A Comparative Study of Mesh Methods, Particle Methods and Analytical Models for Multi-Rotor Noise Generation

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Introduction

The development of Urban Air Mobility (UAM) concepts promises significant improvements in urban transportation through increased flexibility, efficiency, and environmental sustainability. Distributed propulsion (DP) systems are particularly attractive due to their novel aerodynamic advantages, such as enhanced redundancy, improved maneuverability, and potentially optimized acoustic performance. However, the application of these systems in densely populated areas poses critical challenges, predominantly associated with their acoustic emissions.

An exemplary DP configuration investigated within this study is shown in Figure 1. This configuration highlights critical phenomena, including aerodynamic rotor-rotor interactions and acoustic interference between distributed tonal noise sources. The accurate modeling and prediction of these phenomena are essential to optimize acoustic characteristics and enhance public acceptance of future UAM systems.

In addressing these modeling challenges, various computational methods have been proposed and applied. The current study assesses three aerodynamic modeling techniques: Blade Element Momentum Theory (BEMT), Vortex Particle Method (VPM), and Lattice Boltzmann Method (LBM). A particular focus is placed on VPM due to its novel capabilities and promising applicability to complex aerodynamic interactions at low Reynolds numbers while maintaing low computational effort. These methods offer different fidelity to control the tradeoff between computational performance and accuracy, facilitating various stages of design and optimization. By evaluating these modeling techniques, the study aims to provide some insights into their respective advantages, limitations, and potential impacts on noise prediction accuracy for multi-rotor DP configurations.

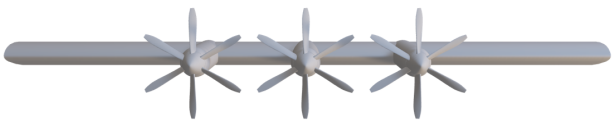

Figure 1: Investigated configuration: Three open rotors ($D \approx 200$ mm) mounted on the leading edge of a wing with a low tip gap, operating at relatively low Reynolds number [1]

Aerodynamic Modelling

Accurate prediction of rotor forces is crucial for evaluating tonal noise generation in distributed propulsion configurations. In this study, three aerodynamic modeling techniques are considered: Blade Element Momentum Theory (BEMT), Vortex Particle Method (VPM), and Lattice Boltzmann Method (LBM). Each method possesses advantages and limitations, especially when considering influential aerodynamic phenomena such as low Reynolds number effects and rotor-rotor interactions, that are prominent within the investigated configuration.

Blade Element Momentum Theory (BEMT) [2], coupled with the airfoil analysis tool XFOIL [3], has demonstrated its effectiveness in predicting rotor performance at low Reynolds numbers ($Re < 10^5$). XFOIL efficiently captures essential transitional effects, such as laminar-to-turbulent transition and flow separation or reattachment, which significantly influence rotor forces and consequently the generated noise, making it well suited method for pre-design purposes. However, BEMT is inherently limited to isolated rotor analyses and cannot account for three-dimensional aerodynamic interactions, such as rotor-rotor interaction between closely spaced rotors.

The Lattice Boltzmann Method (LBM) offers high-fidelity modeling, accurately resolving complex flow phenomena, including detailed three-dimensional interactions between adjacent rotors. Nevertheless, accurately capturing low Reynolds number transitional flows and boundary layer phenomena with LBM necessitates extremely fine computational grids, making multi-rotor simulations computationally demanding. Consequently, LBM is primarily suitable for detailed verification, validation, and advanced analysis rather than preliminary design.

The Vortex Particle Method (VPM) emerges as a promising intermediate approach. Within this study FLOWUnsteady, an open-source implementation of Brigham University [4,5] has been used. By combining particle-based numerical modeling of the flow field with airfoil polars obtained from XFOIL, VPM effectively captures transitional effects and rotor-rotor aerodynamic interactions with variable fidelity. This flexibility allows researchers to strike a favorable balance between computational cost and model accuracy, making a priori VPM particularly suitable for parametric studies and design optimization

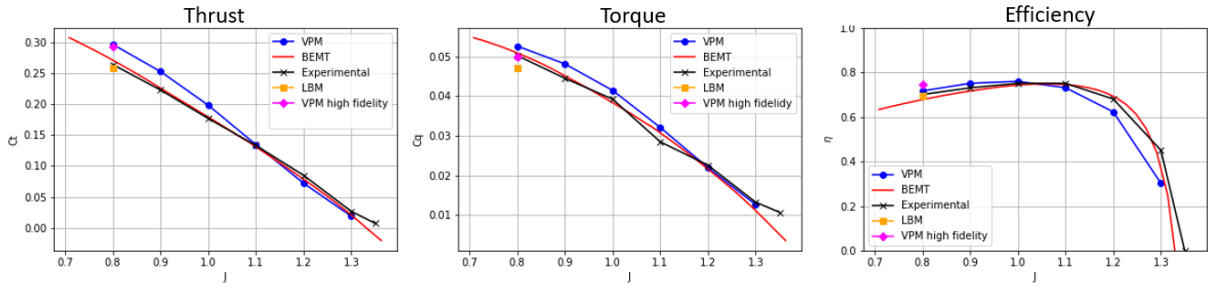

Figure 2: Comparison of single propeller performance for range of operational points by different modeling approaches

in multi-rotor configurations operating at low Reynolds numbers. The basics of this method are briefly introduced in the next section.

Vortex Particle Method

The Vortex Particle Method [4,5] is a particle-based numeric method, where the fluid is represented by particles characterized as incompressible fluid volumes moving with velocity $\mathbf{u}$ and carrying vortex strength Γ_p. Variable fidelity can be achieved by adjusting the particle size. The governing equation solved in the free field is the Navier-Stokes equations in vorticity form using a filtered Large Eddy Filter:

$$\frac{d}{dt}\bar{\boldsymbol{\omega}} = (\bar{\boldsymbol{\omega}} \cdot \nabla)\bar{\mathbf{u}} + \nu\nabla^2\bar{\boldsymbol{\omega}} - \mathbf{E}_{\text{adv}} - \mathbf{E}_{\text{str}} \qquad (1)$$

where $\bar{\boldsymbol{\omega}}$ represents the filtered vorticity, $\bar{\mathbf{u}}$ is the filtered velocity, ν is the kinematic viscosity, while $\mathbf{E}_{\text{adv}}$ and $\mathbf{E}_{\text{str}}$ denote the sub-filter scale stresses due to advection and vortex stretching, respectively.

In VPM, lifting surfaces are discretized as line sources, asserting forces based on airfoil polars derived from XFOIL. To account for 3D effects a tip loss and stall delay model is used. This enables efficient and accurate modeling of rotor forces, critical for tonal noise analysis in multi-rotor systems.

Single rotor performance

To evaluate the accuracy and reliability of the selected aerodynamic models, single rotor performance metrics (thrust, torque, and efficiency) are computed and compared against experimental data [6] across a range of advance ratios $J = v_\infty/(nD)$ as given in Figure 2. The free-stream velocity is denoted v_∞, n are the revolutions per second of the rotor and $D \approx 0.2$ m is the rotor diameter.

At a fixed free-stream velocity $v_\infty = 30$ m/s, a variation of n is performed. BEMT closely matches the experimental data in predicting rotor performance for all operational points. The high-fidelity LBM results [7] closely align with experimental measurements, validating its suitability for detailed analyses. However, due to its computational cost, its usage is limited to a single operation point of $J = 0.8$.

For the VPM, two distinct deviations from experimental data are identified. At low J, meaning fast rotational speed where high angles of attack at the airfoil are expected, VPM tends to overestimate rotor thrust. Secondly, at low rotational speed and at very low Reynolds numbers, where e.g. laminar separation bubbles can occur, VPM predicts windmilling conditions occurring earlier than observed experimentally. Nonetheless, VPM predictions showed satisfying agreement with the experimental data affirming its capabilities for capturing steady aerodynamic performance across varied operational points.

Radial distribution of rotor forces

At the reference advance ratio of $J = 0.8$ the radial distributions of rotor forces are analyzed using BEMT, VPM, and LBM as depicted in Figure 3. A qualitative agreement between models is observed, particularly regarding the general shape and peak locations of thrust and torque distributions along the rotor radius. However, the VPM model overestimated thrust compared to BEMT and LBM, which exhibited closer alignment with each other. The comparison of total force with experimental data is tabulated in Table 1 and further confirms the superior accuracy of the BEMT and LBM methods, with thrust predictions within a few percentage points of the measured values, whereas the VPM shows higher deviations. For the torque a better quantitative agreement can be observed. These insights are crucial for understanding the capabilities and limitations of each model in accurately capturing aerodynamic behaviors essential for noise prediction in multi-rotor systems.

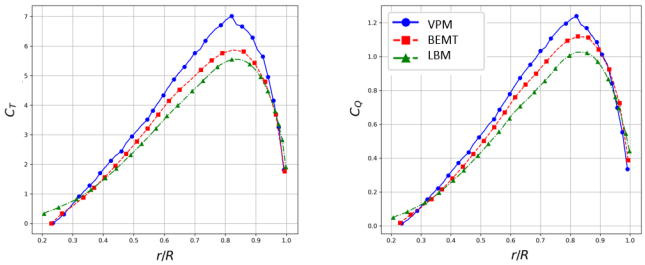

Figure 3: Radial distribution of thrust and torque coefficients at $J = 0.8$

Rotor-rotor interaction

In closely spaced multi-rotor configurations, each rotor operates within the aerodynamic potential field generated by the neighbouring rotor. These rotor-rotor interactions lead to periodic fluctuations of aerodynamic

	Thrust	Δ_{exp}	Torque	Δ_{exp}
Exp.	18.59 N	-	0.71 Nm	-
BEMT	18.86 N	+1.5%	0.72 Nm	+1.4%
LBM	18.16 N	−2.3%	0.69 Nm	−2.4%
VPM	20.15 N	+8.4%	0.73 Nm	+2.8%

Table 1: Thurst and Torque comparison of different models with experimental data at $J = 0.8$

loads, particularly at the rotor blade tips, significantly affecting rotor performance and noise emissions.

Mean thrust distribution and thrust fluctuations of the central rotor computed by LBM and VPM are presented in Figure 4. Both methods qualitatively capture the periodic fluctuations induced by adjacent rotors; however, VPM predicts higher mean thrust and a higher amplitude of thrust fluctuations compared to LBM. These deviations arise from inherent differences in modeling assumptions and fidelity.

The periodic force fluctuations caused by rotor-rotor interactions are critical, as they directly excite tonal noise. The acoustic modeling techniques used in this study will be further discussed in the next chapter.

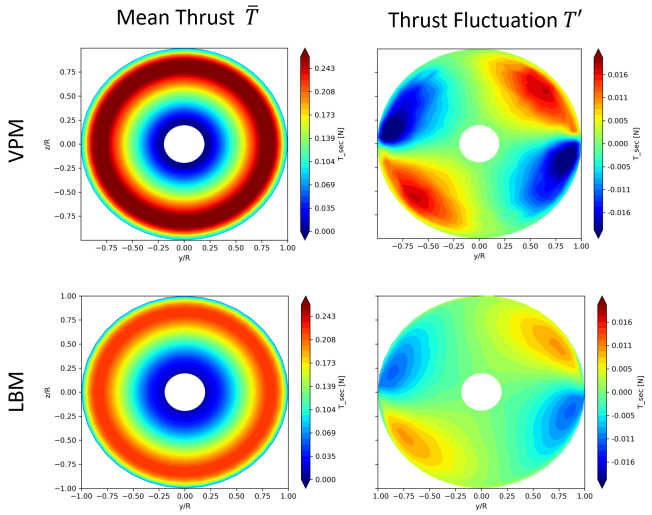

Figure 4: Spatial thrust variation of a single blade of the central propeller

Acoustic modeling

The directivity of tonal noise generated by the multi-rotor configuration is analyzed by two approaches:

- A FW-H simulation based on the LBM simulation data [7]. A widely used numerical approach that can calculate noise emission based on high fidelity aerodynamic simulation input.
- An simplified approach based on the acoustic analogy with VPM simulation input, that is further explained within the next section.

Analytic noise model

The first part of the acoustic model aims to determine the directivity of tonal noise of a single rotor configuration. Therefore, an analytical approach based on the acoustic analogy is used. The modal sound pressure at an observer position $\mathbf{x}_{obs}$ in the frequency domain is calculated by solving a radial integral over the rotor blade length [8]:

$$p_m^{\omega}(\mathbf{x}_{obs}) = B \int^{R} g_m^{\omega} e^{-i(k_x x_{LE} + m\theta_{LE})} \sigma_m^{\omega} dr \qquad (2)$$

This contains two main components:

- Green's function g_m^{ω}, which propagates the noise sources into the far field
- Source term σ_m^{ω}, representing different noise-generation mechanisms

The noise generating mechanisms for this configuration consists of the profile thickness as well as steady and unsteady loading of the blade that are extracted from VPM simulation data. Further details on the derivation and specific formulations of the source terms are available in [8].

The noise generation of the multi-rotor configuration is calculated by complex addition of all occurring noise sources of each rotor. The acoustic interference between distributed noise source are accounted for by a model based on linear superposition [9]. Former studies have shown that acoustic interference for this configuration is highly influential on the directivity and level of the tonal noise mission [10].

By employing this method, it is possible to efficiently analyze and predict the noise directivity of single and multi-rotor systems, providing valuable insights into tonal noise characteristics and their dependence on rotor configuration and operational conditions.

Tonal Noise Directivity

Finally, the tonal noise directivity of the multi-rotor configuration is compared between the two modeling approaches: VPM combined with acoustic analogy (VPM+AA) and LBM combined with the Ffowcs Williams–Hawkings method (LBM+FW-H). The comparison considered two observer polars, one downward-facing and one sideways-facing arc at the blade passing frequency (BPF), its first two harmonics and the cumulated tonal noise as shown in Figure 5.

Both modeling approaches exhibit good agreement in terms of the overall directivity patterns and trends across the analyzed frequencies. This consistency confirms the validity of both methodologies for capturing the essential acoustic characteristics of multi-rotor configurations. The agreement of both methods in directivity are less satisfactory for the sideways facing polar. The reason for that is unclear but could be related to nearfield effects, that are neglected for the VPM+AA-method.

However, due to the overestimation of propeller forces observed with VPM, there is a corresponding overestimation in sound pressure level (SPL) predictions compared to the LBM+FW-H results. This discrepancy underscores the importance of accurately modeling aerodynamic forces to ensure reliable aeroacoustic predictions.

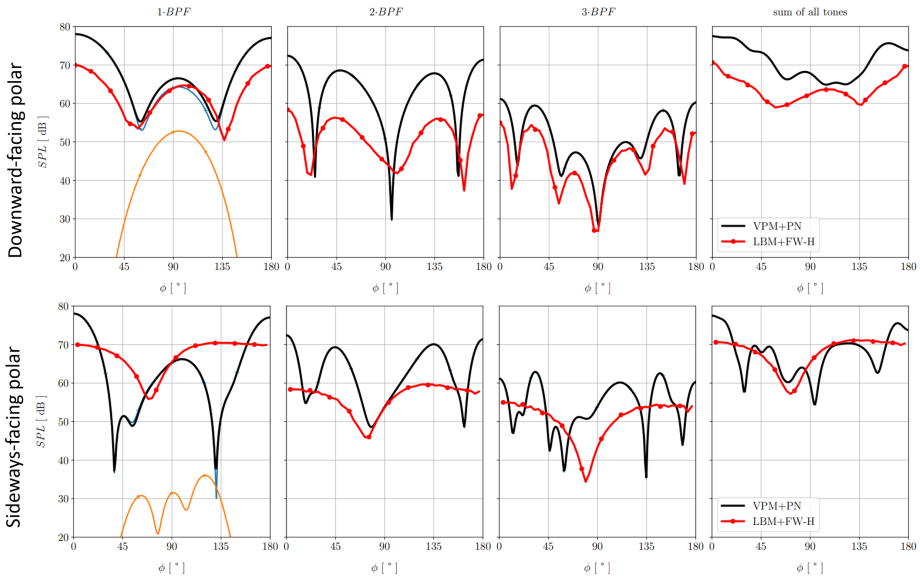

Figure 5: Tonal noise directivity of multi-rotor configuration

Conclusion

This study compared different approaches for predicting rotor forces, aerodynamic interactions, and tonal noise emissions in multi-rotor urban air mobility configurations. Each method was evaluated regarding computational efficiency, accuracy, and suitability for different design stages.

BEMT coupled with XFOIL accurately predicted isolated rotor performance at low Reynolds numbers, making it suitable for preliminary design. However, it could not capture three-dimensional rotor interactions, limiting its use in detailed multi-rotor analyses.

LBM accurately resolved rotor forces and rotor-rotor interactions, closely aligning with experimental data. Its high computational demands, however, restrict its application mainly to detailed verification studies.

VPM provided a balance between computational efficiency and accuracy, effectively capturing key aerodynamic interactions and transitional effects. Nonetheless, it tended to overestimate rotor thrust at higher rotational speeds, leading to acoustic prediction discrepancies.

Acoustic directivity patterns showed good agreement between the mixed (VPM+Acoustic Analogy) and numerical (LBM+FW-H) methods. Discrepancies mainly arose from variations in aerodynamic predictions, underscoring the importance of accurate aerodynamic modeling for reliable acoustic forecasts. The results of this study motivate the further application of the VPM method for the acoustic investigation of open rotor installation effects.

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