

Abstract

The proliferation of small unmanned aerial vehicles (SUAVs) over the last decades has greatly increased the demand for compact, efficient, and reliable propulsion systems. Despite significant technological progress, small-scale propellers still suffer from low aerodynamic efficiency due to the low chord-based Reynolds numbers and the challenging operative conditions encountered in a typical mission profile. These challenges lead to unsteady loading and performance degradation, ultimately limiting flight endurance, payload capability, and platform stability. This thesis addresses these critical aerodynamic issues by conducting a comprehensive experimental and numerical investigation of an open-geometry, small-scale propeller operating in challenging scenarios, such as non-axial inflow and dynamic maneuvers.

An extensive experimental campaign was performed in the wind tunnel at Politecnico di Torino, using load measurements and planar Particle Image Velocimetry to characterize thrust, torque, and wake topology in both axial and cross-flow conditions. Large Eddy Simulations (LES) were then used to provide high-fidelity insights into the unsteady flow physics, including vortex dynamics, wake deflection mechanisms, and azimuthally varying blade aerodynamics. This numerical dataset enabled the formulation of a simplified wake-skew modelling approach suitable for propellers in cross-flow.

To explore transient operational conditions, a mid-fidelity Vortex Particle Method solver (VULCAINS), developed at ONERA, was validated against experiments and URANS simulations in steady-state conditions. The validated tool was subsequently employed to analyse maneuvering scenarios relevant to typical SUAV missions, including rapid rotational speed variations and propeller tilting. These analyses revealed the presence of load hysteresis, transient performance overshoots, and significant changes in the wake structure that are not captured under steady-state assumptions.

The findings deepen the current understanding of small-scale propeller aerodynamics and expand the available performance and wake database beyond classical axial-flow/hovering configurations. This work supports the development of more robust design and control strategies for next-generation SUAV propulsion systems.