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Development of an experimental platform for thrust testing of aircraft electric propulsion system

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Abstract. In the aircraft design development stage, it is very important to test the performance of the propulsion system through static thrust testing of the aircraft, as well as to obtain thrust and power curves of the engine as a function of flow velocity. In this regard, to accurately determine the available static thrust provided by the engine-propeller assembly, engine test benches are commonly used. Additionally, wind tunnel tests are conducted to provide dynamic thrust as a function of wind flow. In this context, the development of an experimental test bench for electric propulsion system thrust testing offers engineering students an applied and multidisciplinary learning environment. For this purpose, a brushless motor and propellers with different diameters and pitches will be used, as variations in these parameters directly affect the thrust of the propulsion system. Thus, this work will contribute to the validation of computational models used for this type of analysis.

Keywords: electric propulsion, thrust testing, experimental platform, performance curves

1 Introduction

Aircraft propulsion systems are responsible for generating the thrust required to propel the aircraft throughout all phases of flight. In recent decades, there has been growing interest in the aeronautical sector in electric motors as alternative power sources due to their environmental, operational, and economic advantages. Eliminating the use of fossil fuels significantly reduces greenhouse gas emissions, contributing to climate change mitigation. In addition, electric motors operate more quietly, reducing noise pollution and improving the quality of life in areas surrounding airports. They also offer greater energy efficiency, resulting in lower operational and maintenance costs. These benefits make electric propulsion a promising alternative for the sustainable aviation of the future.

Thrust testing plays a fundamental role in the development of propulsion systems, especially in electric aircraft, where proper motor selection directly impacts operational efficiency and performance. Different applications

require specific performance characteristics. In cargo transport, for instance, it is essential to use motors that provide high thrust at low RPMs, as seen with the turboprop engine illustrated in Figure 1, which offers an ideal torque-speed ratio to generate sufficient force during heavy takeoffs and low-speed operations. On the other hand, in applications demanding high speed, such as military aircraft, turbojet engines are preferred due to their high rotational speed and lower thrust, favoring lighter weight and better in-flight performance, as also demonstrated in Figure 1.

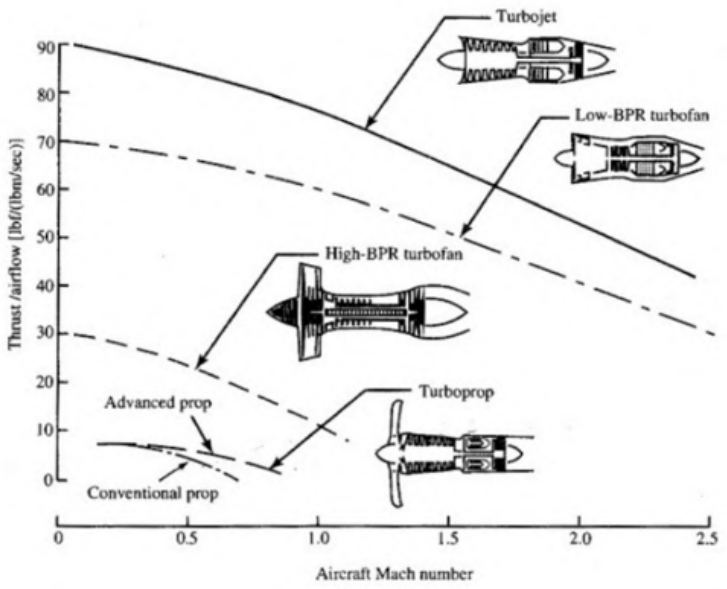


Figure 1. Specific thrust vs. Mach number for various aircraft propulsion systems [1]

By enabling the realistic evaluation of propulsion system performance, thrust testing guarantees that the chosen engine type—whether electric, turbofan, turbojet, or turboprop—suitably satisfies the mission profile and operational needs of the aircraft. This procedure is necessary to maximize energy efficiency, guarantee flight safety, and optimize overall performance. In this way, the importance of thrust testing becomes evident for selecting the correct engine according to its intended application. Furthermore, the data obtained from these tests directly support the selection of the most suitable propeller, contributing to a more efficient propulsion system tailored to the specific needs of the aircraft.

Furthermore, the propulsion system's dynamic behavior is modeled in accordance with the intended use of the mathematical representation of the system. Based on analytical modeling techniques, Alves [2] created a MATLAB computational tool for propeller design in this context. The study's goal was to offer a resource for the design phase that might improve propeller aerodynamic efficiency and operating performance. Using similarity criteria that guarantee dynamic equivalence with a full-scale configuration, Soares [3] presented a methodology for the dynamic identification of subscale aircraft with the goal of obtaining a representative dynamic model through flight testing. Testing the motor-propeller combination in a wind tunnel was a crucial component of this work. It showed that the thrust production decreased as the relative airflow increased, underscoring the effect of inflow conditions on propulsion efficiency.

In order to assist the Aerodesign competition team from UTFPR Curitiba in choosing a suitable propulsion system, Zanardi [4] created a test bench for static and dynamic thrust measurements of brushless motors. In order to determine freestream airspeed during dynamic testing, which were carried out with the bench mounted on a moving platform, the setup comprised sensors for real-time monitoring of motor electrical parameters and a Pitot-static system. A high-efficiency measurement technique for assessing thrust and other performance parameters of electric motor–propeller assemblies was proposed by Kósa [5]. By utilizing calibrated sensors and an automated acquisition procedure that can take many consecutive readings and store the data independently, the system increases measurement repeatability and reliability.

To enhance aircraft efficiency and extend flight endurance, ongoing research in the academic field has focused on electric propulsion systems. However, certain gaps remain—most notably, the need for accurate mathematical models of electric aircraft. Such models are essential for understanding system behavior and enabling simulations and fault prediction under varying operational conditions. In this context, the work by Barufaldi [6] is particu-

larly significant, as it presents both analytical and numerical approaches for evaluating the performance of electric aircraft. The study begins by modeling and characterizing an electric aircraft to support further performance assessments. The proposed methodologies aim to estimate key performance metrics, such as range, flight endurance, and energy consumption, across different phases of flight.

Therefore, the objective of this study is to develop an experimental platform for thrust testing of a brushless motor propulsion unit used in UAS, with the aim of validating theoretical design data and supporting academic research activities.

2 Mathematical modeling of the propeller using blade element theory

To understand and predict the behavior of a dynamic system, a mathematical model is essential. In aircraft design, the development of accurate models is particularly critical to enable reliable performance analysis and effective system optimization. Such models can be derived either from first-principles physics (analytical modeling) or from empirical data obtained through wind tunnel testing, ground tests, and flight tests. As illustrated in Figure 2, the propeller is a fundamental element of the propulsion system, responsible for generating the thrust required to overcome aerodynamic drag and sustain flight. Aerodynamically, a propeller functions as a rotating airfoil that traces a helical path, operating at a positive angle of attack relative to the freestream airflow, thereby producing thrust along the aircraft's longitudinal axis.

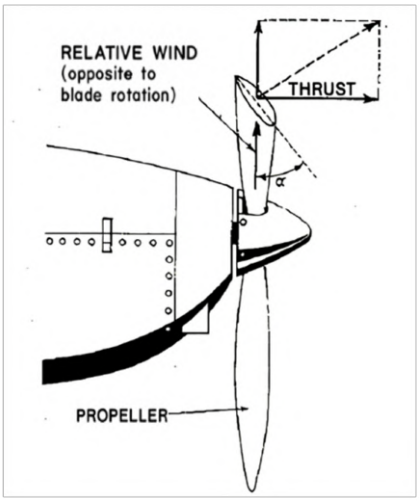


Figure 2. Propeller geometry [7].

It is important to note that, just as in the aircraft itself, there are forces acting on the surface of the propeller airfoil, as illustrated in Figure 3. The lift force dL always acts in a direction normal to the airfoil surface, while the drag force dD is orthogonal to the lift. Additionally, the thrust force dT is aligned with the engine axis, and the torque $r \cdot dF$ is orthogonal to the thrust vector. By definition, the angle of attack α is formed between the chord line of the propeller airfoil and the direction of the relative wind V_R.

In blade element theory, also known as Glauert's Theory, the propeller is treated as a rotating airfoil, and an analysis is carried out on the forces acting on infinitesimal transverse sections of length dr along each blade, as shown in Figure 3. All contributions from the infinitesimal elements dL, dD, dF, dT, and $dQ = r \cdot dF$ are then summed to obtain the total forces and torque on each blade. The goal is to determine the total thrust T and total torque Q generated by the propeller. A description of the modeling process using blade element theory is presented below.

According to Figure 3, the aerodynamic profile of a propeller resembles that of an airfoil, where the resulting aerodynamic force dR is decomposed into a lift component dL and a drag component dD. The thrust dT is a component of dR, and the resulting force dF is the force that generates the torque dQ.

$$dL = C_L \cdot \frac{1}{2}\rho V_R^2 \cdot b\, dr \tag{1}$$

$$dR = \frac{dL}{\cos\gamma} = \frac{1}{2}\rho V_R^2 \cdot b\, dr \cdot \frac{C_L}{\cos\gamma} \tag{2}$$

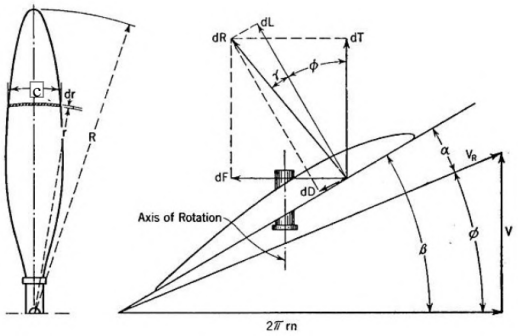


Figure 3. Propeller element used in blade element theory [1].

The thrust dT is defined as a component of the resulting force dR and is given by:

$$dT = dR \cdot \cos(\phi + \gamma), \tag{3}$$

$$dT = \frac{1}{2}\rho V_R^2 \cdot b\, dr \cdot C_L \left[\frac{\cos(\phi+\gamma)}{\cos\gamma}\right] \tag{4}$$

Substituting $V_R = \frac{V}{\sin\phi}$, obtains:

$$dT = \frac{1}{2}\rho V^2 \cdot b\, dr \cdot C_L \left[\frac{\cos(\phi+\gamma)}{\sin^2\phi \cdot \cos\gamma}\right] \tag{5}$$

Similarly, the torque component dQ is expressed as:

$$dQ = r \cdot dT = \frac{1}{2}\rho V^2 \cdot b\, r\, dr \cdot C_L \left[\frac{\sin(\phi+\gamma)}{\cos\gamma \cdot \sin^2\phi}\right] \tag{6}$$

For the static case, when the flow velocity is $V = 0$, it follows from Figure 3 that $V_R = 2\pi nr$, and the thrust dT can be calculated by:

$$dT = \frac{1}{2}\rho V_R^2 \cdot b\, dr \cdot C_L \left[\frac{\cos(\phi+\gamma)}{\cos\gamma}\right] \tag{7}$$

Thus, since dT is given by Equation 4, the force dF can be calculated as:

$$dF = dR \cdot \sin(\phi + \gamma) \tag{8}$$

where:

$$dR = \frac{dL}{\cos\gamma} = \frac{\frac{1}{2}\rho V_R^2 \cdot b\, dr \cdot C_L}{\cos\gamma} \tag{9}$$

Using the equations from blade element theory, the propeller's total thrust T and total torque Q are calculated for both the static and dynamic cases, accounting for wind flow V. In this work, only the static case will be addressed, and the results of the application of this method are presented in Section4.1.

3 Experimental platform development

The platform designed to conduct the bench thrust tests is depicted in Figure 4 with the goal of supporting the propulsion system's sizing and selection process. It guarantees the motor's effective fulfillment of the particular needs of the aviation application. The electrical system's architecture is shown in Figure 5.

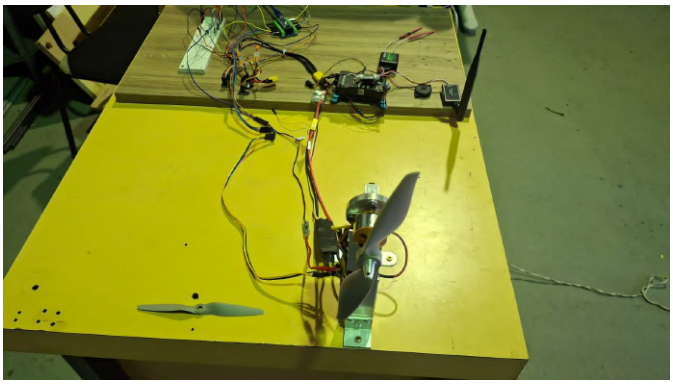


Figure 4. An experimental platform for brushless motor thrust testing.

The brushless motor is attached to the base of a load cell and placed on the bench. An electric motor is driven by a LiPo battery via an electronic speed controller (ESC) as part of the power system. The Pixhawk controller controls the motor, and an Arduino Nano collects data by connecting to particular sensors for thrust, voltage, current, and rotational speed (RPM). The devices utilized in the test bench assembly are described in Table 1.

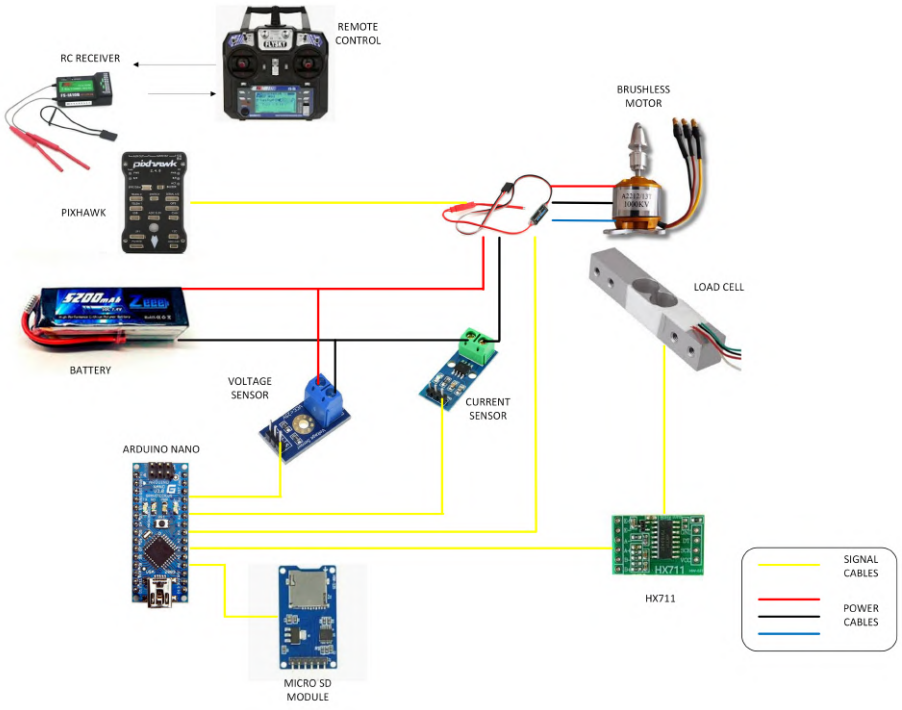


Figure 5. Scheme of the data acquisition system.

Although the Pixhawk controller includes an internal wattmeter, external dedicated sensors were chosen for each electrical and mechanical variable. All measurements were taken at the same sampling rate, set at 10 Hz via the Arduino, promoting uniformity in data collection throughout the tests. For the bench tests, a script was developed so that when the switch on the remote control is activated, the motor starts a constant acceleration. This controlled behavior enables repeatable tests with a standardized input, which is essential for future comparisons between different propeller and motor models, ensuring accuracy and consistency in the results obtained.

Table 1. Electronic and control system specifications.

Power system	Control system	Data acquisition system
Brushless motor A2212 6t, 2,200 KV	Pixhawk PX4 2.4.8, ARM Cortex M4	Arduino Nano
Speed Control (ESC), QM, 40 A	FlySky receptor FS-iA10B	SD card module
Lipo battery, Teranty, 5,200 mAh	RC remote controller FlySky 2.4 GHz	Voltage sensor 0–25 V DC
	Radio telemetry, 3DR, 433 MHz	Current sensor ACS-758, 50 A
		Load cell 20 kg

4 Experimental Tests Results

The results of applying the blade element theory to the manufacturer data APC and the experimental data from the bench test are shown in this section. The results achieved using the blade element theory are discussed in Section 4.1, and the data acquired from the experimental platform is presented in Section 4.2.

4.1 Application of the blade element theory

To determine the thrust and torque of the motor and propeller set, a computational simulation using blade element theory was conducted, taking into account two propellers, APC propeller 6×4 and APC 8×4. The input parameters of the approach might be obtained from the radius versus chord and radius vs angle of attack curves supplied by the APC manufacturer [8]. An average Reynolds number of 10^6 was used to determine the drag polar and lift curves. Also, the airfoil profile of both propellers changes from an E-63 to a NACA-4412. Figure 6 demonstrates that the outcomes of numerical simulation accord well with the information supplied by the APC manufacturer.

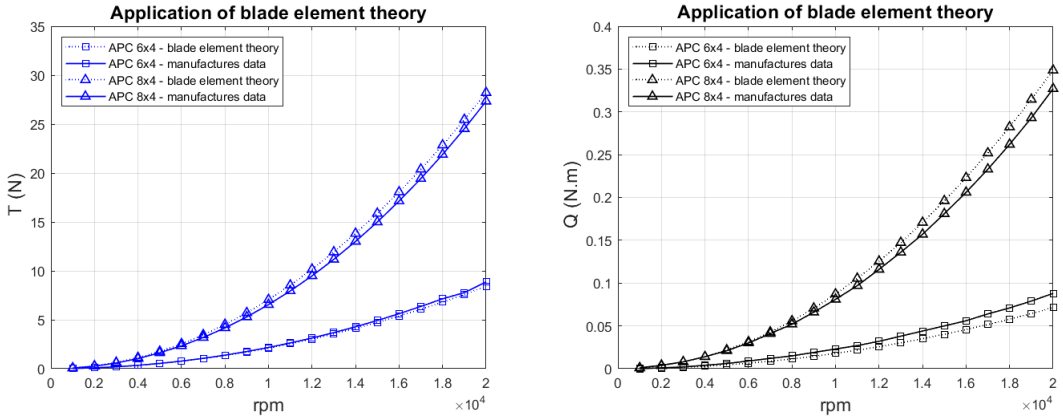


Figure 6. Comparison of performance curves of the propellers obtained by blade element theory [1] and manufacturer's data: (a) RPM versus thrust and (b) RPM versus torque.

4.2 Experimental data

The test bench yielded the RPM vs thrust curves for two distinct propellers, as seen in Figure 7. Based on the findings, the experimental data are closed to the data from the manufacturer. The empirical KV is 2290 based on experimental data without a propeller, and the larger diameter propeller yields, as expected, the maximum thrust.

5 Conclusions

In this work, a framework for bench testing brushless motors used in UAS was developed. The blade element theory results, which were derived from the APC manufacturer's geometry and aerodynamic data, closely match the performance statistics that the APC manufacturer supplied. Therefore, the goal of the computer simulation was to validate the experimental results by comparing them with the manufacturer's data. There is good agreement

Table 2. Experimental data obtained from static tests.

Configuration	Maximum power	Maximum current	Voltage	Maximum thrust	Maximum RPM
Without propeller	-	1.78 A	11.41 V	-	26,130
APC propeller 6x4	118 W	11.29 A	10.45 V	7.24 N	18,960
APC propeller 8x4	227.4 W	26.22 A	8.67 V	15.1 N	12,610

(-) Note: A considerable value of power and thrust is not expected for the engine without propeller, therefore the values are not displayed.

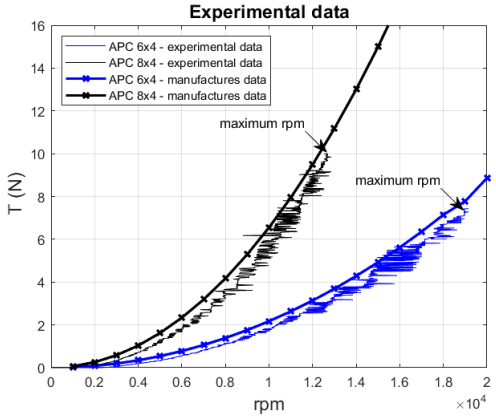


Figure 7. Comparison between the thrust data from the manufacturer and the experimental data.

between the computational results and the experimental results from the brushless motor bench test. It will be crucial to compare more various motor and propeller combination setups in future research.

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