Human Powered Submarine Propeller Design

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***Abstract* – While all parts of a submarine contribute to its overall performance, the propeller blade design is often neglected due to the difficulties in analyzing the impact in design changes combined with a lack of previous research in blade designs for the power and speed requirements as dictated by a human powered vehicle. To aid us in the design of our propeller, we have created a program to take a set of constraints as input, create a blade design using those constraints, use a combination of theories to get a performance metric for that blade using finite element analysis, and finally to output parameters required for the manufacturing of the blade and the calculated performance of that blade. This paper will discuss the techniques we used and the rational behind the tradeoffs we choose to use in our program, as well as how it and other supporting programs are allowing us to produce higher performance propellers and to continue to expand our knowledge in this area.**

I. Introduction

Each year various national and international teams gather to compete in a human powered submarine competition that allows them to test both the design and implementation of their respective submarines. The American Society of Mechanical Engineers (ASME) and International Submarine Races (ISR) alternately hold these submarine races. The race is basically a drag race with each submarine making runs by itself down a 300 ft course and passing through a set of timing gates that record its speed. The object is simple; obtain the fastest speed possible. Currently the world record for propeller driven human powered submarines is set at 7.192 knots (8.276 mph or 3.7 m/s) by the submarine Omer 4 fielded by École de Technologie Supérieure. We, the University of California at San Diego (UCSD) Human Powered Submarine Team, have made it our goal to break this record in upcoming competitions. Although many design features are crucial to achieving maximum speed, having a well-designed propeller is essential. Many past submarines built both by UCSD and other schools have left propeller design as an area with much room for improvement. This important area has been neglected for two reasons. First, it is a complex problem and there is surprisingly little information available that directly applies. Second, building an entire submarine in a year is quite a monumental task and many teams simply run out of time and are unable to dedicate the time required to properly analyze a propeller blade.

II. Propeller Design Requirements

There are some very stringent design restrictions that go along with building a human powered vehicle. The two most important are that the vehicle must be large enough for the pilot to fit on or inside and the maximum power output is set by what a human is capable of outputting. When trying to make a human powered submarine as fast as possible, these constraints translate into two major goals. First, make the submarine as small and streamlined as possible while still allowing room for the pilot and internal systems. This will, in turn, limit the drag on the hull of the submarine that limits the top speed. Second, deliver as much of the power provide by the pilot to the surrounding water in the form of forward thrust. This is accomplished through an efficient drive train and a propeller that is designed to meet the power output of the pilot and the maximum attainable forward speed of the submarine.

By the time we began work on the propeller design process, many aspects of the possible propellers had already been established. The hull and drive train of the submarine had already been designed. The hull size and design specified the drag force the propeller had to overcome. We had also decided that we wanted the propeller to be variable pitch. Other teams have propellers that go as far as to constantly control the propeller's pitch to maintain constant torque, but we opted for a much simpler system that has only two settings; full speed, around which the propeller is optimized, and a feathered ramp up setting used to make the propeller more efficient during the acceleration process. The mechanism required to vary the pitch needed a certain amount of space, so the hub diameter was set at 7 inches.

The rest of the known design requirements came from our restrictions as humans. Through some research and observation we found that humans are most comfortable and effective pedaling at a cadence of about 60 to 100 RPM. In water this should be slightly lower in the 50 to 80 RPM range. We also found that a fit human can output about 1 HP (745 Watts) for very short durations of less than 30 sec, and .4 to .6 HP (300 to 375 Watts) for extended durations. With losses due to pedaling in water as well as losses in the drive train, the propeller was designed around a power input of about 350 Watts.

Manufacturing and materials limitations created a whole other set of restraints. The propeller had to be strong enough to hold up to the loads placed under it during operation. This basically translated into minimum thickness at various locations on the propeller blade. Since these loads could not be determined until the propeller was designed, reasonable values were assumed and the final designs were structurally analyzed before being chosen.

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With these restrictions to work around, the next step was to develop a tool that allowed both creation of various designs and the prediction of their performance. To do this, the basics of propeller theory must be clearly understood.

III. Propeller Theory

A. Basic Principle

A propeller works by creating a pressure difference on each side of the blade. This pressure difference acting on the area of the blades results in a net force. The component of this force acting in the direction of travel is the forward thrust, but there will also be components of this force acting in other directions. The key to an efficient propeller design is to make the thrust component of the force as dominant as possible.

B. Momentum Theory

Rankine first proposed propeller momentum theory in 1865. The theory represents the propeller as an imaginary "actuator" disk across which there exists a discontinuous pressure jump. The following assumptions are made: pressure and velocity are uniform over the disk, rotation imparted to the flow is negligible, and the fluid is both incompressible and inviscid. With these assumptions Bernoulli's equation can be applied between flow far ahead of the propeller and flow at the front of the disk, and to flow just behind the disk and flow far behind the disk. This coupled with conservation of mass and representing the pressure difference across the disk as the thrust divided by the area of the disk allows the following result to be derived: the velocity of the flow through the propeller is the average of the velocity far ahead and the velocity of the slipstream induced by the propeller.

Betz did similar analysis in 1920 that included rotation of the slipstream as well. By applying conservation of angular momentum to the actuator disk model the following relationship can be derived. The angular velocity of the slipstream will be twice that at the propeller disk.

C. Blade Element Theory

When the propeller is no longer viewed as an imaginary disk and the geometry of the blades is taken into account, the analysis gets somewhat more involved. Due to the rotation of a propeller, the conditions felt as by the blade as you move in the radial direction vary. This significantly complicates the problem requiring some simplifying assumptions to be made. One obvious first idea is to do the following: divide the blade into a discrete number of elements, analyze each one individually using two-dimensional airfoil theory, and sum the results. This is referred to as Blade Element Theory and was first introduced in the late 1800's by Froude (1878) and Taylor (1893). This theory is limited in that it is not equipped to take into account any of the radial flow along the blade, tip effects, or disturbances in the incoming flow induced by the other blades or the apparatus to which the propeller is attached.

D. Momentum Blade Element Theory

Another method involves combining the results of the two previous ones. To do this an iterative approach is needed. First an analysis is done using simple blade element theory. The results of this are then compared to the results of the momentum theory. A correction is made, and the process is repeated until the two results converge. This theory has proven to yield fairly accurate results for propellers with light loading. Propeller loading is the power per unit area. If loading is light the three-dimensional and tip effects are kept to a minimum and it is reasonable to analyze each element individually using the two dimensional approximation. In the case of the submarine, we have a small amount of power to deal with so as long as the blades are not made too small and the rotational velocity is kept low, the loading should be kept low and this theory should be acceptable. For these reasons as well as ease of implementation I chose to use this theory to design the propeller for the submarine.

IV. Implementation

The analysis of a blade design can be broken up into three parts: the choice of the blade's shape, the analysis of that blade geometry at the target operating conditions, and the performance of the blade in non-ideal operating conditions. We created two programs in Matlab to perform these tasks. The first, *Propcalc*, creates a propeller design around a set of operating conditions and design specifications then returns the geometry of the propeller as well as the propeller's performance at the specified operating conditions. From this it can be decided whether a design is worth considering. The other program, *Propanalysis*, which takes designs created by *Propcalc* and creates characteristic curves that show the propeller's performance over a range of operating conditions. It also allows the performance of a feathered propeller to be predicted.

A. Blade Shape

The first thing to consider when designing the blade shape is what angle of attack should be used for each element. So simplify the process and using knowledge of the family of airfoils considered, three degrees was chosen. In addition, at each element, an airfoil cross-section must be chosen. Four digit NACA airfoils have data widely available on them, and they can be generated numerically from their four digit names so we choose to restrict ourselves to airfoils that can be represented by a NACA number. In choosing an airfoil to use, there are a few features that are key. An airfoil works by creating a pressure difference between its top and bottom faces. To do this, the flow must be accelerated over the top of the airfoil, thus decreasing its pressure. The flow must first be pushed out of the way, and then drawn back together. However, if the airfoil requires the flow to close together to rapidly, it can cease to follow the contour of the airfoil and separate, closing somewhere down stream. A low-pressure turbulent region forms in the region of separation resulting in huge increases in drag. The trick is to find an airfoil that will prevent separation for the given operating conditions.

To find an airfoil that suited our needs, a pair of programs, *FoilFinder* and *FoilWrapper* were created. *FoilFinder* generates all of the NACA numbers within a specified range, and calls *FoilWrapper* that uses PABLO [5] to compute the flow around the airfoils for a specified Reynolds number and angle of attack. The program uses brute force to sift through thousands of possibilities and brackets the results based on desired features. These features included; laminar flow over the entire upper and lower surface, as well as separation occurring in the last third of the airfoil. The results of this analysis revealed that the 56xx series of airfoils worked well for our operating conditions.

Once the family of airfoils was chosen all that is left was deciding exactly which one to use and scaling it to the appropriate chord length. Since our propellers are actually going to be made and used, material limitations placed restrictions on how thin our airfoils could be made. From this we specified a set of minimum thicknesses along the blade and used them as well as the specified chord length distribution to calculate a NACA number. Cubic splines were used to create a set of smooth curves that defines both the desired chord length distribution as well as the minimum thickness distribution. From the combination of the desired chord length and thickness a NACA number can be generated within the 56xx series that satisfies those conditions.

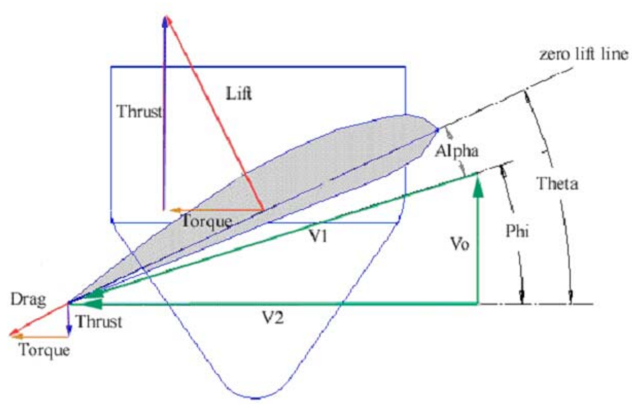

Fig. 1: Airfoil Element Visualization

With these parameters determined, the propeller's geometry has been defined except for the pitch distribution (θ) at each element at radius r defined by $\theta(r)$. However, the desired angle of attack for each element, α, has been specified and from here out the program iteratively computes what pitch distribution will match the desired angles of attack. With the pitch distribution known, the performance of the propeller is calculated including power required, efficiency, and thrust. From these values it is possible to evaluate whether the design is satisfactory.

B. Target Design Condition Performance

To determine the performance at a specified set of operating parameters, we iteratively find a solution that simultaneously satisfies both the blade element equations and the axial and angular conservation of momentum relationships as discussed above (Section III.D). To do this we introduce the inflow factors, *a* and *b*, defined such that: the axial velocity felt at the blade element equals *a* times the velocity of the free stream, and the angular velocity felt by the blade element equals *b* times the angular velocity that would exist at the blade element without any induced swirling of the slip stream. In other words,

$$V_0 = a * V_\omega \quad (1.1)$$
$$V_2 = b * \omega * r \quad (2.1)$$

From the geometry of the propeller we can determine

$$V_1 = \mathrm{sqrt}((V_0)^2 + (V_2)^2) \quad (3.1)$$
$$\Phi = \mathrm{atan}(V_0 / V_2) \quad (4.1)$$

The momentum theory discussed earlier gives us (in the axial direction):

$$V_0 = (V_{slipstream} - V_\omega) / 2 \quad (5.1)$$
$$V_{slipstream} = V_m + 2 * V_0 \quad (5.2)$$
$$V_{slipstream} = V_\omega * (1 + 2 * a) \quad (5.3)$$

Using Bernoulli's equation with the conservation of axial momentum,

$$DT = 2 \pi r * \rho * V_\omega * (1+a)*(V_\omega*(1+2*a)-V_\omega) * dr \quad (6.1)$$
$$DT = 2 \pi r * \rho * (V_\omega)^2 * (1+a) * 2 * a * dr \quad (6.2)$$
$$DT = 4 \pi r * (V_\omega)^2 * (1+a) * a * dr \quad (6.3)$$

In the angular direction we get,

$$V_{\theta(slipstream)} = 2 * b * \omega * r \quad (7.1)$$

With a momentum balance this gives us,

$$DQ = 2 \pi r * \rho * V_\omega * (1+a)*(2*b*\omega*r) * r * dr \quad (8.1)$$
$$DQ = 4 \pi r^3 * V_\omega * (1+a) * b * \omega * dr \quad (8.2)$$

Using 2-Dimensional airfoil lift and drag data for the coefficients of lift and drag C_L and C_D, blade element theory gives us,

$$DT = (\rho*(V_1)^2 *c*(C_L \cos(\Phi)-C_D \sin(\Phi))*B*dr)/2 \quad (9.1)$$
$$DQ = (\rho*(V_1)^2 *c*(C_L \sin(\Phi)-C_D \cos(\Phi))*B*dr)/2 \quad (10.1)$$

where *B* is the number of blades

This system can be solved iteratively for the inflow factors, *a* and *b*. Once they have been found the pitch distribution of the blade can be determined since

$$\theta = \alpha + \Phi \tag{11.1}$$

Solving this system of equations is trivial if everything is known but the inflow factors. However, this is not the case. The lift and drag coefficients, C_L and C_D, need to be found and this requires either looking up data in charts, or using 2D airfoil theory to compute them. If table lookup is used, then the computer must stop at every iteration and ask the user for input. This severely handicaps the iterative process and makes the process very slow. Instead we opted to search for an existing program to calculate the coefficients.

At the point where this procedure needs C_L and C_D, a fair bit is known about the conditions existing at a particular element. Provided that the operating conditions are specified along with the airfoil cross-sections and desired angle of attack for each element, one has everything needed to compute these coefficients. A shareware Matlab program called PABLO [5] does exactly what is needed, but it is based around a graphical user interface and is thus unsuitable for use in an automated iterative solution. The interface took as input the angle of attack of each cross section, the Reynolds number, and a four digit NACA number. Quoting from the program's home web page (references from the quote are under the Pablo References section), "The inviscid flow is solved using a Panel Method [1]. Three different kinds of singularity distributions can be used. (Constant-strength sources, Constant-strength doublets, Linear vortices) The boundary layer equations use the inviscid flow velocity provided by the panel method, but the effect of the boundary layer on the inviscid flow is not taken into account, as in Panda [2]. The boundary layer model is described in [3]. It uses Thwaites' equations for the laminar part of the flow, and Head's equations for the turbulent part. Michel's criterion is used to locate transition. The drag coefficient is computed using the Squire-Young formula."

There were a few things that needed modifications however. First, the GUI had to by bypassed to be able to directly call the program from within our program. After this modification was made, PABLO is accessed as a function called *foil* that takes as input the four-digit NACA number, the Reynolds number, and the angle of attack. It returns the coefficient of lift, drag, the location of the center of pressure, and the minimum coefficient of pressure. At present the coefficient of pressure is unused, it was included in case we were ever using it for a situation where cavitation could be an issue.

Another issue that needed correcting was that the momentum blade element theory used defines the angle of attack as being from the zero lift line of the airfoil, but PABLO defines the angle of attack from the chord line which the airfoil is created around. To resolve this, a function called *getZero* was created that simply looped through foil changing the angle of attack until it returned a coefficient of lift of zero. This offset was then subtracted from the specified angle of attack to obtain the angle of attack desired by the PABLO code.

The center of pressure, X_{cp}, of each element was used when aligning the elements with each other to create a blade that has little moment around the propeller root. This not only lessens the loading on the root, but also makes feathering the blades much easier.

With all of these functions in place, *Propcalc* has everything it needs to calculate and return the efficiency, power required, and any other performance measurements needed. The program has thus created a propeller meeting the specifications and predicted its performance at the design conditions. However, there is still the question of the propeller's performance outside of the design conditions such as when the submarine is moving at a different speed, or the pilot is pedaling at a different cadence. To answer this question another program, *Propanalysis*, was created.

C. Non-Optimal Conditions

To simulate the performance of the blade at non-optimal operating conditions, *Propanalysis* computes all of its information based around one operating condition, the advance ratio, *J*.

$$J = V_0 / \omega * d \tag{12.1}$$

The advance ratio is a dimensionless number used to correlate propeller data. To predict the propeller's performance over a large range of operating conditions, such as at different axial and angular velocities, the dimensionless coefficients above such as efficiency, coefficient of thrust, and power, must be calculated for a range of advance ratios. The plots of these coefficients versus advance ratio are called the propeller's characteristics.

To create these characteristics *Propanalysis* was developed. This program is very similar to *Propcalc*, however, it holds the propeller's geometry constant and calculates the propeller's performance for varying *J* as opposed to above where the propeller's pitch distribution is varied to maintain the specified angle of attack for each element at one *J* value. To allow a propeller's design to be passed between programs and stored for future use, a geometry matrix, *geom*, an n by 11 matrix was created where n is the number of elements used in the calculation and 11 is just the number of values needed to represent a single element of the blade.

Propanalysis, the program that creates the propeller's characteristics, as mentioned above, the only difference is that the propeller's geometry is now being held constant, so instead of having the angle θ be a function of a specified *a* and Φ calculated from the velocities V_0 and V_2, a is now a function of a specified θ and Φ is still calculated from the velocities felt by the blade element. Equivocally,

<u>*PropCalc*</u>

$$\theta = \theta(\Phi, \alpha) \qquad (13.1)$$

<u>*Propanalysis*</u>

$$\alpha = \alpha(\Phi, \theta) \qquad (14.1)$$

To create useful characteristics, the propeller's performance is calculated over a range of advance ratios. Since we designed our drive train with a three to one gear ratio so using the cadence discussed earlier this set our optimum angular speed for the propeller at about 150 RPM.

Keeping this constant, the incoming flow was varied from nearly zero to 4m/s (the world record). From this and the specified propeller diameter, our range of advance ratios was set. The following is a sample output from *Propanalysis*.

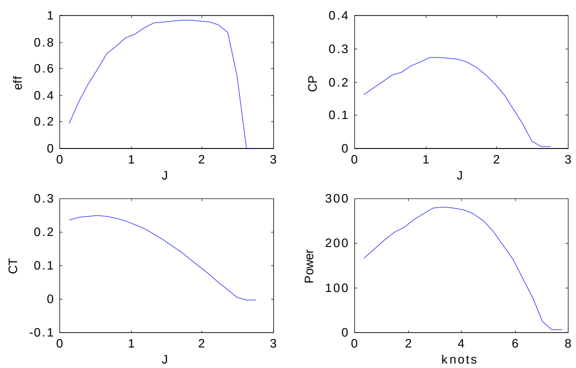

Fig. 2. *Propanaylsis* Output

The curves shown above are essential to choosing a propeller design. From them we can see how a propeller will perform over a range of operating conditions and try to match its performance to our needs.

Propanalysis can also be used to simulate the performance of a feathered propeller. By changing the pitch distribution *θ(r)* by a constant angular offset, the characteristics will be created for a feathered propeller. Feathering the propeller will shift the characteristics to the left or right. However, since the propeller can only be optimized for one advance ratio, maximum efficiency will decrease with increasing feather in either direction. Since the axial and rotational velocities felt along the blade are not linearly related there exists only one pitch distribution that creates a uniform angle of attack for all elements. The further the propeller is feathered the larger the angle of attack varies along the blade. In extreme cases, areas of the blade can be stalling while other areas are operating at a desirable angle of attack. The increased drag felt by elements with a poor angle of attack results in decreasing the overall efficiency of the propeller. Although maximum efficiency suffers from feathering, the efficiency of the feathered propeller when it is not at its design advance ratio may still be much higher than that of the unfeathered propeller at the same advance ratio. All of this can be seen in the characteristic curves created by *Propanalysis*.

With these tools all that is left to do is fit a propeller to a particular application. With respect to the submarine, the propeller analyzed above fit our needs well so we decided to use it for our first propeller. The next step is to take the design information created by these programs and turn it into a real, functioning propeller.

V. Propeller Construction Overview

Building a propeller is not a simple task. The complex curves and precise angular measurements make the task very well suited some sort of computer numerically controlled process.

Our first ideas involved using the rapid prototyping machines at UCSD's super computer center to create a three-dimensional dummy propeller blade. From this we would make a mold that would be used to make carbon fiber blades. We went so far as to have dummy blades cut out on the paper cutting rapid prototyping machine, but after a few failed mold-making attempts we decided to rethink things.

We had originally shied away from directly machining the blades because it would be very difficult, if not impossible with only a three-axis mill. However, after looking into it a bit more we discovered that our machine shop actually has a rotary fourth axis that can be bolted onto the three-axis Haas CNC mill. Upon discovering this we decided that direct machining was the way to go.

No matter which method we decided to use, we would need to create a solid model from which code for the machine could be created. The output geometry matrix was specifically created in a way that would facilitate this. The procedure would go something like this.

- Generate the NACA profiles as .dxf files using one of many free programs
- Import these into a solid modeling program such as Solidworks or ProEngineer and align them all along a common edge.
- Scale them all by changing the chord length to the value specified in the geometry matrix
- Shift them all over by the xCp (x coordinate of the center of pressure) value.
- Loft a surface between them all
- Attach a root to the blade

To aid the solid modeling process, some C programs were written that take the outputs of *Propcalc* and create a .stl file of the propeller blade which can be viewed either in a solid modeling program or in a custom made OpenGL viewer specifically designed for this purpose. This is very useful not only for blade manufacturing, but for making sure that the data in the geometry matrix makes sense and represents a reasonable model that will result in an acceptable blade.

Using cam software such as MasterCam, G-code can be created for the mill to use to create the propeller blades. The blades will then be milled out of inch and a half square aluminum bar stock. Since theory is often not exactly reproduced in practice, we plan on making a number of the best blades generated by the programs and testing them all to see which one perform the best.

VI. Concluding Statements

By creating our own finite element analysis software and using it to not only decide which type of propeller blade will yield the best performance, but also to aid in the construction of the designed blade, we have improved the performance of our submarine as well as cut production time in regards to manufacturing the propeller blades. Through continued refinement of the programs, use of automated searching of alternate blade designs, and a more detailed analysis of the individual blade's characteristics across a wider range of operating conditions we hope to further improve upon our design as well as provide the potential for continuous computer controlled pitch for the propeller while the submarine is underway. This would allow the best performance out of the blade possible in all conditions and thus better acceleration and ability to reach top speed.

References

[1] McCormick, Barnes W. : *Aerodynamics, Aeronautics, and Flight Mechanics*. John Wiley & Sons, Inc. , 1979.

[2] Von Mises, Richard : *Theory of Flight*. Dover Publications, Inc., New York, 1945

[3] I.H. Abbott and A.E. Von Doenhoff, *Theory of Wing Sections*, Dover Publications Inc, NewYork, 1959

[4] *"Analysis of Propellers:* Glauert Blade Element Theory." Aerodynamics for Students, Department of Aerospace, Mechanical, and Mechatronic Enginering, University of Sydney web page. http://www.aeromech.usyd.edu.au/aero/propeller/prop1.html

[5] PABLO
KTH- The Royal Institute of Technology, Department of Aeronautics. Stockholm, Sweden
Programmed by Christian Wauquiez, 1999
Contact : Prof. Arthur Rizzi, http://www.nada.kth.se/~chris/pablo/pablo.html

PABLO References

[1] Katz and Plotkin : Low Speed Aerodynamics, From Wing Theory To Panel Methods. McGraw-Hill Inc., 1991

[2] Ilan Kroo : PANDA - A Program for Analysis and Design of Airfoils. © Desktop Aeronautics, 1988.

[3] Jack Moran : An introduction to Theoretical and Computational Aerodynamics. John Wiley and sons, 1984.

[4] I.H. Abbott and A.E. Von Doenhoff, Theory of wing sections, Dover Publications Inc, NewYork, 1959