Chapter 12
Test Bench for Electric Propellers and Distributed Propulsion

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Nomenclature

EDF	Electric Ducted Fan
DP	Distributed Propulsion
ESC	Electronic Speed Controller

12.1 Introduction

In today’s world, the drone industry is quickly expanding, their role is becoming more vital, and an increasing number of drones are conceived to effectively conduct military, humanitarian and rescue missions among others. However, one of their major limitations is their endurance (or range), which limits their application purposes. Many existing technologies are being upgraded and new ones are being developed to further push these limits. Fundamentally, there are two main ways to increase the endurance of a drone (without modifying its geometry), and this is done either by having a higher power density of the power source (more energy for the same weight) or having a more efficient propulsion system, the latter will be done here. This paper is focused on exploring an existing but rather unpopular technology, known as electric ducted fans and to quantify the effect of the duct.

It is important to have a clear definition of what distributed propulsion (DP) really is. It is defined as the spanwise distribution of the propulsive thrust stream such that overall, the vehicle benefits in terms of structural, aerodynamic, propulsive, and/or other efficiencies (Kim 2010). On the other hand, electric ducted fans are electric powered propellers equipped with a duct. To conduct this study rightfully, it was essential to have a test bench on which electric ducted fans (EDFs) and propellers could be tested.

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T. H. Karakoc et al. (eds.), *Advances in Electric Aviation*, Sustainable Aviation,
https://doi.org/10.1007/978-3-031-32639-4_12

However, although the final aim is to fully explore the benefits of DP, this paper focuses on the effect of the presence of the duct around the propeller for electric drone motors (the results can be scaled up using non-dimensional numbers theory)

12.2 State of the Art

The actual number of projects exploring the advantages of electric DP are limited. It was decided here to show a promising ongoing concept plane that the French society Office National d'Etudes et de Recherches Aérospatiales (ONERA) has been developing. This plane, which uses DP is known as the AMPERE (from French "Avion à Motorisation rePartie Electrique de Recherche Expérimentale", which basically means it is a DP research plane). It uses a distributed electric propulsion with an electric ducted fans system and should be capable of transporting up to 6 persons within a 500 km range in 2 h (2017). One of their aims is to achieve optimal propulsion while keeping the drag on the plane as low as possible. To do so, their project aims to use EDFs. Indeed, the concept plane is built such that 32 independent motors are installed on its wings. These electric motors are supposed to be driven by 8 hydrogen fuel cells. Onera has planned for different configurations of the plane, one with a top mounted wing with leading edge EDFs (Fig. 12.1), while the other is a low mounted wing with canard configuration with EDFs mounted on the trailing edge. No published results have been found concerning the aerodynamic performance of the AMPERE (Dillinger et al. 2018) but a wind tunnel testing on a one-fifth scaled model has already been shown in a Paris (Sigler 2017) conference with some interesting results regarding the boundary layer attachment on the airfoil allowing for greater performance.

Fig. 12.1 Ampere DP concept plane

12.3 Method

To study the effect of the duct on the propulsive force and the consumed power, it is mandatory to have a fully functional and reliable test bench. Thus, a test bench was built to measure different physical variables of the tested motors.

The test bench (Fig. 12.2) was built and equipped with throttle, torque, thrust, rpm, current, voltage, temperature, static, and dynamic pressure sensors. All of the data is then collected and processed by an Arduino Mega board and sent to a Raspberry Pi from which it is transferred to MATLAB where it is analyzed and treated. Before exploiting the results of the test bench, it is important to validate the measurements taken by the data acquisition system. For the following parameters (rotational speed, voltage, current, and thus power), the measurements have been compared to those of the Scorpion Tribunus I. Indeed, this high-quality electornic speed controller (ESC) is equipped with various internal sensors allowing for the latter parameters to be recorded and thus compared to those of the test bench. The comparison, although chosen not to be shown here, shows a good working condition of the test bench. With an increasing sampling frequency, the difference between both acquisition system seems to reduce.

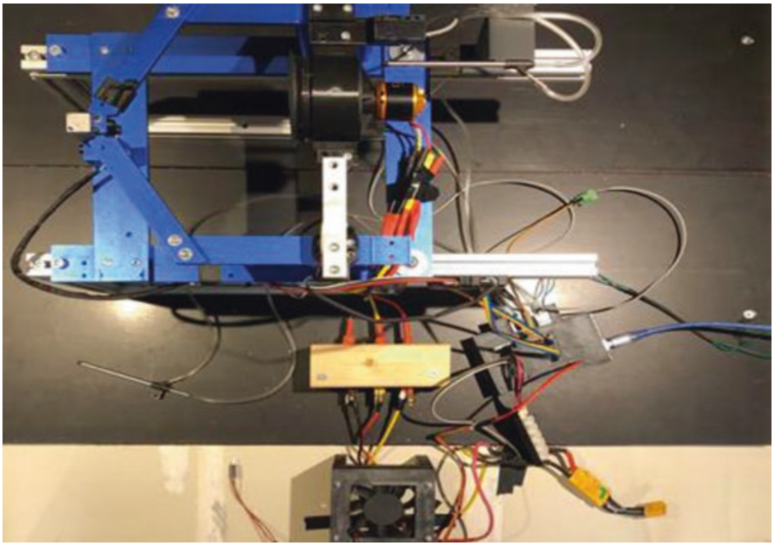

Fig. 12.2 EDF test bench. (View from the top)

12.3.1 Calculation

For what regards the validation of the thrust measurement, the theoretical versus experimental values have been confronted. However, to do so, a good estimate of the thrust has to be computed. Thrust is computed using the thrust formula (https://www.grc.nasa.gov/www/k-12/airplane/turbth.html. Accessed 10 Nov 2020) of a turbojet:

$$\dot{\mathrm{F}} = \dot{\mathrm{m}}\left(vj - va\right) \tag{3.1}$$

As we are in static conditions with no air current, the aircraft velocity (va) is considered to be null. To compute the exhaust flow velocity (vj), a pitot tube sensor has been used. Indeed, from the dynamic pressure the air velocity can be computed as follows:

$$v = v_j = \sqrt{\frac{2P_{\mathrm{dyn,out}}}{\rho}} \tag{3.2}$$

Where the air density (ρ) is computed with the temperature and pressure sensors (through means of a BME280 that is a reliable sensor from which we can assume the data is adequate and precise enough) using the perfect gas law. Additionally, the mass flow is needed. It was initially computed with the following equation (Kubica 2017):

$$\dot{\mathrm{m}} = \rho v A \tag{3.3}$$

Where A is the swept section of the propeller blades. This method gave poor results, the reason being that the exhaust velocity was computed as being constant (pitot tube measurement in a fixed position). To correct this mistake, the boundary layer must be considered. By precisely positioning the pitot tube at different locations along a constant radial position and assuming no flow conditions on the walls, a real exhaust velocity profile has been made. By later interpolating the data points and then by integrating in function of the radius distance to the shaft, a more accurate mass flow and thus thrust have been computed. This finally gives an error on the thrust of 18% versus 58% for the first approximation. This residual error is assumed to be due to approximations done throughout the computations and sensor precisions. The measurements of the test bench are thus validated and considered to be reliable for the remainder of the study.

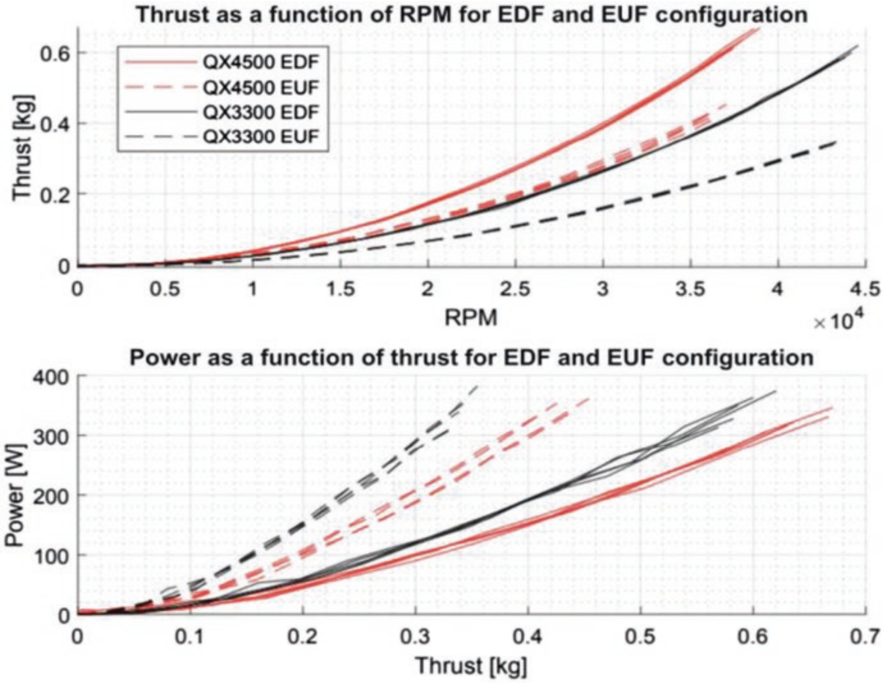

Fig. 12.3 Power consumption and thrust production in function of motor RPM with and without duct

12.4 Results and Discussion

Many factors influencing the EDF's performance have been treated in detail throughout the study, such as for instance the influence of the battery charge/discharge and the blade profile on its performance, the electronic speed controller's impact on the control of the EDF and more. The most interesting results deemed for this paper are the impact of the duct on the thrust production and power consumption. These are shown in Fig. 12.3 (where EUF stands for Electric Unducted Fans, which is basically a simple propeller) for two different EDFs (the QX3300 and QX4500). The two different colors represent each of the motors. The dotted lines are with the duct mounted while the full lines represent the propeller without a duct.

From this figure, it can clearly be seen that integrating a duct around the propeller allows for a much higher thrust production (first approximation leads to an increase of around 35% in comparison to the same propeller without duct, at maximum thrust) and a power reduction (for the same produced maximum thrust) of around 50%. These improvements are due to the more uniform flow beneath the propeller and the disappearance or decrease of blade tip vortices, allowing for a higher efficiency of the fan. It is important to notice that the increase in parasitic drag due to the presence of the duct has not been studied and this is an important parameter which will be integrated in future work of the project.

12.5 Conclusion

In conclusion, the presence of the duct increases consequently the static thrust of a given propeller. Moreover, for the same thrust, the power consumption is also considerably reduced. This clearly shows an improvement in the performance of propellers when being equipped with a duct, the different parameters of this duct are yet to be studied. However, note that for this study, the blades were not optimized to work without duct as they were extracted from an EDF. Indeed, a clean perpendicular cut of the blade can be seen instead of a fine ending of the blade tips, thus the difference in performance should be a little lower when compared to a propeller of the same size but with optimized geometry. The benefits from combining DP and EDFs is now clearer and will be further studied. However, as stated earlier, adding a duct will increase the overall parasitic drag of the system. Thus, the challenge integrating this technology will be having a bigger positive than negative impact.

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