

# **Variable Pitch Propeller Design Tool Development**

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## **ABSTRACT**

This research was initiated by three members of the Human Powered Submarine club established at FAU. With intentions to efficiently generate a record breaking propeller design for the club's new submarine, we have established a graphical and numerical system that is both effective and educational. This tool produces values for a set of propeller parameters that can be generated by using a custom designed MATLAB® graphical user interface that can be compared to CFD modeling, physical measurements, and user variation. This tool is flexible enough to incorporate multiple hull shapes and propeller configurations while producing quantitative results for accurate comparisons of modifications in order to give any user, new or experienced, a concept of how different factors affect the propeller's overall performance without longhand calculations.

The current results of this project include a tool that identifies limiting factors of underwater vessels and a graphical interface that allows users to design propellers. Our MATLAB® GUI tool and SolidWorks® CFD analysis will be verified and calibrated using small scale modeling of prop and hull. This will ease data interpretation and enhance tool usability. So far we have discovered that such things as the nominal wake can have a 7% difference in projected speeds when considered in the calculations.

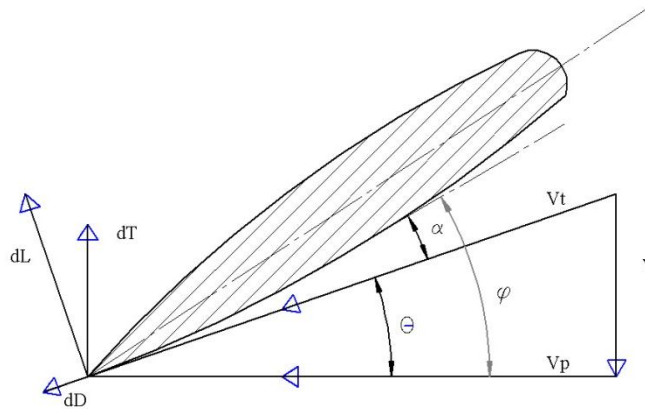
**Keywords:** MATLAB, Propeller, Wake, GUI

## **1.0 BACKGROUND**

Propellers are used to create thrust to propel a vehicle through a fluid. A propeller rotates by torque being transferred from the drive mechanism to the shaft; it pushes the fluid (in our case, water) backwards which causes the vessel to move forward. As the velocity of the vessel increases the water flowing into the propeller also increases. This inflow of water creates a desired lift effect on the surface of the prop but is also accompanied by a drag force. The net thrust produced (lift force minus drag force) depends on several factors, a few being the geometry of the propeller, total torque transferred to the prop, vehicle design, maximum speed and fluid density (Carlton 2007).

As the prop is rotating, the surface of the blade encounters the fluid at an angle of attack which is responsible for generating lift. The flow angle is determined by the incoming fluid velocity and propeller rpm. This angle varies with vehicle speed and prop rotation. The pitch is the sum of these two angles, and the blade is designed to maintain a constant thrust along its radius while accounting for these dynamic quantities. This is what gives propellers their characteristic twisted shape. Figure 1.1 shows these angles according to one radial section of the blade. These features are considered to produce a maximum thrust at a designed vehicle and prop speed.

The newest submarine hull has been designed to break the world record for fastest human powered submarine which currently rests at 8.035 knots (14.9km/hr. 9.2mph). One of our main propeller design constraints is that the pilots can only maintain maximum speeds for a short period of time. These maximum speed intervals are directly dependent on the driver(s) capacity to pedal. What this means is that our propeller will not experience a steady torque and as a result, neither the incoming fluid flow nor the submarine speed will be steady. This affects the angle of attack and total thrust that will be produced.



**Figure 1.1: Blade Element Angle and Vector Layout (see Table 1.1 for nomenclature)**

So far, we have described some of the main variables and parameters that needed to be considered while laying down the ground work for designing our prop design tool. Even though there are many more variables to be considered, we effectively narrowed our design focus to consider the variables that allow us to approximate maximum thrust based off empirical data and theoretical formulation put together by the National Advisory Committee for Aeronautics (NACA). Using this approach we have established a sound method for verifying our final propeller design tool by comparing theoretical results with empirical data.

**Table 1.1: Blade Element Theory Nomenclature**

A	surface area of element	V	Total incoming fluid velocity
$\alpha$	angle of attack	$V_p$	Axial flow component
c	chord length	$V_t$	Tangential flow velocity component
$C_D(\alpha)$	coefficient of drag, $C_{Dmax}(1-\cos(2\alpha))$	n	revolutions per second
$C_L(\alpha)$	coefficient of lift, $C_L \sin(2\alpha)$	dr	radius differential chord
dD	incremental drag, $(\rho AV^2 C_D)/2$	r	radius
dL	incremental lift, $(\rho AV^2 C_L)/2$	$\phi$	blade pitch
dT	Incremental thrust, $dL \cos(\theta) - dD \sin(\theta)$	$\theta$	angle of incoming fluid
dQ	Incremental torque, $dL \cos(\theta) + dD \sin(\theta)$		
$\rho$	Fluid density		

We used the following graphical analysis and data interpolation methods to identify the range of values for the angle of attack ( $\alpha$ ) that would produce maximum thrust for a given wing section. This method can be used with any graph of wing sections contained in Appendix IV of Theory of Wing Sections (Abbott and Doenhoff 1959). Three variables to be evaluated throughout this process are  $C_L$ ,  $C_D$  and  $\alpha$ .

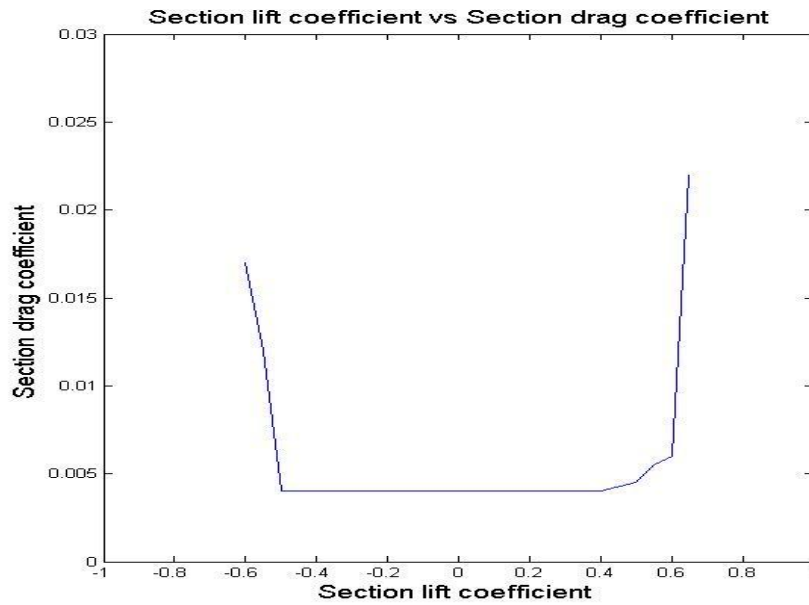


Figure 1.2:  $C_L$  vs.  $C_D$

We selected “NACA 66-221 Wing Section” and began to inspect the graph of “Section lift coefficient,  $C_L$  vs. Section drag coefficient,  $C_D$ ” in Figure 1.2. We found  $C_D$  to be approximately constant at 0.004, for values of  $C_L$  that fall between 0 and 0.4.

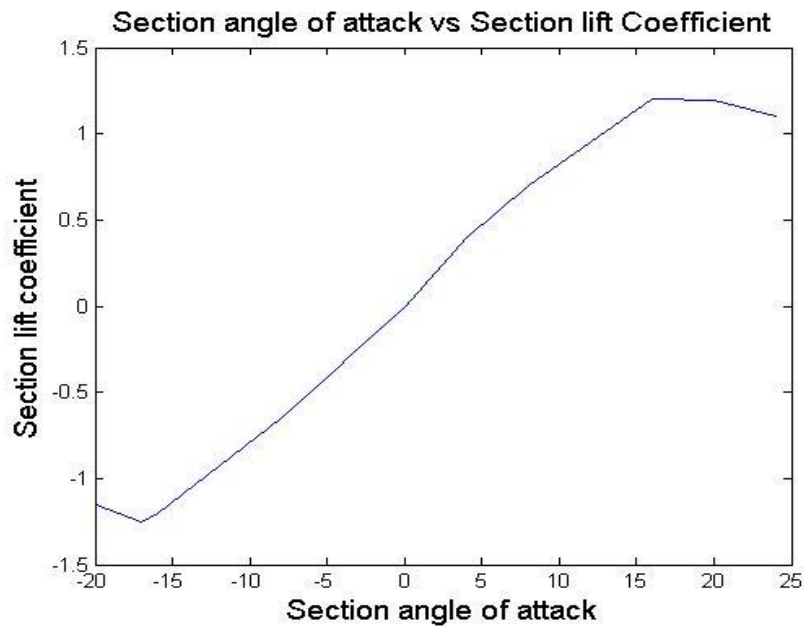
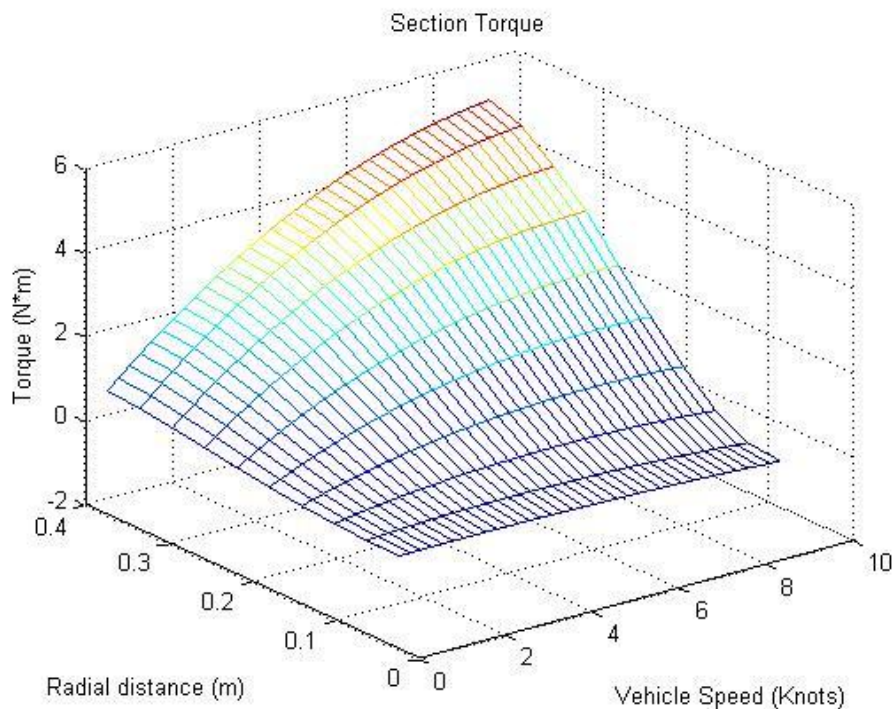


Figure 1.3:  $\alpha$  vs.  $C_L$

We moved to the graph of “Section Angle of attack vs. Lift Coefficient”, Figure 1.3 and found  $\alpha$  to range between 0 and 4 degrees for values of  $C_L$  (0 to 0.4) found in the previous graph. In order to achieve maximum thrust,  $\alpha$  must remain between 0 and 4 degrees.

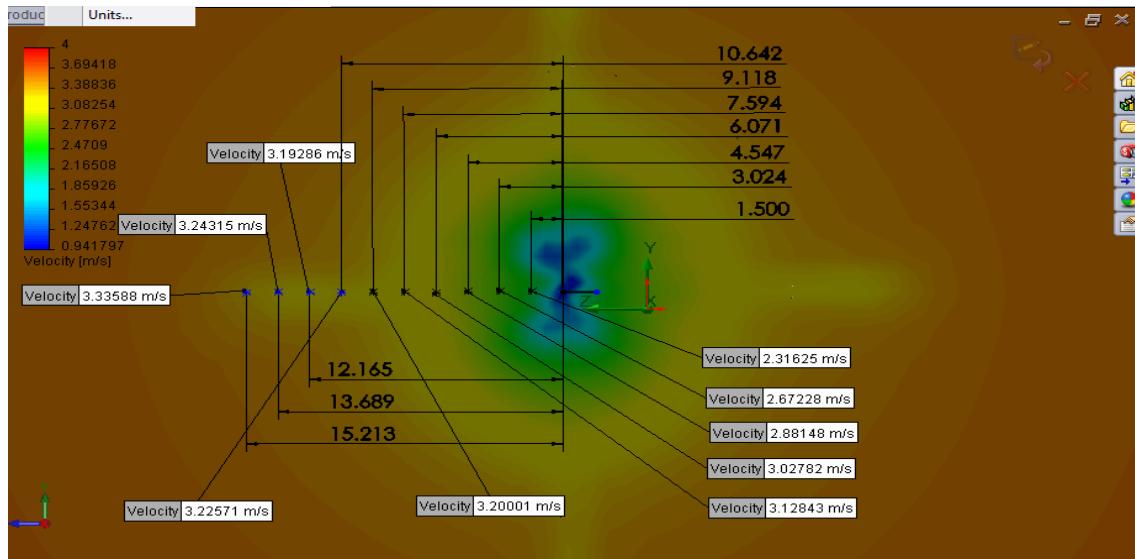
## 2. Design Tool Development

Based off NACA foil wing section theory the thrust and torque of the propeller should be able to be approximated numerically if the NACA foil shape is known. In the effort to develop this tool accurately, we began from a known reference, the one man submarine in the HPS fleet (Talon 1). The propeller’s chord lengths and pitch angles were measured along sections of the radius while the foil shape was estimated. We numerically recreated the existing propeller for to verify our design tool. By knowing the chord lengths and pitch angles along radial sections of the propeller, the calculations for thrust and torque are relatively straightforward when the vehicle target speed and prop rpm are identified. In an effort to utilize MATLAB® to gain a fuller understanding of the propeller’s characteristics, the formulas were applied to each section at incrementing speeds until a goal velocity was reached. This form of analysis creates outputs such as Figure 2.1. This mesh plot shows how each section of the prop reacts in open water at speeds from 0 to 9 knots. This type of plot can show what areas of the prop are responsible for certain effects or behaviors at different speeds. To illustrate this behavior, it can be seen that the torque spikes at the tip of the prop as the velocity increases compared to the rest of the blade. This information can greatly influence design changes to make an efficient prop. This graphical representation will be a helpful learning tool when combined with the MATLAB® GUI described in Section 3.



**Figure 2.1: Torque calculations done at each radial section over a range of speeds.**

One major flaw so far in this design is that the hull was not accounted for in the calculations and thus SolidWorks® was integrated into the tool. Normally, a free stream velocity constant derived from a wake constant is considered to describe the speed experienced by the propeller in comparison to the speed of the vehicle. In an effort to accurately simulate the operating conditions of the prop, we considered the nominal wake of the vehicle according to CFD models that ran on SolidWorks® Flow Simulation. Results analyzed with a cut plot are shown in Figure 2.2. This is an image of the varying velocities in the area that the propeller operates. The probe points show the numerical value at the radial distances tested in the MATLAB® program.



**Figure 2.2: Velocity plot of the nominal wake of Talon 1**

Instead of using one constant for all radial sections, there are different constants for each radial section which can be plugged in or created with a derived formula. This way the numbers will more accurately represent the conditions experienced by the prop for a more accurate result. Currently, multiple CFD tests are being run on a model of Talon 1 to get a better grasp on how these constant distributions vary with different vehicle speeds. The differences in the results due to this consideration are subtle when looked at graphically, but the change is easier to compare when observing the theoretical vehicle speed where the torque limit is reached, which is represented in Table 2.1.

**Table 2.1: Predicted max speed with current torque allowance.**

<b>Free Stream Velocity parameter</b>	<b>Open water(1)</b>	<b>Constant (0.85)</b>	<b>Gradient from hull</b>
Theoretical max speed	6.25 knots	7.50 knots	7.00 Knots

When considering the velocity gradient caused by the hull, there is an 11% difference in projected speed from open water testing and a 7% difference from a using single constant. This positive and negative change in projected speed shows how dependent the prop is on the inflow velocities. These considerations are not large, but they will be continuously modified with feedback from more tests to fine tune our tool.

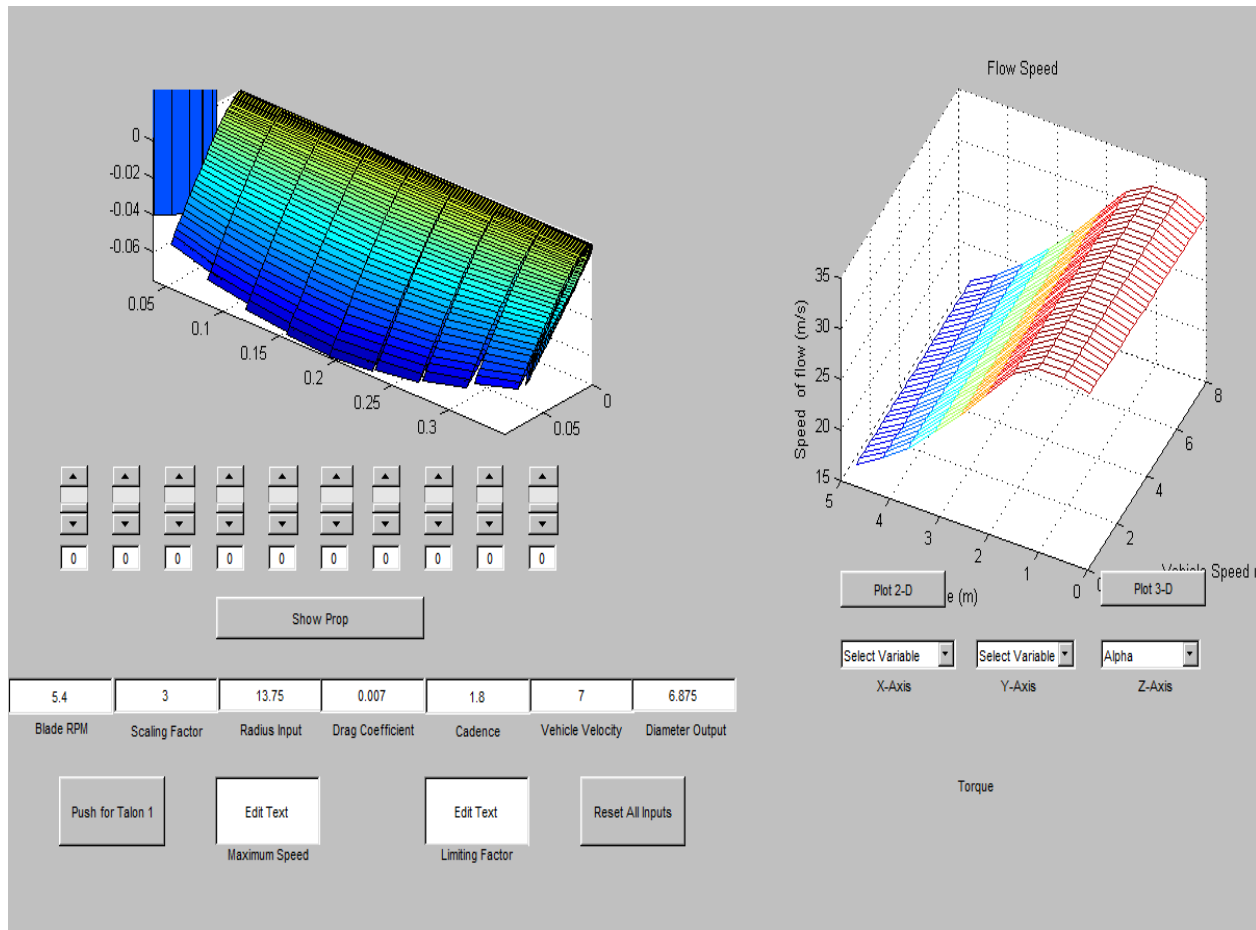
Another use of SolidWorks® in this study is to characterize the hull's drag with respect to velocity. Similar to what was done with the two man hull in its design, CFD analysis outputs forces in the axial direction, which are interpreted as the vehicle's drag at the tested speed. These values don't affect the prop's output as much, but they do define its efficiency and the limiting factors of the program, so it can calculate when the vehicle has hit its max speed. Also CFD tests are being run on sample models of NACA foil shapes to verify our mathematical approach with our numerical testing and outside empirical data. One future goal is to take these generated shapes and perform model testing in a flow tank at the facilities in Dania Beach, FL. These scale tests will be much more accurate to the full scale results than our current computational models.

This small scale model testing is a goal for future understanding of how accurately these numerical estimations add up against real world tests. It will provide confidence for future users who want to see verified results. So far, there are many interactions that are not accounted for in our modeling. Comparing these theoretical products to real world models will allow us to calibrate our findings in ways we cannot currently model. The variations in the propeller's geometry will be analyzed in an effort to better understand the principles behind propeller design in

practical terms; ultimately the goal is to design a propeller that will bring our new submarine up to its desired speed. Additional testing being planned is human power characterization. Once we complete this underwater characterization we will have empirical data that will serve as an input that will realistically represent our torque and rpm parameters. A relationship between the two will help define the vehicle's dynamics.

### 3. Graphical User Interface (GUI):

There were two intentions when the development of the graphical interface was initiated. The main focus of the interface is to streamline the use of MATLAB® script that was developed for the propeller design. When the script was first being developed, it became problematic when the dimensions of the propeller needed to be changed because the users would have to edit the code each time this needed to be done. This caused the goal of applying this script to other propellers to become unrealistic if this approach was not altered. By allowing the user to change the values without editing the code of the design tool this issue was bypassed. The secondary use of the design tool is to allow students who do not have experience in propeller design to have an interactive way to learn the material. This is useful because students may be discouraged when dealing with the large amount of information that is associated with propeller design. By providing visual representations, students will have an experience similar to that of a videogame by seeing immediate changes in figures and outputs due to their efforts.



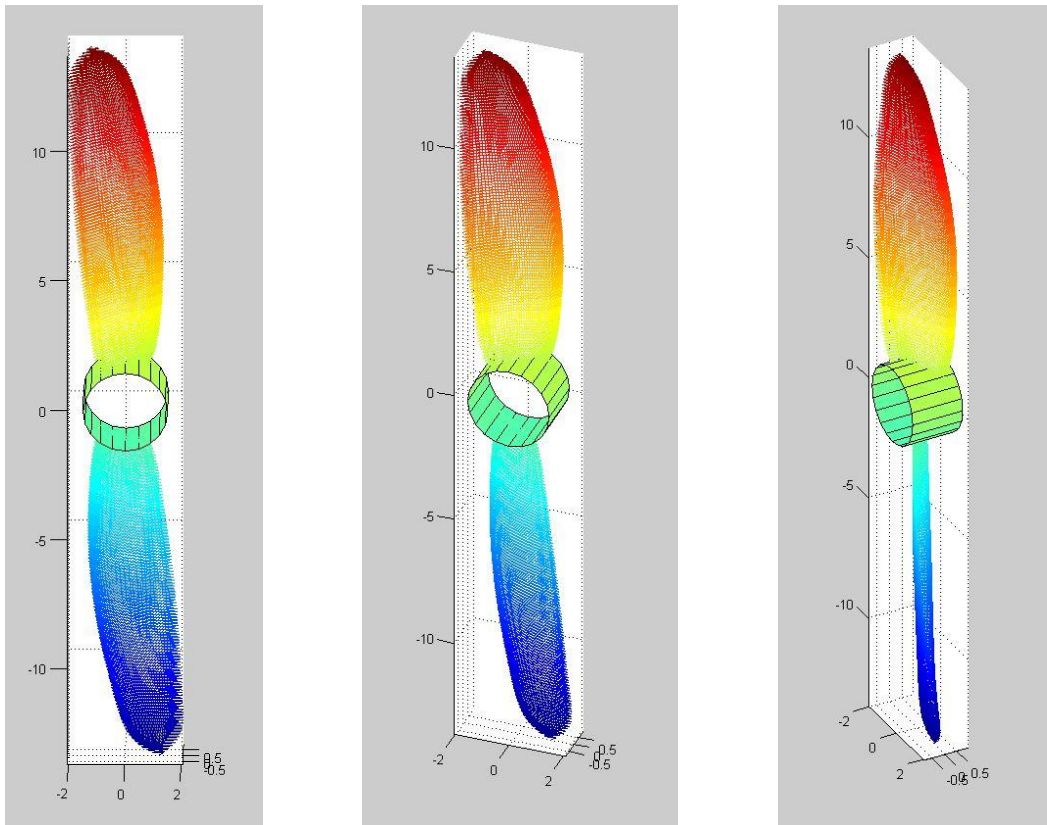
**Figure 3.1: Graphical Interface for Design Tool**

The graphing section of the interface is expected to allow a user to select variables to be plotted against each other with a total of three popup menus to choose from. If the user wishes to only view a two dimensional plot, they will select two variables and click the “Plot 2-D” button located on the upper right hand corner of the interface. An error message will alert the user if they choose variables of different sizes or if other factors restrict the plot

from being properly displayed. If the user wishes to view a three dimensional plot, the user selects three variables from the popup menus and clicks the “Plot 3-D” button located directly to the right of the two dimensional plot button. For three dimensional plots, the rotational feature is enabled so the user can view figures from different perspectives, which has proven to be useful in the analysis.

The input section, located in the center of the interface is able to receive specified propeller parameters provided by the user. These parameters include the rotational speed of the shaft, gear ratio, wake velocity constants, radius of the propeller, pitch distribution and its chord lengths. This section will also receive the desired velocity of the vessel that the propeller is intended for. With these inputs, the graphical interface will display the calculated results of the diameter, the index of the chord length being entered, the rotational speed of the propeller, and the velocity of the vessel being used in calculations. The interface will have a reset button at the bottom of this section to clear all inputs in case an error is made or if the user wishes to start over for any other reason.

The final section of the interface utilizes the propeller creator function developed in MATLAB®. As stated previously, the propeller to be designed will be given certain parameters specified by the user and will then be displayed graphically in the interface. Since the purpose of this project is to develop a variable pitch propeller for the Human Powered Submarine Team, a propeller editing tool will be incorporated into the interface to allow users to determine how the propeller should be shaped. Based on the rotation of the variable pitch propeller at given speeds of the vessel, certain sections of the propeller are expected to produce more drag than lift. This editing tool will allow users to adjust these sections with the use of slider callbacks with the purpose of increasing propeller efficiency at higher velocity ranges.



**Figure 3.2: 3D prop view for GUI Design Tool**

Figure 3.2 depicts a 3D view of a prop design that allows the user to evaluate blade surface characteristics in different frame views.

Further goals of the graphical interface are the following:

- Provide the ability to generate subplots of variables to allow better comparison of information. This ability to graph desired variables against each other on command is a much more efficient way of viewing the data when compared to searching through pre-generated figures. This will streamline the feedback end of the system which will lead to better analysis.
- Provide the ability to create a library of results from various tests.
- Incorporate a functional help menu to troubleshoot issues.
- Allow the user to select the units (SI or Imperial) in which he or she plans to design the propeller in.
- Provide a library of NACA airfoil shapes from which the user can select from. This will provide further ease of use of the interface and expedite the production of propellers for future submarines and other aquatic vessels.

By streamlining the efforts of propeller design, this interface allows users to experiment with the creation of both fixed and variable pitch propellers. It's simple and responsive nature encourages newer students in the field to learn more about propeller theory while maintaining the capacity for advanced development. The development of this interface was an educational project that provided those involved with a broad range of skills and experience in the fields of programming along with propeller design.

#### **4. Results**

After an initial basic prop design tool was designed several FAU students tried the tool. There was a positive response by the student users. The tool facilitated the students to understand the physical aspects of a prop and how changes to the essential input variables affected the design of such. This understanding was further enhanced, as noted by the students, by the fact that changes in the input variables are updated automatically through the design tool which in turn updates the graphical appearance of the prop, enabling the students to associate physical with theoretical parameter changes.

#### **5. Conclusion**

The propeller design tool served its purpose of facilitating users to design a propeller without having to have an in depth knowledge of blade element theory and helped users move away from tedious long hand calculations. Even though the tool itself still needs to be calibrated against a physical model, we conclude that the tools initial phase of development was satisfactory and on the correct developmental path. The design tool proved to be cost effective, easy to use and future development will allow it to produce reliable and useful results.

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