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A HUMAN-POWERED-AIRCRAFT PROPELLER DESIGN

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ABSTRACT

Improving the efficiency of the propeller will make a significant impact on aircraft performance. It is a critical part of any human-powered aircraft (HPA) project to design a high efficiency propeller. The more efficient a propeller is, the more energy the pilot can save for staying longer and higher in the air. The Royal Aeronautical Society previously offers a prize for a competition called the Kremer Prize for the first team to fly a specific mission using a human-powered aircraft. The Penn State Sailplane Team has designed and fabricated an aircraft, named *Zephyrus*, for this mission. The previous propeller design has yet to be tested for aerodynamic efficiency and structural integrity. It was directly taken from a previous HPA propeller design developed for this project, but intended only for temporary use. Because different flight requirements and design details have a huge influence on propeller efficiency, it is necessary to design a new propeller that has better efficiency to power *Zephyrus*. This thesis includes two major sections. The first section is the analysis of previous propeller design. The results show some problems of the previous propeller. One problem is the thrust that previous propeller design provides, when operating at its designed rpm, does not overcome the drag of the aircraft at cruise condition. The second section deals with the designs of two new propellers. The two new propellers can operate at higher efficiency at a given velocity of the aircraft and still generate enough thrust to complete the Kremer Prize mission.

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ACKNOWLEDGEMENTS

I would like to acknowledge Dr. Mark Maughmer for advising me on the study of propeller design. His expertise on aerodynamics and design process helped me to get through the difficult times while studying analysis and design of a propeller. The books and articles he recommended resolved most of my questions and pointed me a clear direction to move on. I would also like to acknowledge Collin Russo for his efforts on the fabrication and testing of propellers. Collin and other group members, including David Blyton and Chris Cavanaugh, spent large amount of time in the laboratory making propellers and optimizing the propulsion system of *Zephyrus*. I would also like to acknowledge the help from Dr. Jack Langelaan. His advices and suggestions on airfoil selection and usage of XFOIL really helped this thesis to move forward.

NOMENCLATURE

AOA	=	angle of attack
B	=	number of blades
C_p	=	power coefficient, *P/pn3D5*
C_T	=	thrust coefficient, *T/pn2D4*
c	=	blade section chord
D	=	propeller diameter, *2R*
P	=	power into propeller
Q	=	torque
R	=	propeller tip radius
r	=	radial coordinate
T	=	thrust
V	=	freestream velocity
ϕ	=	blade twist angle
η	=	propeller efficiency
p	=	fluid density
Ω	=	propeller angular velocity
rpm	=	rate of rotation
local efficiency	=	thrust efficiency of airfoil cross section
Twist difference	=	The difference between twist angles of the root and the tip of the blade
Twist	=	The angle between the chord line and the plane of rotation of the propeller

Chapter 1

Introduction

A human-powered aircraft is one whose sole flight power source is the muscular output of the pilot. Pilot energy is transferred to the propellers through a bicycle-like mechanical drive device to generate thrust for the airplane. Usually, HPAs use propellers to achieve thrust. This thesis will describe the design process of a new propeller for an aircraft called *Zephyrus*. *Zephyrus* is being created in the Flight Vehicle Design and Fabrication class, known as the sailplane class, in the Department of Aerospace Engineering at Penn State University. The goal of *Zephyrus* is to win the Kremer Prize, which is considered a significant award in HPA history.

The propeller design of an HPA emphasizes the improvement of efficiency based on an old design. For instance, MUSCULAIR 1 is one of the most successful designs in HPA history. This design set a world speed record and won the Kremer Prize of $10,000 in 1984 [1]. The efficiency of the propeller of MUSCULAIR 1 was increased from 82% to 86% by using the modified propeller of another vehicle, SOLAIR 1 [1]. For *Zephyrus*, the previous propeller design has yet to be tested for aerodynamic efficiency and structural integrity. It was directly taken from the previous HPA propeller design developed for this project, but intended only for temporary use. Because different flight requirements and design details have a huge influence on propeller efficiency, it is necessary to design a new propeller that better matches the performance requirements of *Zephyrus*.

Because the previous propeller is being fabricated for upcoming flight tests of *Zephyrus*, the first section of this thesis is the theoretical analysis of previous propeller design. The verification is mainly running software codes that are XFOIL and XROTOR. The analysis results show the propeller efficiency with respect to rpm and at a given thrust. In addition, these results indicate several possible improvements about new propeller design. These improvements set the goal of the new design and guide the process of new propeller design.

The second section is the design of a new propeller. The process involves initial design, computational code analysis, and iterations. Two different new propeller designs are finalized in the end. One has two blades and the other one has three blades. The three-blade propeller operates at more ideal rpm but provides lower propeller efficiency. Moreover, the larger weight and weight balancing of three-blade propeller are other disadvantages compared to two-blade propeller. Finally, a comparison of three different propeller designs, the previous design and two new designs, are discussed in terms of propeller efficiency, rpm and structure. Considering the difficulty of designing a hub with a variable pitch device and the weight of the structure of the propeller, all three propeller designs are using fixed pitch. Therefore, the pitch angle of the new propeller designs is fixed so that the aircraft can achieve the highest propeller efficiency at cruise condition.

The last section of this thesis is the fabrication of propeller. This thesis introduces both the methods and the process of the fabrication. Three propeller designs all follow the same fabrication process. By the time this thesis is finished, the previous design is successfully constructed and ready to do field tests. The fabrication of new designs just starts and will be completed by the end of this year. Therefore, no field tests have been obtained for any of the propeller designs. All the results are limited to theoretical analysis and design. Another limitation is the structural analysis and the spar tube design of the propeller. A brief discussion about spar tube design is in the chapter of fabrication and the chapter of future work.

Chapter 2

Penn State *Zephyrus* Human-Powered Aircraft

Figure 2-1 *Zephyrus* flight test

The initial design of a HPA to complete the Kremer Prize mission was completed by students enrolled in the Flight Vehicle and Design course in 2009. Since then, various design changes were made to achieve better performance of the aircraft. The aircraft is designed to have a cruising speed of 11.5 m/s (24 knots). Its total length is 7.2 m. It has a wing area equals 15.2 m^2 with wingspan equals 22.5 m. The empty aircraft weight is 26.5 kg. The total aircraft weight is 90 kg. The designed maximum L/D is 40 [2]. In addition, a tractor propeller configuration is determined so that the aircraft is “pulled” through the air, as opposed to the pusher propeller. The aircraft is designed to be as light as possible and fly no faster than necessary for completing the mission in order to minimize the power required. The first prototype of the aircraft was finished and test flown in the spring of 2011. This version did not include a fuselage fairing, was un-ballasted for pilot weight, and was propelled by electric motor driven propellers. The next test flight of this prototype flew in the spring of 2012. As shown in Figure 2-1, the aircraft included the addition of 63.5 kg ballast in a temporary fuselage fairing to simulate the weight of the pilot. Again, this test flight was a simple straight and level flight at low altitude and was also flown using electric power. All parts of the aircraft are now in the final fabrication stages and ready for a turning flight test.

Chapter 3

Historical Perspective of HPA Propeller Design

There are three main aspects of propeller design and analysis covered in this thesis: design, analysis and fabrication. As shown in Table 3-1, this literature review considers all three aspects. By reviewing the methods, theories, and tools developed regarding propeller design, this thesis introduces some successful HPA designs in history and discusses how they will affect the propeller design, analysis, and fabrication of *Zephyrus*.

Table 3-1 Summary of relevant literatures

Authors	Category	Method / Theory
Hermann Glauert	Design	Momentum theory and blade element theory
E. Eugene Larrabee	Design	HELICE
Hermann Glauert	Design	Blade element theory
Mark Drela	Design	XFOIL
E. Eugene Larrabee	Analysis	Minimum induced loss theory
Mark Drela	Design & Analysis	XROTOR/QPROP/QMIL
Neal Willford	Fabrication	Material selection

Design

The theories of designing a propeller had been well developed since 1920s. Hermann Glauert published his first edition of *The Elements of Airfoil and Airscrew Theory* in year 1927 [3]. This book was considered a breakthrough in propeller history. It became the most well organized introduction to the fundamental principles of aerodynamics. In the book, Glauert pointed out the importance of momentum theory and blade element theory. Before Glauert's book, people tried to apply the lifting-line theory to propeller design. However, neither analytical nor experimental results showed that lifting-line theory could be used to explain the aerodynamic performance of a rotating propeller. For this reason, new theories were needed to give reasonable explanations to propeller performances. That is why the momentum theory and blade element theory were combined to become propeller theory. In addition, the blade element theory provides more detailed knowledge.

The later, Professor E. Eugene Larrabee of MIT's Department of Aeronautics and Astronautics is known as "Mr. Propeller" in the HPA community. In his research paper, "Propeller Design and Analysis for Pedal Driven and Other Odd Aircraft," Eugene Larrabee used a software code he developed named HELICE. Because a simple theory has been developed for the design of high efficiency propellers and the prediction of their performance, the difficult part turns out to be the accuracy of applying the theory. Although the design calculations can be carried out with hand calculators, the propeller performance calculations are more easily presented using a programmable digital computer. Therefore, this article is a great reference that discusses the algorithms used in HELICE and its applications [4].

According to blade element theory, before designing a propeller, the aerodynamic characteristics of an airfoil need to be provided to the software codes with the data needed for propeller design [5]. The method of calculating the characteristics of an airfoil is to choose a number of stations along the blade, and use XFOIL to predict the airfoil characteristic of each station. XFOIL is an interactive program for the design and analysis of subsonic airfoils. It consists of many useful functions such as viscous analysis, airfoil design, and redesign [6]. Mark Drela designed XFoil in 1986. The main goal was to combine the speed and accuracy of high-order panel methods with an integral boundary layer method.

There are many successful HPAs in history. Gossamer Condor was the aircraft which won the first Kremer prize. The aircraft used a very large wing area to produce lift so that the drag penalty from the wire bracing used for structural purposes became negligible [7]. It is powered by a pusher propeller, which ensures the maximum aerodynamic performance of the large wing. Gossamer Albatross won the second Kremer prize for crossing the English Channel, a 35.82 km distance, in 2 hours and 49 minutes [8]. Gossamer Albatross and Gossamer Condor had similar pusher propeller design. The reason of using pusher propeller was that both aircrafts were controlled by a large horizontal canard stabilizer. Musculair

2 set the fastest speed record with 44.32 km/h in a closed circuit. It won another Kremer prize due to its achievements on high speed. The aircraft used a traditional wing and empennage layout with a pusher propeller generating thrust from behind. Daedelus 88 was another historical HPA design which flew from the island of Crete to mainland Greece, a distance of 119 km, in 3 hours and 54 minutes [8]. This aircraft used a tractor propeller to achieve the maximum efficiency at the low speed and low Reynolds numbers of HPAs.

Analysis

Propeller analysis is complex. During flight, the aircraft will make movements such as climbs, descents, turns, pull-ups, and so on. Each single movement has different design requirement. In other words, designing is similar to finding a point in a graph, which is the optimal point of flight condition. However, analysis is to find out all the other points and connect them to a curve.

E. Eugene Larrabee details in another research paper that propellers having minimum induced loss theory [9]. This is an excellent entry point of propeller analysis. The theory of minimum induced loss leads to the specification of a radial distribution of bound circulation on each blade for lowest drag loss. Along with the integration of the airfoil aerodynamics obtained from XFOIL, Larrabee's code will design a propeller having minimum induced power loss at a given design point. In addition, a program is needed to analyze the performance of the propeller at off-design conditions. XROTOR is an interactive program for the design and analysis of ducted and free-tip propellers and windmills. The program takes considerations of design parameters including twist optimization, incoming flow effect, interactive modification of rotor geometry and multi-point integration. Mark Drela also wrote XROTOR. QPROP and QMIL are alternative programs, which are more geared for doing parameter sweeps and coupling propellers to motors [10].

Fabrication

In Neal Willford's work, "Give It a Whirl Propeller Design and Selection," he includes a section talking about propeller materials and fabrication. Propellers are typically made from wood, aluminum, or composites. Wood, such as walnut, oak, birch, and mahogany have been used since aviation's early days and are still good choices for fixed-pitch propellers [11]. For *Zephyrus*, it will use fixed-pitch propellers due to the structural concerns of its power shaft. Wood has high strength for the weight. This reduces the problems of manufacturing the very thin trailing edge of the propeller. Aluminum is one of the best propeller materials. It is most durable and very cheap. However, aluminum propeller can operate at certain frequencies due to the effect from engine power pulses, rpm, and aerodynamic forces. This can cause the propeller blades to fatigue. Finally, composite propellers are becoming more and more common homebuilt airplanes. For the *Zephyrus,* the weight of the aircraft is the most critical concern. Solid wood or aluminum materials are too heavy, so is solid composite material. Therefore, Foam made and carbon fiber laid up blades are designed and fabricated. Both fiberglass and carbon fiber have been successfully used, and can result in propellers lighter than others made of wood and aluminum.

Chapter 4

Analysis of Previous Propeller Design

The previous propeller design was directly taken from the previous HPA propeller design developed for this project, but intended only for temporary use. In addition, some of the design objectives are missing from previous reports. Therefore, it is essential to do the performance analysis of the previous design. This step leads to finding the possible improvements from the previous design to the new design.

General characteristics of propulsion system of *Zephyrus*

In this thesis, XROTOR is the main tool used to analyze the previous propeller design. To analyze a propeller, XROTOR needs to take in several basic characteristics of the propeller, including target goal of rpm, blade geometry, and properties of airfoil sections.

Table 4-1 shows all the general characteristics of the propulsion system of *Zephyrus* that would affect the analysis of previous propeller design [2].

Table 4-1 Parameters of initial propeller design

Number of blade	2
Target goal of rotational speed	90 rpm
Initial airfoil selection	E864, E856, PSU94-097
Weight	1.5 kg
Aircraft flight speed	11.5 m/s
Tip radius	1.5 m
Hub radius	0.15 m
Number of radial stations	11
Human power output	350 w
Cruise power required	200 w

Propeller radial stations

Table 4-2 shows the detailed information of previous propeller blade [2]. The values provided in the table are 11 distributed radial stations starting from 10% to 99% of the length of the blade. These numbers are from the measurement of actual propeller blade. Using the method of interpolation and extrapolation, XROTOR models the blade from root to tip continuously in three-dimensional space based on given radial stations.

Table 4-2 Radial stations of previous propeller design

#	r/R	Radius (m)	Chord (m)	Twist (degree)	Thickness (m)
1	0.10	0.150	0.0997	85.5	0.0169
2	0.20	0.300	0.1322	80.0	0.0165
3	0.30	0.450	0.1708	74.0	0.0154
4	0.40	0.600	0.2001	68.5	0.0180
5	0.50	0.750	0.2164	63.3	0.0195
6	0.60	0.900	0.2187	58.7	0.0197
7	0.70	1.050	0.2070	54.5	0.0186
8	0.80	1.200	0.1804	50.7	0.0162
9	0.90	1.350	0.1343	47.3	0.0121
10	0.95	1.425	0.0979	45.8	0.0088
11	0.99	1.485	0.0491	44.4	0.0044

Airfoil section properties

Starting from the root of the blade, the previous design uses the Eppler E856 propeller airfoil, the Eppler E854 propeller airfoil, and the PSU94-097 winglet airfoil respectively [2]. Because the root of a propeller has a small effect on generating thrust and improving efficiency, this paper will only focus on detailed aerodynamic properties of the PSU94-097 winglet airfoil that is used from 30% radial distance to the tip of the propeller.

The PSU94-097 winglet airfoil

The PSU94-097 airfoil was designed for use on winglets of high-performance sailplanes. The advantages of this airfoil are its ability to operate at relatively low Reynolds numbers and its small thickness. The range of Reynolds number of an operating propeller on *Zephyrus* is very low. From this perspective, the PSU94-097 airfoil is a good choice for the propeller of *Zephyrus*. Both the theoretical and experimental data of this airfoil are easy to acquire from XFOIL results and wind-tunnel tests. Figure 4-1 through Figure 4-4 show the plots of theoretical and experimental data of this airfoil.

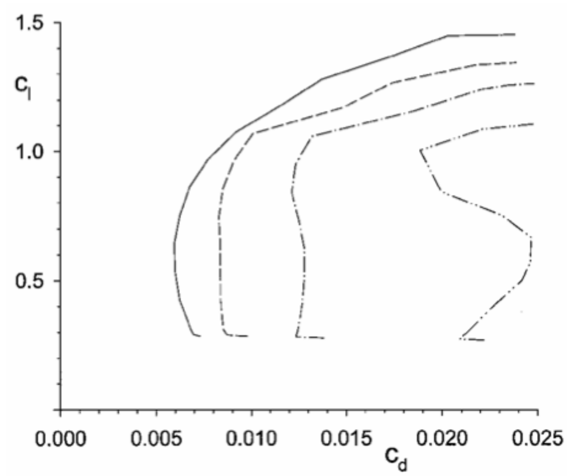

Figure 4-1 Theoretical section characteristics of the PSU 94-097 airfoil (a)

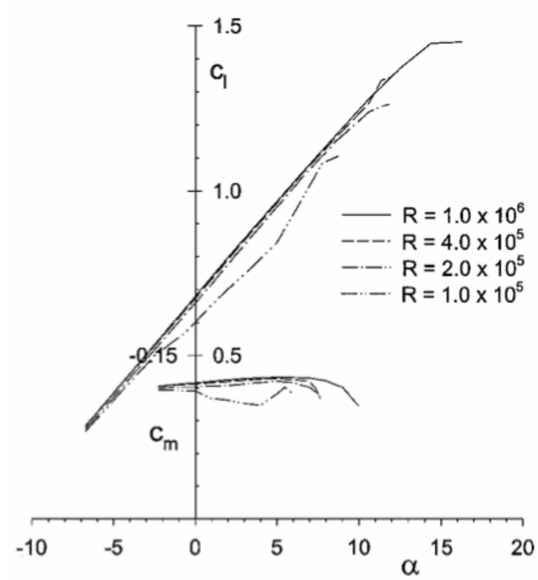

Figure 4-2 Theoretical section characteristics of the PSU 94-097 airfoil (b)

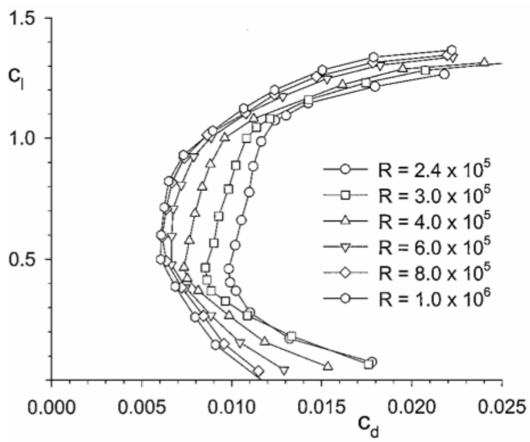

Figure 4-3 Measured section characteristics of the PSU94-097 airfoil (a)

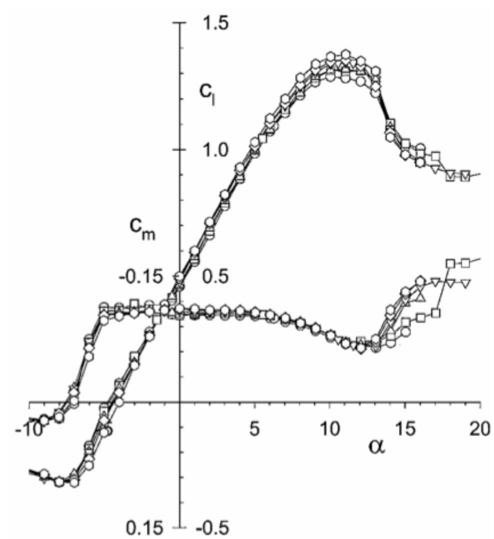

Figure 4-4 Measured section characteristics of the PSU94-097 airfoil (b)

The Eppler 856 and Eppler 854 propeller airfoils

The aerodynamic properties of E856 and E854 airfoils can also be found through XFOIL. Both airfoils are thicker than the PSU 94-097, due to the structural requirement of the root of the propeller. Figure 4-5 and Figure 4-6 show the plot of aerodynamic properties of each airfoil respectively. Because both of these airfoils are only used in the root of the blade, only polars of low Reynolds number are included in the figures.

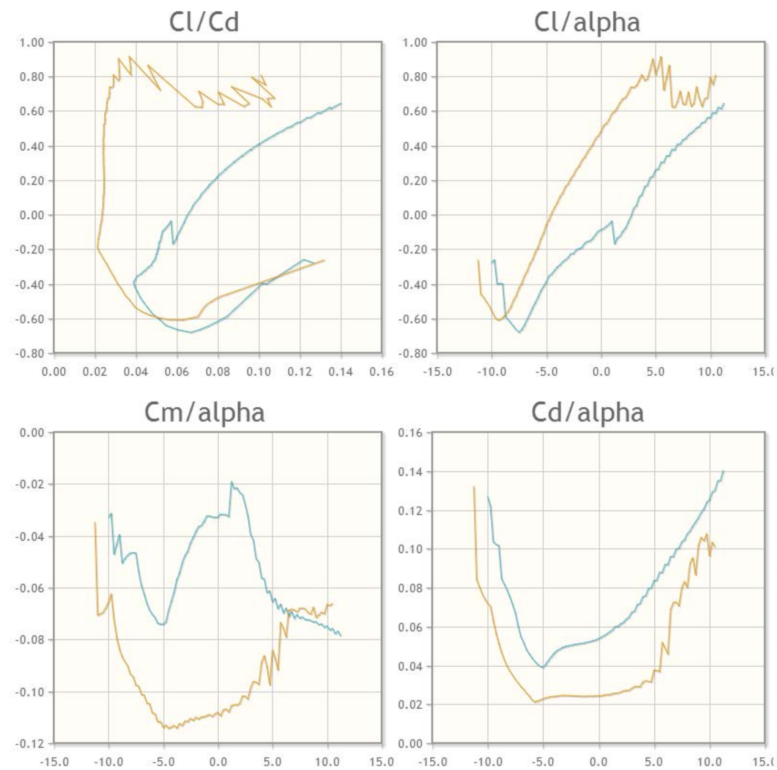

Figure 4-5 Airfoil properties of the E856 at Re = 50,000 (green) and Re = 100,000 (yellow)

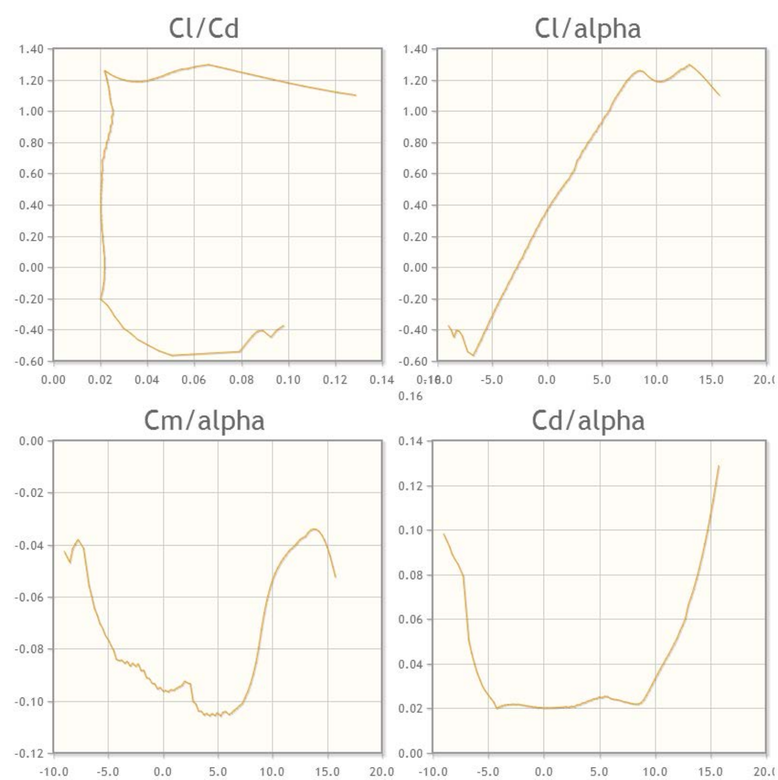

Figure 4-6 Airfoil properties of the E854 at Re = 100,000

Operating Reynolds number

The Reynolds number relates the size of the propeller, its airspeed, and the fluid the propeller is moving through. In both the analysis of previous propeller and the new propeller design, the fluid is air at sea level on a standard day. Table 4-2 shows the chord lengths and radial distributions of different propeller stations. These values are used in the calculations of corresponding Reynolds numbers.

For all radial stations, the axial velocities along the rotating axis are the same and equal to the airspeed velocity of the aircraft. The tangential velocities vary with the radial distance from the station to the center of the hub. The tangential velocity is calculated with Equation 4.1,

$$V_t = r * \Omega \tag{4.1}$$

Where, r = radial distance (in meter) of the cross section from the root of the blade

Ω = rotational speed (in rad/s) of the propeller

Then relative velocity is calculated with Equation 4.2,

$$V_r = \sqrt{V_t + V_{axial}} \tag{4.2}$$

Where, V_{axial} = airspeed (in meter per second) of the aircraft

Finally, the Reynolds number of each station is found with Equation 4.3,

$$Re = \frac{c * V_r}{v} \tag{4.3}$$

Where, c = chord length (in meter) of the cross section

ν = kinematic viscosity (in m^2/s) of standard atmosphere.

Airfoil properties in XROTOR

Table 4-3 shows the aerodynamic properties of blade sections. Each row of aerodynamic data for the blade corresponds to a radial station on the blade. Therefore, there are 11 “aero sections” in the table. Linear interpolation is used to define the aerodynamic properties for radial stations in between two neighbor stations. These values are used as inputs of XROTOR.

Table 4-3 Aerodynamic properties of radial stations of previous propeller design

#	Airfoil	r/R	CLmax	CLmin	CDmin	Cm	Mcrit	REexp	REref
1	E856	0.10	0.70	-0.60	0.03	-0.08	0.8	-0.4	0.8e5
2	E854	0.20	1.23	-0.60	0.02	-0.08	0.8	-0.4	1.0e5
3	PSU94-097	0.30	1.25	-0.35	0.06	-0.10	0.8	-0.4	1.4e5
4	PSU94-097	0.40	1.25	-0.35	0.06	-0.10	0.8	-0.4	1.8e5
5	PSU94-097	0.50	1.25	-0.35	0.06	-0.10	0.8	-0.4	2.0e5
6	PSU94-097	0.60	1.25	-0.35	0.06	-0.10	0.8	-0.4	2.2e5
7	PSU94-097	0.70	1.25	-0.35	0.06	-0.10	0.8	-0.4	2.2e5
8	PSU94-097	0.80	1.25	-0.35	0.06	-0.10	0.8	-0.4	2.0e5
9	PSU94-097	0.90	1.25	-0.35	0.06	-0.10	0.8	-0.4	1.6e5
10	PSU94-097	0.95	1.25	-0.35	0.06	-0.10	0.8	-0.4	1.2e5
11	PSU94-097	0.99	1.25	-0.35	0.06	-0.10	0.8	-0.4	0.6e5

Where Mcrit is critical Mach number, REexp is Reynolds scaling exponent number, and REref is reference Reynolds number. The drag is scaled by a Reynolds number scaling based on a reference Reynolds number and a scaling number.

XROTOR has the function that the variables for each aerodynamic section may be displayed or altered with an editing tool. Through the parameters in this function, user can describe the characteristics of the plots of CL vs. alpha, CD vs. alpha, Cm vs. alpha, and CL vs. CD to XROTOR. When the properties of each airfoil are imported, XROTOR can recognize the airfoil and predict the performance of the blade. The reason of importing airfoil properties is that XROTOR can use those data about airfoil sections to simulate the profile drag of the propeller. Later, when calculating the propeller efficiency, XROTOR will consider the effect of the profile drag. For example, section number 3 of an arbitrary blade, where r/R equals to 0.3 is displayed in the following format, as shown in Table 4-4:

Table 4-4 Detailed aerodynamic properties of each blade section

Sect# = 3   r/R = 0.3000

1) Zero-lift alpha (degree)	: 0.00	8) Cl at minimum Cd	: 0.150
2) d(Cl) / d(alpha)	: 6.280	9) d(Cd) / d(Cl^2)	: 0.0040
3) d(Cl) / d(alpha) @ stall	: 0.100	10) Reference Re number	: 2000000
4) Maximum Cl	: 2.00	11) Re scaling exponent	: -0.2000
5) Minimum Cl	: -1.50	12) Cm	: -0.100
6) Cl increment to stall	: 0.200	13) Mcrit	: 0.620
7) Minimum Cd	: 0.0070		

Efficiency and thrust analysis

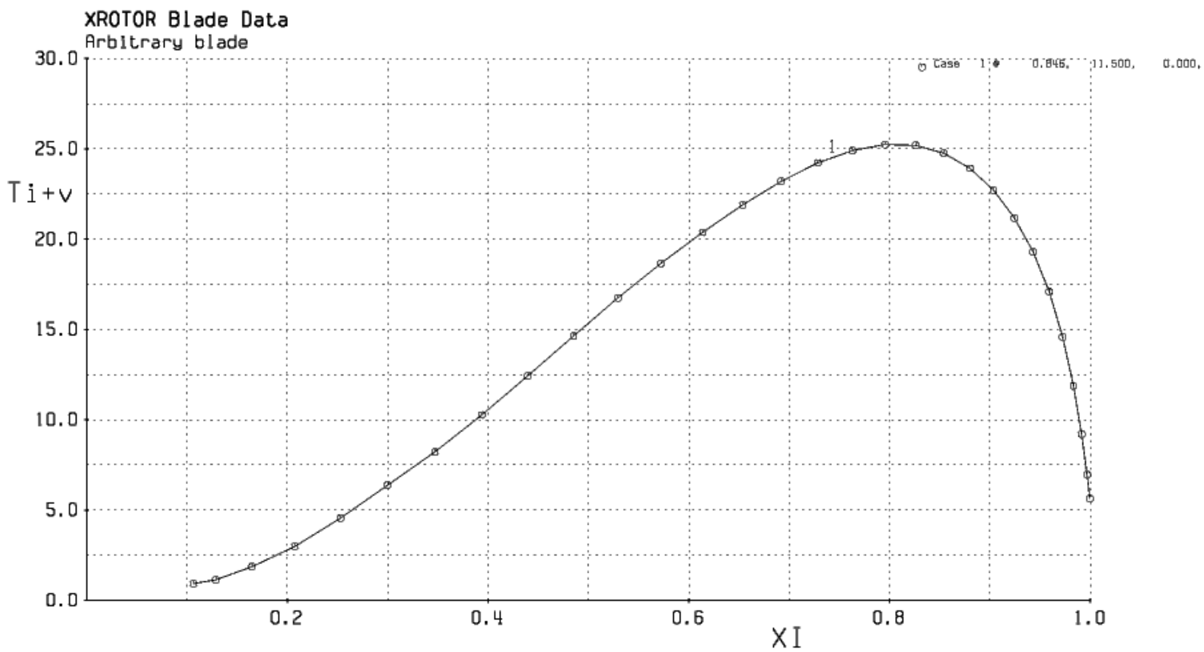

Figure 4-7 Radial distribution of thrust of the previous propeller design

After the propeller geometry and all airfoil properties are entered properly XROTOR can start to analyze the performance of the given propeller. XROTOR uses Graded Momentum Formulation to calculate induced velocities and induced losses. This method treats the rotor blades as lifting lines, and assumes the disk loading is relatively low and, hence, the wake contraction and the wake self-deformation are small. Graded Momentum Formulation is the classical theory of propellers revived by E.E. Larrabee. It relies on the Betz-Prandtl tip loss factor which assumes that the rotor has a low advance ratio. The major advantage of this method is extreme computational economy. According to Momentum-Blade element theory, the propeller efficiency is defined as TV and P is, in this case the shaft power of the drive-train system. Thus,

$$\eta = \frac{TV}{P} \tag{4.4}$$

Where, T = thrust (in Newton) from the propeller

V = freestream velocity

According to the research human power output, a trained cyclist can produce about 400 W of mechanical power for an hour or more [12]. Taking into consideration of transmission losses from human to the propeller, the shaft power of the propeller of the aircraft, P, is assumed no larger than 350 W. Because the freestream velocity equals to 11.5 m/s, the efficiency of the propeller is determined by the value of thrust. XROTOR calculates the thrust of a propeller by numerically integrating Equation 4.5 and Equation 4.6

$$dT = dL * \cos(\phi + \alpha_i) - dD * sin(\phi + \alpha_i) \tag{4.5}$$

$$dL = \frac{1}{2} * \rho * V_E^2 * c * C_l * dr \tag{4.6}$$

dL is the differential lift force. Similar to the finite wing theory, α_i is an induced angle of attack resulting from the induced velocity. ϕ is the angle between the relative velocity V_R and the plane of rotation of the propeller. V_E is the tangential component of V_R along the blade. In addition, c is the chord of the blade and C_l is the section lift coefficient which can be calculated from

$$C_l = a * (\beta - \phi - \alpha_i) \tag{4.7}$$

a is the slope of the lift curve of local airfoil and β is the angle formed by zero lift line and plane of rotation. Figure 4-7 shows the calculation result from XROTOR about thrust element of the previous propeller design.

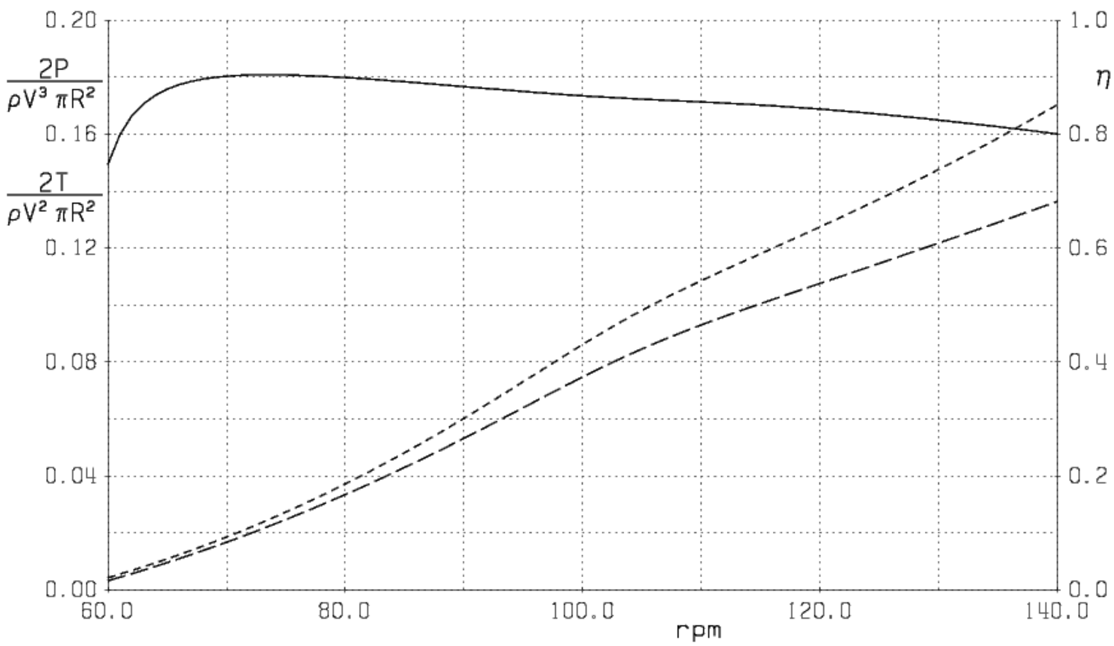

Figure 4-8 Efficiency (solid line) vs. rpm of the previous propeller design

Figure 4-8 shows the efficiency (solid line), pressure coefficient (dashed line), and thrust coefficient (dashed line) versus rpm of the propeller. It is a plot exported directly from XROTOR, however, only the curve of propeller efficiency will be analyzed and discussed in this thesis. The pressure coefficient and thrust coefficient play an internal role in finding the propeller efficiency. The analysis result shows that the highest efficiency of the propeller occurs when rpm equals 74. The highest efficiency of the previous propeller design is 90.44%. In addition, the thrust generated when the propeller is operating at highest efficiency is 13.2 N and the corresponding power required is 180 W.

Problems of previous design

Combining the requirements of the propeller design of *Zephyrus* with the analysis results above, there are four problems with the previous propeller design.

- D to the low Reynolds number effect (70,000 ~ 200,000), the propeller can never achieve the efficiency and thrust as predicted in XROTOR. Even though the PSU 94-097 airfoil is designed for low Reynolds numbers, its minimum operating Reynolds number is still higher than the range of Reynolds numbers where the previous propeller lives. At such low Reynolds numbers, the airfoils of the propeller are too thick to prevent the transition from laminar flow to turbulent flow. This causes the airfoil can never reach its maximum L/D. The other two problems get worse because of this first problem. This problem can be shown from the "Not Convergent" in XFOIL. Therefore, the previous airfoil needs to be replaced with a thinner airfoil.
- 90 rpm is the best rpm of the aircraft in terms of transaction efficiency of the drive-train system. So when designing the propeller, it is better to let the propeller can operate at an rpm that is close to 90. The previous propeller is designed to operate at 74 rpm so that the propeller can achieve its highest propulsion efficiency. Therefore from the perspective of achieving highest propulsion efficiency, the previous propeller is not well suited for *Zephyrus*. One goal of new propeller design is to move the highest efficiency point closer to 90 rpm.

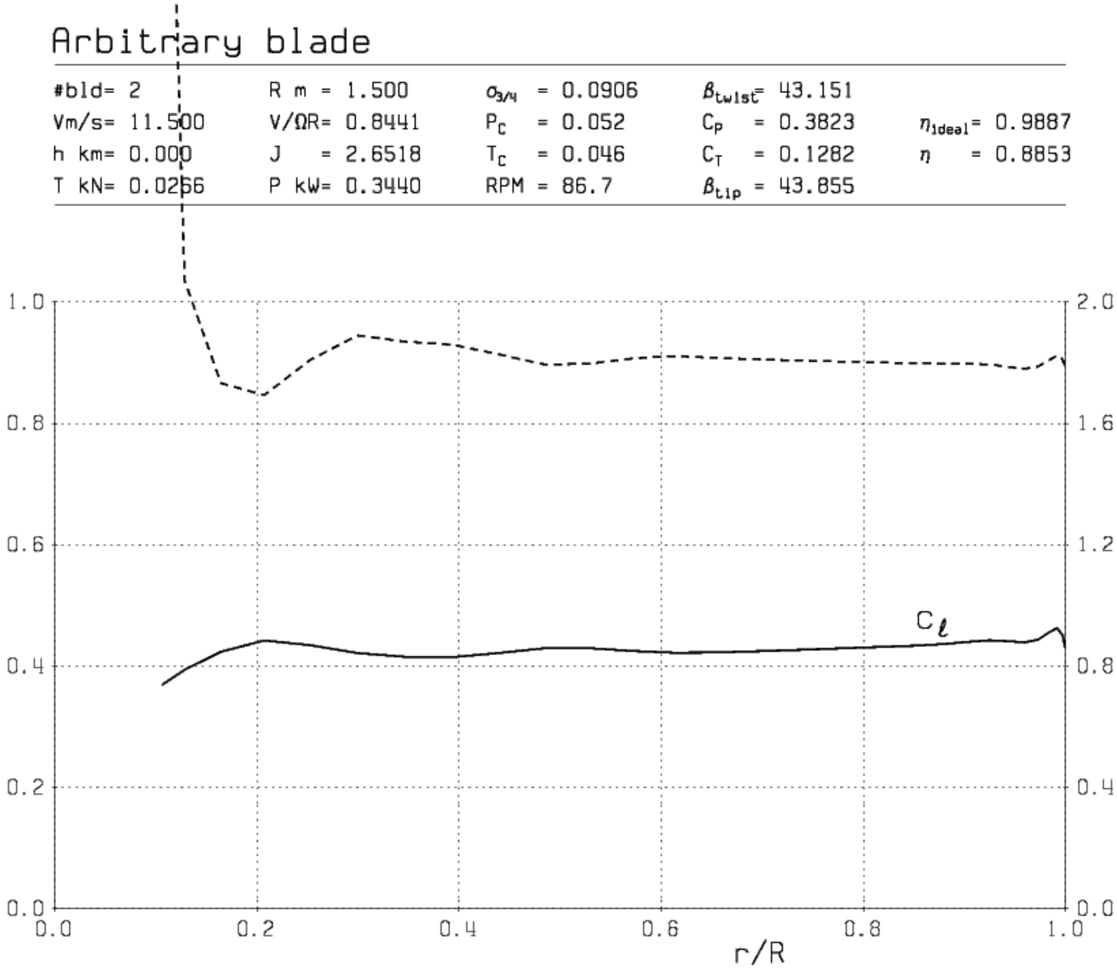

Figure 4-9 Cl and location efficiency of previous propeller at thrust = 26.6 N

- The previous propeller can only provide 13.2 N of thrust at 75rpm. However, in order to obtain its target L/D during cruise, *Zephyrus* needs to have 26.6N of drag. This means the propeller needs to provide the same amount of thrust for the aircraft to achieve steady level flight. As shown in the table in Figure 4-9, it turns out that the previous propeller needs to rotate at 87 rpm in order to provide 26.6 N thrust. The propeller efficiency is 88.53% at 87 rpm. From the perspective of powering the aircraft with sufficient thrust, the previous propeller cannot operate at its best rpm.

Chapter 5

New Propeller Design

The goal of new propeller design is to improve the efficiency at a given thrust. Two new designs are made. The first design gives better propeller performance in terms of rpm. The second design gives better performance in terms of structure and weight. Each design has its advantages and disadvantages. The details of the analysis of both new designs are discussed in later section. To achieve the goal of new propeller design, there are four aspects that need to be considered in both new designs:

- 26.6 N is the amount of thrust that is needed to overcome the drag of the aircraft so that the aircraft can achieve its maximum L/D of 40 [1]. Therefore, how efficient the propeller is when the thrust equals 26.6 N is the most important operating point, and new propeller design should focus on that.
- According to previous Penn State HPA design report, from the perspective of transmission from drive-train to the propeller. The optimum rpm for the aircraft is 90 rpm. A larger radius gear was found to reduce the loads on the chain of the drive-train. However, values between 70 rpm and 150 rpm are still acceptable [1].
- The output power from human (pilot) is around 400 W [12]. Taking into consideration of transmission losses from human to the propeller, the power required of the propeller of the aircraft is assumed no larger than 350 W.
- Structural feasibility of the propeller needs to be considered while designing. The root of the blade is thick enough to be inserted the carbon fiber spar. The ratio of the chord over the radius should be no less than 0.065.

General design parameters of new propeller designs

General design parameters of the new propeller remain the same as the ones of previous propeller design. As shown in Table 5-1, only the target goal of rotational speed is increased from 90 rpm to 100 rpm. One reason of this change is that a rpm around 100 can give better thrust efficiency in terms of aerodynamics of the propeller. Another reason is that the increase of rpm can take use of the human power more efficiently.

Table 5-1 General design parameters of new propeller designs

Number of blade	2 & 3
Target goal of rotational speed	100 rpm
Aircraft flight speed	11.5 m/s
Tip radius	1.5 m
Hub radius	0.15 m
Number of radial stations	11
Human power output	400 w

Choice of airfoil

Due to the problem of the thickness of the PSU 94-097 airfoil at low Reynolds numbers of the propeller, a thinner airfoil, the AG45c-03f is chosen as the new outer airfoil. The E856 and the E854 airfoils are still used from the root to 20% radial distance of the new propeller. The AG45c-03f is an airfoil designed by Dr. Mark Drela from MIT. It is a thin airfoil designed for model aircraft. The biggest feature of this airfoil is still its good performance at low Reynolds number. The AG45c-03f airfoil has smaller maximum thickness at a quarter chord and lower profile drag compared to the PSU 94-097. As shown in Figure 5-1, this new airfoil can still perform well at very low Reynolds number. Table 5-2 shows the comparison of detailed geometry data between PSU94-097 and AG45c-03f. A direct view of the shapes of two airfoils is shown in Figure 5-2.

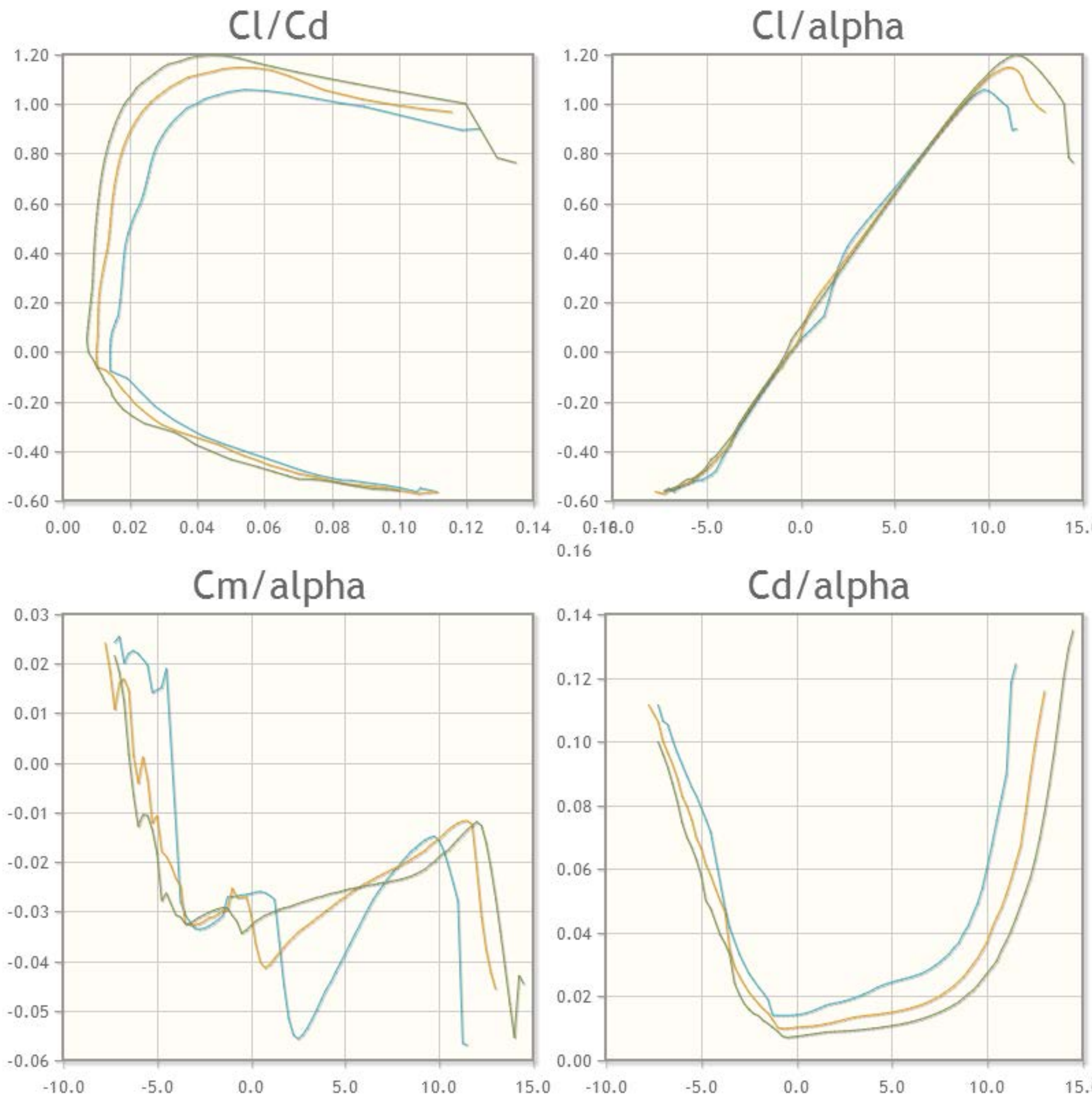

Figure 5-1 Airfoil properties of the AG45c-03f at Re = 50,000 (blue), 100,000 (yellow), and 200,000 (green)

Table 5-2 Comparison between the PSU 94-097 and the AG45c-03f

	PSU 94-097	AG45c-03f
Max Thickness	9.7% at 32.3% chord	6.9% at 23.5% chord
Max Chamber	4% at 46.3% chord	2% at 31.7 chord

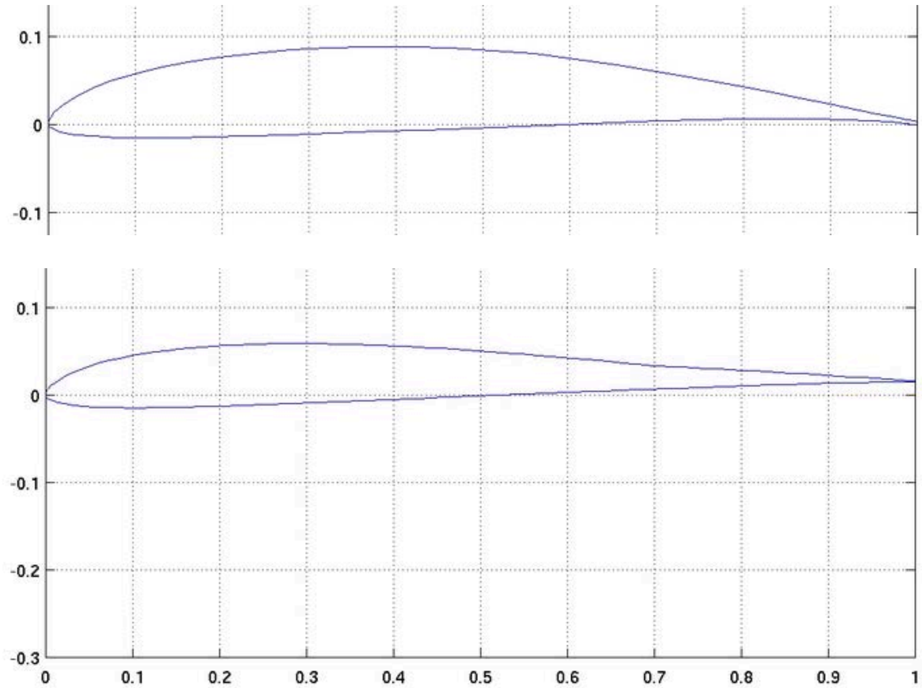

Figure 5-2 The PSU 94-097 (above) and the AG45c-03f (bottom) airfoils

Design process

The design process allows calculation of a rotor chord and blade angle (c/R, beta) distributions to achieve a minimum induced loss (MIL) circulation distribution. It is also the Betz-Prandtl distribution (Graded-Momentum Formulation).

- The design of a new propeller is begun by inputting all general design parameters (Table 5-1) of the new propeller into XROTOR. In XROTOR, the design parameters contain two redundant pairs which are advance ratio & rpm and thrust & power. Only one parameter in each pair needs to be described. The remaining parameter is then a result of the design calculation.

- After the geometry of the new propeller is created, the airfoil section data needs to be updated in XROTOR. If no airfoil information is provided, XROTOR will use its default airfoil. The same airfoil will be applied everywhere from the root to the tip of the designed blade. Therefore inputting airfoil section data is a critical part in new propeller design. The procedure of editing airfoil section is the same as the one mentioned in “Previous Propeller Analysis” section. A number of aerodynamic properties of the airfoil such as maximum CL, minimum CL, minimum CD, lift curve slope, and the reference Reynolds number are asked in order to describe the airfoil. In the new propeller design, there are 11 radial stations distributed along each blade.
- The optimized twist of the blade is another critical part in propeller design. The OPTIMIZATION command in XROTOR can twist the rotor (the beta distribution) so that the propeller can achieve a MIL circulation while holding the previous chord distribution fixed. However, the OPTIMIZATION is not necessarily the best in an overall sense, since the rotor may be made worse at other operating points. In most cases, manual iterations on changing blade twist angle are made throughout the new propeller design. A large number of iterations have to be performed in order to find the best trade-off between blade twist angle, propeller efficiency, and rpm.
- Scaling the chord of each radial station along the blade is another factor that can affect the efficiency of the propeller. After the geometry of the blade is created, the chord of each radial station can be scaled by a specific value or any linear function. Because the scaling of the chord has influence on propeller efficiency, it also causes the twist angle of the blade to change indirectly. Therefore, the trade-off between blade twist angle and scaling of the chord also needs iterations so that the propeller can achieve its highest possible efficiency and be structurally safe at the same time.

Design results

Table 5-3 and Table 5-4 shows the final results of both new blade designs, including how the 11 radial stations are distributed, what the different airfoils are, geometry of the blade, and twist angle of each station. In the tables, the twist angle is not directly exported from XROTOR. XROTOR gives the angle β of the propeller, which is the angle between the plane of rotation of the propeller and zero lift line of the airfoil section of the blade. The twist angle displayed equals to β plus zero lift AOA of the corresponding airfoil.

$$twist\ angle = \beta + AOA_0 \tag{5.1}$$

In this case, because the zero lift AOA of the AG45c-03f airfoil is -0.8 degree, so the value of β is the value of twist angle plus 0.8. In addition, Table 5-5 shows the comparison of the geometries of three propeller blades, including the average chord of the blade and the twist angle.

Table 5-3 Geometry of new propeller blade (2 Blades)

# Station	Airfoil	r/R	c/R	Twist (degree)
1	E856	0.111	0.0704	86.53
2	E854	0.204	0.0913	79.55
3	AG45c-03f	0.330	0.1216	70.42
4	AG45c-03f	0.456	0.1394	62.08
5	AG45c-03f	0.575	0.1426	55.06
6	AG45c-03f	0.685	0.1342	49.36
7	AG45c-03f	0.781	0.1181	44.86
8	AG45c-03f	0.861	0.0972	41.42
9	AG45c-03f	0.924	0.0736	38.90
10	AG45c-03f	0.969	0.0488	37.22
11	AG45c-03f	0.994	0.0253	36.30

Table 5-4 Geometry of new propeller blade (3 Blades)

# Station	Airfoil	r/R	c/R	Twist (degree)
1	E856	0.111	0.0663	87.42
2	E854	0.204	0.0958	81.18
3	AG45c-03f	0.330	0.1408	73.05
4	AG45c-03f	0.456	0.1752	65.73
5	AG45c-03f	0.575	0.1947	59.66
6	AG45c-03f	0.685	0.2024	54.84
7	AG45c-03f	0.781	0.1991	51.10
8	AG45c-03f	0.861	0.1842	48.30
9	AG45c-03f	0.924	0.1555	46.29
10	AG45c-03f	0.969	0.1123	44.97
11	AG45c-03f	0.994	0.0598	44.25

Table 5-5 Comparison of geometries of blades

	Average chord (m)	Twist (degree)
Previous Design	0.155	41.1
New design (2 Blades)	0.145	50.2
New design (3 Blades)	0.216	43.2

Analysis of new propeller

Table 5-6 Comparison of previous design and new designs

	Rpm	Thrust (N)	Power (W)	Efficiency
Previous Design	87	26.6	344	88.53%
New design (2 Blades)	113	26.6	336	92.23%
New design (3 Blades)	96	26.6	339	90.96%

As shown in Table 5-6, based on the previous propeller design, the goal of first new design is to make the propeller achieve higher efficiency when generating the required thrust. With two new designed blades, the first new propeller can increase the efficiency by about 4% while generating 26.6 N of thrust. A 4% of increase in propeller efficiency is considered a good improvement, especially when *Zephyrus* lives a very narrow design range due to the nature of human powered aircraft. Meanwhile, the power required from the propeller slightly drops from 344 W to 336 W, which means that the torque acted on the shaft of the propeller becomes smaller. Overall, the result indicates that less power is required from the pilot in order to obtain the same propeller performance. However, the rpm of the new design has to go up along with the increase of efficiency. This is due to the less chamber of the new airfoil than the previously selected airfoil. The AG45c-03f airfoil does not provide as high lift coefficient as the PSU 94-097 airfoil when operating at the same Reynolds number. In order to achieve even greater propeller efficiency, the AG45c-03f airfoil has to operate at a higher Reynolds number, which causes the rpm of the propeller going up. The increase ratio from 87 rpm of the previous propeller design to 113 rpm of the new design is 29.8%.

The other new propeller has another general parameter that is different from the previous propeller. It has three blades instead of two blades. The result from XROTOR shows that the three-blade propeller design has efficiency 91% that is in between the previous design and the two-blade design. The power required of the propeller is below 350 W. The biggest advantage of three-blade design is that it can maintain the optimum propeller rpm of the aircraft. Figure 5-3 shows the thrust per element with respect to the radius for all three propeller designs. In the plot, “arbitrary blade” is the blade design of the previous propeller. The other two curves are new blade designs. The area under each curve represents the total thrust generated by a single blade. Because the total thrust from each propeller is fixed, equals to 26.6 N, so the area under “3 blade” curve is much smaller than the other two curves.

In summary, the two-blade propeller design can provide the best efficiency, but requires a larger transmission gear to satisfy the increase in rpm. The three-blade propeller design does not have the highest propeller efficiency, but can hold the rpm of the propeller at the preferred level. Another disadvantage of three-blade design is its structure weight. Based on the design from XROTOR, the average chord length of the three-blade design is the largest among all three designs. In addition of the added blade, more weight is added to the aircraft due to the propeller.

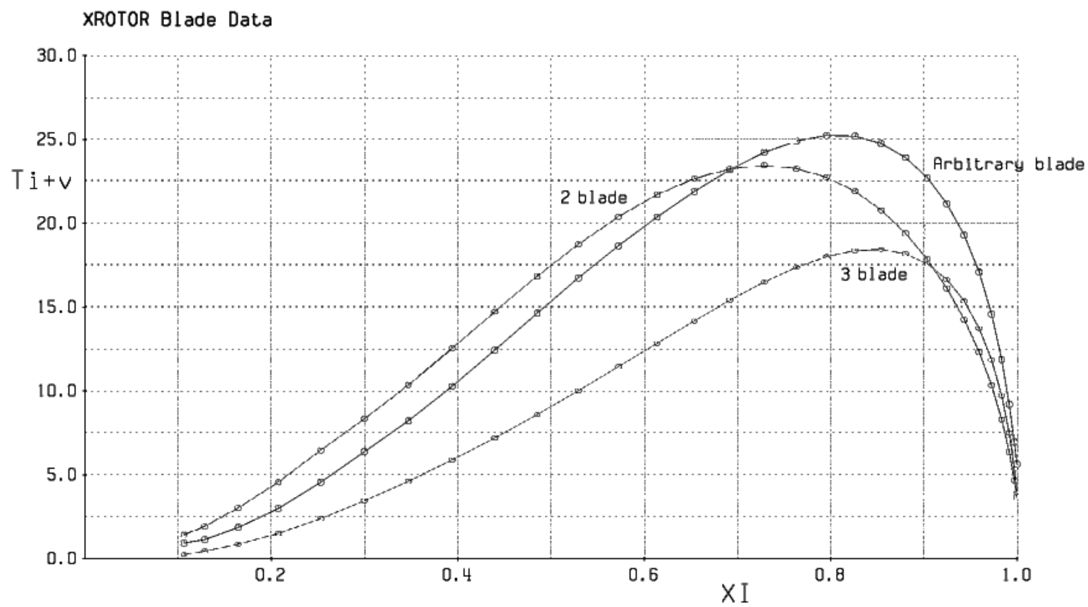

Figure 5-3 Radial distributions of thrust of three blade designs

Chapter 6

Fabrication

The methods and materials used in fabricating propellers for *Zephyrus* are consistent from the previous propeller design to the new propeller designs. So the following images are from fabrication of the previous propeller design.

- Cutting Foam core

The materials used in one single blade are one foam core, one carbon fiber spar, three carbon fiber strips, and fiberglass. The propeller blade's body is composed of dense green foam cut roughly to the contours of the blade as designed. The blade began as a block of foam that was milled into the correct shape with a Computer Numerical Control (CNC) machine in the architecture building. The machine also creates a groove that that is used to imbed the carbon fiber spar. The foam core defines the shape and geometry of the propeller blade. However, it is very thin and soft. There are many flaws along the trailing edge of the blade.

- Inserting carbon spar

Figure 6-1 Inserting carbon fiber spar

A carbon fiber spar is inserted into foam core to support the blade, mainly the bending moment and torque of the blade. Figure 6-1 shows the position of the carbon fiber spar in the blade. In this figure, the spar is located from the root to the middle of the previous blade. For new propeller design, the groove for spar is set to be 12 inches deep starting from the root of the blade. Once the groove is properly sized, the carbon fiber tube is epoxied into the blade.

- Smoothing with spackling and sanding

Figure 6-2 Sanding and spackling

Because CNC machine is not a highly accurate cutting machine, the trailing edge of the blade is full of flaws. Fast N' Final Lightwegith Spackling is a material used to fill holes, small cracks, and other minor surface defects in the foam. Therefore, after the spar is inserted, the trailing edge is filled with numerous coats of spackling and then sanding down to smooth. The number of times filling spackling is applied depends on the condition of the trailing edge. It usually takes three to five repeats of this step. The strength of spackling is as strong as foam. Figure 6-2 shows the sanding step between the usages of spackling.

- Adding carbon strips

As shown in Figure 6-3, after the sand-spackle process makes most areas on the foam smooth, carbon is added to make the blade more structural strong. If the spar tube is short (less or equal to 12 inches), a piece of carbon cloth needs to be added to the root on both sides of the blade. If the spar tube is long, this extra piece of carbon cloth is not necessary. Another two strips of uni-directional carbon fiber are added along the length of the carbon fiber spar to both surfaces of the blade. For all carbon fiber strips, a batch of epoxy mixed with hardener at a ratio of five parts epoxy to two parts hardener is used to perform the layups. After one day, sand down the strip to make its surface as smooth as the foam surrounding it.

Figure 6-3 Adding carbon fiber strips and sanding

- Laying up fiberglass

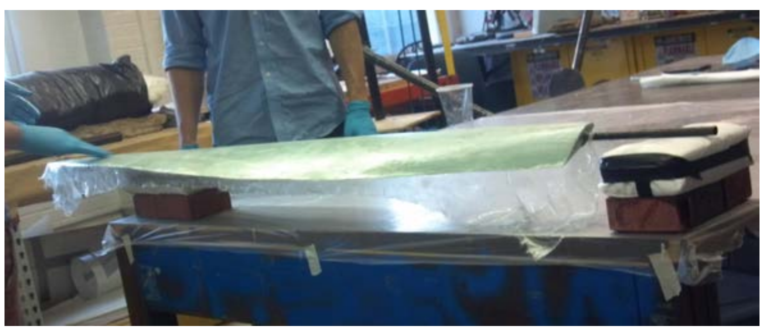

Figure 6-4 Laying up fiberglass

After more sanding and removing the imperfections from the blade's body, fiberglass lay-up process begins. As the carbon fiber strips are epoxied on the foam, epoxy is also used in fiberglass lay-up. Saturate a piece of fiberglass that is large enough to cover one side of the blade with epoxy. Then it needs to be quickly flipped onto the side of the blade that has also been epoxied. Carefully squeeze out air bubbles between the fiberglass and the foam. The excess fiberglass on the side is left around the edge. After an hour and a half, cut down the excess edge of the fiberglass to about 1 cm, and fold around the edge. The lay-up process is next repeated on the other surface of the blade. Repeat the same procedure of laying up fiberglass and let the excess fiberglass dry on the side. The drying of the fiberglass is shown in Figure 6-4.

- Smoothing with micro balloons and sanding

Once the lay-up process is finished and has dried for one day, excess fiberglass on the second surface is cut away. Then, more sanding makes the whole blade's surface as smooth as it once was. The lay-up process makes the blade much stronger, but it also makes the surface of the blade much rougher. Any air bubbles formed beneath the fiberglass needs to be cut out. Then these bubbles flows are filled with micro balloons. The micro balloons are also mixed with epoxy. A day is needed to let the fixed area dry. Since micro balloons are bad to health, proper ocular and respiratory protections are used to prevent any injuries or health risks.

- Priming and Painting Surface

The last step of fabricating blade is priming and painting the blade's surface. Primer is applied to the surface with four to five coats. After each coat, the blade is sanded with 1200 grit sandpaper to let the surface as smooth as possible. After the final coat of primer dries, a coat of white spray paint is added to the surface so that the blade construction is finished.

Figure 6-5 Final paint

Chapter 7

Conclusion and Future Work

The goal of this thesis is to find out the "best" propeller design to power *Zephyrus*, a human-powered aircraft. The answer of what the "best" design is goes to the trade-off among several aspects: the propeller efficiency, rpm of the propeller, thrust, power output from the pilot, the transmission efficiency of drive-train, the propeller weight, and structural concern. The analysis of the previous propeller gives a general idea of how efficient the propeller of *Zephyrus* is and what shape it is. Also, possible improvements are seen from the analysis result. This work provides a good start of the new propeller design and points out the direction.

It turns out that a better propeller design of *Zephyrus* does exist. Two different new propeller designs are made with XROTOR. One new propeller design has two blades, which is the same as the previous propeller design has. It can offer 4% higher propeller efficiency than the previous propeller design when generating the same amount of thrust. The disadvantage of this design is its high operating rpm. The increase on rpm will drop the transmission efficiency of drive-train system. The other new design has 3% higher propeller efficiency than the previous propeller design. In addition, it can almost operate at the optimum rpm of the drive-train system. However, this new design has three blades, instead of two blades. This causes a greater propeller weight, a harder balancing and testing process, and a different structural and spar design.

Even though new propeller designs have been made, the final "best" propeller has not been achieved yet. There is still a lot work on propeller design needs to be done to help *Zephyrus* win the Kremer prize:

- Testing of these propellers is a very important work that has to be done in the near future. Propeller test will measure thrust, torque, and rpm. During static thrust test, strain gauge can be used to measure thrust and torque. If necessary, the output signals can be amplified through a signal-conditioning amplifier. During dynamic thrust test, freestream velocity must be measured besides all the other values. The velocity can be determined by measuring the dynamic pressure. The required performance coefficients can be calculated based on the user input atmosphere temperature, pressure, and the measured dynamic pressure. The results from the tests of both static thrust and dynamic thrust will provide important feedback on new propeller design. In addition, propeller tests can be used to check the results from XROTOR. Therefore, it will also help the usage of the software.

- Structural design, which is mainly the spar design and the hub design, is another remaining design problem. There are two different spar designs in previous propeller design. One has a larger diameter and the other one has a larger length. However, neither of the two spar designs has been tested in any structural tests. Because the material properties of the propellers are different among various HPAs, field tests and their recordings are necessary for the propeller design of *Zephyrus*. Any redundant design on diameter and length of the spar will have a significant effect on the design of the blade shape. The spar inserted into the blade largely determines the thickness of the root, the chord length near the root, the choice of airfoils along the blade and so on. The two new propeller designs from this thesis have taken the unknown spar design into consideration. The root section of each new propeller design is thick enough to be inserted the previous larger-diameter spar.
- The choice of airfoils of the blade is not finalized. The airfoil is changed from the PSU 94-097 to the AG45c-03f. The decrease on airfoil thickness causes the fabrication problem. The thinner the airfoil is, the higher the relative errors are, and therefore, the stricter requirements are for these hand-making propellers. Additionally, there still are

improvements on propeller efficiency from the perspective of aerodynamic performances of the airfoil. For example, the penalty of switching airfoil from the PSU 94-097 to the AG45c-03f is the drop on maximum L/D of airfoil section of the blade.

- New technology about fabrication is likely to be applied on propeller design of *Zephyrus*. The previous construction method and process waste a lot of material and take very long time to complete. Because additive manufacturing technology, such as 3D printing, has been used in aerospace industry, the structure of the propeller of *Zephyrus* is also possible to be printed by a 3D printing machine.

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- HTML Web Design

Publications and Papers

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