

SIMULATION OF AERODYNAMIC GROUND EFFECT FOR TILTED PROPELLERS USING VISCOUS SURFACE-VORTICITY PANEL METHOD

Shahfiq Shahjahan[1] & Vivek Ahuja[1]

[1]Siemens Digital Industries Software Inc., Plano, TX 75024, USA

Abstract

This study investigates the aerodynamic performance of small-scale propellers operating in ground effect using Simcenter™ Flightstream™, a mid-fidelity viscous surface-vorticity panel method solver designed for efficient rotorcraft analysis. Simulations were performed for a T-Motor 13" × 4.4" propeller across multiple ground clearances and tilt angles, and benchmarked against experimental measurements and high-fidelity CFD data. The results demonstrate strong predictive accuracy both out of ground effect and in proximity to the ground, with thrust ratio deviations below 3% and vertical thrust component errors under 4.4%. Larger discrepancies occur at very low clearances where wake interaction becomes increasingly complex; however, overall performance indicates that Simcenter Flightstream balances computational speed and accuracy effectively. These findings support its suitability for early-stage UAV/MAV rotor design and parametric assessments involving confined or near-ground flight operations.

Keywords: Ground Effect, Panel Method, Propeller Aerodynamics, UAV/MAV Design

1. Introduction

Unmanned Aerial Vehicles (UAVs) and Micro Air Vehicles (MAVs) are rapidly expanding their range of applications [1]. Traditionally, these aerial robots have served as flying sensors for perceptual tasks, including remote surveillance and reconnaissance [2, 3], visual inspection of large infrastructures [4, 5], and aerial filming [6, 7]. However, emerging applications, such as package delivery [8], contact-based inspections [9, 10], warehouse inventory monitoring [11], and aerial robotic manipulation more broadly [12], require these rotorcraft to operate in close proximity to obstacles or within confined environments. In such scenarios, propellers encounter altered aerodynamic conditions, which disrupt the natural development of rotor wakes and affect the propeller performance [13].

Numerous studies have explored the impact of ground effect on rotor aerodynamic performance through both experimental and theoretical approaches. Experimentally, early investigations primarily measured rotor thrust and shaft power during hovering near the ground [14]. These studies demonstrated that ground effect can reduce shaft power consumption and enhance hovering efficiency. As flow visualisation technologies advanced, techniques such as smoke flow visualisation [14], wide-field shadowgraphy [15], and particle image velocimetry (PIV) [16] were adopted to capture the geometry and evolution of rotor tip vortices under ground effect conditions. Theoretically, several aerodynamic models were developed to characterize ground effect in its early stages. Betz [17] introduced a mirror image method based on momentum source theory, using mirrored sources to simulate ground boundary conditions. Additional approaches, including free-wake theory [18], and jet theory [19] have also been applied to analyse rotor behavior in ground effect. However, these theoretical models often rely on substantial experimental data to calibrate correction factors. As a result, their applicability

is limited when dealing with the complexity of rotor flow fields and performing detailed ground effect analyses across different rotor configurations.

Accurately predicting the flow around rotors operating in ground effect requires simulations grounded in first-principles methods. Kutz et al. [20] utilised the Reynolds-Averaged Navier-Stokes (RANS) equations to model the flow around a single rotor in ground effect. Their study provided detailed insights into the geometric configuration of tip vortices and the resulting rotor thrust coefficients, with simulation results closely aligning with experimental data, demonstrating the validity of their approach. However, the high computational cost associated with Computational Fluid Dynamics (CFD) simulations makes them impractical during the conceptual and preliminary design phases, where rapid assessment of multiple configurations is required. In contrast, unsteady free-wake panel methods offer a more computationally efficient alternative. These methods are capable of capturing rotor wake behaviour under a variety of flight conditions including hover, while requiring only a fraction of the computational resources demanded by full Navier-Stokes solvers [21].

This study assesses the accuracy of Simcenter™ Flightstream™, a viscous surface-vorticity panel method solver, in simulating propellers operating in ground effect. The objective is to determine how accurately and efficiently Simcenter Flightstream can predict aerodynamic forces under these conditions, making it a potential tool for use in early-stage rotorcraft design.

2. Model Geometry

The propeller selected is a small-scale T-Motor propeller with a diameter of 18 inches and a pitch of 4.4 inches (a figure with the chord and pitch distribution will be added in the final paper).

3. Computational Setup

3.1 Introduction

Mid-fidelity flow simulations in this study were conducted using the Simcenter Flightstream flow solver - a highly efficient, compressible, subsonic, three-dimensional surface-vorticity panel method with viscous coupling capabilities [22]. Simcenter Flightstream has been developed by Research in Flight under several NASA and United States Air Force (USAF) SBIR/STTR development contracts [23–27].

The solver utilises resolved surface vorticity to compute aerodynamic load distributions via an advanced Fast Multipole Method (FMM). Originally devised for generalised n-body problems in gravitational fields [22], FMM has since been extended to various potential-driven problems, including electrostatics and potential flow. Its core approach involves aggregating distant (far-field) source or doublet bodies into singular composite representations, simplifying the evaluation of their net effect on a near-field body. While the influence of near-field elements is calculated with $\mathcal{O}(n^2)$ accuracy, the contribution of far-field elements is computed using a reduced set of representative clusters. In Simcenter Flightstream, these clusters are modelled as localised three-dimensional point doublets that collectively reflect the net vorticity strengths of the original far-field panels.

For viscous flow analysis, Simcenter Flightstream includes both laminar and turbulent boundary layer models, along with a transition model. These models, originally two-dimensional, have been adapted for application along generalised three-dimensional on-body surface streamlines. They offer computational efficiency while remaining applicable to most wall-boundary conditions, except in cases involving three-dimensional crossflow. The laminar boundary layer model is based on the Thwaites integral method, a standard two-parameter approach utilising the momentum integral equation [24].

Turbulent boundary layer modelling in Simcenter Flightstream follows the approach developed by Standen [28], selected for its robustness and applicability across subsonic Mach numbers. Though numerically improved, the model retains the core methodology of Standen's original formulation, tailored for compressible, subsonic, turbulent flows along body streamlines. Outside the boundary layer, the flow is assumed to be compressible, subsonic, and isentropic. Simcenter Flightstream also models laminar and turbulent separation phenomena, requiring an effective transition model to determine the point of switch between the two regimes. For this, the solver employs the model by Dvorak et al. [29], which is used in the present analysis.

Additionally, unsteady flow simulations are supported through Simcenter Flightstream's time-domain solver. This is coupled with a motion definitions module that allows arbitrary motion inputs including rotation, translation, acceleration, flapping, and morphing. These motion definitions can also be integrated into complex mechanical systems, enabling the simulation of dynamic and time-dependent flow scenarios.

3.2 Grid Setup

Since panel methods such as Simcenter Flightstream require only a surface grid, this section of the paper focuses solely on surface-related parameters. The propeller blades are meshed using Simcenter Flightstream's Component Cross Section (CCS) Geometry format. Custom-defined sectional airfoil coordinates along the blade were provided in ASCII format. When imported into Simcenter Flightstream, a lofted surface body with anisotropic quadrilateral surface grids was automatically generated based on the specified chordwise and spanwise mesh refinement.

Mesh grid parameters for both the propeller and ground regions were selected based on best practices established in prior studies [23–28, 30]. The complete surface mesh is illustrated in Figure 1, with a detailed breakdown of mesh settings for each component provided in Table 1.

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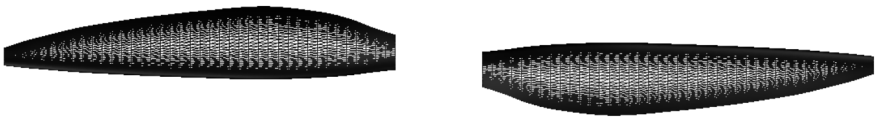


Figure 1 – Simcenter Flightstream surface grids for the propeller

Table 1 – Simcenter Flightstream grid parameters

Parameter	Propeller	Ground
Chordwise points	120	50
Spanwise points	40	50
Surface directional growth rate	1.1 (Dual-sided)	1.0
Total face count	24,146	

3.3 Performance and Convergence

Unsteady flow simulations in Simcenter Flightstream were executed on a 28-core CPU with the 13th Gen Intel(R) Core(TM) i7-13850HX (2.10 GHz) processor and 64 GB RAM, utilising all 28 cores for parallel computation. The average solution time was approximately 30 minutes per simulation.

Solver convergence criteria were set to 10^{-5} for aerodynamic loads and moments at each time step, ensuring a sufficiently accurate steady solution. Viscous coupling was activated for all runs to account for boundary layer effects. Given Simcenter Flightstream's classification as a mid-fidelity solver, this setup was deemed to provide a suitable compromise between computational cost and solution fidelity.

4. Results

The results from the simulations of the T-Motor propeller 13" $\times$ 4.4" propeller with and without ground effect are discussed in this section. In each case, the aerodynamic predictions from Simcenter Flightstream are compared against experimental and CFD data from Garofano-Soldado [31] across a range of different rotational rates and ground height.

4.1 Out of Ground Effect

Figure 2 compares the static performance of the propeller as predicted by Simcenter Flightstream, CFD, and experimental measurements. The results show that as the rotational speed and consequently the Reynolds number increases, the thrust coefficient rises, while the torque coefficient remains nearly constant. The prediction errors for thrust and torque are under 5% and 10%, respectively.

Under static conditions, the accuracy of rotor performance prediction is closely linked to the model's ability to capture blade tip vortex structures [32]. The results presented in this section indicate that Simcenter Flightstream is capable of reliably predicting aerodynamic forces on the propeller in an unobstructed, free-flow environment. While it may not resolve tip vortex structures as precisely as higher-order CFD schemes, its performance is considered sufficient for capturing overall force characteristics in such conditions.

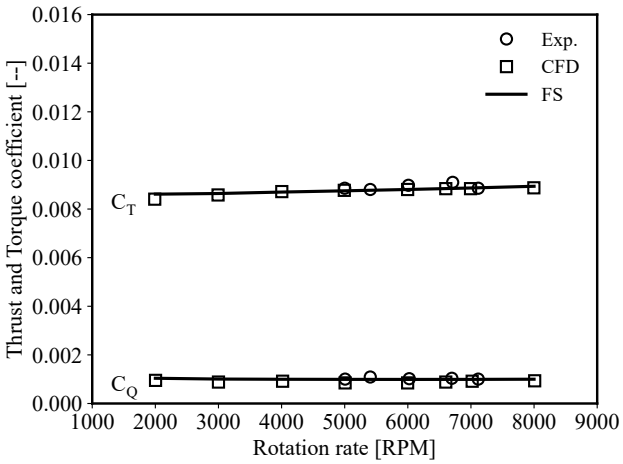


Figure 2 – Comparison of the static performance of the T-Motor propeller 13" $\times$ 4.4" for different rotational rates with experimental and CFD results [31]

4.2 In Ground Effect

This section presents a comparison of the aerodynamic coefficients predicted by Simcenter Flightstream against both experimental and CFD results [31], with a ground surface placed beneath the propeller to simulate operation in ground effect.

All three approaches analyse a co-planar configuration, where the rotor is parallel to the ground ($\theta = 0°$), as well as three tilt angles: $\theta = 0°$, $10°$, and $30°$. Additionally, ten vertical distances from the propeller's centre of rotation to the ground surface were evaluated: $z/R = 0.6$, 0.75, 1, 1.5, 2, 2.5, 3, 3.5, 4, and 5. For all simulations in this section, the propeller's rotational speed is fixed at 6300RPM.

Figure 3 shows the variation in the thrust ratio, defined as the ratio of thrust in ground effect (IGE) to out of ground effect (OGE), as a function of ground clearance. The Simcenter Flightstream predictions show excellent agreement with both experimental and CFD results, with a maximum error of less than 3%.

Furthermore, the expected trend is accurately captured: as the distance from the ground increases, the thrust gradually decreases, indicating a diminishing ground effect as the propeller moves further from the surface. When the rotor operates close to the ground, its wake is constrained in the axial direction and cannot expand downward as freely as it would in an unobstructed environment. Due to the non-slip condition at the ground surface, the flow is forced to expand radially upon reaching the ground. This interaction between the rotor wake and the ground plane leads to the formation of vortex structures beneath the rotor, commonly referred to as the ground vortex [33]. The observed increase in thrust near the ground is primarily attributed to the reduction in downwash velocity beneath the propeller, which enhances the overall pressure difference across the rotor disk.

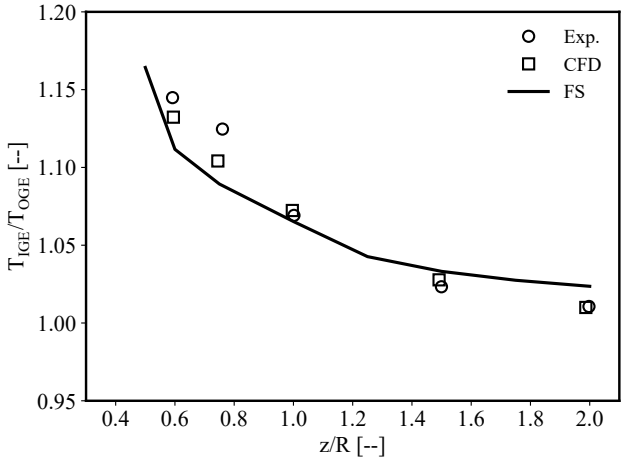


Figure 3 – Comparison of thrust ratio $T_{\mathrm{IGE}}/T_{\mathrm{OGE}}$ for $\theta = 0^{\circ}$ against both experimental and CFD results [31]

Figure 4 presents a comparison of the vertical and horizontal thrust components across varying propeller tilt angles and ground heights. Once again, excellent agreement is observed, with Simcenter Flightstream accurately capturing the trends in both components as a function of tilt angle and ground clearance. The maximum error in the vertical thrust component is 4.4%, while the horizontal thrust component shows a maximum deviation of 10%.

It is noted that discrepancies between Simcenter Flightstream predictions and experimental data are more pronounced at lower ground heights, where the interaction between the propeller wake and the ground surface becomes more significant. Nevertheless, considering the significantly lower computational cost of Simcenter Flightstream compared to high-fidelity CFD methods, the level of accuracy achieved is considered acceptable for use in preliminary design and analysis.

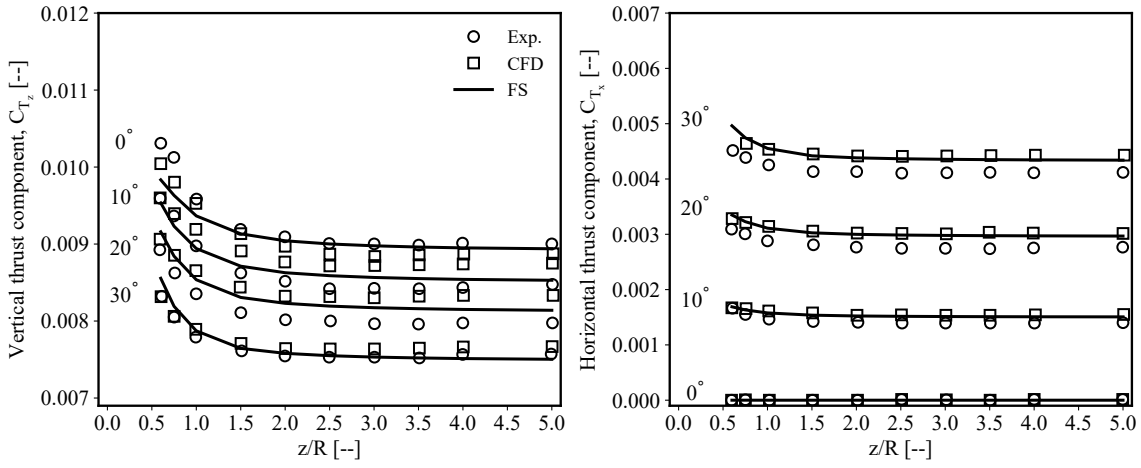


Figure 4 – Comparison of vertical and horizontal thrust component with tilt angles against both experimental and CFD results [31]

5. Conclusions

This study evaluated the capability of the mid-fidelity solver Simcenter Flightstream to predict the aerodynamic performance of small-scale propellers operating in ground effect (IGE), with particular focus on the influence of tilt angle and ground proximity. The solver's predictions were benchmarked against experimental data and high-fidelity CFD simulations for a T-Motor 13" $\times$ 4.4" propeller under a range of operating conditions.

Simcenter Flightstream accurately captured the overall trends in thrust and torque outside of ground

effect, with prediction errors remaining below 5% and 10%, respectively. Within ground effect, the solver successfully reproduced the expected increase in thrust as ground clearance decreased, achieving a maximum thrust ratio error of less than 3%. When evaluating tilted configurations, the solver showed strong agreement in both vertical and horizontal thrust components, with respective maximum errors of 4.4% and 10%. Slight deviations were observed at lower ground heights, likely due to stronger and more complex wake-ground interactions that pose challenges for mid-fidelity methods.

These results indicate that Simcenter Flightstream offers a compelling balance between accuracy and computational efficiency. It is particularly well-suited for early-stage rotorcraft design and parametric studies, where rapid assessment of multiple configurations is required.

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