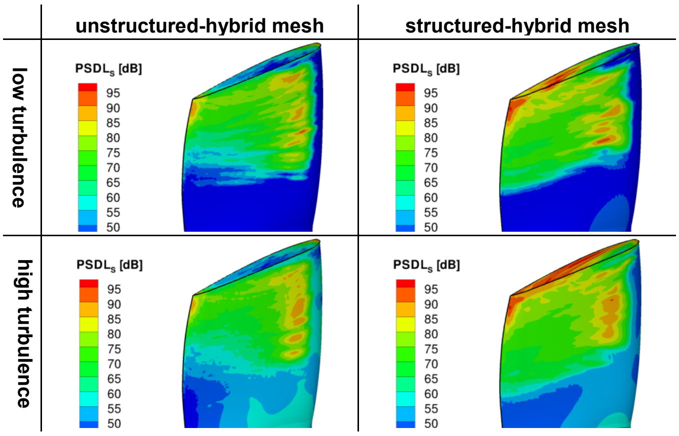

Figure 5: Numerical prediction of the *PSDL* (1/3 octave band averaged) of the surface pressure fluctuations on the blade suction side at 2000 Hz center frequency for the two mesh topologies at different inflow turbulence intensities.

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