Low-Re μUAV Rotor Design

Oscar Rubio, Fidel Gutiérrez, Juan Carlos Zuñiga and Marcelo Funes-Gallanzi

Abstract This paper presents a novel approach to the design, optimization and testing of rotors for small helicopters using Bezier curves as airfoils. Blade design with low Reynolds numbers (5,000–60,000) is seriously affected by air viscosity; therefore our approach to this scenario is to analyze the propellers through the use of 3D BEM/VPM (Blade Element Momentum/ Vortex panel method) theory, further refined by estimates of blade tip and blade root losses. In addition, the code used throughout this report creates a CAD file that allows the propeller to be visualized in 3D. This report also contains the rotor build for a micro-helicopter with its results compared to the performance of current propellers; the rotor features a 15 cm blade under a 10,000 Reynolds number at cruising speed.

Keywords Low-Re rotors · MAV · μUAV · Bezier airfoils · BEM/VPM

O. Rubio (✉)
Mechatronics Student, ITESM Campus, Guadalajara, Mexico
e-mail: O.Rubio.Rivera@gmail.com

F. Gutiérrez
AVNTK S.C, Av. Chapalita, 1143, Guadalajara, Jalisco, Mexico
e-mail: fidel@avntk.com

J. C. Zuñiga
Department of Mathematics, Universidad de Guadalajara,
Av. Revolución 150, Guadalajara, Jalisco, Mexico
e-mail: juan.zuniga@red.cucei.udg.mx

M. Funes-Gallanzi
Ardita Aeronáutica SA de CV San José, 3016 Guadalajara, Jalisco, Mexico
e-mail: mfg@ardita-aeronautica.com

J. Klapp et al. (eds.), *Fluid Dynamics in Physics, Engineering and Environmental Applications*, Environmental Science and Engineering,
DOI: 10.1007/978-3-642-27723-8_46,

1 Introduction

Recently, micro-air vehicles (MAVs) have gained a lot of interest because they have many promising civil and military applications including inspection of difficult-to-access structures, search and rescue, deliver of micro payloads, communications relay and remote/distributed sensing. An unmanned system represents an emerging sector of the aerospace market. Rotary-wing MAVs have had military-focused application by armed forces around the world, however, their used in the civilian sector have increased due to the advantages of these kinds of aerial machines will bring to their business.

Despite the growth in the micro-helicopter industry, one of the disadvantages in the design of MAVs is that in order to move with agility, their rotors consume vast amounts of energy and as a consequence this decreases their flight time.

In order to improve flying time and payload capacity, a set of simulations were created to research the design of low-Reynolds number rotors, by giving the user the freedom to design the airfoil, followed by its analysis with the capability of tip/root corrections to be made, and in addition, allows the optimization and 3D assembly of the propeller for manufacture. The objective of our research is challenging because high-accuracy implies a 3D viscous flow modelling using experimental data correlations to account for the fact that viscous effects cannot be scaled. The design of low-Reynolds number rotors is complex, which is why only few dare to undertake in their research and development, since viscous effects are a major influence in the flow-fields of these types of propellers. Based on a large body of previous work (Bohorquez 2003; Bohorquez 2010; Harrington 1951), we have implemented one of the most advanced algorithms that exist in this area of aeronautics.

At first stage, we created a 3D blade and sliced into a set of airfoils using Bezier curves, as this type of arcs work better on an airfoil at low-Reynolds numbers (Bohorquez 2010). Then, we performed a viscous analysis of the profile, in order to obtain its aerodynamic coefficients and this information was then filtered to pick the best airfoils. The finest profiles were evaluated with a combination of BEM/VPM, taking into account the root and tip losses. After these simulations were done, we created the coordinates of the entire blade to allow it to be exported into CAD format.

The objective is to create a complete rotor design, from the airfoil to the propeller, with all the engineering simulations needed to cover the required criteria. This rotor design would increase MAV flight time allowing them to get more work done with the same amount of energy or increasing the maximum payload allowed.

2 Blade Design Program

The blade design program is a series of computational codes that are used to design and refine low-Reynolds number propellers. It enables the user to create airfoils using Bezier curves so that the new blade can be modified to the specific purpose of its application. The mathematical methods used within these codes are Blade Element

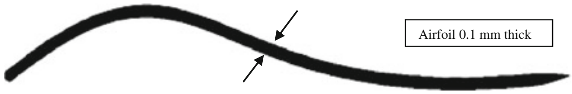


Fig. 1 It shows a simple airfoil built-up with Bezier curves. A Bezier curve was chosen due to its easy manufacture, geometry and high performance benefits in small scale-vehicle

Momentum theory (BEM) and Vortex Panel Method (VPM), combined with Bezier approximations and MIT's *xfoil* subsonic airfoil development system (Bohorquez 2003; Bohorquez 2010; Harrington 1951; Drela and Youngren 2001). The only requirement for the user is to input a three-dimensional design through the parameters needed to describe the blade, such as: camber, reflex, thickness, number of blade slices, radius and the operating low-Reynolds number.
The simulations consist of several steps, such as:

1. Airfoil construction.
2. Airfoil aerodynamic analysis.
3. Airfoil Data Validation.
4. Blade analysis.
5. 3D Coordinates export.

3 Airfoil Construction

The airfoil construction is done in this step, where the user introduces their parameters, the profiles are built with Bezier curves. The Bezier curve satisfies the restriction specified by the designer, this arc-shape conform a single unit, and this will give the form of the airfoil. Figure 1 shows an example of such arc-shape.

The user needs to type the parameters for camber, reflex and thickness of the profile; it can introduce different values for each factor. The simulations were created by combining each set of parameters to create different shapes, the objective in this stage is to design large batches files of wings with a certain range of restrictions and evaluate all of them at once and take the best choice. Finally, we created a file with 2D coordinates for every single profile designed.

4 Airfoil Aerodynamic Analysis

In order to analyze every single airfoil created, we performed several *xfoil*-analysis. This is done by using the*xfoil* code written by Drela and Youngren (2001). The *xfoil* algorithm contains a series of routines and functions for the viscous analysis of the airfoil plus many other features.

Since, it was created many profiles until this stage; it needs to automate the reading and execution of the code. We have created MATALB interface in which the user just needs to set up the range of parameters such as the *angle of attack*, the

XFOIL Version 6.94

Calculated polar for: BEZ062017010

1 1 Reynolds number fixed Mach number fixed

xtrf = 1.000 (top) 1.000 (bottom)
Mach = 0.000 Re = 0.010 e 6 Ncrit = 7.000

alpha	CL	CD	CDp	CM	Top_Xtr	Bot_Xtr
-20.000	-1.0365	0.27181	0.26088	0.1497	1.0000	0.1316
-19.800	-1.0287	0.26822	0.25732	0.1484	1.0000	0.1349
-19.600	-1.0242	0.26762	0.25677	0.1467	1.0000	0.1371
-19.400	-1.0182	0.26559	0.25481	0.1451	1.0000	0.1391
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
19.400	1.0210	0.26283	0.24729	-0.0911	0.3292	1.0000
19.600	1.0257	0.26416	0.24864	-0.0927	0.3285	1.0000
19.800	1.0306	0.26560	0.25009	-0.0943	0.3276	1.0000
20.000	1.0359	0.26726	0.25180	-0.0959	0.3264	1.0000

Fig. 2 It shows the data acquire from the aerodynamic analysis to the airfoil. Among all the results, it shows both lift and drag coefficients (CL & CD respectively) of the control surface. Also, its shows the angle of attack considered

height blade as well as the operating the Reynolds number. The MATLAB interface searches both angle of attack and Reynolds number desired and it using *xfoil* to evaluate each airfoil, it creates a new data-base. After, it examines the profile, it is written a file for each profile, where it specifies both the lift and drag generated in each angle of attack. An example can be shown in Fig. 2.

At this point we have the aerodynamic analysis of each profile, we need to know if the desired characteristics has a real blade geometry.

5 Airfoil Data Validation

In order to validate the data, it needs to check for congruence of every single profile. That is why we have created a code that allows the user to verify the output files generated in the 2D analysis, the examination is done using different criteria based on experimental results.

The purpose of this MATALB interface is to make easy for the user to look for the right set of profiles, because there are many data profiles, it takes a long time to go on each file and check the lift and drag coefficients they have at each angle of attack. That is why we decided to make a batch program where the user just puts in the parameters he wants and the computer will read all the files and outputs a file with the names of the best airfoils, subjected to the experimental data.

This "*chosen airfoils*" file will help us in the next step, since we know which profiles are the best and that fit the restriction of the project we can do a 3D viscous analysis, just on these airfoils.

6 Blade Analysis

We now have everything we need to construct the whole blade in 3D and analyze it. In this part of the algorithm, we are going to obtain the final results of performance of our design and now the user can choose which profile is the best and fits his needs.

The designer needs to introduce some variables, so we can create the whole blade, these parameters are the "chosen airfoils" file with the names of the best airfoils, number of blades, blade radius, type of taper, root and tip measurements, blade cut out, collective pitch and twist type.

We can then launch the program to initiate the simulation of blade performance. The simulation uses BEM/VPN theory, BEM give us a basic insight of the blade performance but this useful results cannot be used as a standalone code to design propellers, that why the idea arose to combine it with VPM. The VPM theory calculates the pressure distribution around the arbitrary airfoil based upon an assembly of vortices of appropriate strength between coordinates specified in the airfoil coordinate file.

After we get the results from the calculations, we also include the losses generated at the tip and the root, giving our program 15% more efficiency. The amalgamation of this entire test will give you an estimate of blade performance which is the closest result to reality. After the mathematical iterations have finished we are going to see the performance graphs of each blade, these diagrams are:

- Trust vs RPM
- Torque vs RPM
- Power vs RPM
- FOM vs RPM

We can now compare each blade and select the best one for the job, or evaluate where the designs are lacking some characteristics we need and change some variables to adjust it as we desire. This is when aerodynamic evaluation ends and if arrived to an acceptable design, we can take it to the next stage, which is to get the CAD design so we can go and manufacture it.

7 3D Coordinate Creator

We are at the final phase, this module generates the X, Y, Z coordinate of the profile that we designed. The user just needs to input the name of the airfoil that is going to be formed and the blade attributes.

The code will perform lineal interpolation to build the blade from the root to the tip, and at the end the output there is a single text file containing the propeller coordinates in millimeters and a rough graph of the design in MATLAB as is shown in Fig. 3.

With the coordinates of the file, we can import it into a mechanical computer aided design, this will draw the curves that constitute the blade, as shown in the Fig. 4, so we just need to unite them as a solid, and then finally we have our blade design ready to be manufactured.

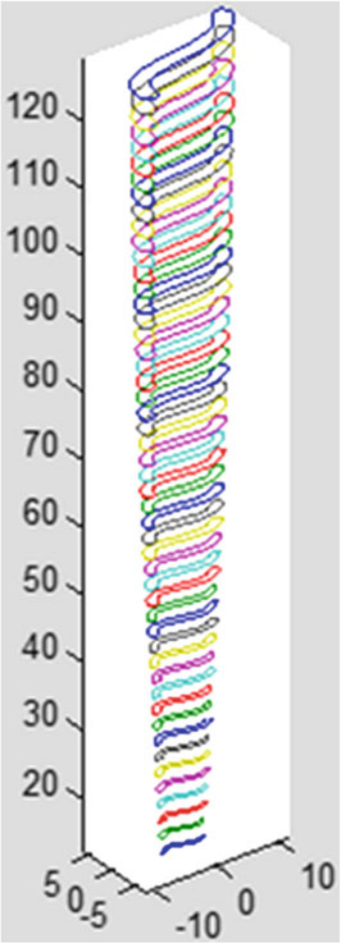


Fig. 3 It shows the wired-design seen in 3D. It shows the length of the blade that we designed and the measurement of the root and tip chord. The program assembles the wing by generating 50 profiles and stacking them up each other. The graph generated by MATLAB

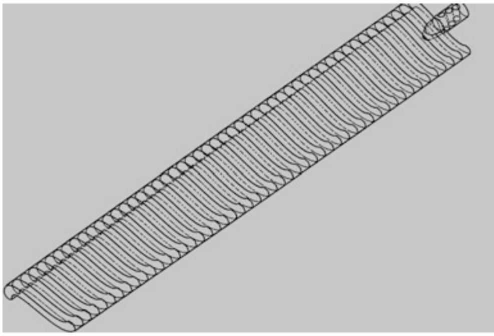


Fig. 4 The airfoils is shown when was exported to a CAD environment. Note that those profiles can form a solid body

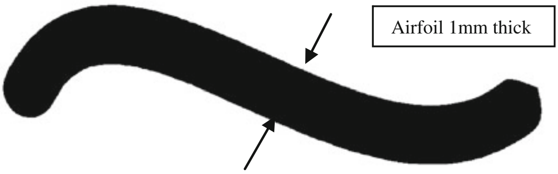


Fig. 5 The profile shown is the one we designed, as you see the airfoil is thicker than in Fig. 1, where the airfoil was 0.1 mm and now it is 1 mm wide. This change was due to manufacturing processes and load capacity of the MAV. It also has increase in camber and presents a more profuse reflex on the tail

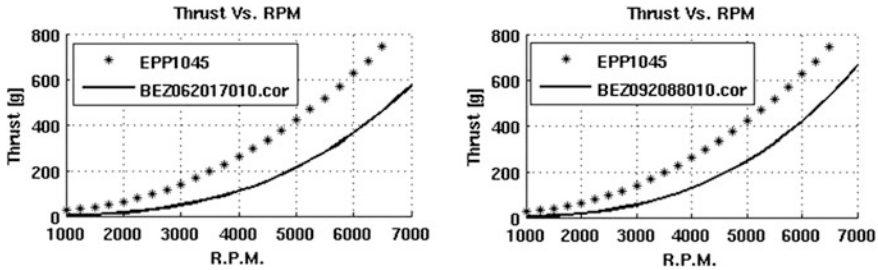


Fig. 6 Thrust graphs. (*Left*) current blades; (*Right*) designed blades. We observe that the new blades outrun the current ones by almost a 100 g. The increase of camber has improved our design. NACA EPP1045 ideal

8 New Rotor Design

As stated before, we are using the codes to design a new rotor for micro-helicopters with the purpose of enhancing the flying time of the aircraft.
The blade design we require has the following restrictions:

- Low-Reynolds number (10,000).
- 15 cm radius rotor.
- Above 1 mm thickness.
- Low energy consumption.
- High load capacity.

So we are restricted by these parameters, we need to fulfill all of them so the performance can be improved and fit in the micro-helicopter. The 1 millimeter and above thickness arises due to the resolution of the machines available for manufacture. We designed several airfoils for this blade but the only airfoil that exceeded all the rest is the one shown in Fig. 5, that has a high camber and reflex, this is for compensating the losses generated by the width.

The performance of the designed airfoil improves on a previous one by 50%, making this rotor suitable for manufacturing. The first improvement we can see is the thrust where the new design has over 17% more as shown in Fig. 6.

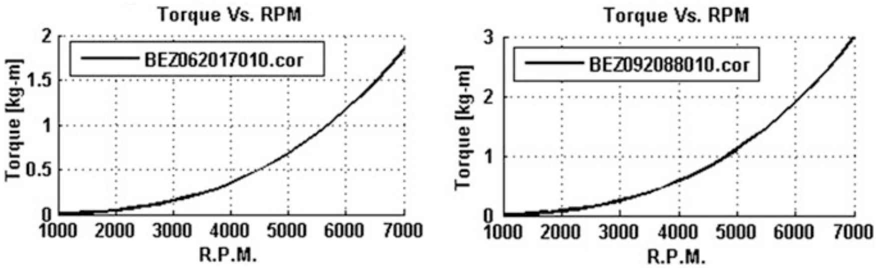


Fig. 7 Torque graphs. (*Left*) current blades; (*Right*) designed blades. As the graphs are showing our new design has amplified to 3 [kg-m] @ 7 R.P.M. from 1.8 [kg-m] @ 7 R.P.M.This means that we can carry more weight without demanding an extra effort to the motors. NACA EPP1045 ideal

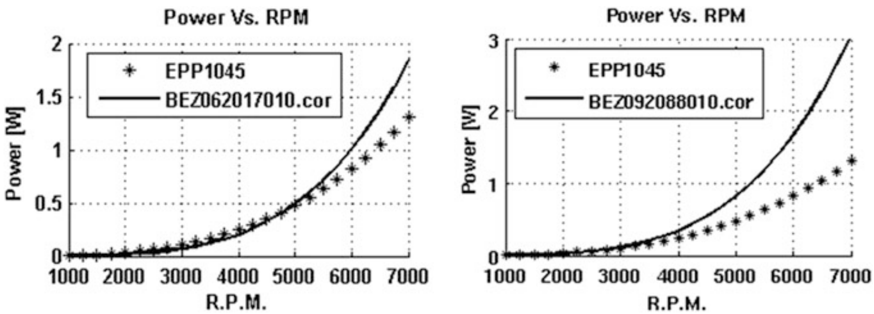


Fig. 8 Power graphs. (*Left*) current blades; (*Right*) designed blades. Due to the modifications to the width where we increase ten times the original size. We can see and increment of the power in 1.2 W. NACA EPP1045 ideal

The next comparison highlights the difference between the blades as shown in Fig. 7, the new blade has a maximum torque of 3.0 kg/m and the current one has a 1.85 kg/m, this means we have 63% more torque.

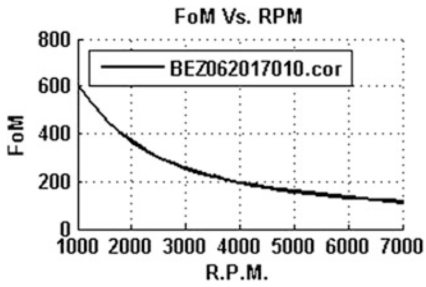
The power requirement of the new design needs more watts, but that is because it is thicker, but even with this loss our design works better because our curve is more linear and the thrust and torque are greater as shown in Fig. 8.

We can see in the FOM (Figure-of-Merit) graph that the designed blade is better than current blade (Fig. 9), since it has surpassed the performance of the previous rotor, we decided to manufacture it.

We introduced the resulting curves from the 3D generator coordinates program, and the propeller blade we got is the one shown in the Fig. 10.

In order to eliminate more losses or instability in the tip we have added wing-lets, this will help the performance of the blade steadiness and reduce vibrations on the rotor, the lateral wing-lets are shown in Fig. 11.

In order to attach the blade to the motor we have designed a fitting which not only will support the blades and connect them to the motor, but that can also change the angle of attack, with a simple mechanism, it can be adjusted to 0, +10, −10, +5, −5 and +15 degrees (Fig. 12). Adjustment of the angle of attack will



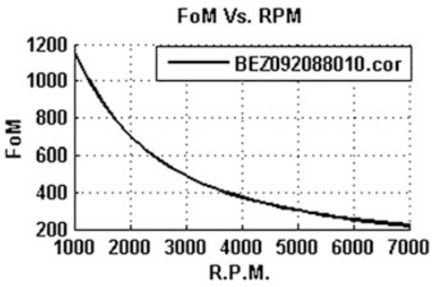


Fig. 9 FOM graphs. (*Left*) current blades; (*Right*) designed blades. It can observes than the new blades overcome the existing ones, even after the modification in thickness to the latest propeller, it is heavier and with a bigger area it generates more drag; but regardless of this it is superior

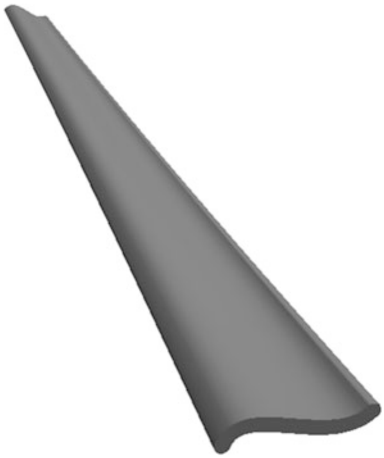


Fig. 10 It shows the witness the solid body of the blade in CAD format. We are able to see the blade and evaluate the angle of twist, length, and chord measurements and perform structural test with the desire material to manufacture

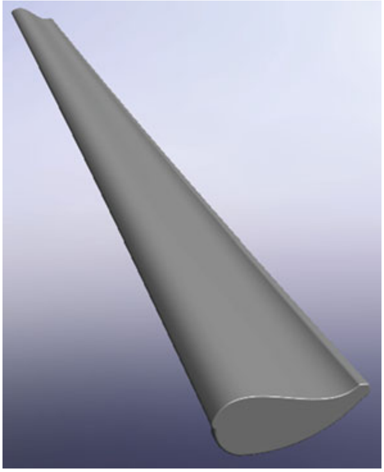


Fig. 11 The blade with the lateral fin added. Compare with Fig. 10, we can observe a more smooth finish to prevent air bubbles at the end of the wing, and to give stability to the rotors by minimizing vibrations

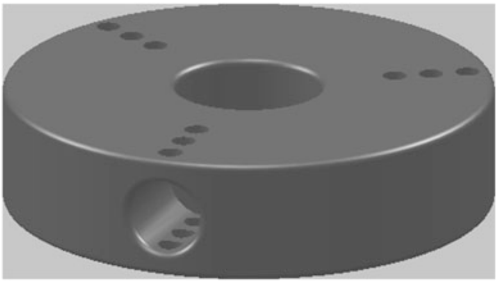


Fig. 12 Rotor concector fitting is an element that we have incorporated to the system, so the user can customize the angle of attack without having to manufactured a whole different blade. The propellers have a connection rod attach to their body with the holes properly arrange in diverse angles. Modifying the angle of attack is going to alter the performance of the rotor to enhance some properties but of course decreasing other ones

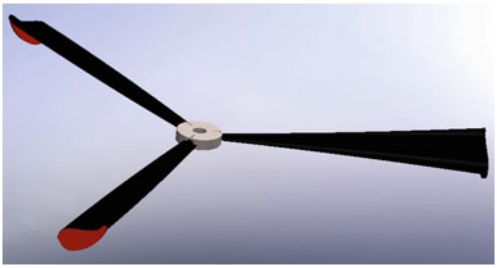


Fig. 13 It shows the final CAD model of the rotor, this is a great way to see the whole rotor; we can evaluate the measures of it and perceive how it looks like before we send it to manufacture. The drawing is going to be used in the rapid prototyping machine for its construction. Also notice the connection rotor-blade we mentioned in Fig. 12

allow testing/modification of the rotor behavior without designing a new one or including servos in to the system.

The (Fig. 13) shows the complete rotor, ready to be manufactured..

9 Conclusions

The main results in this research, the development and optimization of software able to create, analyze and build micro helicopter blades, and a specific propeller micro-helicopter design, manufactured at the available facilities at ITESM.

Furthermore, Bezier curves make perfect airfoils in this low-Reynolds number range, because of the following characteristics:

1. Higher maximum lift.
2. Lower minimum drag.
3. Low dependency of lift and drag coefficients with low-Reynolds number.

4. Minimal hysteresis loops when cycling Reynolds numbers or angle of attack.
5. Low sensitivity to ambient turbulence.

The airfoil analysis in 2D gives us a good basic knowledge of the aerodynamic behavior of the profile, but the more informative results are obtained in the 3D viscous analysis, at which point we can see the performance of the blade, and with the incorporation of root and tip losses we obtain 15% more accuracy.

The combination of BEM/VPM allows a complete examination of the propeller, the BEM gives us a rough view of interaction between the fluid and the blade, but with VPM we add a fine touch at the end, evaluating the conduct of the airfoils and air passing around them. With the implementation of these two theories we acquire a closer approximation.

With the help of the coordinate generator code, it is easier to see and build a rotor; this program helps the user to construct the blade instead of just making the calculations. With CAD design the users can get a glimpse of the blade and how it will look like if they machine it. The machines to manufacture nowadays need the CAD drawing to make the design real, so with this program you will save some time.

The new blade that we designed shows great performance overcoming the old rotors the helicopter has installed, we can see and improve in almost all the features, thrust 17%, torque 63% and the FoM is 400 units higher at low RPM, all of these variables will make the helicopter consume less energy with greater capability.

The software developed, not only gives the user freedom to design complex low-Re 3D blades, but it also outputs a manufacturing-ready file, helps to take theory to practice, extending Mexican manufacturing, engineering, design and industrial capabilities.

Finally, the program herein described is a complete compound tool for propeller engineering design. It takes you from the designing of the airfoil, to the evaluation of each profile, filter the best designs, analyze them with 3D viscous theories and build the blade on CAD software.

References

Abbot D (1959) Theory of wing sections. Dover, Canada

Asher DP (2010) A low order model for vertical axis wind turbines. Am Inst Aeronaut Astronaut 28th AIAA Applied Aerodynamics Conference, 2010–4401, 1–9

Bohorquez SS (2003) Design, analysis and hover performance of a rotary wing micro air vehicle. J Am helicopter Soc 80–87

Bohorquez PS (2010) Small rotor optimization using blade element momentum theory and hover tests. J Aircr 47, 268–283

Castillo LD (2005) Modelling and control of mini-flying machines. Springer, London

Conslisk (1997) MODERN HELICOPTER. Helicopter Aerodyn 29, 515–567

Drela M, Youngren H (2001) XFOIL 6.9. United States

Gupta L (2005) Comparison of momentum and vortex method for the aerodynamic analysis of wind turbines. Am Inst Aeronaut Astronaut 43rd AIAA Aerospace Sciences meeting and Exhibit, 1–24

Harrington R (1951) Full scale tunnel investigation of the static-thrust performance of a coaxial helicopter rotor, NACA

Hazra J (2007) Aerodynamic Shape Optimization of Airfoils in. Aerospace Computing Lab (ACL) report 2007-4, Stanford university, USA

Little J, Moler C (1994) Matlab. Natick, Massachussets, United States: The MathWorks, Inc

Kunz (2003) Aerodynamics and design. Dissertation, 1–204

Morris H (2000) Design of micro air vehicles and flight test validation. pp 1–22

Pestov S (1998) jEdit

Reid M (2006) Thin/cambered/reflexed airfoil development. A Thesis Submitted in the Requirement for Master of Science in Mechanical Engineering, Rochester Institute of Technology, 1–184

Sunada YY (2002) Comparison of wing characteristics. J Aircr 39(2), 331–338

Taamallah DR (2005) Development of a rotorcraft mini-uav system demonstrator. IEEE 2:11.A.2-1–11.A.2-15