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Hydrodynamic Optimization Method and Design Code for Stall-Regulated Hydrokinetic Turbine Rotors

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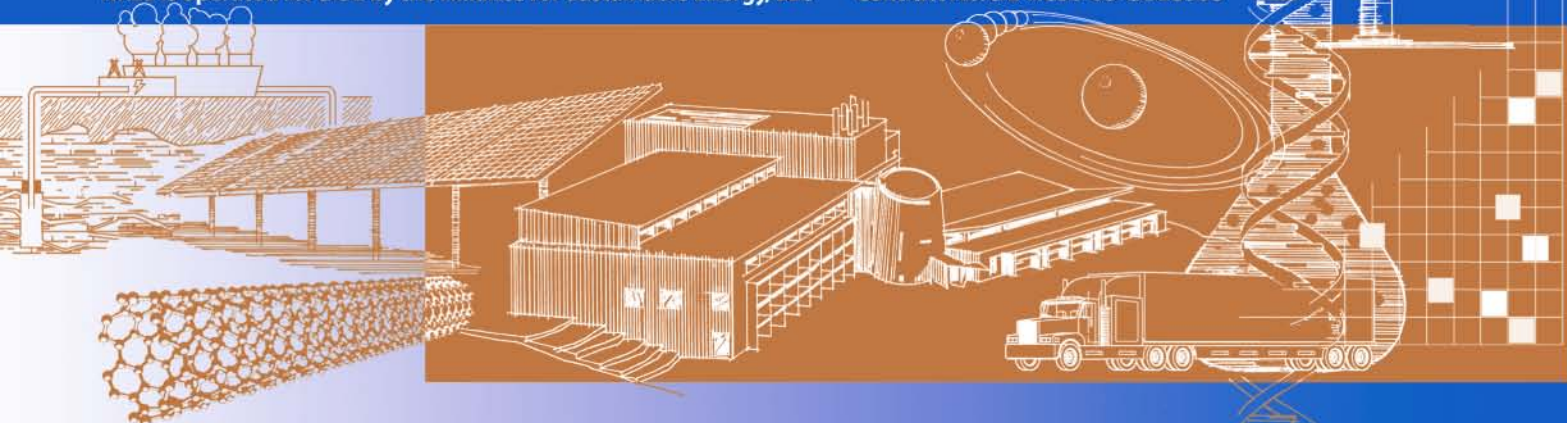
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**A Hydrodynamic Optimization Method and
Design Code for Stall-Regulated Hydrokinetic
Turbine Rotors**

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Abstract

This report describes the adaptation of a wind turbine performance code for use in the development of a general use design code and optimization method for stall-regulated horizontal-axis hydrokinetic turbine rotors. This rotor optimization code couples a modern genetic algorithm and blade-element momentum performance code in a user-friendly graphical user interface (GUI) that allows for rapid and intuitive design of optimal stall-regulated rotors. This optimization method calculates the optimal chord, twist, and hydrofoil distributions and rotor speed which maximize the hydrodynamic efficiency² and ensure that the rotor produces an ideal power curve and avoids cavitation. Optimizing a rotor for maximum efficiency does not necessarily create a turbine with the lowest cost of energy, but maximizing the efficiency is an excellent criterion to use as a first pass in the design process. To test the capabilities of this optimization method, two conceptual rotors were designed which successfully met the design objectives.

1. Introduction

Hydrokinetic turbines are a class of “zero-head” hydropower which uses the kinetic energy of flowing water to drive a generator. Hydrokinetic turbines operate on many of the same principles as wind turbines and share similar design philosophies. The most notable difference is that the density of water is about 850 times greater than air density, so the energy in a given flow stream is much greater for a hydrokinetic turbine than for a wind turbine. Average flow velocities for a tidal or river flow, however, tend to be an order of magnitude less than the flow velocities at a good wind site. The net impact is that the Reynolds numbers tend to be in the same range for both wind turbines and hydrokinetic turbines, which allows for much of the same experimental airfoil/hydrofoil data to be used in the design process. Additionally, hydrokinetic turbines can be analyzed and designed using the same incompressible flow techniques used for wind turbines. Unlike wind turbines, however, hydrokinetic turbines must be designed to avoid cavitation—a condition in which low pressures on the hydrofoil’s surface can result in local boiling of the water and lead to accelerated wear and increased load uncertainty.

Hydrokinetic turbines typically operate in flow regimes where the flow direction is more predictable than for wind turbines, hence yaw mechanisms can be simplified or eliminated. Wind turbines have grown in size over the past few decades, and use larger rotors and taller towers to take advantage of the faster winds aloft and to maximize the use of plant infrastructure. In contrast, hydrokinetic turbines are limited in size by the dimensions of the channel in which they are placed. Passively controlled fixed-speed stall-regulated hydrokinetic turbines are unlikely to attain an annual energy production (AEP) as great as actively controlled variable-speed variable-pitch turbines, which are common in the wind industry. Fixed-speed stall-regulated rotors, however, have the potential to be more reliable and less costly due to the absence of extra control mechanisms and because they include fewer moving parts. Moreover, in environments that have less variability in flow conditions—such as rivers as compared to tidal straits—the added complexity and cost of a variable-speed rotor and variable-pitch blades might not be economically justifiable.

² Hydrodynamic efficiency is defined as the ratio of the mechanical power output at the input shaft to the total power available in the free stream flow.

The design process for stall-regulated rotors involves many variables which often have complex trade-offs. Performing trade studies between all possible design variations through traditional direct or iterative approaches is a time-consuming and exhausting process. Also, it could be possible that multiple optimal solutions exist, and it can be difficult to distinguish which solution truly is the best—such studies are well suited to numerical optimization approaches. Traditional gradient-based optimization methods (such as Newton’s method) offer fast convergence times but can fail to converge on the global optimal solution in the presence of multiple minima/maxima. Although genetic algorithms (GA) converge much more slowly than gradient-based methods, GAs have a unique advantage such that they can effectively search the solution space and converge on a globally optimal solution by comparing and selecting the superior of all locally optimal solutions. Genetic algorithms have become successful in solving a wide variety of optimization problems, and have proven to be especially useful in the design of wind turbines [1, 2].

2. Hydrodynamic Model

This rotor optimization code takes advantage of the National Wind Technology Center’s existing wind turbine performance code WT_Perf [3] to use as the hydrodynamic model. WT_Perf relies on blade-element momentum (BEM) theory to predict the steady-state performance of wind and hydrokinetic turbines. Blade-element momentum theory—an extension of actuator disk theory—is a combination of two different theories, conservation of momentum theory and blade element theory, and generally is attributed to Betz and Glauert.

Conservation of momentum theory refers to a control volume analysis of the forces at the rotor plane based on the conservation of linear and angular momentum. Conservation of momentum states that the loss of pressure or momentum through the rotor plane, which occurs as the fluid passes through the rotor plane, is caused by work done on the turbine blades by the moving fluid. Conservation of momentum theory then allows calculation of the induced velocities in the axial and tangential directions from the momentum lost by the moving fluid. A flow field, characterized by the axial and angular induced velocities, is used to define the local flow conditions at the rotor hydrofoils. Blade-element theory is an analysis of forces which assumes that the blades can be divided into many smaller elements which act independently of surrounding elements. Given the local flow conditions and the blade geometry, the hydrodynamic forces on these blade elements can be calculated. Blade-element theory then sums these elemental forces along the span of the blade to calculate the total forces and moments exerted on the turbine.

The two approaches are combined into BEM theory, which is used to relate the geometry of the rotor and the lift and drag characteristics of the rotor hydrofoils to the rotor’s ability to extract power from a moving fluid. Additionally, BEM theory assumes:

- Incompressible, inviscid, and steady-state flow field;
- No cavitation;
- Forces on the blades are determined only by the lift and drag characteristics of the blade’s hydrofoil shape; and
- Blade elements operate as two-dimensional hydrofoils with no interaction between blade elements.

Despite the limitations described, BEM theory has been used widely as a reliable model for predicting wind turbine performance, and even has been used successfully to predict hydrokinetic turbine performance. A more-thorough explanation and derivation of the BEM governing equations can be found in many wind turbine design handbooks [4].

2.1 Introduction of Cavitation Constraint

If cavitation is avoided then the theory of BEM is assumed to be valid for an axial-flow hydrokinetic turbine. A cavitation constraint was introduced into the WT_Perf model to ensure that the calculated outputs are valid. The condition required to avoid the inception of cavitation is given by equation 1 [5], where σ is the non-dimensional cavitation number and C_{pmin} is the minimum local pressure coefficient of the hydrofoil. If the condition in equation 1 does not hold true, then the local static pressure of the moving fluid has dropped to a value that is less than the vapor pressure, and the continuity of flow is broken by the formation of vapor bubbles; cavitation has begun.

Cavitation is greatly dependent on the pressure distribution of the moving fluid around the hydrofoil. The pressure at a point on the surface of the hydrofoil is defined by the pressure coefficient, C_p . The values of the pressure coefficients are dependent on the angle of attack, Reynolds number, surface roughness, and shape of the hydrofoil. Pressure coefficients typically are measured in wind-tunnel tests, or can be calculated using numerical methods. The non-dimensional cavitation number, defined by equation 2, takes into account the change in pressure due to the axial and tangential induced velocities at the rotor plane.

The local velocity at the rotor plane is given by equation 3. Using the relation in equation 1, the local velocity required to induce cavitation can be calculated using equation 4. To ensure that the rotor does not experience cavitation, V_{loc} must never exceed or equal $V_{cavitate}$ at any location along the blade.

$$\sigma + C_{pmin} \geq 0 \quad (1)$$

$$\sigma = \frac{P_{atm} + \rho gh + \frac{1}{2}\rho V_{\infty}^2 a(2-a) - \frac{1}{2}\rho(\Omega r a')^2 - P_v}{\frac{1}{2}\rho V_{loc}^2} \quad (2)$$

$$V_{loc} = \sqrt{[V_{\infty}(1-a)]^2 + [(\Omega r)(1+a')]^2} \quad (3)$$

$$V_{cavitate} = \sqrt{\frac{P_{atm} + \rho gh + \frac{1}{2}\rho V_{\infty}^2 a(2-a) - \frac{1}{2}\rho(\Omega r a')^2 - P_v}{-\frac{1}{2}\rho C_{pmin}}} \quad (4)$$

2.2 Application of Stall-Delay Models

One of the simplifying assumptions of BEM theory is that spanwise flow along the blade is neglected. In reality, the presence of spanwise flow can cause significant augmentations in lift, drag, and pressure along the blade, especially near the blade root. This optimization code requires the lift, drag, and pressure coefficients of the hydrofoils as inputs. These lift, drag, and pressure coefficients usually are measured by testing airfoil sections in a wind tunnel, and there

are many publications in which this data is readily available [6–8]. Because of the inability of non-rotating wind-tunnel tests to simulate the influence of three-dimensional (3D) spanwise flow present in wind and hydrokinetic turbines, stall-delay models are used to apply corrections to the two-dimensional (2D) airfoil data. The application of 3D corrections to the 2D hydrofoil data can significantly increase the accuracy of the WT_Perf predictions for unyawed flows.

Accounting for stall-delay for stall-regulated rotors is especially important for accurately predicting the peak power and post-stall performance. In this optimization code, the user has the choice to correct the lift and drag coefficients using the Selig/Du [9] or Eggers [10] stall-delay models. These stall-delay models have shown to increase the accuracy of BEM predictions and the use of the appropriate stall-delay model is left to the user's discretion. At present, a suitable model to apply stall-delay corrections to the pressure coefficients is unavailable.

2.3 Verification of Hydrodynamic Model

In 2007, Verdant Power installed an array of 6 35-kW turbines in the East River of New York City to demonstrate hydrokinetic tidal technology. In cooperation with Verdant Power, the NWTC was able to begin validating the WT_Perf hydrodynamic model by modeling the Verdant Power 35-kW Gen4 hydrokinetic turbine. The Verdant Power 35-kW Gen4 turbine, shown in Figure 1, is a fixed-speed stall-regulated turbine with a 5-m rotor diameter.



Figure 1. The Verdant Power 35-kW hydrokinetic turbine

After the input parameters for the WT_Perf model were verified to accurately represent the existing Verdant Power turbine, the code's accuracy was verified by comparing the code's predictions to data measured from the Verdant Power turbine during full-scale operation. The percent error between the measured and WT_Perf predicted mechanical power is shown in Figure 2. Uncertainties in the measured data from the Verdant Power turbine were unavailable at the time, so to calculate the percent error, as shown in Figure 2, an uncertainty of zero was assumed for the measured mechanical power. The WT_Perf model showed good agreement with the experimental data. It was observed that the accuracy of the WT_Perf model should be sufficient for use as a design tool for future hydrokinetic turbines.

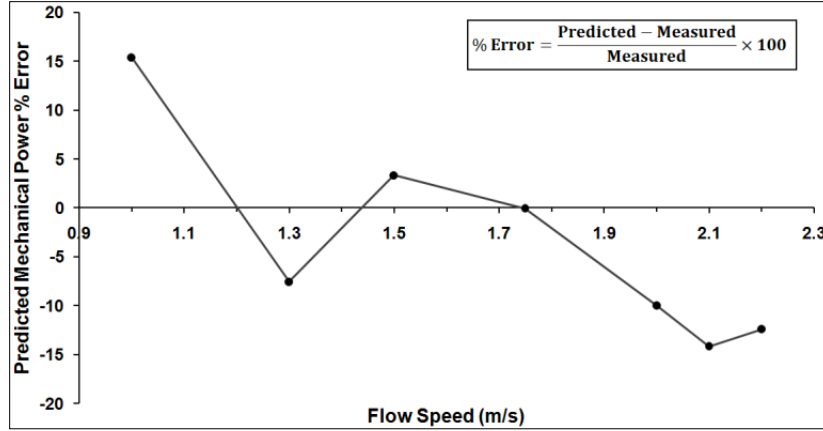


Figure 2. WT_Perf predicted power percent error for the Verdant Power Gen4 turbine

3. Overview of Rotor Optimization Code

This rotor optimization code couples a single objective genetic algorithm with the WT_Perf hydrodynamic model in a user-friendly graphical user interface that allows for rapid and intuitive design of optimal stall-regulated rotors. This rotor optimization code takes advantage of a modern GA developed by The MathWorks as part of the MATLAB Optimization Toolbox [11]. This optimization method calculates the optimal chord, twist, and hydrofoil distributions and rotor speed which maximize the hydrodynamic efficiency and ensure that the rotor exhibits power regulation via hydrodynamic stall, with the constraint that cavitation be avoided.

For structural and hydrodynamic motives, upper and lower bounds must be placed upon the chord, twist, and percent thickness distributions. And in addition, each distribution is required to decrease monotonically from the blade root to tip. Although the optimization code cannot select which hydrofoils should be used in the blade design, the optimization code can calculate an optimal placement of hydrofoils along the span of the blade when a family of hydrofoils (with corresponding lift, drag, and pressure coefficients) is input by the user. The hydrofoil distribution is modeled as a percent thickness distribution, where the percent thickness value determines which hydrofoil in the family—and thus which lift, drag, and pressure coefficients—are applied in the WT_Perf performance model. The rotor speed is calculated by a trial and error method within the optimization algorithm. Currently, the rotor diameter and rated power are held constant in this optimization method.

3.1 Rotor Optimization Algorithm

This optimization method defines 15 variables as the optimization variables, which together define the chord, twist, and percent thickness distributions, as illustrated in Figure 3. The chord, twist, and percent thickness distributions are each defined at 5 control points: the blade hub, the blade tip, and then at evenly spaced points in between. To limit the variables needed to completely define the blade geometry, Bezier curves are fit through the control points and WT_Perf then is evaluated at a sufficient resolution along the blade, as illustrated in Figure 3. The percent thickness distribution in Figure 3 illustrates an example where the user input three airfoils which had percent thicknesses of 18%, 21%, and 24%. As shown in Figure 3, the percent thickness distribution is transformed into a step function, where the steps correspond to the airfoils/hydrofoils input by the user. The control points of the chord, twist, and percent thickness distributions are subject to upper and lower bounds, and are also required to decrease

monotonically from the blade root to tip. These bounds and constraints are enforced so that the GA will converge on structurally and hydrodynamically feasible blades shapes without over-constraining the problem.

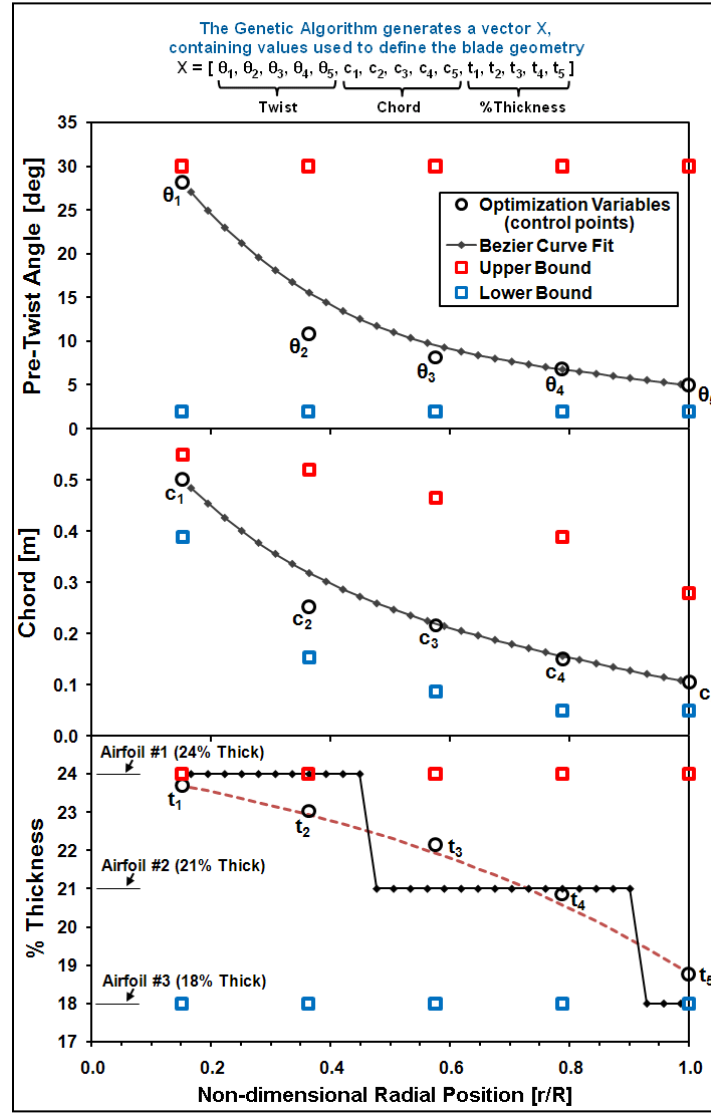


Figure 3. The blade geometry distributions are each defined by a Bezier curve fit through the control points

In GA terminology, an individual is a vector containing values for the 15 optimization variables, and a set of individuals is called a population or generation. The GA is initiated by creating an initial population of randomly generated individuals that satisfy the constraints of the problem and sufficiently sample the solution space. Each individual from the initial population represents a possible blade shape and is assigned a fitness value which represents the degree to which the individual satisfies the rotor design criteria (i.e., achieves maximum hydrodynamic efficiency, regulates power via hydrodynamic stall, and avoids cavitation). In this method, the lowest fitness values represent optimal solutions which best satisfy the rotor design criteria and high fitness values represent blade shapes that performed poorly. The GA continues to search for individuals

with the lowest (best) fitness values from one population to the next. The intelligence of the GA search algorithm comes from its ability to selectively allow individuals to reproduce—thus creating subsequent populations of potentially better-performing individuals. Subsequent populations are generated as parent individuals reproduce with one another through the operations of crossover and mutation. Crossover is a reproductive function in which the child individual consists of varying proportions of traits from the parent individuals. Mutation is a reproductive function in which the child individual contains elements of the parent individual that have been randomly altered from their original state.

By giving individuals having the lowest fitness values greater probabilities of being able to reproduce, subsequent populations can retain many of the best traits of individuals from previous generations and contain even better-performing individuals. If succeeding populations of individuals become too similar to each other, however, the GA can converge prematurely on non-optimal (local) solutions. Therefore, the diversity of succeeding generations is kept high through the use of crossover and mutation, and also by allowing poorly performing individuals to occasionally reproduce. This process of allowing individuals to reproduce from one generation to the next and searching for the lowest fitness value continues either until a blade shape is found which meets all the design specifications (i.e., has a sufficiently low fitness value) or until a maximum number of generations has been processed. Occasionally the genetic algorithm could produce blade shapes that experience cavitation or whose performance is so poor that the WT_Perf analysis fails to converge. These individuals are assigned an arbitrarily high (poor) fitness value to decrease their chances of propagating into future generations. A flowchart of the rotor optimization algorithm is illustrated in Figure 4.

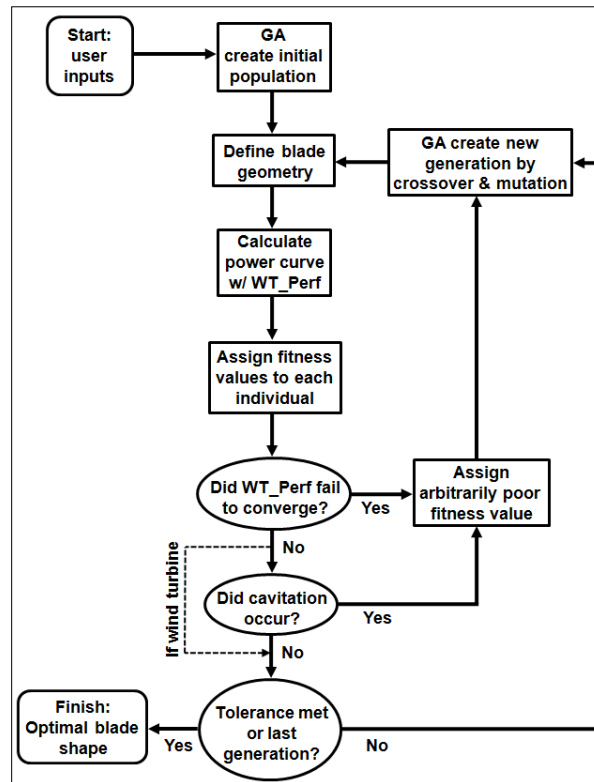


Figure 4. Flowchart of the rotor optimization algorithm

3.2 Defining Optimal Solutions and the Fitness Function

A fitness function is defined which allows the GA to mathematically determine whether a blade shape sufficiently meets the design requirements. In this optimization method, an optimal stall-regulated rotor is one which produces an ideal power curve—that is, the rotor should operate at high efficiencies from its cut-in to rated flow speed, and then should begin to hydrodynamically stall and maintain a constant power output as the flow speed approaches and exceeds the rated speed of the turbine. The lowest fitness values are assigned to rotors which closely follow this ideal stall-regulated power curve.

The fitness function is defined by equation 5, where $Area_1$ and $Area_2$ are defined by equation 6 and equation 7, respectively. The values w_1 and w_2 are weight values; however, experimentation has shown that the values of w_1 and w_2 have no noticeable effect on the optimization results or convergence rate. Therefore the default values of $w_1=w_2=1$ are used. Figure 5 further illustrates how the fitness function and its quantities of interest— $Area_1$ and $Area_2$ —are defined.

$$F = w_1 Area_1 + w_2 Area_2 \quad (5)$$

$$Area_1 = \int_{V_{cut-in}}^{V_{rated}} P_{Betz} - P_{turbine} dV_{\infty} \quad (6)$$

$$Area_2 = \int_{V_{rated}}^{V_{cut-out}} |P_{turbine} - P_{rated}| dV_{\infty} \quad (7)$$

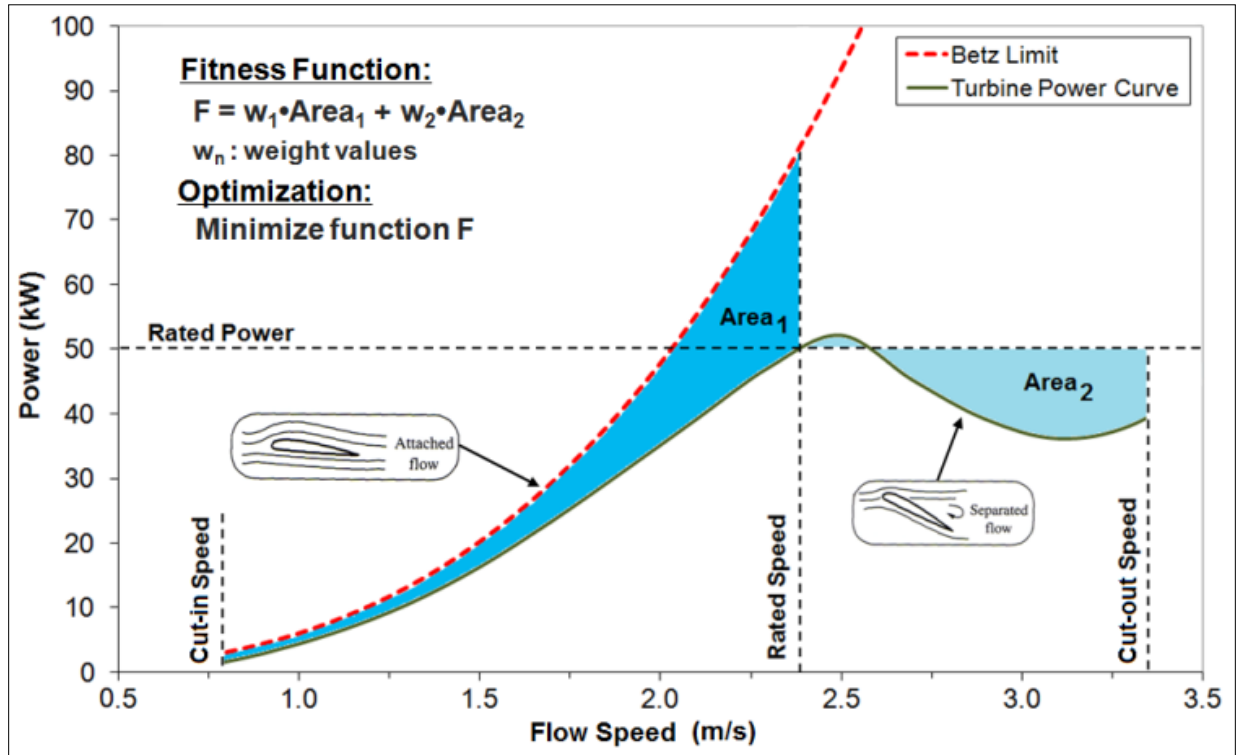


Figure 5. Example power curve for a stall-regulated turbine, and definition of the fitness function and its quantities of interest

The Betz limit is used as a practical upper limit on the highest efficiency attainable. To maximize the efficiency of the turbine, the area between the Betz limit and the turbine power curve (Area₁) is minimized. An ideal stall-regulated turbine would maintain a constant rated power output as the flow speed increases beyond the rated flow speed of the machine. It therefore is ideal to minimize the area between the line of rated power and the turbine power curve (Area₂). Thus, within realistic bounds set upon the optimization variables, an optimal blade shape is found when Area₁ and Area₂ are minimized (i.e., the fitness function is minimized) and when cavitation is avoided.

3.3 Optimization Code Sample Results

Two conceptual rotors were designed to test the capabilities of this optimization method, referred to herein as the NACA and Risø rotors. Both rotors had three blades, a 5-m diameter, a rated power of 35 kW, and a rated speed of 2.1 m/s. In addition, both rotors were designed for a river depth of 10-m and a hub height of 4.5-m. For the NACA rotor, seven airfoils from the NACA 44XX family ranging from the NACA 4417 to the NACA 4411 were given as inputs. For the Risø rotor, three modern airfoils designed specifically for wind turbine applications were given as inputs: the Risø-A1-18, Risø-A1-21, and Risø-A1-24. The Selig/Du stall-delay model was used to correct the lift coefficients and the Eggers stall-delay model was used to correct the drag coefficients. Figure 6 shows the mechanical power and efficiency for the NACA and Risø rotors. The rotor optimization code converged on these solutions in approximately 2 hours on a modern PC after processing 50 generations for each rotor, where each generation consisted of 200 individuals.

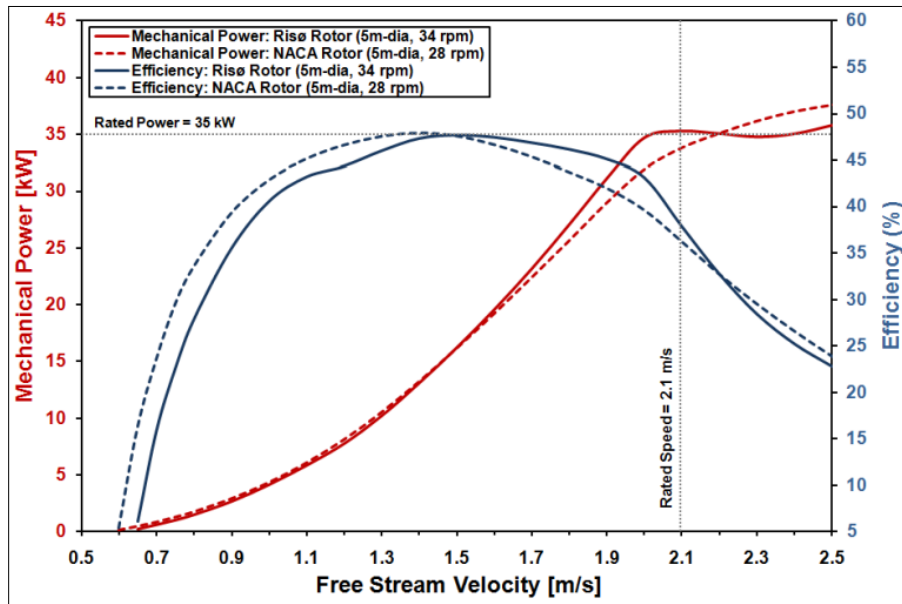


Figure 6. The power and efficiency curves are shown for two conceptual optimal rotors produced by the optimization code

The optimization method produced satisfactory results. The NACA and Risø optimal rotors both reached peak efficiencies of approximately 48% and avoided cavitation up to a flow speed of 2.5 m/s. The NACA rotor was not able to stall as effectively as the Risø rotor. The NACA 44XX foils are more susceptible to cavitation than the Risø-A1-XX foils; therefore the GA may have been preventing large angles of attack for the NACA rotor—which would help prevent cavitation

but also limit stall capability. The NACA 44XX airfoils were designed to stall very gradually, whereas stall occurs more suddenly for the Risø-A1-XX airfoils. The Risø airfoils were designed for stall-regulated turbines, and the power curve produced by the Risø rotor produces a very ideal power curve with good efficiencies and nearly constant power output above rated speed. Comparing the power curves for both rotors clearly shows that the ideal power curve is met much more effectively when using airfoils designed specifically for stall-regulated turbines. Note that the Risø rotor was capable of reaching its rated power at flow speeds less than the rated speed—this suggests that the rotor diameter was oversized and that an ideal power curve also could be achieved with a smaller rotor diameter. Overall, the optimization method was successful in producing rotors which have satisfactory power curves and which avoid cavitation.

Figure 7 shows the optimized blade geometry (twist, chord, and percent thickness distributions) for the NACA and Risø rotors produced by the optimization code. The NACA 44XX and Risø-A1-XX hydrofoil families both use the naming convention where the “XX” represents the actual maximum percent thickness of the hydrofoils. The optimization code produced realistic twist and chord distributions which follow characteristics of the closed-form Betz optimum blade [4].

Although seven hydrofoils were input for the NACA rotor, the optimization method converged on only the thickest hydrofoils. This was partially expected because the thinner NACA hydrofoils are the most susceptible to cavitation, and the GA was effectively eliminating blade shapes which cavitate from subsequent generations. Cavitation is greatly dependent on the pressure distribution around the hydrofoils, and thicker hydrofoils tend to be more resistant to cavitation due to their relatively lower peak suction pressures compared to thinner hydrofoils, which can have large peaks in their suction pressure distributions. The Risø-A1-XX hydrofoils are much thicker hydrofoils and are more resistant to cavitation—therefore it also was partially expected to see the GA converge on a solution which contained the entire set of Risø-A1-XX hydrofoils.

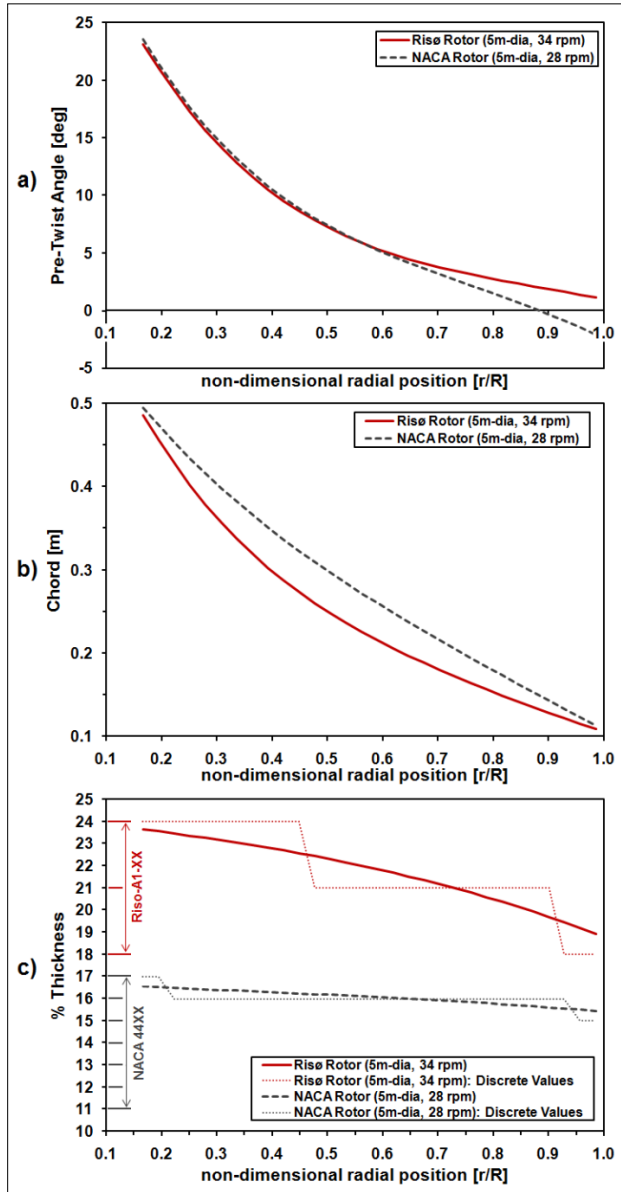


Figure 7. Optimal blade geometry produced by the optimization code

4. Conclusions and Recommendations

It was shown that the wind turbine performance code, WT_Perf, could be adapted to predict the performance of a hydrokinetic turbine with sufficient accuracy. An optimization method was also presented, in which the optimal chord, twist, and hydrofoil distributions and rotor speed were successfully calculated to produce optimal stall-regulated hydrokinetic turbine rotors. This optimization method was successful in consistently producing rotors which avoid cavitation, produce ideal power curves, and have realistic blade geometries—it therefore should be a useful tool to those who design stall-regulated rotors. Defining a blade geometry to produce an optimal stall-regulated rotor is a time-consuming and unintuitive process, and is best suited to numerical approaches such as the optimization method presented herein.

Optimizing a rotor for maximum hydrodynamic efficiency does not necessarily create a turbine with the highest annual energy production (AEP) or lowest cost of energy (COE), but maximizing the efficiency is an excellent criterion to use as a first pass in the design process. Future improvements are planned for this optimization code, in which maximizing AEP and minimizing COE can be introduced as alternate objectives. The inclusion of AEP and COE as design objectives would provide more meaningful results to the design engineer. The capability to design actively controlled variable-speed variable-pitch turbines will also be included into future versions of this optimization code. Additionally, the inclusion of more advanced stall-delay models could improve the accuracy of the BEM performance predictions. The inclusion of a stall-delay model which could correct the pressure coefficient data would be especially useful, as this would improve the accuracy of the cavitation inception predictions.

This optimization code is a work in progress, and this paper reflects an early version of the code. This code is free to use and is open source. To obtain this optimization code (available Q4 2009), please visit <http://wind.nrel.gov/designcodes/>.

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List of Variables

a	Non-dimensional axial velocity induction factor
a'	Non-dimensional tangential velocity induction factor
c	Chord length [m]
C_{Pmin}	Minimum pressure coefficient
C_p	Power coefficient
g	Gravitational constant [m/s^2]
h	Depth from free surface to point of interest on the blade [m]
P_{atm}	Atmospheric pressure (absolute) [N/m^2]

P_{rated}	Constant power maintained at flow speeds $> V_{\text{rated}}$ [kW]
P_{Betz}	The Betz limit power curve [kW]
P_{turbine}	The actual turbine power curve [kW]
P_V	Vapor pressure (absolute) [N/m^2]
r	Local rotor radius [m]
R	Tip rotor radius [m]
t	Non-dimensional percent thickness (maximum thickness/chord)
V_{∞}	Free stream velocity [m/s]
V_{loc}	Local relative velocity at the rotor plane [m/s]
V_{cavitate}	Local relative velocity at which cavitation is induced [m/s]
V_{rated}	Flow speed at which turbine ideally begins producing constant power [m/s]
$V_{\text{cut-in}}$	Flow speed at which turbine begins producing power [m/s]
$V_{\text{cut-out}}$	Flow speed at which turbine stops producing power [m/s]
Θ	Pre-twist angle [deg]
σ	Non-dimensional cavitation number
ρ	Fluid density [kg/m^3]
Ω	Rotor speed [s^{-1}]

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14. ABSTRACT (Maximum 200 Words) This report describes the adaptation of a wind turbine performance code for use in the development of a general use design code and optimization method for stall-regulated horizontal-axis hydrokinetic turbine rotors. This rotor optimization code couples a modern genetic algorithm and blade-element momentum performance code in a user-friendly graphical user interface (GUI) that allows for rapid and intuitive design of optimal stall-regulated rotors. This optimization method calculates the optimal chord, twist, and hydrofoil distributions which maximize the hydrodynamic efficiency and ensure that the rotor produces an ideal power curve and avoids cavitation. Optimizing a rotor for maximum efficiency does not necessarily create a turbine with the lowest cost of energy, but maximizing the efficiency is an excellent criterion to use as a first pass in the design process. To test the capabilities of this optimization method, two conceptual rotors were designed which successfully met the design objectives.						
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