Hydrodynamic Optimization of Marine Propeller and Numerical Investigation of Contra-Rotating Propeller

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ABSTRACT

Here, two approaches have been accomplished. First, a propeller design method based on vortex lattice algorithm is developed and a gradient based optimization algorithm is implemented to optimize the shape and efficiency of a propeller. Second, a method for analysis of a Contra-Rotating propeller (CRP) has been developed. For analysis of the hydrodynamic performance parameters, a vortex lattice method was used by implementing an open-source code which is called OpenProp. One of the Sequential Unconstraint Minimization Techniques (SUMT) is employed to minimize the torque coefficient as an objective function, while keeping the thrust coefficient constant as a constraint. Also, chord distribution is considered as a design variable. A DTMB 4119 propeller has been optimized to achieve a lower torque coefficient than the original value. The scheme presented here is more efficient and less time consuming with respect to conventional methods. Solution of the optimization problem showed that nearly 13% improvement for propeller efficiency and nearly 15% decrease in torque coefficient is possible. The method presented for Contra-Rotating propeller (CRP) analysis is called coupled. Cavitation analysis has been done to show the robustness of the scheme.

KEYWORDS: Marine propeller, Gradient-based optimization, Vortex lattice method, CRP, Coupled method.

1. INTRODUCTION

In this article, a propeller optimization scheme is illustrated based on vortex lattice (lifting surface) method. The objective is to improve the efficiency of a propeller by optimizing the propeller's non-dimensional chord distribution and defining the torque coefficient as an objective function by keeping the thrust coefficient constant as an equality constraint, across the operating condition which is defined by the advanced ratio, j. The proposed optimization algorithms is one of the Sequential Unconstrained Minimization Technique, SUMT, a gradient based algorithm.

The complexity of flow field in which the propeller must operate efficiently will lead a designer to lay out a propeller to overcome the most of dilemma. Another difficulty which arises during propeller action is the variation of inflow which has a great influence on propellers. Hence, a range of designing is widely restricted for designers.

A development of the Momentum theory for marine propellers was the start point of hydrodynamic analysis of rotary wings. Betz [1] has firstly introduced the lifting line theory and Goldstein [2] and Lerbs [3] have consequently improved the method, respectively. The odorson has extended the vortex theory for highly loaded propeller. Rand and Rosen [4], Chang and Sullivan [5] as well as Chiu and Peters [6] used the lifting line theory for their works. Later on, Eckhart and Morgan [7] have proposed the Lifting-Surface correction factors and then have been developed during the first decade of 1960 by Pien [8] and Kerwin [9]. Chord distribution, wing tip shape and twist angle has been shown by McVeigh and McHugh[10] and Walsh et al. [11] that are the main factors which control the performance of straightened blade propellers. Lee [12] has applied the vortex lattice methods for prediction of hydrodynamic performance of marine propellers. Khot and Zweber [13] have optimized the structure of a composite wing by using gradient based algorithm. A twist angle distribution and a span wise chord distribution have been optimized by Cho and Lee [14] utilizing Gradient based optimization with penalty function method. Also, investigating the possibility of maximizing the efficiency by utilizing Genetic algorithm has been done by Lee and Lin [15]. Later on, Plucinski et al. [16] have optimized a self-twisting propeller, using Genetic algorithm by considering the orientation angles of the fibers in each layer as the design variables for efficiency improvement. For design optimization, a propeller performance analysis program has been developed and integrated into a Genetic algorithm by Christoph Burger [17]. Recently, Hsin et al. [18] has used the Adjoint method and Lagrange multiplier for both design and optimization of propeller.

In this paper, a propeller optimization scheme is illustrated based on vortex lattice (lifting line) method. The objective is to improve the efficiency of a propeller by optimizing the propeller's non-dimensional chord distribution and defining the torque coefficient as an objective function by keeping the thrust coefficient constant as a constraint, across the operating condition which is defined by the advanced ratio, j. The proposed optimization algorithms is Sequential Unconstrained Minimization Technique, SUMT, a gradient based algorithm.

Also, a numerical investigation for CRP has been done and cavitation analysis regarded to these kinds of problems using coupled method has been developed.

2. OPENPROP

OpenProp is the design and analysis tool for propellers and turbines. The code is written in MATLAB M-code and the numerical model is based on vortex lattice lifting line methods. The capability of the code has been tested by validating an experiment results and the numerical method which is used in OpenProp. OpenProp began in 2001 and developed by Kerwin [19] in 2007. The code has been developed by Stubblefield in 2008 and Epps in 2009, respectively. The good agreement between experimental data and numerical calculations done by OpenProp and a commercial package is shown here.

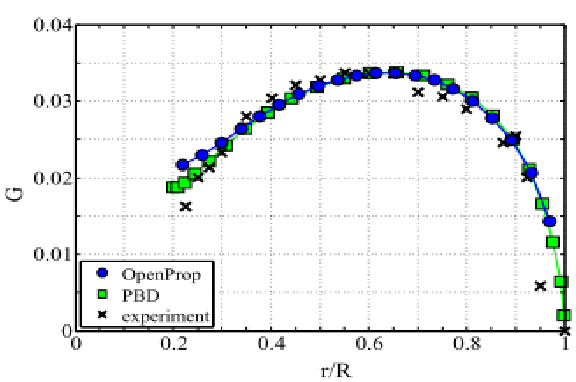

Fig. 1. Validation of Circulation results calculated by OpenProp and comparison with experimental data and PBD, reprinted with permission from Epps [20].

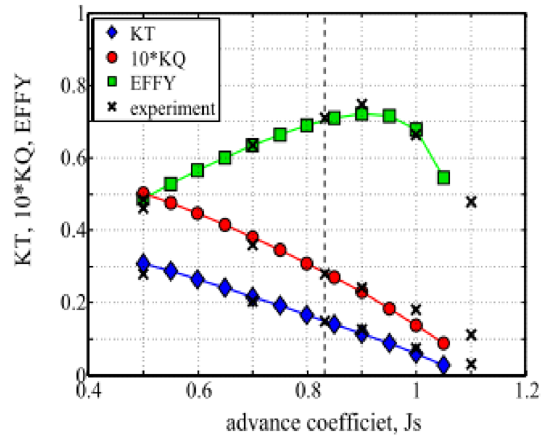

Fig. 2. Validation of thrust and torque coefficients and efficiency calculated by OpenProp and comparison with experimental data, reprinted with permission from Epps [20].

First, the circulation distribution has compared as it is shown in "Figure 1". Second, thrust and torque coefficients as well as final efficiency distribution over the range of propeller performance have been done and the results are shown in "Figure 2". The above illustrations convinced us to rely on this code and use that as a package to calculate our hydrodynamic performance needs.

3. PROPELLER LIFTING LINE FORMULATION

The calculation here in, is based on moderately loaded lifting line theory, by which a propeller blade is represented by lifting line, with trailing vorticity aligned to the local flow velocity (i.e., the vector sum of free-stream plus induced velocity). The induced velocities are computed using a vortex lattice, with helical trailing vortex filaments shed at discrete stations along the blade. The blade itself is modeled as discrete sections, having 2D section properties at each radius. Loads are computed by integrating the 2D sections load over the span of the blade. The velocity/force diagram shown in "Figure 3" illustrates the velocities and forces (per unit span) on a 2D blade section in the axial e_a and tangential e_t directions. The propeller shaft rotates with angular velocity ωe_a, such that the apparent tangential (swirl) inflow at radius r is $-\omega r e_t$. Also shown in "Figure 3" the axial and tangential inflow velocities, $V_a = -V_a e_a$ and $V_t = -V_t e_t$; induced axial and tangential velocities, $u_a^* = -u_a^* e_a$ and $u_t^* = -u_t^* e_t$; and the total resultant inflow velocity, V^* which has magnitude,

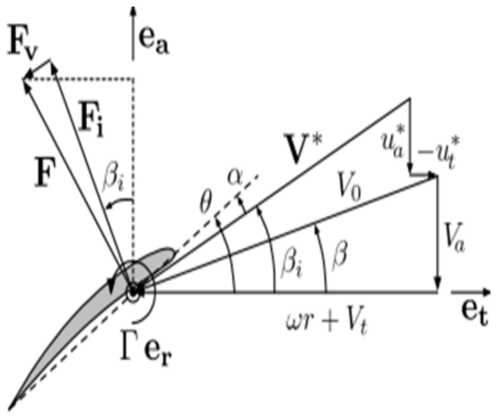

Fig. 3. Propeller velocity/force diagram, as viewed from the tip towards the root of the blades. All velocities are relative to a stationary blade section at radius r, reprinted with permission from Epps [20].

$$V^* = \sqrt{(V_a + u_a^*)^2 + (\omega r + V_a + u_t^*)^2} \quad (1)$$

and is oriented at pitch angle,

$$\beta_i = \arctan\left(\frac{V_a + u_a^*}{\omega r + V_a + u_t^*}\right) \quad (2)$$

to the e_t axis. Also shown in figure 3 are the angle of attack, α; blade pitch angle, $\theta = \alpha + \beta_i$; circulation, Γe_r; (inviscid) Kutta-Joukowski lift force, $F_i = \rho V^*(\Gamma e_r)$; and viscous drag force, F_v, aligned with V^*. Assuming the Z blades are identical, the total thrust and torque on the propeller are

$$T = z\int_{r_h}^{R} (F_i \cos\beta_i - F_v \sin\beta_i)dr(\hat{e}_a) \quad (3)$$

$$Q = z\int_{r_h}^{R} (F_i \sin\beta_i + F_v \cos\beta_i)rdr(-\hat{e}_a) \quad (4)$$

where $F_i = \rho V^*\Gamma$ and $F_v = \frac{1}{2}\rho V^{*2}(C_D)c$ are the magnitude of inviscid and viscous force per unit radius, ρ is the fluid density, C_D is the section drag coefficient, c is the section chord, r_h and R are the radius of the hub and blade tip, respectively.

The power consumed by the propeller is the product of torque and angular velocity

$$P = Q\omega \quad (5)$$

Where $P \succ 0$ indicates that power is being put into the fluid by propeller (i.e. the torque resists the motion). The useful power produced by the propeller is TV_s, where V_s is the ship speed (i.e. free stream velocity), so the efficiency of propeller is [20]

$$\eta = \frac{TV_s}{Q\omega} \quad (6)$$

After the above calculations, thrust and torque coefficients as well as advanced ratio are calculated as follow

$$K_T = \frac{T}{\rho n^2 D^4} \quad (7)$$

$$K_Q = \frac{Q}{\rho n^2 D^5} \quad (8)$$

4. INVERSE DESIGN

First, to show the capability of the hydrodynamic analyzer code, the inverse design has been done by a nearly ill-posed initial guess. This part was just done to prove the validity of the results which has been calculated by OpenProp code. For this purpose, the circulation distribution along the blade has been chosen to get reach to our desired circulation distribution. Here, is the function by which we have explored the validation of the code

$$I = \int \left| G - G_{desired} \right| \quad (9)$$

The result of this calculation and consistency with experimental data is shown in "Table 1".

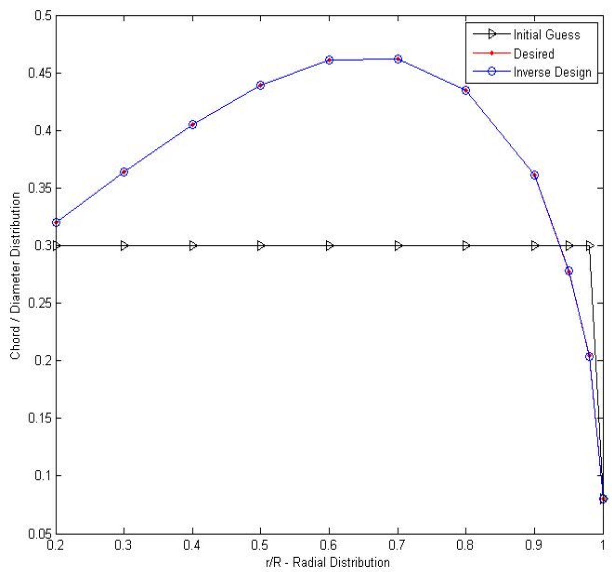

Fig. 4. Result of propeller inverse design.

5. OPTIMIZATION ALGORITHM

Generally speaking, optimization algorithms are categorized as two major sets. The first one is gradient-based algorithms and the other one is non-gradient-based algorithms. The act of choosing each set is depending on pros and cons related to each category as well as specific conditions for a problem.

For Gradient based algorithms, the simplest way of calculating derivatives for functions is Finite Difference method. If the round-off error is important, the Complex method will be beneficial. There are so many methods in order to calculate the derivatives such as sequential quadratic programming (SQP) which is the most popular methods for constraint optimization problems. For unconstraint optimization problems, Quasi-Newton methods play an important role. Also, adding penalty terms to constraint formulation, one can get unconstraint approach. One of the sequential unconstraint optimization techniques named extended linear interior penalty function method (EIPM) was used here. One of the most considerable differences between gradient-based and non-gradient-based algorithms is the existence of linear trend associated with number of design variables, while in the latter methods the cost of calculations is increased drastically by increase in number of design variables.

The Extended linear Interior Penalty function Method (EIPM), one of the sequential Unconstrained Minimization Techniques (SUMT), is employed as one of the optimization techniques. The aforementioned technique transforms a constrained optimization problem into a series of unconstrained optimization problems and constructs pseudo-objective function using penalty functions.

A constrained optimization problem is stated as [21]:

$$\text{minimize } f(x) \tag{10}$$

$$\text{subject to } g_j(x) \le 0,\ \text{j=1,m}$$

$$h_k(x) = 0,\ k = 1, l$$

where $f(x)$ is objective function. $g_j(x)$ and $h_k(x)$ are inequality and equality constraints, respectively. The transformed unconstrained optimization problem is also stated as:

$$pseudo-objective\ \phi(x, r_p, r_p^{\prime}) = f(x) + r_p P(x) \tag{11}$$

where r_p is a multiplier and will increase in each iteration until it reaches to a pre-defined value, and $P(x)$ is a penalty function consists of equality and inequality constraints. The final form of the transformed constrained optimization problem is

$$S^k = -H^k \nabla F(x^k) \tag{12}$$

$$H^{k+1} = H^k + D^k \tag{13}$$

where D^k is defined as follows [22]:

$$\left[D^k\right] = \left[M_i\right] + \left[N_i\right] \tag{14}$$

$$\left[M_i\right] = \lambda_i^* \frac{S_i S_i^T}{S_i^T g_i} \tag{15}$$

$$\left[N_i\right] = -\frac{\left(\left[H_i\right] g_i\right)\left(\left[H_i\right] g_i\right)^T}{g_i^T \left[H_i\right] g_i} \tag{16}$$

where $g_i = \nabla f\left(X_{i+1}\right) - \nabla f\left(X_i\right) = \nabla f_{i+1} - \nabla f_i$.

The iterative procedure is,

I. Start with initial design variables as a vector x^0 and initiate Hessian matrix H^0. (commonly identity matrix, $H^0 = I$)
II. Finding search direction, $S^k = -H^k \nabla F(x^k)$
III. Finding step length, λ by a univariate optimization process which determines the amount of change in the search direction.
IV. Updating design variables and then calculating gradient and Hessian of the function, $x^{k+1} = x^k + \lambda S^k$
V. Checking convergence criteria and going to step II.

Here, non-dimensional chord distribution is considered as design variables, in fact 11 variables.

The test case which has been used was a DTMB 4119 propeller of which the geometry characteristics are listed in "Table 1".

Table .1. Geometry definition of DTMB 4119 propeller [23].

r/R	c/D	p/D	qr	IT/D	tm/C	fm/C
0.2	0.32	1.105	0	0	0.2055	0.01429
0.3	0.3635	1.102	0	0	0.1553	0.02318
0.4	0.4048	1.098	0	0	0.1180	0.02303
0.5	0.4392	1.093	0	0	0.09016	0.02182
0.6	0.4610	1.088	0	0	0.0696	0.02072
0.7	0.4622	1.084	0	0	0.05814	0.02003
0.8	0.4347	1.081	0	0	0.04206	0.01967
0.9	0.3613	1.079	0	0	0.03321	0.01817
0.95	0.2775	1.077	0	0	0.03228	0.01631
1.0	0.0	1.075	0	0	0.0316	0.01175

Other characteristics that should be considered are:

1. The propeller inflow is uniform.
2. The propeller has 3 blades, i.e. N = 3.
3. The hub-to-diameter ratio is 0.2.
4. The propeller has no skew and no rake.
5. The blade sections are designed with NACA 66 modified profiles and a camber line of a = 0.8.
6. The propeller advanced ratio is $j = 0.833$.
7. The direction of rotation is right-handed.

6. OBJECTIVE FUNCTION

The objective function would be the torque, and the equality constraint function would be given in terms of thrust like below:

$$Minimize\ f(x) = k_Q(x) \tag{17}$$

$$Subject\ to\ h(x) = \frac{k_t - k_{t0}}{k_{t0}}$$

Where X represents design variables, f(x) is objective function, and h(x) is equality constraint.

7. RESULTS AND DISCUSSION

The results for circulation distribution as well as the above optimization are as follow, where higher circulation keeps the efficiency higher:

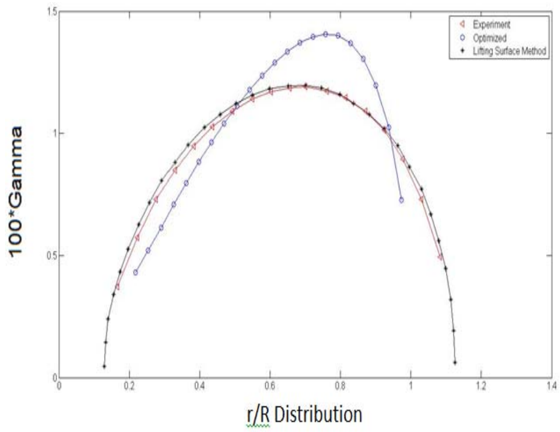

Fig. 5: Radial Circulation distribution. Initial (Lifting Surface Method), Experiment, and Optimized.

Table 2: Optimized propeller in comparison to the original one.

Type of propeller	K_t	K_Q	η
DTMB 4119	0.1468	0.0264	0.7375
Present (Optimized)	0.147	0.0227	0.8589

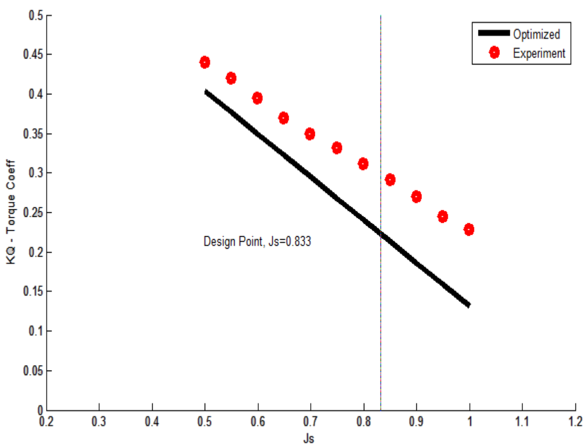

Fig. 6: Reduction in torque coefficient distribution with respect to advanced ratio. Initial (Lifting Surface Method), and Optimized.

"Figure 5" show that the redesigned propeller has the higher value of efficiency due to higher circulation distribution. The magnitude of thrust and torque coefficient as well as efficiency can be seen in table 2. It is obvious that efficiency improvement due to this optimization process is promising and significant torque reduction, as it is obvious in "Figure 6", is high enough to propose this scheme for practical applications.

7.1. Coupled Method [24]

This method was developed by Kerwin, Coney and Hsin (1986) and is an extension of the variational optimization approach for single propeller design. The optimization procedure enables one to determine both the division of loading between CRP components and the radial distribution of loading (circulation) on each component simultaneously since the two propellers comprising the set are regarded as a unit. This method can also be applied to other multi-component propulsors, such as propellers with pre or post swirl stators or vane wheels, provided a computational scheme for calculating the interaction velocities exists.

For the second part of numerical investigation, the schematic of a CRP using coupled method is shown in "Figure 7". Cavitation analysis has been done for the very propeller and the result is shown in "Figure 8".

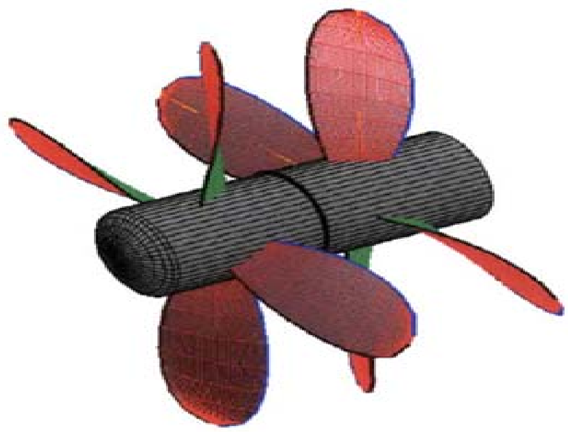

Fig. 7: Schematic of a CRP.

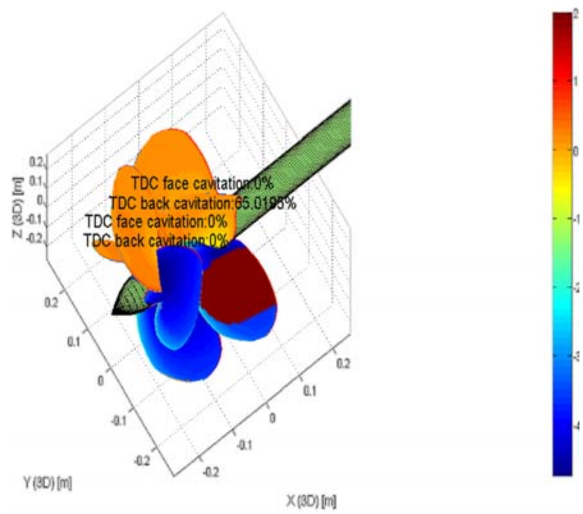

Fig. 8: Cavitation analysis of a CRP.

8. CONCLUSION

In this article to validate our scheme, first we note that our physical analysis tool (OpenProp) is intensively validated, as shown in "Figure 1", "Figure 2" and "Figure 4" for our DTMB 4119 propeller. The result of OpenProp has compared with experimental data.

Here we applied gradient based optimization algorithm to a given propeller geometry. For gradient based algorithm we have used non-dimensional chord distribution as design variables and have kept thrust coefficient constant as an equality constraint. Moreover, we have applied inverse design scheme to an initial guess for our propeller geometry. "Figure 4" showed that, as expected, very good agreement between our results and experimental data. "Table 2" has compared hydrodynamic shape parameters achieved by optimization algorithm with initial values. The efficiency improvement of propeller (nearly 13%) showed the optimized circulation distribution was higher than the experimental values, which higher circulation lead to higher lift force and consequently higher efficiency can be achieved. Also, torque coefficient reduction has been shown in "Figure 6" by which nearly 15% improvement can be considered possible.

Last but not least was implementation of coupled method for contra-rotating propeller in order for cavitation analysis. The hydrodynamic code has been developed to both optimization algorithm and cavitation analysis by which later can give a handy help to a designer to meet further hydrodynamic requirements.

List of Symbols

ω	Angular velocity, rps	C_D	Section drag lift
V_a	Axial inflow velocity, m/s	r_h	Hub radius, m
V_t	Tangential inflow velocity, m/s	R	Blade tip radius, m
u_a^*	Induced axial velocity, m/s	η	Propeller efficiency
u_t^*	Induced tangential velocity, m/s	K_T	Thrust coefficient
V^*	Resultant inflow velocity, m/s	K_Q	Torque coefficient
V_s	Ship speed, m/s	t_m	Maximum thickness, m
β_i	Pitch angle, deg	f_m	Maximum camber, m
θ	Blade pitch angle, deg	qr	Rake
Γ	Circulation	IT	Skew, deg
F_i	Inviscid lift force, N	J	Advanced ratio
F_v	Viscous drag force, N	n	Propeller rate of rotation per minute, rpm
T	Propeller thrust, N	ρ	Density of water, kg/m^3
Q	Propeller torque, N	P	Power consumed by propeller, W
Z	Number of blades	G	Circulation function
r	Section radius, m		
D	Propeller diameter, m		
c	Blade chord, m		

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