Propeller Representation in Full-Vehicle CFD: Actuator Disk Versus Body-Force Modeling Approaches

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Abstract: This paper presents the application of an advanced body-force propulsor model to a wing-blowing propeller and its comparison with a traditional actuator disk model. These models are used in RANS simulations of a flying vehicle with tight coupling between airframe and propulsors, specifically a blown-lift wing in which propellers blow onto a flap to produce high lift. We compare predicted load distribution, propeller performance, jet properties, and wing performance for a range of operating conditions. The body-force model is better able to predict interactions between wing and propellers, and adapts to the local flow in a way that better mimics actual propeller operation.

Keywords: Propeller Modeling, Body-Force, Actuator Disk, Blown-Lift, Aerodynamics, Computational Fluid Dynamics.

1 Introduction

Recent flying vehicle developments have focused on increasing efficiency (to reduce emissions) and enhance air-mobility for regional and urban markets. This has led to aircraft concepts in which the airframe and propulsion systems are tightly coupled, whether via boundary layer ingestion or distributed wing-mounted propulsion. The analysis and design of these types of vehicles require accurate modeling of the interactions between propeller and airframe, and advanced propulsor models are needed for CFD of these vehicles.

Traditional actuator-disk models, with prescribed total thrust and load distribution, can generally adequately represent isolated propulsors, but fail in off-design conditions with large flow-propeller misalignment, or when propeller and airframe flow-fields are coupled. A body-force model that incorporates the propeller geometry and the local flow conditions is better able to represent propulsor behavior and response in a variety of conditions, but adds complexity. The goal of this paper is to determine whether a body-force model is required, or whether actuator-disk approach is sufficient, to simulate wings with distributed electric propulsion.

We consider a blown-lift flapped-wing with propellers distributed along the span that blow on the wing to produce high lift and enable take-off and landing over very short distances. The wing and propeller geometries used in the present study are adopted from a sub-scale wind tunnel experiment conducted by MIT [1], which provides a test bed for studying the capabilities of propulsor models. This work was funded by a NASA STTR Phase I project and carried out in collaboration with Electra.aero.

2 Methodology

2.1 Solver

The open-source CFD code ADflow [2] is used to perform compressible Reynolds-Averaged Navier-Stokes (RANS) simulations with the Spalart-Allmaras turbulence model. Both the actuator disk model and the body-force model are implemented and tested.

2.2 Propeller Models

The actuator disk model specifies a total thrust that is radially distributed following Betz optimal circulation distribution with Prandtl's tip loss correction. Its local force per volume has a roughly elliptical distribution.

The body-force modeling approach inherits the idea of turbomachinery through-flow models that aim to create the necessary flow turning instead of directly specifying the blade loading. We use a form of the body-force model that we previously developed for modeling turbofan-type engines, and which replaces the propulsor blades with a source field to produce the equivalent work input and flow losses via use of the local flow-field velocity and blade camber and thickness distributions. A detailed description of the model can be found in [3].

3 Example Result

As Figure 1 shows, there are noticeable differences between the actuator disk and body-force models. Body-force model predicts higher loading at the bottom of the propeller where the advance ratio is locally lower. This results in a thicker jet sheet formed at the flap trailing edge.

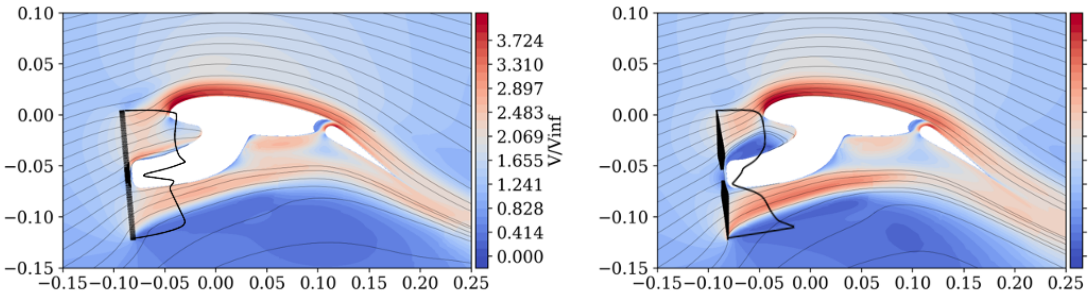

Figure 1: Blown-flap velocity contours and streamlines on spanwise plane for wing at 5° angle of attack with 30° flap deflection angle and blowing coefficient $\Delta c_j = 3.0$: comparison between actuator disk model (left) and the body-force model (right).

References

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