AUV Propellers: Optimal Design and Improving Existing Propellers for Greater Efficiency

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***Abstract*-Propeller design is a significant process that is overlooked in many design situations. Using propeller vortex lifting line code and two-dimensional analysis with Brockett diagrams, a propeller design can be optimized for an Autonomous Underwater Vehicle with a given design speed by varying blade number, propeller diameter, hub position, and chordlength distribution over a given range of RPS appropriate to the AUV's thrusters [1]. Initial design decisions from PVL code chose a three-bladed 0.625m diameter propeller at 2RPS, with a hub located at r/R(0.2) and an efficiency of 0.7091. Final propeller design modified the chord distribution to improve distributed lift coefficients and to ensure that shallow-water operations would not experience cavitation effects. The final design geometry used the same values of the propeller blade number, diameter, RPS and hub location as the initial design, but at an efficiency of 0.7642.**

While off-the-shelf propellers, such as those designed for model airplanes, can have high calculated efficiencies relative to actuator disk theory, the lift coefficient at each radial position and the resulting stalling effects must be considered. Comparison of an existing design with an optimized design improves existing propellers and contributes to the process of choosing future off-the-shelf propellers.

I. Introduction

Intuition tells us that model airplane propellers are not the ideal solution for an AUV.[1] In the case of an airplane, the fluid density of air is much less, ~1/1000 of that of water. Also, the typical RPM value intended for a model airplane's propeller is between 6,000 and 10,000 RPM, which is significantly greater than that of the AUV used in this study [2].

The reason for lack of optimization lies mainly in the cost. In designing a vehicle, off-the-shelf components are very desirable. It would be much more costly to design and fabricate a propeller design than it would be to order one that has already been tested and can easily be replaced. The AUVs considered in this paper often do not require high speeds compared to REMUS AUVs [3], and off-the-shelf propellers suffice [4]. Therefore, many AUV designs incorporate a commercially available model airplane propeller.

In a situation in which fabricating and testing propellers is prohibitively expensive, or it is desirable to use existing propellers, modifications can be made to improve performance in propeller efficiency. This analysis seeks to provide both an ideal design for specific AUV operations, as well as methods for improving performance using off-the-shelf model airplane propellers.

II. Design Methods

A. Propeller Modeling

Today, computers allow a detailed optimization of propellers. Propeller design is used to model the hub geometry with an image vortex. Hub and tip loading effects can be considered in rigorous analysis. After optimizing an initial design, the propeller performance undergoes two-dimensional analysis, including determining minimum pressure coefficients and local lift coefficients. Rigorous design methods use multiple iterations of many parameters to calculate a highly efficient propeller design.

There are many methods for propeller design [1], but in this study, propeller vortex lifting line code will be used along with two-dimensional analysis using the Brockett diagram [5] to meet the AUV specifications. These two design methods will lead to design of an optimal propeller, as well as calculate the efficiency of existing propellers, which will determine performance flaws. The resulting analysis will provide recommendations for altering the existing parameters to improve overall propeller efficiency, considering the effects of minimum pressure coefficients and ranges of lift coefficient.

B. AUV Specifications

There are several aspects which must be considered in propeller design. The propeller design for the AUV must meet the following criteria as in [4,6]:

Design speed, Vs, is 1m/s.
Inflow wake velocity variation, vvar =/-0.03m/s.
Design depth is 200m to 1km.
Cavitation effects will be tested for a depth of d = 2m.
Propeller type is assumed free tip double screw.

[1] The AUVs modeled in this study are the SeaBED prototype and its successors, JAGUAR and PUMA, all of which are intended for low-speed operations.

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The required forward thrust at operational cruising speed for the AUV is 150N, or 75N per propeller [7].

Tests taken from thrusters of a previous AUV show that it is most acceptable to model the propeller at 2RPS.

The following are characteristics of the existing propeller considered in analysis:

The propeller has three blades, or z = 3.

The hub is 0.031m, and is 0.0104 in terms of r/R.

The diameter, D, is 0.594m.

The chordlength distributions, c/D with respect to r/R, where r is the location on the radius and R is the radius length were measured using calipers.

C. *Vortex Lifting Line Codes*

Propeller vortex lifting line codes provide a powerful method for assessing the characteristics of a propeller. In this analysis, PVL Code, [8], was used in combination with MATLAB code.

The analysis considers both the optimal propeller design for the given design criteria, as well as the efficiency of the existing propeller. In finding an initial propeller design, PVL.exe was used with an input of variables, as in [1], including:

The number of blades, z.

The advance coefficient, $J = V_s / ND$. (1)

The desired thrust coefficient, $C_T = \dfrac{T}{\frac{1}{2}\rho V_S^2 (\pi R^2)}$. (2)

Axial flow ratio, V_a/V_s.

Due to the placement and size of the thrusters, the ratio of Va to Vs is one for this particular AUV. Nonetheless, a function was created to determine the effects of axial flow for alternative propeller placement or diameter of a body affecting fluid flow entering the propeller [9]. [2] The axial flow considers several important factors. The first factor is in the case that the ratio of the propeller blade diameter to the hull diameter is not equal to one. The data was extended to include a case of a ratio of up to 1.8. Additionally, the practical assumption was made that axial flow is constant for all r/R values less than 0.225. Otherwise, the spline would model a value of zero or less at the hub, which is not possible.

Initial propeller geometry was chosen by varying parameters of the blade number, diameter, and revolutions per second. The blade numbers analyzed range from 3 to 6. The diameter varied from 0.5 to 1.0m, since the values of the advance coefficient, were within an acceptable range of 0.3 to 1.9. Rotational speeds appropriate for the analyzed thruster range from 1 to 3 RPS.

[2] Data from the experimental Huang Body 1 relating axial flow to radial position was splined such that it returns values for axial flow for any range and any spacing of values for radial position.

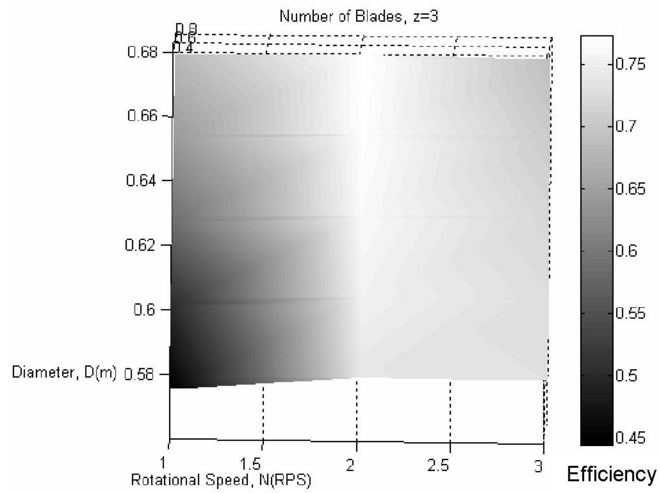


Figure 1. Choosing a Blade Based on Rotational Speed, Diameter, and Efficiency.

The results were assessed as shown in Fig. 1, using a contour plot. Three to six blades were assessed, but only the results for a three-bladed propeller are shown.

The initial design exhibits three blades, since a three-bladed propeller is more efficient in *all ranges* of diameter and rotational speed than the others. This is because a larger number of blades with a smaller diameter provide greater efficiency for the lowest range of N, whereas the three-bladed propeller provides the most efficiency at the design speed of 1.0m/s. Furthermore, the three-bladed propeller has a wide range of high efficiency (0.70 or more) at all ranges of desirable values for N. It is interesting to note that the maximum efficiency on the 3-blade propeller is for smaller values of N. Since this is the lowest of the considered values for N, it will be taken as an outlier, and not an influential part of the design decisions. The blade chosen that best satisfies all the desirable values of N, is 0.625m in diameter, with an initial calculated efficiency of 0.7091.

D. *Chordlength Optimization*

Further optimization of the chosen propeller shape is achieved through consideration of the result of chordlength on pressure distribution and the local lift coefficient. Here, a goal lift coefficient is around 0.5 at the hub, where r/R = 0.2. The lift coefficient can be determined by dimensionalizing gamma at each radial location, using the following two equations:

First, $\Gamma = 2\pi G V_S R$. (3)

Then, $C_L = \dfrac{2\Gamma}{V^* c}$. (4)

The total velocity of the lifting line, V*, can be found by using B_i, and calculating ωr less ut* given from APLOT.plt in PVL. The geometry is as shown in Fig. 2.

TABLE I
FINAL OPTIMIZED PROPELLER PERFORMANCE VS. RADIUS POSITION

r/R	V*	B	Bi	CL	G	σ	-CPmin
0.2000	1.2788	51.8538	57.9439	0.4936	0.0228	43.7157	0.56
0.2500	1.4060	45.5278	51.9462	0.4871	0.0239	118.7362	0.55
0.3000	1.5478	40.3256	46.7912	0.4867	0.0258	97.8371	0.53
0.4000	1.8621	32.4814	38.6047	0.4866	0.0293	67.4235	0.49
0.5000	2.2023	26.9896	32.5685	0.4754	0.0314	48.0748	0.48
0.6000	2.5581	22.9968	28.0254	0.4599	0.0317	35.5383	0.46
0.7000	2.9242	19.9909	24.2683	0.4075	0.0293	27.1253	0.38
0.8000	3.2973	17.6570	20.8232	0.3519	0.0235	21.2771	0.33
0.9000	3.6749	15.7984	17.5931	0.3120	0.0146	17.0847	0.27
0.9500	3.8645	15.0050	16.0380	0.2578	0.0091	15.4287	0.24
1.0000	4.0543	14.2864	14.5165	0.2391	0.0005	13.9991	0.22

TABLE II
BLADE GEOMETRY FOR OPTIMIZED PROPELLER, USING ML TYPE NACA, A=0.8, AND NACA-66 SECTIONS

r/R	P/D	c/D	Δα	fo/c	to/c	rake/D	Skew
0.2000	1.0660	0.2269	2.6878	0.0335	0.079	0	0
0.2500	1.0609	0.2193	2.4448	0.0331	0.078	0	0
0.3000	1.0590	0.2148	2.2207	0.0330	0.070	0	0
0.4000	1.0599	0.2029	1.8460	0.0330	0.055	0	0
0.5000	1.0638	0.1885	1.5609	0.0323	0.050	0	0
0.6000	1.0693	0.1693	1.3438	0.0312	0.046	0	0
0.7000	1.0635	0.1545	1.1756	0.0277	0.041	0	0
0.8000	1.0340	0.1275	1.0426	0.0239	0.039	0	0
0.9000	0.9809	0.0801	0.9355	0.0212	0.030	0	0
0.9500	0.9455	0.0572	0.8896	0.0175	0.025	0	0
1.0000	0.9042	0.0032	0.8479	0.0162	0.023	0	0

The value of sigma can be found from the following equations:

$$h = h_o - (r/R)(\tfrac{D}{2}) \text{, where } h_o = \text{operating depth.} \quad (5)$$

$$\sigma = \frac{Patm + \rho gh - Pvap}{\frac{1}{2}\rho V^{*2}} \quad (6)$$

Sigma is used later on in comparison with the minimum pressure coefficient, where σ > C_{Pmin} in order for cavitation not to occur [1]. Due to the relatively low RPSs needed for this vehicle and the operating depth, cavitation is not likely to occur [6]. However, the case in which cavitation could present problems will be investigated by analyzing propeller pressure coefficients at a shallow operating depth of 2m.

A large aspect of the 2-D design in this analysis utilizes the Brockett diagram with NACA-66 sections [4] in finding the camber ratio, f_o/c and the inflow variation bucket width, Δα, is used to determine the thickness ration, t_o/c and local pressure distribution coefficient, C_{Pmin} [1]:

$$\Delta\alpha = \tan^{-1}\left(\frac{v\,\mathrm{var}}{V^*}\right)2 \quad (7)$$

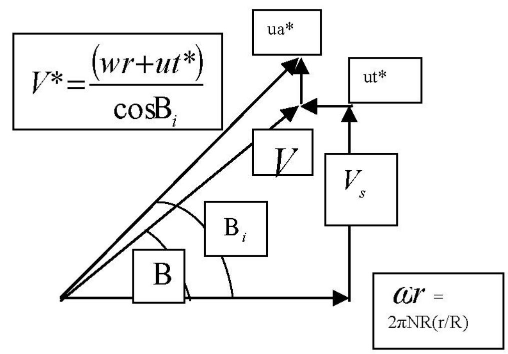


Figure 2. Geometry for determining total lifting line velocity, V*, as in [1].

$$\frac{f_o}{c} = \frac{f_{oCHART}}{c}\left(\frac{C_L}{C_{LCHART}}\right) \quad (8)$$

$$f_{oCHART} = 0.0679, \quad C_{LCHART} = 1.0. \quad (9)$$

Cavitation is an important design consideration in shallow-water operations. In addition to being less efficient, partial cavitation creates bubbles which can damage propeller blades through pitting. Some high-speed AUVs avoid reduction on propeller efficiency by super-cavitating [10]. Super-cavitation is not an option for the low-speed AUV analyzed in this paper. Additionally, the thrusters are mounted such that the thruster housing diameter is too small to facilitate super-cavitation. The data for the final propeller design, in which lift and non-cavitation requirements are easily fulfilled, is shown in Table I.

In this design, aspects defining the propeller geometry, including the rake/D and the skew is assumed to be zero. The pitch to diameter ratio, P/D, is calculated thus:

$$P/D = \tan(B_i + \alpha_i)\pi\left(\frac{r}{R}\right),$$

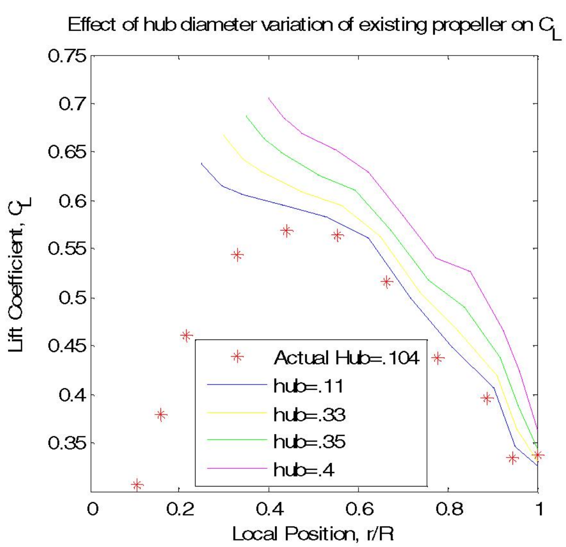
where α_i = 1.54°, from NACA Mean Line a = 0.8. (10)

TABLE III
EXISTING PROPELLER PERFORMANCE VS. RADIUS POSITION

r/R	V*	B	Bi	C_L	G	σ	$-C_{Pmin}$
0.2000	1.0888	68.7862	73.2997	1.0691	0.0143	198.7506	0.93
0.2500	1.1767	59.1563	65.2233	1.2170	0.0169	169.9533	1.02
0.3000	1.2923	51.1250	58.0726	1.3675	0.0211	140.6989	1.12
0.4000	1.5825	39.2448	46.5828	1.3573	0.0289	93.5663	1.09
0.5000	1.9215	31.3387	38.2319	1.3741	0.0342	63.2903	1.05
0.6000	2.2877	25.8917	32.1280	1.3561	0.0365	44.5251	1.02
0.7000	2.6704	21.9756	27.2771	1.2697	0.0349	32.5871	0.95
0.8000	3.0637	19.0490	23.0115	1.1103	0.0289	24.6877	0.81
0.9000	3.4634	16.7904	19.1435	0.8699	0.0185	19.2633	0.63
0.9500	3.6646	15.8456	17.3195	0.6695	0.0117	17.1820	0.49
1.0000	3.8661	14.9993	15.5565	0.6255	0.0007	15.4153	0.46

TABLE IV
BLADE GEOMETRY FOR EXISTING PROPELLER, USING ML TYPE NACA, A=0.8, AND NACA-66 SECTIONS

r/R	P/D	c/D	Δα	fo/c	to/c	rake/D	Skew
0.2000	1.2058	0.0770	3.1565	0.0726	0.067	0	0
0.2500	1.1707	0.0742	2.9210	0.0826	0.061	0	0
0.3000	1.1572	0.0751	2.6597	0.0929	0.053	0	0
0.4000	1.1494	0.0846	2.1720	0.0922	0.047	0	0
0.5000	1.1505	0.0814	1.7890	0.0933	0.037	0	0
0.6000	1.1551	0.0739	1.5026	0.0921	0.032	0	0
0.7000	1.1476	0.0647	1.2873	0.0862	0.028	0	0
0.8000	1.1137	0.0533	1.1221	0.0754	0.023	0	0
0.9000	1.0532	0.0386	0.9926	0.0591	0.021	0	0
0.9500	1.0130	0.0301	0.9381	0.0455	0.019	0	0
1.0000	0.9663	0.0017	0.8892	0.0425	0.018	0	0



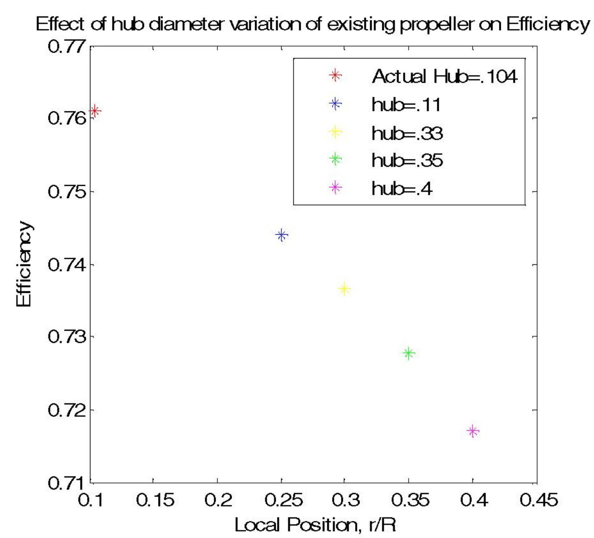


Figure 3. C_L and Efficiency for varying hub diameters and z = 3blades, N = 2RPS, D = 0.594m.

The design requirements can be summarized into Table II, from which the optimized propeller could be fabricated.

Now that an optimal propeller has been designed, a comparison between both off-the-shelf and the designed propeller can be made. This will help to make improvements to the existing propeller, as well as to provide guidance on selecting future off-the-shelf propellers. In order to make a quick comparison, the equivalent of Tables 1 and 2 of propeller geometry are shown for the existing propeller design in Tables 3 and 4. It is important to note that the Table 4 values use optimal calculations for the pitch over diameter.

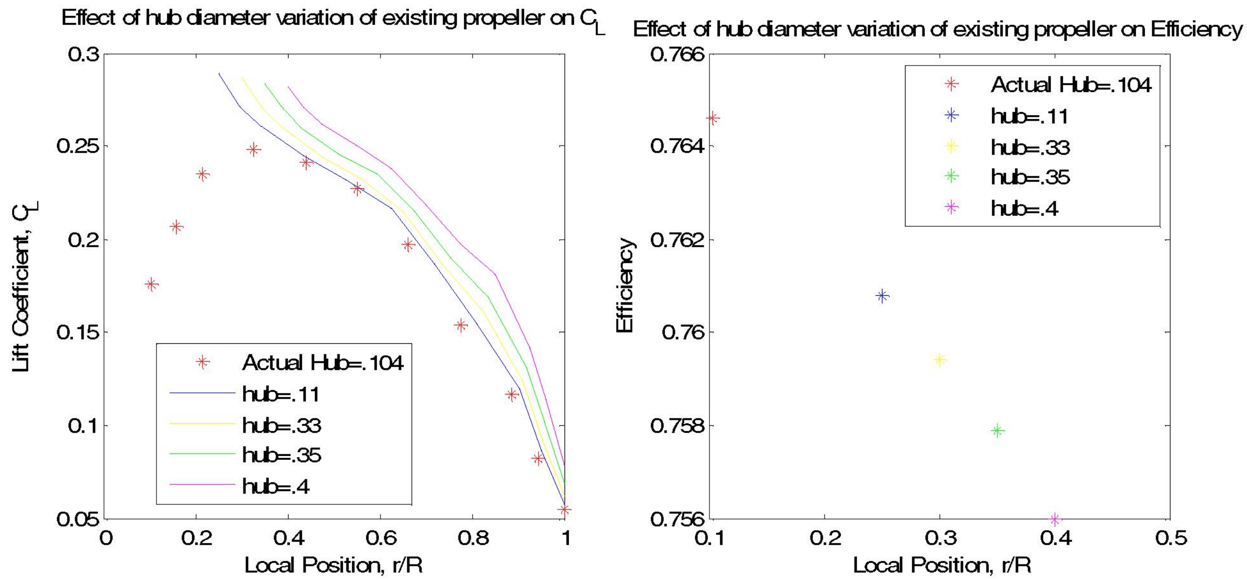


Figure 4. C_L and Efficiency for varying hub diameters and z = 3blades, N = 2RPS, D = 0.76m

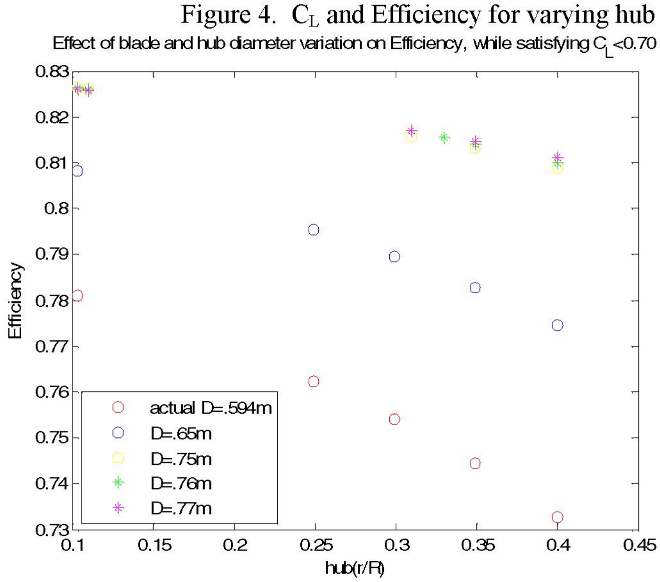


Figure 5. Efficiency vs. variation of blade hubs for different diameters, ‘o’ indicates C_L<0.7 is NOT satisfied, while ‘*’ indicates C_L<0.7.

These values are significantly different from the actual P/D, which is measured as 0.427 for r/R equal to 0.7.

Analysis determined that the lift coefficients on the existing propeller were unacceptably high. Therefore, appropriate analysis determined the effect of hub diameter variation on the lift coefficients, while still considering the effect of hub variation on propeller efficiency, as shown in Fig. 3.

Due to high values of lift coefficients for the model-airplane propeller, the effect of different blade diameters on lift coefficient and calculated efficiency were modeled. A list of criteria determined the chosen propeller design:

The lift coefficient would be reduced to 0.7 or below at the hub, and below 0.25 at the blade tips.

The efficiency would be maximized for z = 3 and N = 2, with the original chord distribution.

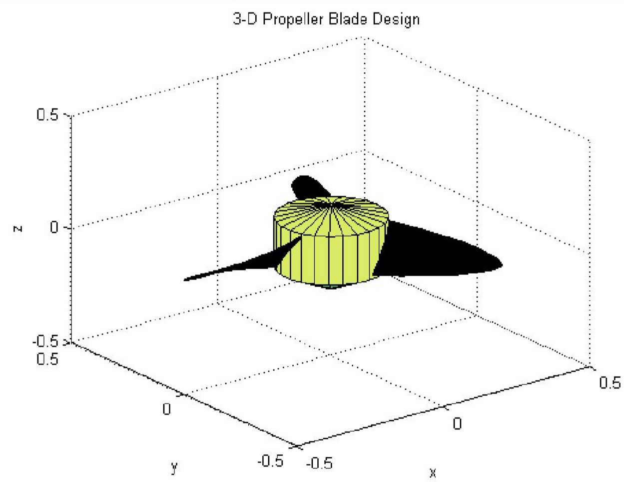


Figure 6. MATLAB representation of optimal modified off-the shelf propeller.

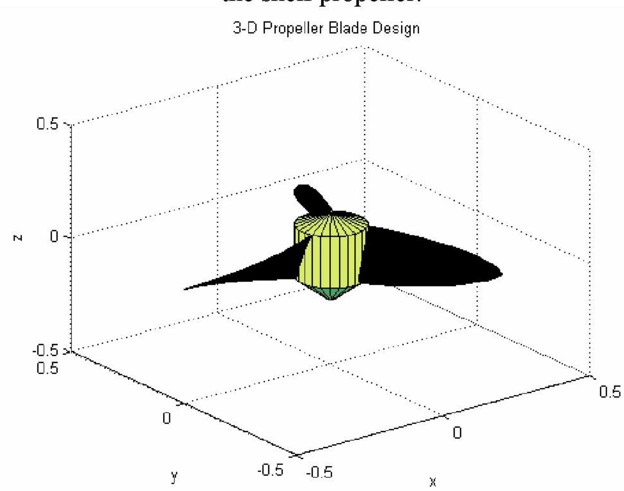


Figure 7. MATLAB representation of final propeller design.

The optimal diameter would be as close as possible to the original diameter, while satisfying the design requirements.

The effect of variable hub diameter for the chosen blade diameter of 0.76m on C_L and efficiency are shown in Figure 4. Using the results shown in Fig. 5, the design chosen was 0.76m, with a hub extending to r/R = 0.31, and an efficiency of 0.8154 and an actuator disk efficiency [1] of 0.9287.

A visual comparison of the off-the-shelf propeller modification and the final propeller design is shown in Fig. 6 and 7.

III. Conclusions and Recommendations

Optimal propeller design emerges from the interaction and adjustment of many parameters. As an AUV's speed of operation decreases, so will the RPS of the propeller. In general, it was found that larger diameter propellers were more efficient for low-speed operations (although they have a limit), and increased RPS resulted in the need for smaller propellers.

The final optimal propeller was designed with three blades, at 2RPS, a hub starting at r/R(0.2), and a diameter of 0.625m. A design depth of 2m resulted in no cavitation effects. The design had a modified chord distribution which resulted in a lift coefficient ranging from less than 0.5 to less than 0.24. The initial propeller design had an efficiency of 0.7091, and the final design had an efficiency of 0.7642, for an improvement of 5.51 percent from optimizing the chord distribution.

The existing propeller required attention specifically to the lift coefficient and the value of P/D. The PVL lifting line code does not take into consideration stalling effects of the propeller due to C_L values greater than one from the hub to r/R = 0.9. In the case of this particular propeller, the lift coefficient values were considerably higher than that of the design propeller, and likely to cause stalling. In order to complete a rigorous analysis, efficiency losses due to high C_L values should be made.

The pitch over diameter value calculated for propeller performance was far lower than the actual value taken at r/R = 0.7. Therefore, the efficiency value calculated for the existing propeller was erroneously dependent on an optimal circulation distribution. The P/D ratio can be increased in future blades by increasing the chordlength or decreasing the propeller diameter.

Under the assumption that the existing propeller is sold off-the-shelf for a scaled range of diameters, analysis showed rewarding performance improvements as a result of increasing the propeller and the hub diameters. The lift coefficients at a 0.76m blade diameter and a hub at r/R equal to 0.31 were within a satisfactory range. Furthermore, the efficiency showed a 3.44 percent improvement, from an efficiency of 0.7810 to 0.8154. The efficiency improvement was actually greater than could be measured using the methods in this analysis, since the effect of stalling was not accounted for in computing the efficiency for the original propeller design. Consideration was made in cutting down the tips of the propeller, but this would be counterproductive due to the fact that the modeled efficiency decreased as propeller diameter decreased, as well as the added effort and cost of modifying the propeller. The optimized design blade did have a lower calculated efficiency, however, the requirements for its range of acceptable C_L values were more stringent, and did not account for loss of efficiency through stalling effects. If the off-the-shelf geometry were held to the range of C_L values less than 0.5, the propeller diameter would get prohibitively large.

Calculations show that many factors contribute to propeller efficiency. Therefore, it is important to recognize that a design with PVL results of high efficiency does not consider stalling effects of high lift coefficients. The actuator disk efficiency serves as a check against efficiency. If a value higher than the actuator disk efficiency is found, it can be eliminated as erroneous. The coefficient of lift and pitch over drag make significant contributions, and should not be overlooked.

There are several methods that merit further investigation, which would modify the existing propellers in order to provide greater efficiency. First, the hub size of the propeller could be increased, which decreases the lift coefficient, and therefore prevents stalling. Additionally, the propeller diameter should be increased to improve efficiency and reduce the effects of stalling. Under the assumption that the same off-the-shelf propeller geometry exists for greater propeller diameters, investigations showed that the lift coefficient, and thus overall performance, could be improved from both of these modification methods.

Further investigation into optimal rotational speed will lead to better designs of AUV propellers. In this design, some approximations were made on the range of practical RPS values, due to minimal information on AUV thruster performance. A factor that was not considered, but is essential to overall AUV performance, is the interaction among the AUV's design speed, thruster speed, and power consumption. However, when detailed AUV information is available, the requirements for the propeller design will become more complex, but the same principles for the geometric design remain the same. Therefore, the MATLAB code and other methods used for this propeller design provide a useful tool for further applications.

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