Multi-Fidelity Vortex Particles Coupling with Lifting Line and Eulerian Methods for 3D Viscous Aeronautical Simulations

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Abstract

This thesis presents the development of a multi-fidelity approach for simulating 3D unsteady viscous flow fields around complex aeronautical configurations, using the Lagrangian Vortex Particle Method (VPM) coupled with either Lifting Line or an Eulerian Unsteady Reynolds-Averaged Navier-Stokes (URANS) methods. The primary goal is to provide a computationally efficient yet accurate method to model vortex dynamics, wake interactions, and the evolution of vortex structures for aeronautical applications. At the core of this method is the VPM, which simulates the evolution of vortices and wake dynamics with minimal numerical dissipation and without the need for domain meshing. This makes it ideal for capturing complex wake interactions present in aeronautical simulations. However, the VPM alone is ill-suited for capturing near-wall effects which are crucial for accurately predicting aerodynamic performance. To address this issue, the VPM is first coupled with the Lifting Line method to model thin lifting surfaces efficiently, allowing for the interaction between the fluid and solid bodies. Additionally, an Eulerian method is integrated to resolve detailed near-wall viscous and compressible effects. This hybrid multi-fidelity approach between the VPM and URANS allows for the simulation of both the transport of the wake in the far field and the evolution of boundary layer interactions near solid surfaces, making it adaptable to a large variety of flow conditions. To alleviate known limitations inherent to the VPM, several contributions are brought forward in this thesis. A dynamic turbulent viscosity model is thus developed for the VPM, improving its handling of viscous diffusion in high-Reynolds flows. To maintain numerical stability, particularly in turbulent regimes, a novel enstrophy-based filtering technique is introduced, helping to preserve vortex coherence in highly dynamic flow fields. The VPM, as well as its coupling with either Lifting Lines or URANS, is validated against analytical, experimental, and numerical reference cases, including, amongst others, analytical vortices, wings, propellers, wind turbines, drones and hovering helicopter rotors. These results demonstrate the accuracy and efficiency of this approach in simulating a large range of complex aerodynamic flows at a reasonable computational cost while being able to capture key flow characteristics. This thesis provides with multi-fidelity coupled methods able to tackle a broad range of aeronautical configurations, positioning the VPM as a powerful tool in modern aerodynamic design optimisation, performance evaluation, and flight simulation.