BLADE GEOMETRY OPTIMIZATION FOR THE DESIGN OF WIND TURBINE ROTORS

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ABSTRACT

This paper describes a blade geometry optimization method for wind turbine rotors in which considerations are given to aerodynamics, structures, noise, and cost. An existing computer program named PROPGA, which is a genetic-algorithm based optimization method for wind turbines, provided part of the foundation for this work. The objective was to develop and implement structures and costs modeling into PROPGA, and enhance its efficiency and overall capabilities including multi-objective optimization. The structure of the blades is modeled, and cost considerations are given to all main wind turbine components. Each cost model is based on a baseline design, which can be of different concept and size than that of the optimized rotors. Overall, the proposed method is an efficient engineering tool to design new or retrofit blades for minimum cost of energy as well as obtaining trade-off curves between competing design objectives.

INTRODUCTION

With the current trend of the wind energy industry of increasing generator and rotor size, and becoming ever more competitive with traditional energy sources, the optimization of wind turbine components is becoming even more important to minimize the cost of energy (COE). Among those components, the rotor accounts for a significant fraction of the total turbine cost and strongly dictates the energy production of the turbine as well as the loads on the machine. Therefore, rotor blade optimization is important.

The first step in a blade design process is typically the optimization of the blade geometry, i.e., the chord, twist, and airfoil distributions as well as the blade pitch and rotor diameter. Traditionally, the blade geometry was optimized for maximum annual energy production (AEP), using a direct-design method based on blade-element momentum theory (BEMT).[1-4] More recently, an inverse-design methodology[5,6] and direct optimization methods[6-10] have been developed for the same purpose. Unfortunately, maximizing AEP can result in a blade that negatively affects its own cost and that of other wind turbine components. As a consequence, the cost of energy (COE) may actually increase, even if there are constraints on the blade loads. Therefore, considerations must be given not only to aerodynamics, but also to structures and cost. Furthermore, the effect of the blade design on the other components of the wind turbine must be quantified to ensure a minimum COE solution, and noise should be considered as well.

From a review of the literature, it appears that the development of multidisciplinary optimization methods for wind turbine blades has received only limited attention. Fuglsang and Madsen[11] from the Risø National Laboratory in Denmark have developed a blade geometry optimization method that considers aerodynamics, structures, noise, and cost. Both fatigue and extreme loads are considered, and multiple constraints can be prescribed. Cost considerations are given to all major wind turbine components in a way that allows comparisons between turbines of equal size and concept. A similar blade optimization method named BLADOPT, is presently under development at the Netherlands Energy Research Foundation ECN.[12] Also noteworthy is that the optimization methods of Risø and ECN are not freely available.

A different approach to a multidisciplinary design method for wind turbine rotors is to combine a multi-objective optimization algorithm with an inverse-design method based on steady aerodynamics, a structural model for the blades, and cost models for all main components. The cost models can be based on a baseline and on key design factors that are influencing the cost of each component. Furthermore, the cost modeling approach can allow for turbines of different concept and size to be considered. Also, noise can be considered without increasing computational demand using a constraint on tip speed. The advantage of this approach is a relatively low computing cost, which is important for an engineering design tool, without significant loss in the accuracy of the performance predictions. Many blade geometries can be investigated

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prior to using aeroelastic and finite-element codes for further analysis and structural design. Furthermore, trade-off curves between different blade design objectives can be obtained.

Although part of the foundation to this approach for blade geometry optimization has been developed with the computer program PROPGA,[7] the crucial elements of structures and costs modeling have not been considered. Therefore, the objective for this research work was to develop and implement structures and costs models into PROPGA, and enhance its overall capabilities including multi-objective optimization. As a result, an efficient engineering method for blade geometry optimization of wind turbine rotors that yields blades for minimum COE has been developed. Even though the cost models are primarily intended for large wind turbines, the method should be also applicable to smaller HAWTs. This paper describes the design approach and the optimization methodology. A separate paper will later focus on the application of this blade geometry optimization method.

DESIGN APPROACH

The design of a wind turbine rotor is complex because there are several design variables, some of which are interdependent, and competing objectives within the definition of the COE. For example, an increase in rotor diameter is beneficial to the energy capture, but the resulting effects on loads may actually increase the COE. The design of a wind turbine rotor is multidisciplinary where considerations must be given to aerodynamics, structures, noise, and cost as well as several other factors. In this section, the approaches taken to account for aerodynamics, structures, noise, and cost, are described separately. The selection of the optimization algorithm is also discussed.

Aerodynamics

The aerodynamic considerations are at the core of the optimization process. Performance predictions are obtained from the computer program PROPID,[5,6] which is an inverse design method for HAWTs that is based on BEMT. Using the inverse design capability of PROPID, desired rotor characteristics, such as the rated power and tip speed, can be prescribed. PROPID also has a multipoint design capability, which means that a large number of different rotor characteristics with correspondingly different conditions can be specified. The airfoil data is accurately modeled in PROPID. Linear interpolation is used for lift and logarithmic interpolation is used for drag according to the local Reynolds number. The airfoil data can be modified for three-dimensional effects using stall-delay models.[13-14]

Structures

Only the structure of the blades is considered although the effects of the rotor on the other wind turbine components are accounted for using cost models that will be later described. For the blades, the hub is modeled as a tube of thickness t_h and diameter d_h, and the airfoil sections are modeled as shown in Fig. 1. Each airfoil section is subdivided into a skin and a spar that can have either one or two shear webs. As indicated in Fig. 1, the overall spar height is taken as 85% of the airfoil thickness t_a, which was derived from the NREL airfoil families,[15] and is representative of most airfoils. The thickness of the hub t_h and spar t_{sp} are sized according to flap bending considerations, and the skin thickness t_{sk} is a user input that should be derived from buckling and minimum thickness considerations.

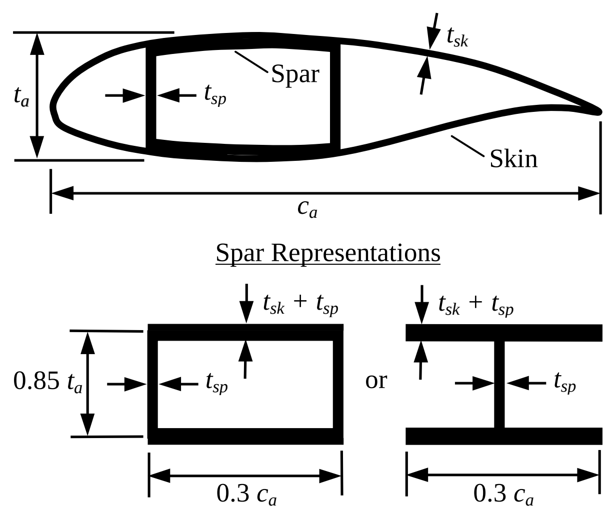

Fig. 1: Modeling of the airfoil section.

To compute the cost of the blades, the blade weight must be estimated, and the following procedure is used. First, the flap-bending load at each blade segment is computed from the thrust distribution for the given load condition. Unless specified otherwise by the user, the IEC 50-year extreme windspeed[16] is used to compute the blade loads when the rotor is parked and fully exposed to the wind. The extreme root bending moment is also computed as it is also needed for cost modeling. The IEC load factor of 1.35 is applied to the static flap-bending loads. The second step is to use the static flap-bending load M to compute the required moment of inertia I of each segment to match a prescribed stress level σ_p along the blade, i.e.

$$I(r) = \frac{M(r)\cdot[t(r)/2]}{\sigma_p(r)} \qquad (1)$$

The thickness t in Eq. 1 represents either that of the hub or the skin and spar for a given blade segment, and the prescribed stress level is a user input. Two prescribed stress levels are needed: one for the hub and skin $\sigma_{\pm 45}$ and one for the spar σ_{uni}. Also, proper partial safety factors for the materials should be accounted for in the prescribed stress levels.[16] Using Eq. 1, the required hub and spar thicknesses can be determined, i.e.,

Hub: $$t_h = \frac{8 \cdot I_h}{\pi \cdot d_h^3} \quad (2)$$

Spar: $$t_{sp} = \frac{1}{\sigma_{uni}} \left\{ \frac{8000}{867} \cdot \left[\frac{M \cdot (t/2)}{c_a \cdot t_a^2} \right] - t_{sk} \cdot \sigma_{\pm 45} \right\} \quad (3)$$

Note that the inertia of the skin and spar about their own axis of rotation and that of the shear web(s) are neglected in Eq. 3. They are typically much smaller than the inertia resulting from the farthest distance of the material, which is taken as half the spar height for both the spar and skin.

From the skin thickness distribution along the blade obtained from Eqs. 2 and 3, the required number of plies of the material considered is computed, from which the effective skin thickness distribution is determined. At this point, the tip deflection of the blade can be checked against a constraint, and material is added if needed. Then, the blade cross-sectional area at each segment is calculated according to Fig. 1 using the effective skin thickness. The blade material volume is then estimated from linear extrapolations of the local cross-sectional area of each blade segment. Finally, the blade weight W_B is obtained from the number of blades N, material volume MV_B and density ρ_B, i.e.

$$W_B = N \cdot MV_B \cdot \rho_B \quad (4)$$

Noise

For the rotor, the main sources of aerodynamic noise are the tip-vortex/trailing-edge interaction, turbulent inflow, and the trailing-edge thickness. Aerodynamic noise can be reduced using strategies outside of the blade geometry optimization process. For example, the noise can be reduced by adopting a proper tip shape,[17,18] and a sharp trailing edge over the outboard section of the blades.[19] Within the optimization method, the noise level can be essentially prescribed by limiting or fixing the tip speed of the rotor, as the aerodynamic noise is predominantly a function of the tip speed.[20] Such an approach results in savings in computational demand by not incorporating noise prediction methods.

Cost

Cost considerations are given to the following components:
• Blades
• Hub
• Drivetrain (shaft, gearbox, brake, and generator)
• Controller
• Nacelle (bedplate and yaw system)
• Tower

The cost of each component is modeled separately using a relative approach to cost modeling. Precisely, the cost is derived from a baseline that is subdivided into a fixed and a variable part. Also, the cost of each component is related to the design parameters of importance for that component. Each design parameter is normalized with the corresponding value from the baseline. Except for the controller, which does not rely on baseline cost, all cost models are expressed in the form indicated below

$$C_i = C_{ib} \cdot \left[c_i + (1 - c_i) \cdot \left(\frac{P_i}{P_{ib}} \right) \right] \quad (5)$$

where C is the cost, i is the component, c is the cost factor representing the fixed portion of the total cost, P represents the design parameters of importance for that component, and subscripts ending with a b are baseline values. The user must input the baseline cost and cost factors of the different components. For example, a cost factor of 20% has been used for the blades in other blade optimization work.[16] The design parameters fall under four categories:
• Rotor characteristics (e.g., rated power)
• Steady loads (e.g., extreme blade root bending)
• Material properties (e.g., ultimate strength)
• Design factors

The design factors account for differences in control strategy (fixed- vs. variable-speed and pitch vs. stall), hub type (rigid vs. teeter), and blade type (rigid vs. flexible) between the optimized rotor and the baseline. Each cost model does not necessarily have design parameters from all categories. The design parameters of importance for each component were selected according to first principles in wind turbine design, and the wind turbine cost modeling work of Harrison and Jenkins.[21] They show good agreement between the results of their cost and weight models and that of existing wind turbines. Table 1 provides a list of the design parameters of importance for each component. Any component can be omitted from the cost analysis by simply using a baseline cost of zero.

Table 1: Design parameters of importance for each component.

Component	Design Parameters
Blades	- Estimated weight - Type of controls, hub, and blades
Hub	- Extreme blade root bending - Material properties - Type of controls, hub, and blades
Low-speed shaft	- Shaft diameter (rotor diameter, torque and weight) - Rotor diameter - Material density - Type of drivetrain
Gearbox	- Rotor torque at rated power - Type of controls and drivetrain
Brake	- Rotor torque at rated power - Type of power regulation
Generator	- Rated power
Power elect.	- Rated power
Pitch actuators	- Total blade surface area - Angular velocity of rotor
Bedplate	- Weight of bedplate (rotor diameter, torque, and thrust) - Type of drivetrain
Yaw system	- Blade root bending at rated power
Tower	- Tower height - Rotor thrust at rated power - Material properties

The proposed relative cost modeling approach has advantages over "absolute" cost models that do not require baseline cost figures. A relative cost model can make use of the cost data of a baseline design, which is typically available within a given wind turbine manufacturer. The baseline cost of some components can also be obtained from weight data and the use of cost multipliers. Consequently, a relative approach to cost modeling is less susceptible to change over time as the technology evolves. When baseline cost data is not available, such as in the case of a baseline rotor design that has been optimized for maximum energy capture, absolute cost models can be used to provide the baseline cost data. Therefore, the relative cost models can always rely on the most advanced absolute cost models that are available.

Blades

The cost of the blades C_B is primarily driven by their design factor F_B, and estimated weight W_B, i.e.

$$C_B = C_{Bb} \cdot \left\{ c_B + \left[(1 - c_B) \cdot \left(\frac{F_B}{F_{Bb}} \cdot \frac{W_B}{W_{Bb}} \right) \right] \right\} \quad (6)$$

Again, the subscripts that end with *b* denote a baseline value. For the blades, the design factor depends on the types of controls, hub, and blade. For example, Harrison and Jenkins[21] suggest that the blades design factor for a fixed speed/pitch wind turbine having a rigid hub and blades is 1 while that of a variable speed/pitch HAWT having a teeter hub and flexible blades is 0.49.

Even though the root flange is not specifically modeled in Eq. 6, it should be accounted for in the baseline blades cost. Also, fatigue considerations to the blade weight and cost can be accounted for in principle if fatigue was considered in the design of the baseline blade.

Hub

The blade root bending moment is an important design driver for the hub. Accordingly, the cost model adopted for the hub is based on the extreme blade root bending moment Mr_E. Consideration is also given to the hub material density ρ_m and allowable stress σ_m. A hub design factor F_H is also used. The cost of the hub C_H is given as

$$C_H = C_{Hb} \cdot \left[c_H + (1 - c_H) \cdot P_H \right] \quad (7)$$

with

$$P_H = \frac{F_H}{F_{Hb}} \cdot \frac{Mr_E}{Mr_{Eb}} \cdot \frac{\rho_m}{\rho_{mb}} \cdot \frac{\sigma_{mb}}{\sigma_m} \quad (8)$$

The hub design factor depends on the same factors than that for the blades, i.e., types of controls, hub, and blade. For example, the hub of a variable-pitch HAWT is typically more expansive than that of a fixed-pitch turbine of the same size because of the added complexity in housing the pitch bearings. Reference 21 can be used to select a proper hub design factor.

Drivetrain

The total cost of the drivetrain C_{DT} accounts for the low-speed shaft, gearbox, brake, and generator, i.e.

$$C_{DT} = C_s + C_x + C_k + C_g \quad (9)$$

where C_s is the cost of the low-speed shaft, C_x is the cost of the gearbox, C_k is the cost of the brake, and C_g is the cost of the generator.

Low-speed shaft

Torque and bending loads are the primary design drivers in sizing the low-speed shaft. Expressing the shaft length as a function of the rotor diameter D, the cost of the low-speed shaft is expressed as

$$C_s = C_{sb} \cdot \left[c_s + (1 - c_s) \cdot P_s\right] \qquad (10)$$

with

$$P_s = \frac{F_s}{F_{sb}} \cdot \frac{D}{D_b} \cdot \frac{\rho_m}{\rho_{mb}} \cdot \left(\frac{D_s}{D_{sb}}\right)^{1/2} \qquad (11)$$

where F_s is the design factor for the low-speed shaft and D_s is shaft diameter. Harrison and Jenkins[21] suggest using a shaft design factor of 1 for a modular drivetrain or 0.25 for an integrated design, and D_s can be expressed as follows

$$D_s = \left[\left(\frac{3 \cdot Q_R}{\sigma_y}\right)^2 + \left(\frac{0.0125 \cdot g \cdot W_{ROT} \cdot D}{\sigma_e}\right)^2\right]^{1/6} \qquad (12)$$

where Q_R is the rated torque of the rotor (Nm), g is the acceleration due to gravity (m/s^2), W_{ROT} is the weight of the rotor (kg), which is taken here as twice the weight of the blades, D is the rotor diameter (m), σ_y is the yield strength of the material (Pa), and σ_e is the endurance limit of the material (Pa). The expression for D_s was derived from Ref. 21, and accounts for safety factors in torque and bending. Also, constants that become irrelevant in computing C_s because of the ratio D_s/D_{sb} were neglected in Eq. 12.

Gearbox

The cost of the gearbox is mainly driven by the torque of the rotor and is expressed in terms of the rated torque and a design factor F_x to account for the type of drivetrain and controls used, i.e.

$$C_x = C_{xb} \cdot \left[c_x + (1 - c_x) \cdot \left(\frac{F_x}{F_{xb}} \cdot \frac{Q_R}{Q_{Rb}}\right)\right] \qquad (13)$$

According to Harrison and Jenkins,[21] the gearbox design factor for a fixed speed/pitch HAWT using a modular drivetrain is 2 while that for a variable speed/pitch wind turbine using an integrated drivetrain is 0.63.

Brake

The function of the brake is to provide a large enough couple to bring the rotor and drivetrain to rest. This couple is proportional to the torque produced by the rotor. Therefore, the cost of the brake is expressed in a way similar to the gearbox, i.e.

$$C_k = C_{kb} \cdot \left[c_k + (1 - c_k) \cdot \left(\frac{F_k}{F_{kb}} \cdot \frac{Q_R}{Q_{Rb}}\right)\right] \qquad (14)$$

where F_k is the brake design factor to account for the strategy used to control peak power. Harrison and Jenkins[21] suggest a F_k value of 1.82 for stall control and of 1 for pitch control.

Generator

The price of a generator is often given in terms of the rated power of the turbine P_R. Accordingly, the cost of the generator C_G is expressed as

$$C_g = C_{gb} \cdot \left[c_g + (1 - c_g) \cdot \left(\frac{P_R}{P_{Rb}}\right)\right] \qquad (15)$$

Controller

The cost of the controller C_C obviously depends on the type of controls used on the turbine. A variable speed/pitch HAWT requires power electronics and a pitch-actuation mechanism, which is not needed for a fixed speed/pitch wind turbine. To account for the effect of the control strategy on the cost of the controller, the following cost model is used

$$C_C = C_e + C_a \qquad (16)$$

where C_e is the cost of the power electronics, and C_a is the cost of the pitch-actuation mechanism. Neither the cost of the power electronics nor that of the pitch-actuation mechanism depends on a baseline because the optimized turbines can have different type of controls than the baseline, and vice versa.

Power electronics

The cost of the power electronics can be expressed in terms of the rated power of the turbine, i.e.,

$$C_e = CM_e \cdot P_R \qquad (17)$$

where CM_e is the cost multiplier for the power electronics ($/kW).

Pitch-actuation mechanism

The size, and thus the cost, of the pitch actuation mechanism depend on the weight of the blades and more importantly on the aerodynamic forces acting on them. As a first order cost model, the total surface area of the blades S (m^2) and the tip speed of the rotor at rated power Vt_R (m/s) are used as the design parameters for the cost of the pitch-actuation mechanism, i.e.

$$C_a = CM_a \cdot S \cdot Vt_R^2 \tag{18}$$

where CM_a is the cost multiplier for the pitch-actuation mechanism ($\$s^2/m^4$).

Nacelle

The two nacelle components that are considered are the bedplate and yaw system, and thus the cost of the nacelle C_N is expressed as

$$C_N = C_p + C_y \tag{19}$$

where C_p is the cost of the bedplate, and C_y is the cost of the yaw system.

Bedplate

The weight of the bedplate depends on the rotor thrust, torque, and weight, as well as the surface area it must cover, which depends in part on the type of drivetrain used. Accordingly, the cost of the bedplate is given as

$$C_p = C_{pb} \cdot \left[c_p + (1 - c_p) \cdot \left(\frac{F_p}{F_{pb}} \cdot \frac{W_p}{W_{pb}} \right) \right] \tag{20}$$

where F_p is the design factor of the bedplate, and W_p is the bedplate weight. Harrison and Jenkins[21] suggest a bedplate design factor of 2.4 for a modular drivetrain, and 0.71 for an integrated design. They also provide an expression for the weight of the bedplate that can be rewritten as

$$\begin{aligned} W_p = {} & K_1 \cdot Q_R + K_2 \cdot T_{max} \cdot D_t + \\ & K_3 \cdot W_{ROT} \cdot D_t + K_4 \cdot D \end{aligned} \tag{21}$$

where K_1, K_2, K_3 , and K_4 are constants (K_1=0.00368 s^2/m^2, K_2=0.00158 s^2/m^2, K_3=0.015 m^{-1}, and K_4=0.341 kg/m), Q_R is the rated torque (Nm), T_{max} is the maximum rotor thrust generated by the rotor (N), W_{ROT} is the rotor weight (kg), which is taken as twice the blade weight, D_t is the tower top diameter (m), and D is the rotor diameter (m).

Yaw system

The main design drivers for the yaw system are the inertia of all components resting on the yaw system, and the blade root bending moment resulting from the rotor thrust. Because weight estimates for all components above the yaw system are not readily available in the proposed method, the cost model adopted for the yaw system is only based on the blade root bending moment at the rated windspeed Mr_R, i.e.

$$C_y = C_{yb} \cdot \left[c_y + (1 - c_y) \cdot \left(\frac{Mr_R}{Mr_{Rb}} \right) \right] \tag{22}$$

Tower

The cost model for the tower is based on the optimal tower design, which simultaneously satisfies the buckling and bending design conditions, and is thus the least expensive option. Although the rotor weight and wind load also contribute to the total bending load at the base of the tower, these two contributions are typically much smaller than that from the rotor thrust.[21] Therefore, the cost of the tower is modeled based on the rotor thrust at rated power T_R, tower height h, and material properties.

$$C_T = C_{Tb} \cdot \left[c_T + (1 - c_T) \cdot P_T \right] \tag{23}$$

with

$$P_T = \frac{\rho_m}{\rho_{mb}} \cdot \left(\frac{T_R}{T_{Rb}} \cdot \frac{\sigma_{mb}}{\sigma_m} \right)^{2/3} \cdot \left(\frac{h}{h_b} \right)^{5/3} \tag{24}$$

Even though the natural frequency of an optimum tower might not be satisfactory, the proposed cost model for the tower is adequate for comparison purposes, which is the main intent in this optimization work.

Cost of Energy

The COE, which is the primary objective function for the optimization process, is defined as

$$COE = \frac{(TC + BOS)}{AEP \cdot AF} \cdot FCR + O\&M \tag{25}$$

In the above equation, *TC* is the total turbine cost ($), *BOS* is the balance of station cost ($), *FCR* is the fixed charge rate, *AEP* is the annual energy production (kWh), *AF* is the availability factor, and *O&M* is the operation and maintenance cost ($/kWh). The turbine cost is determined by adding the cost of all wind turbine components considered. For the balance of station, a fixed cost per kilowatt ($/kW) can be input if desired. The use of a *FCR* is important as the turbine is a one-time expense as oppose to the energy, which is produced over the life of the turbine. The AEP is computed by PROPID for a given windspeed distribution, and the availability factor and fixed charge rate are also inputs. The *O&M* cost is also a user input, which is relevant if the baseline and optimized rotors are not of the same concept. In that case, the *O&M* cost should be selected with consideration to the difference in risk between the two concepts considered. A large number of conceptual differences between the baseline and optimized rotors could yield misleading results to the designer if the *O&M* cost is not properly accounted for. Therefore, comparing the COE of the baseline and optimum rotors of different concepts should be done with care, and a large number of conceptual differences should be avoided.

Optimization Algorithm

The selection of the optimization algorithm depends on the nature of the problem and the characteristics of its design space. In the case of blade geometry optimization, there is a rather large number of design variables, which are both continuous (e.g., chord and twist distributions, blade pitch, etc.) and discrete (e.g., airfoil family, number of blades, etc.). Furthermore, some of these design variables are interdependent (e.g., chord and twist), and there are competing objectives within the definition of the COE that may lead to a multi-modal design space. Therefore, an optimization solver based on a gradient method or “hill-climbing” approach might not be satisfactory for the design of wind turbine rotors.[10] To ensure that the optimization algorithm does not converge to a local optimum instead of the global optimum solution, a robust optimization technique is needed. Another reason for relying on a robust search technique is that the airfoil data that is used in the optimization process is not always smooth as it depends on the airfoil and the resolution of the data.

From the myriad of optimization techniques that are available, a genetic algorithm[22,23] (GA) was selected. Belessis et al. also used a GA for their blade optimization work.[10] In brief, a GA is a global optimization method that mimics Darwin's principle of the survival of the fittest over a set (population) of candidate solutions (individuals) that evolves from one generation to the next. Individuals having a large fitness according to the objective function for the optimization process have a larger probability to “reproduce” in creating the new generation compared with those with a small fitness value. All design variables are coded into a single string (one string per individual), which can be considered analogous to a DNA chain. A GA uses reproduction, crossover, and mutation operators that are probabilistic to guide the search over the generations. In blade geometry optimization, the usefulness of a GA is twofold. First, the robustness of a GA is useful in the case of a multi-modal design space. Second, the population-based search of a GA yields a population of optimum solutions, which is important in the event that there is a large area of the design space that yields optimum results with no clear optima.

Even though minimum COE is the main objective for a wind turbine, minimizing the COE does not provide direct insights between energy production, turbine cost, and the rotor loads that affect the cost of the turbine. The competing objectives within the COE involve several trade-offs, and valuable insights can be gained from trade-off curves that can be obtained using multi-objectives in the optimization process. As any optimization algorithm will take advantage of weaknesses in the problem formulation, trade-off curves can also reveal limitations or anomalies with the cost models. Therefore, optimizing for both minimum COE and maximum AEP can be useful, especially in the early stage of a new blade design.

OPTIMIZATION METHODOLOGY

The proposed blade geometry optimization method supercedes the original PROPGA[7] computer program, which was developed to optimize the chord and twist as well as the blade pitch for maximum AEP. PROPGA has evolved into a multi-disciplinary optimization method that now considers additional design variables and has a multi-objective optimization capability. Over the course of its evolution, PROPGA has been extensively used for trade-off studies and in the design of blades that are used today.[24-27] The new PROPGA, which is simply referred to as PROPGA, retains all previous capabilities of the original code. This section presents the changes and additions made to improve PROPGA, and gives an overview of the optimization procedure.

Design variables and parameters

All design variables that are available with PROPGA and the required inputs are listed in Table 2. The user must prescribe bounds for each design variable.

Table 2: PROPGA design variables and required inputs.

Design Variables	Required Inputs
- Chord	- All fixed design variables
- Twist	- Rotor rpm or tip-speed ratio
- Blade pitch	- Windspeed distribution
- Rotor diameter	- Type of power control
- Airfoil family	- Material properties
- Number of blades	- Airfoil and baseline cost data

The chord and twist are typically defined using a spline with 3-5 nodes along the blade. PROPGA can optimize the rotor diameter as considerations are now given to structures and cost. Also, the best airfoil family from up to four families can be selected. The user must provide the radial position of each airfoil for the respective families.

Design constraints

As in the original version of PROPGA, the use of penalty functions, which reduce fitness if any constraint is violated, can be avoided by using the inverse design capabilities of PROPID to satisfy design constraints. PROPID can be used to satisfy constraints on most rotor characteristics or performance parameters, such as its peak power and tip speed. Difficulty can arise, however, when using inverse design to enforce a large number of design constraints. Inverse design is an iterative process, and thus the runtime for the optimization can be significantly increased. Therefore, a second option to enforce constraints was implemented where a fitness of zero is assessed to a blade geometry that does not meet a constraint. A zero-fitness penalty should not be used to enforce more than one or two constraints, however, because with this approach, the valuable information within infeasible solutions is not considered in the search.[22] The zero-fitness penalty has been found to work well for constraints such as maximum rotor thrust or torque, while inverse design should be preferred to fix rated power and tip speed.

Multi-objective optimization

PROPGA has now the capability of simultaneously optimizing blade geometry for two objectives. The objectives that can be selected are:

- Minimum COE, turbine cost, or cost of any component
- Maximum AEP or power coefficient
- Minimum rotor thrust or torque

Any combination of two objectives can be used to obtain a trade-off curve (Pareto front). Maximizing the power coefficient should only be selected when optimizing blades of turbines operating at variable-speed (constant tip-speed ratio). For the rotor thrust and torque, a windspeed must be specified.

The use of multi-objectives only affects the fitness value of all blade geometries and their ranking. After the value of each objective has been computed, the individuals are grouped in fronts as illustrated in Fig. 2. In this figure, a design space for minimizing two objectives is shown with a population of ten individuals. Each individual is checked against all the others to see if it is dominated. For example, the black individual in Fig. 2a is not dominated by any other individual, i.e., no individual in the hatched region. Accordingly, this individual is grouped in the first front. This process is repeated until all individuals have been included in a front, as shown in Fig. 2b. Then, the same dummy fitness is given to all blades within the same front. The value of the dummy fitness is largest for the first front, and least for the last. To ensure that the trade-off curve is well captured, a sharing function is used.

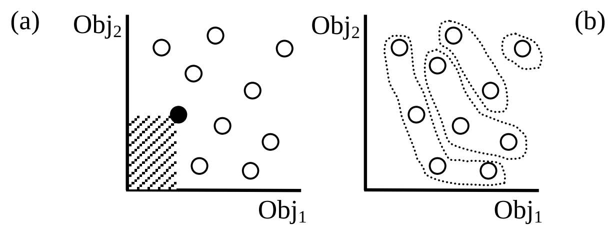

Fig. 2: Ranking process for multi-objectives.

Sharing

Sharing or niching is based on the concept of subdivisions in biological systems where some common traits are representative of each subdivision. The purpose of using a sharing function is to maintain diversity in the population, and the sharing function proposed by Goldberg and Richardson has been implemented into PROPGA.[28] Sharing only affects the fitness value of each blade geometry. The fitness F of each blade geometry is scaled in proportion to the differences in its geometry compared to that of all other blades in the population. Accordingly, the least a blade geometry has in common with other blades, the larger its resulting fitness F_{shared} will be, i.e.,

$$F_{shared} = \frac{F}{differences} \tag{26}$$

The differences are measured using the decoded value of each design variables (phenotypic sharing). In applying the sharing function when there are multi-objectives, the shared fitness is scaled so that it does not exceed that of any blade from a better front. Sharing does not need to occur for all design variables, but the airfoil family and rotor diameter are design variables for which sharing should be applied.

PROPGA runtime

The PROPGA runtime depends, of course, on the number of design variables being optimized, the number of blade segments, and the extent of the analysis of each blade geometry. More importantly, however, the runtime depends mainly on the degree of imbedded inverse design, which can be reduced if a zero-fitness penalty is used to enforce a constraint on maximum rotor thrust or torque.

To improve the efficiency of PROPGA, a convergence criterion was added. In its original version, a PROPGA run ended after a prescribed number of generations. As a result, PROPGA was often continuing a run without yielding additional benefits. Accordingly, PROPGA is now stopped when the increase in the fitness of the best blade geometry from one generation to the next is less than a prescribed percentage x over y consecutive generations. The default values for x and y are 0.1% and 10, respectively. In the case of multi-objective optimization, PROPGA is stopped when z percent of all individuals are grouped in the first front. The default value for z is 90%.

To further increase the efficiency of PROPGA, the extent of the analyses can be refined as the search progresses. For example, approximate evaluations of the energy capture may be used in the early stage of the optimization process by computing the power with large windspeed increments.

PROPGA procedure

PROPGA uses a binary representation of the design variables. For example, a blade with a linear twist and taper constraint could be modeled as follows,

1011|1100|0110|0011|0000|0101|01

where 1011 could represent the rotor diameter, 1100 the chord at the root, 0100 the twist at the root, 0011 the chord at the tip, 0000 the twist at the tip, 0101 the blade pitch, and 01 the airfoil family. The number of bits per design variable depends, of course, on the desired level of discretization. Typically, six to ten bits per design variables are used, except for the airfoil family for which only two bits are needed. The string length is an indication of the complexity of the problem, and the population is sized according to the total number of bits. As a default, PROPGA uses a population size that is four times the string length, giving a population of 104 for the above example. The population size remains fixed from one generation to the next.

The first step in PROPGA is to create the initial population by randomly generating binary strings of the required length. Then, the second step entails the analysis of each blade geometry and satisfying the design constraints, as illustrated in Fig. 3. One or two fitness values are assigned to each blade geometry depending if there are one or two objective functions. If sharing is used, the fitness values are scaled according to the sharing function. Sharing is always used with multi-objectives.

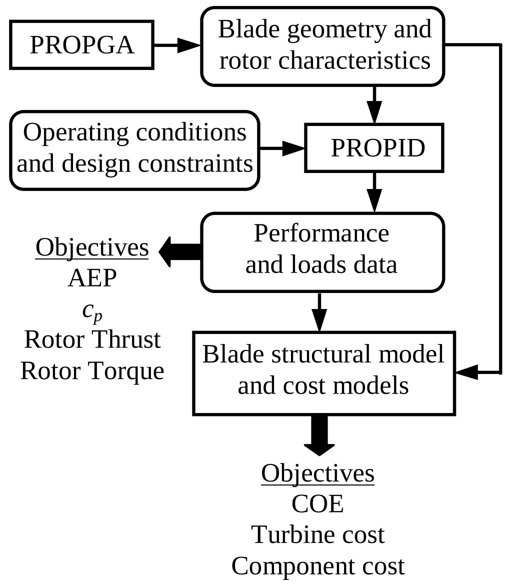

Fig. 3: Flowchart for analyses and satisfying constraints.

The third step is to rank the blade designs according to their respective fitness value or group them into fronts if there are two objectives. The fourth step is the formation of a mating pool, which represents the survival of the fittest aspect of a GA. Blades having a large fitness have a greater probability to access the mating pool. PROPGA uses tournament selection[22] without replacement to select the blades for reproduction. More precisely, the blades are randomly grouped in pairs, and the more fit design directly accesses the mating pool. This process is repeated twice to form a mating pool of the given population size. Each blade geometry in the mating pool is then randomly grouped in pairs forming "mates". Crossover, the fifth step, allows exchange of information between the blades (binary strings) by creating two "offspring" from the two mates. Two types of crossover can be used: single-point or uniform crossover.[22] With single-point crossover, the two mates exchange part of their strings at a randomly selected location as shown below (the symbol | indicates the crossover location).

1111|1111 and 0000|0000 $\Rightarrow$ 11110000 and 00001111

In contrast, uniform crossover implies that the mates exchange each of their bits with a probability of fifty percent. The offsprings generated from crossover form the new generation. As a last (sixth) step in the PROPGA procedure, a mutation operator is applied to each new generation, which involves the small probability (typically, 1/population size) that each bit of each string of the offsprings "mutates" from a 1 to a 0 or vice-versa. Therefore, it is the post-mutation offsprings that actually form the new generation. To ensure increasing fitness from one generation to the next, an elitism criterion[24] is applied where a randomly selected offspring is replaced by the best individual of the previous generation. Finally, steps 2-6 are repeated until the convergence criterion as been satisfied. The flowchart shown in Fig. 4 summarizes the optimization procedure.

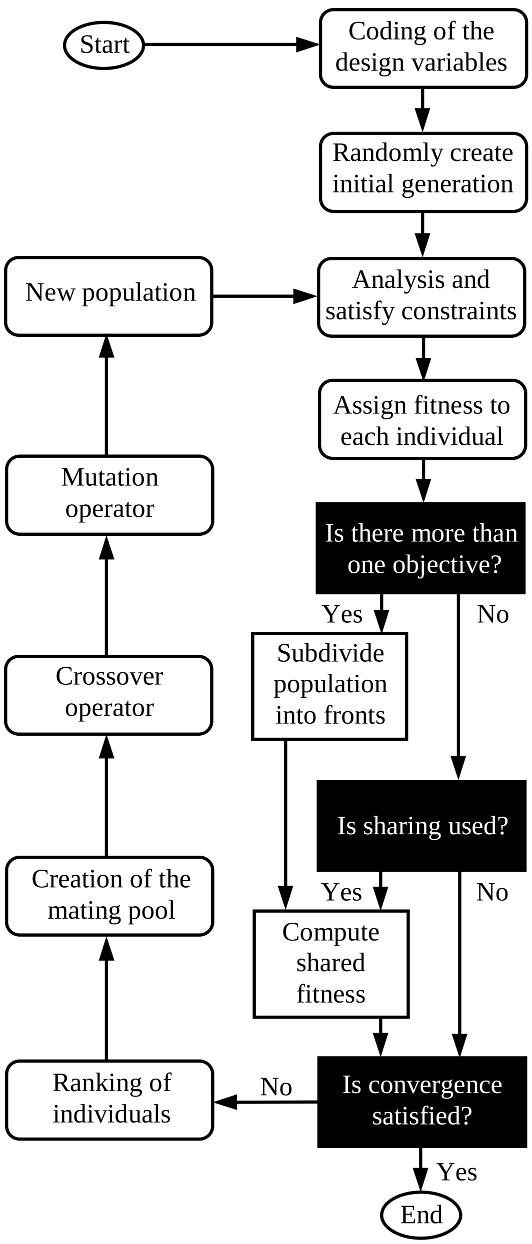

Fig. 4: Flowchart for PROPGA.

SUMMARY AND CONCLUSIONS

A multidisciplinary blade geometry optimization method for HAWT rotors has been presented. This improved version of PROPGA considers structures, noise, and cost as well as aerodynamics. Cost considerations are given to all major wind turbine components using models that are based on a baseline design, which can be of different concept and size than that of the optimized rotors. Particular attention should be given to the operation and maintenance cost, however, when there are conceptual differences between the baseline and optimized rotors. Even though the cost models are primarily intended for large wind turbines, the method should be also applicable to smaller HAWTs. Also, additions and enhancements have been made to the genetic-algorithm part of PROPGA including a multi-objective optimization capability, which provides trade-off curves between competing blade design objectives. These trade-off curves yield valuable insights that optimizing solely for minimum COE does not provide. PROPGA is an efficient engineering tool to investigate several blade geometries prior to using an aeroelastic and finite-element codes for further analysis and structural design.

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