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PREDICTING NOISE SPECTRUM OF A SMALL DRONE ROTOR IN A CONFINED ENVIRONMENT: A LATTICE BOLTZMANN VLES ANALYSIS

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Abstract. The objective of this paper is to study the predictive capabilities of a Very-Large-Eddy-Simulation CFD solver for the simulation of the flow past a small drone propeller blade. The solver is based on a Lattice-Boltzmann Method coupled with an FW-H acoustic analogy to compute the far field noise. The method is able to cope with the anechoic test chamber to predict the complex flow-field and the characteristic boundary layer phenomena (such as laminar separation, transition and reattachment). The acoustic hybrid formulation provides tonal and broadband noise radiation in agreement with the experimental data. Frequency spectrum prediction exhibited a strong low-frequency tonal contribution at multiples of the blade passing frequency related to the interaction with coherent vortical structures in hover, and a high-frequency broadband hump due to the laminar separation bubble at high advance ratio.

Introduction

The design of small rotors, aerodynamically and aeroacoustically efficient, is a research field of great interest. According to a recent experiment of propeller at low Reynolds number ($Re < 70000$) Grande et al. [5] at TU Delft have observed a very complex flow, involving laminar separation, transition, and reattachment, where the size and the position of the Laminar Separation Bubble (LSB) greatly affect the propeller broadband noise spectrum.

The prediction of such non-linear phenomena can be extremely challenging even for high-fidelity (Computational Fluid Dynamics) CFD solvers. Typically, CFD solvers are based on a hybrid turbulence model and use an artificial trip to enforce boundary-layer transition. Previous studies performed by Casalino et al. [2, 3] have been focused on predicting far field noise using Dassault Systèmes PowerFLOW® software, which is based on Lattice Boltzmann Method (LBM) and Very Large Eddy Simulation (VLES). The Lattice-Boltzmann method [3] is based on statistical advection and collision of fluid particles by a number of distribution functions aligned with pre-defined discrete lattice velocity directions. Flow variables such as density and velocity are computed by taking the appropriate moments of the distribution function. The relaxation time and other parameters of the distribution function are computed by considering the turbulent motion computed using a two-equation transport model based on the $k-\epsilon$ re-normalization group theory. Conversely to RANS models, Reynolds stresses are not explicitly added to the flow governing equations but are a consequence of an alternation of the gas relaxation properties that lead the flow towards a state of dynamic equilibrium. LBM/VLES model can be interpreted as an extension of the kinetic theory from a gas of particles to a gas of eddies [4]. It can be demonstrated that the effective Reynolds stresses have a nonlinear structure and are better suited to represent turbulence in a state far from equilibrium, such as in the presence of shear and rotation. Being the LBM low dissipative, compressible, and intrinsically unsteady, it constitutes a well-suited model for aeroacoustics simulations.

In this work, the aerodynamic noise generated by the propeller is evaluated by means of an hybrid FW-H calculation [1] based on a time-advanced solution of Farassat's formulation of the Ffowcs Williams & Hawkings' (FW-H) equation applied to the propeller blades, hub and nacelle surface pressure LBM solution. Although a favorable agreement with experiments was obtained by Casalino et al. in previous studies [2, 3], some inconsistencies were found and possibly attributed to the absence of the experimental test section in the simulation [5] and grid resolution. Therefore, the aim of the present study is to further validate the aeroacoustics and aerodynamic predictive capabilities of the LBM/VLES approach, including the simulation of the actual anechoic test section by means of an Acoustic Porous Medium. Moreover, no artificial trip is used to trigger transition, and the effect of grid resolution refinement on the prediction of Laminar Separation Bubble (LSB) and related phenomena is further assessed.

Computational setup

The propeller geometry considered in TU-Delft experiments [5] is based on 2-bladed APC 9x6 propeller, with 0.30 m of diameter. The angular velocity considered is 4000 RPM, corresponding a Blade Passing Frequency (BPF) of 133.3 Hz; the blade-tip Mach number is 0.19. Two different advance ratios were considered: $J=V_\infty/nD = 0.0$ and 0.6.

The unconfined computational fluid domain is a spherical volume with a radius of 80m, centered around the propeller hub. The mesh (Fig. 1) increases the resolution as the distance from the propeller decreases, using different volumes for each resolution level. The overall mesh size is of 3.8 million voxels. The anechoic TU-Delft A-Tunnel is modelled by means of an Acoustic Porous Medium, using

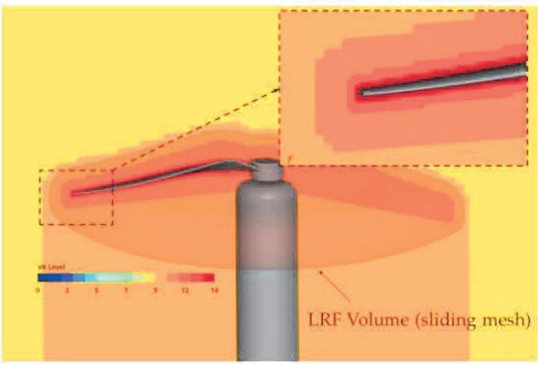

Fig.1 Mesh with different VR level near the blades

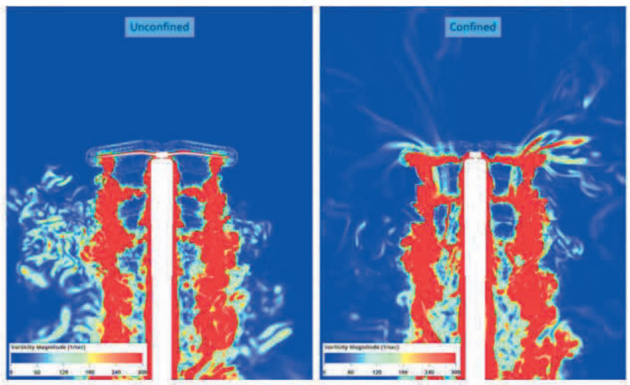

Fig. 2 Istantaneous vorticy field for the unconfined (left) and confined (right) simulation

an equivalent acoustic porosity and tortuosity. The geometry of the inner volume of the test section, as well as the nozzle's geometry were simulated with the actual dimensions of the chamber (6.4m×6.4m×3.2m for the test section, with a 1m wide opening on the ceiling and a 1.4m walls thickness).

Results

The results firstly presented are relative to the hover case in which confinement effects are more significant. To investigate the impact of confinement effects on the turbulence ingested and generated by the propeller, an instantaneous vorticity snapshot can be considered as shown in Fig.2. The confined case shows the expected presence of large vortical structures that are stretched along the flux tube streamlines and ingested by the rotor.

For the aeroacoustics analysis in Fig.3 the comparison between numerical and experimental far field noise for both unconfined and confined simulations is shown. The noise spectra are reported in terms of Power Spectral Density (PSD) versus the frequency normalized by the Blade Passing Frequency (BPF). The unloaded electric motor noise and wind tunnel background noise are included in the plots. It is worth noting that the primary sources of experimental uncertainty are: (i) the background noise, which is responsible for high levels of broadband noise at low frequency; (ii) the loaded electric motor noise and non-perfect balance of blade loading, leading to low-frequency tone increases at harmonics of the shaft frequency (BPF-0.5, 1, 1.5, etc.); and (iii) the unloaded electric motor noise, adding mid-frequency tonal contributions approximately between BPF-5 and BPF-25 and between BPF-50 and BPF-70. It can be observed that BPF-1 is accurately predicted by the numerical simulations for both cases. In the hovering confined case, all tonal peaks from BPF-1 to BPF-10 exhibit an additional tonal contribution resulting from unsteady loading compared due to the ingestion of recirculating vortical structures.

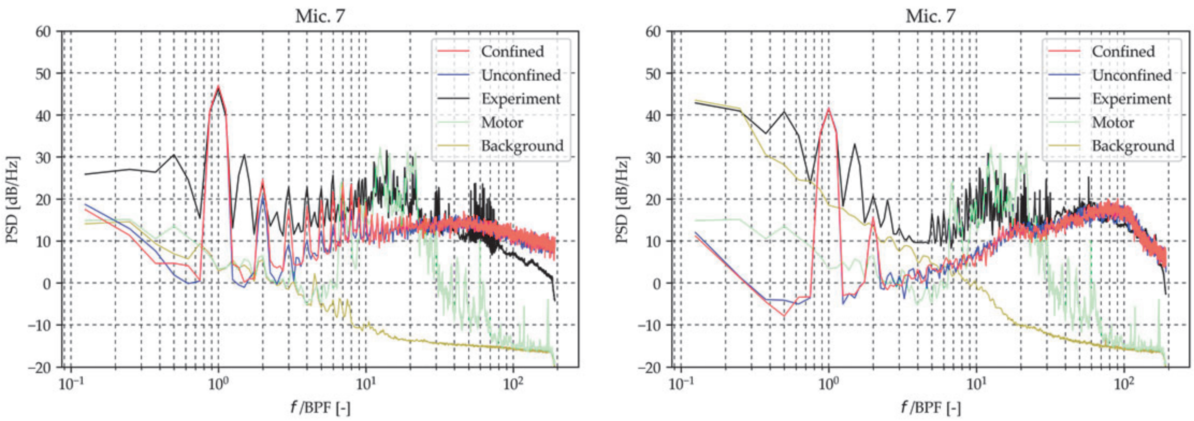

Fig. 3 Far field noise prediction for J=0 (left) and J=0.6(right)

With regards to the broadband noise component, while the case J=0.6 excellently matches experimental results, there appears to be an overestimation of noise levels above BPF-50 in hover for both the confined and unconfined simulations.

Aiming to address the discrepancies of the broadband noise between simulations and experiments and to obtain a better simulation of LSB, additional simulations were considered for the hover case. The mesh resolution was increased with an additional refinement (one level higher than previous simulations, with voxel size half of the previous one). An improvement of the broadband contribution at frequencies above BPF-50 can observed in Fig. 4. The enhanced prediction can be attributed to a better simulation of reattachment points of the LSB. Time-averaged surface streamlines of Fig. 4 clearly show the presence of the Laminar Separation Bubble. The most significant improvement can be observed in the last 25% of the blade span, close to the blades tip where the reattachment point is better aligned with the experiments.

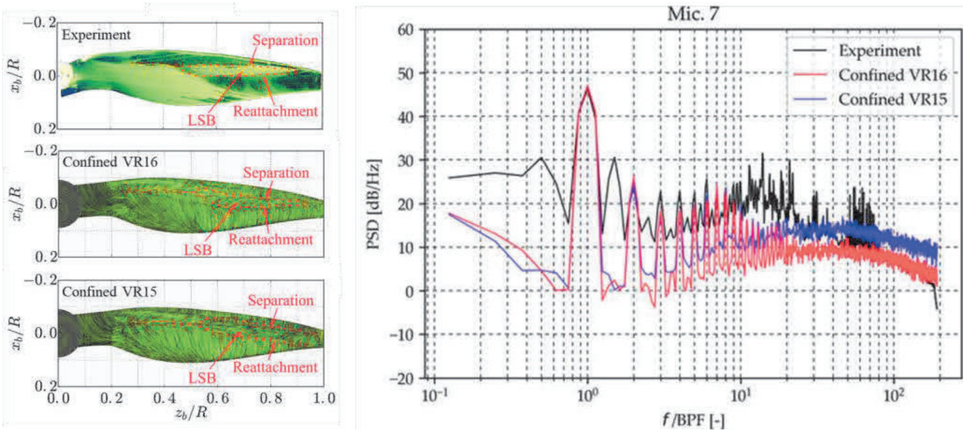

Fig. 4 Comparison of averaged streamlines for the refined simulation along with experimental oil-flow viz (left) and far field noise prediction (right).

Conclusion

This study focused on predicting far field noise spectrum, aerodynamic characteristics and boundary layer evolution (laminar separation, transition and reattachment) for a small drone rotor. Numerical simulations are performed, in both free-field and confined environments, for two different advance ratios by means of the industrial LBM-based CFD solver PowerFLOW®. The simulation aims to replicate experimental studies conducted in TU-Delft. Flow confinement simulation have a significant impact on recirculating turbulence ingested by the propeller, resulting in enhanced tonal noise prediction during hovering. An analysis of the LSB indicates that the observed broadband misprediction in hover was likely caused by an incorrect prediction of the reattachment point of LSB, resulting in an overestimation of the broadband noise. Extra simulations, performed for the hovering case with increased resolution mesh in the proximity of the expected LSB give a better accuracy in predicting trailing-edge noise, with agreement between the simulated broadband component and experimental data. Confined simulations also reveal an enhancement in the mid frequency spectrum due to turbulence impingement noise. This study demonstrates the capabilities of the industrial LBM/VLES software PowerFLOW® in accurately predicting complex flow-field, noise levels and natural boundary layer transition phenomena without the use of artificial triggering systems.

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