Technical Abstract: Propulsion Systems for VTOL Electric Vehicles

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Abstract

The design problem of selecting the best propulsor for an electric vertical take off and landing (e-VTOL) application is explored and a novel criterion is proposed for directly comparing performance of an electric ducted fan (EDF) and propeller in hover. A turbomachinery design approach is used to develop a ducted fan with a non-dimensional thrust to power ratio 103% higher than a VTOL optimised propeller. It is shown that payload size and relative EDF flow area, with respect to propeller area, determines which propulsion system is most suitable. A modular flying test bed with a quadcopter configuration is developed to test each propulsion system.

The report opens with a discussion on current trends in e-VTOL design, noting the range of both propeller and EDF driven systems being developed. The relative merits of an EDF compared to a propeller are explored, concluding that without further analysis there is no clear choice between the two. Literature on the use of EDFs in unmanned aerial vehicles (UAVs) and personal aerial vehicles (PAVs) focuses on fan and duct geometry and ducted fan performance in various operating conditions, but does not address the systems level approach needed to design for a general application. The absence of a turbomachinery approach to fan design is also noted. Both a turbomachinery and systems level approach are taken in the report.

The non-dimensional thrust to power ratio, known as figure of merit, is presented as a method of quantifying propulsor performance in hover and its failure to account for propulsor weight is noted. An ideal ducted fan with a straight exit duct has a theoretical figure of merit 41% larger than an ideal propeller, as in Pereira (2008). A novel 'superiority parameter' is presented from which the most suitable propulsor for a given application can be determined. Requiring less power to maintain static hover with a given payload is achieved when a propulsor's superiority parameter is positive. The design of a 1kg modular flying test bed system is presented. This enables the comparison of a ducted fan and propeller to be made using the superiority parameter.

The aerodynamic design of a 3D printed EDF, required to propel the flying test bed in hover, is presented. The superiority parameter across a geometric design space is evaluated, using a mass model to estimate propulsor weight. The EDF has a single low Reynolds number rotor-stator stage and a diffusing exit duct that gives a theoretical figure of merit 51% higher than an ideal propeller. Mechanical and electrical design is considered and an embodied propulsor design presented.

Propulsors are tested on a fixed test stand to determine stationary performance. The propeller is found to have an aerodynamic efficiency of 67%, and the EDF a figure of merit 103% larger than the propeller, with an aerodynamic efficiency of 90%. Aerodynamic loss is hypothesised to result primarily from low Reynolds number flow separation from the blades, skin friction from high surface roughness, and shroud clearance flow loss. The superiority parameter was found to be within 2% of the predicted value, validating the mass model. At the design payload the superiority condition is not satisfied, however, the range of payloads and propulsor area ratios required to satisfy the superiority condition are evaluated and a design chart is presented, enabling the choice of EDF or propeller for a given application to be made.

Recommendations for future work are rationalised in light of the project outcomes. In particular, contra-rotating EDFs (CRDFs) are discussed as having the most potential for further study. As in Waldren *et al.* (2019), thrust output can double compared to a non-contra-rotating ducted fan (NDF) meaning fewer propulsors are required to maintain hover. It is shown the superiority condition can be satisfied at lower payloads and propulsor area ratios when using a CRDF compared to a NDF due to the subsequent reduction in propulsor weight.