

Coupling a Numerical Optimization Technique with a Panel Method or a Vortex Lattice Method to Design Cavitating Propellers in Non-Uniform Inflows

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Abstract

In this study, a nonlinear optimization method, which is coupled with either a panel method or a vortex lattice method, is used to design open propellers in uniform, circumferentially averaged or non-uniform inflow. A B-spline geometry with 4×4 control points is used to ensure that the propeller blade is accurately defined with fewer parameters. The optimization objective is to maximize the efficiency of the propeller while satisfying the given propeller thrust, and different cavity area or pressure constraints are applied. The influence of those constraints are studied, and propeller geometries are designed in different cases. The optimal efficiency as a function of the thrust coefficients are compared with those from other references, and the optimal circulations from this method are compared with those predicted from the lifting line optimization theory. It is shown that this method satisfies the optimization objectives and can be used in the practice of designing cavitating propellers.

Keyword: optimization; panel method; vortex lattice method; cavitating propeller design

Introduction

The preliminary design of marine propellers has been gradually developing in the past. Generally, the methods used can be categorized into two types [Kerwin and Hadler, 2010]. The first one involves using systematic series of propellers, whose open water characteristics are already known, either from experimental tests or from computational fluid dynamic simulations [Yeo et al., 2014]. A widely known example is by using the Wageningen B-screw series [van Lammeren et al., 1969]. The second type of methods do not require and are not limited to the known propeller series, but are based on the optimal radial distribution of circulation. These methods need the circumferentially averaged inflow, and are more adapted to the nominal wake field downstream of the ship hull.

An alternative approach can be seen as an improvement of the second type of methods. Mishima and Kinnas [1997] developed a numerical optimization method which is coupled with a Vortex Lattice Method (VLM) to design the cavitating propellers in the non-uniform inflow. A major advantage of this method is that it considers the circumferential variance of the inflow, which is important in predicting the periodic pressure fluctuations and the vibrations on the ship hull caused by the propeller in unsteady non-axisymmetric inflows. This method uses a B-spline to represent the blade geometry, and the optimization objective and constraints (thrust, torque, cavitation area, etc.) are approximated via second-order Taylor expansions. This method allows a constrained amount of cavitation in the design and thus can be applied to design propellers working under a moderate or even high loading. A numerical code called CAVOPT-3D (3-Dimensional CAVitating propeller blade OPTimizaiton) was developed and later improved by Griffin and Kinnas [1998] to include the minimum pressure constraints and a one-variable quadratic skew optimization.

In the Ocean Engineering Group of University of Texas at Austin, the prediction of flows around propellers has been studied intensively in the past decades. The two major codes are MPUF-3A, which uses the VLM, and PROPCAV (PROPeller CAVitation), which uses the Boundary Element Method (BEM, more commonly known as the panel method). Some major improvements in MPUF-3A include: the thickness loading coupling scheme by Kinnas [1992], the unsteady wake alignment scheme and the non-linear terms in pressure evaluation by He [2010], etc. In PROPCAV, Kinnas et al. [2007] coupled the panel method with a boundary layer solver XFOIL [Drela, 1989] and developed the viscous/inviscid interaction method; Tian and Kinnas [2012] introduced a pseudo-unsteady wake alignment scheme

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(full wake alignment scheme, or FWA) to improve the accuracy of the predicted propeller performance, especially at low advance ratios.

In this paper, the nonlinear optimization method is coupled with the newest version of MPUF-3A and PROPCAV to design cavitating propellers. Different constraints will be applied, and various inflows, including uniform, circumferentially averaged and non-uniform inflow will be used. The efficiency and optimal circulation from the current method will be compared with those from other references [Kerwin and Hadler, 2010] or the lifting line optimization method [Menéndez Arán and Kinnas, 2014].

Methodology

The vortex lattice method and the panel method

In the VLM, line vortices and sources are placed on the mean camber surface of the blade and the trailing wake, and the strengths of those singularities are determined by solving the potential flow which satisfies the kinematic boundary condition and dynamic boundary condition. The resultant velocity \vec{V} can be written as the summation of the individual contributions as:

$$\vec{n} \cdot \vec{V} = \vec{n} \cdot (\vec{V}_\Gamma + \vec{V}_Q + \vec{V}_I + \vec{V}_B + \vec{V}_O) = 0, \quad (1)$$

where \vec{V}_Γ is the velocity induced by the line vortices on the key blade and wake, \vec{V}_Q the velocity induced by the cavity sources on the key blade and wake, \vec{V}_I the inflow velocity, \vec{V}_B the velocity induced by the line sources, which represents the thickness of the blade, and \vec{V}_O the induced velocity by the other blades and wakes.

In the panel method, the total flow velocity \vec{q} is decomposed into an incoming flow \vec{q}_{in} and a propeller-induced flow \vec{U}_{ind} (the perturbation velocity),

$$\vec{q} = \vec{q}_{in} + \vec{U}_{ind}. \quad (2)$$

\vec{U}_{ind} can be treated as the potential flow which is governed by the Laplace's equation

$$\vec{U}_{ind} = \nabla\phi, \quad \nabla^2\phi = 0, \quad (3)$$

where ϕ is the perturbation potential.

The Kutta condition is required which means the velocity must remain finite

$$|\nabla\phi| < \infty \quad \text{at the trailing edge.} \quad (4)$$

By using the Green's identity, (3) can be written in the boundary integrated form:

$$2\pi\phi_p = \iint_{S_H} \left[\phi_p \frac{\partial G(p, p')}{\partial \mathbf{n}_{p'}} - G(p, p') \frac{\partial \phi_p}{\partial \mathbf{n}_{p'}} \right] dS + \iint_{S_W} \Delta\phi_w \frac{\partial G(p, p')}{\partial \mathbf{n}_{p'}} dS, \quad (5)$$

where S_H is the surface of the hydrofoil or propeller blade, duct, and hub, S_W the surface of the trailing wake, G the Green's function, which is defined as $1/R(p, p')$ in 3D and $2\ln R(p, p')$ in 2D, and R the distance between the two points p and p' .

More details of the VLM and the panel method can be found in Lee [1979] and Lee [2002] respectively.

The B-splines propeller blade geometry

The camber of the propeller blade geometry is represented as a B-spline surface, as shown in figure 1. 13 parameters are chosen to determine the movement of each vortex at each optimization iteration to specify the improved blade geometry. The advantage of using B-spline geometry is that much fewer variables are needed in the optimization (compared with the traditional geometry definition by the distribution of chord length, skew, rake, pitch etc.), while each point on the blade surface is uniquely specified. The non-uniform B-spline surface is defined as

$$P(u, w) = [x(u, w), y(u, w), z(u, w)] = \sum_{i=0}^{N_u-1} \sum_{j=0}^{N_w-1} d_{ij} N_{i,4}(u) N_{j,4}(w), \quad (6)$$

where d_{ij} are the B-spline control points, $N_{i,4}(u)$ and $N_{j,4}(w)$ B-spline basis of order 4, u and v parameters for B-splines, and N_u and N_w are number of B-spline control points in u -direction and w -direction.

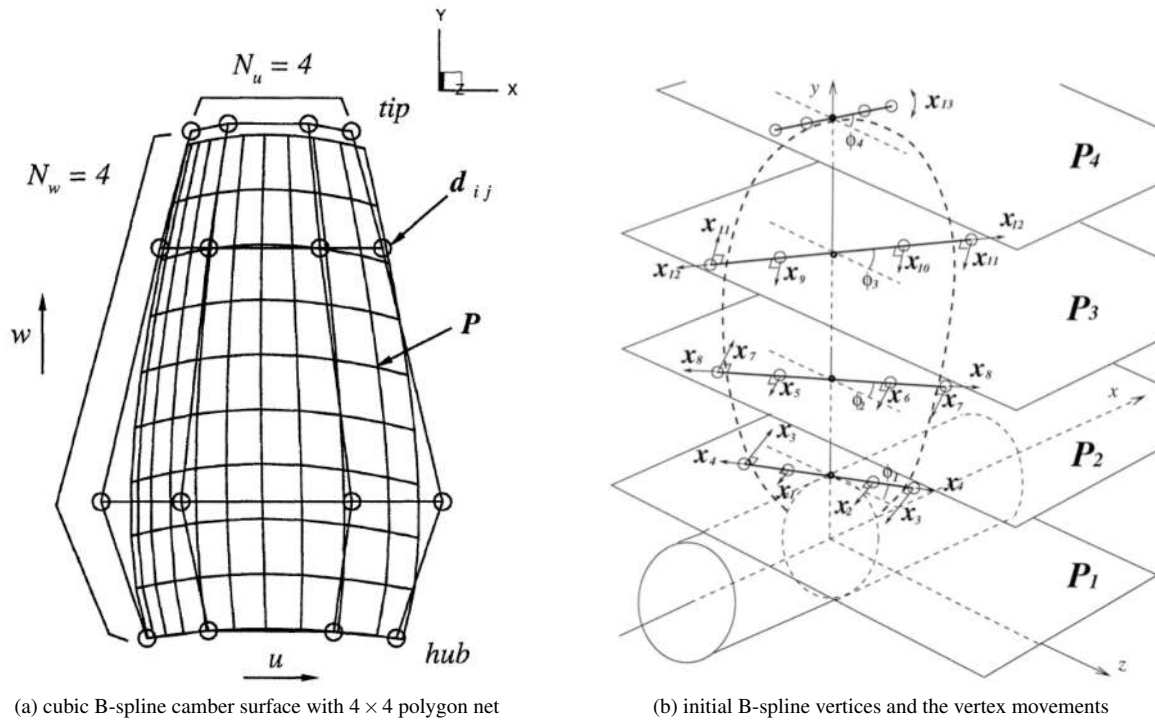


Figure 1: The B-spline blade geometry from Mishima and Kinnas [1997]

The numerical optimization method

The general constrained optimization problem is defined as

$$\text{minimize } f(x) \quad (7)$$

$$\text{subject to } g_i(x) \leq 0 \quad i = 1, 2, \dots, m \quad (8)$$

$$h_x(x) = 0 \quad i = 1, 2, \dots, l \quad (9)$$

where $f(x)$ is the optimization objective function, $g_i(x)$ the inequality constraints and $h_i(x)$ the equality constraints. In the present method, the design objective is to minimize the torque for a given thrust so that the propeller can achieve the highest efficiency. The equality constraint function is the thrust coefficient and the inequality constraints can be the maximum allowable back/face cavity area (CA), the maximum allowable blade rate cavity volume velocity harmonics, the maximum allowable cavity length at the tip and the minimum difference between the lowest pressure and the vapor pressure, shown as

$$\sigma - \text{MAX}(-C_p) \geq BTOL \quad (10)$$

where σ is the cavity number, defined as

$$\sigma = \frac{P_0 - P_v}{\frac{\rho}{2} n^2 D^2} \quad (11)$$

where P_0 is the pressure far upstream, P_v the vapor pressure, ρ the fluid density, n the propeller rotational frequency and D the propeller diameter. The pressure coefficient is defined as

$$C_p = \frac{P - P_0}{\frac{\rho}{2} n^2 D^2} \quad (12)$$

where P is the pressure on the propeller surface.

The objective function and the constraint functions are approximated as second-order Taylor expansions. More details of this method can be found in Mishima and Kinnas [1996] and Mishima and Kinnas [1997].

Results and discussion

Case 1. Uniform inflow, unconstrained

This method is first applied to design a 5-blade cavitating propeller subject to uniform inflow, without any constraints. The hub radius over the blade radius is 0.3. The target KT is 0.35, and the cavity number is 3.5. The advance ratio equals 1.0, which is defined as

$$J_s = \frac{V_s}{nD}, \tag{13}$$

where V_s is the ship speed. The Froude number, defined as

$$Fr = \frac{n^2 D}{g}, \tag{14}$$

where g is the acceleration of gravity, is taken as infinitely large. A large Froude number means that the cavitation is not influenced by the gravity.

The optimization process converges in about 500 iterations, as shown in figure 2c. Since there are no constraints on the optimization, there is some cavitation in the design, as shown in figure 2b. The propeller geometry and the optimal distribution of the pitch (P), chord length (c) and maximum camber (f), are shown in figure 2a and figure 2d.

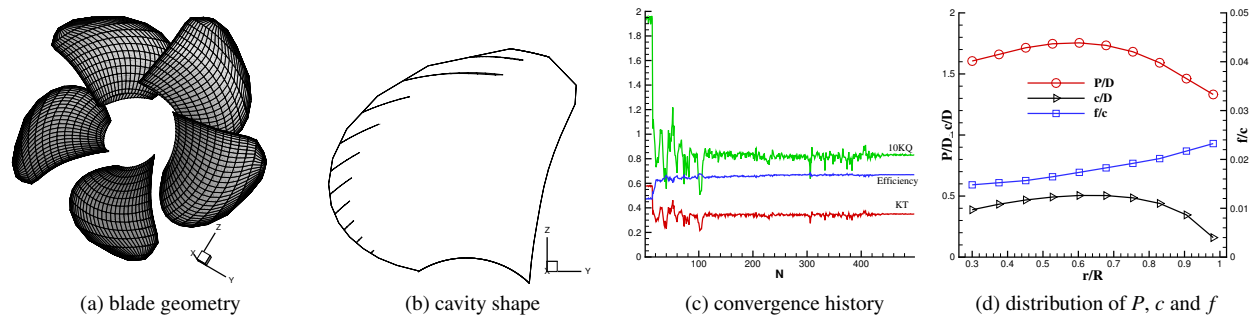


Figure 2: A 5-blade cavitating propeller is designed in uniform inflow without any constraints

Case 2. Circumferentially averaged inflow, constrained as no cavitation

In the inflow shown in figure 3a, there a low axial velocity region where blade angle equals 0 (12 o'clock), which can be considered as the influence of the ship hull boundary layer. The axial velocity is normalized by the ship speed. In this case, the inflow is circumferentially averaged, and the target KT is 0.5. The constraint is chosen so that the lowest pressure is greater or equal to the vapor pressure (i.e., setting $BTOL = 0$ in equation 10). All the other conditions are the same as in *Case 1*. These design conditions and constraint lead to a square tip propeller blade without any cavitation, as shown in figure 3b. However, some information of the non-uniform inflow is missing in averaging, especially when the variation in the circumferential direction is big. Consequently, even the optimal design satisfies the no cavitation constraint, there might be some cavitation at some blade angles in the non-uniform inflow, especially where the axial velocity is low, as shown in figure 3c and figure 3d.

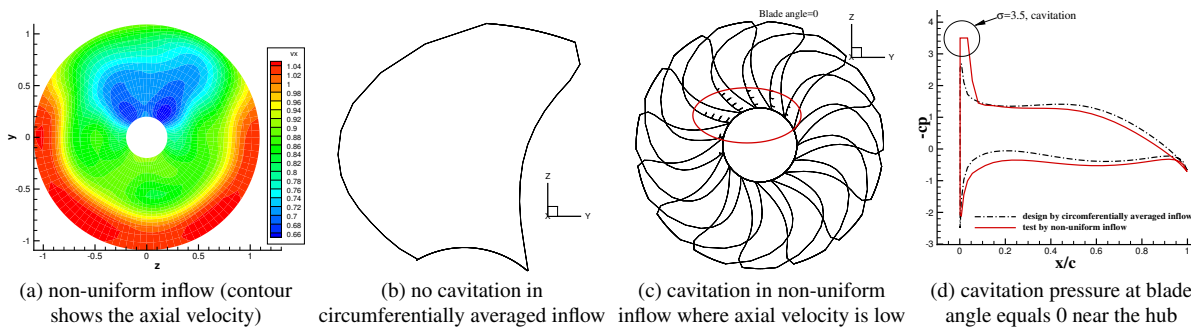


Figure 3: Propeller blade designed with no-cavitation constraint in the circumferentially averaged inflow might still show some undesirable cavitation in non-uniform inflow where the axial velocity is low.

Case 3. Non-uniform inflow with constraint on the cavity area

In this case, the cavitating propeller is designed in non-uniform inflow, which is one of the advantages of the presented method. The cavity number is 2.5, and the Froude number is 5.0. All the other design conditions are the same as in *Case 1*, except that the inflow in figure 3a is used (non-uniform, without being circumferentially averaged). The constraint is to limit the cavity area (non-dimensionalized by the blade area) as 0.2 or 0.3, as shown in figure 4a. If the maximum allowable cavity area is 0.2, the efficiency of the optimal propeller is 71.2%, while if the maximum cavity area is 0.3, the efficiency is 72.4%. Those efficiencies are close, however, the case with a smaller maximum cavity area will have wider blade near the hub, as shown in figure 4b. The pitch distributions of those two cases are similar.

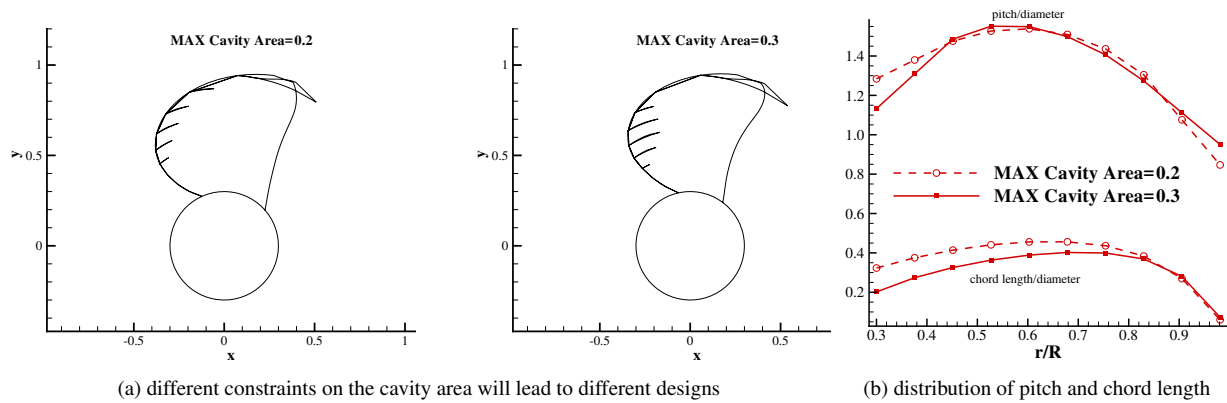


Figure 4: Wider blade near the hub is needed in the case with more strict constraint on cavity area.

Optimal efficiency and circulations compared with other references or methods

For a given advance ratio, Kerwin and Hadler [2010] showed the ideal efficiency from the actuator disk model in uniform inflow, with the effect of swirl included ($J_s = 1.0$). These efficiencies are compared with those of the optimal propeller blades designed by the current method, both in the uniform inflow and non-uniform inflow, as shown in figure 5. The efficiency curve from the optimal blades are lower than those from the actuator disk model, as expected. The circulations from the optimal propeller agree well with the results from the lifting line optimization method [Menéndez Arán and Kinnas, 2014], as shown in figure 6.

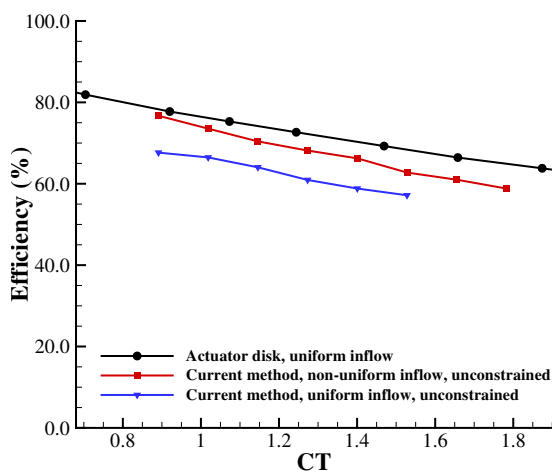


Figure 5: The efficiencies from the current method are compared with the results from the actuator disk model ($J_s = 1.0$). The thrust coefficient CT is defined as $CT = \frac{Thrust}{\frac{1}{2} \rho \pi V_s^2 R^2}$.

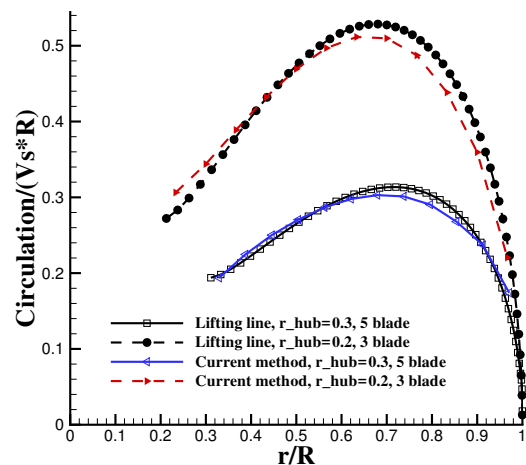


Figure 6: The optimal circulations from the current method agree well with the results from the lifting line optimization method for two cases with different hub radius and number of blades.

Conclusion

In this paper, a numerical optimization method, which is coupled with a vortex lattice method or a panel method, is applied to design cavitating propellers in uniform, circumferentially averaged or non-uniform inflows. Outputs of this method include the 3-dimensional propeller blade geometries, together with the optimal distribution of the chord length, maximum camber, pitch and skewness. Results show that the design objectives (minimize the torque for given thrust) and constraints (maximum cavity area, minimum pressure, etc.) can be satisfied. It is also shown that with a smaller allowable cavity area, the optimal propeller has a wider blade near the hub. The efficiencies as a function of the thrust are compared with the ideal value from the actuator disk model, and a reasonable trend is observed. The circulations of the optimal propeller blades agree well with those predicted from the lifting line optimization method. Finally, this numerical technique can be a useful and reliable tool in designing marine propellers with controlled amount of cavitation.

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References

- Mark Drela. XFOIL: An analysis and design system for low Reynolds number airfoils. In *Low Reynolds number aerodynamics*, pages 1–12. Springer, 1989.
- Paul E Griffin and Spyros A Kinnas. A design method for high-speed propulsor blades. *Journal of Fluids Engineering*, 120(3):556–562, 1998.
- Lei He. *Numerical simulation of unsteady rotor/stator interaction and application to propeller/rudder combination (also UT-OE Report 10-05)*. PhD thesis, The University of Texas at Austin, Austin, TX, 2010.
- Justin E Kerwin and Jacques B Hadler. *Principles of Naval Architecture Series: Propulsion*. The Society of Naval Architects and Marine Engineers (SNAME), 2010.
- Spyros A Kinnas. A general theory for the coupling between thickness and loading for wings and propellers. *Journal of Ship Research*, 36:59–68, 1992.
- Spyros A Kinnas, Hanseong Lee, Hong Sun, and Lei He. Performance prediction of single or multi-component propulsors using coupled viscous/inviscid methods. In *Proc. 10th Int. Symposium on the Practical Design of Ships and other Floating Structures, Houston, TX, 2007*.
- Chang-Sup Lee. *Prediction of steady and unsteady performance of marine propellers with or without cavitation by numerical lifting-surface theory*. PhD thesis, Massachusetts Institute of Technology, 1979.
- Hanseong Lee. *Modeling of unsteady wake alignment and developed tip vortex cavitation*. PhD thesis, The University of Texas at Austin, Austin, TX, 2002.
- David H Menéndez Arán and Spyros A Kinnas. On fully aligned lifting line model for propellers: An assessment of betz condition. *Journal of Ship Research*, 58(3):130–145, 2014.
- Shigenori Mishima and Spyros A Kinnas. A numerical optimization technique applied to the design of two-dimensional cavitating hydrofoil sections. *Journal of Ship Research*, 40:28–38, 1996.
- Shigenori Mishima and Spyros A Kinnas. Application of a numerical optimization technique to the design of cavitating propellers in nonuniform flow. *Journal of Ship Research*, 41:93–107, 1997.
- Ye Tian and Spyros A Kinnas. A wake model for the prediction of propeller performance at low advance ratios. *Int. J. Rotating Machinery*, 2012, 2012.
- WPA van Lammeren, J D van Manen, and MWC Oosterveld. The Wageningen B-screw series. *Trans. SNAME*, 77, 1969.
- Kiam B Yeo, Wai H Choong, and Wen Y Hau. Wageningen-B marine propeller performance characterization through CFD. *Journal of Applied Sciences*, 14(11):1215–1219, 2014.