PRACTICAL MODIFICATIONS FOR LOW REYNOLDS NUMBER PROPELLER APPLICATIONS

A Thesis by

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Bachelor of Art, Bethany College, 2005

Submitted to the Department of Aerospace Engineering and the Faculty of the Graduate School of Wichita State University in partial fulfillment of the requirements for the degree of Master of Science

December 2009
PRACTICAL MODIFICATIONS FOR LOW REYNOLDS NUMBER PROPELLER
APPLICATIONS

The following faculty have examined the final copy of this thesis for form and content, and
recommend that it be accepted in partial fulfillment of the requirement for the degree of Master
of Science with a major in Aerospace Engineering

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ACKNOWLEDGMENT

I would like to thank my adviser L. Scott Miller and, Monal P. Merchant for all their patience.

I would also like to thank Thayer Aerospace for the use their equipment and operators.
Applications for Unmanned Aerial Vehicles (UAV) and, specifically, Micro Aerial Vehicles (MAV) are increasing. As is the case for all aircraft, propulsion plays a significant factor in overall vehicle performance.

Most small UAV or MAV propellers are commercial, off-the-shelf products given their availability and low cost. Unfortunately, the off-the-shelf propellers are not tailored to a specific vehicle and/or mission. Only limited technical and performance data is available for the propellers.

A number of modifications have been used on larger (manned) aircraft propellers and rotors in the past to improve performance. Examples of possible modifications include vortex generators, cut tips, and tip sails. An investigation was conducted with the following goals:

1. Experimentally measure the performance impact of various modifications on UAV/MAV-class propellers
2. Study the practical applications for such modifications to UAV/MAV’s
3. Evaluate the utility of related propeller performance prediction tools

Experimental and basic analytical investigations address these goals. Special emphasis was placed on studying simple, practical, and cost effective modifications.

This investigation shows that after testing 24 modifications a number of practical modifications to improve propeller performance do exist. 2-Propeller, leading edge notches, and Gurney flap modifications all improve thrust while leading edge notches and Gurney flap modifications also improve cruise efficiency.
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NOMENCLATURE

$C_{0.75}$ Chord at the 75% Radius

$CMM$ Coordinate Measuring Machine

$C_T$ Thrust Coefficient

$Cp$ Power Coefficient

$D$ Propeller Diameter

$GF$ Gurney Flap

$IPTS$ Integrated Propulsion Test System

$J$ Advance Ratio

$Mcr$ Critical Mach Number

$RPM$ Revolutions Per Minute

$R_{0.75}$ ¾ Radius Location

$Re$ Reynolds Number based on the Chord at the 75% Radius Location

$V_t$ Tangential Velocity

$V_\infty$ Freestream Velocity

$q$ Dynamic Pressure of Wind Tunnel

$Q$ Torque of Propeller

$T$ Thrust of Propeller

$\mu$ Freestream Viscosity

$n$ Revolutions Per Second

$\eta$ Propeller Efficiency

$\rho$ Freestream Density

$\Omega$ Radians per second
CHAPTER 1
INTRODUCTION

Applications for Unmanned Aerial Vehicles (UAV) and, specifically, Micro Aerial Vehicles (MAV) are increasing. As is the case for all aircraft, propulsion plays a significant factor in overall vehicle performance.

UAV propulsion systems, especially in the case of MAVs, typically utilize propellers driven by gas or electric motors. UAV/MAV propellers of 6- to 22-inch diameters are the focus of this investigation.

UAV Propeller Differences

A number of important differences between larger manned aircraft and UAV propellers exist. One of the most challenging differences is in the Reynolds number range. Based on the 75% radius chord, UAV propellers operate at very low Reynolds numbers between 30,000 and 300,000. Maintaining performance, relative to larger propellers that operate at over a million Reynolds number, is very challenging under such circumstances. Separated laminar flows typically create problems.

Most UAV propellers are commercial, off-the-shelf products given their availability and low cost (associated with the worldwide hobby industry). Unfortunately, the off-the-shelf propellers are not typically tailored to a specific vehicle and/or mission. Additionally, only limited technical and performance data is available for these propellers [1].

Designing and constructing new propellers for UAVs is typically avoided given the cost of development and the availability of low-cost hobby propellers. Interestingly, there may be more interest in modifying existing propellers to better tailor their performance to a specific vehicle or mission.
Modifications

A very common propeller modification, especially for hobbyists, is to simply “clip the tip” (i.e., trim off a small portion of each blade’s tip). This change typically allows higher rotational speeds, which can improve performance. Other changes are possible, including the addition of vortex generators (VGs) and tip shape modifications. Indeed, a number of these options have been tested on larger aircraft propellers and rotors. Unfortunately, the performance impact of such changes has not been documented for low Reynolds numbers or UAV applications.

Investigation Goals

Based on the above discussions, the goals of the current investigation include:

1. Experimentally measure the performance impact of various modifications on UAV/MAV-class propellers

2. Study the practical applications for such modifications to UAV/MAVs

3. Evaluate the utility of basic propeller performance prediction tools for these applications

Experimental and analytical investigations address these goals. Special emphasis is placed on studying simple, practical, and cost effective modifications.
CHAPTER 2
BACKGROUND

The interest in modifying propellers or rotors is not new. A number of researchers have worked on this goal as outlined in Table 1.

TABLE 1

SUMMARY OF ROTOR MODIFICATION INVESTIGATIONS

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Time</th>
<th>Modification</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACA/NASA</td>
<td>Early 60’s</td>
<td>Vortex generators</td>
<td>20% increase in thrust (Ref. 2)</td>
</tr>
<tr>
<td>Purdue</td>
<td>Early 80’s</td>
<td>Bi-Blade and Tip-Sails</td>
<td>Showed improvement of 1%-5% in efficiency (Ref. 3-4)</td>
</tr>
<tr>
<td>Hobbyist</td>
<td>50’s-present</td>
<td>Clip-Tips</td>
<td></td>
</tr>
</tbody>
</table>

NASA Experiments

NACA, and later NASA, conducted a modified helicopter rotor study using vortex generators in the 1960’s. Vortex generators showed improvements of up to 20% in static thrust for a two blade rotor with a diameter of 37.68 feet. Figure 1, which comes from the NASA report, shows a drawing of the modified blade. Note that all values are in inches and degrees [2].

Vortex generators are known to promote flow attachment at high angles of attack. The suppression of flow separation increases blade lift and therefore rotor thrust.
**Purdue University Study**

Purdue University, in a 1980’s study of high efficiency propellers, looked into the use of tip-sails and bi-blade configurations applied to general aviation aircraft, using a vortex lattice code and during flight testing.

Tip-sails tested on a Cessna 172 propeller showed a 3.5% improvement in efficiency [3]. Corresponding analytical data showed an efficiency improvement of 1%-5%. It was found that the lift distribution with tip-sails approached that of ducted propellers.

Bi-blades are created when one propeller is stacked in front of another. They were not experimentally evaluated, but analysis was conducted that showed similar improvement to tip-sails (1%-5%) [4].
Hobbyist

A number of Radio Control (R/C) hobbyists and racers modify their propellers. One of the most popular modifications -- mentioned previously-- is cutting off the tips. The rule of thumb applied to propellers approximately in the range of 8-20 inch diameters is that removing 1-inch off the diameter will increase the RPM by 1,000. The difference in RPM changes the propeller Reynolds number, yielding a performance improvement.

Another R/C racers’ rule of thumb is that a smoother propeller will perform better. A smoother surface finish can reduce flow separation.

Other

A number of other modifications can be considered for investigation. Some configurations, believed to be practical and relatively simple to implement on small diameter propellers, are discussed below.

Figure 2. Example of 45-degree configuration spacing [6]

Multi-bladed propeller modifications can be made by stacking two propellers on the same hub, similar to Purdue’s bi-blade configurations but with the ability to control the angle between
blades. A 45-degree configuration seen on some helicopter tail rotors (e.g. the Apache helicopter seen in Figure 2) is one such configuration. Others include the X-configuration similar to standard multi-blade propellers but with one propeller is stacked in front of the other [5].

Expanding the blade chord can also increase lift. One easy way to do this is to add a flat plate to the trailing edge, extending the blade chord. An increase in lift surface area would improve propeller performance.

![Airfoil with chord extension](image)

**Figure 3. Airfoil with chord extension**

Gurney flaps are used in a number of wing applications to improve L/D performance [7]. An increased L/D improves both thrust and efficiency. Applications of Gurney flaps to propellers represent a simple modification of possible favorable impact.

Trips, short for trip strips, are a way to control separation points or to even delay separation at low Reynolds numbers. Wind tunnel engineers use trips to delay flow separation on small models by promoting boundary layer transition prior to adverse pressure gradients [8]. By reducing flow separation, improvements in lift and drag are possible; therefore, an improvement in thrust and efficiency will result.

Leading edge notches have been used to control flow over wings especially at higher angles of attack [7]. These features create strong vortical flows that energize the boundary layer
and delay flow separation. With a delay in flow separation, the stall angle will be increased, resulting in improved maximum lift.

None of these modifications have been applied to UAV/MAV propellers. A study of a number of modifications seems worthy, so a number of modifications were selected as outlined in Table 2. The modifications represent a variety of practical configurations.

TABLE 2
MODIFICATIONS SELECTED FOR STUDY

<table>
<thead>
<tr>
<th>Modification Name</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Propeller</td>
<td>X-config., 45-Degree config., Bi-blade config.</td>
</tr>
<tr>
<td>Cut Tips</td>
<td>7% off the radius</td>
</tr>
<tr>
<td>Tip Shape</td>
<td>Center, Forward, Aft</td>
</tr>
<tr>
<td>Gurney Flap</td>
<td>5%, 2.5%, 1% percent chord in height</td>
</tr>
<tr>
<td>Trips</td>
<td>35% and 55% of chord plus, bottom of blade</td>
</tr>
<tr>
<td>Surface Finish</td>
<td>80grit, 100grit, 400grit, alumin.</td>
</tr>
<tr>
<td>Flat Plate Chord ext.</td>
<td>150% and 50% percent chord</td>
</tr>
<tr>
<td>Vortex generators</td>
<td>VGs</td>
</tr>
<tr>
<td>End Plates</td>
<td>End Plate one, End Plate two</td>
</tr>
<tr>
<td>Leading Edge Notches</td>
<td>50%, 65%, and 75% of radius</td>
</tr>
</tbody>
</table>
To study propeller modifications in a logical fashion, a baseline propeller was first selected. Detailed geometry for the test propeller was then obtained for use with airfoil and rotor performance prediction tools. Additionally, the propeller was evaluated experimentally. The effectiveness of the analysis method and propeller modifications can also be evaluated with this approach. This chapter describes this process in detail.

The flow chart in Figure 4 shows the process by which analytical data was obtained and compared with experimental data.

**Baseline Propeller Selection**

A single propeller type was chosen for study. All theoretical and experimental tests were conducted on this propeller. To select this propeller in a reasonable manner requirements put forward in a U.S. Navy Call to Contractors [9] were used. Two primary requirements considered were thrust and RPM. Another consideration in the selection was the planform: a planform was
desired to simplify the accuracy of performance predictions. After considering the above factors, the 14-6 K series Master Airscrew was chosen because its thrust, operating RPM, and diameter were similar to desired values, plus, the planform was the simplest available.

Figure 5. Baseline propeller for study (14-6 Master Airscrew)

Airfoil coordinate data was obtained using a coordinate measuring machine (CMM). Two sets of data were obtained, one from Thayer Aerospace and another from the NIAR. The two sets of data compared within an uncertainty of 0.0005 inches or 0.3% of max thickness. The uncertainties of the airfoil geometry were taken from the CMM calibration

**Airfoil Performance**

As explained earlier, airfoil data for a number of stations were obtained. Figure 6 shows the stations measured on the propeller.
Airfoil data was extracted at 11 stations along the blade and 22 precision points taken around the airfoil. Then these airfoils were compared to published airfoil geometry data, and 5 out of 6 were found to match published geometry data for NACA airfoils [10]. Station 11 (last 2% of radius) was the only airfoil that did not compare to published data. Station 11 was modeled as a flat plate because it had blunt ends and a maximum thickness of 2.8%. A complete list of airfoil geometry data is presented in Table 3.

The CMM data gives dimensional airfoil data and the airfoil’s position relative to a defined point. From this data the position as percentage of radius, chord distribution, and twist angle of the station was found. A ruler and protractor were used to confirm the results of the CMM. Results were presented in the following Table 3.
TABLE 3

BASELINE PROPELLEGEOMETRY

<table>
<thead>
<tr>
<th>Station Number</th>
<th>Airfoil (NACA)</th>
<th>Radius (% of R)</th>
<th>Chord (c/R)</th>
<th>Twist angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16-1222</td>
<td>0.19</td>
<td>0.16</td>
<td>27.5</td>
</tr>
<tr>
<td>2</td>
<td>16-920</td>
<td>0.28</td>
<td>0.18</td>
<td>23.3</td>
</tr>
<tr>
<td>3</td>
<td>16-920</td>
<td>0.37</td>
<td>0.18</td>
<td>19.2</td>
</tr>
<tr>
<td>4</td>
<td>16-916</td>
<td>0.46</td>
<td>0.17</td>
<td>16.2</td>
</tr>
<tr>
<td>5</td>
<td>16-913</td>
<td>0.55</td>
<td>0.17</td>
<td>13.3</td>
</tr>
<tr>
<td>6</td>
<td>16-913</td>
<td>0.64</td>
<td>0.15</td>
<td>12.8</td>
</tr>
<tr>
<td>7</td>
<td>16-913</td>
<td>0.73</td>
<td>0.14</td>
<td>11.6</td>
</tr>
<tr>
<td>8</td>
<td>16-913</td>
<td>0.82</td>
<td>0.13</td>
<td>10.3</td>
</tr>
<tr>
<td>9</td>
<td>16-913</td>
<td>0.91</td>
<td>0.13</td>
<td>9.0</td>
</tr>
<tr>
<td>10</td>
<td>16-710</td>
<td>0.98</td>
<td>0.10</td>
<td>8.0</td>
</tr>
<tr>
<td>11</td>
<td>Flat plate</td>
<td>1.00</td>
<td>0.10</td>
<td>8.0</td>
</tr>
</tbody>
</table>

XFOIL

A popular airfoil analysis code was used to predict section aerodynamic characteristics for input to a rotor performance program. XFOIL is an interactive analysis code. This code uses an inviscid linear vorticity panel method to predict pressure distributions. Source distributions
superimposed on the airfoil and the wake are used to model displacement thickness. The transition point is found by $e^9$-type amplification formulation. Karman-Tsien compressibility correction are used. The limits of this code are at Mcr-conditions (Maximum Mach number seen on the blade is 0.58), where the compressibility correction breaks down, and at a Reynolds number below 100,000, the code stops comparing well with experimental data [11]. This code was used because of its popularity and easy access.

Input geometry data for XFOIL was obtained (based on results summarized in Table 3) from Javafoil, an airfoil coordinate generator [12] and checked against Abbott and Von Doenhoff [10]. Additionally, to validate proper code use, XFOIL runs were made at higher Reynolds numbers and compared to experimental data [12]. The higher Reynolds number data (1,000,000) were compared in Figures 8 and 9. This does not imply that the lower Reynolds number data is correct, but it does indicate that the geometry input was correct and that the code was working.

<table>
<thead>
<tr>
<th>Cd</th>
<th>Cl vs. Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACA 16-709</td>
<td>XFOIL (NACA 16-709)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angle of Attack (degrees)</th>
<th>C_l vs. AOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Reynolds Number 1,000,000</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8. Drag polar, $C_l$ vs. $C_d$ comparing experimental and XFOIL data

Figure 9. $C_l$ vs. AOA airfoil data comparing experimental and XFOIL data
XFOIL was used to produce airfoil data for XROTOR input. Data was obtained for a reference Reynolds number of 300,000. Figures 10 and 11 summarize section data.

![Figure 10. Drag polar, $C_l$ vs. $C_d$ for baseline propeller airfoil data](image1.png)

![Figure 11. $C_l$ vs. AOA for baseline propeller airfoil data baseline](image2.png)

**XROTOR**

XROTOR is an interactive program for design and analysis of ducted propellers, free tip propellers, and wind turbines. XROTOR uses lifting-line theory with a Prandtl-Glauert compressibility correction. It calculates induced velocities by numerically solving for the exact perturbation potential flow field about a helical vortex sheet wake with first-order correction for self-induction. A limitation in this effort was a lack of documentation for this code and a limited input format capability [14]. Nonetheless, the code does enjoy a high-degree of popularity.

XROTOR uses three general inputs: airfoil performance data, propeller geometry, and flight conditions. Propeller geometry, for XROTOR runs, includes number of blades, hub radius, total radius, and chord distribution. The chord and twist distribution were obtained from the
CMM data. Flight conditions for analysis include airspeed, RPM, and flow density. This information was taken from the baseline experimental propeller testing.

**Combined Blade Element and Momentum Code**

A Combined Blade Element and Momentum Code (CBEMC), written by the author, was also utilized along with XROTOR. CBEMC used a sixth order curve fit to input airfoil data. It was also written to be as simple a method as possible. This program’s results were similar to XROTOR (baseline data presented in results section) when a comparison was done.

**Integrated Propulsion Test System**

The Integrated Propulsion Test System (IPTS) is the experimental system utilized to measure propeller performance. It can be broken down into three sub-parts the sensor/motor platform, signal conditioning, and power and data processing. The sensor/motor platform is mounted on a C-strut in the 3x4 foot low speed wind tunnel test section. Located outside the test section, were a collection of signal conditioning equipment along with independent power supplies for the motor and RPM sensor plus, a laptop used for data processing (see Figure 12).

Located in the 3x4 Low Speed Wind Tunnel (LSWT) at Wichita State University, the IPTS can achieve a range of advance ratios by varying tunnel speed. The 3x4 LSWT is an open return wind tunnel capable of dynamic pressure of 38psf. The dynamic pressure is measured with a pitot-static tube and a 1-psid Honeywell pressure transducer, with a rated output accuracy of +-.05% Full Scale (FS). The pitot-static is also cross checked with a manometer.
A two component load cell, measuring thrust and torque to an accuracy of ±0.05% FS is mounted on a C-strut in the test section of the 3x4 LSWT. An adapter allows a range of motors to be connected to the IPTS; in this case, a brushed AstroFlight electric motor from the Cobalt family is used.

To measure RPM, a magnetic pickup is used. This requires a metallic tab to spin with the propeller. The RPM is both recorded automatically and checked with a multi-meter that measures Hz. The power required for the magnetic pickup was provided by an independent power supply placed outside the test section.

Signal conditioner, amplifiers, and opto-isolators are located outside of the test section. The conditioned signals are then fed into a 16-bit A2D card and a laptop. An in-house Visual Basic® (VB) code is use to apply blockage corrections and output performance curves for $C_T$, $C_Q$, $C_P$ and $\eta$. 

Figure 12. Diagram of IPTS taken for reference 1
The following standard propulsion equations were used.

\[ C_p = \frac{\Omega Q}{\rho n^3 D^5} \]  
(Coefficient of Power) (1)

\[ C_Q = \frac{Q}{\rho n^2 D^5} \]  
(Coefficient of Torque) (2)

\[ C_T = \frac{T}{\rho n^2 D^4} \]  
(Coefficient of Thrust) (3)

\[ J = \frac{V_\infty}{nD} \]  
(Advance Ratio) (4)

\[ n = \frac{RPM}{60} \]  
(Rotation per second) (5)

\[ \eta = J \frac{C_T}{C_p} \]  
(Efficiency) (6)

\[ V_t = \sqrt{V_\infty^2 + (\Omega \cdot R_{0.75})^2} \]  
(Tangential velocity) (7)

To obtain a range of advance ratios and get complete performance curves, the power to the motor is held constant and the tunnel speed is varied. The step size for the tunnel q-sweep was determined from calculations based on Combined Blade Element and Momentum Theory (CBEMT).

Power to the motor is provided by a DC power supply located outside the test section of the wind tunnel. The power supply is set and monitored throughout a run to maintain maximum power to the motor (within the current limits of the motor).

The data reduction routine makes propeller slipstream momentum corrections and uses a wind off zero at both the beginning and end of a run. Repeated runs were made to check that data was repeatable.
Uncertainties in coefficients are dependent on the particular propeller and the advance ratio but were about 0.05% in $C_T$ and $C_Q$ and about 0.003% in $C_P$ [1].

The IPTS was used to measure $C_T$, $C_Q$, $C_P$, and $\eta$ in this study because of its low uncertainties and ease of use.
CHAPTER 4
RESULTS AND DISCUSSION

This chapter presents propeller test data, analysis and results. Discussions of relevant flight regions were provided first, so as to better frame the potential impact of propeller modifications to UAV/MAV vehicles.

Example Data

The example (Figure 13) was divided into 3 key flight regions. Below an advance ratio of 0.2, typically, corresponds to takeoff. At the RPM tested, this condition was at or below 40 ft/s. The region above an advance ratio of 0.55 was a region of maximum speed for the UAV. For the RPM tested, this would correspond to a flight speed above 110 ft/s. The region between takeoff and high speed referred to as the cruise region. A point around an advance ratio of 0.4 (i.e., the cruise point) was where maximum efficiency occurs. Looking at the RPM tested, this corresponds to a cruise speed around 70 ft/s.

Figure 13. Baseline propeller data from IPTS
To assist in identifying the impact of propeller modifications, a series of graphs were made showing the percent difference between the baseline and a specific change. Equation 8 was used to find those percentages. Results were graphed against the advance ratio.

\[
\text{Percent of Baseline} = \frac{\text{Modification} - \text{Baseline}}{\text{Baseline}}
\]

Figure 14 shows the XROTOR analysis was within approximately 10% of IPTS for most of the runs and that the CBEMC does not perform as well as XROTOR. 10% error can be reasonable for initial design applications.

Seen in Figure 15, the certainty of the predicted performance of the 2-propeller (and other) modifications were less than desired. The trends of performance improvement or harm were reasonable but not accurate.
Because of this outcome, no further XROTOR analysis data was presented to confuse the readers. In short, XROTOR fails to reasonably model the examined modifications.

![Comparison between baseline XROTOR and CBEMC analysis](image)

**Figure 14.** Comparison between baseline XROTOR and CBEMC analysis

Most importantly, Figure 13 and Table 4 outline the baseline propeller behavior. As has been discussed earlier, performance modifications and predictions were to be evaluated relative to this experimental data.
Figure 15. 2-propeller comparison of XROTOR with baseline

To verify the repeatability repeated runs were made on different days. Representative results were shown in Figure 16. The data shows the difference between runs to be less than 3%.

Figure 16. Comparison of repeat runs of Cut Tips
Table 5 outlines the test matrix (i.e. each modification and sub-configurations) examined. Text sections following this table include photographs and results for the wind tunnel tests.

**TABLE 5**

**TEST MATRIX**

<table>
<thead>
<tr>
<th>Modification Name</th>
<th>Run name or configuration name</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Propeller</td>
<td>X-Configuration, 45-Degree, Bi-Blade</td>
</tr>
<tr>
<td>Cut Tips</td>
<td>Cut Tips</td>
</tr>
<tr>
<td>Tip Shape</td>
<td>Aft, Center, and Forward</td>
</tr>
<tr>
<td>Gurney Flap</td>
<td>GF-1, GF-2, GF-3</td>
</tr>
<tr>
<td>Trips</td>
<td>Trip #1, Trip #2, and Trip #3</td>
</tr>
<tr>
<td>Surface Finish</td>
<td>SF80, SF400, SF aluminum</td>
</tr>
<tr>
<td>Flat Plate Chord Extension</td>
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<tr>
<td>Vortex Generators</td>
<td>VG</td>
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<tr>
<td>End Plates</td>
<td>End Plate 1, and End Plate 2</td>
</tr>
<tr>
<td>Vertical Slots</td>
<td>Slots1, Slots 2, and Slots 3</td>
</tr>
</tbody>
</table>

**2-Propeller**

For the 2-Propeller modifications, the three configurations were made by placing the blades in various orientations relative to each other. The X-configuration was close in configuration to off-the-self four bladed propellers as seen in Figure 17. Figure 18 shows the 45-degree configuration that was similar to some helicopter tail rotors. The bi-blade configuration in Figure 19 was closely related to work sighted earlier (Purdue).
The 45-degree configuration showed the best improvement in thrust but was less efficient compared to the other 2-propeller configurations. Overall, the modification increases takeoff and cruise thrust at the cost of decreases in efficiency and, as might be expected, increasing power required.
Gurney Flaps

The Gurney Flap were made with a 0.014 inch thick piece of balsa wood and cyanoacrylate glued over the outer 60% of the blade radius. This was done because of the
difficulty in applying the Gurney flap around the hub and the fact that most of the lift was produced on the outer 60% of the blades. Again three configurations were shown: GF-1 with the height of the Gurney Flap at 5% of the chord (0.0525 inch) in Figure 23, GF-2 with a height of 2.5% of the chord (0.0263 inch) seen in Figure 24, and GF-3 with a height of 1% of the chord (0.0105 inches tall) in Figure 25.

Figure 23. GF-1 with a 5% chord

Figure 24. GF-2 with a 2.5% chord

Figure 25. GF-3 with 1% chord

Thrust and power required both increases compared to the baseline most notably at high advance ratios. Also important to note: that at low and medium advance ratios (takeoff and
cruise from Figure 13) efficiency was lower, but at higher advance ratios or in the maximum speed region, the efficiency was improved.

Figure 26. Results for GF-3

Figure 27. Results for GF-1

Figure 28. Results for GF-2
Trips

Trip #1 were made using four 0.5 inch wide pieces of aluminum tape (each 0.004 inches thick) positioned over the top of the propeller blade at 35% of the chord (Figure 29). The second configuration (Trip #2) was a 0.25 inch wide piece of tape at 55% of the chord. This position was chosen based on data from XFOIL (Figure 30). A third configuration (Figure 31) Trip #3 was the same as Trip #2 with a second piece of tape on the bottom at 80% chord.

Figure 29. Trip #1

Figure 30. Trip #2

Figure 31. Trip #3

Thrust and efficiency for all three configurations were reduced at most advance ratios but most notably at high advance ratios.
Cut Tips

The Cut Tips reduced the diameter by 1 inch or 7% (Figure 35). The test confirms the rule of thumb discussed in earlier sections (i.e., operating RPM’s increase). The thrust was
improved, but the efficiency was reduced for low to medium advance ratios. Note that both efficiency and thrust increased slightly at higher advance ratios.

Figure 35. Cut tips

Figure 36. Results for cut tips

**Leading Edge Notches**

Leading edge notches were made by cutting a 0.05 inch wide and 0.15 inch deep notch into the propeller (Figure 37-39). The leading edge notches 3 configuration had notches cut at
50%, 65%, and 75% of the radius. Leading edge notches 2 had notches at 65% and 75% of the radius, and leading edge notches 1 had a notch cut at 75%. Bondo was used to fill slots as needed to generate different configurations.

![Leading edge notches 3](image37.jpg)

**Figure 37. Leading edge notches 3**

![Leading edge notches 2](image38.jpg) ![Leading edge notches 1](image39.jpg)

**Figure 38. Leading edge notches 2**  **Figure 39. Leading edge notches 1**

Both leading edge notches 1 and leading edge notches 2 increased thrust, power required and efficiency. The increase was most pronounced at higher advance ratios. Leading edge notches 3 showed the opposite effect on performance.
Figure 40. Results for leading edge notches 1

Figure 41. Results for leading edge notches 2

Figure 42. Results for leading edge notches 3
Tip Shapes

The tips were cut into a triangular shape to make the three configurations seen in Figure 43-45; one with the point of the triangle in the center of the blade, another with the point forward and the last with the point aft. The angle and amount cut off was based on a commercial, off-the-shelf 14-10APC with a scimitar blade design.

![Figure 43. Tip shape aft sweep](image1)

![Figure 44. Tip shape forward sweep](image2)

![Figure 45. Tip shape center sweep](image3)

Figures 46, 47, and 48 show all three configurations led to decreases in thrust, power required and efficiency.
Surface Finish

A test of surface finish was conducted to see how sensitive the surface of the blade was to roughness. Sand paper was used for its reproducible results and availability. The paper was glued on the top and the bottom of the blades. Unfortunately, the leading and trailing edges could not
be covered given that the paper was not malleable enough to conform to the small radii. Tests with 80 and 400 grit sand paper and aluminum tape were conducted (Figures 49-51).

![Figure 49. Surface finish test with aluminum tape](image1)

![Figure 50. Surface finish test with 80 grit sand paper](image2)

![Figure 51. Surface finish test with 400 grit sand paper](image3)

Results compared to the baseline were not effective in this case because of the thickness of the paper -- 0.008 inches (0.8% of chord) -- possibly leading to tripped or separated flow; therefore, without a study of these possible effects, a comparison to the baseline does not make sense. By comparing the three configurations, an understanding of the effect of the surface finish on performance can be found.
Figure 52. Results for Surface finish test with aluminum tape

Figure 53. Results for Surface finish test with 80 grit sand paper

Figure 54. Results for Surface finish test with 400 grit sand paper
Chord Extension

Flat plate chord extensions were made of cardboard (Figure 55) and tape (Figure 56). The goal of the chord extensions was to increase the lifting area. The cardboard chord extension was made by smoothly cutting and then gluing a piece of cardboard so that both ends equal the chord and the center was 200% chord (Figure 57). The tape chord extension was made with packing tape to make a uniform chord of 1.7 inches (161%) seen in Figure 56.

![Figure 57: Diagram of Chord Extension](image)

The cardboard was not strong enough to handle the forces involved and failed; therefore, no results were presented for this configuration. Tape chord extension was successful in
producing data, but that data shows a negative impact for all advance ratios. It was possible that
the tape deformed under aerodynamic loads.

Vortex Generators

Vortex generators were made of a strip of aluminum tape with generators cut into the
tape as seen in Figure 59. The vortex generators were 0.075 inches height and spaced at 0.075
inches apart. This spacing and height was determined by how small they can be made within the
constraints of this investigation. That being said, a notable problem with making the vortex
generators was that maintaining constant angles was not easy.

Figure 58. Results for Tape Chord Extension
Tests with a strobe light were conducted to verify that the vortex generators stayed at the given angle seen Figure 59. Vortex generators were placed at 55% of blade chord similar to trip #2 although at high advance ratio the results were similar to trips #2, but at advance ratio below 0.5, the results differ greatly. The vortex generators produce a loss of both thrust and efficiency (Figure 60).

Figure 59. Vortex generators

Figure 60. Results for vortex generators
End Plates

Two configurations of end plates were examined. End plate 1 was a flat plate of balsa wood and end plate 2 was an airfoil shaped piece of balsa wood. Note that end plate 1 goes above and below the blade (Figure 61): End plate 2 only extends above the blade.

Figure 61. End plate 1
Figure 62. End plate 2

The End Plates 2 failed to complete a run and End Plate 1 did not improve the performance of the propellers as seen in the results in Figure 63.

Figure 63. Results for end plates 1
**Results Summary**

For quick reference, graphs of efficiency and thrust coefficient including the best modifications were summarized in Figures 64 and 65 along with the baseline for comparison. These figures show no new information, but they highlight the most significant results presented in previous sections.

**Figure 64.** Comparison of the efficiency of the most effective modifications

**Figure 65.** Comparison of the thrust coefficients showing the best improvement
CHAPTER 5

CONCLUSIONS

A summary of this investigation and conclusions are presented in this section.

One goal for this investigation was to experimentally measure the performance impact of various modifications on UAV/MAV-class propellers. This goal was met by testing 24 modifications and configurations on a generic UAV/MAV propeller.

A secondary goal was to study the practical applications for such modifications to UAV’s/MAV’s. This goal was evaluated by considering only simple modifications and by using tools and supplies easily found at a hobby shop or hardware store. All modifications were evaluated for improvement in thrust, efficiency, or a decrease in power required over a range of flight conditions. Results are outlined in the list in Table 5.

<table>
<thead>
<tr>
<th>Takeoff</th>
<th>Cruise</th>
<th>High Speed</th>
<th>No Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Propeller (thrust)</td>
<td>Trips (power required)</td>
<td>Leading Edge Notches (thrust)</td>
<td>Smaller Tip Chord</td>
</tr>
<tr>
<td>Trips (power required)</td>
<td>Leading Edge Notches (thrust)</td>
<td>Gurney Flap (thrust)</td>
<td>Smooth Surface Finish</td>
</tr>
<tr>
<td>Leading Edge Notches (thrust)</td>
<td>Cut Tips (thrust)</td>
<td></td>
<td>Vortex Generators</td>
</tr>
<tr>
<td>Gurney Flap (thrust)</td>
<td></td>
<td>End Plates</td>
<td></td>
</tr>
<tr>
<td>Cut Tips (thrust)</td>
<td></td>
<td>Chord Extensions</td>
<td></td>
</tr>
</tbody>
</table>

With the experience gained in building these modifications; a number of issues arise. One was the size, for example, making a Gurney flap less than 1% of a 1.05 inch chord without special or precision tools was difficult and requires a great deal of experience and craftsmanship.
The final goal of this investigation was to evaluate the utility of propeller performance prediction tools using XROTOR and an in-house CBEMC. XROTOR and the CBEMC tests compare to within 10% of the baseline propeller, but only show approximate trends for the modifications considered. Issues using these codes include geometry limitations of not being able to input a tip shape or more complex propeller geometry. The fact that none of the codes examined included three-dimensional effects was another issue. In short, neither analysis code reasonably models the examined modifications.
CHAPTER 6
RECOMMENDATIONS

The following avenues for further investigations were presented to help add some perspective.

Data presented here was for only a limited number of modification sub-configurations (i.e. 3 or less). It’s very possible that improved configurations exist. The construction of modification for this test was limited to crude methods. Better and more sophisticated fabrication methods could possibly improve performance. Last, a simple analysis tool would help identify modifications more quickly and more efficiently. To summarize the following further requirements were needed.

- Consider optimizing a specific modification
- Study improved construction technique
- Enhance performance prediction tools
REFERENCES


