6 Design Example and Demonstration

In this chapter, a design example was introduced to demonstrate the applications of MPVL. This design example also serves as user's manual and shows the users how to start with the parametric analysis GUI to optimize the propeller parameters. With the optimized propeller parameters, the users can then produce a complete propeller design by using the single propeller design GUI.

6.1 Parametric Analysis and Optimization

A propeller design consists of three fundamental global parameters: the number of blades, the propeller speed and the propeller diameter. Different combinations of those three parameters result in different propeller efficiencies. Therefore, it is necessary to perform a parametric study to determine the optimum propeller parameters. The parametric analysis GUI is programmed to calculate the propeller efficiency of each combination of the three propeller parameters and to graphically present the efficiency curves.

Before conducting the parametric analysis in MPVL, input fields in the GUI must be introduced first. In the following paragraphs, the input fields were introduced from the left to the right and from the top to the bottom of the GUI. Also see Figure 6.1 for reference.

Number of Blades: The minimum and maximum numbers of blades are two and six respectively. Propellers normally have number of blades within this range. Users are able to modify this constraint in the **MPVL.m** file.

Propeller Speed: The unit of this input filed is in RPM. The restrictions are that the value must always be positive, the maximum value must be greater than or equal to the minimum value, and the increment should never be negative.

Propeller Diameter: The unit of this input field is in meter. The restrictions are that the value must always be positive, the maximum value must be greater than or equal to the minimum value, and the increment should never be negative. Also, this field should always be greater than the hub diameter.

Required Thrust: The required thrust is related to the calculation of the thrust loading coefficient (C_T) and the thrust coefficient (K_T). The unit of this input field is in Newton.

Ship Speed: This input field is related to the calculation of the advance coefficient (J) and the thrust loading coefficient (C_T). The unit of this field is in meter per second.

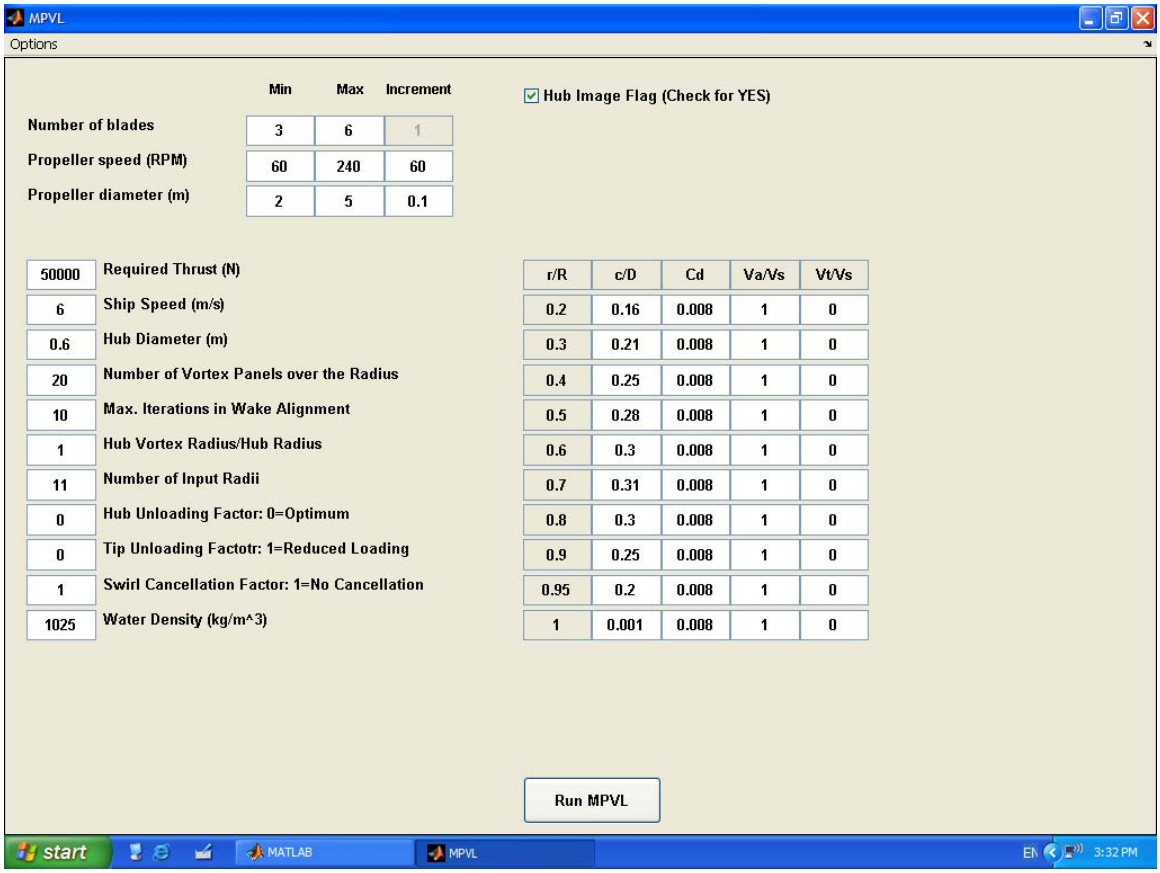

Figure 6. 1 Inputs for Parametric Analysis

Hub Diameter: Most propellers have a hub diameter which is greater than 15% of the propeller diameter. Normally, 20% to 30% of the propeller diameter would be a reasonable guess for this input field. The unit of this input field is in meter.

Number of Vortex Panels over the Radius: This input field represents how many vortex panels the blade will be divided into and thus effects the resolution of the propeller blade. The Cubic Hermite Polynomial Function[26] is then adopted to interpolate the chord distribution, the drag coefficient and the inflow velocities on each vortex panel. Usually, twenty panels would provide sufficient resolution. Increasing the number of panels will cost more time on unnecessary data interpolations.

Maximum Number of Iterations in Wake Alignment: This input field determines how many iterations MPVL is allowed to align the wake. Like PVL, MPVL is a wake-adapted method which calculates the circumferential volumetric mean inflow and then optimizes circulation and pitch distribution. Ten iterations are usually sufficient for the program to converge and align the wake.

[26] (Hanselman and Littlefield 2005, 340)

Ratio of the Hub Vortex Radius to the Hub Radius: M.H. Wang[27] computed the hub drag as a function of the ratio of vortex core radius to hub radius. Kerwin[28] agreed that the precise value of this ratio is not critical. For convenience, this ratio was assumed to be one for this design example.

Number of Input Radii: This input field determines how many input data points will serve as the original data to be interpolated with the number of vortex panels over the radius. That means the value of this field is arbitrary but smaller than the number of vortex panels over the radius.

Hub and Tip Unloading Factor: These two factors decide the degree of hub and tip unloading, and their values range from zero to one. The hub and tip unloading factors are defined as the fractional amount that the difference between the optimum values of tan β_i and tan β are reduced[29]. For example, if the hub unloading factor is zero, tan β_i - tan β at the hub is retained at its optimum value from Betz/Lerbs criterion[30]. If the hub unloading factor is one, tan β_i - tan β at the hub is set to zero, and the values up to the mid span of the blade are blended parabolically to the optimum value. The same procedure applies to the tip. In this design example, the hub and the tip were not unloaded, and therefore the two factors were zero.

Swirl Cancellation Factor: The swirl cancellation factor is zero for contra-rotating propellers in which the tangential induced velocities from each blade row exactly cancel[31]. This way, the net circulation at the hub can be designed to be zero, and there will be no hub vortex and no hub vortex drag. In this design example, there was no swirl cancellation, and therefore the value of this factor was one.

Water Density: The water density depends on the users' preference. The default value is 1,025 kg/m^3 for seawater.

Hub Image Flag: This input field is located on the upper right side of the GUI. By checking this option, a hub image is present, and the circulation has a finite value at the hub[32]. Unchecking this option will lead to a zero circulation at the root of the blade.

The tabulated editable textboxes on the right of the GUI contain four input fields. The first column of the table is the non-dimensional chord distribution (*c/D*) over the radius. The second column is the drag coefficient (Cd) over the radius. The third and the fourth columns are the ratios of the axial and tangential inflow velocities to the advance velocity over the radius. For simplicity, these four input fields are set to start at 20% of propeller radius (r/R=0.2) and end at the blade tip (r/R=1). MPVL automatically interpolates these four input fields in accordance with the number of input radii and the hub radius.

[27] (Wang 1985)
[28] (Kerwin 2001, 184)
[29] (Kerwin 2001, 185)
[30] (Kerwin 2001, 162)
[31] (Kerwin 2001, 184)
[32] (Kerwin 2001, 181)

Figure 6.1 shows a screen shot of the parametric analysis GUI and the value of each input field for this design example. Several assumptions must be mentioned. First, this propeller was assumed to operate in the open water and also uniform inflow. Thus the axial inflow velocity ratio (V_a/V_s) was set to one and the tangential inflow velocity ratio (V_t/V_s) was set to zero. Second, the drag coefficient was assumed to be 0.008 everywhere along the radius of the propeller. Finally, the non-dimensional chord distribution was arbitrary in this example. After all the input fields were revised, the parametric analysis was performed by clicking the "Run MPVL" pushbutton at the bottom of the GUI.

After the calculation process was complete, the propeller efficiency curves were plotted. See Figure 6.2. The data cursors were used to mark desired data points as shown in the figure. As expected, the propeller with a larger diameter, slower speed and less number of blades had the higher efficiency. However, in reality the propeller parameters must be restricted in size and speed. It is the purpose of the parametric analysis to reveal the efficiencies under different combinations of the propeller parameters to help the designers determine the optimum parameters for the design.

For this design example, it was assumed that the optimum propeller diameter was restricted to three meters due to the aft body geometry. An increase in the number of blades reduces the thrust per blade, thereby reducing the intensity of the disturbing forces[33] which cause propeller induced vibration. For that reason, a five-bladed design was adopted. Finally, the propeller speed was to be determined. The propeller speed can vary by means of mechanical gearing and therefore was flexible. It was shown in Figure 6.2 that a three-meter in diameter and five-bladed propeller had the highest efficiency at 120 RPM (green line). After all, the users are free to decide the constraints of the three propeller parameters. Now, the three major propeller parameters had been determined, and the single propeller design was ready to be conducted.

[33] (Edward 1988, 167)

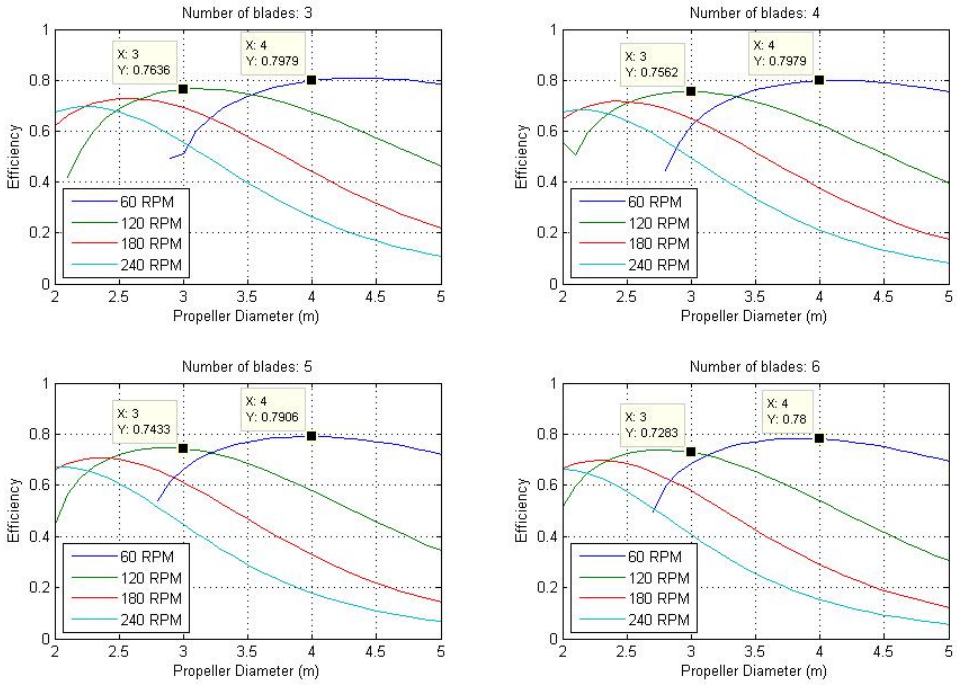

Figure 6. 2 Efficiency Curves of the Design Example

6.2 Single Propeller Design

In the previous section, the three major propeller parameters were determined: five-bladed, three-meter in diameter and with the optimum speed of 120 RPM. The single propeller design GUI was then launched. Most input fields were identical to the ones in the parametric analysis GUI. However, several more input fields were required in the single propeller design GUI. Figure 6.3 shows a screen shot of the single propeller design GUI and the inputs for this design example.

At the lower left corner of the GUI, four additional input fields are shown. The first one is the shaft centerline depth in meters. It is required for the calculation of cavitation number (σ). The second input field is the inflow velocity variation. It is required for the calculation of pitch angle variation ($\delta\beta_i$) which is related to the cavitation buckets. The third input field is the ideal angle of attack. It is required for specific meanline type to calculate the pitch angle. The fourth input field is the number of points over the chord. It is required to decide the resolution of the propeller blade.

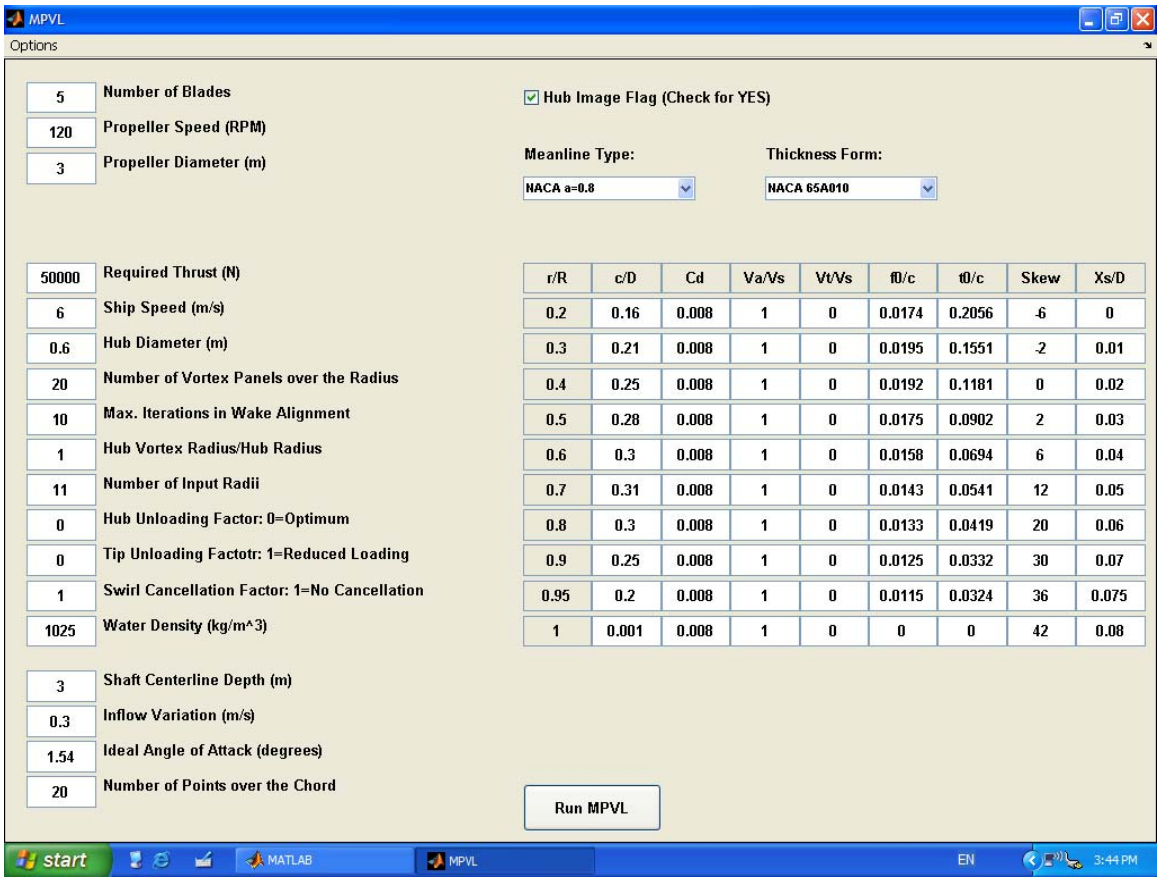

Figure 6. 3 Inputs for Single Propeller Design Example

On the upper right side of the GUI, two pop-up menus are shown. One of them is for selecting the meanline type, and the other one is for selecting the thickness form. Two options are available for the meanline type: the NACA a=0.8 and the parabolic meanline. Three thickness forms are available: the NACA 65 A010, the elliptical and the parabolic thickness forms. For this design example, the NACA a=0.8 meanilne and the NACA 65 A010 thickness form were selected.

Finally, the maximum camber distribution (f_0/c), the maximum thickness distribution (t_0/c), the skew in degrees and the non-dimensional rake (X_s/D) were required for propeller geometry calculations. Skew is often applied to reduce the propeller-induced unsteady forces and susceptibility to cavitation when operating in a wake[34]. Rake is often adopted to increase the clearance from the hull thereby reducing the propeller induced vibration. After all input fields were revised, the single propeller design was performed by clicking "Run MPVL" pushbutton at the bottom of the GUI.

[34] (Edward 1988, 184)

After the calculation process was complete, the graphical and text reports were created. Figure 6.4 presents the graphical report of this design example. The figure in the upper left corner shows the non-dimensional circulation vs. the radial position. The upper right figure shows the axial and tangential inflow velocities and the axial and tangential induced velocities vs. the radial position. The figure in the lower left corner shows the undisturbed flow angle β and the hydrodynamic pitch angle β_i vs. the radial position. Finally, the lower right figure shows the chord distribution vs. the radial position. Figure 6.5 presents the two-dimensional propeller blade profile. For simplicity, only five profiles were plotted in the figure. The chord length, the pitch angle, the camber, the thickness, the skew and the rake were shown. This figure can also be animated in MATLAB® to dynamically examine the change in blade profile from the root to the tip of the blade. Finally, the three-dimensional propeller image was created. See Figure 6.6. This figure presents the resultant propeller geometry including the propeller diameter, hub diameter, number of blades, camber distribution, thickness distribution, pitch angle, skew and rake. It provides an instant graphical presentation of the propeller design.

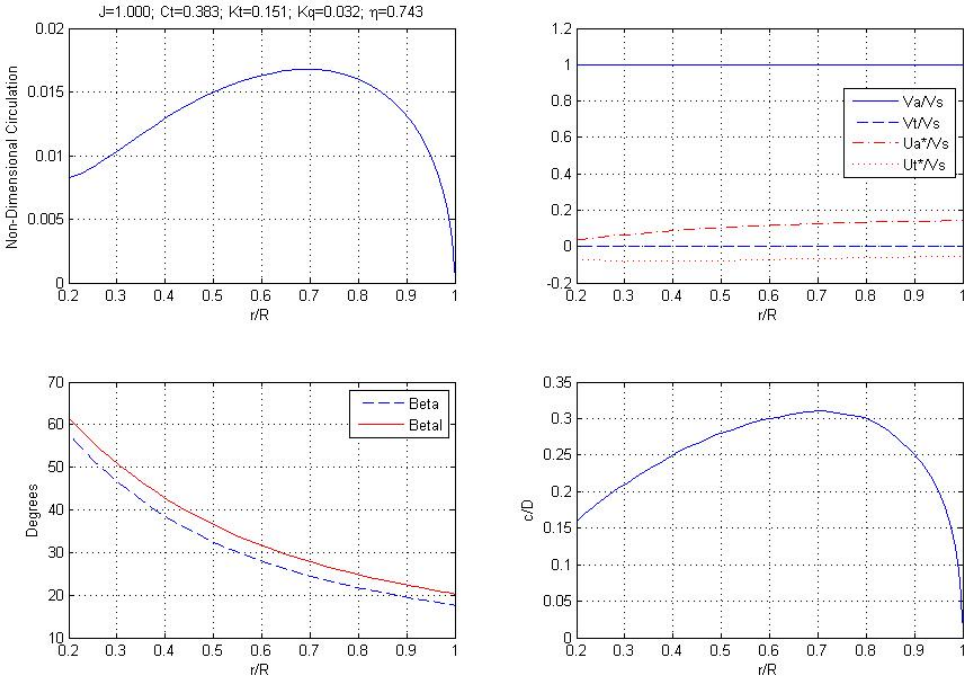

Figure 6. 4 Graphical Report of the Design Example

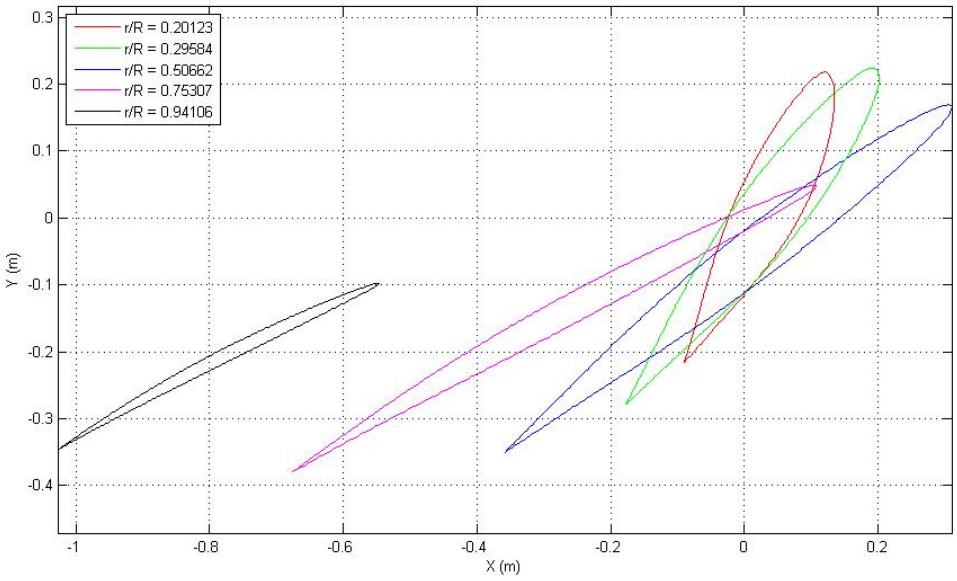

Figure 6. 5 2D Blade Profile of the Design Example

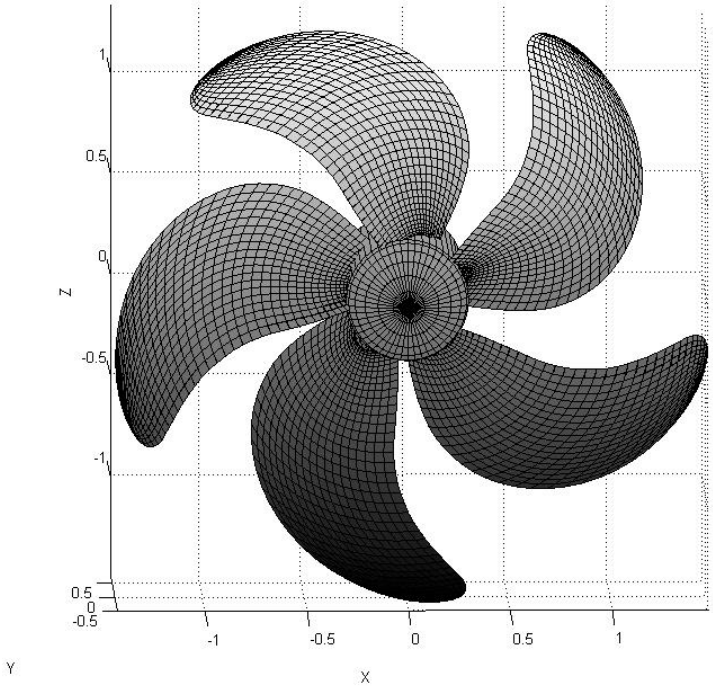

Figure 6. 6 3D Propeller Image of the Design Example

Four text files were also created to present and store the important information of this specific trial. Table 6.1 was the first table created. It contains the input data of MPVL and was identical to the input file of PVL. Table 6.2 was the second table created. It contains the outputs of MPVL and was identical to the output file of PVL. Table 6.3 was the propeller performance table which was the third table created. This table was intended for the cavitation calculations. It provides information on the sectional lift coefficient (C_L), the cavitation number (σ) and the pitch angle variation ($\delta\beta_i$). With this information, a Brockett diagram[35] can be used to check for cavitation for NACA foils. Table 6.4 was the last table created. It contains the essential propeller geometry data which can be used for manufacturing purpose.

```
2007-03-07 15:45:49 MPVL_Input.txt
20      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
5       Number of Blades
1.000   Advance Coef., J, Based on Ship Speed
0.383   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  0.18632  0.00800    1.00  0.0000
0.30000  0.21000  0.00800    1.00  0.0000
0.40000  0.25000  0.00800    1.00  0.0000
0.50000  0.28000  0.00800    1.00  0.0000
0.60000  0.30000  0.00800    1.00  0.0000
0.70000  0.31000  0.00800    1.00  0.0000
0.80000  0.30000  0.00800    1.00  0.0000
0.90000  0.25000  0.00800    1.00  0.0000
0.95000  0.20000  0.00800    1.00  0.0000
1.00000  0.00100  0.00800    1.00  0.0000
```

Table 6. 1 MPVL Input Text File of the Design Example

[35] (Edward 1988, 210)

MPVL_Output.txt
MPVL Output Table

Ct= 0.3834
Cp= 0.5158
Kt= 0.1506
Kq= 0.0322
Va/Vs= 1.0000
Efficiency= 0.7433

r/R	G	Va	Vt	Ua	Ut	Beta	BetaI	c/D	Cd
0.20123	0.008304	1.00000	0.0000	0.03698	-0.06796	57.699	61.449	0.16068	0.00800
0.21105	0.008357	1.00000	0.0000	0.03977	-0.06968	56.454	60.288	0.16604	0.00800
0.23045	0.008631	1.00000	0.0000	0.04527	-0.07266	54.096	58.073	0.17635	0.00800
0.25894	0.009246	1.00000	0.0000	0.05325	-0.07605	50.872	55.002	0.19075	0.00800
0.29584	0.010201	1.00000	0.0000	0.06316	-0.07896	47.096	51.343	0.20818	0.00800
0.34022	0.011398	1.00000	0.0000	0.07420	-0.08066	43.094	47.388	0.22713	0.00800
0.39100	0.012700	1.00000	0.0000	0.08544	-0.08081	39.149	43.407	0.24687	0.00800
0.44693	0.013970	1.00000	0.0000	0.09608	-0.07951	35.459	39.608	0.26533	0.00800
0.50662	0.015094	1.00000	0.0000	0.10560	-0.07709	32.141	36.130	0.28157	0.00800
0.56862	0.015986	1.00000	0.0000	0.11375	-0.07399	29.240	33.041	0.29498	0.00800
0.63138	0.016574	1.00000	0.0000	0.12052	-0.07060	26.755	30.360	0.30420	0.00800
0.69338	0.016797	1.00000	0.0000	0.12602	-0.06722	24.658	28.075	0.30992	0.00800
0.75307	0.016593	1.00000	0.0000	0.13042	-0.06405	22.913	26.156	0.30687	0.00800
0.80900	0.015904	1.00000	0.0000	0.13389	-0.06121	21.478	24.568	0.29814	0.00800
0.85978	0.014689	1.00000	0.0000	0.13660	-0.05876	20.316	23.275	0.27676	0.00800
0.90416	0.012935	1.00000	0.0000	0.13867	-0.05672	19.395	22.246	0.24696	0.00800
0.94106	0.010670	1.00000	0.0000	0.14022	-0.05511	18.688	21.455	0.21196	0.00800
0.96955	0.007965	1.00000	0.0000	0.14131	-0.05390	18.175	20.879	0.16555	0.00800
0.98895	0.004921	1.00000	0.0000	0.14201	-0.05311	17.842	20.504	0.10815	0.00800
0.99877	0.001664	1.00000	0.0000	0.14235	-0.05271	17.677	20.319	0.03954	0.00800

Table 6. 2 MPVL Output Text File of the Design Example

Performance.txt
Propeller Performance Table

r/R	V*	beta	betai	Gamma	Cl	Sigma	dBetai
0.201	3.867	57.70	61.45	0.4696	0.504	16.394	2.07
0.211	4.044	56.45	60.29	0.4726	0.469	14.968	2.12
0.230	4.397	54.10	58.07	0.4881	0.420	12.633	2.22
0.259	4.919	50.87	55.00	0.5229	0.371	10.061	2.32
0.296	5.599	47.10	51.34	0.5768	0.330	7.730	2.41
0.340	6.423	43.09	47.39	0.6446	0.295	5.843	2.46
0.391	7.370	39.15	43.41	0.7182	0.263	4.410	2.46
0.447	8.417	35.46	39.61	0.7900	0.236	3.358	2.42
0.507	9.537	32.14	36.13	0.8536	0.212	2.596	2.35
0.569	10.702	29.24	33.04	0.9040	0.191	2.046	2.25
0.631	11.884	26.75	30.36	0.9373	0.173	1.646	2.15
0.693	13.051	24.66	28.07	0.9499	0.157	1.354	2.05
0.753	14.176	22.91	26.16	0.9383	0.144	1.139	1.95
0.809	15.230	21.48	24.57	0.8994	0.132	0.980	1.86
0.860	16.188	20.32	23.28	0.8306	0.124	0.862	1.79
0.904	17.024	19.39	22.25	0.7314	0.116	0.774	1.73
0.941	17.720	18.69	21.45	0.6034	0.107	0.711	1.68
0.970	18.257	18.18	20.88	0.4504	0.099	0.668	1.64
0.989	18.623	17.84	20.50	0.2782	0.092	0.640	1.62
0.999	18.808	17.68	20.32	0.0941	0.084	0.627	1.61

Table 6. 3 MPVL Propeller Performance Text File of the Design Example

Geometry.txt

Propeller Geometry Table

Propeller Diameter = 3.0 m
Number of Blades = 5
Propeller Speed= 120 RPM
Propeller Hub Diameter = 0.60 m
Meanline Type: NACA a=0.8
Thickness Type: NACA 65A010

r/R	P/D	Skew	Xs/D	c/D	f0/c	t0/c
0.201	1.24	-5.9	0.000	0.161	0.0088	0.2049
0.211	1.24	-5.5	0.001	0.166	0.0083	0.1993
0.230	1.23	-4.5	0.003	0.176	0.0077	0.1887
0.259	1.23	-3.4	0.006	0.191	0.0071	0.1741
0.296	1.23	-2.1	0.010	0.208	0.0064	0.1569
0.340	1.23	-1.1	0.014	0.227	0.0057	0.1389
0.391	1.23	-0.2	0.019	0.247	0.0051	0.1210
0.447	1.23	0.9	0.025	0.265	0.0044	0.1040
0.507	1.23	2.2	0.031	0.282	0.0037	0.0886
0.569	1.23	4.5	0.037	0.295	0.0031	0.0753
0.631	1.23	7.6	0.043	0.304	0.0026	0.0641
0.693	1.24	11.5	0.049	0.310	0.0023	0.0550
0.753	1.24	16.0	0.055	0.307	0.0020	0.0472
0.809	1.25	20.8	0.061	0.298	0.0017	0.0410
0.860	1.25	25.7	0.066	0.277	0.0016	0.0357
0.904	1.25	30.5	0.070	0.247	0.0014	0.0331
0.941	1.25	34.9	0.074	0.212	0.0013	0.0326
0.970	1.26	38.3	0.077	0.166	0.0009	0.0257
0.989	1.26	40.7	0.079	0.108	0.0003	0.0105
0.999	1.26	41.9	0.080	0.040	0.0000	0.0012

Table 6. 4 MPVL Geometry Text File of the Design Example

Equations 6.1 to 6.5 were the formulas used in the propeller performance calculation.

Total Inflow Velocity: $V^* = \sqrt{(V_a + u_a^*)^2 + (\omega r + V_t + u_t^*)^2}$ (6.1)

Circulation: $\Gamma = G \times 2\pi R V_A$ (6.2)

Sectional Lift Coefficient: $C_L = \frac{2\,\Gamma}{V^* c}$ (6.3)

Sectional Cavitation number: $\sigma = \frac{P_\infty - P_{vapor}}{\frac{1}{2}\rho V^{*2}}$ (6.4)

Pitch Angle Variation: $\delta\beta_i = tan^{-1}\left(\frac{\tan(\beta_i)\cdot\omega r + \delta V_A}{\omega r}\right) - tan^{-1}\left(\frac{\tan(\beta_i)\cdot\omega r - \delta V_A}{\omega r}\right)$ (6.5)

V_a is the axial inflow velocity. V_t is the tangential inflow velocity. u_a^* is the induced axial velocity. u_t^* is the induced tangential velocity. ω is the propeller angular velocity. r is the local radius. G is the non-dimensional circulation. R is the propeller radius. V_A is the advance velocity. c is the chord length. P_∞ is the hydrostatic pressure. P_{vapor} is the vapor pressure. β_i is the hydrodynamic pitch angle, and δV_A is the axial inflow variation.