Doctoral Dissertation
Doctoral Program in Aerospace Engineering (35^{th}cycle)

Numerical Simulation and Aerodynamic Design of Small-Scale Rotary-Wing for Unmanned Aerial Systems in Terrestrial and Martian Applications

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Politecnico di Torino
2023

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2023

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

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Small-scale rotary-wing Unmanned Aerial Systems (UAS) have gained increasing attention for various applications such as environmental monitoring, search and rescue, military surveillance, and Martian exploration. However, the design of these UAS requires careful consideration of their aerodynamic performance, particularly of their rotors, which play a crucial role in the overall efficiency and stability of the system. Numerical simulation is a crucial tool for designing small-scale rotors, as experimental testing of these systems can be expensive and time-consuming. However, the accuracy of numerical simulations depends on the fidelity of the models used, and the computational cost of high-fidelity models can be prohibitive.

In this thesis, we explore different numerical approaches to simulate the aerodynamic performance of small-scale rotors, ranging from reduced-order models based on the blade element momentum theory and vortex methods to high-fidelity Computational Fluid Dynamics (CFD) simulations. We can distinguish two low Reynolds number regimes. The very-low Reynolds number regimes, with Reynolds number, comprised between $10^4 - 10^5$, and the ultra-low Reynolds number regime where Reynolds number falls below $10^3 - 10^4$. The former is typically found in small-scale UAS performing terrestrial applications. In this regime, the boundary layers usually present transition to turbulence, and separations bubbles are typical. The former is typically found in high altitudes on Earth and the Martian atmosphere. The exotic combination of high subsonic Mach numbers and ultra-low Reynolds numbers requires thoroughly revising the design guidelines for airfoils and rotors operating in these conditions. Different validation exercises of the flows in these regimes have been performed, showing how computational fluid dynamics, with the appropriate experimental validation, can be used to gain invaluable insight into complex rotor and airfoil aerodynamics. We also discuss different efficient airfoil and rotor geometries designed ad-hoc for the Martian operation regime, stating the substantial differences from traditional lifting surfaces. All the developed reduced order models used for the design in low Reynolds number conditions have been

packed into a Matlab APP, *ROT-8*, including different design and analysis modules for rotors and airfoils.

Building on the previous studies, several UAS terrestrial applications have been assessed, applying the lessons learned on rotor modeling in realistic dynamical systems. These applications are the study of an innovative passive swashplateless rotor, the analysis of multicopter maneuvers, focusing on those close to obstacles, and finally, the assessment and numerical modeling of a multicopter spraying operation in the vineyard scenario. These applications require understanding the dynamic fluid-body interactions coupling aerodynamic and dynamic solvers. We have created a virtual testing environment implementing quadcopters and hexacopters, including a PID controller that allows reproducing real maneuvers like hovering near obstacles or flying and spraying over a vineyard. In particular, for the vineyard application, we couple multicopter maneuvers, aerodynamics, and droplet trajectories to assess the effectiveness of the spray operation. The developed model has been verified with other simplified and well-known reduced-order models, and experimental validation of the multiphase rotor-droplet interactions has been performed.