An Open Source Parametric Propeller Design Tool

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Abstract-**An open source computational propeller/turbine design tool, the user-friendly open source MIT Propeller Vortex Lattice Lifting Line Program (OpenProp), is presented in this paper. This code has applications in propeller design for AUV and ROV thrusters as well as conventional propellers. The code is also being utilized for tidal turbine design. OpenProp is designed to be a fast parametric design tool for use by engineers with little training in propeller design. This tool can also be used by more experienced designers, as a preliminary design tool, to produce a starting design for further refinement using more advanced design and analysis codes.**

Various design examples are presented, including an ROV propeller design and a contra-rotating AUV Thruster design. These propellers were constructed and performance tested. The performance data for these propeller designs is also presented. The code was validated against the US Navy's PLL code and these results are also presented. The OpenProp propeller design tool is part of a suite of open source tools under development for rapid design, building and testing of propeller design models.

I. Introduction

OpenProp is a vortex lifting-line based propeller design for light to moderately loaded propellers. The design uses MATLAB to create a user-friendly Graphical User Interface (GUI) for inputting propeller design parameters. OpenProp features both a detailed parametric design analysis for initial propeller optimization, and a single propeller design option. Fig. 1 provides a screenshot of the typical output of a propeller design, showing the predicted performance and details of the output propeller blade shape.

OpenProp's propeller design algorithm is based on a 3D vortex lattice lifting line analysis of a user-specified number of vortex panels along the propeller span, with vorticies and control points placed using the cosine spacing method. A helical wake model is incorporated which is aligned with the flow at the lifting line, giving the code the capability to design moderately loaded propellers.

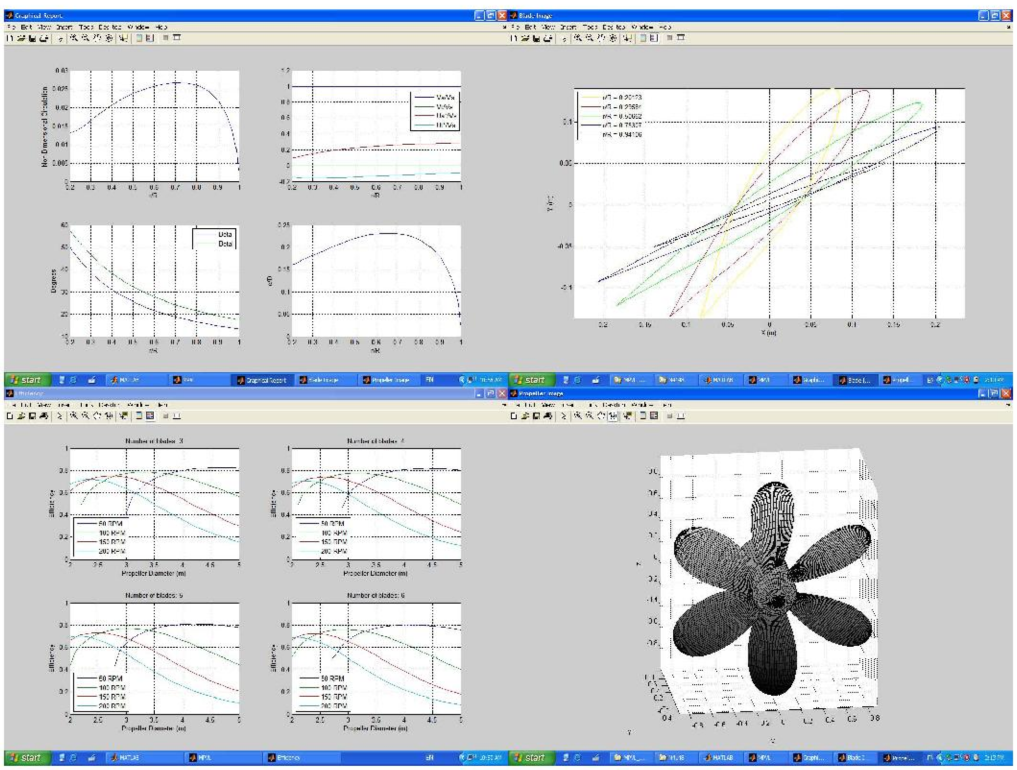

Figure 1. OpenProp Single Propeller Design sample output [2].

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The radial loading distribution is optimized using Lerbs criteria and thus can optimize performance for radially varying circumferential mean inflow. The propeller blade sections are generated using meanline and thickness forms selected by the user. These sections are set at an ideal angle of attack to the locally computed lifting line flow. From user input, a parametric analysis with varied number of blades, blade speed, and size is performed. Also, the geometry for a detailed single blade design is produced. User inputs are guided by population of fields in the GUI, and since the source code is available as an m-file, the GUI is highly modifiable.

The geometry created by the blade design software can successfully be converted into a stereolithography (.STL) file using a NURBS modeling program, such as RHINO. The STL files can be read and printed into model blades or molds. The OpenProp software gives users the ability to quickly optimize the propeller design, create the propeller geometry and produce the model prototype or mold. OpenProp is easily adaptable in its original MATLAB form, but is also usable as a standalone executable file for non-MATLAB users.

This propeller design software is part of a suite of open source tools currently under development. OpenProp provides a foundation for further advancement of capabilities within the code. Some planned extensions of the code are:

- Turbine design capability (tidal turbines, windmills)
- Ducted design
- Cavitation analysis capability
- Structural analysis capability
- Multiple element propulsors (stators, contrarotating propellers, etc.)

As an open source tool, OpenProp allows others to easily add their own features and capabilities.

II. OpenProp Code

OpenProp is an open-source propeller design tool that has the capability to manufacture propeller blades from desired design inputs. The OpenProp propeller design tool is based on the FORTRAN programs originally developed by Professor Justin Kerwin at MIT in 2001[1], translated into MATLAB as MPVL code released by Hsin-Lung Chung in May 2007 [2]. OpenProp operates using an evolved MPVL code, while expanding upon MPVL's applications, and it has been modified to create scripting for 3D printable files. OpenProp creates a user-friendly interface to quickly input design characteristics and output performance data and propeller blade geometry.

A. Theory and Validation

OpenProp is based on traditional vortex lattice lifting line theory, as described by Kerwin [1][3] and Coney [4]. The optimization algorithm is based on Lerb's criteria, which is an extension of the Betz criteria requiring that the ratio of the inflow to outflow angles be constant for the optimum design. The Lerbs criteria allows for radially varying circumferential mean inflow, which is provided as an input. This gives the code some capacity to deal with a non-uniform inflow profile.

The force distribution on each blade is represented by a vortex lattice line extending from hub to tip. The hub is represented by image vortices and the wake trailers are represented as constant pitch helical vortices. The solution starts with a guess at the vortex strengths assuming a propeller efficiency close to actuator disk theory and scaled to match thrust. Next, induced velocities due to the vortex system are computed at the lifting line, and the wake helices are iterated in this procedure until they align with the local flow and the Lerbs criteria is met. This computes the optimum circulation distribution. Since hub loading often needs adjustment to prevent cavitation, the code allows for hub circulation modification [1][3]. Thus, the wake is aligned with the propeller blade, which is a method that has traditionally been called 'moderately loaded lifting line theory'. This theory breaks down for heavily loaded propeller design because the wake trailers are assumed to be of constant pitch and diameter.

Once the circulation distribution is determined, the code uses 2D strip theory to construct the 3D blade. At each radii, the lift is computed from the circulation distribution, along with the local velocity at the lifting line. A 2D foil section is fit to the input chord length and thickness and the section is then placed at the ideal angle of attack relative to the local flow. The camber is adjusted to achieve the required lift (in a 2D strip sense). In this fashion, the entire propeller blade is 'built'. Currently, only the Brockett modified NACA a = 0.8 meanline with NACA 63 thickness distribution is available for the foil (Brockett[5]). More foil section choices are planned for future versions of the code.

The MPVL implementation was validated against the original code of Kerwin [3] as well as against the US Navy's PLL code, and this validation is described by Chung [2]. In summary, the MPVL code calculation validated by Chung matches the results of [3] to the fifth decimal place. The agreement with PLL is within a percent on circulation for a typical propeller design, the difference being due to the differing optimization algorithms of the two codes [2].

B. Parametric Analysis

Three parameters provide the foundation for propeller design: the number of blades, the propeller speed, and the propeller diameter. Various combinations of these three key parameters result in different efficiencies. Thus, a parametric study allows for propeller parameter optimization. The 'Parametric Analysis' GUI is a computational tool that calculates and graphically represents propeller efficiency.

OpenProp is tailored to a propeller user's design needs, therefore, the 'Parametric Analysis' GUI requires user input for the following characteristics:

- Number of blades
- Propeller speed
- Propeller diameter
- Required thrust
- Ship speed
- Hub diameter
- Number of vortex panels over the radius
- Maximum number of iterations in wake alignment
- Ratio of hub vortex radius to hub radius
- Number of input radii
- Hub and tip unloading factor
- Swirl cancellation factor
- Water density
- Hub image flag

All of the fields within the GUI are populated with initial values, based on the US Navy 4148 propeller, as a guide to users. Each of the input fields are modifiable, and 'Parametric Analysis' can run any desired number of times without having to exit the program [2].

C. *Single Propeller Design*

Once the parameters for a propeller with a viable efficiency curve has been established, the desired inputs are entered into the 'Single Propeller Design' GUI of OpenProp. Determining the geometry for a single propeller utilizes both the results from the propeller parameterization, as well as additional inputs, resulting in a user-specific design. Input fields entered for the 'Parametric Analysis' are populated with the same values for the 'Single Propeller Design.' There are also several additional input fields, including: shaft centerline depth, inflow variation, ideal angle of attack, and the number of points over the chord. Additionally, two types of meanlines are available within the program: the NACA a=0.8 and the parabolic meanline. The thickness forms available include: NACA 65 A010, elliptical, and parabolic. OpenProp is easily modified to accommodate additional meanlines and thickness forms.

A single propeller can be designed and quickly evaluated graphically. One of the file outputs of the 'Single Propeller Design' is the blade geometry. This feature of OpenProp automatically transforms x, y and z coordinates of the designed propeller blade geometry into a command file that can be read by a CAD program. The user opens the command file in a CAD program, such as RHINO, or another modeling program, and has the option of saving their design as a useful stereolithography (.STL) file, or as an Initial Graphics Exchange Specification (.IGES) file [6]. The single propeller design option creates both a propeller geometry and a corresponding scripting code which allows the propeller to be created as a .STL file and then printed on a 3D printer, as shown in Fig. 2. Propeller designs can be modified and saved with the OpenProp tools repeatedly, at no cost to the user.

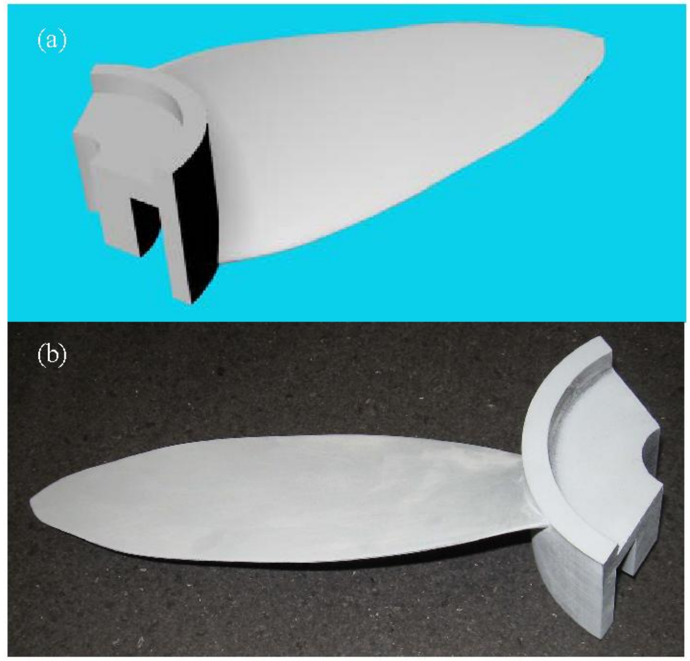

Figure 2. Propeller design in CAD (a) and the 3D printed result (b).

III. PROPELLER PROTOTYPING

Material options for a Fusion Deposition Modeling (FDM) printer include three types of plastics: ABS, polycarbonate, and an ABS/polycarbonate blend. While ABS solids can be easily filed down to a smooth finish, if necessary, after printing, the material's tensile and flexural strengths and modulus of elasticity are not comparable to that of the ABS/polycarbonate blend. Additionally, the polycarbonate and the ABS/polycarbonate are more rigid than ABS, and therefore undergo less deformation from the desired propeller prototype geometry [6].

Another option is to use the printed propeller blade as the geometry from which a polyurethane mold can be cast. Using this method, propellers can be manufactured from a hard polyurethane, or other substance which affords greater loads to be subjected upon the propeller blades both in prototype testing and for use on underwater vehicles. The additional benefit to constructing a mold is that it is more economical than using an FDM machine, and multiple molds can be made, decreasing the manufacturing time [6].

IV. USING OPENPROP FOR PROPELLER DESIGN

OpenProp allows users even with limited backgrounds in propeller design to produce a prototype propeller. The process for using OpenProp to produce a usable file that can be read by a 3D printer is illustrated in Fig. 3. First, the user has the option to determine design boundaries with the 'Parametric Analysis' tool in OpenProp. Desired characteristics of the vehicle may be entered into the 'Parametric Analysis' GUI of OpenProp in order to determine the range of appropriate propeller characteristics that should be used as input for the 'Single Propeller Design' of OpenProp.

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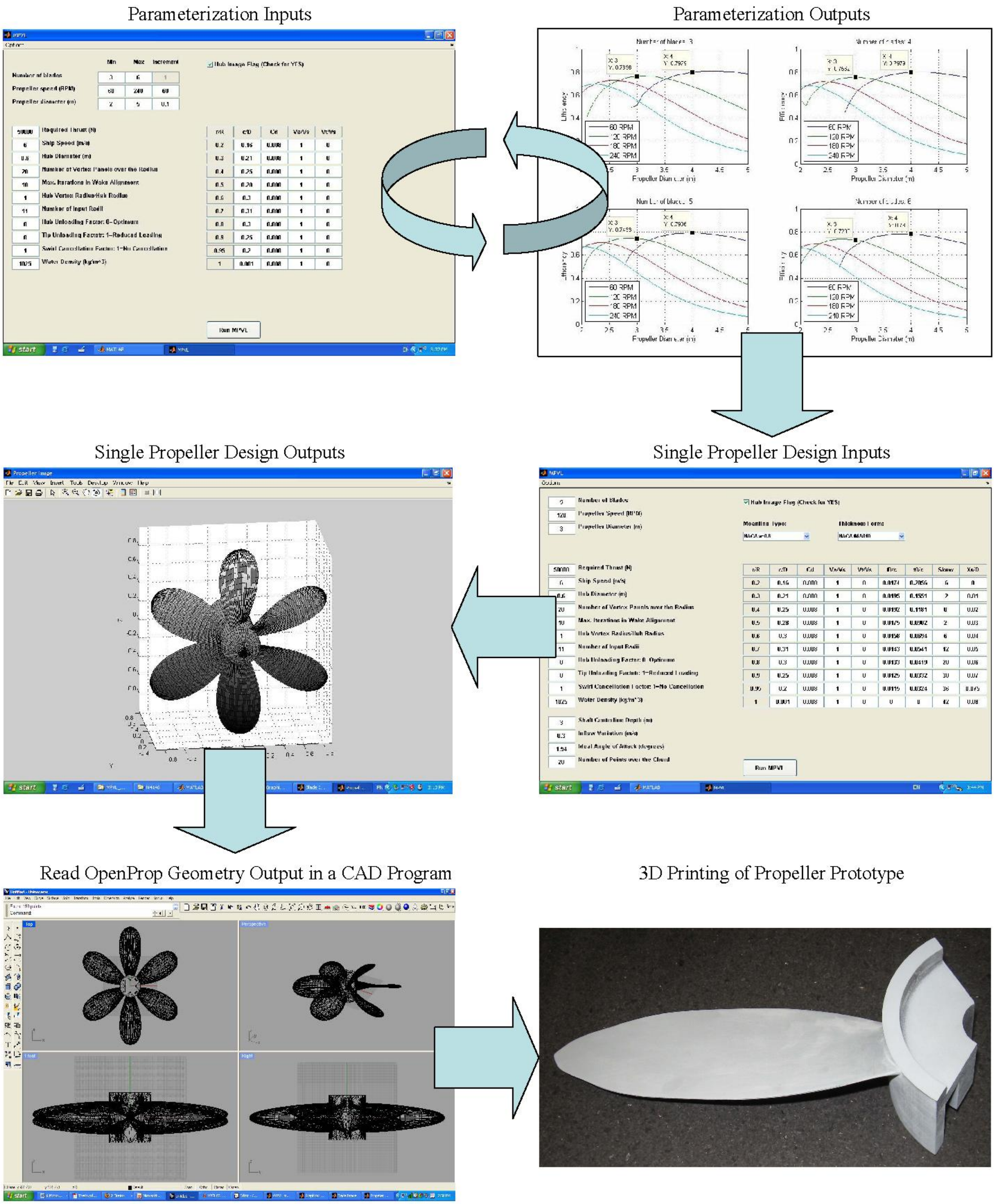


Figure 3. OpenProp design-to-prototyping process.

Next, the user enters desired design characteristics in the 'Single Propeller Design' option of OpenProp. The user has the option to create a filename and save a variety of propeller initial inputs and outputs, including geometries that can be read as command files into a CAD program and saved as .STL files. The .STL files can be read and printed into model blades, from which molds may be made. The .IGES files are recognized by a variety of CAD programs.

OpenProp uses several simple steps to guide propeller users of all propeller design backgrounds in rapidly creating the optimal propeller geometry for their design specifications that can be printed, tested, and ultimately put to use. OpenProp is an open-source MATLAB-based code, which is highly modifiable for the experienced user. MPVL is also accessible as an executable file, for non-MATLAB users [2].

V. Case Studies

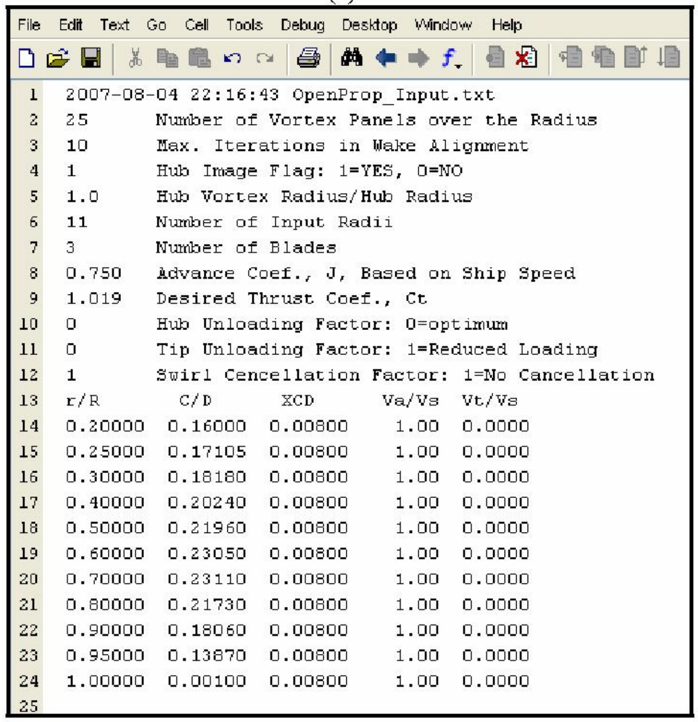
The OpenProp code is adaptable to a variety of propeller missions. The design example in which OpenProp is used to create a printable file for the OpenProp 4148 propeller blade is outlined. The case study involving the development and construction of contra-rotating AUV thrusters and the printing of underwater propellers designed for low-speed, high-drag vehicles are also described. It is our intent that these case studies will provide the OpenProp user with guidance in using its propeller-producing capabilities for a wide range of propeller design criteria.

A. *OpenProp Model Propeller Printable File*

OpenProp can be used in a straightforward process to create propellers optimized for a set of necessary design characteristics. In this case, OpenProp will be used to analyze and create the geometry for a model based on the US Navy 4148 propellers. The propeller design is a 1:8 scale model, with characteristics are determined by using the dimensionless characteristics of the thrust coefficient, 0.225 and the advance coefficient, 0.75. The model has three blades, 0.25 m in diameter. The propeller is designed to run in a tank that can simulate a vehicle speed of 5 m/s, and a thruster that can run at 1600 RPM. OpenProp saves the initial design characteristics in an 'input' file, as in Fig. 4.a.

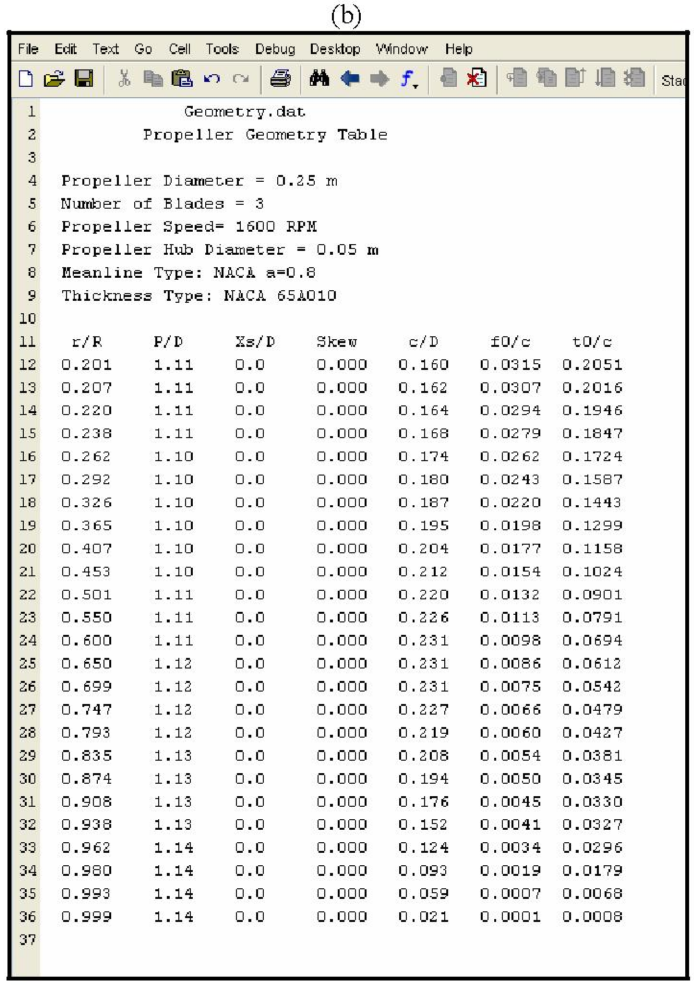
OpenProp creates files which output the propeller geometry, a summary of the propeller's design characteristics, and the propeller performance. The propeller geometry file (Fig. 4.b) records the propeller diameter, number of blades, propeller speed, hub diameter, meanline type, thickness form, pitch, skew, rake, chord distribution, camber distribution and thickness distribution. Propeller geometry provides a means for manufacturing. The propeller performance file (Fig. 4.c) is useful for cavitation analysis and contains a table which lists the total inflow velocity (V*), the undisturbed flow angle (β), the hydrodynamic pitch angle (βi), the vortex sheet strength (Gamma), the lift coefficient (C_L), the cavitation number (δ), the pitch angle variation δβi, maximum camber ratio and maximum thickness ratio over the radius. OpenProp computes a summary of propeller design characteristics (Fig. 4.d) at radial increments, in addition to the design thrust coefficient and propeller efficiency, which in this case is 0.6745 [2].

(a)



```
2007-08-04 22:16:43 OpenProp_Input.txt
25       Number of Vortex Panels over the Radius
10       Max. Iterations in Wake Alignment
1        Hub Image Flag: 1=YES, 0=NO
1.0      Hub Vortex Radius/Hub Radius
11       Number of Input Radii
3        Number of Blades
0.750    Advance Coef., J, Based on Ship Speed
1.019    Desired Thrust Coef., Ct
0        Hub Unloading Factor: 0=optimum
0        Tip Unloading Factor: 1=Reduced Loading
1        Swirl Cencellation Factor: 1=No Cancellation
r/R      C/D      XCD       Va/Vs  Vt/Vs
0.20000  0.16000  0.00800   1.00   0.0000
0.25000  0.17105  0.00800   1.00   0.0000
0.30000  0.18180  0.00800   1.00   0.0000
0.40000  0.20240  0.00800   1.00   0.0000
0.50000  0.21960  0.00800   1.00   0.0000
0.60000  0.23050  0.00800   1.00   0.0000
0.70000  0.23110  0.00800   1.00   0.0000
0.80000  0.21730  0.00800   1.00   0.0000
0.90000  0.18060  0.00800   1.00   0.0000
0.95000  0.13870  0.00800   1.00   0.0000
1.00000  0.00100  0.00800   1.00   0.0000
```

(b)



```
          Geometry.dat
       Propeller Geometry Table

Propeller Diameter = 0.25 m
Number of Blades = 3
Propeller Speed= 1600 RPM
Propeller Hub Diameter = 0.05 m
Meanline Type: NACA a=0.8
Thickness Type: NACA 65A010

 r/R     P/D    Xs/D   Skew    c/D     f0/c    t0/c
0.201   1.11    0.0    0.000   0.160   0.0315  0.2051
0.207   1.11    0.0    0.000   0.162   0.0307  0.2016
0.220   1.11    0.0    0.000   0.164   0.0294  0.1946
0.238   1.11    0.0    0.000   0.168   0.0279  0.1847
0.262   1.10    0.0    0.000   0.174   0.0262  0.1724
0.292   1.10    0.0    0.000   0.180   0.0243  0.1587
0.326   1.10    0.0    0.000   0.187   0.0220  0.1443
0.365   1.10    0.0    0.000   0.195   0.0198  0.1299
0.407   1.10    0.0    0.000   0.204   0.0177  0.1158
0.453   1.10    0.0    0.000   0.212   0.0154  0.1024
0.501   1.11    0.0    0.000   0.220   0.0132  0.0901
0.550   1.11    0.0    0.000   0.226   0.0113  0.0791
0.600   1.11    0.0    0.000   0.231   0.0098  0.0694
0.650   1.12    0.0    0.000   0.231   0.0086  0.0612
0.699   1.12    0.0    0.000   0.231   0.0075  0.0542
0.747   1.12    0.0    0.000   0.227   0.0066  0.0479
0.793   1.12    0.0    0.000   0.219   0.0060  0.0427
0.835   1.13    0.0    0.000   0.208   0.0054  0.0381
0.874   1.13    0.0    0.000   0.194   0.0050  0.0345
0.908   1.13    0.0    0.000   0.176   0.0045  0.0330
0.938   1.13    0.0    0.000   0.152   0.0041  0.0327
0.962   1.14    0.0    0.000   0.124   0.0034  0.0296
0.980   1.14    0.0    0.000   0.093   0.0019  0.0179
0.993   1.14    0.0    0.000   0.059   0.0007  0.0068
0.999   1.14    0.0    0.000   0.021   0.0001  0.0008
```

(c)

Performance.txt

Propeller Performance Table

r/R	V*	beta	betai	Gamma	Cl	Sigma	dBetai
0.201	4.180	49.93	58.88	0.1513	1.807	14.615	2.19
0.207	4.306	49.06	58.09	0.1515	1.742	13.770	2.22
0.220	4.558	47.39	56.57	0.1528	1.632	12.292	2.27
0.238	4.932	45.08	54.40	0.1561	1.503	10.495	2.34
0.262	5.425	42.31	51.74	0.1616	1.372	8.671	2.40
0.292	6.031	39.29	48.74	0.1693	1.247	7.014	2.45
0.326	6.741	36.20	45.56	0.1786	1.131	5.612	2.47
0.365	7.545	33.20	42.35	0.1886	1.023	4.479	2.46
0.407	8.429	30.38	39.23	0.1985	0.925	3.587	2.42
0.453	9.379	27.80	36.30	0.2076	0.834	2.896	2.35
0.501	10.380	25.50	33.60	0.2150	0.754	2.363	2.28
0.550	11.415	23.47	31.17	0.2203	0.682	1.953	2.19
0.600	12.468	21.70	29.00	0.2230	0.621	1.637	2.09
0.650	13.521	20.16	27.09	0.2228	0.571	1.391	2.00
0.699	14.557	18.84	25.43	0.2194	0.522	1.199	1.91
0.747	15.561	17.72	23.99	0.2126	0.481	1.049	1.83
0.793	16.516	16.76	22.76	0.2024	0.448	0.931	1.76
0.835	17.407	15.95	21.72	0.1886	0.416	0.838	1.70
0.874	18.220	15.28	20.84	0.1715	0.389	0.764	1.64
0.908	18.942	14.73	20.11	0.1512	0.363	0.707	1.59
0.938	19.563	14.28	19.53	0.1280	0.345	0.663	1.55
0.962	20.071	13.94	19.07	0.1023	0.329	0.629	1.52
0.980	20.459	13.69	18.74	0.0745	0.314	0.606	1.50
0.993	20.721	13.52	18.52	0.0453	0.298	0.590	1.49
0.999	20.854	13.44	18.41	0.0152	0.277	0.583	1.48

(d)

kMPVL_bare_Output.txt

kMPVL_bare Output Table

Ct= 1.0186
Cp= 1.5102
Kt= 0.2250
Kq= 0.0358
Va/Vs= 1.0000
Efficiency= 0.6745

r/R	G	Va	Vt	Ua	Ut	Beta	BetaI	c/D	Cd
0.20079	0.033516	1.00000	0.0000	0.10502	-0.17395	49.934	58.880	0.16018	0.00E00
0.20709	0.033578	1.00000	0.0000	0.10984	-0.17640	49.050	58.052	0.16158	0.00E00
0.21958	0.033918	1.00000	0.0000	0.11934	-0.18077	47.393	56.567	0.16436	0.00E00
0.23007	0.039740	1.00000	0.0000	0.13319	-0.18600	45.000	54.405	0.16044	0.00E00
0.26227	0.041162	1.00000	0.0000	0.15074	-0.19116	42.310	51.742	0.17372	0.00E00
0.29179	0.043119	1.00000	0.0000	0.17100	-0.19490	39.288	48.738	0.18007	0.00E00
0.32618	0.045475	1.00000	0.0000	0.19275	-0.19654	36.200	45.557	0.18733	0.00E00
0.36489	0.048027	1.00000	0.0000	0.21471	0.19573	33.195	42.349	0.19517	0.00E00
0.40730	0.050554	1.00000	0.0000	0.23587	-0.19261	30.376	39.234	0.20376	0.00E00
0.45275	0.052854	1.00000	0.0000	0.25535	-0.18758	27.802	36.301	0.21215	0.00E00
0.50052	0.054750	1.00000	0.0000	0.27273	-0.18122	25.500	33.603	0.21957	0.00E00
0.54987	0.056100	1.00000	0.0000	0.28781	0.17410	23.459	31.168	0.22617	0.00E00
0.60000	0.056792	1.00000	0.0000	0.30074	-0.16671	21.697	29.000	0.23050	0.00E00
0.65013	0.056737	1.00000	0.0000	0.31160	-0.15941	20.154	27.053	0.23094	0.00E00
0.69948	0.055870	1.00000	0.0000	0.32065	-0.15247	18.845	25.430	0.23110	0.00E00
0.74725	0.054143	1.00000	0.0000	0.32814	-0.14605	17.718	23.953	0.22730	0.00E00
0.79270	0.051532	1.00000	0.0000	0.33430	-0.14026	16.750	22.761	0.21880	0.00E00
0.83511	0.048034	1.00000	0.0000	0.33933	-0.13514	15.954	21.715	0.20830	0.00E00
0.87382	0.043673	1.00000	0.0000	0.34340	-0.13070	15.281	20.838	0.19359	0.00E00
0.90821	0.038499	1.00000	0.0000	0.34666	-0.12695	14.728	20.113	0.17559	0.00E00
0.93773	0.032589	1.00000	0.0000	0.34922	-0.12386	14.283	19.528	0.15175	0.00E00
0.96193	0.026043	1.00000	0.0000	0.35117	-0.12142	13.938	19.073	0.12380	0.00E00
0.98042	0.018983	1.00000	0.0000	0.35257	-0.11960	13.685	18.739	0.09287	0.00E00
0.99291	0.011545	1.00000	0.0000	0.35349	-0.11840	13.519	18.519	0.05859	0.00E00
0.99921	0.003874	1.00000	0.0000	0.35390	-0.11701	13.437	18.410	0.02111	0.00E00

Figure 4. Propeller input values (a), geometry characteristics (b), caviation performance (c), and summary of characteristics (d).

The test case presented reveals the files which OpenProp produces for analysis purposes, and shows that the geometry for a model based on the US Navy 4148 propeller can easily be produced.

B. *Contra-Rotating Propellers*

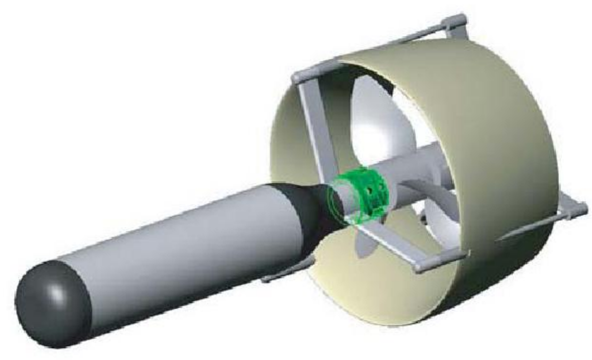
Thrusters for contra-rotating propellers were designed to fill a void in small scale marine propulsion. Many current systems, including commercial and institution-grade vehicles, rely on substandard propellers. They pay the penalty in capability and efficiency. Propeller design is a well-known problem with theoretical and computational solutions. The tools to optimize thruster designs exist, and should be used.

The design objective was a small DC electric thruster that would provide high thrust (C_T = 3.8 at 1 m/s) without sacrificing efficiency. A contra-rotating propulsor was chosen because energy lost to swirl in the wake of the forward propeller is canceled by the aft propeller. The loading is split between the two propellers, enabling each to be more efficient. Adding a duct distributes the loading even further.

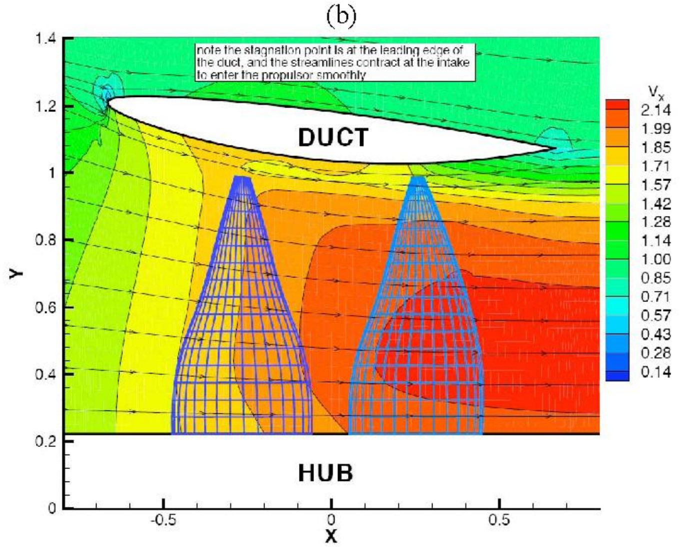
Using lifting line methods enabled us to explore a large parametric domain before optimizing the design. In our case, geometry was then refined in a coupled vortex lattice and axisymmetric Euler flow solver (PBD 14.36) [7]. The prototype propellers and duct were CNC milled in high density polypropylene, as represented by Fig. 5.a.

They were tested in a closed channel recirculating water tunnel [8] and also on a student-built ROV [9]. The axial and tangential velocities are shown in Fig. 5.b,c. Performance was close to predictions, with the exception of required torque. This was attributed to manufacturing and measurement issues. Cancellation of swirl is shown in Fig. 5.c. This contra-rotating propellers case study demonstrates the ability of lifting line code to provide propeller performance analysis for multiple-element propulsors.

(a)



(b)



(c)

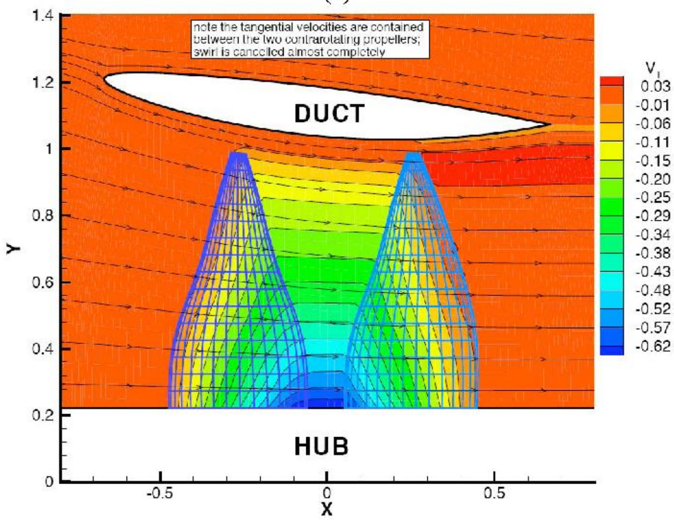


Figure 5. Contra-Rotating Propellers in CAD (a) and the corresponding axial (b) and tangential (c) velocities [8].

C. Propeller Design for an Autonomous Underwater Vehicle

Thrusters were designed using lifting line code for a slow-moving high-drag underwater vehicle. The thrusters used a three-blade propeller design, optimized for a vehicle with an advance coefficient of 0.5621 and coefficient of thrust of 0.5413 [10].

Lifting line code was used to create the propeller geometry, and the geometry was transformed into a .STL file, which was printed on an FDM machine, using an ABS/Polycarbonate blend of materials. The AUV propeller was printed to the geometry specified by the .STL files, and the result is shown in Fig. 6.

Figure 6. Case study: Propeller design for a high-drag Autonomous Underwater Vehicle.

Propellers can be printed for actual use by underwater vehicles to a size limited to that of the area in the 3D printing machine. For example, the FDM printer used in Fig. 6 is capable of printing to dimensions of 15 long by 18 inches wide. Therefore, the diameter of prototypes is limited to a 15 inch diameter unless the blades are printed separately. The case study AUV propellers were designed to interlock with a hub piece, as in Fig. 6.

VI. Conclusions and Future Work

A numerical code for the rapid design and prototyping of simple marine propellers has been presented in this paper. The code is open sourced under the GNU public license and written in MATLAB, making it a useful platform for those interested in modifying the code and adding their own extensions. Currently the code can design moderately loaded free tip propellers. Although the prototyping utilities can handle propellers geometries with significant skew and rake, these geometries are beyond the capabilities of the design algorithm; the code can be used in more advanced design as a means to create a 'starting' blade for use in more advanced codes such as 3D lifting surface codes like MIT's PDB code [8].

Three case studies were presented which demonstrated the use of the code and its capabilities. The first case study shows how dimensionless characteristics can be used to create a scaled model of a given propeller design. The case of the contra-rotating AUV thruster showed how the code might be used as part of a more advanced design process. The case study of a large single AUV propeller was presented to demonstrate how a propeller with a diameter exceeding the size of an FDM might be designed and printed. The code provides utilities to generate 3D printed prototypes using RHINO as the CAD tool for the final generation of the 3D printable files for the propeller.

The authors plan to add more advanced features to the design suite, and encourage others in the propeller design community to further develop the code to match their needs (a benefit of an open source code). Future extensions to the code which are currently underway include:

- Numerical optimization algorithm
- Ducted and banded propeller design
- Multi-blade row design
- Coupling with advanced 2D foil section design codes
- Cavitation analysis
- Strength analysis
- Utilities for prototyping using SolidWorks and other CAD platforms

The open-source code for OpenProp is provided in MATLAB m-file format or as a stand-alone executable file for PCs. The code, as well as version updates, can be found online at http://web.mit.edu/openprop/.

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