

Proplet Propeller Design/Build/Test Final Report May 6, 2005

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Executive Summary

The purpose of this project was to design a propeller for RC use that increases the efficiency of the propulsion system. This design used proplets on the blade tips to increase performance.

In order to design this propeller, aerodynamic analysis tools and optimization techniques were incorporated. The design was primarily done using a Goldstein blade analysis and the CMARC 3D commercial panel code. These tools allowed a propeller to be designed that showed a theoretical 10% increase in efficiency in the design flight regime.

To build this propeller a plug was cut from acrylic on a 5-axis CNC machine. This plug was used to make a silicone rubber mold. The mold was used to lay up a hybrid carbon fiber and fiberglass propeller.

The final outcome of this project was a durable propeller that has a 5-10% efficiency increase over standard industry RC propellers at a given thrust requirement. This propeller met the design goals in increasing efficiency and using a repeatable construction technique.

Project Purpose and Design Mission

The goal of this project was to design, build and test a propeller for electric remote control aircraft that uses proplets to increase its efficiency for a given diameter in standard RC flight regimes. Specifically, the propeller was designed for use on the Model High Altitude Airship shown in Figure 1 that is being developed at the Purdue Aerospace Sciences Laboratory. Because of the low velocities at which the airship operates, the propeller was designed to be most efficient at low advance ratios ($0 < j < 0.6$). The project included designing a propeller that would increase the efficiency while still providing the required thrust for forward flight and maneuvering. A propeller with increased efficiency could also be used on a small UAV such as the Calmar UAV (see Figure 2) developed at Purdue University. Because these aircraft are battery powered, the efficiency of the propulsion system is directly related to the flight duration.



Figure 1: High Altitude Airship Model



Figure 2: Calmar UAV

Background Information

In order to understand how a proplet can improve the performance of a propeller the basic parameters of propeller design and performance must be understood. Equation 1 through Equation 4 are fundamental measures for propeller performance. The first is the advance ratio. This is the ratio of the free stream flight speed to the tip speed of the propeller. The performance of a propeller depends primarily on advance ratio. As stated above, the airship model operates primarily at advance ratios below 0.6 because the flight speeds are low. This design will also be a fixed pitch propeller which will limit its performance to being best within a pre-determined range of advance ratios. For this design the intended advance ratio range was from 0 to 0.6 which allows the propeller to operate with a free stream from 0 to 30 ft/sec and RPM up to 8000. The efficiency of the propeller is calculated as the ratio of usable power to the power that must be given to the propeller by the motor in order to spin it. The thrust coefficient is similar to the lift coefficient of a wing in that it represents the force coefficient which provides useful thrust.

$$j = \frac{V_\infty}{ND}$$

Equation 1: Advance Ratio

$$\eta_p = \frac{T \cdot V_\infty}{2\pi N \cdot M_x}$$

Equation 2: Efficiency

$$c_t = \frac{T}{\rho \cdot N^2 \cdot D^4}$$

Equation 3: Thrust Coefficient

$$c_p = \frac{TV_\infty}{\rho N^3 D^5}$$

Equation 4: Power Coefficient

N=rotational speed (rotations/second)
D=propeller diameter
T=thrust generated
M_x=moment about shaft

In addition to the equations that are used to quantify propeller performance, there are important geometrical definitions in dealing with a propeller. For this discussion, the propeller always rotates about the z-axis and the y-axis is along the blade span. In this reference frame the angle of each airfoil section on the blade is located with a spanwise y coordinate as well as a β angle which is the angle between the x-y plane and the chord of the section. As is typical with propellers the β angles decrease from root to tip so that each airfoil section stays within a desired 2D angle of attack range where it operates most efficiently. Figure 3 shows a typical beta distribution for a propeller of this size and shows how it changes from root to tip.

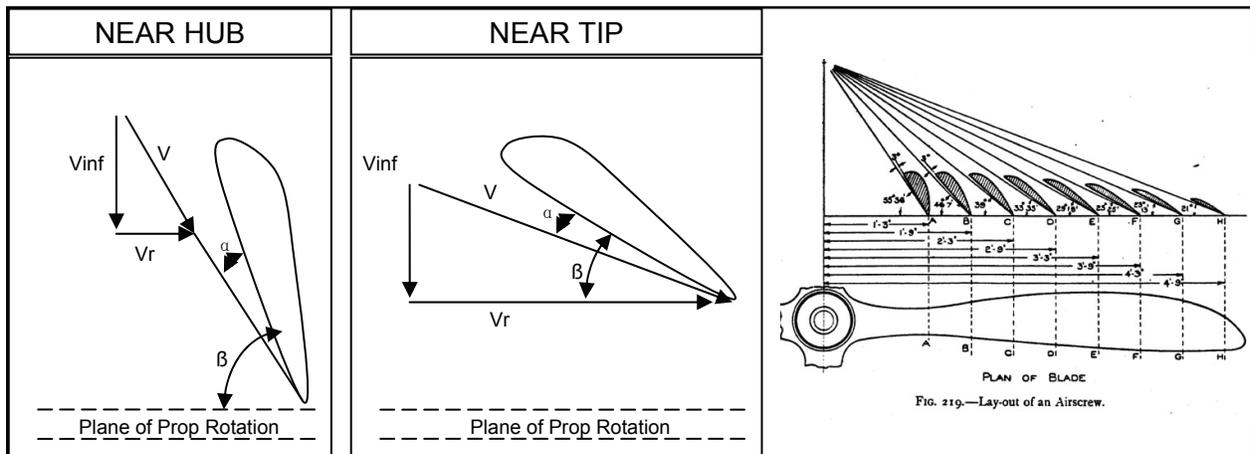


Figure 3: Typical Propeller Geometry

Many studies have been done on the use of several types of propeller tip devices. Some of the earliest studies of these devices date back to Prandtl and Betz who began investigating the use of end plates on finite wings. This research was continued in the Sixties and Seventies as Cone and Whitcomb studied non-planar lifting surfaces and winglets. In the Eighties winglets were first applied to airplane wings and experiments began with end-plates and tip-modified propellers. The purpose of using non-planar lifting devices on a wing or propeller blade is to use the vortex (and the resulting downwash) to change the load distribution on the wing and increase the overall performance at the tip. Winglets have been applied to the design of many aircraft including the Boeing 747 and 737 aircraft. Winglets are comparable in performance to extending the wing by some margin. Extending the tip may however have loading and structural implications that are difficult to deal with. In the case of a propeller, the diameter of the propeller is often determined by the sizing of the rest of the aircraft and by the aerodynamic effects that the propeller may have on the rest of the aircraft. Because of this and structural limitations, extending the length of a propeller blade is often difficult and so winglets or proplets, in this application, become a useful option for increasing performance. Figure 4 shows typical winglet geometry for aircraft wing applications and Figure 5 shows the typical trend of performance increase with the use of tip devices.

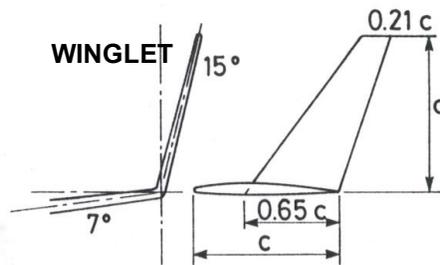


Figure 4: Typical Winglet Geometry

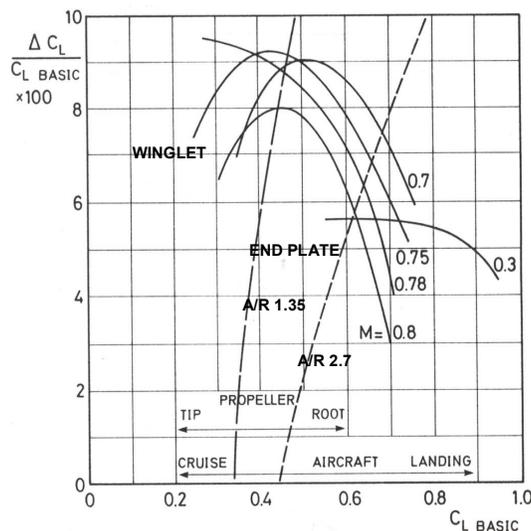


Figure 5: Tip Device Performance Benefits

New load distributions were found by Andersen and Andersen and in the Nineties work began on the KAPPEL propeller, a marine propeller design with curved blades near the tip. This was a revolutionary design for marine propellers that greatly increased efficiency while

reducing the vibration and noise. The KAPPEL design has highly non-planar geometry and the theory of its performance enhancements relate to the application of similar geometry to aircraft propellers. The geometry of marine propellers is somewhat different due to the density of the fluid and rotation rate. Marine propellers can be made much heavier and can have much more out of plane geometry because the structure of these propellers is typically solid and very strong. Figure 6 and Figure 7 show a KAPPEL propeller and a plot of its performance compared to a standard marine propeller.

Many studies have been done on the effects of winglets on aircraft wings but it was difficult to find research and writing on the application of similar devices to aircraft propellers. The theory is the same as on the wing of an aircraft although special techniques must be used to model the rotation of the propeller. There are several very relevant pieces of literature on this topic. The first is Itoh's article on the study of propellers with small blades on the blade tips. This article is a general study of the use of blade tip non-planar lifting surfaces. The full text was written in Japanese and so far only the abstract has been located in English. The second is Anderson's study of Tip-Fin Propellers and their Performance. Lastly, Sullivan, Chang, and Miller published a study on the effects of proplets on the performance and noise of propellers. This article suggested that the performance of a propeller with proplets would be greater than the performance of a standard propeller at lower advance ratios. This means that the low speed flight performance is better for a propeller with tip devices.



Figure 6: KAPPEL Marine Propeller

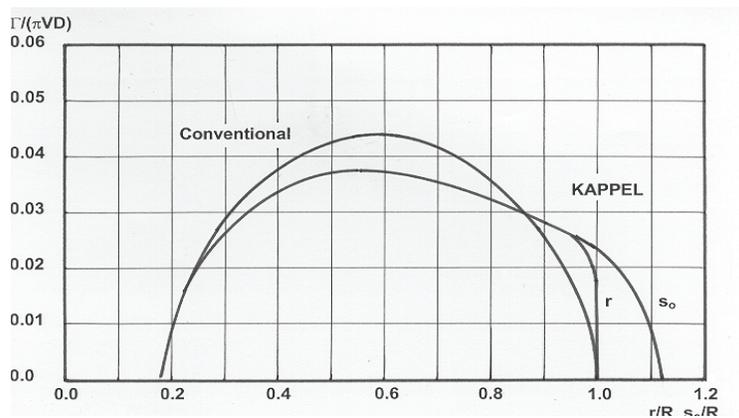


Figure 7: KAPPEL Marine Propeller Performance

Final Propeller Design

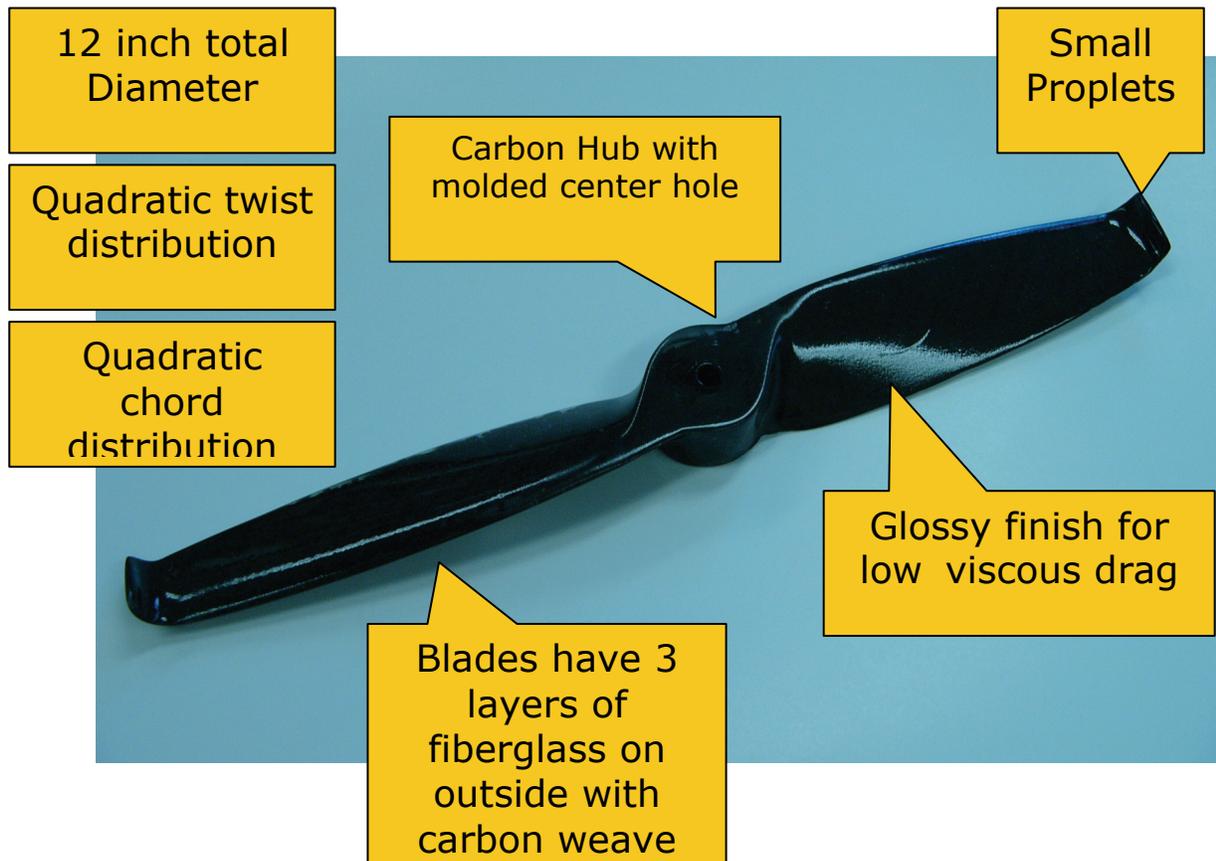


Figure 8: Final Propeller Design

The final propeller design shown in Figure 8 was designed, built, and tested for this project. The methods of each phase of this project are detailed in the rest of this document as are the detailed geometries of the final design.

Spiral Design Method

In order to design the proplet propeller a method called spiral design was implemented. This method differs from a traditional product development in which a request for proposal initiates a long design phase followed by construction, testing, and delivery of a final product. In spiral design, the product goes through several phases, or spirals of development, each of which contains elements of design, building, and testing. In a spiral design, information learned from the early spirals can greatly help in the development of the final product as well as decreasing design cost and risk that is introduced by finalizing a design that has not been tested in some capacity. Figure 9, which was borrowed from an industry software design, shows the difference between a typical waterfall design and a spiral design process. In the waterfall design there is no significant progress in a final product until the last third of the design period. The spiral design allows for the progress to be spread out throughout the product development timeline. Figure 10 shows the progress timeline for the proplet propeller project.

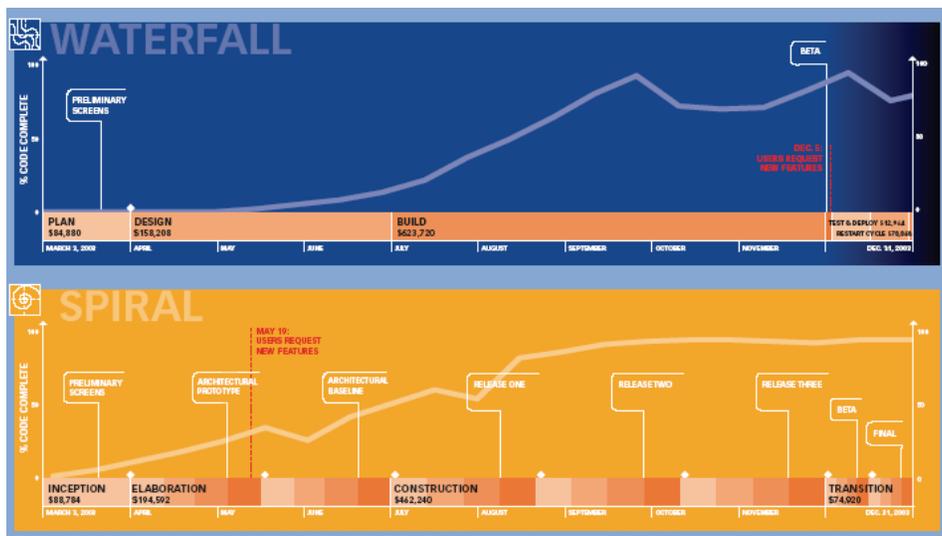


Figure 9: Waterfall and Spiral Design

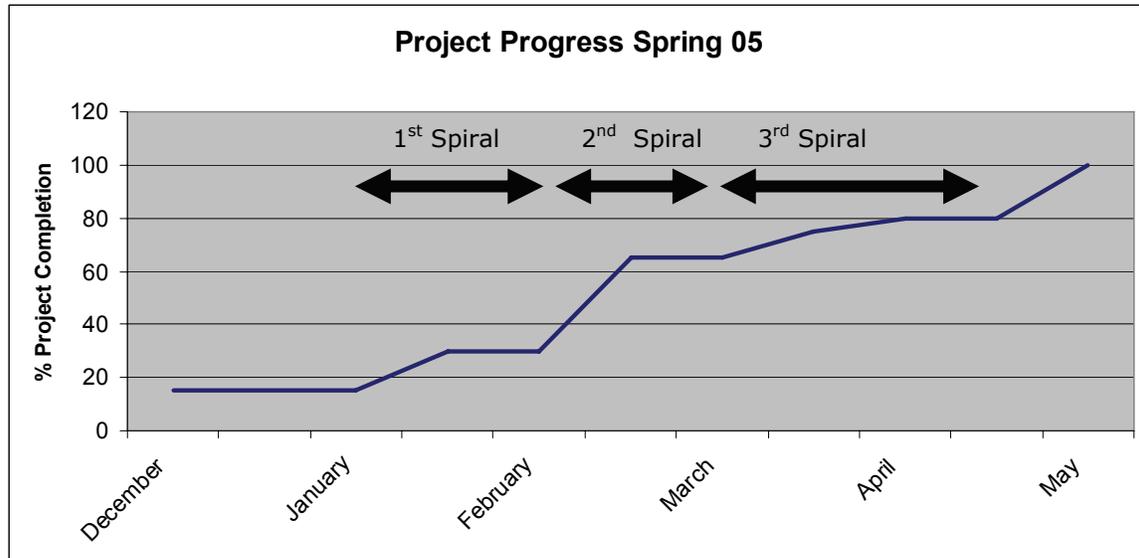


Figure 10: Progress of Propeller Project

In order to successfully use spiral design each spiral must be intentionally defined so that its results will be meaningful to the final product. The goals for each spiral were defined early in the spiral process but these goals were often modified to fit the specific timeline and design progress.

Three spirals were used in the design of this propeller. The first spiral focused primarily on familiarizing the design team with propellers and with the testing of propellers. The second focused on the detail design of the proplet propeller and increasing the detail and accuracy of the design and testing of spiral one. In the final spiral the design underwent minor changes and the primary focus was on the details of construction techniques and the testing of the final product.

The goals of spiral one were to choose and test the analysis software that would eventually be used to design the propeller, to built propellers with proplets, and to gain experience testing these propellers. The software development included the choice of aerodynamic analysis tools as well as the development of the core programs in the design software set. Another accomplishment of the first spiral was to begin to integrate the software and automate it so that an optimization could be done on the design. The primary tool of aerodynamic analysis was CMARC, a commercial 3D panel code. In the first spiral a CMARC model of a propeller similar to the ones currently used on the Purdue Airship Model were tested. The generation of the CMARC input file was automated which required testing many different propeller shapes and advance ratios to find functions defining the appropriate time steps for a given design. Spiral one also saw the completion of the test stand and testing apparatus that was then used to test modified factory propellers. Making modifications to existing propellers simplified the construction of spiral one while allowing the goal of gaining testing experience to be completed. Spiral one also included the study and use of several programs and information from previous work on proplets by Bryan Redman in AAE 415.

From the first spiral, experience was gained in testing a propeller as well as in the basic design principals of propellers. The testing results also showed that proplets which were not properly designed would not increase the performance of propeller as the modified propeller with added proplets performed less efficiently than the unmodified propeller.

Spiral two was primarily focused on the detailed design of the propeller and the finalizing of the design method. The design accomplishments of this spiral include an automation of the design software, partial optimization success, and the completion of a proplet geometry trade study. This information proved valuable in the final propeller design. A solid model of the propeller was also made and automated that allowed for visualization of the propeller and geometry for computer aided manufacturing. Although no propellers were build during the second spiral the techniques that would be used to build the final propeller were researched and tested. With the primary design completed and a review done of the design, information for choosing the final propeller geometry was available for the next spiral. In testing spiral two was used to research means of increasing the accuracy of the spiral 1 method. This included finding more accurate measurement devices and becoming more familiar with the test apparatus and electronics.

During the third and final spiral the design was finalized. This was done making slight modifications to the design software of spiral two and choosing the final geometry of the blade as well as detailing the design of the hub. Spiral three included the fabrication of an acrylic propeller and a silicon rubber mold that were used for making the final propeller. The final propeller was then tested in several configurations.

Design Detail

The flowchart in Figure 11 shows the goal for the software suite developed. Initially an airfoil section was chosen using XFOIL. Along with this, various input parameters are put into an optimization loop. This optimization takes one point in the design space and uses the geometry generation script to make the propeller geometry. This geometry is then analyzed in CMARC. The results from CMARC are then put back into the optimizer. Once a specific geometry is settled on, the geometry generation code outputs the optimized geometry to a Catia model. This Catia model then outputs the geometry to SurfCam which creates tool paths to cut the propeller with the 5-axis CNC machine.

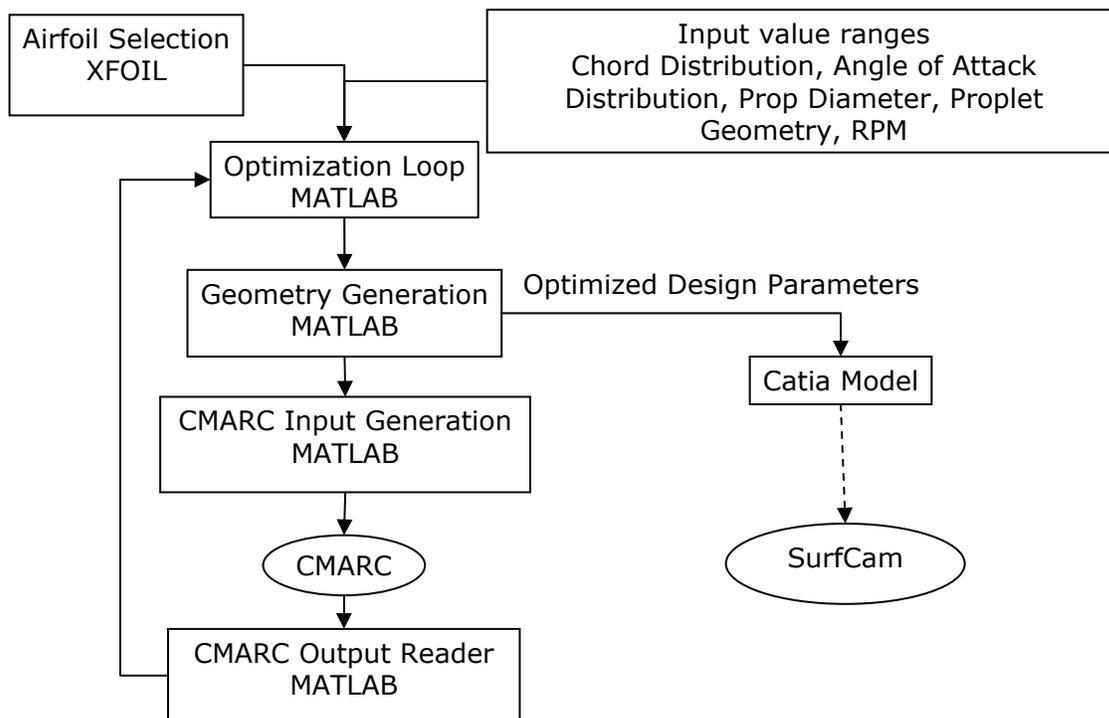


Figure 11: Software Suite Flowchart

Due to optimization complications, a modified software layout was used in the final propeller design. This method is shown in Figure 12. Instead of running an optimization around the entire process, the optimization is split in two sections. One section uses CMARC to perform trade studies on the proplet design. The other section optimizes a propeller without proplets. These two were then combined and the design point was verified with the original software suite.

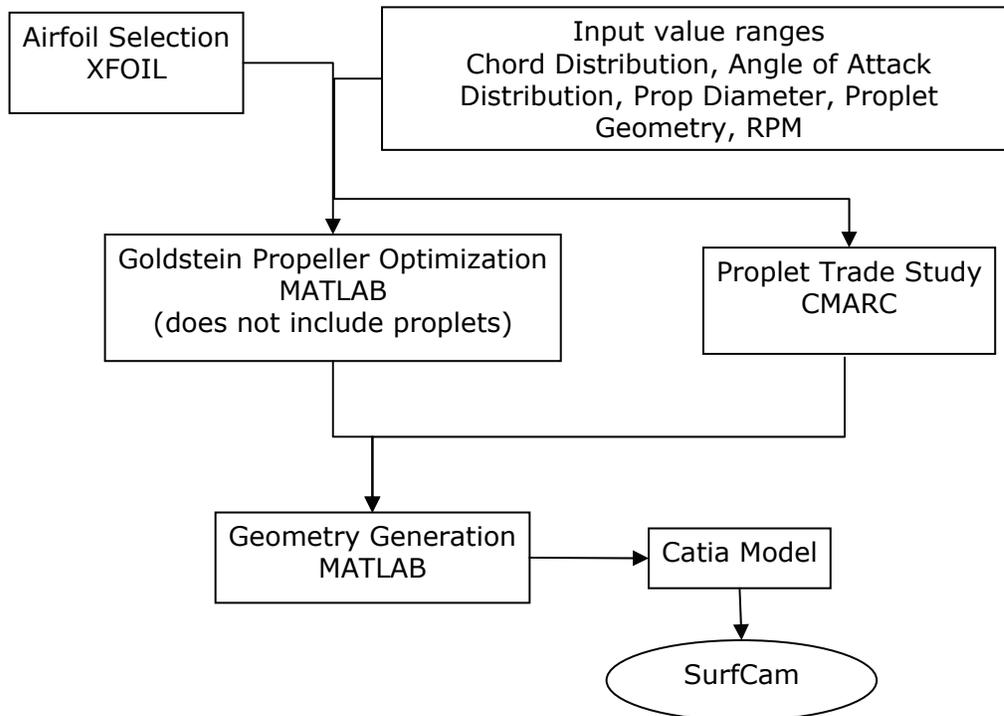


Figure 12: Modified Software Suite Flowchart

The geometry generation script used in this process produces a matrix of three dimensional coordinates which describe cross-sections of the propeller's blades. A single airfoil section is used throughout the propeller blade and scaled based on a specified chord distribution. The blades are created in four distinct sections. The first section creates airfoil cross-sections for the straight part of one blade. The second section creates airfoil sections for the blend radius, the curved section at the end of the blade which blends into the proplet. The third section creates airfoil sections for the proplet, these cross sections are an extrusion of the last section of the blend radius. The fourth section mirrors the first blade made to create the rest of the blades on the propeller.

The number of points along the airfoil cross-section and the number of cross-sections along the blade span can be simply varied. The straight section geometry is defined by quadratic chord and angle of attack distributions. The proplet geometry is controlled by five input parameters; the angle of rotation of the proplet off a span wise line, the blend radius, the length of the proplet after the blend radius section, the sweep angle of the proplet section, and the angle of attack of the proplet. Note that the input proplet geometry does not change the overall propeller diameter which is held constant based on another input parameter.

The analysis and design tools chosen for designing this propeller each have different strengths and weaknesses. For the 2D airfoil analysis, XFOIL was chosen. XFOIL is a panel code that computes the performance of airfoils including viscous effects. Although it works best at higher Reynolds number, airfoils that are not too thick can converge at low Reynolds numbers and the solution is trustworthy providing convergence and a reasonable pressure distribution.

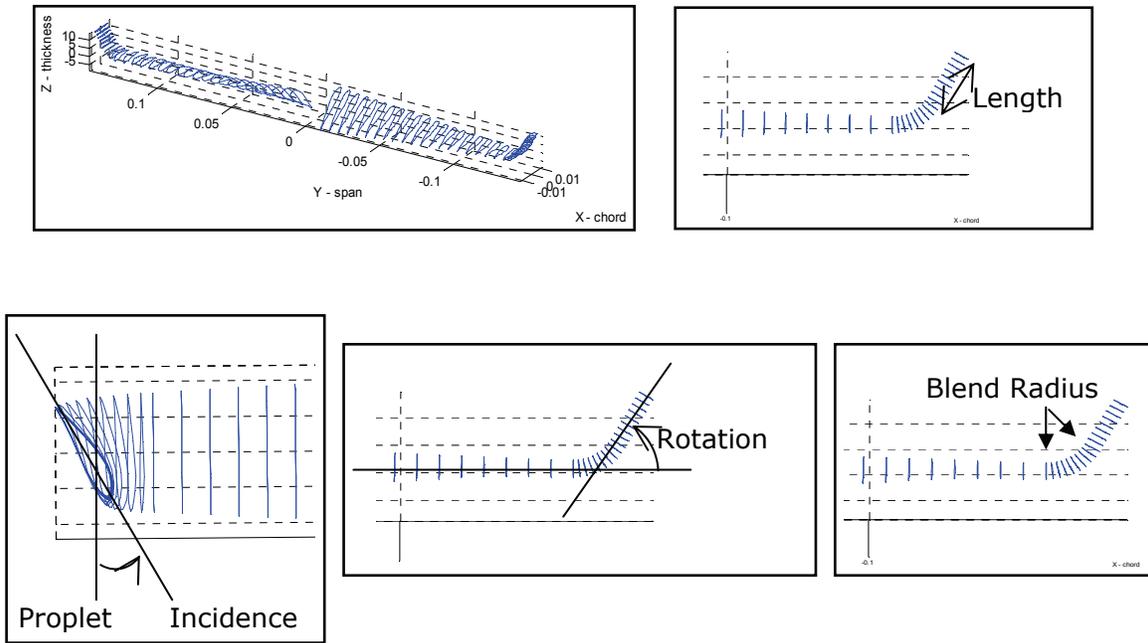


Figure 13: Propeller Geometry Specification

For the 3D analysis of the propeller aerodynamics two programs were used. The first was a Fortran code called gold.f that uses the Goldstein method to analyze propeller performance. This code was developed by Prof. J. P. Sullivan. The Goldstein method includes viscous effects by including the drag of each airfoil section in its computations. It does not however fully simulate the full viscous effects or the effects of separation. The Goldstein code takes in blade geometry and uses a matrix of influence coefficients to compute the effects of each blade on the others. This method has proven to be very accurate for standard propeller performance in the past although it does not compute the full blade pressure distribution.

The limiting factor in using the Goldstein method is that it does not allow for the use of out of plane blade geometry like a proplet. To analyze the effect of proplets two possible routes were explored. The first method attempted was to create a vortex lattice code that would use a system of bounded vortices to emulate the blade and wake acting on a set of control points on the blade surface. Although this code is partially functional it was decided not to continue debugging and testing it because of the time considerations for this project. In place of the vortex lattice code, a CMARC model of the blade was developed by modifying the model used in the original 415 proplet project.

CMARC is a 3D panel code that uses panels covering the surface of the blade with a bounded vortex around and a control point at the center of each panel. CMARC does not include the viscous effects that are important to this design, but does allow for out of plane geometry. CMARC also computes the influence of the blade panels on the wake panels which are flexible. Unlike the vortex lattice code, the wake is not simply shed with the free stream and rotation of the propeller, but the velocities induced by the blade determine where the wake goes. This allows for more accurate computations. Figure 14 below shows the CMARC model of the propeller blade and Figure 15 shows the wake geometry determined by CMARC. Using CMARC was useful in understanding the performance of proplets, but in order to use it as intended by the initial software design, the generation must be automated. CMARC input files are very sensitive to changes, especially concerning the wake. If the wake is not properly defined, it will either hit itself or the solid geometry. In either case CMARC may or may not converge but the solution is not correct. This and

other complications led to the inability to use CMARC in the full automation of the propeller design.

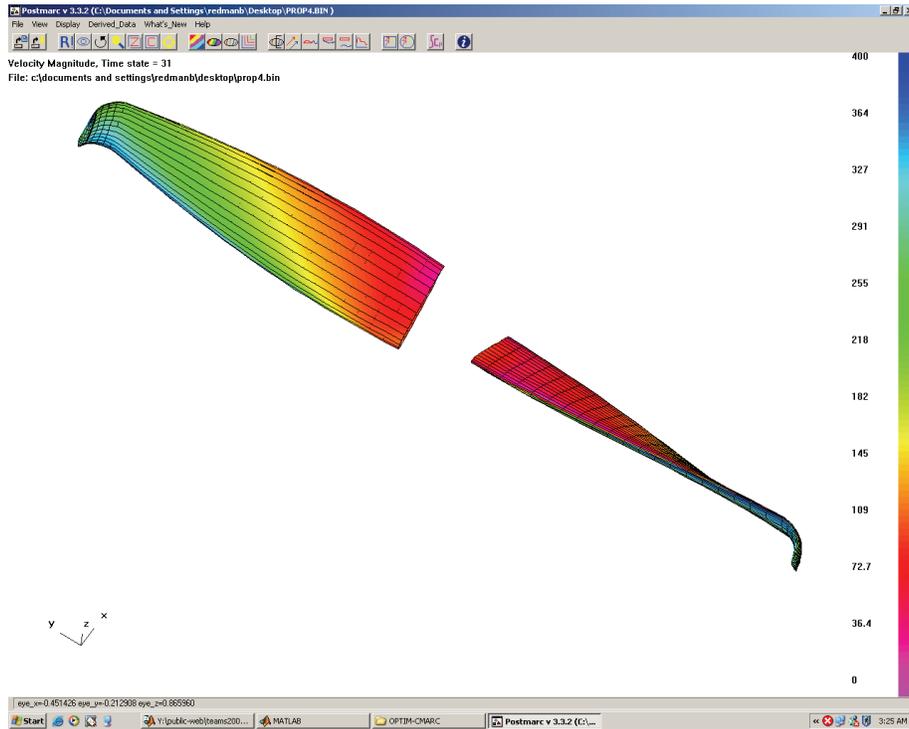


Figure 14: Cmarc Propeller Model

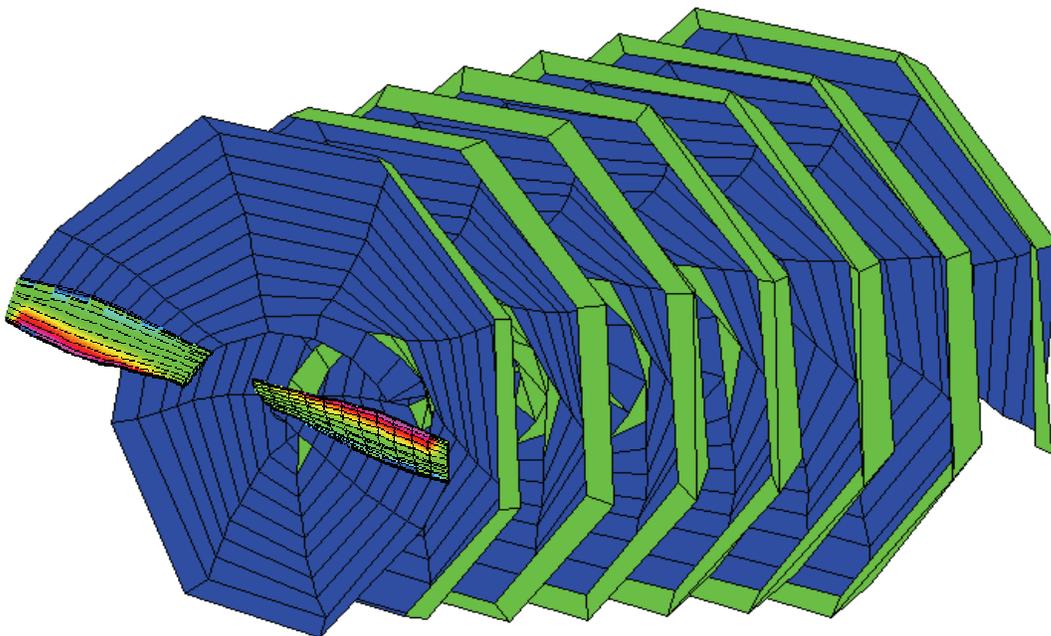


Figure 15: CMARC wake model

Airfoil selection is an important part of the design of a propeller. As stated above, XFOIL was used to analyze the 2D blade geometry. The airfoils selected for testing came from the UIUC airfoil database and are Eppler airfoils designed specifically for propellers. The challenge in testing these airfoils is the low Reynolds number at which they will operate. The size and relatively low speed of the propeller blade make the Reynolds number of the airfoils typically less than 100,000. At this Reynolds number XFOIL does not converge easily. Eight different airfoils were initially tested of which the E222 and E224 were chosen as final candidates. The E222 has the best performance but the trailing edge is significantly thinner than the E224 which could prove difficult in manufacturing. Because of this the E224 was chosen as the primary airfoil for the propeller. In the final design this airfoil occurs over most of the blade but is stretched in thickness somewhat near the hub for structural considerations. Figure 17 shows the L/D of these airfoils vs angle of attack. Many of the airfoils would not converge at angles over 2-3 degrees because of their thickness and the low Reynolds number.

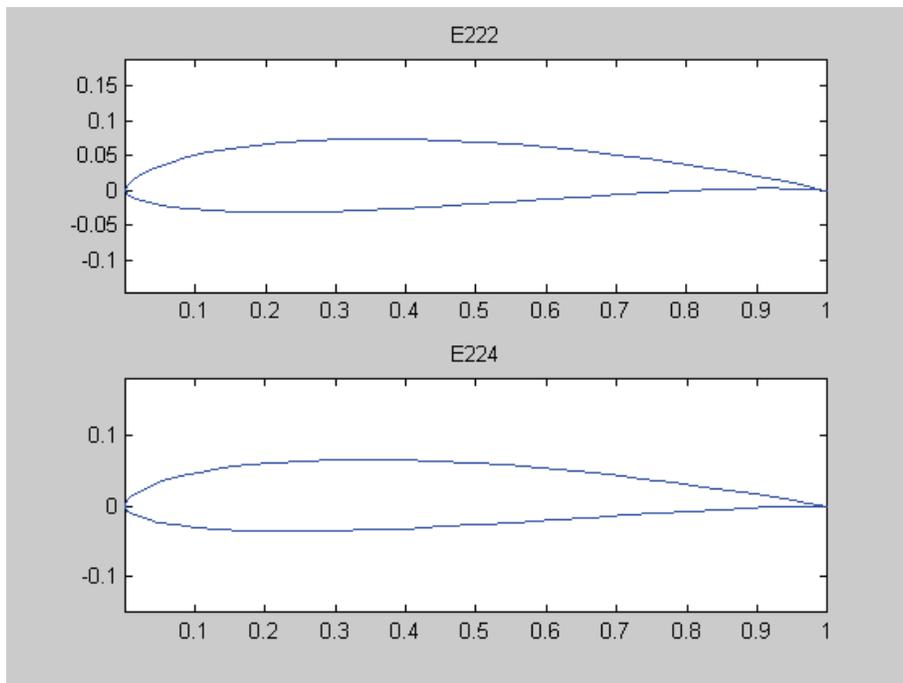


Figure 16: Eppler Airfoil Sections

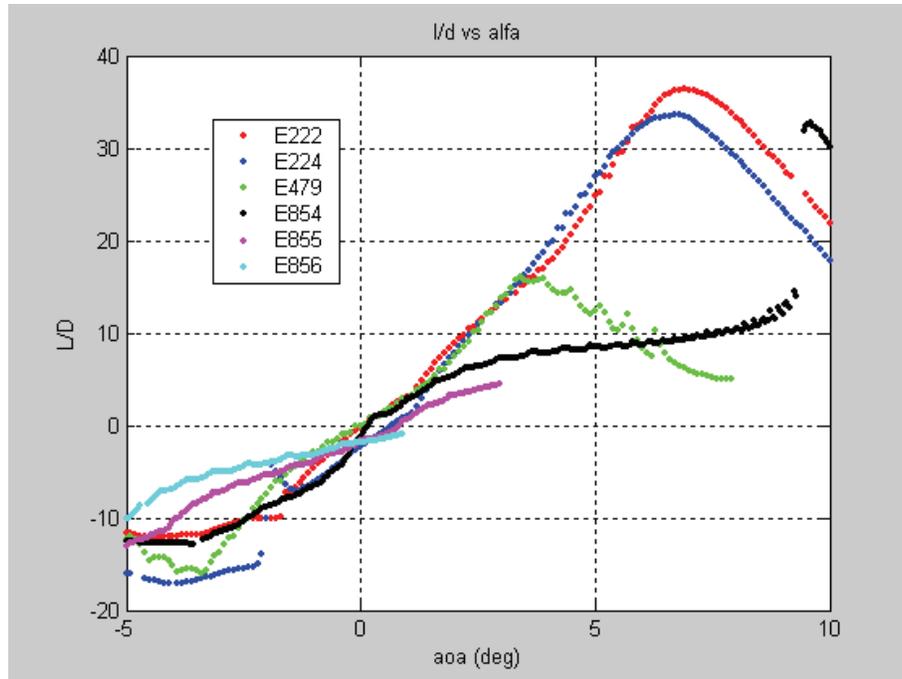


Figure 17: Eppler Airfoil Performance

As seen in the software flowcharts, this suite requires the ability to integrate multiple software packages. The suite is based in MATLAB but requires the creation of text files, execution of a Microsoft DOS program, reading text files from the system disk, and deleting files from the system disk all from within MATLAB. Since CMARC is a Microsoft DOS program, the optimization routine could not be run on a computational server. Limiting computational resources to a single personal computer to run the entire optimization greatly increased the time required to run the optimization code.

The goal of optimization is to minimize the value of the objective function such that a given set of constraints are not violated. For the propeller design the objective was to maximize the efficiency. The objective was easily converted to the proper form by multiplying the efficiency result by negative one. A method of multi-objective optimization was implemented; efficiency in different performance ranges were weighted and combined to form the returned efficiency.

Some common problems with design optimization are: the time required to run the optimization, integrating various pieces of analysis software, and a multi-modal design space. The time issue is fairly obvious; some analysis required to evaluate the fitness of a design can be complex and takes considerable amounts of time by itself and optimization seeks to repeat the analysis numerous times. Fortunately the analysis software for the propeller was designed to be easily integrated with optimization; this would not be a factor. For the design of the propeller it was almost certain that there would be a multi-modal design space. The problem with such a design space is that an optimization routine can become trapped in a local minimum point that is less than optimal.

Several optimization techniques were available for this design; the two most suitable methods were Sequential Quadratic Programming and the Genetic Algorithm. The Genetic Algorithm is actually a pseudo optimization technique, but is well suited to complex problems as it does not use gradients of the objective function and is, theoretically, immune to local minimum points. In the Genetic Algorithm various design variables are assigned

"genes" that consist of a series of zeros and ones to represent possible values for that variable; all variables are combined to form a chromosome. Through a series of evaluations of various chromosomes the best designs are given preference as new generations are formed from combinations of chromosomes in the current generation; there is some allowance for mutation. In this way the design is evolved using the principle of natural selection. In theory this results in a "good" solution, but it cannot be proven to be truly optimal. Since the Genetic Algorithm evaluates such large number of possible design points in each generation (proportional to the number of design variables), computation time is usually very large. Parallel computing can easily be applied to reduce this, but because of the lack of such computer resources, limited time, and the time needed to implement the genetic algorithm it was decided that Sequential Quadratic Programming (SQP) would be the best choice for optimization. There was also some concern about using the Genetic Algorithm because constraints on the design, such as minimum thrust, could only be included as a soft penalty on the design; it would have been relatively easy to violate the constraint.

In SQP the objective function and its gradient are evaluated at a given point. Exact gradients can be used when available, but for the purposes of designing the propeller the numerical gradients were used. With the function and gradient information at a particular point a quadratic approximation of the system at that point can be formed; constraints at this point are approximated as linear functions. The approximated system is easily optimized using simple techniques. The new point chosen as the optimum is used to generate a new approximation and the process is repeated. When the optimum value returned from these approximations converges to a single value within predefined tolerance levels the optimum value is returned. Unlike the Genetic Algorithm, there is no way to escape from local minimums with SQP, therefore choosing a good initial design is important. The validity of an optimal solution can be verified by checking to see if the optimum converges to the same point for several initial designs.

Using MATLAB it was relatively easy to implement an SQP algorithm; the function FMINCON included as part of the Optimization Toolbox performs the optimization when it is given: the objective function, upper and lower variable bounds, linear constraints, and a function with any nonlinear constraints on the optimization. The objective function took the design variables as described and invoked the geometry generation program to create the desired blade. This geometry was then exported to a CMARC input file and CMARC was executed to analyze it. A root mean squared averaging of the efficiency at several advance ratios was imported back into the MATLAB script and multiplied by negative one before being returned as the result of the objective function. The only constraint besides the variable bounds on the optimization was that there be a minimum amount of thrust at a specified RPM; this was evaluated by CMARC and was returned in the constraint function for FIMINCON.

When the optimization routine was executed it appeared that the design space was very multi-modal. Regardless of the initial design point it would only run for a short time and move very little from the initial point; a single optimum, or near optimum could not be determined. Because of this complication a different approach was used to come up with a final propeller design. The first step in this new method was to perform a trade study on the effects of each of the proplet design variables. This analysis was performed using CMARC and took about 37 hours to complete. Figure 34 through Figure 37 in the Appendix show the results of the trade study varying the rotation angle, radius of curvature (on inner and outer surfaces), length, and angle of incidence. The trade studies show that the proplet is most effective at increasing thrust when it is perpendicular to the blade; this is logical since this allows for the longest possible blade. Small radii of curvature on the inner and outer surfaces were the most effective. Longer proplets had a positive effect on the thrust,

but also had negative ramifications on efficiency and they were kept small. A small negative angle of incidence was found to be beneficial.

The data from these trade studies were used to generate a quadratic response surface; the minimum point on this response surface was used for the proplet design. A full optimization could be completed using a similar method, repeating with a new response surface generated around the chosen point. However, this approximate method of optimization is extremely time consuming and would have required several days to generate the number of sample points to do it properly for even one step. Optimizing this one response surface was an adequate approximation for the design of this propeller.

Tools that required less processing time than CMARC were available to evaluate the performance of the propeller blade if no proplets were present. Using a Goldstein analysis method to evaluate the effectiveness, SQP was used to optimize the blade chord and pitch distributions without the presence of the proplets. Optimization took about 20 hours and evaluated approximately 200,000 different blade configurations. The final propeller took the designed proplets and combined them with the optimized blade. It was known that this would not yield the optimum result as the interactions between the blade and the proplets would affect the design of both, but it did provide a good starting point for the full optimization routine. As in previous cases, however, the SQP optimizer did not move significantly from the initial design and it is unlikely that the design is truly optimal.

Final Design Outcome

The final geometry of the proplet propeller is very similar to most RC aircraft propellers with one exception. Because it is made to operate at low advance ratios, the chord of the final propeller blade is much larger than a standard propeller. This allows the same thrust to be produced but at a lower pitch, keeping the blade airfoil sections near to the angle of attack where they have the greatest L/D. By maximizing the L/D of these airfoil sections, the performance can be greatly increased. In Figure 18 the final propeller geometry is shown. Figure 19 and Figure 20 plot the chord and twist distribution of each propeller blade. This design does not include the hub detail which was added in the Catia model rather than the geometry generation program.

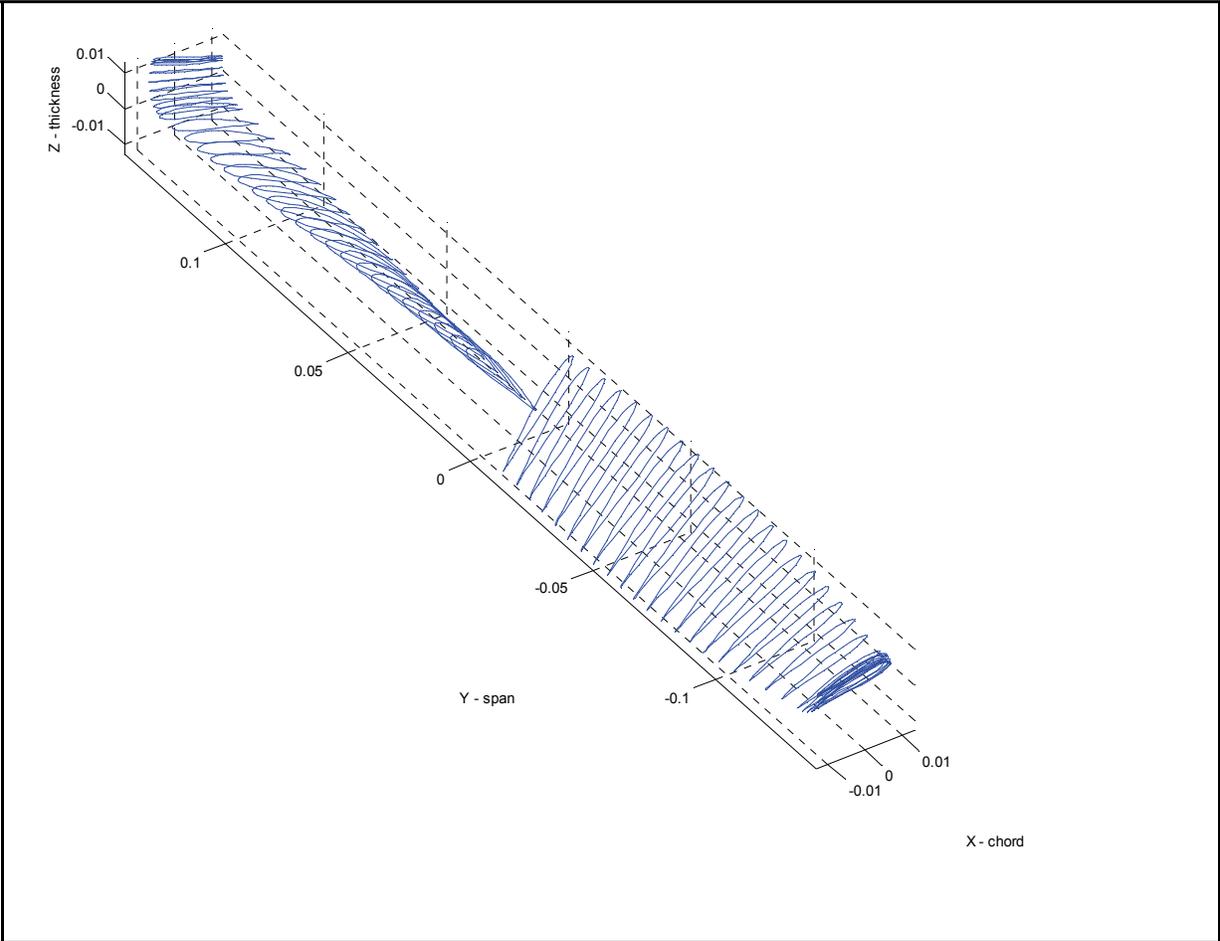


Figure 18: Final Propeller Design

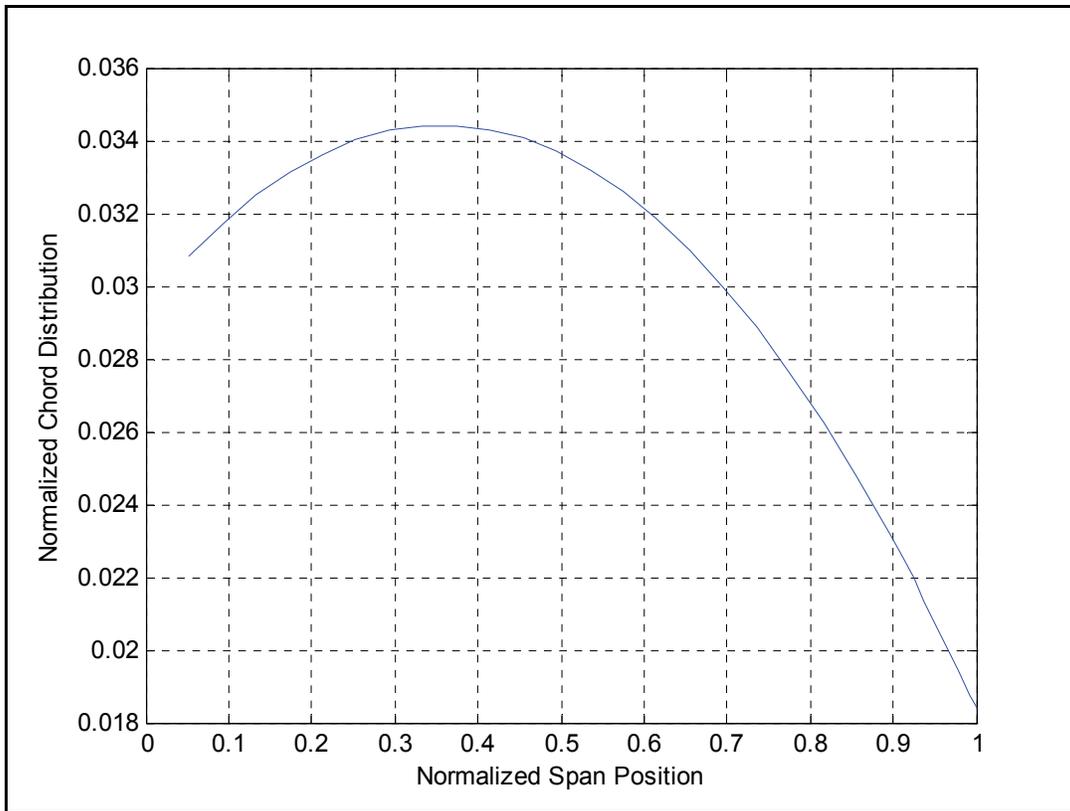


Figure 19: Final Propeller Design Chord Distribution

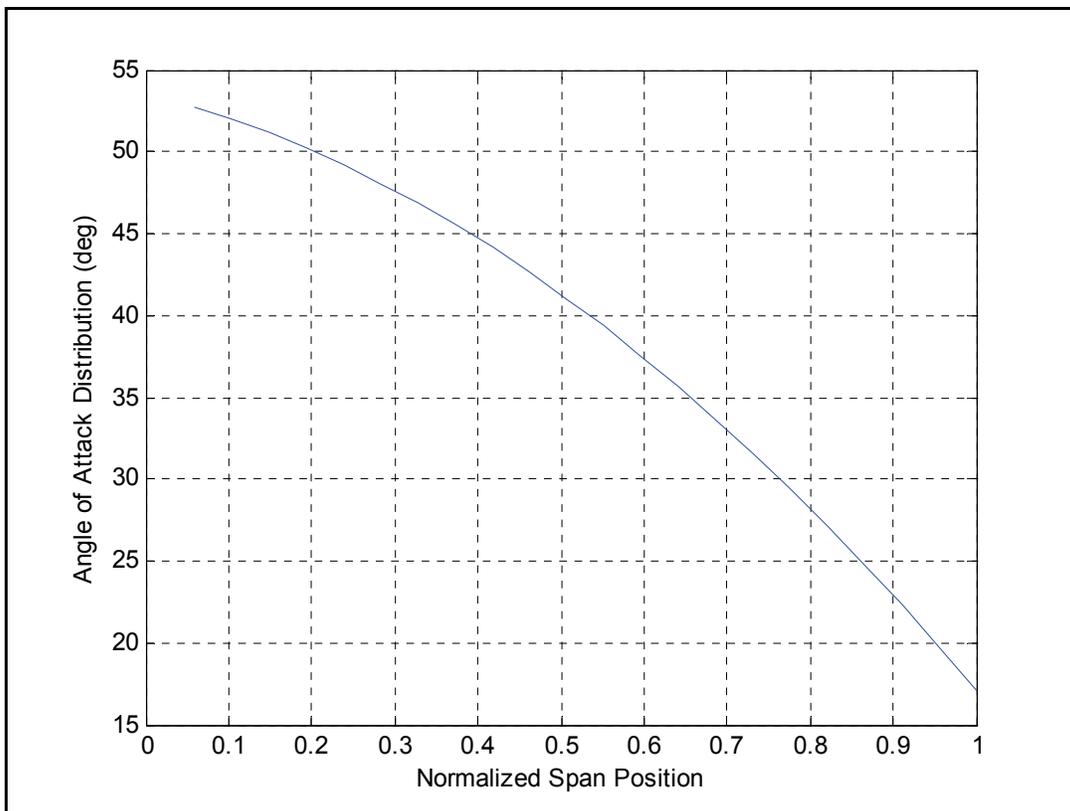


Figure 20: Final Propeller Design Angle of Attack Distribution

Construction Detail

The ultimate goal of the proplet propeller project was not only to design and fabricate a more efficient propeller utilizing the aerodynamic benefits that proplets provide for a set diameter, but also to create a fabrication process that was easily repeatable; providing a good product and one that would remain consistent with each fabrication. Though a composite propeller was the original proposal, there are a large number of complications involved in the construction of one regardless of the molding method to be used. The first proposal was to design and CNC a four part mold from acrylic in which to lay-up both halves of the composite blades and hub as one piece. The danger of such a design was in the complete accuracy required to mechanically fasten the mold pieces together as the propeller would have a very thin geometry that would be difficult to maintain. Also much design time as well as valuable CNC time would be lost if the mold failed to work properly or if the release failed, and the part was permanently fused to the mold.

It then became apparent that injection molding a plastic propeller would be the best option since it was without doubt the most repeatable and simple fabrication process. Plastic had also proven itself to be structurally sufficient with a number of propellers of the same scale already on the market. The downfall of injection molding however would be the cost of the plastic as well as the great expense of building the mold, which would need to be aluminum and contain a number of electric heating elements placed precisely to assure an even heat distribution in and out of the oven. These costs would have far exceeded the project budget.

The only option remaining was to manufacture a propeller to use as a plug to create a flexible mold in which the composite propeller could be made. This method had many drawbacks as well. The plug could not be made by SLA fabrication as one team already had Mechanical Engineering's time invested in their project. The plug would need to be machined. Both the geometry and materials used would pose problems in machining a plug as will be discussed later. Other complications included the surface smoothness of the plug, finding an affordable option for molding material, creating a mold without bubbles on the blade surface, and laying up a complicated and very thin composite propeller. Upon considering these complications it became apparent that much focus should be devoted to simplifying the construction methods as much as possible.

One of the main design considerations for building a composite propeller was the molding method and molding material to be used. In order to create a mold capable of producing a number of propellers, it would need to be durable and most importantly there would need to be assurance that the plug lay-up would not adhere to and ruin the mold. A material capable of maintaining a complex geometry under the pressure required to keep the mold halves seated together, as well as being flexible enough to aid in releasing itself from that geometry would be required. Past projects by Professor Sullivan and his class utilized a liquid silicone rubber molding compound for this very purpose. It was reasonably rigid yet flexible and could release from most any material without the use of a mold release agent. This would have been ideal since the surface quality of our blades would have a great impact on the propeller's efficiency. All that would be required is a smooth, nearly mirror-like finish on our plug and that surface would be recreated in the mold rather than picking up roughness which cannot be avoided with the use of a mold release. These surface imperfections though small are quite important since the scale of the propeller is also small. This would mean that while the imperfections may be small to the eye, they would seem quite large with respect to the propeller blades and the airflow over them. This silicone rubber, made by Dow Corning, is called Silastic. After finding several suppliers it became

obvious that the amount needed was too small to be purchased without nearly doubling the cost with the addition of a small-order fee. Ultimately another silicone rubber compound called Hobby Mold, made by the Hobby Craft Company, was chosen for its immediate availability, material qualities comparable to Silastic, and it could be purchased in a useful amount that would not exceed the budget. These silicone rubber materials consisted of a white rubber and a blue activator which are to be mixed 10:1 by weight in order to harden properly.

Once the material had been decided on, the molding method was the next construction priority. The method most commonly used in the past with rigid molds was to CNC both halves of the mold so that they would always bolt or pin together in the same way. With rubber molds, two halves of a box would be machined and one half of the mold would be poured into one box half at a time. The two rigid box halves would also pin or bolt together for the composite curing. The main downfall of this method was that much time was still required to determine the propeller geometry. Even the overall diameter was not yet known and some construction needed to get under way to prevent a serious time crunch later on. This proved to be good planning as the plug CNC process suffered several setbacks as will be discussed later on.

The design that was decided upon allowed for flexibility once the propeller design would be finished. An aluminum basin, shown in Figure 21, was built to serve as the pouring container for both the top and bottom halves of the mold. It would require no top so that the propeller could be suspended for the first pour and could be easily adjusted if necessary. The release of the mold from this basin would be accomplished by the smooth aluminum walls and the design of the walls themselves. The floor of the mold basin was riveted with countersunk rivets to one side of a 3.5 inch aluminum 'L-channel' which also provided one wall of the pour basin. A second wall enclosed the other long side and was rolled to enclose one short side of the basin before attaching to the 'L-channel' wall. Lastly the other short-side wall was essentially rolled to a 'U' shape and would attach to both the 'L-channel' wall and the other long wall. These attachments were provided by nut-plates which are a common fastener used for aircraft access panels on the external wings and fuselage. They are riveted to the backside of a machine screw hole and their threaded portion is free to move a small amount in a bracket. This allows the walls to screw together and be moved around in order to minimize the cracks between the walls and floor of the mold before tightening them down. The mold basin walls were designed this way for two reasons. First, such a deep mold would require removable walls in order to remove the rubber mold after the second pour was made. Also since the mold was designed with excessive length, the 'U' shaped wall could be brought in once the final diameter of the propeller with proplets was known. All that would be required is to drill new screw holes in the two long basin walls since the nut-plates were part of the 'U' shaped wall.

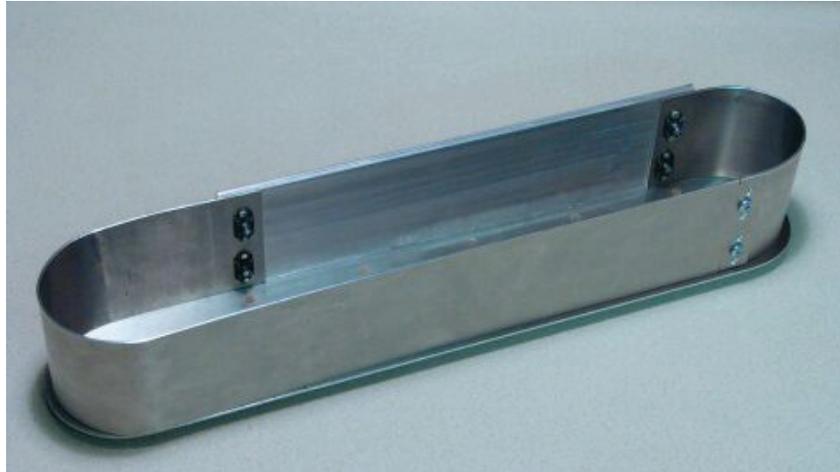


Figure 21: Mold Basin

In order to create the silicon rubber mold for fabricating a solid composite propeller a plug was made in the exact shape of the final design. In considering how to make this plug and what materials to choose there were several considerations. The timeliness of the method was important because the entire construction process would be paused while the plug was made. The surface quality of the final plug was also very important because the surface would translate directly to the mold and final propeller. Imperfections in the plug geometry and surface would be present in the final propeller as well. Lastly, the cost of the method was important.

The possible methods of creating the plug included injection molding, LDR through mechanical engineering technology, or cutting on a CNC router. The decision was made to cut the plug on the ASL 5-axis CNC machine because injection molding was too time consuming and expensive and LDR proved to be too expensive for the remaining project budget.

In order to CNC the plug a material had to be chosen that would cut quickly, be relatively inexpensive, possess good surface quality after cutting, and be hard enough to be rigid even when cut very thin. The materials considered for the plug were medium density fiber board available from a hardware store, acrylic stock that was available from the plastic scrap area at ASL, and aluminum purchased from the Purdue central machine shop. The MDF was decidedly too soft for so thin a cut and the surface quality would not be good enough without considerable hand work after cutting. The aluminum was thought to be an option so the stock was purchased with the intent of attempting first on the acrylic and using the aluminum if the acrylic didn't work. When the first attempts to cut the plug from acrylic stock were made the surface quality after cutting was excellent and it was decided to use the acrylic because it could be cut much faster than the aluminum.

To cut the plug tool paths were generated using Surfcam® which imported the geometry of the blades from the Catia model using a universal IGES file format. The cutting technique was to cut the top side of the propeller including the inside of the proplet surface but to leave the hub and the proplet tips attached to the stock. These attachments would stabilize the propeller while the second side of the blade was cut. The first cut was a z-rough cut that spiraled through the material leaving only 0.03 inches of material on the final blade surface. This cut took approximately 30 minutes. The final surface of the blade was cut

using a planar cut and a lubricant for cutting aluminum was applied to the surface to prevent micro-chipping on the final surface.

Because of the thin blade geometry it was decided to use foam to fill the first cut while cutting the second side. The foam chosen to fill this space and support the blade was Great Stuff® expanding foam. This foam could be sprayed into the gap, would adhere desired surfaces, and would harden in several hours. Once dry the extra foam was trimmed off and the second cut commenced. The second cut followed the same procedure as the first with a rough cut removing most of the material and a planar cut finishing the blade surface. The outside surfaces of the proplets were then cut using another rough and planar set. When the CNC job was done the propeller was done with the exception of trimming it from the stock acrylic at the hub and proplets and lightly sanding the surface.

During this process there were several challenges that introduced delays in the plug fabrication. The first is that the stock acrylic was not uniformly thick as was assumed, causing one propeller to have blades that varied significantly in thickness. Another obstacle was the fact that the expanding foam took several hours to fully harden. This prevented the entire cutting process from taking place at one time. Re-zeroing the CNC machine on such a small part has inherent errors. The geometry also posed a challenge as the acrylic would chip at the trailing edge because the material was so thin.

After several damaged plugs were cut, adjustments were made to the mounting of the stock, cut speeds and step sizes, zeroing techniques for the CNC machine; these problems were for the most part eliminated resulting in a plug that had a smooth surface and geometry very close to the designed geometry from the Catia® model. It was decided that this plug would be used to make the mold.

Prior to pouring the mold, a test of the material was done using one end of a first-spiral wooden propeller with proplets. The materials were weighed out on a pan scale and mixed 10:1 by weight as required. The result was disheartening as the material was very compressible and easily deformed. It would not have been suited for making the mold this project required. Since a scale was not available over the range of time needed, that could accurately weigh a few pounds of material at a time, a gram scale was used to weigh 20mg of each material to compute the densities of both the base and the activator. These densities were used to calculate the needed volume of activator per a known volume of total mold material in order to still mix them 10:1 by weight. This method provided a significantly improved product once the mold was made.



Figure 22: Propeller Hangers

Pouring the mold was simple but required a lot of hand work. First the propeller was suspended, proplets down, the needed distance from the basin bottom. The prop hangers used were taped to the back blade face and hung from small 'L-beams' that were supported by the basin walls, one hanger for each blade. Also a hole in each 'L-beam' supported one steel pin coated with petroleum release agent. These pins would assure that the mold halves would always go together properly and not slide off of each other if that was also a possibility. This setup is illustrated in Figure 22. Another tapered paper-wound pin was coated with release and installed in the center hub mounting hole. This pin ensured that no rubber would enter this hole and it would also be maintained with this pin during the composites lay-up. The first pour came up to the top of the hub in order to cover the entire top blade surface. Once that material had hardened, it was removed from the basin. Then great care and much time was taken to cut away the rubber at each short side in order to expose only one surface of the proplets and then further pieces were cut away until only the back face of the propeller and hub were exposed. Some walls were left around the hub so that composites could be more easily layered up there, and a small ridge was left at the trailing (lower) edge of each blade so that it could be seen where the blade stopped for the composite lay-up. This also minimized the vertical surfaces that would need to mate up once the mold top was put on. Most difficult in this process was cutting the flexible rubber which deformed some before it would cut. This was especially true at the leading edge of each blade. The material had to be cut to the very edge of the blade and not under it, as doing so would create a large ridge or nub on the leading edge of the composite blade. Next, petroleum release was applied to the pins and the entire mold bottom, as the material will stick to itself. Then the mold bottom along with the plug (which was never removed from the mold bottom and had its entire back surface exposed) was placed again into the basin with all three pins installed for the second pour. A photo of the setup prior to the second pour can be seen in Figure 23. This pour was straightforward and created the other half of the mold.



Figure 23: First Mold Pour

There was one problem with pouring the mold that wasn't mentioned above so the process could be more easily read and understood. Along with resizing the basin to minimize the amount material needed for the mold; high density foam was cut into two flat pieces that would be placed under the blades for the first pour just inside the proplets. This would further reduce the amount of material required. Holes were put into the top-surface of this foam and an undercut at the bottom so the foam would remain attached inside the bottom

half of the mold. Since the foam would be quite buoyant in the rubber compound it was taped and glued to the mold basin floor. This would prevent the foam from floating the propeller plug out of the mold, introducing many air bubbles into the system, and contacting the plug blades ruining the surface of them in the mold. Though much care was taken, the foam proved to be too buoyant and floated loose to cause the issues listed above. Hours were spent saving the process and painstakingly removing the bubbles from the material after the foam was removed. Ultimately, the blades were painted with the rubber, allowing the bubbles to rise to the surface to be popped. The suspended plug and rig was then placed back into the basin, resulting an excellent, bubble-free surface once the mold had hardened.

Choosing the composite materials for the propellers and the lay-up process was relatively easy since no rigid structural requirements needed to be met. The main concerns included surface smoothness of the blades, bending rigidity primarily at the centripetally loaded proplets, weight of the propeller which would greatly affect dynamic efficiency, impact resistance, and ease of lay-up. As can be seen in Figure 24, the carbon or graphite composite is stronger and more rigid than the fiberglass by a factor of 25 on average, making it the best option for strength. However carbon fiber also has pour impact resistance and is susceptible to delamination upon impact. This can be seen in Figure 25. S-glass is the best option for impact resistance that is also easy enough to cut as well as trim after the composite has cured. One main focus of the selection process was to determine what materials were readily available from Professor Thompson’s composite lab and other sources. A few types of S-glass weave and a carbon fiber weave were options. The carbon fiber was a thick mat satin weave that didn’t seem too suited for laying up inside a thin geometry. It would be difficult to cut into blade shapes or tapering strips and would easily deform and fall apart once cut. One S-glass fabric had a very small plain weave which had been used by construction before with great success as it is easy to cut into shapes and would give the best possible surface to the blades.

	Graphite Composite (aerospace grade)	Graphite Composite (commercial grade)	Fiberglass Composite
Cost \$/LB	\$20-\$250+	\$5-\$20	\$1.50-\$3.00
Strength (psi)	90,000-200,000	50,000-90,000	20,000-35,000
Stiffness (psi)	$10 \times 10^6 - 50 \times 10^6$	$8 \times 10^6 - 10 \times 10^6$	$1 \times 10^6 - 1.5 \times 10^6$
Density (lb/in³)	.050	.050	.055
Specific Strength	$1.8 \times 10^6 - 4 \times 10^6$	$1 \times 10^6 - 1.8 \times 10^6$	363,640 - 636,360
Specific Stiffness	$200 \times 10^6 - 1,000 \times 10^6$	$160 \times 10^6 - 200 \times 10^6$	$18 \times 10^6 - 27 \times 10^6$
CTE (in/in-F)	$-1 \times 10^{-6} - 1 \times 10^{-6}$	$1 \times 10^{-6} - 2 \times 10^{-6}$	$6 \times 10^{-6} - 8 \times 10^{-6}$

Figure 24: Composite Properties

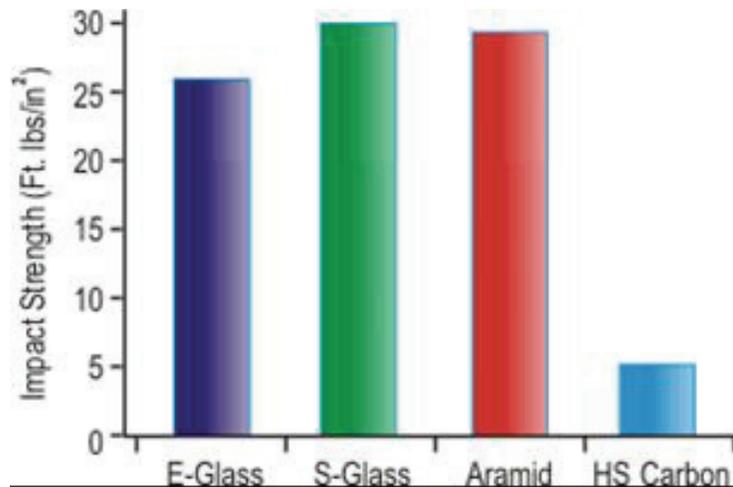


Figure 25: Composite Impact Resistance

The best method was to use a hybrid lay-up to obtain the benefits of both materials. The S-glass on the outer surfaces would provide both impact resistance and surface smoothness. It would be cut into blade shapes extending into the hub, three layers on each side of the blade, with 0°-45°-0° orientation with respect to the blade span. Each half of the mold had the fiberglass laid into it and carbon fiber strand would fill the bulk of the blade span-wise and be laid up entirely in the bottom half of the mold. The carbon fiber would serve to minimize weight while maximizing strength and rigidity in the primary direction of loading. For the first propeller, the hub was mostly filled with fiberglass with the exception of some carbon strand that ran the entire length of the propeller through the hub. The second lay-up was simplified as the carbon mat was cut to fit the blades in a few layers with success. To lighten the propeller, carbon fiber was also used to fill the hub. After the lay-up was completed, an excess of resin was poured inside the bottom half of the mold, and the top of the mold was put on with the two locating pins installed, and weights were added to the top of the mold assembly. The excess resin would then be free to bleed out of the sides of the mold. Once the blades were removed from the mold they needed to be trimmed up and balanced. Lastly, paint or clear-coat was used to improve the surface quality further. After each of the propeller prototypes were tested, the prototypes were cut off of one propeller and it was balanced to create our reference propeller. Pictures of the lay-up process and the final propellers are in the Appendix, Figure 40 through Figure 47.

Test Detail

Three testing methods were utilized during the course of this project. Static, dynamic, and structural stability tests were completed on the propellers to determine the general performance.

In spiral one, all three tests were completed. This was the sole application of the structural stability test, to ensure safe operation in the High Contraction Wind Tunnel. Spirals two and three contained static and dynamic tests of the propellers shown in Figure 26.

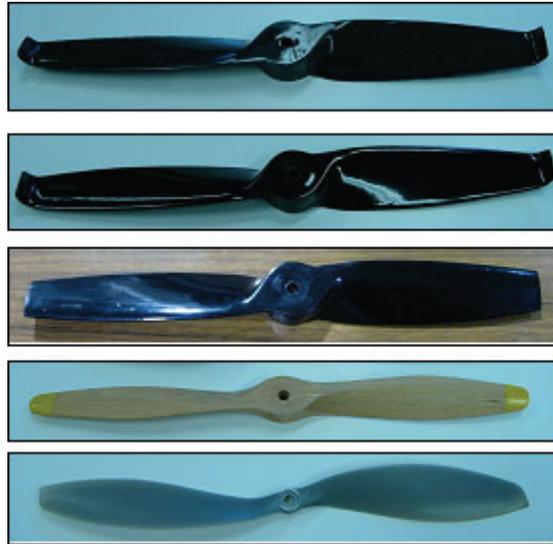


Figure 26: Spiral 3 Propellers

To obtain a quantitative measure of propeller performance, a number of parameters were determined. Dynamic tests required the measure of incident wind velocity, torque applied by the motor in operation, rotations per minute (RPM) of the propeller, voltage and amperage supplied to the propulsive system, and the force resultant in the plane of operation. The static tests required the measure of all the dynamic variables aside from incident wind velocity. As is clear from the propeller introduction, all of the variables are required to calculate the performance metrics of J , C_p , C_T , and η .

Data for all tests were compiled via two means, either through direct numerical or visual record. The structural stability test results were confirmed through visual means, no signs of damage were observed from operating the spiral one propeller up to several thousand RPM.

The High Contraction Wind Tunnel is outfitted with standard apparatus for aerodynamic measurement. A pitot-static tube linked to a manometer provided the necessary data to calculate incident wind velocity.



Figure 27: High Contraction Wind Tunnel Manometer

An optical tachometer was used in conjunction with a reflective tape on the surface of the propeller blade to provide tip RPM figures. The direct current (DC) power supply came fitted with gauges used for voltage and amperage measure, shown in Figure 28.



Figure 28: DC Power Supply

A force balance present on the High Contraction Wind Tunnel was used for measurement calibration and data record for static and dynamic tests. This provided thrust measurement for the propeller in operation. Other devices were used in the experiments other than direct data tools. Radio control was used to operate the motor; therefore a radio handset, radio receiver, and speed controller were used. To record the experiments a laptop computer provided a means of data recording, while digital cameras recorded events and test equipment layout.

The test stand for this propeller testing was designed and manufactured this semester as part of this project. The force balance within the High Contraction Wind Tunnel existed with a mounting fixture for airfoils used in the AAE 334 laboratory class. The existing fixture was measured, and a corresponding part was milled into the shaft of the torque cell. Thus the torque cell was mounted to the force balance, however the torque cell itself, could not be attached to the motor. Therefore a mounting block made of acrylic was milled to connect these components. The test stand within the test section may be seen in Figure 29. Furthermore, the optical tachometer was mounted down-wind of the propeller in the test section shown in Figure 30.

One of the first tasks was to create a test stand for a motor/torque cell assembly to be mounted to the force balance in the High Contraction Wind Tunnel. Initially, in order to mount the test assembly to the steel mount in Figure 42, designs were made which utilized aluminum square stock, aluminum angle or "L", and box aluminum. However, these proved unnecessary once the torque cell was obtained, as it was already mounted to an aluminum shaft, which was utilized in the final test assembly. Figure 43 shows the slight modification

being made to the shaft, comprised of two holes which were drilled, counterbored, and tapped. The larger, counterbored diameter fit over the outer diameter of the steel shafts in the tunnel, and small, threaded pins, which screwed into the aluminum shaft, fit into the inner diameter of the tunnel's steel shafts. Figure 44 shows the shaft/pin assembly mounted in the tunnel. The next piece fabricated was the acrylic adapter block, seen in Figure 45. Acrylic was chosen simply because of its availability at ASL and its rigidity. Special consideration had to be taken for thickness of the block to allow proper clearance for the motor's protruding main shaft, as well as the amount of bolt thread available in the torque cell. Since the torque cell and motor had to essentially be mounted flush to the adapter block, the holes in the adapter block were counter-bored to allow clearance for the bolt heads. The result was a compact torque cell/motor package, easily removed from the tunnel and stored. Precise machining was required to ensure minimal play between each member of the assembly in order to minimize the loss of testing accuracy. The final assembly, seen in Figure 29, slid onto the wind tunnel mount snugly with no play or looseness to speak of and allowed for precise and repeatable tests.

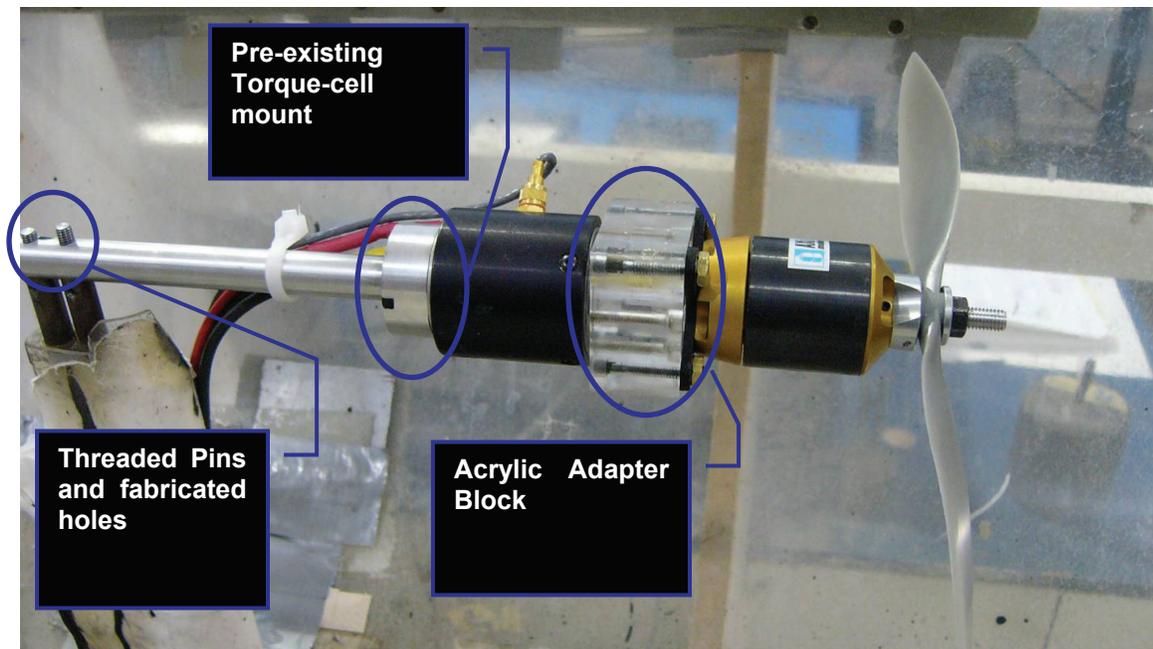


Figure 29: Test Stand



Figure 30: Optical Tachometer and Reflective Tape

Outside of the test section, wires from the respective instruments connected to digital display boxes, while power and control cables ran back to the test support equipment.

The main source of discrepancy and numerical limitation in the tests performed is the measure of amperage and voltage from the DC power supply. Since the gauge on the power supply is accurate at best to one decimal place, and amperage supplied is a critical metric of power consumption (thus performance), this was a critical limitation to the test accuracy. In spiral three the Eagle Tree Systems Electric Expander was researched as a method of increasing the power measurement accuracy but during the final testing the system failed to work properly for unknown reasons.

Test Results

The figures below show the performance data that was collected in the test of the final propellers and the reference propellers. The static test does not show that the designed propellers yield more thrust at a given RPM but this makes sense in light of the smaller C_t values at which they function. The three designed propellers perform the very close to the same statically which does not agree with the expected result that a propeller with proplets would have increased static thrust.

The dynamic plots of c_t and c_p show that the designed propellers perform at a lower c_t and c_p than the factory propellers. This is because of the designed thrust maximum of 3 lbf. The CMARC data is also plotted in the C_T and C_P plot but does not agree well with the tested result. This is due to the viscous effects that are not present in the CMARC model as well as an error that must exist in the CMARC code. This error is shown by the fact that the point of zero thrust is not the same in the CMARC data as in the actual data. Viscosity aside, these two tests should generate zero thrust at approximately the same advance ratio.

To see the performance benefit of the designed propellers the efficiency is the measure of interest. The final proplet propeller has the highest operational efficiency with advance ratio less than 0.6. This means that in the entire flight regime of the airship, this propeller will use the least energy to propel the airship with the same thrust. This is further demonstrated in plotting the efficiency vs thrust. A higher efficiency at the same thrust means you are getting the same thrust result for propulsion and control but are using less power from the batteries. This result meets the goal of the propeller design, to design a propeller that will increase flight time by increasing propulsion efficiency.

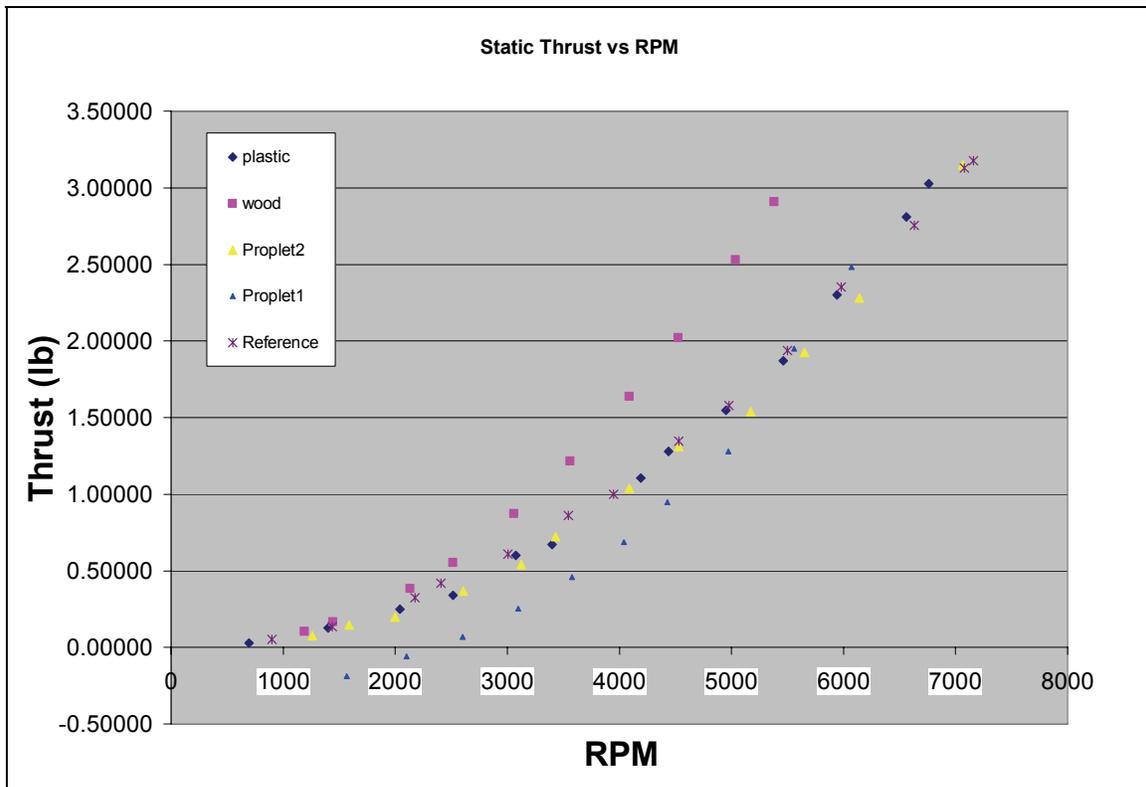


Figure 31: Static Thrust vs. RPM

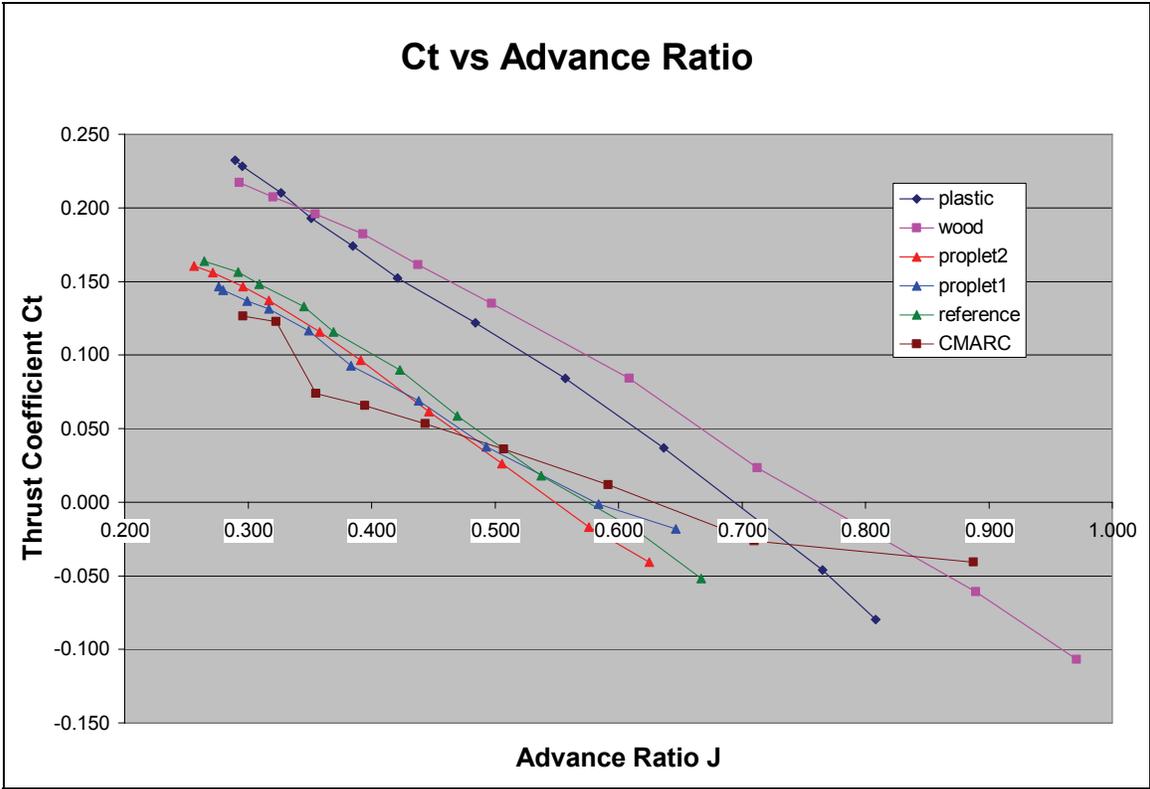


Figure 32: C_t vs. Advance Ratio

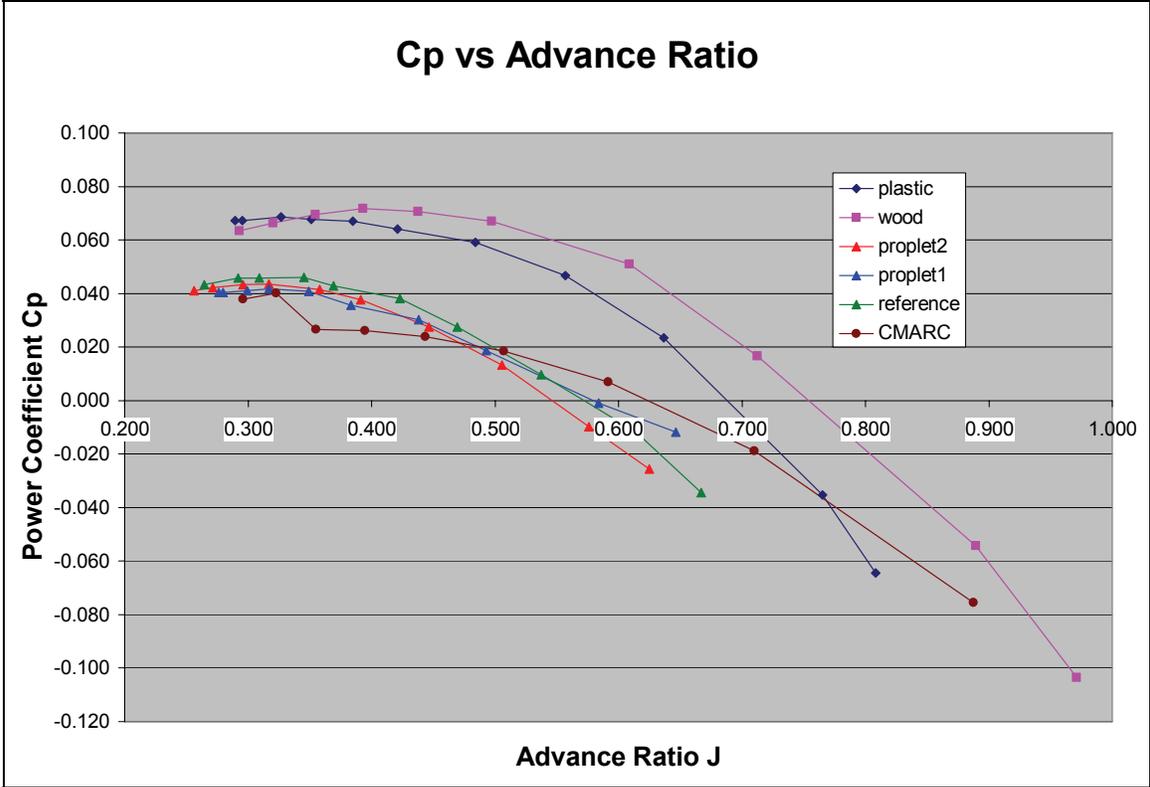


Figure 33: C_p vs. Advance Ratio

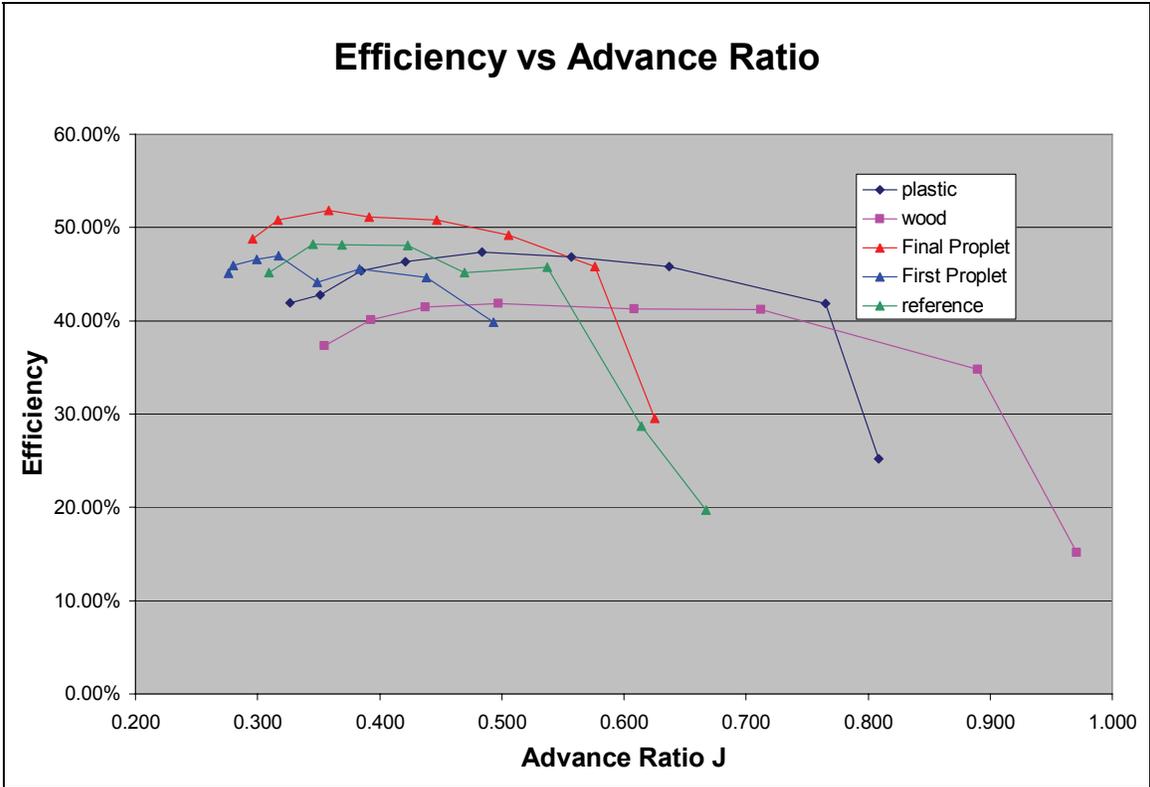


Figure 34: Efficiency vs. Advance Ratio

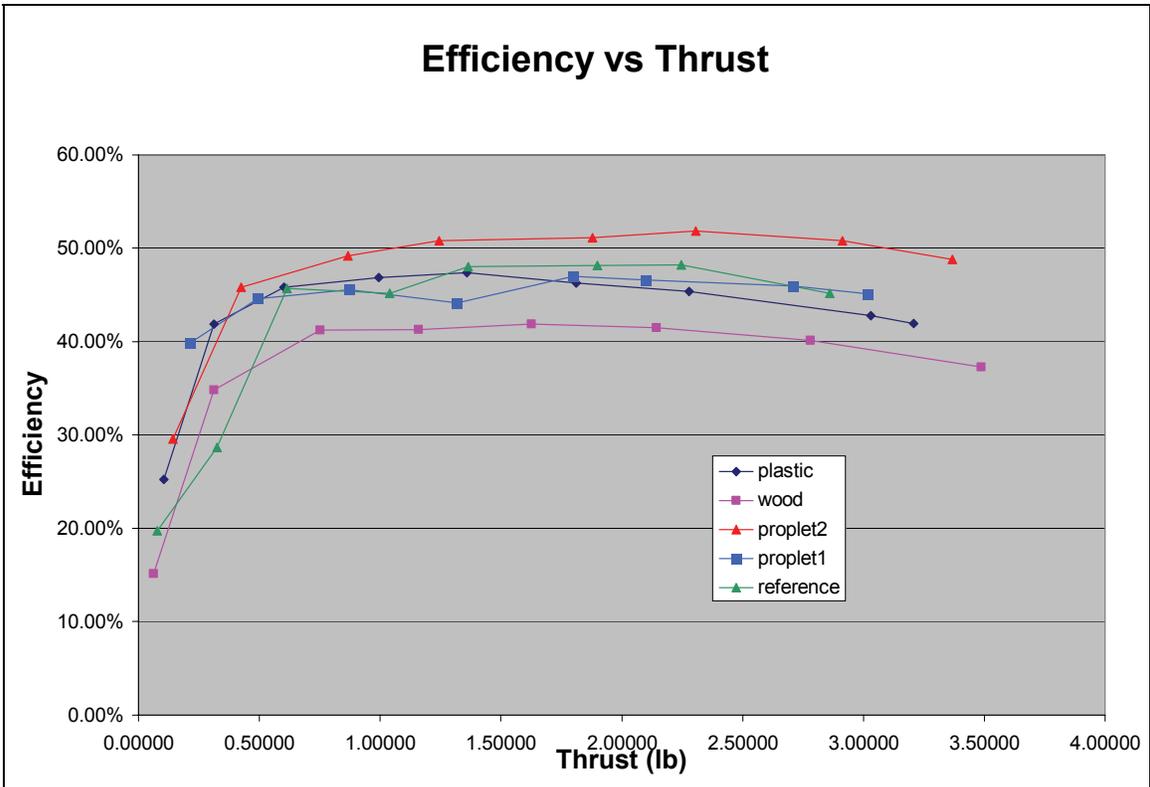


Figure 35: Efficiency vs. Thrust

Conclusions

The decoupled design optimization produced a proplet propeller with an increased efficiency for RC applications when compared to standard propeller designs. The designed propeller performed best at low advance ratios (less than 0.6). This range of advance ratios was a design consideration and was chosen based on the maximum design velocity of the High Altitude Airship (HAA) and maximum propeller rotation speed based on the motor used on the HAA. Although the designed propeller performed better with proplets, the proplets must be very thin to increase performance. A thick proplet create losses due to drag that outweigh the benefits it produces.

Initial testing showed that silicon rubber made an excellent mold material for making an RC sized composite propeller. The material proved rigid enough to hold its form under the pressure required to squeeze out extra resin but pliable enough to allow for easy release of the propeller after the composite is set up. The hybrid fiberglass and carbon fiber layup made a propeller which is stiff and impact resistant. The fiberglass also created a smooth surface finish. The main problem in the construction process was cutting a small, thin part on the CNC machine. The acrylic stock tended to chip and splinter on the thin trailing edge of the blade. To avoid this problem, an alternate plug material such as aluminum could be used.

Several measures could be taken to improve the design process. First off, a genetic algorithm would better fit this optimization problem since it has a multi-modal design space. Also, the airfoil selection and structural analysis could be integrated into the optimization. The final propeller discussed was thicker than needed to be on the safe side and avoid flexing of the proplets. Due to the strength of the composite lay-up, the hub could be thinner and of smaller diameter and remain structurally sound. Although the designed propeller performs better than commercial propellers, a more optimal solution could be found if the proplet and blade optimizations remained coupled as in the initial software flowchart. With enough computer resources and time an integrated optimization could be employed, perhaps with an aerodynamic analysis tool that includes viscous effects. This more advanced aerodynamic analysis would better simulate propeller performance.

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Appendix

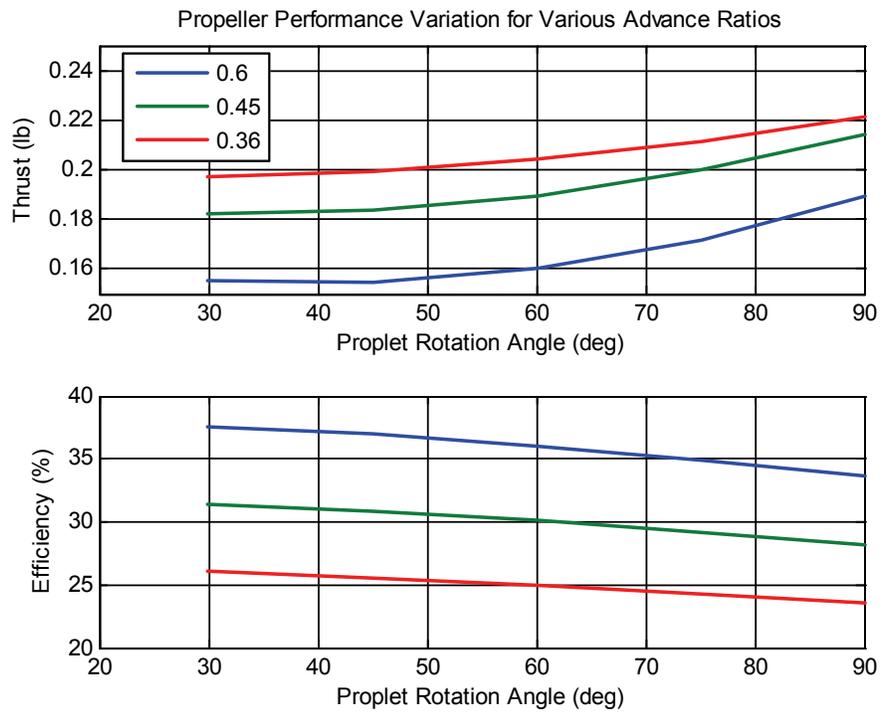


Figure 36: Propeller Trade Study

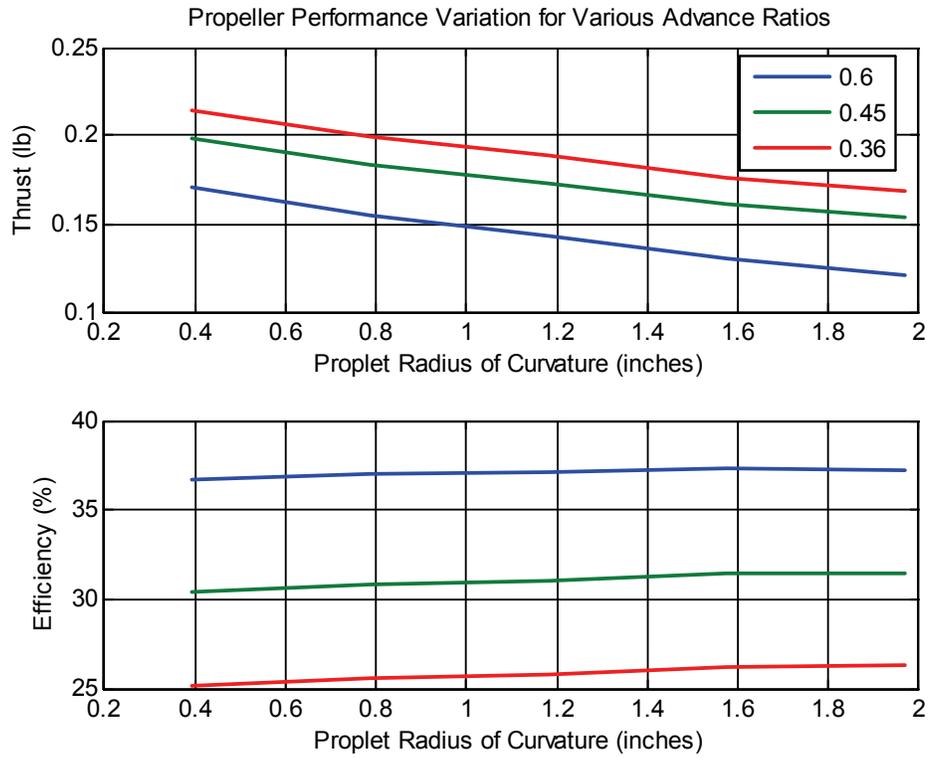


Figure 37: Proplet Trade Study

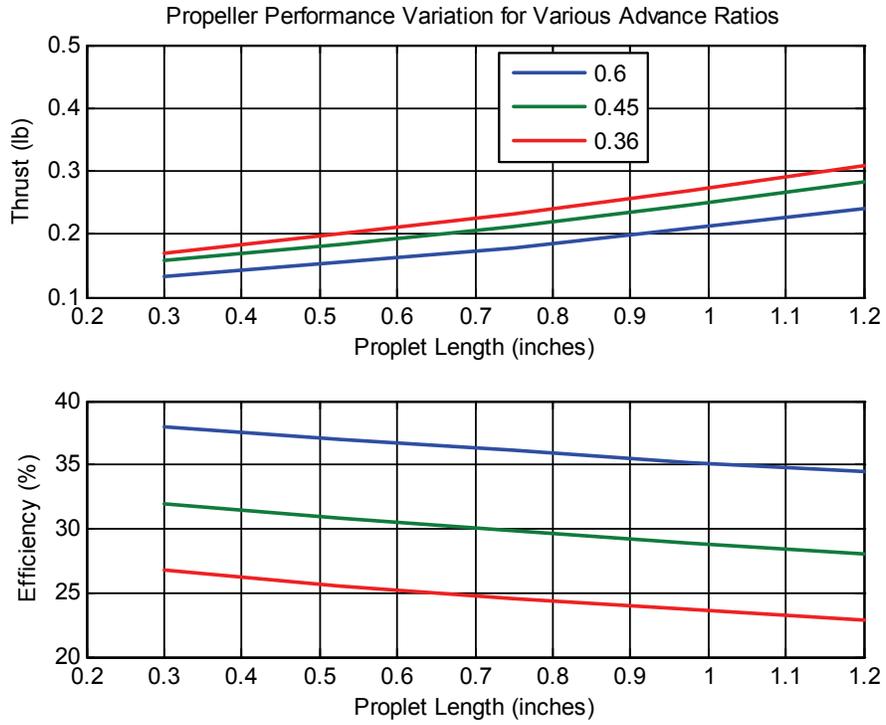


Figure 38: Proplet Trade Study

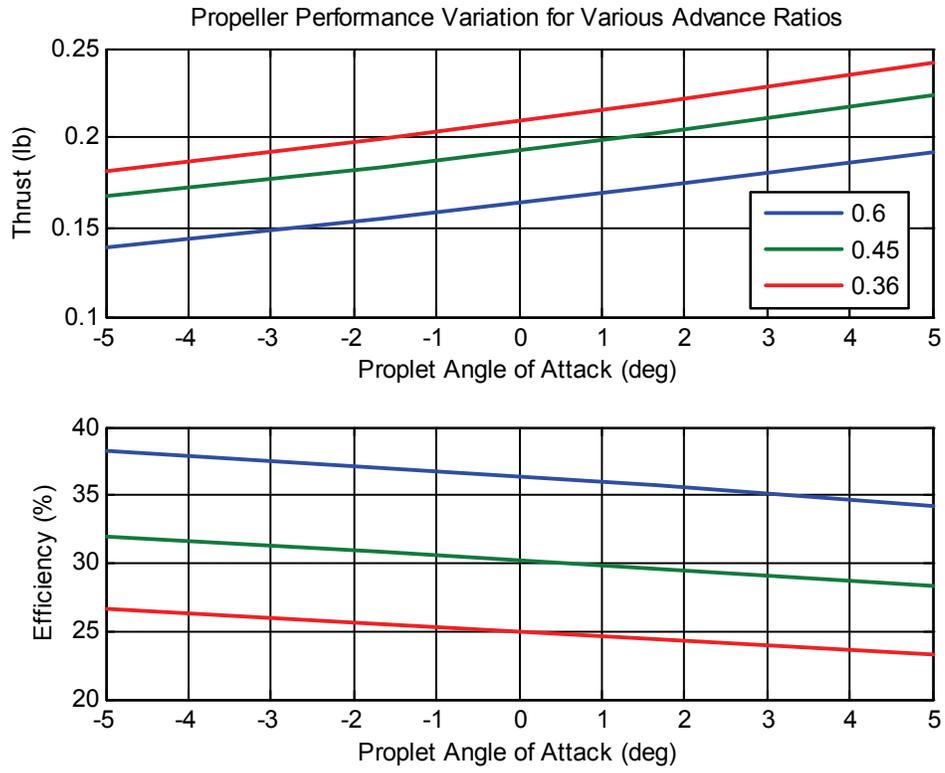


Figure 39: Proplet Trade Study



Figure 40: Composite Layup

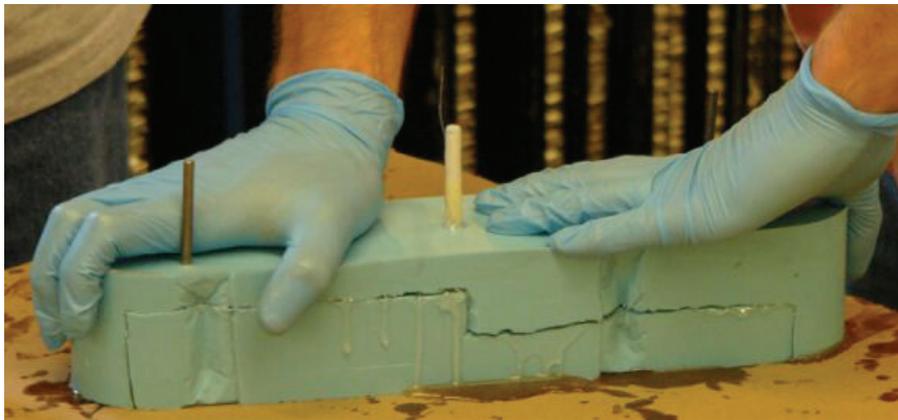


Figure 41: Completed Composite Layup



Figure 42: High Contraction Wind Tunnel Mount

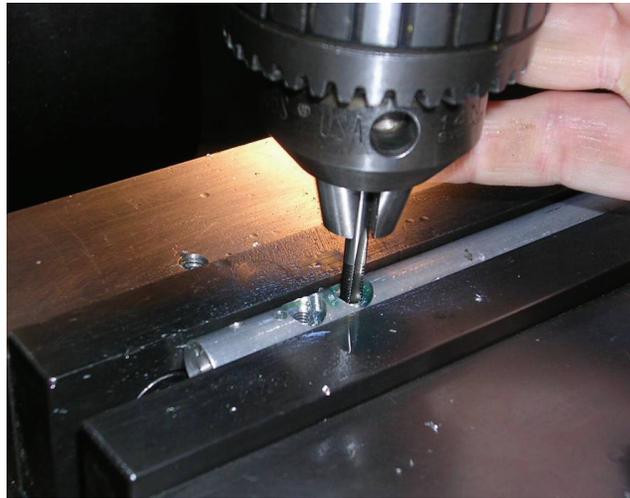


Figure 43: Tapping Aluminum Shaft on Torque Cell



Figure 44: Torque Cell Mounted in High Contraction Wind Tunnel



Figure 45: Milling Acrylic Interface Block



Figure 46: Propeller With Proplets



Figure 47: Propeller With Proplets Cut Off