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Masters Project Report

# 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 criteria 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 the geometry of the EDF inlet and exit duct, as well as the performance of the ducted fan at 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.

The non-dimensional thrust to power ratio, Figure of Merit ($M_F$), is presented as a method of quantifying propulsor performance in hover and its failure to account for propulsor weight is noted. Theoretical $M_F$ of an isentropic EDF is shown to be $\sqrt{2\sigma}$ where $\sigma$ is the exit duct inlet-to-exit area ratio, whereas the theoretical $M_F$ of an isentropic propeller is 1, as in Pereira (2008). A novel 'superiority condition' 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, $\Sigma$, is positive.

The design of a 1kg modular flying test bed system is described. Manufacturer's performance data for a VTOL optimised propeller, verified by experiment, is used to determine the system efficiency in hover. EDF performance is compared to this VTOL optimised propeller.

The aerodynamic design of a 3D printed EDF required to propel the flying test bed in hover is presented, in which the superiority parameter across a geometric design space — defined by the casing radius and blade hub-to-tip ratio — is determined using a mass model. The EDF has a single low Reynolds number rotor-stator stage operating speed at 6000 RPM and an exit duct area ratio of $\sigma = 1.13$, giving a theoretical $M_F = 1.51$. Mechanical and electrical design is considered and an embodied propulsor design presented. For a payload of 1kg it is determined the superiority condition will not be satisfied.

Propulsors are tested on a fixed test stand to determine stationary performance. The propeller is found to have a $M_F = 0.67$ and a corresponding aerodynamic efficiency of 67%, and the EDF a $M_F = 1.36$ and a corresponding aerodynamic efficiency of 90%. Loss is hypothesised to result primarily from low Reynolds number flow separation from the blades, skin friction from high 3D printer induced surface roughness, and shroud clearance flow mixing. The superiority parameter was found to be $\Sigma = -0.82$, within 2% of the predicted value, validating the mass model. The range of payloads and propulsor area ratios required to satisfy the superiority condition are evaluated and a map is presented enabling the choice of EDF or propeller for a given application to be made.

Contra-rotating EDFs (CRDFs) are discussed as a potential for further study. Defining the non-dimensional operating point in a rotating reference frame — as in Waldren *et al.* (2019) — shows the thrust output to 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.