Portuguese Air Force

Air Force Academy Research Center

MSc Aerospace Engineering

Flight Performance and Propulsion

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List of Abbreviations

AFA	Air Force Academy
BET	Blade Element Theory
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CIAFA	Air Force Academy Research Center
CSV	Comma-Separated Values
KBE	Knowledge Based Engineering
MRF	Multiple Reference Frame
RANS	Reynolds-Averaged Navier-Stokes
RPM	Revolutions Per Minute
STEP	Standard for the Exchange of Product Data
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Take-Off and Landing

Abstract

Unmanned Aircraft Systems (UAS) are increasingly becoming part of military operations.

The work developed aims to contribute to the preliminary design of the propulsion system of a VTOL UAV, under development at the Portuguese Air Force Academy Research Center (CIAFA), by calculating the thrust produced by several off-the-shelf propellers, using different methods, in order to select a propeller that meets the project requirements and in order to benchmark the different methods for estimating propeller thrust.

In order to calculate the thrust of the several off-the-shelf propellers, various methods were investigated, namely: wind tunnel tests, CFD simulations and the development of a Knowledge Based Engineering (KBE) application using ParaPy combined with Blade Element Theory (BET).

The main outputs of the work developed are: a ParaPy application capable of generating different propeller geometries and estimating the thrust generated by that geometry for a given flight condition; performance parameters of the T-MOTOR P20x6 measured in wind tunnel tests and calculated using CFD simulations and analytical methods (BET).

The results indicate that CFD simulations using the MRF model are a good alternative to wind tunnel testing, with an error generally smaller than 10% when compared to experimental data, allowing for a much cheaper and thorough alternative. Regarding the ParaPy application implementing BET for propeller thrust calculation, results suggest that it should only be used to get rough estimations of the thrust generated by a propeller, due to its inconsistent results caused by limitations in the panel code (XFoil) used to calculate the aerodynamic properties of the blade elements (airfoils).

DISCLAIMER: This article is a summary of a report written previously by the author as a result of his internship at the CIAFA. This article will focus mainly on the development of the KBE application for propeller thrust estimation, with the goal of highlighting the potencial of using KBE, coupled with ParaPy's capabilities, in order to automate many of the design and analysis processes required in the preliminary design phase of an engineering product. Therefore, other information like the one regarding the results of the tests for the suitability of the propellers for the VTOL UAV requirements, the wind tunnel setup, the CFD setup, the generation of the propeller CAD model, etc., is considered to be outside of the scope of this article and thus will not be presented here in detail.

1 Introduction

Unmanned Aircraft Systems represent the future of aviation. While big aviation companies aim at producing high end certified aircraft, smaller companies focus on developing small and low cost UAS for a wide variety of civil and military applications.

Given the increase in availability of small and affordable UAS, their operations have grown extensively in the last few years, both in the civil and military domain. The capability for being used in both domains allows for operations at reduced cost, which justifies an increase in the military use of these systems. [1]

In Portugal, the Air Force Academy Research Center (CIAFA) ensures the full cycle of requisite-design-development-flying of all UAS flown in at the Portuguese Air Force.

The work developed at the CIAFA was related to an ongoing project, whose objectives were to design, produce and test fly a VTOL UAV. More specifically, the key driver of this project was the propulsion system design, characterisation and testing.

This article will start by introducing the problem statement, followed by the methodology used, as well as, the outcome of the work developed. Finally, conclusions about the outcome will be drawn and some recommendations for future work will be presented.

2 Problem Statement

One of the ongoing projects at the CIAFA, was the design and production of a Vertical Take-Off and Landing Unmanned Aerial Vehicle with a MTOW of 15 kg and an endurance of 2 hours.

The propulsion system of this UAV was still in the preliminary design phase and thus, had to be selected and characterised. Since the CIAFA does not produce their own propellers for their UAVs, this would have to be an off-the-shelf component.

2.1 Purpose

The main purpose of this project was to contribute to the preliminary design of the propulsion system of the VTOL UAV by simulating, with CFD software, the thrust generated by an off-the-shelf propeller in order to verify if it met the project requirements.

The secondary purpose of this project was to develop an alternative way of simulating the thrust of a propeller, namely through a KBE application implementing Blade Element Theory and then providing benchmarking comparison between the CFD results, the results from the KBE implementation of the BET using ParaPy and the experimental results measured in the wind tunnel.

2.2 Methodology

In order to simulate the thrust of a propeller, using CFD software, a CAD model of the propeller is needed. Therefore, the first step was extracting measurements from several sections of the physical propeller in order to create a CAD model of it in SolidWorks.

After creating the CAD model, it could then be imported into CFD software (Ansys CFX), where several analysis were performed for different flight conditions, matching the conditions of the wind tunnel tests, in order to validate the CFD results.

After validating the CFD results, the thrust generated by the propeller in 3 main flight conditions was simulated using Ansys CFX and the results were used in order to determine if the propeller met the project requirements.

In order to develop a ParaPy application capable of calculating the thrust generated by a propeller, the application needed to have access to the geometry of the propeller and to a certain set of engineering rules (equations) that could calculate the thrust generated by a certain geometry for a given flight condition.

There were two ways that the geometry of the propeller could be defined in the application, either by providing a parametric geometry model through an input file or by importing a STEP file with the geometry of the propeller. The way of defining the engineering rules that allowed for the calculation of the thrust force was by using Blade Element Theory.

In order to benchmark the different methods for calculating the thrust of the propeller, the results from the wind tunnel tests, CFD and BET were compared to the values provided by the manufacturer of the propeller.

2.3 Overview

The main steps taken in order to solve the problem presented previously, were the following:

1. Development of a CAD model of the propeller;
2. Simulation of the propeller thrust using CFD software;
3. Wind tunnel testing of the propeller to calculate thrust;
4. Development of an application using ParaPy to calculate the thrust of a propeller based on BET;
5. Comparison between the results of the various methods of thrust calculation;
6. Drawing conclusions regarding the suitability of the propeller in order to satisfy the project requirements.

3 Literature Review

In order to develop a ParaPy application that can calculate the thrust of a propeller, Blade Element Theory can be used for the calculations needed for the thrust estimation.

3.1 Blade Element Theory

The Blade Element Theory (BET) estimates the thrust of a propeller by dividing each blade in several sections, called blade elements. By considering each element as an independent two-dimensional airfoil, the aerodynamic forces can be calculated based on the local flow conditions at the element. After determining the aerodynamic properties, they are summed up to evaluate the properties of the complete propeller. [2]

The BET can account for varying blade geometry, change in the airfoil's chord, angle-of-pitch and aerodynamic characteristics. It also allows to estimate the torque and therefore determine the power required. [2]

The BET has some limitations: it assumes that the flow inside the streamtube is uniform, that the forces on each blade element can be treated as two-dimensional (neglecting spanwise flow), that the blade is rigid (ignoring aeroelastic effects). One drawback of the BET is that it needs a special correction at the hub and tip to account for diminished lift and for a skewed inflow. [2]

The formulation of the BET and its application will be presented in greater detail in section 4.1.3.

4 Methodology

In order to tackle the problem of the UAV Propulsion System and determine if the propeller met the project requirements, different approaches were considered, the methodology and the work done for each approach is described in the following sections.

4.1 KBE Application (ParaPy)

ParaPy was chosen as the platform to develop an application capable of calculating propeller performance parameters such as thrust, torque, power and efficiency using Blade Element Theory.

ParaPy is a software that allows to build parametric, rule-based software applications that automate simulation-driven engineering design processes. [3]

The methodology used in order to develop the application and its main elements are described in the following sections.

4.1.1 Propeller Geometry

In order to calculate the performance parameters of the propeller, the application needed to have access to a geometric model of the propeller. Two different methods for providing a geometry were implemented.

The first and simpler one was by importing a STEP file with the geometry, making use of the CAD model previously created. This method guaranteed that the geometry used for the CFD simulations was exactly the same as the one used for the BET calculations and thus allowed to draw comparisons between the results obtained with the different approaches. An example of one of the geometries imported is presented in Figure 2a.

The second and more complex, but also more versatile, method was by generating the propeller directly with the ParaPy modelling toolbox using an Excel (CSV) input file where different parameters of the propeller were defined. This method allowed to generate several different propeller geometries with a variable number of blades very quickly and flexibly without the need to use a different software to create complex CAD models. As an extra feature, this method also allowed to export a STEP file of the generated geometry so that it could possibly be analysed using different analysis software.

The geometric parameters defined in the Excel input file that was used to generate the propeller geometry inside the application are presented in Figure 1.

In the "Propeller" section, the user could define the propeller diameter, the geometric pitch and the number of blades.

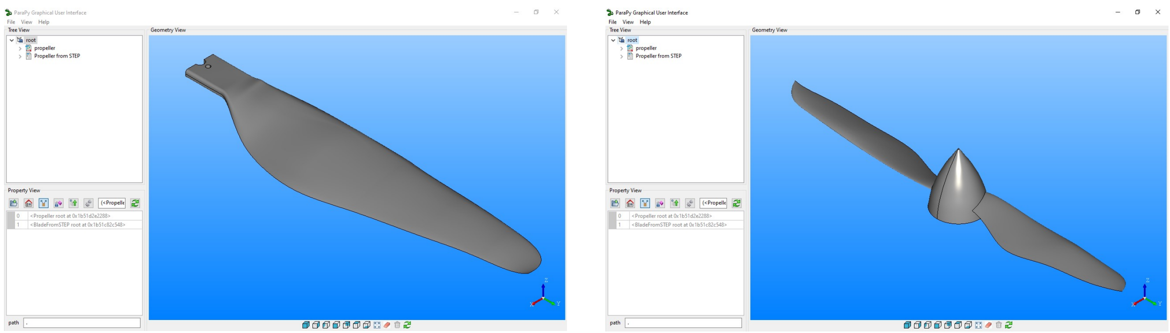
In the "Blade" section, the user could define as many sections as needed and specify for each section: the name of the airfoil, via a drop down list containing the names of several .dat files with the coordinates of the given airfoils (a small library of airfoils was provided with the application but more airfoils could easily be added), the chord of the airfoil, a thickness factor to possibly adjust the thickness of the airfoil, the angle of attack of the airfoil and the X, Y and Z coordinates of its leading edge.

In the "Hub" section, the user could define the hub type via a drop down list containing the names of the different types of hubs available (cylindrical or conical), each one with an automatic sizing based on empirical rules related with the propeller diameter.

Propeller:					
Total Diameter [in]	20				
Geometric Pitch [in]	6				
Number of blades	2				
Blade:					
Airfoils:	Airfoil 1	Airfoil 2	Airfoil 3	Airfoil 4	Airfoil 5
Airfoil Name	Eppler_64	Eppler_64	Clark_Y	Clark_Y	Clark_Y
Chord [m]	0.02	0.03	0.05	0.025	0.005
Thickness Factor	1	1	1	1	1
Angle of Attack [deg]	0	10	6	3	0
X-coordinate [m] (L.E.)	-0.0489	-0.0589	-0.0593	-0.0579	-0.0566
Y-coordinate [% of blade radius]	0	25	50	75	100
Z-coordinate [m] (L.E.)	0.004	0.0099	0.0091	0.0083	0.0095
Hub:					
Hub Type	conical				

Figure 1: Example of Excel geometry input file

Based on the input file, the application would then generate a propeller with the correct type and number of blades and with the correct type of hub. An example of one of the geometries generated using an input file is presented in Figure 2b.



(a) Blade geometry imported from STEP file

(b) Propeller geometry generated inside the app

Figure 2: Example of the two different methods of providing a propeller geometry to the application

4.1.2 XFoil Analysis

In order to determine the lift and drag coefficients of the airfoils of the different sections used for the BET calculations, a link with an external analysis tool was needed. For this purpose, an XFoil analysis routine was created.

The application divided the blade in a user-defined number of blade elements by intersecting equally spaced planes (parallel to the chord-wise direction of the blade) with the geometry of the propeller. The geometry of each of these blade elements (airfoils) was imported into XFoil and the flow conditions for the analysis were determined using preliminary calculations from the Blade Element Theory.

The values of lift and drag coefficients of each airfoil, computed by XFoil, were then imported to the BET section where they would be used for further calculations.

4.1.3 BET Calculations

The implementation of the Blade Element Theory into ParaPy was adapted from one of the examples about applying BET described in the book *General Aviation Aircraft Design: Applied Methods and Procedures* by Snorri Gudmundsson. [2]

The BET requires some inputs about the flight conditions such as the forward speed, altitude, propeller RPM and the number of blade elements to be used for the analysis. These inputs were provided using a different worksheet tab in the same Excel input file used for the propeller geometry section.

The following is a high-level summary of the BET process flow. Firstly, it performs preliminary calculations about the Flight Conditions. Secondly, it performs calculations about the Blade Geometry such as determining the radial position for each blade element. Thirdly, it performs calculations about the Airspeed Components such as the Mach number for a given blade element. Fourthly, it performs calculations about the Flow Angles such as the helix angle and the induced flow angle. Fifthly, it calculates the Reynolds number for a given blade element and uses XFoil to determine the Lift and Drag Coefficients for that blade element. Sixthly, it calculates the Blade Element Differentials, namely differential lift, drag, thrust, torque and power. Seventhly, it calculates Prandtl's Tip and Hub Loss Coefficients. Eighthly, it calculates the Blade Element Differentials Prandtl Corrected. Ninthly, it calculates the totals for Thrust, Torque and Power. Finally, it calculates some Additional Information such as thrust, torque and power coefficients, advance ratio and propeller efficiency.

5 Outcome

The main outcomes of the work developed at the CIAFA in order to determine if the propeller met the project requirements for the VTOL UAV and to benchmark the different methods of calculating propeller thrust are discussed in the following sections.

5.1 KBE Application (ParaPy)

The results of the ParaPy application, using Blade Element Theory to estimate the thrust of the T-MOTOR P20x6 propeller, are presented in Table 1. Since the BET cannot be used for a flow velocity of 0 m/s, only cases with a flow velocity of 20 m/s were considered for this analysis.

Table 1: BET results

Flow velocity [m/s]	**RPM [rev/min]**	**Thrust [N]**
20	4500	-10.6
20	6700	9.4

Unfortunately, using XFoil to compute the lift and drag coefficients of the airfoils of the blade elements, brings some limitations to the application because the analysis depends on the airfoil geometry and also, the airfoils of propeller blades usually operate at highly negative angles of attack, which causes the XFoil analysis to not converge for certain combinations of airfoils and angles of attack (which depend on the RPMs of the propeller and the forward velocity of the UAV), making it only possible to use this method to calculate the thrust of some combinations of propellers and RPMs/flight velocities.

5.2 Comparison of results

Figure 3 shows a graph where the results, for a flow velocity of 0 m/s, have been plotted.

The values from the manufacturer were obtained from the T-MOTOR website [4], on the specifications of the P60 Pin K170 brushless motor combined with the P20x6 carbon fiber propeller, which is the same setup that was used in the wind tunnel tests.

It can be seen from the graph that the CFD simulations always under-predicted the thrust generated by the propeller when compared to the wind tunnel experiments. It can also be seen that the values provided by the manufacturer are conservative, in the sense that they are always lower than the results obtained experimentally and obtained via CFD analysis.

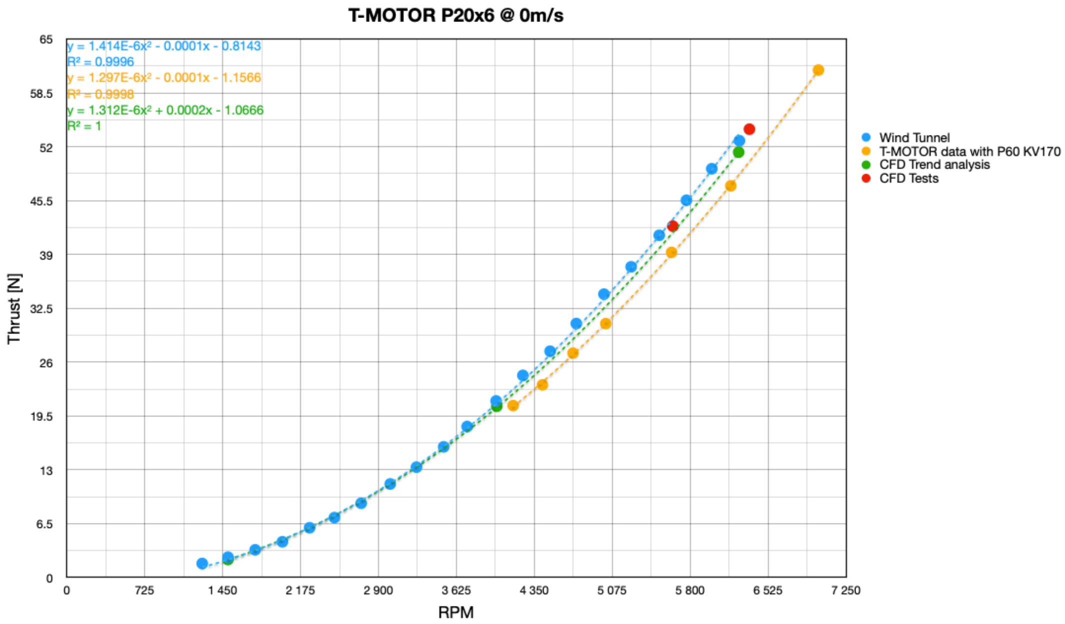


Figure 3: Plot of Thrust at different RPM for flow velocity of 0 m/s

Figure 4 shows a graph where the results, for a flow velocity of 20 m/s, have been plotted.

It can be seen from the graph that, once again, the CFD simulations always under-predicted the thrust generated by the propeller when compared to the wind tunnel experiments. It can also be seen that the BET application gives inconsistent results, being more accurate in the thrust prediction for higher RPM values, which makes sense, since for the same flow velocity, a lower RPM results in a more negative AoA at the propeller, which is one of the previously identified limitations of the *XFoil* analysis making it harder to converge to a proper solution.

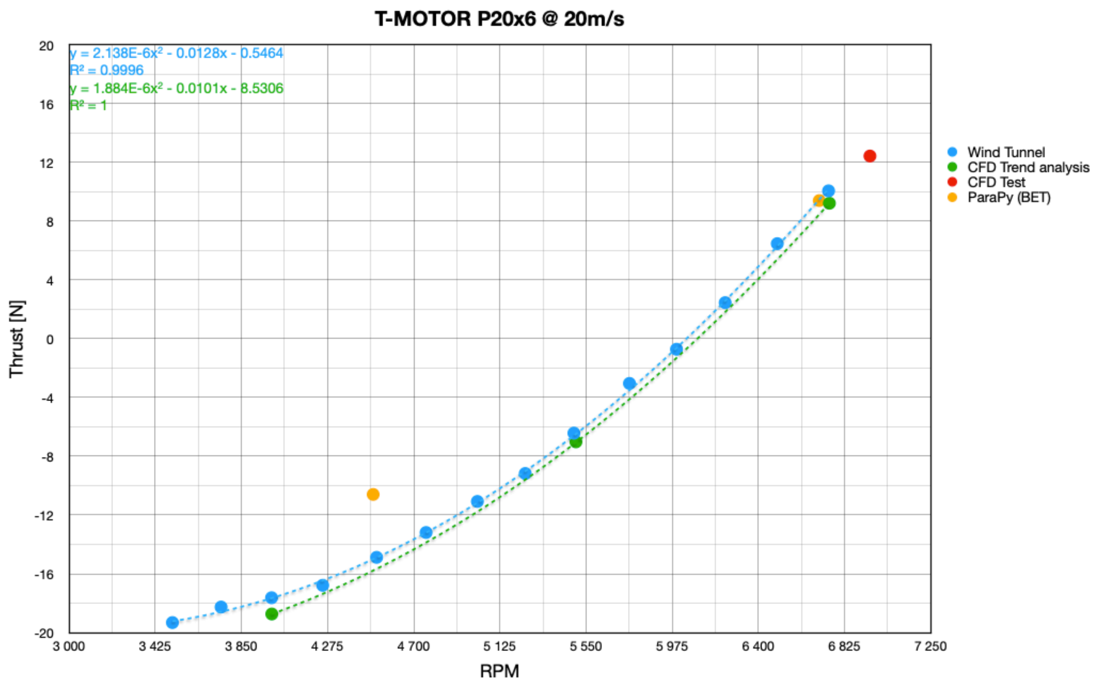


Figure 4: Plot of Thrust at different RPM for flow velocity of 20 m/s

6 Conclusions

In the last few years, Unmanned Aircraft Systems operations have grown extensively and an increase has been registered in the military use of these systems.

With the goal of contributing to the preliminary design of a VTOL UAV with a MTOW of 15 kg, being developed at the Portuguese Air Force Academy Research Center (CIAFA) at the time of the internship, several different off-the-shelf propellers were tested in the wind tunnel and analysed using computer software, in order to find out the best combination of propellers for the propulsion system of the UAV and in order to benchmark different methods of predicting propeller thrust.

The results of the comparison between the different methods of predicting the thrust generated by a propeller show that CFD simulations using the Multiple Reference Frame (MRF) model allow one to obtain accurate results with an error generally smaller than 10 % when compared to experimental results and, therefore, allow for a much cheaper and thorough alternative to wind tunnel testing. The results also show that analytical methods like the Blade Element Theory (BET), implementing panel codes such as XFoil should not be preferred to CFD simulations or wind tunnel tests because they produce inconsistent results; they can however be used as a quick way of roughly estimating the thrust produced by a propeller.

7 Recommendations for Future Work

From the main conclusions of the work performed during the internship, several recommendations for future efforts are done.

For the ParaPy application using Blade Element Theory to calculate the thrust generated by a given propeller, it is recommended that an alternative method of automatically calculating the lift and drag coefficients of the blade elements (airfoils) is investigated in order to overcome the limitations regarding the convergence of panel methods (such as XFoil) for highly negative angles of attack.

References

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[3] *ParaPy - Knowledge Based Engineering Platform.* ParaPy. (2021). Retrieved 7 March 2021, from https://www.parapy.nl.

[4] P60 Pin KV170 T-MOTOR Store. (2021). Retrieved 10 March 2021, from https://store-en.tmotor.com/goods.php?id=420