Numerical Investigation of Propeller Boundary Layer Ingestion Noise using CABARET on rotating meshes

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Introduction

Urban air mobility (UAM) vehicles have garnered significant attention recently for their potential to revolutionize urban transportation. These vehicles, which include electric vertical take-off and landing (eVTOL) aircraft and flying taxis, are being designed with a particular focus on propeller placement. One innovative approach is to position the propeller downstream of the wing and close to the fuselage. This design choice offers the advantage of improving fuel efficiency and overall performance by allowing the engine to ingest the turbulent boundary layer developing over the wing [2,3]. However, this approach generates noise when the propeller interacts with the incoming turbulence. Understanding the noise generation due to the interaction of turbulence with the propeller is important for designing quieter aircraft and requires further research to explain the noise generation mechanisms. To gain deeper insights into turbulence-rotor ingestion noise, a numerical investigation using Large Eddy Simulation (LES) was conducted, based on the experiments conducted at the University of Bristol [2,3]. The numerical investigation involves examining the noise generated by a single two-bladed propeller immersed in a boundary layer over a flat-plate and an S-shaped wall surface, corresponding to zero and adverse pressure gradient boundary layer flows. Fig. 1 shows the schematic of the test-case to investigate the turbulence-rotor ingestion noise.

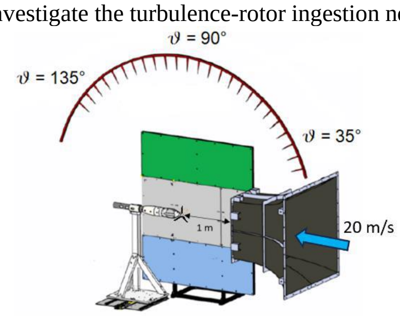

Fig. 1 Schematic of the investigation of turbulence-rotor ingestion noise.

Methodology

Test Cases

Two test cases were investigated. The first test case involved the rotor interaction with the turbulence developing over a flat plate. In this case, the rotational frequency of the rotor was 6500 RPM, and the free-stream velocity was U_∞= 33 m/s. For the second setup, the propeller was positioned at various locations downstream of the S-shaped curve, specifically at 480 mm, 800 mm, and 1000 mm from the nozzle exit. The propeller rotated at 6500 RPM with a free-stream velocity of U_∞= 27 m/s. The numerical mesh is generated on ANSYS ICEM and corresponds to 0.7million grid points.

Flow and Noise solution Methods:

The flow and noise solutions using LES is based on Compact Accurately Boundary-Adjusting High-REsolution Technique (CABARET) method on rotating meshes [1]. The CABARET algorithm inherits good dissipation and dispersion properties of the CABARET method of fixed grids. The computation using sliding meshing methodology involves maintaining flux conservation at the sliding interface. This is implemented using the so-called super mesh approach. This approach involves projecting the contact faces located on either side of the sliding interface onto an intermediate virtual surface. The implementation of this technique is cantered on the application of sub-cell and sub-face solution reconstructions specifically designed for the sliding interface within hexahedral meshes, instead of remeshing the grid near the rotating blades at each time step. Furthermore, the dispersion properties of the CABARET method at small Courant–Friedrichs–Lewy (CFL) numbers are further improved by a modification of the conservative flux calculation. Additionally, an asynchronous time-stepping algorithm is incorporated resulting in fast-turnaround time of the solution. The CABARET method is further implemented on Graphics Processing Units (GPUs) architecture and is applied for the numerical investigation in this study.

The far-field noise is computed via the Ffowcs Williams and Hawking (FW-H) method. Multiple penetrable surfaces are used confining the rotor and a downstream wake region. The surfaces are left open at the bottom wall surface. A total of 12 acoustic integration surfaces

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is utilised. The far field signals obtained from each FW-H surface are averaged in order to eliminate the spurious noise generated by vorticity crossing the acoustic integration surfaces.

Preliminary Results

Time-Averaged flow solutions:

Fig.2 shows a comparison between the velocity profile and the hotwire measurements for both setups. The boundary and the flow trend are accurately predicted for both setups; however, for the second setup (right figure), the re-circulation zone near the wall surface is not accurately captured. The discrepancy can be attributed to the too coarse grid resolution near the S-shaped wall, which cannot support modelling of the adverse flow gradient flow effects. Nonetheless, for both setup the comparison is appropriate, and the resulting simulations can be used for far-field noise calculations.

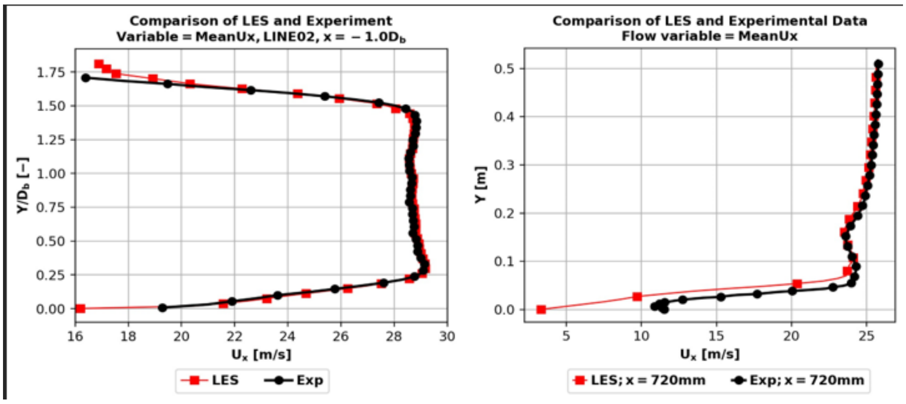

Fig. 2 Mean-flow velocity results [left - Setup A – Flat Plate, Right - Setup B – S-Shape].

Farfield Noise:

Fig. 3 compares the far field noise spectra predictions with the experiment for both setups. The comparison shows that the LES predictions are accurate in comparison with the experiment with tones being reasonable well-captured. In Addition, for Setup B, the broadening and amplification of low frequencies can be associated with the Welch averaging applied with a relatively short interval for the Fourier transform. In the final paper, a more accurate postprocessing technique of the time signal will be applied to preserve the prominent low-frequency tones in the acoustic spectra. At the same time, the broadband spectra at mid-frequencies are well represented. The accuracy of acoustic predictions deteriorates at high frequencies especially where the wake effects become more important. This discrepancy is associated with the current coarse grid resolution and will be addressed by performing a fine grid simulation.

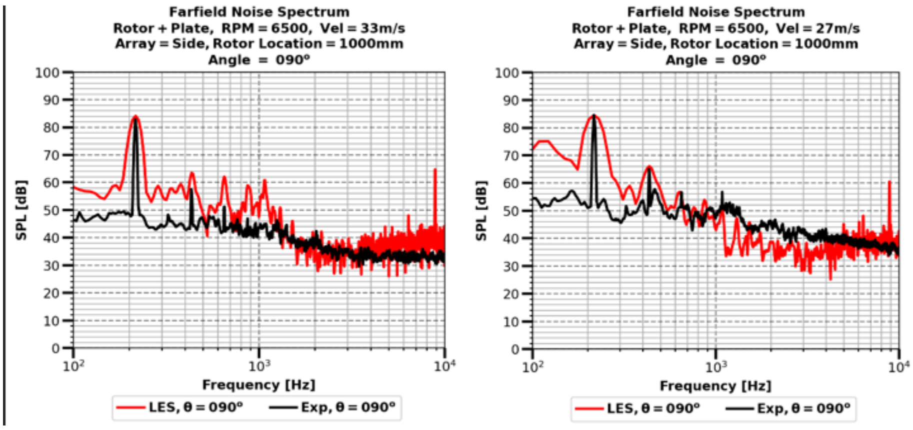

Fig. 3 Comparison of the preliminary far field noise spectra predictions with the experiment for side array at 90-degree observer angle [left - Setup A – Flat Plate, Right - Setup B – S-Shape].

Future Work

Further results will include comprehensive validation of acoustic predictions for side and overhead arrays from the experiments. More quantitative and quantitative analysis will be performed to characterise the noise generation by mild and adverse pressure gradient boundary layer.

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