Analysis of Boeing SB-1 Defiant rotor shape in an application for low-noise propellers in hobby-scale UAVs

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α Personal research project

Abstract

Based on the extensive use of UAVs in military and intelligence gathering operations, a potential solution to excessive propeller noise is investigated based on the spanwise blade geometry profile already in use in the Boeing SB-1 Defiant aircraft. A particle-based solver using `SIMULIA xFlow` software, using the Lattice-Boltzmann method, and Wall-Adapting Local Eddy (WALE) viscosity model are used to obtain the aerodynamic noise spectrum, omitting the energy equation for faster computation, as well as the speed regime being entirely subsonic thus negating the importance of temperature changes of the air. Through pressure oscillations at a specific sensor location derived from numerical simulation, the sound pressure level in the frequency domain is obtained. Using a proven calculation model and method as well as under single rotational speed chosen as the RPM of peak efficiency of a motor in a given size range, the distribution of the sound pressure level of the propeller with different geometry profile along the spanwise is analyzed, and the influence of the blade shape on the aerodynamic noise of the propeller is obtained. This research aims to compare the aerodynamic noise of the new blade based on the Boeing SB-1 Defiant rotor's shape to the blade geometry which is common for off-the-shelf products for this range of motor sizes of 22mm in diameter at the same rotational speed of 16000RPM, indicating whether the blade aerodynamic noise can be effectively reduced with this method.

Keywords: Sb-1; Uav; Drones; Propeller; Cfd; Xflow.

1 Introduction

Propeller noise generated by turbulent airflow belongs to the branch acoustics called aeroacoustics and is generated by the propeller's rotation at high speeds. Currently established methods for reducing propeller noise according to Wu et al. [2019] include reducing the intensity of the sound source or/and employing interference-based noise reduction techniques. The present study aims to decrease propeller aerodynamic noise by improving the propeller design to lower the sound source's intensity. Specifically, the study will investigate the applicability of solutions used by Boeing in designing the Defiant's rotor spanwise shape, such as sharp edges and swept rotor tips, to reduce noise. Numerical simulations will be used to analyze the propeller aerodynamic noise and determine whether this approach can achieve the noise reduction objective.

2 CFD Methodology

In order to investigate the effectiveness of the aerodynamic noise reduction with this design, computational fluid dynamics (CFD) simulation with direct noise computation is required. DNS approach requires obtaining pressure field oscillations, thus both compressible and unsteady flows need to be resolved. This is very challenging using classical Navier-Stokes equations approach as resolving the unsteady compressible NS equations for turbulent flows is extremely computationally expensive. On the other hand, the lattice-Boltzmann method (LBM) is exceptionally efficient for dealing with unstable, low-speed compressible, and highly turbulent flows. Subsonic aeroacoustics is therefore one of the method's primary benefits, which is rapidly becoming a preferred alternative to classic Navier-Stokes solvers.

The propeller's flow field information will be obtained using `XFlow` - an LBM-based CFD solver for its built-in aeroacoustics analysis features. During the flow field calculation process setup first, the far-field lattice size of size 0.15m is chosen for the entire domain, which is later sub-divided using the refinement algorithm down to the scale of 2.93×10^{-4}m at the wall boundaries, while the total domain size is 0.5m × 0.7m × 0.5m in respectively x,y,z directions - y being both rotational and vertical axis. The domain is large enough to avoid any interaction with the moving fluid while the boundaries are set to gauge pressure of 0 Pa with non-reflective boundaries. The time step at the far-field is $2.54 \cdot 10^{-4}s$ and the simulation contains between 4 million lattice elements at frame 0 and 52 million at frame 27 and is run for 0.007s which is sufficient for 2 full propeller rotations at which point the significant amount of turbulence is able to develop while being a good balance of the computational cost. The increase in lattice element number is due to the increasing complexity of wake turbulence and dynamic lattice refinement. Air used in the simulation is at standard 101325 Pa of pressure and based on ideal gas law the speed of sound is 340.11 m/s. The simulation took for 70 hours using 8 threads running at 4.77GHz.

The turbulence model chosen is the Wall-Adapting Local Eddy (WALE) model with WALE constant $C_W = 0.2$, as it provides consistent properties in both near-wall regions as well as the far field, additionally, it is well suited for both turbulent and laminar flows Brionnaud et al. [2016]. In the sound spectrum calculation, the aerodynamic noise is measured by a single sensor located 0.09m away from the center axis on the zx plane. The sound pressure level (SPL) in the frequency domain of the aerodynamic noise of the propeller at the rotational speed of 16000RPM for both geometries is obtained based on the pressure level fluctuations at the sensor location.

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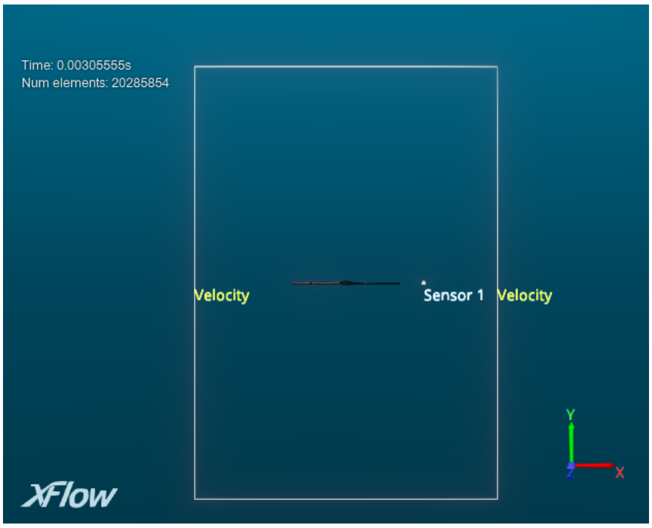

Figure 1: Visualization of the computational domain.

3 Propeller Design

The design is centered around a hub with a diameter of 9mm along with a 5mm central hole for attachment to the motor using a standard M8 nut. The blade section profile of choice is e63-il as it is the profile with the highest C_L/C_D ratio at Re=50000 on http://airfoiltools.com/ database, and the flow in this domain occurs entirely below Re of 50000. Maximum C_L/C_D ratio of 52 occurs at $\alpha = 5.0°$ thus this blade twist angle has been chosen. This geometry will be later referred to as the e63 propeller.

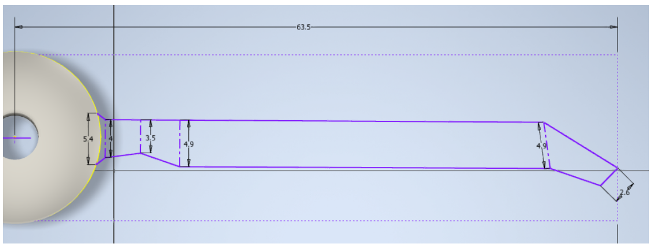

Figure 2: Spanwise geometry of the blade.

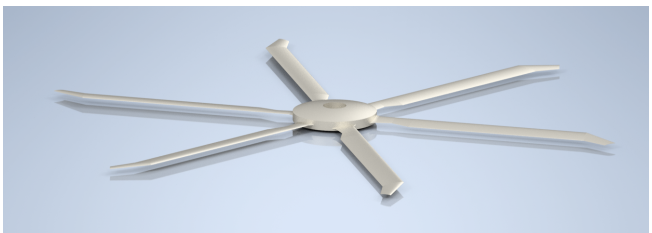

Figure 3: Visualization of e63 propeller geometry.

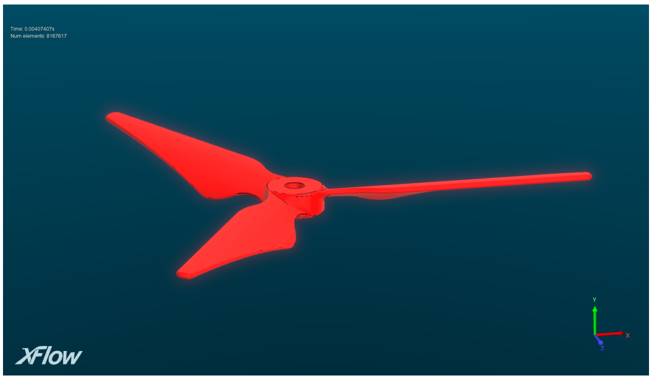

Figure 4: Visualization of reference propeller geometry.

4 Results Analysis

The turbulent air generated by the propeller's rotation produces pressure variation which in turn produces broadband noise. As can be seen in Fig.5 the difference in noise signature is apparent and quite significant even despite the lacking amount of data due to the short simulation time. This however, showcases how a comparison of different geometries can be successfully made without requiring a great number of computational resources as would be needed with the alternative in form of the Navier-Stokes equation method.

Additionally in Section 5.1 Figures containing volumetric field renderings can be found.

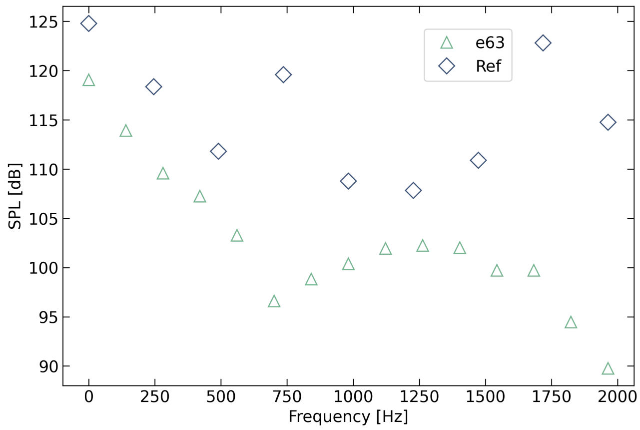

Figure 5: Sound Pressure Level distribution for both designs

5 Conclusion

As it can be seen the investigated e63 propeller does indeed show lowered broadband noise signature and thus such a method of varying the spanwise profile of the blade has been shown to be an effective method of improving aerodynamic performance in a desired way. Further on more research is needed to verify simulation results by comparing them to experimental data.

5.1 Additional Figures

In the figures presented below the intensity of vorticity can be seen rendered as a volumetric field with transference law "a". Whereas the other two figures showcase the velocity field cross-section profiles, in which the formation of tip vortices can be seen.

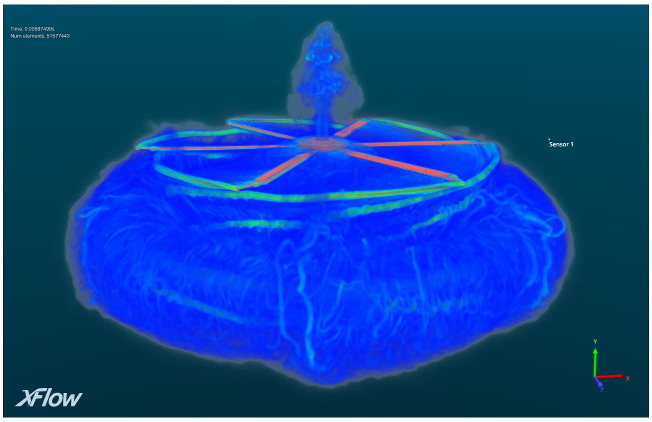

Figure 6: Volumetric Field with Vorticity Intensity for e63 propeller.

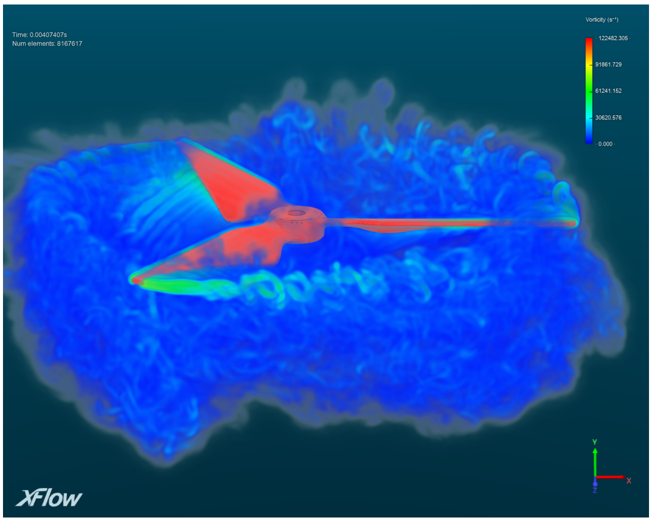

Figure 7: Volumetric Field with Vorticity Intensity for reference propeller.

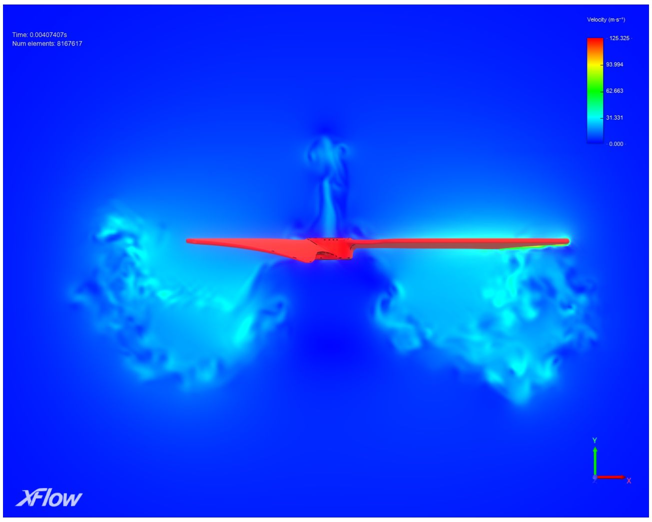

Figure 8: Velocity field cross-section for reference propeller.

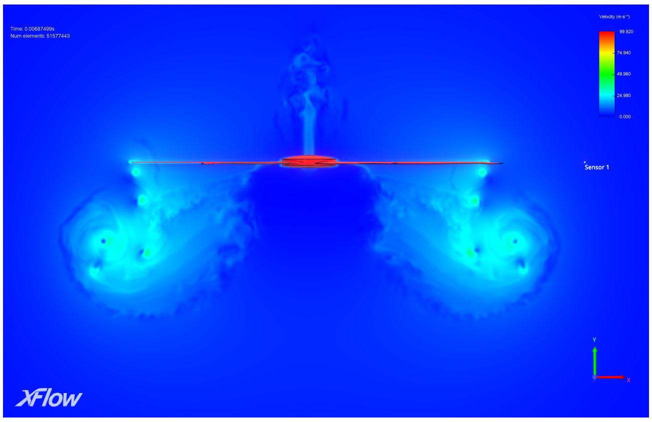

Figure 9: Velocity field cross-section for e63 propeller.

References

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