Propeller Design and Analysis for a Small, Autonomous UAV

by

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ABSTRACT

An experimental study was performed to design and analyze a “pusher” propeller for use by a small, expendable, autonomous unmanned aerial vehicle (UAV) whose mission was to descend from 30,000 feet to sea level at an approximately constant descent rate over a 3-hour mission duration. The entire propeller design process, from airfoil selection to final part generation in the computer-aided drafting program SolidWorks is described. QMIL and QPROP were the programs of choice for producing a propeller design focused on yielding minimum induced losses for optimal aerodynamic efficiency given a conservative aerodynamic design point. The TA22 airfoil defined the propeller cross section and NEU-012-030-4000 DC brushless motor was selected to power the propeller. The initial propeller design was modified to comply with size constraints set by the mission.

Wind tunnel tests were conducted to determine the effect of fuselage blanketing on propeller performance. Of particular interest was comparing the power required to propel the aircraft at a given airspeed for a configuration in which the propeller was mounted behind the fuselage, and one in which the propeller was not obstructed by an upstream object and instead isolated in the incoming airstream. It was empirically found that fuselage blanketing had a significantly detrimental impact on each of the 4 propellers used in testing. It was therefore recommended that the hub section of the propeller be redesigned to mitigate drag and propulsive losses resulting from reduced momentum in the blanketed region of the propeller. This recommendation was applied to the included propeller design and propeller betas in the hub region were reduced using qualitative methods.

Thesis Supervisor: Prof. Robert John Hansman, Jr., PhD
Title: Professor of Aeronautics and Astronautics and Engineering Systems
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Chapter 1

Overview/Executive Summary

This thesis documents the research and analysis conducted on the design and manufacturing of a propeller to be used by the MIT 16.821 course, Flight Vehicle Development, in its development of a relatively small environmental survey vehicle for use by MIT Lincoln Labs. The mission proposed requires the aircraft to record sensor data taken during a steady descent from 30,000 feet to sea level. The aircraft was to remain in-flight for approximately 3 hours. This research project was conducted following the generation of preliminary propeller designs developed in 16.82, Flight Vehicle Engineering.

The design of the propeller involved extensive use of the subsonic airfoil aerodynamic analysis program XFOIL, as well as the numerical propeller optimization programs QMIL and QPROP.* XFOIL was used to obtain aerodynamic characteristics of the design airfoil such as basic lift and drag coefficient parameter values. These values were then applied to QMIL and QPROP, which incorporated mission environment characteristics at a conservative design point to develop a preliminary propeller geometry designed for minimum induced losses. These programs accounted for performance parameters of the driving motor selected for the mission. Input and output geometry files were modified to conform to the strict mission requirements and iterated until satisfactory performance specifications were achieved. Such constraints posed by the operational overview included the geometric size limitation that the propeller diameter could not exceed 3 inches without becoming a folding propeller so that it would fit into its protective casing.

Following theoretical verification of sufficient thrust and efficiency provided by the propeller, SolidWorks models were developed to manufacture the propeller for thrust and efficiency testing. Creating a solid part of the propeller design was accomplished via a Matlab script which imported radius, chord and beta values from a spreadsheet into SolidWorks via the “Curves through XYZ Points” feature, and converted via the “Convert Entities” feature. The propeller airfoils were imported as 20 different slices which were lofted together to produce a fully defined solid part in SolidWorks.

*Produced by Mark Drela of MIT.
Propeller thrust tests were then conducted in a 1 foot-by-1 foot wind tunnel. Tunnel velocities reflected design flight speeds at sea level. Tests were conducted to directly compare power consumption values for propellers mounted in two different configurations. One configuration involved the propeller operating behind the fuselage as a pusher in accordance with the aircraft design. The other configuration involved the propeller operating in the free stream with no obstructions. Empirical power consumption values were compared to theoretical predictions.

Chapter 2

Theoretical Background for Propeller Performance and Design*

2.1 Fundamentals of Propeller Performance

A propeller blade (see figure 2-1) is simply a rotating airfoil, similar to an airplane wing, which produces lift and drag. It has both induced upwash and downwash due to the complex helical trailing vortices that it generates. The two most important performance parameters of a propeller for design and analysis projects such as this are the thrust and torque it produces.

![Propeller Blade Cross Section](image)

Figure 2-1: Depiction of a propeller blade cross section (airfoil).*

The thrust (T) and torque (Q) generated by a propeller blade can be represented as:

\[ dT = dL \cos(\phi + \alpha_i) - dD \sin(\phi + \alpha_i) \]

\[ dQ = r[dL \sin(\phi + \alpha_i) + dD \cos(\phi + \alpha_i)] \]

\[ dL = \frac{1}{2} \rho V_e^2 c C_i d \]

\[ dD = \frac{1}{2} \rho V_e^2 c d\alpha \]

The Integral Momentum Theorem can be applied to a propeller using actuator disk theory to find its performance relative to common design parameters. Take figure 2-2 to represent a typical control volume taken for the analysis of a propeller, or actuator disk, where the +x direction points left.

![Figure 2-2: Control volume for propeller analysis.](Image)

Recall that Newton’s second law for a control volume of fixed mass can be written to relate external forces to changes in inertia and momentum:

\[ \sum \vec{F} = \int_V \rho dV + \int_V \rho \frac{D\vec{u}}{Dt} dV \]

where the first term is the sum of all external forces on the prescribed control volume, the second term corresponds to forces due to the change in inertia for an accelerating vehicle exposed to force \( F_0 \), and the third term is the change in momentum of the mass in the control volume.

Applying this relationship to an object traveling in the x-direction, we can rewrite as:

\[ \sum F_x - F_{0,x} = \int_V \left[ \frac{\partial (\rho u_x)}{\partial t} \right] dV + \int_s u_x (\rho \vec{u}) \cdot \vec{n} ds \]

where the first term is again the sum of forces on the control volume, the second term is the change of momentum of the mass in the control volume over time, and the third term is the

change in momentum flux across the control volume surface. The forces acting on the control volume are composed of pressure, body, and skin friction forces. For steady flow with no acceleration of the vehicle, we have:

\[ \sum F_x = \int u_x(\rho \bar{u}) \cdot \bar{n} \, ds \]

Here it is assumed that the flow outside of the propeller stream tube does not vary in total pressure, which is reasonable for steady-level flight conditions. Since the pressure forces are balanced everywhere along the control surface, the only force acting on the control volume is due to the change in momentum flux across its boundaries. Consequently, thrust becomes:

\[ T = \dot{m}(u_e - u_0) \]

The power expended equals the power imparted onto the fluid, which is equivalent to the change in kinetic energy of the flow as it passes through the propeller. The power imparted to the fluid:

\[ P_{fluid} = \dot{m} \left( \frac{u_e^2}{2} - \frac{u_0^2}{2} \right) \]

and the propulsive power, or rate at which useful work is done, is given by the product of thrust and flight velocity. Propulsive power = thrust x flight velocity = \( Tu_0 \). The propulsive efficiency is the ratio of this useful rate of work to the power imparted to the fluid, or:

\[ \eta_{prop} = \frac{2}{1 + \frac{u_e}{u_0}} \]

This propeller efficient is the product of viscous profile efficiency \( \eta_v \), which accounts for viscous profile drag on the blades, and an inviscid Froude efficiency \( \eta_i \) which accounts for the kinetic energy lost in the accelerated propwash. Thus,

\[ \eta_{prop} = \eta_v \cdot \eta_i \]

An upper limit and estimate of the inviscid Froude efficiency term is given by:

\[ \eta_i \leq \frac{2}{1 + \sqrt{1 + T_e}} \]
where for steady level flight

\[ T_C \define \frac{T}{2\rho V^2\pi R^2} = \frac{D}{\frac{1}{2}\rho V^2\pi R^2} = \frac{S}{\pi R^2} C_D. \]

In level flight, since we can approximate \( W = L \), we can find the thrust and propulsive power:

\[ W = L = \frac{1}{2} \rho V^2 S C_L, \]

\[ V = \left( \frac{2W}{\rho S C_L} \right)^{\frac{1}{2}} \]

\[ T = D = \frac{1}{2} \rho V^2 S C_D = W \frac{C_D}{C_L}, \]

\[ P_{prop} = TV = DV = \frac{1}{2} \rho V^3 S C_D = \left( \frac{2W^3}{\rho S} \right)^{\frac{1}{2}} \frac{C_D}{C_L} \]

Of particular interest is the case in which a minimum amount of energy is used to maintain desired flight performance. Assuming a relatively constant total aircraft weight, the time \( t \) and shaft energy \( E_{shaft} \) required to fly a distance \( d \) is

\[ t = \frac{d}{V} \]

\[ E_{shaft} = P_{shaft} t = \frac{T d}{\eta_{prop}} \]

For sustained level flight of a distance \( d \), we can represent shaft energy and power as:

\[ E_{shaft} = \frac{1}{\eta_v} \left( \frac{1}{2} + \frac{1}{2} \left( \sqrt{1 + \frac{S}{\pi R^2} C_D} \right) \right) (W_e + W_p) d \left( \frac{C_D}{C_L} \right) \]

\[ P_{shaft} = \frac{1}{\eta_v} \left( \frac{1}{2} + \frac{1}{2} \sqrt{1 + \frac{S}{\pi R^2} C_D} \right) \left( \frac{2(W_e + W_p)^3}{\rho S} \right)^{\frac{1}{2}} \left( \frac{C_D}{C_L} \right)^{\frac{3}{2}} \]
2.2 DC Motor-Propeller Matching

A key consideration in propeller design involves motor-propeller matching, in which it is of paramount importance to drive the motor with high efficiency at the design point, which dictates propeller rotational velocity required for steady-level flight in this mission. A DC brushless motor was selected as the primary motor source for this mission. This section will provide a concise theoretical background for motor-propeller matching for a DC motor power source.*

The equivalent circuit model displayed in figure 2-3 fairly accurately describes the behavior of an electric motor. The internal back-EMF \( v_m \) is proportional to rotation rate \( \Omega \) via the motor speed constant \( K_v \). Applying conservation of energy in conjunction with circuit equations, the motor parameters can be expressed in terms of motor current \( i \) and terminal voltage:

\[
Q_m(i) = \frac{i - i_0}{K_v}
\]

\[
\Omega(i, v) = (v - iR)K_v
\]

\[
P_{shaft}(i, v) = Q_m\Omega = (i - i_0)(v - iR)
\]

\[
P_{elec}(i, v) = vi
\]

\[
\eta_m(i, v) = \frac{P_{shaft}}{P_{elec}} = \left(1 - \frac{i_0}{i}\right)\left(1 - \frac{iR}{v}\right)
\]

![Figure 2-3: Equivalent circuit for a brushed DC electric motor.](image)

*Lecture notes, MIT. Professor Drela. 3 March 2005.
These relationships depend on motor characteristics, where $K_v$ is assumed to be in units of $\frac{\text{rad}}{\text{s}}$, which are typically provided by electric motor manufacturers. To aid in modeling for matching the motor to the load applied, a propeller in our case, a function for current can be written as:

$$i(\Omega, v) = \frac{v - \frac{\Omega}{K_v}}{R}$$

This can be inserted into the above equations to obtain performance relations as functions of motor speed and voltage:

$$Q_m(\Omega, v) = \frac{\left(\frac{v - \frac{\Omega}{K_v}}{R} - i_0\right)}{K_v}$$

$$P_{shaft}(\Omega, v) = \frac{\left(\frac{v - \frac{\Omega}{K_v}}{R} - i_0\right)}{K_v}$$

$$\eta_m(\Omega, v) = \frac{1 - \frac{i_0 R}{v - \frac{\Omega}{K_v}}}{v K_v} \Omega$$

These functions are sketched versus motor speed in Figure 2-4 to provide an understanding of the influence of propeller RPM on key performance parameters.
The first plot is a simple motor-torque curve. The second serves as a reminder that the motor propulsive power has a roughly parabolic shape with optimum max power occurring along that parabolic curve. The third curve then follows in showing that motor efficiency is maximized and then falls more sharply with increasing in rotational speed beyond the max-efficiency point than with a slower rotational speed below the max efficiency point. The equilibrium operating speed \( \Omega \) of the motor/prop combination occurs when the torques balance, which can be written symbolically as:

\[
Q_m(\Omega, v) = Q(\Omega, v)
\]

Figure 2-4: Motor output variables versus motor speed and applied voltage.\(^1\)

Chapter 3

Introduction to Propeller Design

3.1 Mission Requirements

This section outlines the steps taken to design the propeller used for mission execution in 16.821. The design process involved the use of two key propeller optimization programs that generated a propeller geometry with minimum induced losses (MIL) given design point operating conditions and the driving motor as input conditions. After using QMIL\(^2\), an

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\(^1\) Lecture notes, MIT. Professor Drela. 3 March 2005.

\(^2\) Produced by Mark Drela of MIT.
executable, to generate a preliminary propeller design to yield MIL for the design condition, mission constraints led to considerable modifications to the propeller geometry. These constraints changed the preliminary battery configuration due to a need for increased voltage required to power the aircraft at sufficient thrust throughout the entire mission duration. Prior to delving into the design process, it is important to understand the general mission and constraints of this propeller design imposed by the mission objectives.

The mission can be summarized as an attempt to launch a 15.8 cm long, foldable-wing surveillance aircraft that deploys from a rectangular case whose interior dimensions measure 60mm × 46mm × 172mm. This case is launched out of tactical jet at over 100g. The size constraints posed on the propeller design are thus derived from the final geometry of the fuselage and the dimensions of the protective casing out of which the plane is deployed. Figure 3-1 shows the protective casing in which the plane is stored during at beginning of missions and which places an upper size limit on the diameter of a non-folding propeller. It was determined that the propeller hub radius was to be held at approximately 0.01m, and the tip radius is not to exceed 0.0381m, or 1.5 inches. These geometric constraints led the propeller to vary its shape several times during various design iterations that each sought to address each of these size requirements independently. One key decision related to the constrained propeller radius was, for example, whether a folding propeller was wiser to incorporate than a new power source. The initial propeller designed for MIL was longer than size constraints allowed, and a new battery configuration was required if the propeller were not to have to fold. Since a folding propeller incorporates high levels of mechanical and aerodynamic design risk, it was determined that the foremost desire was for a rigid, non-folding propeller, and the battery configuration was changed to accommodate this need.
3.2 Flow Chart of the Propeller Design Process

This section will illustrate the propeller design process and briefly describe each of the steps taken to design and analyze the propeller central to this thesis. Figure 3-2 indicates each process step undertaken in the design of the propeller in the order in which it was completed.

![Propeller Design and Analysis Flow Chart](image)

Figure 3-2: Propeller Design and Analysis Flow Chart

An airfoil is first chosen to provide aerodynamic performance called for by the specific flight mission. Completing this step is based on analyzing historical data and requires considerable experience to properly execute. The TA22 airfoil was selected for this mission. The airfoil shape entered into XFOIL, which output the key aerodynamic performance parameters of the airfoil. An operating design point, consisting of the velocity with which the aircraft must travel, the thrust the power the propeller must produce, preliminary propeller hub/tip geometry and atmospheric conditions data such as air density, is then decided upon before actual optimization and propeller shape design can commence. QMIL is then used to develop a propeller geometry calculated for minimum induced losses. This propeller geometry, then in the
form of a .prop file, and flight settings such as propeller RPM, flight velocity, and input voltage, are read into QPROP. QPROP provides a spreadsheet format for its outputs of the propeller performance values. These primarily include thrust generated, overall system efficiency, and motor power consumption. Upon confirming that the propeller is sufficiently efficient and powerful, its .prop file is read into MATLAB. A MATLAB script cuts the designed propeller blade into 21 airfoil sections and stores them as solid part for convenient use in SolidWorks. SolidWorks is then used to design the propeller, with a resulting finished part. Propellers are tested in the 1-by-1 foot wind tunnel to compare power required with and without the fuselage blanketing the hub region of the propeller. Manufacturing methods, primarily for mass production, are discussed in Appendix E.

3.3 Design Point and Design Airfoil Selection

The first step in aerodynamic design such as this is to determine a design point from which to base designs such as this one. This design point is typically taken to represent conservative operating conditions in which it is expected that the aircraft will fly. Note that this mission involves a steady descent of our aircraft from 30,000 feet to ground over a 3-hour timeframe. The design point selection methodology for this mission was based on expected wind speeds in an area representative of that in which the mission is to take place in the future. The representative location for this mission was taken to be Edwards Air Force Base in southern California. Wind speeds were tabulated based on averaged weather data recorded over several years. It was decided that a conservative estimate for wind speed would be the 75% percentile wind speeds measured over the top 10,000 feet of our operations envelope (20,000 to 30,000 feet). This wind speed occurs at 24,000 feet. The corresponding required aircraft flight velocity given its aerodynamic characteristics was calculated to be 24.7 m/s, the design flight speed. This value of flight speed was used to generate a preliminary nominal airfoil for minimum induced losses.

A key introductory task in propeller design is selection of an airfoil that is conducive to the operation at hand and provides aerodynamic characteristics that will provide lift at reasonable efficiencies throughout the extremes of an operating envelope. The operation defined for the purposes of design in 16.821 requires steady-level flight for a light aircraft operating at altitudes of 0 to 30,000 feet above sea level. The aircraft must remain within a prescribed descent zone
and operate constantly at steady-level for 3 hours. According to Dr. Drela of MIT, the focus of airfoil selection should be matching of motor and propeller torques. For the current design condition of 24.7 m/s at 24,000 feet, the optimal airfoil shape is likely one with high pitch-to-diameter ratio. Figure 3-3 shows how propeller rotational speed relates to propeller efficiency, thrust, and torque with a given input voltage. This figure specifically plots the key propeller and motor operating parameter values which result from a specified flight speed $V$ and applied motor voltage $v$. The torque-matching condition is applied to first determine the required motor speed $\Omega$. The vertical dotted line indicates how all of the other primary motor parameters can then be determined from the motor and propeller characteristics curve. It is therefore important to obtain high propeller efficiency at the rotational speed that optimizes motor efficiency. Total (propeller times motor) efficiency typically falls in the 60%-90% range.

**Figure 3-3: Prop and motor parameters obtained from specified $V$ and $v$.**

The motor mission was given prior to the initiation of this propeller design, which significantly reduced the motor-propeller torque matching iterations required for total (prop times motor) efficiency optimization. The selected motor was the NEU-012-030-4000. The

*Lecture notes, MIT. Professor Drela. 3 March 2005.*
TA22 airfoil, which exhibits a long and slender radial profile, was selected for preliminary analysis. This airfoil is shown in figure 5-1. The airfoil remained the basis airfoil throughout the entire analysis discussed in this thesis with geometric modifications made for the sake of operating efficiency and mission size requirements. The TA22’s aerodynamic characteristics had to be analyzed prior to use of QMIL and QPROP for minimum induced loss propeller design.

3.4 Obtain Airfoil Lift and Drag Coefficients from XFOIL

In order to use QMIL and QPROP for propeller MIL optimization, the basic aerodynamic properties of the selected TA22 airfoil were extracted from XFOIL, an interactive program developed by Dr. Drela for design and analysis of subsonic isolated airfoils. These properties include $C_{L0}$, $C_{L\alpha}$, $C_{L\text{ming}}$, $C_{L\max}$, $C_{D0}$, $C_{D2}$, $C_{D21}$, $C_{L\text{CD0}}$, and a reference Reynold’s Number. Figure 3-4 defines these parameters with respect to $C_L$, $C_D$ and $\alpha$. $C_{D21}$ was taken as equal to $C_{D2}$. The reference Reynold’s Number was assumed at 75% of the radius and was taken to be 55,000. Flight Mach number was assumed to be 0.089.

![Figure 3-4: Representation of aero parameters with respect to alpha and lift/drag coefficients.](http://web.mit.edu/drela/Public/web/)

3.5 Use of QMIL and QPROP for Propeller Design

Continuing with the design point determination process, propeller hub and tip radii had to be set. Upon iterating both propeller hub and tip lengths in the MIL optimization programs QMIL and QPROP while considering the geometric design constraints posed by the mission, the hub radius was set at 0.010m and the tip radius at 0.032m. Note that the propeller is symmetric.

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1 Propeller recommended by Prof. Mark Drela of MIT.
about the axis of rotation (driving shaft axis). QMIL and QPROP make use of the motor-propeller relationships established in the theoretical background section of this thesis to provide a notional propeller geometry with minimum induced losses, which corresponds to maximal propulsive efficiency for an actuator disk providing thrust to an object in air. QMIL transforms a text file that includes the number of blades desired, the aerodynamic parameters determined in XFOIL, maximum and minimum expected lift coefficient values, the propeller hub radius, and propeller tip radius. This file also requires insertion of the design point airspeed, blade rotation rate, and desired thrust. Note that thrust can be easily determined for steady-level flight knowing the aircraft speed and drag coefficient, which was determined by the aerodynamics group in 16.821. An initial rotational speed is taken as that which maximizes motor efficiency at a prescribed voltage input equal to approximately the voltage capacity of the power source. A final propeller rotational speed can be determined by iterating following relationships during the design phase while incorporating geometric constraints posed by the mission:

\[ P = \frac{T \cdot V}{\eta_{prop}} \]

\[ P = i \cdot v \cdot \eta_{motor} \]

\[ T \sim c \cdot C_l \cdot \Omega \]

\[ v = \frac{\Omega}{K_v} + i_o R \]

The last term in the last equation is typically negligible compared to the first two, and thus is often neglected, as will be done in this discussion. These relationships provide the voltage and rotational speed required to operate the aircraft at a specific point. The design point is applied foremost to these formulas.

The design point rotational speed is based directly on the craft speed requirement, mass, and lift and drag coefficients since for this mission it can be approximated that steady-level (lift = weight) flight is desired for a descent from 30,000 ft. to sea level over 3 hours. Using the preliminary TA22 airfoil and the required thrust of approximately 0.30N, which provided the necessary lift given the aerodynamic characteristics of the plane itself, the design RPM was
taken to be 40,000. This value was eventually changed to 37,000 RPM for slightly greater total efficiency values.

Once the speed, rotational velocity and aircraft thrust were specified, a hub and tip radius had to be set. The initial tip radius was set at 1.5 inches, since this was the maximum propeller diameter without requiring a folding propeller given the size requirements of the aircraft packaging. This value was reduced to 1.26 inches for enhanced total efficiency. The hub section radius was set such that it ended right as the propeller was directly exposed to the incoming airflow, and no longer hidden, or blanketed, behind the rear of the fuselage. Figure 3-5 indicates the end location of the hub, such that the tip piece of the propeller, which provides the vast majority aerodynamic thrust, is exposed to the incoming airflow as much as usefully possible. The hub is an important component of the propeller because it provides structural stability to the entire propeller.

![Figure 3-5: The hub end located where the rear fuselage opens to the airstream.](image)

This concludes the information that is input into the .mil file for use by QMIL to generate a propeller as a .prop file with minimum induced losses. The propeller file is output with 21 lines that each contains values for propeller radius, chord and beta at staggered locations along the propeller radius. Beta values decrease from root to tip. The root can structurally withstand more load than the tip, which requires the tip to experience less aerodynamic loading. Chord also decreases as propeller radius increases. The .prop file can be read into QPROP for performance analysis of the propeller for a combination of input parameters, including rotational speed, input voltage, and flight speed. The resulting file is returned as an .out file and can be read into a spreadsheet. It contains the key performance characteristics of the propeller given the specified input parameters. Of particular interest to this type of propeller analysis are the output values for
thrust, input voltage, motor efficiency, propeller efficiency, electrical power and overall efficiency. These are all specified for each permutation of the specified inputs. Table 3.1 provides two sample lines of the key parameters that would be output for a single velocity run.

<table>
<thead>
<tr>
<th>V(m/s)</th>
<th>rpm</th>
<th>T(N)</th>
<th>Volts</th>
<th>effmot</th>
<th>effprop</th>
<th>eff</th>
<th>Pelec (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.7</td>
<td>4.29E+04</td>
<td>0.5754</td>
<td>10.5</td>
<td>0.8169</td>
<td>0.6663</td>
<td>0.5443</td>
<td>26.11</td>
</tr>
<tr>
<td>24.7</td>
<td>3.70E+04</td>
<td>0.3149</td>
<td>8.9</td>
<td>0.7715</td>
<td>0.6926</td>
<td>0.5343</td>
<td>14.55</td>
</tr>
</tbody>
</table>

Table 3.1: Sample performance data output from QPROP.

The performance parameter results most closely observed and controlled during design iterations were thrust, voltage, and total efficiency. A minimum thrust of 0.28N was required for comfortable operation at our design point, and the corresponding voltage had to be below what was maximally provided by the 3s3p, 10.5V voltage source ultimately selected for use. Once these requirements were satisfied and the propeller met the size constraints set by the mission, the overall efficiency—displayed as eff—become the key parameter of interest during iteration.

Chapter 4

QMIL and QPROP Iteration with Results

4.1 QMIL Input Parameters

<table>
<thead>
<tr>
<th>Number of Blades = 2</th>
<th>CL0 = 0.29302</th>
<th>CL_a = 5.81383</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL_min = -0.8000</td>
<td>CL_max = 1.2000</td>
<td></td>
</tr>
<tr>
<td>CD0 = 0.016202</td>
<td>CD2 = 0.04769</td>
<td></td>
</tr>
<tr>
<td>CD21 = 0.04769</td>
<td>CLCD0 = 0.30</td>
<td></td>
</tr>
<tr>
<td>Reref = 55000</td>
<td>REexp = -0.500</td>
<td></td>
</tr>
<tr>
<td>XIdes (r/R locations were design CL is specified):</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>CLdes (specified CL):</td>
<td>0.40</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 4.1: TA22 aerodynamic characteristics read into QMIL.
As mentioned previously, the TA22 was used as the design airfoil throughout the entire duration of this propeller design project. Therefore the XFOIL coefficients did not vary. These coefficients, as represented in the .mil file for use in QMIL, are given in table 4.1.

Fluid constants for use by QMIL were taken as shown in Table 4.2.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density</td>
<td>1.225 kg/m³</td>
</tr>
<tr>
<td>Air dynamic viscosity</td>
<td>1.78x10⁻⁵ kg/m-s</td>
</tr>
<tr>
<td>Speed of sound through air</td>
<td>340 m/s</td>
</tr>
</tbody>
</table>

**Table 4.2:** Fluid constants used during propeller design.

The next step was to prescribe propeller hub radius, speed, rotational velocity, and required thrust. The flight velocity at the design point was given by the aerodynamics team based on wind speed at the design point and lift requirements given the aircraft lift and drag coefficients. The design point was selected to be 24,000 feet altitude with 75% wind speeds for a conservative estimate. The aircraft speed at the design point was found to be 24.7 m/s, and the thrust required was approximately 0.30N. The rotational speed was selected to maximize motor efficiency for an input voltage equal to the power supply capacity of 10.5 V. This value was initially set at 40,000 RPM, and then modified to 37,000 upon further blade geometry iteration. The hub radius was set where the rear fuselage edges met with the incoming airstream. The tip radius was set at 1.5 inches due to sizing constraints. The final parameter values for use in QMIL are represented in table 4.3. These values provided QMIL with all the information it required to generate a propeller geometry at this design condition that provided maximum propulsive efficiency, or minimum induced losses. The next step was propeller modification.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub radius</td>
<td>0.0100 m</td>
</tr>
<tr>
<td>Tip radius</td>
<td>0.0320 m</td>
</tr>
<tr>
<td>Aircraft speed at design point</td>
<td>24.7 m/s</td>
</tr>
<tr>
<td>Rotational velocity of motor shaft</td>
<td>37,000 RPM</td>
</tr>
</tbody>
</table>

**Table 4.3:** Operational parameters set by mission constraints and design point conditions.
4.2 Propeller Tip Geometry Modification

Following the use of QMIL to generate a preliminary propeller with minimum induced losses, QPROP could be used to accurately predict the performance of the propeller-motor combination. This required a file containing motor parameters. QPROP reads this tabular file in .motor format. Its contents for the purposes of this project are given in table 4.4. These values were all determined empirically by using standard electronic measuring devices.

<table>
<thead>
<tr>
<th>Motor type</th>
<th>Brushless DC motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor resistance (Ohms)</td>
<td>0.3</td>
</tr>
<tr>
<td>Motor current (Amps)</td>
<td>0.3</td>
</tr>
<tr>
<td>Motor (K_v) (rpm/Volt)</td>
<td>4400</td>
</tr>
</tbody>
</table>

**Table 4.4:** Key motor parameters for use by QPROP in propeller performance prediction.

During initial QPROP iterations, concerns arose pertaining to the tip geometry output in the .prop file. The chord of the propeller at the tip was less than 2mm. This alarmed fellow 16.821 team members because they had no experience manufacturing an airfoil with such small chord. It was therefore proposed that the tip section of the propeller be modified to have tip chord at least 6mm. The last 4 of the 21 “slices” which constituted the propeller shape as output by QMIL were modified to taper to a 6mm tip chord at the propeller tip. Three iterations were executed and the design with sharper taper toward the tip was calculated to be most efficient of the three investigated modification options. Table 4.5 compares the initial to modified (and final) radius, chord and beta profile for the propeller’s outboard most 4 data “strips,” corresponding to the 4 solid curve cross sections in the tip section of the propeller.

<table>
<thead>
<tr>
<th>Previous Profile</th>
<th>Modified Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r)</td>
<td>(c)</td>
</tr>
<tr>
<td>2.93 cm</td>
<td>6.66 mm</td>
</tr>
<tr>
<td>3.04 cm</td>
<td>5.28 mm</td>
</tr>
<tr>
<td>3.15 cm</td>
<td>3.13 mm</td>
</tr>
<tr>
<td>3.20 cm</td>
<td>1.76 mm</td>
</tr>
</tbody>
</table>

**Table 4.5:** Change in propeller geometry near the tip to accommodate manufacturing.
The beta values were held constant. One idea was to hold the product of beta \times chord constant as an attempt to maintain relatively constant lift. Running this supplementary modification through QPROP for performance analysis, however, yielded a lower total efficiency value than that which resulted from unmodified beta values. It was therefore decided that the beta values at the radial propeller profile where chord values were modified would be held as they were initially.

4.3 Iteration in QPROP for Power Source Selection and Flight Performance Data

With a preliminary, modified propeller configuration acquired through QMIL, an important first step in performance analysis was to determine whether the maximum propeller radius was more efficient than a smaller radius. The performance data for the 1.5 inch radius configuration output by QPROP are given in table 4.6. The thrust with this configuration is sufficient and total efficiency = 52.29%.

<table>
<thead>
<tr>
<th>V(m/s)</th>
<th>rpm</th>
<th>T(N)</th>
<th>Volts</th>
<th>effmot</th>
<th>effprop</th>
<th>eff</th>
<th>Pelec (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.7</td>
<td>3.70E+04</td>
<td>0.3066</td>
<td>8.897</td>
<td>0.7709</td>
<td>0.6783</td>
<td>0.5229</td>
<td>14.48</td>
</tr>
</tbody>
</table>

Table 4.6: Performance values for the 1.5 inch radius blade design.

Tests were run for several (approximately 15) variable-radius blade geometry configurations with a maximal efficiency convergence around the value of radius = 3.2 cm, or 1.260 inches. The output parameters for this 1.26 inch radius configuration are given in table 4.7.

<table>
<thead>
<tr>
<th>V(m/s)</th>
<th>rpm</th>
<th>T(N)</th>
<th>Volts</th>
<th>effmot</th>
<th>effprop</th>
<th>eff</th>
<th>Pelec (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.7</td>
<td>3.70E+04</td>
<td>0.3115</td>
<td>8.899</td>
<td>0.7712</td>
<td>0.6872</td>
<td>0.53</td>
<td>14.52</td>
</tr>
</tbody>
</table>

Table 4.7: Performance values for the 1.26 inch radius blade design.

It was evident that a significantly shorter blade radius could be implemented with even higher overall efficiency than the 1.5 inch radius case conforming to the upper size bound posed by mission requirements. This new propeller radius of 1.26 inches was used in the remaining propeller analysis.

Once the propeller geometry had been obtained through QMIL and then modified for both manufacturing and efficiency purposes, it was important to determine which battery type would suffice for serving as the power source for the motor and propeller in flight throughout the 3-hour mission duration. The two proposed battery configuration options were 2s4p, for a cumulative 7 volts maximum voltage availability, and a 3s3p configuration, which would
provide 150% of the 2s4p configuration for a cumulative 10.5 volts maximum voltage. The 2s4p configuration was preferred because it was more compact, providing the fuselage with a smoother surface (less bulge), and it also weighed less than the other option. To test whether the 2s4p configuration would suffice for the mission, an input propeller rotational velocity of 37,000 rpm and voltage of 7 volts were input to QPROP. The resulting performance values were as follows:

<table>
<thead>
<tr>
<th>V(m/s)</th>
<th>rpm</th>
<th>T(N)</th>
<th>Volts</th>
<th>effmot</th>
<th>effprop</th>
<th>eff</th>
<th>Pelec (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.7</td>
<td>29,770</td>
<td>0.07213</td>
<td>7</td>
<td>0.595</td>
<td>0.548</td>
<td>0.3261</td>
<td>5.463</td>
</tr>
</tbody>
</table>

*Table 4.8: Performance values for the 2s4p battery configuration.*

Clearly the 2s4p battery configuration does not provide sufficient thrust for this mission. Tables 4.6 and 4.7 provided clues that this would be the case since they specify driving voltages of 8.9 V needed to attain the required thrust. The 3s3p, 10.5 volt battery configuration was used for further propeller analysis.

Table 4.7 provides the performance data of the selected propeller geometry. A motor efficiency of 77% and propeller efficiency of 69% are above average for relatively small, thin propellers such as this, and a combined efficiency of 53% was in line with the team’s expectations given similar optimal total efficiencies observed prior to this project. The next step in collecting useful data to present to the investors of the propeller was determining its performance at various altitudes, or flight velocities. In collaboration with the aerodynamics group, the operation flight velocity range was assumed to be 10 m/s – 30 m/s. Consequently, propeller performance iterations were conducted in QPROP by varying propeller blade rotational velocity until Ω bounds were determined by those that just satisfied the 0.30 N (ultimately 0.29 N) thrust requirement for the 10 m/s case (lower bound) and 30 m/s flight speed case (higher bound). Although these flight speed tests were run with sea level conditions, their results provided useful information regarding motor efficiency and capability. Blade rotational velocity was bounded between 26,000 RPM and 41,000 RPM. Simulations were then run for flight speeds between 10 m/s and 30 m/s in increments of 2 m/s while simultaneously varying propeller Ω from 26,000 to 41,000 RPM in increments of 1,000 RPM for reasonable resolution. Power requirements were determined by the lowest Ω that produced above 0.29 N thrust for each flight velocity case. This force value was chosen as a reference from which to acquire data at various airspeeds. These tests were all run assuming a single air density, and thus represents flight speed
at sea level. Of particular interest were voltage, electrical power, and total efficiency values, which are displayed in Table 4.9, which increments flight velocity by 4 m/s and italicizes the design point performance data. Power increases approximately linearly with airspeed, and efficiency drops noticeably at lower flight speeds. Of particular interest is the motor efficiency over this relatively tight range of airspeeds for sea level conditions. Figure 4-1 expresses propeller total efficiency as a function of flight velocity for conditions at sea level.

<table>
<thead>
<tr>
<th>V(m/s)</th>
<th>rpm</th>
<th>T(N)</th>
<th>Volts</th>
<th>effmot</th>
<th>effprop</th>
<th>eff</th>
<th>Pelec (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>26,000</td>
<td>0.2973</td>
<td>6.308</td>
<td>0.7255</td>
<td>0.4882</td>
<td>0.3542</td>
<td>8.393</td>
</tr>
<tr>
<td>14</td>
<td>29,000</td>
<td>0.312</td>
<td>7.025</td>
<td>0.7436</td>
<td>0.5783</td>
<td>0.4300</td>
<td>10.16</td>
</tr>
<tr>
<td>18</td>
<td>32,000</td>
<td>0.3188</td>
<td>7.734</td>
<td>0.757</td>
<td>0.6371</td>
<td>0.4823</td>
<td>11.90</td>
</tr>
<tr>
<td>22</td>
<td>35,000</td>
<td>0.3177</td>
<td>8.436</td>
<td>0.7667</td>
<td>0.6732</td>
<td>0.5161</td>
<td>13.54</td>
</tr>
<tr>
<td>24.7</td>
<td>37,000</td>
<td>0.3115</td>
<td>8.899</td>
<td>0.7712</td>
<td>0.6872</td>
<td>0.53</td>
<td>14.52</td>
</tr>
<tr>
<td>26</td>
<td>38,000</td>
<td>0.3087</td>
<td>9.13</td>
<td>0.7734</td>
<td>0.6913</td>
<td>0.5346</td>
<td>15.01</td>
</tr>
<tr>
<td>30</td>
<td>41,000</td>
<td>0.2915</td>
<td>9.814</td>
<td>0.7772</td>
<td>0.6936</td>
<td>0.539</td>
<td>16.22</td>
</tr>
</tbody>
</table>

**Table 4.9**: Performance data for final propeller design at sea level flight velocities.

This table provides theoretical instructions for the user of the design aircraft as to which propeller rotational speed to apply at each flight speed, provided altitude density variations are accounted for.

![Prop Total Efficiency](image)

**Figure 4-1**: Propeller total efficiency versus airspeed at sea level.
Chapter 5

Generating Solid Part from Propeller Design

5.1 Conversion of .prop File Parameters to a Solid Model via MATLAB Script

Following analysis conducted in QPROP with the final propeller design iteration, the radius, chord and beta values provided in the .prop file output from QMIL were taken as individual slices and converted to planar solid model sketches for importing into SolidWorks. A MATLAB script*, was modified to apply to the new propeller geometry. The script was used to convert a text file with corresponding chord, radius and beta values listed in columns (those from the .prop file output from QMIL) to “solid curves” for direct implantation into SolidWorks in order to develop a solid part of the propeller. The script takes the propeller geometry text file and TA22 airfoil geometry text file as inputs. The code makes use of MATLAB’s “textread” feature to interpret the appropriate propeller geometry data from the text files. Chord, radius and beta values are converted to the desired units, the number of solid curve slices is inserted, and dimensionless slices are generated. The radius and chord values, in conjunction with the airfoil shape, generate appropriately sized slices for use in SolidWorks. The slices are then rotated in both x- and y-coordinates according to the beta value they possess. A solid curve slice is then written as a .sldcrv file for direct import into SolidWorks. The code in this text-to-solid curve converting MATLAB script has been included in Appendix B. The script outputs the shape of the propeller by plotting the chord of the blade along the radius, as well as a view of the TA22 airfoil cross-section, as shown in figure 5-1.

*Originally written by MIT SM Candidate 2LT Nicholas Carter.
Figure 5-1: Propeller radius-chord relationship and TA22 geometry.

5.2 Conversion of an array of “Solid Curves” in SolidWorks to a Closed, Lofted Part

Each of the 21 slices saved as a solid curve contained X, Y, Z values that were interpreted by Solidworks via its “curve through XYZ points” function as a “slice.” Each slice was converted into a sketch. Figure 5-2 presents a sample array of slices inserted into a SolidWorks part file. Note that chord and beta values are automatically preserved as they were in the original .prop data file because of the dimensioning and rotation specified in the MATLAB conversion script.

Figure 5-2: An array of propeller cross section slices imported into SolidWorks.

The propeller slices were imported and spaced evenly away from the propeller hub as prescribed by the QPROP output file. They were placed on individual planes referenced from one another. The “front” plane was taken to represent the center of the propeller, and each of the 21 strips was taken at 1.1mm increments along the radius of the propeller. The planes were created via the “Reference Geometry” → “Plane” feature in SolidWorks, and were established
from root to tip with each plane referenced from the neighboring propeller slice. The hub section, not included in the slices imported to SolidWorks, was not included and was designed later in accordance with basic structural and aerodynamic design principles. Once the planes were properly spaced relative to the propeller root, each slice was converted into a solid entity and closed before any lofting and part creation could take place. To accomplish this, each slice plane was selected and the “Sketch” feature was selected for plane modification. The existing solid curves were selected, and the “Convert Entities” feature was selected to transform the slices into solid sketches which could then be extruded, lofting, or manipulated in many other ways.

Figure 5-3 displays the design stage in which a slice had been selected (with the sketch plane activated) and converted to a solid sketch. To complete this process, a line was drawn on the sketch plane to connect two ends of the airfoil at the trailing edge such that a closed surface could be formed. This process was repeated for each of the 20 other slices on their corresponding planes until 21 solid curves had been produced. The SolidWorks part file was then ready undergo lofting among its strips such that a continuous, curved part that connects each of the resulting airfoil cross-sections could be generated.

SolidWork’s “Loft” feature was used to take each of the 21 solid sketches along the propeller radius and add continuous, linear twist distributions between them to generate a smooth propeller in a manner that is aerodynamically feasible. The result is depicted in figure 5-4, which highlights each of the trailing edges of the strips along the loft.

Once the propeller blade tip section had been lofted, a hub section needed to be created. That section
includes the circular extruded hub and the propeller section that is blanketed behind the aircraft fuselage. The end of this section closes to the propeller hub was described as the “hub end” in figure 3-5. Several options existed regarding how the hub section was to be designed. This section included the propeller from its hub to a radial distance near where the propeller escapes obstruction by the fuselage and enters the free stream. Since the propeller half consisted of 21 lofted cross sections, the cross section nearest this fuselage obstruction-to-free stream interface was taken to represent a “blanketing plane.” The two primary ideas for shaping the hub section of the propeller included (1) a gradual twist from the inward-most tip slice beta value to lower betas at the hub (more horizontal to the free stream), and (2) maintain the entire hub beta value equivalent to the tip slices nearest the propeller root, for a constant beta value of 36.319 degrees. The hub section was referred to in the CADing process as inward of the blanketed plane, which was near the boundary where the propeller became blanketed by the aft part of the fuselage. See figure 5-5 for a visual representation of the blanket plane, which runs orthogonal to the propeller radius. The first, manually twisting the design, option was selected as a means of modifying the hub section of the propeller for enhanced performance. The idea was that the significantly decelerated flow blanketed by the fuselage could produce some thrust at lower betas. The fundamental concept was to reduce the beta, or airfoil effective angle-of-attack, of everything inside of the blanket plane for reduced drag and increased propulsion. In low speed situations, a propeller should not exhibit high betas, since that presents what becomes essentially a flat plate directly into the oncoming flow. Imagine the propeller as the predominant velocity component as it rotates with its high beta airfoil section orthogonal to the direction of rotation. A significant axial velocity that would exist ordinarily during flight to provide a resultant airflow vector along

Figure 5-5: Blanket plane defined near the free stream-fuselage interface.
the propeller chord would be blanketed by the fuselage. This would result in airflow roughly orthogonal to a propeller cross section at high beta, representative of flow directed at the wide dimension of flat plate. A flat plate rotating in low speed flow at several thousand RPM can be quite detrimental to a propeller’s efficiency and performance. A stalled prop operating at low speed will provide little to no thrust and relatively high drag. In the blanketed section, defined as inward of a chord-wise plane located about 10mm radially outward from the propeller center, the beta values were therefore reduced for enhanced efficiency. The blanketed plane corresponded to the propeller cross section slice plane closest to the fuselage-free stream interface. To rotate the blade in the blanketed region, the propeller airfoil cross sections in the region were unlinked by undoing their “convert entities” features. The entities were then rotated with respect to the part origin. The innermost beta values were changed by rotating the blade cross sections with respect to the origin via approximation and qualitative aerodynamic guidelines, such as smooth and continuous tapering. There were human factors associated with this approximation.* Since there was no analytical model known for cases such as this fuselage blanketed situation, a smooth taper of decreasing betas beginning at the blanketed plane was deemed appropriate for propeller efficiency improvement. The intent was to generate a productive, reasonable local angle-of-attack in the blanketed section considering the lower momentum flow present in this region that leads high-beta airfoil sections to serve as detriments rather than benefits to overall propeller performance.

The second blanketed region design option was investigated because it may be relevant for reasons related to manufacturing ease, structural stability, and the relatively little aerodynamic performance contribution to the propeller provided by the propeller hub section. This last point is reflected in the performance data resulting from the case run where a zero hub radius was set. This case actually resulted in no increase in efficiency at the design point than the case in which the hub constituted nearly one-third of the propeller radius. Performance data for the no-hub case were given by QPROP as shown in Table 5.1. This data is exactly the same as that for the final configuration which includes a hub (and no data for the hub section in the .prop file). The no-hub file, however, has the root beta at approximately 85 degrees, which is very high. The data for the no-hub case does not reflect this mission in which a fuselage blankets the propeller hub. Therefore, a feasible alternative to that presented here is maintaining the propeller beta value constant and equal to that on the blanket plane. This alternative may prove more

*Hub section beta adjustment conducted by Tony Tau of MIT.
conducive to mass production. However, the blanket plane beta value may be too high and the pros and cons of this alternative are to be considered in-depth before it is to be implemented.

<table>
<thead>
<tr>
<th>V(m/s)</th>
<th>rpm</th>
<th>T(N)</th>
<th>Volts</th>
<th>effmot</th>
<th>effprop</th>
<th>eff</th>
<th>Pelec (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.7</td>
<td>37,000</td>
<td>0.3115</td>
<td>8.899</td>
<td>0.7712</td>
<td>0.6872</td>
<td>0.53</td>
<td>14.52</td>
</tr>
</tbody>
</table>

**Table 5.1.** Performance data for zero-hub case.

Beta values radially inward of the blanket plane were decreased. The beta value at the hub-propeller intersection was decreased from 85 degrees to approximately 40 degrees. This represented a 10 degree decrease in beta from the blanket plane. The blanket plane therefore served as an inflected point of the curvature of the propeller trailing edge, as evidenced in figure 5-6. This figure also illustrates the change in local airfoil cross section location to considerably lower beta values. Note that the resulting curve along the trailing edge is relatively symmetric about the blanket plane. Roughly the same curvature involved in the beta increase from tip to the blanket plane was used in decreasing beta inward of the blanket plane.

Following hub airfoil section beta modification, a cylindrical hub section was designed. This hub section is intended to fit directly onto the NEU-012-030-4000 DC electric motor shaft for quick and effective motor-propeller attachment during assembly. The hub outer diameter was 4mm and the inner diameter was designed as 2mm. The hub was extruded 4mm and placed such that the propeller edge could wrap fully around it and incorporate filleted edges for a smooth, aerodynamically sound propeller-hub interface. The fillets were designed to cover the entire propeller-hub interface and had radii of 0.4mm. Figure 5-7 shows these fillets. These fillets were designed with the consideration that propellers often break at the hub-propeller interface during testing and operation. It is important
to maintain structural integrity at this interface by filleting for a thickened interface region for mitigated structural failure. To complete the propeller part, the other propeller blade (half of the part) needed to be incorporated. The "circular pattern" feature was used to revolve the propeller half that had existed up to the design of the cylindrical hub 180 degrees around to the other side of the hub. The resulting and final propeller part appears as illustrated in figure 5-8. The hole marked by the hub inner diameter has not yet been included, and will in pre-production designs. Since motor shafts are prone to variability, this design feature remained undefined.

![Final propeller part](image)

**Figure 5-8:** Final propeller part.

**Chapter 6**

**Propeller Testing**

Of obvious importance is the need to test a designed propeller configured as it would be operating during the mission for which it was designed. Although this is typically done foremost to determine whether the physical propeller provides the thrust and efficiency required by the mission, the propeller design presented in this thesis was not manufactured due to time constraints, and tests were run with similar propellers and for a different purpose. Since the propeller specifically designed for the mission outlined in this thesis was not manufactured, four test propellers, each with characteristics resembling the specially designed propeller, were mounted onto the test stand depicted in Appendix C for testing in the MIT 1 foot-by-1 foot wind tunnel. The objective of the tests was to compare the electrical input power required to provide a
prescribed amount of thrust at various tunnel velocities for the cases in which the propeller is mounted behind the aircraft fuselage and that in which it is mounted in the free stream and without an object altering the incoming airstream. Wind tunnel speeds were chose to correspond to operating altitudes for the mission. Tests were run at tunnel velocities ranging from 25 MPH to 55 MPH.

6.1 Preparation for Testing

In order to compare propeller performance in the open free stream configuration versus the blanketed (by the fuselage) configuration, a full set of testing materials was acquired and built. A fuselage was built using 0.9” thickness 6061 aluminum stock, a foam cutter, sand paper, a sheet bender, a band saw, several drill bits and drill, and a grinder. A fuselage was built to the match the aircraft outer mold line design as provided by the aerodynamics team. This was accomplished by using a foam cutter run at a feed of 3 inches/minute. The test stand shown in Appendix C was then fabricated from the 0.9” thick aluminum stock. The two 0.5” flanges protruding from either side of the 12” stand were bent 90 degrees using a sheet metal bender. Motors will be affixed to the flanges so that they are aligned in the wind tunnel free stream. The flange midway along the beam served as the motor mount for the aircraft fuselage blanketed case, whereas the flange at the beam’s end involved a motor-propeller mount in the free stream and without fuselage interference. Again, performance for these two cases was compared by juxtaposing power requirements for maintained thrust at specified wind tunnel velocities. A hole the length of the motor was bored through the rear of the fuselage to encase the motor during testing. A slot was cut using the band saw to allow the test stand rod to slide in near the fuselage rear as the motor is inserted into the aft of the aircraft. The two holes drilled at the bottom of the test shaft were used to screw the apparatus onto a drag cell, which was installed to power supplies and measurement devices at the 1-by-1 wind tunnel site. The drag cell was mounted to a large, thin piece of sheet metal stock via an L-bracket with one large bolt. See figure 6-1 for a depiction of the test stand while a fuselage-mounted propeller was undergoing power consumption testing.
6.2 Testing Procedure

During testing, the wind tunnel mount was clamped to a slab of sheet metal that was taller than the wind tunnel and its supports. This allowed the propellers to suspend freely in front of the tunnel to receive the full, unperturbed air stream. The rig allowed for propellers to be mounted in both a behind fuselage, or blanketed, configuration as well as in a free stream configuration where the fuselage did not obstruct airflow through the propeller. The propellers were wired to a power supply providing 11.0 volts at idle. The drag cell was connected to a power readout device that was zeroed by adjusting propeller thrust during testing to indicate a force balance in the drag cell between the incoming airstream producing drag and the thrust of the active propeller. This force balancing corresponded to steady-level flight of the fuselage. Figure 6-2 provides a depicting of the testing apparatus set-up. Note that only one propeller was
mounted at a time, and that this figure shows both mounted propeller configurations. The fuselage was mounted during all test configurations.

![Power consumption testing apparatus set-up.](image)

**Figure 6-2:** Power consumption testing apparatus set-up.

Testing was conducted in order to compare power requirements of a propeller in the free stream versus the same propeller behind the fuselage as it will be during operational flight. Testing was conducted with 4 different propellers, 7 different wind tunnel speeds, and 2 propeller configurations. The motor mounted above the fuselage (isolated in the free stream) was faired by taping a conical section to the rear of the motor to reduce profile drag and trailing vortices that would contribute to inconsistencies in the drag data. Prior to collecting data, the drag cell’s gain was set such that 300 output units corresponded to about 1N of force (the force of a 100g mass) in the tunnel axial direction. It was also important to then tare out the force contribution of the mounting rig so that the motor would not have to be overworked in order to zero the drag cell. Power was recorded when the drag cell was balanced and read zero units, in order to determine the power consumption required to operate at steady-state. In addition to taring drag produced by the mounting rig, induced drag and profile drag of the UAV wings, which were not represented in these tests, were considered in testing by adding another 30 units, or about 0.1N, of drag, for the final tare value. This balancing of the drag cell was performed by running the wind tunnel at the test speeds without the mounted fuselage. The corresponding forces measured would be subtracted from the cases in which the fuselage was mounted. The
units to be subtracted for a fair drag assessment of the aircraft are shown in Appendix D. This result would apply for both the above- and behind-fuselage test cases because the propellers mounted in either case would provide their own equivalent thrust and drag contribution.

Testing followed determining tare values. The force on the drag cell was measured by a Measurements Group 2131 Peak Reading Digital Readout. The power supply for the motors was a TE Power Supply HY3005. Wind tunnel pressure readings were converted to air flow velocities via a Zahm’s Table configured for the 1 foot-by-1 foot tunnel where testing took place. Velocities were incremented in 5 MPH steps from 25 MPH to 55 MPH for each propeller case—mounted on the fuselage and then in the free stream. The same motor was used for all testing to account for any discrepancies in performance that may have existed among motors. Discrepancies were found during testing to be quite significant, which resulted in the use of only one—not two—motors. The other motor was simply switched with the active one when data acquisition was switched from behind the fuselage to above and in the free stream. As noted previously, this other motor was required to maintain a consistent tare value established for the case in which the fuselage and fuselage motor were absent from the mounting rig, but in which the free stream, upper motor was present.

A value of 30 units was set on the peak reading digital readout to represent induced and profile drag of the aircraft not represented by the fuselage in testing. The wind tunnel velocity was then set to the test value and allowed to equilibrate for about 10 seconds. Then a remote was used to signal to the receiver to increase motor power until the peak reading digital readout displayed the tare value indicated in Appendix D. Once this occurred, the voltage and current were recorded manually from the power supply display, such that the power equation relating current and voltage would be used to determine the power required for the aircraft to maintain steady-level flight at that test velocity:

\[ P = i \cdot v \]

These values were taken for each propeller at the different test velocities for both the blanketed and free stream configuration cases. This provided a direct comparison between the power required to power the propeller when it is in its nominal, free stream design environment such as
that assumed in QPROP, versus that needed to power the propeller in its blanketed state when it is mounted to the rear of the design aircraft’s fuselage. The results are shown below.

6.3 Propeller Testing Results

Figures 6-3, 6-4, 6-5, and 6-6 indicate the power consumption rates for the behind fuselage and free stream configurations for four different propeller cases, Propellers A, B, C, and D. Propeller A represents the propeller tested that most closely resembles the full propeller shape designed in this thesis. Propeller B is Propeller A without chopped ends, which were shortened in Prop A for a closer diameter match to the designed propeller. Propeller C was more rectangular as seen from above the span and less tapered chord-wise along the radius. Propeller D was a longer, more twisted, and more slender propeller than the others. The propellers are displayed in Table 6.1

<table>
<thead>
<tr>
<th>Name</th>
<th>Propeller Shape</th>
<th>Model</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prop A</td>
<td>Most similar to final propeller design, chopped ends</td>
<td>GWS EP-3030</td>
<td></td>
</tr>
<tr>
<td>Prop B</td>
<td>Same as Prop A but uncut and longer than design propeller</td>
<td>GWS EP-3030</td>
<td></td>
</tr>
<tr>
<td>Prop C</td>
<td>Longer than design propeller and more rectangular blade surface</td>
<td>GWS EP-0320</td>
<td></td>
</tr>
</tbody>
</table>
Table 6.1: Propellers used in power consumption testing.

It is empirically evident that power consumption increases more than linearly as air speed increases, at least up to 55 MPH. Of particular interest is the observation that the blanketed propeller case had higher power consumption than the free stream case for every tested velocity and mounting configuration. This may have serious implications for the design of the aircraft and propeller, since QPROP does not account for the blanketing effect. Also, it is shown that the "chopped" propeller case demonstrated the lowest power consumption for the air speeds tested. The rectangular propeller exhibited intermediate power consumption, and the long, slender propeller required the most power to maintain steady-level flight at each tested airspeed. This finding agrees with that given by QMIL/QPROP iterations, in which it was determined that the designed propeller diameter is more efficient than longer propellers. Also, the chopped Prop A and undisturbed Prop A, which most closely resembled the geometry of the designed propeller, gave the most efficient power consumption results. This is reassuring because the most efficient propeller was that which correlated closes design propeller with respect to both twist and diameter length. This finding plays a role in verifying the efforts applied to design in QPROP. Further research and consideration must, however, be applied to the affect of blanketing on propeller performance if the aircraft design of 16.821 is to be implemented with confidence.
Figure 6-3: Power consumption data for the closest propeller geometry to the proposed design.

Figure 6-4: Power consumption data for Prop A without chopped ends.
**Figure 6-5:** Power consumption data for rectangular propeller shape.

**Figure 6-6:** Power consumption data for long, slender propeller.
Chapter 7

Thesis Conclusion

This thesis documents the work conducted by Ian Tracy, MIT S.B. ’11, to design and analyze a propeller for use by Lincoln Labs through the course 16.821. The propeller was designed to propel an aircraft with 15.8 cm fuselage length at steady-level flight from 30,000 feet to sea level at a constant descent rate over approximately 3 hours. Typical wind speeds over a representative mission area were used to establish a conservative aerodynamic design point that represented the conditions present during typical missions. Aerodynamic parameters of the nominal TA22 airfoil were extracted in XFOIL for use in propeller geometry design and optimization. A nominal propeller design was output from QMIL, which generated a propeller geometry for minimum induced losses during flight for optimal aerodynamic efficiency. The resulting propeller geometry was then modified based on mission size constraints and further iterations which focused on aerodynamic efficiencies that could be acquired through varying propeller hub and tip radii. The final propeller design diameter was less than the aircraft protective size constrained value of 3 inches. Thus the propeller did not need to be folded while still possessing optimal efficiency at the design point. The total efficiency provided by the final propeller design was 53.0% according to QPROP. The thrust at this efficiency exceeded the 0.29N required to keep the aircraft flying steady at the design point. This design thrust requirement was applied to each of the altitudes and flight velocities that the aircraft is expected to experience during flight in order to determine the blade rotational velocity and input voltage requirements at each altitude.

Testing of propellers that were geometrically similar to the designed propeller indicated that the blanketing effect posed by the rear mounting configuration specified by the 16.821 aircraft design is significant and must be understood in greater detail for a confident design to take form. In each tested case, the power consumption requirement at a given airspeed was greater for the blanketed (design) case than that for the propeller operating in free stream. The latter is the case assumed by propeller design programs such as QMIL and QPROP. It is recommended that the propeller designed in this thesis be produced, tested and modified in order to achieve the greatest operating efficiency for flight speeds representative of those expected to
be required during practical missions. Testing results aligned with design results, as longer propellers proved to be less efficient than the smaller propellers that most closely resembled the size of the final propeller design. These modifications would most likely take place toward the hub of the propeller to take optimal advantage of the aerodynamics present in the blanketed region of the rear mounted propeller. This may perhaps lead to a significant increase in total propeller efficiency—the desired outcome.
Appendices

Appendix A: Here are the final .prop file radius, chord, and beta values, including the modified tip geometry, which constitutes half of the propeller (one blade). The propeller was designed with 2 blades.

Test Prop

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Appendix B: This is the MATLAB file used to convert r, c, and beta values in the .prop file to sketches to be closed and lofting to one another in a CAD program such as SolidWorks.

(Filename: Prop_Slice_Generator.m)

```matlab
clear all
close all
c1c

% Create and output propeller geometry text files for solidworks
Propeller_Geometry = 'TestPropX4o.txt';
Airfoil_Geometry = 'TA22.txt';

[r, c, beta] = textread(Propeller_Geometry) % (m, m, deg)
[x_c, z_c] = textread(Airfoil_Geometry); % (-, -)
c = c*1000; % Chord Length (mm)
r = r*1000; % Radius Length (mm)
beta = beta*pi/180; % Angle from rotational velocity vector to lower blade edge (rad)
n = 20; % Number of slices
hold on

% Create dimensional slices
for i = 1:n+1
    x = x_c*c(i); % Dimensional Chord (mm)
y = z_c*c(i); % Dimensional Height (mm)
X = x*cos(-beta(i)) - y*sin(-beta(i)); % Rotated x-coordinate
Y = y*cos(-beta(i)) + x*sin(-beta(i)); % Rotated y-coordinate
Z = ones(157,1)*r(i);
P = horzcat(-X, Y, Z);
dlmwrite(['Slice ' int2str(i) '.sldcrv'], P, 'delimiter', '	', 'precision', 8)
plot3(Z, -X, Y); % (cm)
grid
end
axis([0 60 -30 30 -7 1])
xlabel('Radius (mm)', 'fontsize', 18)
ylabel('Chord (mm)', 'fontsize', 18)
zlabel('Height (cm)', 'fontsize', 18)
title('Propeller Geometry', 'fontsize', 18)
figure
plot(x_c, z_c, '-b')
axis([0 1 -0.5 0.5])
xlabel('Unit Chord (x/c)', 'fontsize', 14)
ylabel('Unit Height (z/c)', 'fontsize', 14)
title('TA22 Airfoil Geometry', 'fontsize', 14)
```
Appendix C: This a drawing of the test stand on which propellers and a foam version of the aircraft fuselage were mounted in order to determine the power requirement differences between a propeller operating in the free stream and the same propeller operating behind the fuselage of the aircraft as in the current aircraft design.

Note: all dimensions in inches.
Side edges all possess 0.05 inch radius fillets to replicate grinding performed to give part side an airfoil shape.
Appendix D: These are the tare values for each test air speed. These units were effectively subtracted from drag cell force readings to eliminate the drag contributions from the mounting test rig.

<table>
<thead>
<tr>
<th>Units Required to Tare the Tunnel Mount Rig</th>
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<tr>
<td>25 MPH</td>
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<tr>
<td>105 Units</td>
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<td>129 Units</td>
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</table>
Appendix E: Propeller Manufacturing

Since this propeller is to be manufactured for Lincoln Labs via a form of manufacturing that is cost-effective and can be applied to each custom-designed propeller, significant thought was invested in the method with which this relatively small propeller is to be produced—perhaps on a mass scale. The three major options for propeller manufacturing that were considered for this propeller were CNC milling, carbon molds and injections molding. CNC milling involves a direct means of transferring computer-aided design (CAD) drawings to machine code for a systematic production of the propeller. This form of manufacturing, however, is difficult for 3-dimensional part of this nature due to tolerance and clamping constraints. Direct CNC milling requires machine time that may need be devoted to other facets of aircraft production. Carbon molds constitutes a simpler method of fabricating the propeller by overlaying carbon layers in a mold that has been machined. Only one mold is necessary before mass manufacturing can occur. The downside to this manufacturing method is its inexact nature and the difficulty associated with aligning finite-thickness carbon sheets in a manner that conforms to the geometry of the .03m radius, 2mm tip chord propeller proposed in this report. There is also an obvious production rate cap associated with this manual form of propeller fabrication. The final form of manufacturing, injection molding, is similar to milling because it involves transferring CAD files to machine code that systematically produces the piece. This form of machining involves designing molds for the propeller that can be used repeatedly for several propellers. It is more practical than milling because it more easily produces 3-dimensional parts, and not just faces. It however, requires machine time and the difficulty of producing a propeller of this geometry and size remains unknown. Further, injection molding may excessively limit the amount of structural integrity that can be exhibited by the propeller. A quote was provided by FirstCut for injection molding molds, and the company indicated that the part has a significantly smaller thickness to part length ratio than most injection molded parts. This is indicated in figure E-1. This may lead short shot or flash to result in a injection molded propellers, which will require additional part alterations before the part could
be used. These issues could potentially be resolved via the implementation of side action gates for plastic injection from the sides of the propellers—near the tips.

Two special options were proposed.* One involved using a commercial, direct-milling service to quickly produce the prototype part. The other option was to use a special 3-D printer. The commercial technique would be executed through FirstCut CNC machining. The commercial CNC cutting method was determined to be too risky. Over half of the propeller was deemed to be cause for concern because of its low thickness, which according to the FirstCut could lead to a thinner resulting part, chipping, warping, bending, or break out. The concerned region is provided in figure E-2. Note that this was not the final propeller design. The message provided by FirstCut implies that direct milling may not be the safest manufacturing technique with regards to preserving the shape of the propeller and avoiding warping of the propeller cross section. The 3D printing option involves the use of Objet’s Connex 500 printer. This method was more expensive than the commercial option, and could be accomplished in one pass because the propeller is considered to be relatively topologically flat. The materials to be used were FullCure720 or VeroWhite. Both of these materials are relatively hard, strong plastics that are somewhat brittle. These materials would have only been used for the prototype propeller during initial testing, and not for mass production or long missions. Another possibility for manufacturing involves first 3D printing the part and then adding a layer of epoxy to the resulting part to obtain smooth surfaces and a template for mold production. This method was deemed to be too inexact and shape-altering in nature.

*Proposed by Andrew Marecki of MIT Mechanical Engineering.