Design • Analysis • Research

Electric Ducted Fan Design

1. Introduction

Design, Analysis and Research Corporation (DARcorporation) started on ducted fan design and testing in the early two thousands and has worked on multiple ducted fan projects with a diameter ranging from two inches to over two meters for many customers, including major OEMs. This white paper outlines the design process and presents verification testing of an electric ducted fan (EDF) for small UAV integration. An example UAV design by DARcorporation is shown in Figure 1.1, which was developed in 2015 as a technology demonstrator. The augmented safety is a result of six or more rotors: if one propulsor runs into a problem, the diametrically opposed propulsor can be switched off to maintain stability, without the need for emergency rated cross shafting. Eight rotors are used in this design, so each motor could be smaller and the failure of a propulsor will lead to less thrust loss as compared to devices with fewer rotors.

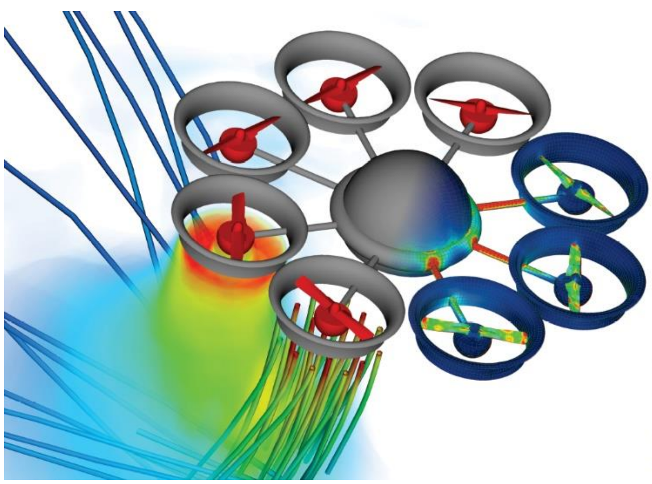

Figure 1.1 Example Ducted Fan UAV Design

The UAV propulsion system is also designed to be able to stay aloft with two failed or switched off propulsors.

2. Preliminary Design

The design goal is to produce an efficient EDF design that can produce 2 kg equivalent maximum thrust with an overall diameter including the duct of 10 inches. The duct is designed to be 3D printed and assembled in-house.

Using Blade Element Momentum (BEM) theory and an estimated efficiency from previous designs of similar size and Reynolds number, the shaft power required is estimated at 260 Watt. From this power requirement and accounting for the worst-case losses from both the motor and electronic speed controller (ESC), the center body is sized to fit a motor with a maximum power rating of 500 W.

3. Detailed Design

The ducted fan is designed with the aid of a significantly updated version of DFDC (Reference 1) as well as DARcorporation in-house optimization and analysis tools. DFDC is a 2D panel code that combines a vortex sheet panel grid and BEM theory. Design results include torque, RPM and power. DFDC has been modified to match actual measured data and to improve the prediction methods.

The duct is designed to be relatively short to reduce the total weight, but is also constrained by performance loss from possible flow separation around the lip and duct exit, if the duct is too short. Figure 3.1 shows the duct and center body geometry and the surface pressure distributions in DFDC. A flow field representation of airflow velocity vectors is shown Figure 3.2.

Design • Analysis • Research

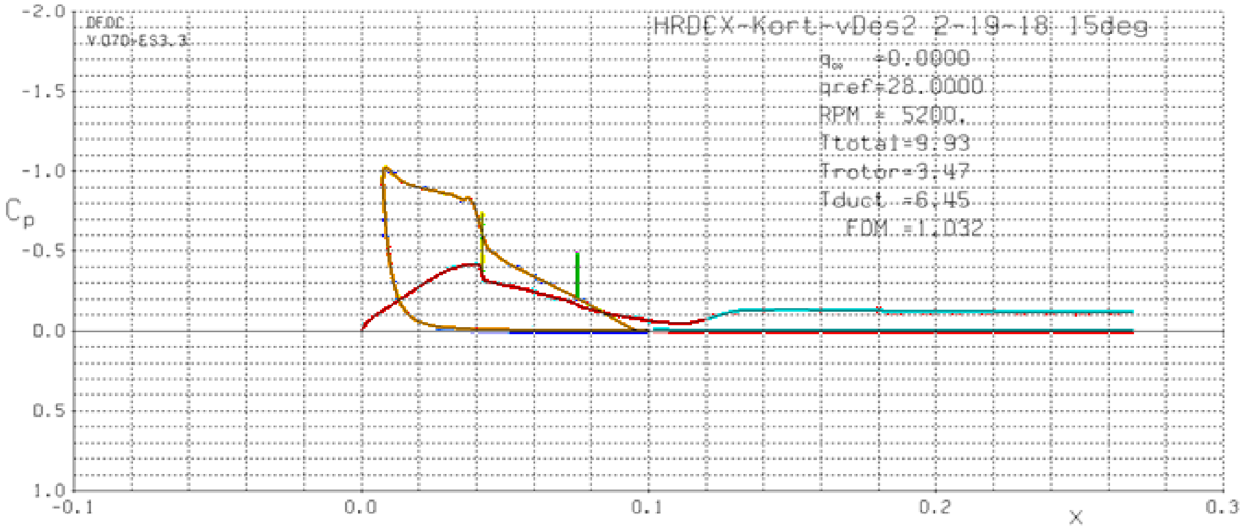

Figure 3.1 DFDC Detailed Design

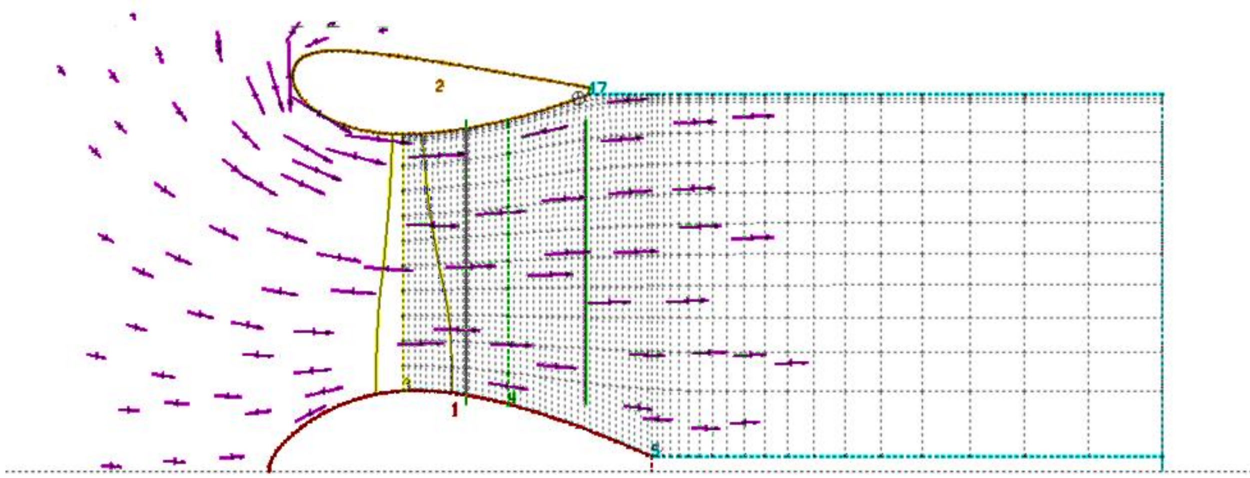

Figure 3.2 Velocity Vector Field Through Duct

Four stator blades are used aft of the rotor. This serves two functions. First, the center body must be supported inside the duct and they are also used for flow control. Second, depending on the stator orientation, the swirl created by the rotor can be augmented or reduced. Generally, the rotational component of flow velocity is reduced, so that the flow momentum is directed fully along the duct axis and thus producing increased thrust. Stators and other types of guide vanes have been used for flow control inside of ducts since before the invention of the jet engine. Both axial compressors and turbines take advantage of controlling flow rotation with vanes to improve performance. Figure 3.3 shows the flow direction viewed perpendicular to the duct axis and the stator effect. Black arrows represent blade motion and blue arrows represent airflow component direction.

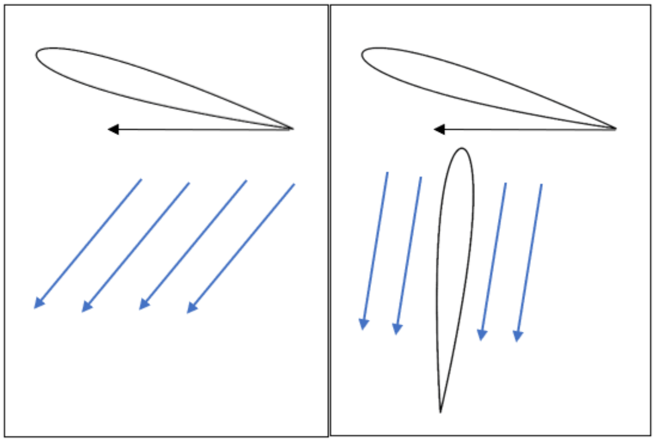

Figure 3.3 Stator Flow Angle Control. Rotor Only with No Stator (left), Rotor and Stator (right)

Stators could be symmetric or cambered depending on the application. DARcorporation also put twist and airfoil variation along the span of the stators. They could also be swept and tapered to improve flow quality or affect flow downstream. Stators are also effective to add or remove swirl as is done in jet engines for over decades. The stator cross-section of the example ducted fan is shown in Figure 3.4.

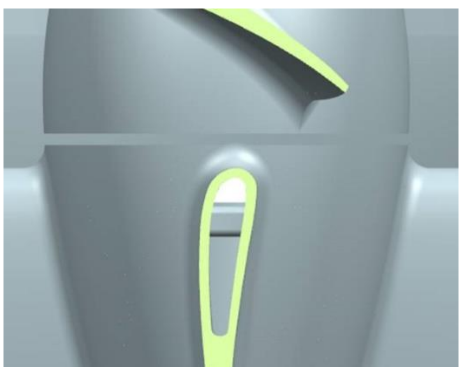

Figure 3.4 Stator Cross-section

4. Motor Selection

Once a rotor torque curve is established, it can be used to predict motor performance based on the manufacturer specifications. The main source of loss in an electric motor is power dissipation from the wire resistance. Other losses are present, but can be estimated from predicted power draw and motor specifications. For motor selection purposes, these losses can be considered fairly constant across motors of similar weight and size.

For maximum flight time, a balance must be struck between decreasing motor weight and the accompanying decrease in motor performance with the set maximum load that comes with using smaller motors.

Using the reported winding resistance and idle currents of the motor, the efficiency can be estimated and compared. The KDE 515 motor is selected for use after review of available motors within the selected range. At maximum thrust the efficiency is acceptable at above 80%. This number could be improved, but larger motors that would be more efficient weigh more, which negate their better performance considering increase in required thrust. Estimated motor performance for the duct operational envelope is shown in Figure 4.1.

This analysis also provides the required input voltage to reach maximum thrust. The power supply is set to 6S LiPo at 22.2 Volt. ESC efficiency is predicted through resistance measurement and an estimated switching loss dependent on load. Figure 4.2 shows the prediction as well as the combined system efficiency.

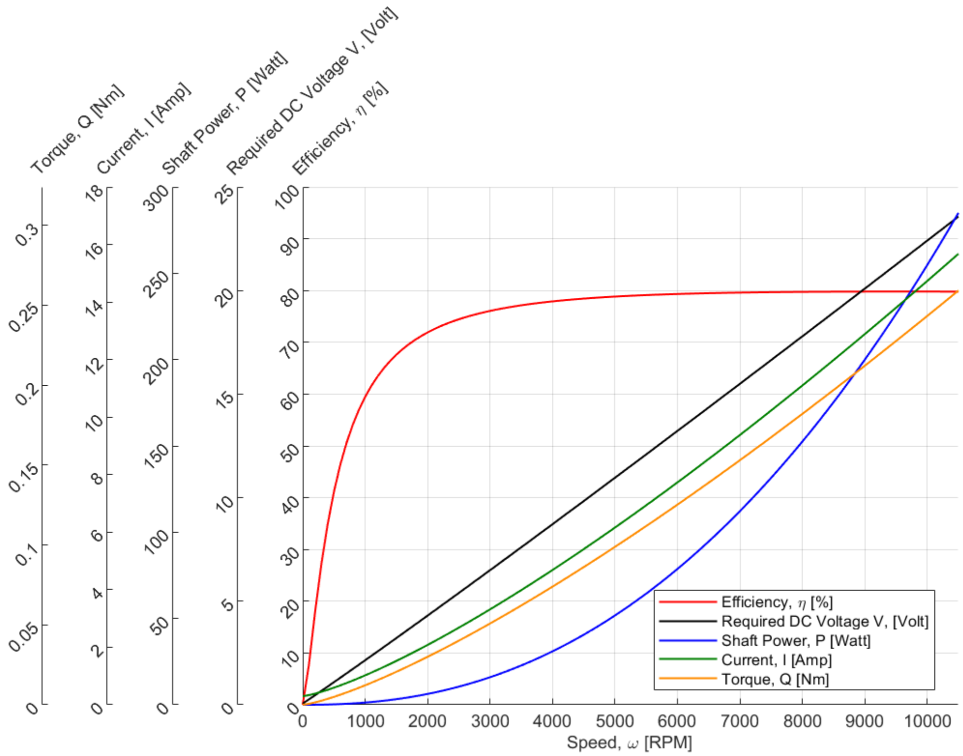

Figure 4.1 KDE 515 Motor Performance Estimations

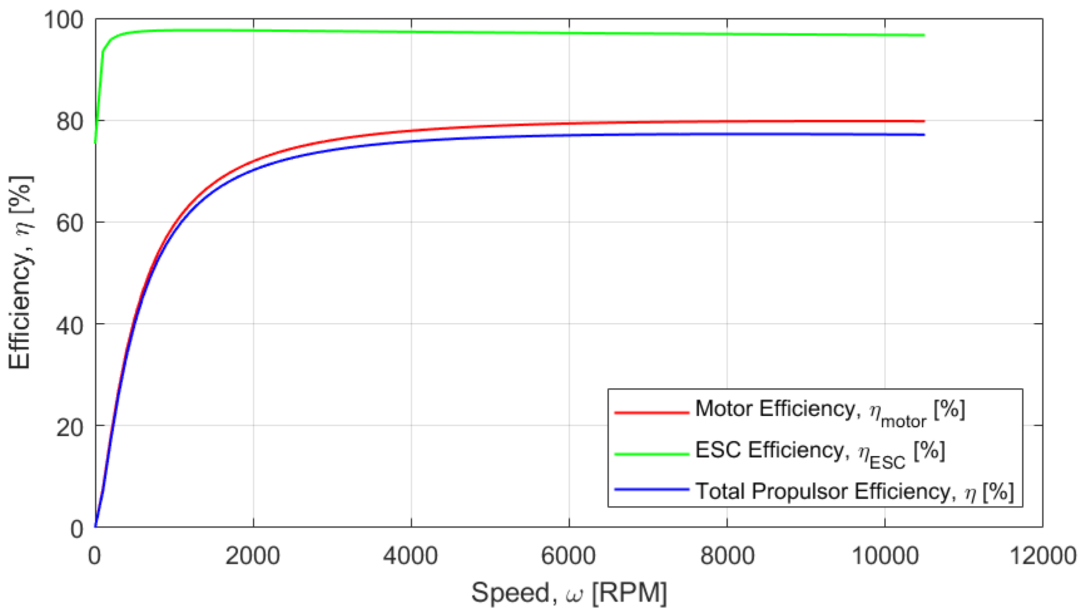

Figure 4.2 Predicted Propulsor Component Efficiency

5. Prototyping and Testing

The example duct is 3D printed in sections using the Formlabs Form2 printer. Eight alternating sections are assembled with every other section containing a slot to install a stator. The 4 stators come together to form the center body. Stators are hollow to reduce weight and allow for the passthrough of the power wires from the ESC, which has been done for many years in wind tunnel models, manned aircraft, commercial ducted fans and in many RC airplanes using ducted fans. An example of such common way of wiring attachment is shown in Figure 5.1 where wiring is attached to the inlet vane. Figure 5.2 shows an example of wiring running through one of the stators in an off-the-shelve commercially available ducted fan.

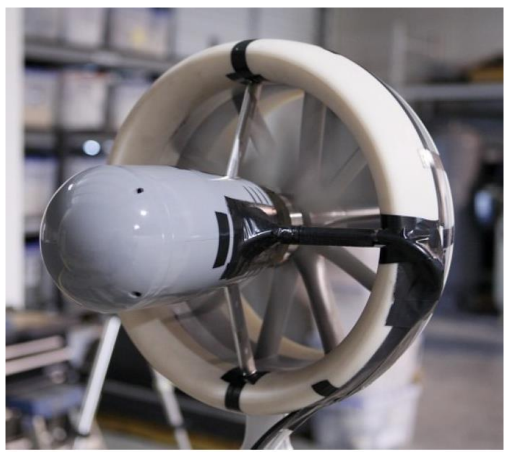

Figure 5.1 Ducted Fan with Wiring Routed along the Stator Leading Edge (Reference 2)

Figure 5.2 EDF 64 Ducted Fan with Wiring Routed in the Stator

If the stator is too thin, wiring could run on the outside too and often a little bump is molded into the stator airfoil to run wiring through. Figure 5.3 shows such a configuration.

Figure 5.3 Ducted Fan with Wiring Routed on Top of Stator

To facilitate motor cooling, a second rotor inside the spinner is added to pump air through the center body, similar to a Mercury all-metal electric ducted fan. This is a common parctice to address heat buildup. This technique was originally implemented for turboprop engine inlets to avoid ingestion of turbulent air flow behind propellers (Reference 3). Two UAV scale fans that implement this strategy for cooling are shown in Figure 5.4. The Mercury fan, shown with its stator section removed, has the fan aft of the motor. The AEO Aircraft fan is in front, which is similar to the DAR ducted fan. The principle of cooling or getting airflow throught the spinner is over 80 years old, applied in WWII engines already.

Figure 5.4 Mercury 104 EDF (left), AEO Aircraft EDF 64 (right)

Methods to calculate the effciciency of ducted spinners, as they are called, can be found in Reference 3 and also have been implemented in the Advanced Aircaft Analysis (AAA) software since 1991 (Reference 4).

Stators can be different with a variation in airfoils, camber, twist, sweep and taper to straighten the air flow and counteract any undesirable yawing moment or rolling moment depending on installation. Many ducted fans installed on blimps use variable camber through a hinged stator to control yaw or pitch. Stators do not need to be the same. Figure 5.5 shows a DARcorporation designed ducted fan installation taken from a 2004 patent filing, where the airfoil variation and camber variation are different depending on the stator.

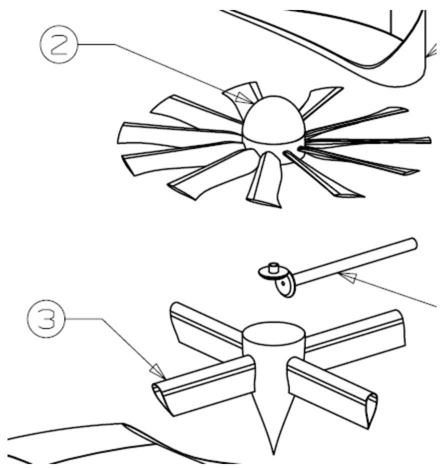

Figure 5.5 UAV Ducted Fan and Stators (2004)

In that design a drive shaft runs through one of the stators. The stators and duct flow have been analyzed in Computational Fluid Dynamics (CFD), because of the nature of the duct design and to allow for a single engine ducted fan. Carefully designed stators are needed to counter act any moments. On multipropulsor designs (quadcopters, hexacopters, octocopters), the ducted fan could also be tilted to counteract any undesired moments.

The completed example ducted fan CAD is shown in Figure 5.6.

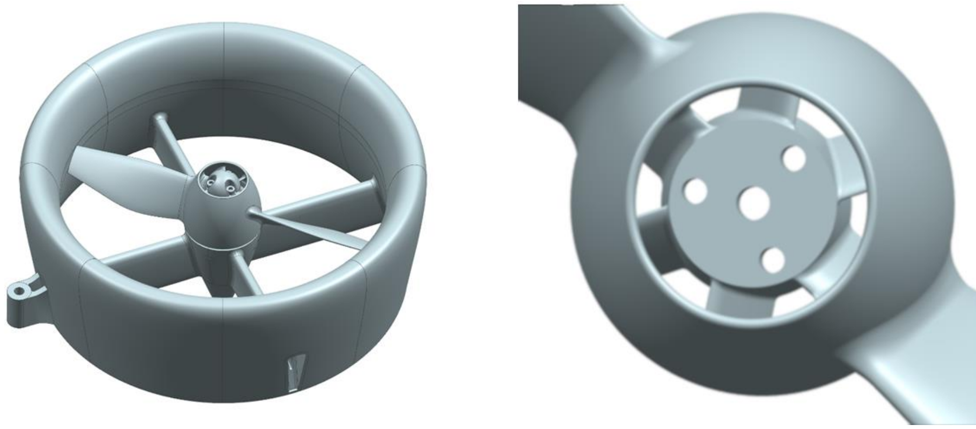

Figure 5.6 Final Ducted Fan CAD

To ensure that the rotor does not fail structurally during operation, structural analysis is performed. Figure 5.7 shows a stress distribution of the first iteration. A safety margin of at least 2 is applied to account for material uncertainties of the printed resin. The highest stress levels are seen in the spinner internal fan blades.

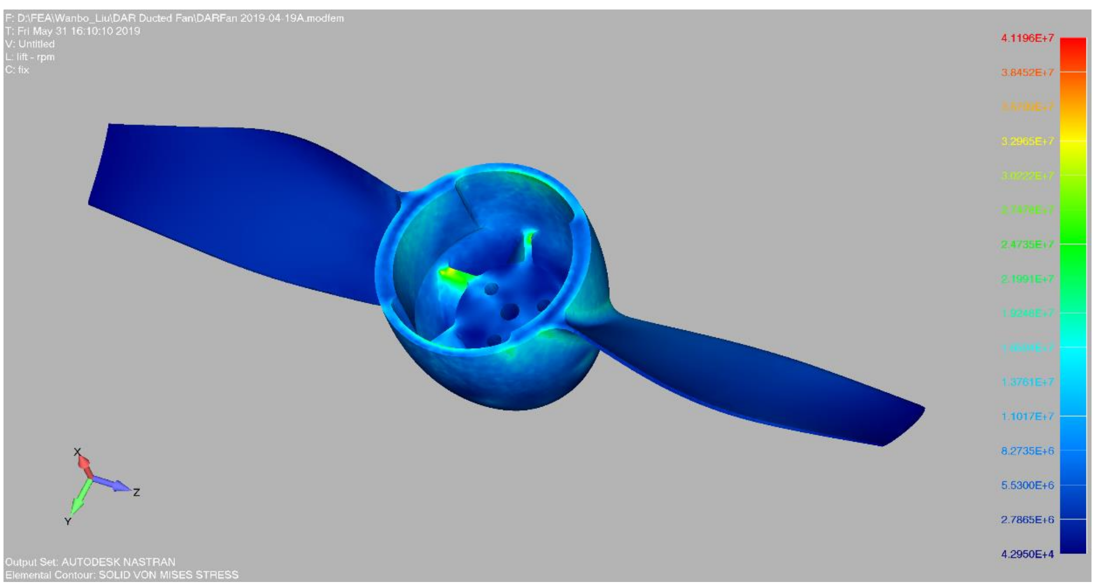

Figure 5.7 Finite Element Analysis of Ducted Rotor

Duct pieces are assembled with a strap clamp jig and bonded together. One of the prototypes is shown mounted on the DARcorporation test stand in Figure 5.8.

Figure 5.8 EDF on Test Stand

6. Test Results

Both analytical and experimental results of the DARcorporation EDF design are presented in Figure 6.1. The total system power draw is shown with thrust as the relevant value for calculating vehicle endurance. The system power is under predicted with higher error at lower thrust values. This is due to ESC MOSFET (Metal-Oxide Semiconductor Field-Effect Transistor) switching losses, which are larger at low RPM.

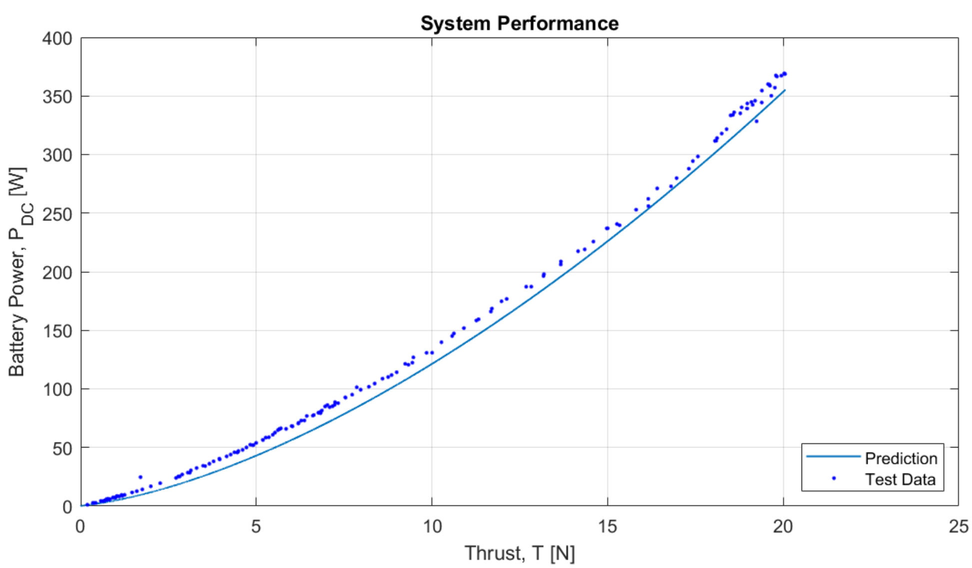

Figure 6.1 Comparison of Test Results with Prediction

7. Vehicle Analysis

Preliminary vehicle sizing of an octocopter vehicle is completed to estimate flight time. Estimated component weight break down is presented in Table 7.1. Structural weight is based on the actual weight of the test article plus allowances for fasteners and a center body. Electric component weight is compiled from currently available ESCs and motors as well as the wiring to connect them. There is no structural optimization performed and the duct components are oversized for rapid production without detailed structural FEA. Thus, further weight reduction is possible.

Table 7.1 Estimated Vehicle Weight Breakdown

Structures	4.3 kg
Internal Electronics and Motors	1.6 kg
Battery (6S 23,000 mAh)	2.5 kg
Payload	1.5 kg
Total	9.9 kg

Each propulsor unit uses 185 Watt drawn from the battery to produce a hover thrust of 1.24 kg. With a commercially available, 511 W-hr battery this should allow for around 21 minutes of flight time.

8. Conclusions

An all-up weight for this configuration is estimated to be 9.9 kg. The battery with 511 W-hr allows for 21 min of flight time with 1.5 kg payload. Without the payload the flight time will be increased to 27 min and if the payload is exchanged for an additional battery the flight time is increased to 33 min. Flight time can be further increased through structural optimization and weight reduction.

The designed ducted fan vehicle has the capability of carrying more payload in a smaller form factor than an open rotor design of similar size. It also has the benefit of reduced noise and hazard as the fans are enclosed by the ducts. For an open rotor of similar diameter to produce the same thrust would require a 70% increase in power. This would increase the required size of all electrical components.

The use of 3D printing allows for quick turnarounds with lower cost in the design-test cycles. The entire process of design, CAD, prototyping, assembly and testing is completed in only 3 weeks.

9. References

1. DFDC, Version 070-Es3.3, MIT ACDL and Esotec Developments, Boston, Massachusetts and Slocan, British Columbia, 2015.
2. Osgar John Ohanian III, “Ducted Fan Aerodynamics and Modeling, with Applications of Steady and Synthetic Jet Flow Control”, PhD dissertation at Virginia Polytechnic Institute and State University, 2011.
3. Roskam, J., “Airplane Design - Part VI”, DARcorporation, Lawrence, Kansas 2008.
4. DARcorporation, Advanced Aircraft Analysis (AAA) Version 1.0 (1991) – Version 4.1 (2020)

10. Further Information

Please contact Design, Analysis and Research Corporation for more information.