MULTI-OBJECTIVE OPTIMIZATION OF WIND TURBINE BLADES USING LIFTING SURFACE METHOD

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ABSTRACT

This paper describes a multi-objective optimization method for the design of horizontal axis wind turbines using the lifting surface method as the performance prediction model. The aerodynamic code for the design method is based on the lifting surface method with a prescribed wake model for the description of the wake. A multi-objective optimization algorithm approach is employed for the optimization of wind turbine blades with 3D stacking line (swept leaned blades). The Non-dominated sorting genetic algorithm II (NSGA II) is used to facilitate the multi-objective optimization and to find the global optima of high-dimensional problems. The scope of the optimization method is to achieve the best trade off of the following objectives: maximum of annual energy production and minimum of blade loads including thrust and blade root flap-wise moment. To illustrate how the optimization of the blade is carried out the procedure is applied to NREL Phase VI rotor. The result shows the optimization models can provide more efficient designs.

Keywords: wind turbine; lifting surface method; free wake model; multi-objective optimization

INTRODUCTION

Wind turbine is a mechanical converter transforming wind energy into electricity. Aerodynamic design level of wind turbine blades has a direct impact on energy capturing capacity of the rotor, the choice of other components besides blades, the implementation of control strategies, and the reliability of the turbine as a whole, especially the capital of power output. Increasing the rotor sweeping area to enhance power output only through geometrically scaling the components to increase the rotor diameter has been realized, with the volume of each component generally increasing as the cubic of the dimensions. Therefore, there is a need to control the blade volume (mass), and reduce all sorts of aerodynamic loads thus lowering the requirements of structural strength of the blade itself and each component, during the design phase of blade geometry to improve wind energy capturing. The ultimate goal of large scale wind turbine blade optimized design is to lower the cost of energy production, which is subjected to a variety of factors: annual energy production, structural loads and noise generation etc. The aerodynamic profiles of the blades have crucial influence on the aerodynamic efficiency of wind turbine rotors. There is an increased interest in the study of the blades with 3D stacking line (swept leaned blades) to improve aerodynamic efficiency and reduce the air-loads and noise of the rotors.

There have been many papers published recently for the design of wind turbine rotors. Selig et al. [1] combined a genetic algorithm with an inverse design method as an optimization method for stall-regulated horizontal-axis wind turbines. The object was to maximize the annual energy production (AEP). Thumthae and Chitsomboon [2] using CFD simulation for wind turbines with untwisted blade to determine the optimal angle of attack that produces the highest power output.

Lanzafame and Messina [3] proposed a new design for inexpensive wind turbine with high power coefficients. The new wind turbine blade was subdivided into two, each with a different pitch angle, to optimize aerodynamic flow, absence of twist and with variable chord along the blade. The aerodynamic prediction model was based on blade element momentum theory based on their previous work [4]. Bumsuk et al[5] developed software for designing the optimum shape of multi-MW wind turbine blades with single objective such as securing high performance, minimizing thrust force, and limiting the range for chord length and twist angles by comparing with the initial blade models. Fuglsang and Madsen [6] presented a numerical multi-disciplinary optimization method for design of horizontal axis wind turbines. The method included multiple constraints and the object was the minimum cost of energy, which is determined by the design giving fatigue and extreme loads and the annual production of energy. A sequential quadratic programming (SQP) method was used to optimize the cost of energy (COE) by Kenway and Martins [7]. The objective was to maximize the AEP while keeping the cost fixed to the original baseline design. Xudong et al. [8] used a gradient-based method for the optimization of three different wind turbine rotors with the objective of minimum COE. An aero-elastic code which includes BEM method and structural dynamic model were employed for the optimization. A particle swarm optimization algorithm was developed by Liao et al. [9] for minimizing the blade mass of a 1.5MW wind turbine.

However the optimization of the wind turbine blades involves many objectives such as AEP, the air loads of the blades and rotors, and the mass of the blades. Improving one objective will inevitably deteriorate the others. A multi-objective optimization problem does not have a single

62 solution which is better than others. Instead there are a set of compromised solutions, each of which
63 is better than the others in one objective. There were few multi-objective optimization used for
64 wind turbine design.

65 Benini and Toffolo [10] described a multi-objective optimization method for the design of stall
66 regulated horizontal-axis wind turbines. In order to spread the solutions over the entire
67 Pareto-optimal set, an improved diversity preserving mechanism was integrated to the optimization
68 algorithm which is called genetic diversity evaluation method. Their results indicated that the COE
69 required HAWTs having high AEPs but low blade loads and low blade weights.

70 Giguere and Selig [11] developed a multi-objective optimization method with the
71 aerodynamics, noise and cost taking consideration in the wind turbine blade geometry design. A
72 multi-objective evolutionary algorithm (MOEA) is used for the optimization.

73 So far NSGA II has also been used as MOEA method for wind turbine and other
74 turbomachinery blade design. Wang et al. [12] used NSGA II for the optimization of the 5MW
75 NREL offshore wind turbine [13]. The objectives are the maximum power coefficient at the design
76 wind speed and minimum blade mass. Iaccarino et al. [14] used NSGA II for the wind turbine blade
77 design with the objectives of power coefficient and noise levels under uncertainty. NSGA II
78 algorithm was also used by Zhang et al. [15] for the multi-objective shape optimization of
79 helico-axial multiphase pump impeller. Axial compressor blade shape optimization was performed
80 by multi-objective optimization by Samad and Kim [16, 17]. The NSGA-II algorithm is also
81 successfully applied in various power system problems such as multi-objective siting of DG units in
82 power system [18], multi-objective generation expansion planning [19], coordinate the charging

process of plug-in hybrid electric vehicles (PHEVs) in the context of energy hubs [20] and reactive power planning [21].

Particle swarm optimization (PSO) [22] is recognized as another simple concept algorithm, with easy coding implementation, robustness to control parameters and computational efficiency. Moore and Chapman [23] first extended the PSO strategy for solving multi-objective problems. Multi-objective particle swarm optimization (MOPSO) has been widely applied for renewable energy multi-objective optimization problems. Avril et al. [24] presented a multi-objective design of hybrid PV–battery based on PSO. Moghaddam et al. [25] presented an expert multi-objective adaptive modified PSO for optimal operation of a typical micro-grid with RE sources accompanied by a back-up micro-turbine–fuel cell–battery hybrid power source.

Over the five decades many studies have been applied to reduce the aerodynamic losses in axial-flow compressor through the design optimization of swept and leaned (dihedral) blades. Smith and Yeh [26] presented a method for including the effects of sweep and lean (dihedral) in the design of axial-flow compressor blading. It is evident that the rotor performance can be improved by 3D-design (sweep and lean). Amano and Malloy [27] compared the aerodynamic performance of straight and swept wind turbine blade using CFD method. The authors concluded that the swept blade maintains maximum efficiency at lower wind speeds and delayed the stall point resulting in an increase in power at higher oncoming wind speeds. Chattot [28] considered different wind turbine blade tip modifications, sweep, dihedral and winglets based on the Coldstein vortex model. The results indicated that, from the aerodynamic point view, the power capture could be enhanced with these tip modifications. The author also implied that further study was needed to understand

better these effects especially for the nonlinear behavior with respect to the blade with bending modification. Liu [29] developed a time domain, panel method for tidal turbine performance evaluation, design and optimization.

This paper employs a genetic algorithm NSGA-II for the multi-objective optimization design of wind turbine blades. The optimization model is presented in the following section. To illustrate the application of the optimization model, an optimization design is obtained based on the NREL PHASE VI rotor. Two objectives the AEP and the thrust of the rotor are optimized with 4 variables by controlling the 3-D shape of the blade (sweep and dihedral). The NSGA-II algorithm provides the Pareto optimal front of conflicting objectives by searching compromised solutions which give enhanced results of both objectives. The aerodynamic results analysis show that the tip vortex of the dihedral blade has an overall influence all along the blade.

AERODYNAMIC MODEL

A lifting surface method is used as the blade model in order to take into account the 3D blade geometry of the blade and the 3D of the flow on the blade. Fig. 1 presents the rotor body frame coordinates with the z-axis pointing upstream. The blade is divided into chord-wise and span-wise panels. The computational costs of using the lifting surface model is much higher than a simple lifting line model although the lifting surface model can take the 3D shape (sweep and lean) into account. In the present blade model, only one chord-wise panel is used and the blade is divided into finite number of span-wise segment which was named as the Weissinger-L model [30]. The bound vortices are set at the 1/4 chord and control point are located at the 3/4 chord at the center of each

panel. In spite of chord wise simplification of original lifting surface model, the results of Weissinger-L model which applied for backward swept wings showed an excellent agreement with those of the lifting surface model [30]. In the next section the prediction results of a two bladed wind turbine from both the simplified lifting surface model, Weissinger-L model and lifting surface model will be compared and discussed.

The free vortices trailed from the ends of the bound vortices at each panel extend downstream forming sets of horseshoe filaments. The trailed wake vortices comprise the near wake sheet and far wake represented by a single tip vortex. The near wake extends from the bound vortices, and then rolls up into the far-wake.

The circulation and the lift of each horseshoe segment is assumed to be constant. However the adjacent segments may have unequal loadings and there for have different circulation strength. The circulation strength of each horseshoe filaments is determined by satisfying the boundary condition on the control point at each panel. The flow on each control point is influenced by the bound vorticity of each segment and all the vortices trailed behind the blade. The induced velocity at the control point by the vortices is calculated by means of Biot-Savart law. The boundary condition implies that the incident velocity on the blade section which is normal to the span-wise segment at the control point should be zero to prevent flow penetrate the blade:

$$\vec{V}_\infty \cdot \vec{n}_i + \vec{w}_i \cdot \vec{n}_i = 0, \quad i = 1, \dots, Ns \quad (1)$$

The induced velocity at the i^{th} control point $\vec{w}_i$ equals to the sum of the induced velocities from the bound vortices, the near wake and the far wake:

$$\vec{w} = \vec{V}_B + \vec{V}_{NW} + \vec{V}_{FW} \quad (2)$$

The geometry structure of the far-wake is important for the induced velocity calculation at the control point. A relaxation free wake model is used for the determination of the far-wake shape. Assuming the wind turbine is working under convectional condition, the potential factor dominate the whole flow and the viscous factor have small influence on the wake. The vortex line can be assumed as material lines convected through the flow field at the local velocity, and a Lagrangian fluid particle is used for the description of the motion of a point on the far-wake filament (see Fig 1).

$$\frac{d\vec{r}}{dt} = \vec{V}(\vec{r}) \quad (3)$$

where $\vec{r}$ is the position of the control point on the far-wake(free wake). On the right hand of Eq(3) the velocity $\vec{V}(\vec{r})$ at the control point is split into two contributions: the free stream velocity and induced velocity. The induced velocity term is comprised of the self and mutually induced velocities in the wake as well as the bound vortex on the blade:

$$\vec{V} = \vec{V}_\infty + \vec{V}_{indv} \quad (4)$$

In the rotor fixed coordinates, the position of the control point on the far-wake can be defined with the blade azimuthal location, ψ , as the temporal coordinate and vortex age, ζ , at the spatial coordinate, then the left hand of Eq(3) can be written in terms of ψ , ζ :

$$\frac{d\vec{r}}{dt} = \frac{\partial \vec{r}}{\partial \psi} \frac{d\psi}{dt} + \frac{\partial \vec{r}}{\partial \zeta} \frac{d\zeta}{dt} \quad (5)$$

Numerical solution of free wake methodologies have been studied over decades, including relaxation schemes [31-34] and time-marching schemes [35, 36]. The time-marching methods can potentially present the best level of approximation to the rotor wake problem with the fewest

restrictions in application. However these methods have been found to be rather susceptible to numerical instabilities [37]. On the other hand the relaxation methods enhance the ability of controlling the non-physical wake instabilities through explicit enforcement of wake periodicity. Such approaches can only be used at steady-state problems.

In the present work, the aerodynamic prediction model is used to calculate the annual energy production from a wind turbine at a given wind distribution. It is sufficient to apply the steady lifting surface method with relaxation free-wake model to compute the steady power curve. A five point central difference approximation is used for both the temporal and spatial derivative. The detailed information can also be referred to Ref. [38]. [39].

Computational costs analysis and validation of the aerodynamic model

Before the aerodynamic model can be used in the design process for prediction of the loads and power output, the effectiveness of the present aerodynamic model need to be verified.

In order to verify the aerodynamic model, the numerical predictions obtained from the present model are compared with the experimental measurements. The measurements from a two-bladed model turbine which has been performed by Haans et al. [40, 41] will be used as a test case. The wind turbine is placed in an open-jet tunnel at Delft University of Technology. In the present study, the wake geometry measurements in both axial and yawed flow condition and the measured thrust coefficient under axial flow condition will be used. The wind speed at which the experiment measurements were taken was kept constant at 5.5m/s with the free-stream turbulence intensities of 1.2. The tip speed ratio

was changed by altering the rotational speed of the turbine. More detailed description of the experiment can be found from ref [40].

Weissinger [30] showed that the lifting surface model with one panel placed ($m_{chord}=1$) along the chord-wise of the wing had excellent result compared with the model with several panels placed along the chord-wise for the backward wing as the air-plane wing has large aspect ratio. Fig.2 gives the normalized CPU time ($t/t_{mchord=1}$) and normalized predicted thrust coefficient ($C_T'/C_{T_{mchord=1}}$) for tip speed ratio $\lambda=8$ and the tip pitch of $\theta_p=0^\circ$ using lifting surface method with different number of panels (m_{chord}) along the chord-wise of the blade. In the present work only one panel ($m_{chord}=1$) is used along the chord-wise of the blade. As can be seen from Fig.2, with the increase of m_{chord} the computational time costs increase dramatically. However all the predicted C_T with different m_{chord} has nearly the same value. Thus only one chord-wise panel is used $m_{chord}=1$.

Fig.3 compares the predicted and measured rotor thrust coefficient (C_T) for three different $\theta_p=0^\circ$, 2° , 4° . Notice that there is good agreement between the predicted and measured C_T at low load condition (large θ_p or small λ). At small tip pitch ($\theta_p=0^\circ$, 2°) as the tip speed ratio increases there is a slightly difference between the predicted and measured C_T . When the wind turbine is working under heavy loaded condition (small tip pitch or large tip speed ratio), the wind turbine blade experience 3D effects such as stall delay and increased values of the lift force coefficient especially at the inboard regions of blade.

Fig.4 gives the comparison of the tip vortex geometry structure obtained from the experiment and calculated from the present free-wake model for $\lambda=8$ and different θ_p under axial inflow condition. The free wake model can capture the main character of the wake behind the rotor well. After the tip vortex

released, the tip vortex expands following the downstream. With the decreasing of the θ_p , the expansion of the tip vortex reduces because of the reduction of the induced velocity at the disc of the rotor plane with smaller C_T . With the decreasing of the load on the rotor, the circulation on the blade also decreases and it has less influence to the downstream. Consequently the pitch of the tip vortex increases with the increasing of the pitch angle of the blade which is represent well with the free wake model.

OPTIMIZATION DESIGN PROCESS

In this paper, the design of a wind turbine blade is formulated as a multi objective optimization problem with respect to blade geometry and operation condition. For a given wind distribution, the ultimate goal of wind turbine rotor design is to obtain the maximum of energy in a year and the minimum cost of the turbine. Another important point is to choose the proper variables and constraints. In the following subsections, the design objective and variables in the optimization design model are presented.

A multi-objective approach gives a set of solutions while single objective approach just gives only one optimal solution. It should be noted that these objectives are competing: improving one objective will deteriorate the others. There a number of methods [42] available for multi-objective optimization solution.

As an improved version of NSGA [43], the well-known NSGA II [44] is a MOEA which combines the non-dominated sorting procedure with a genetic algorithm to find a set of evenly distributed solutions to a multi-objective optimization problem. It has been demonstrated to be one

of the most efficient and popular algorithms for multi-objective optimization. Simplicity, effectiveness, modularity and low number of user-defined parameters, are the main factors determining the popularity of NSGA-II among multi-objective optimization methods [45] which also has a number of high-quality, open-source software implementations that are freely available[46]. It has also been shown that NSGA-II outperforms two other contemporary multi-objective evolutionary algorithms[21]: Pareto-archived evolution strategy (PAES) [47] and SPEA [48] in terms of finding a diverse set of solutions and in converging near the true Pareto-optimal set. In addition, the Weissinger-L model is an efficiently computational cost aerodynamic model which only takes a few seconds for getting the aerodynamic prediction results of each case. Thus the NSGA II is choosing as the multi-objective optimization algorithm in the present work.

Pareto-optimality defines how to determine the set of optimal solutions of the multi-objective approach. The solution among this set is better than the others in terms of one objective but worse in terms of the other. The curve formed by joining these solutions is known as a Pareto-optimal front. The concept of Pareto dominance and optimality can be expressed for a multi-objective minimization problem:

$$\text{Minimize } f(x) = (f_1(x), \dots, f_m(x))$$

$$\text{Subject to } g(x) = (g_1(x), \dots, g_m(x)) \leq 0$$

where x is the decision vector of n design variables

$f_i(x)$ are the m objective functions

$g_i(x)$ are the constraints

241 Considering two decision vectors x_1 and x_2 , x_1 is said to be dominate x_2 :

242 if $\forall i \in \{1, 2, \dots, m\} : f_i(x_1) \leq f_i(x_2)$ and

243 $\exists i \in \{1, 2, \dots, m\} : f_i(x_1) < f_i(x_2)$.

244 In the present work the NSGA-II handles the design variables chosen and the searches for the
245 group of optimal solutions following the principle of Pareto concept. The lifting surface method
246 with prescribed wake model deals with the aerodynamic performance prediction of wind turbine
247 rotors. Fig.5 illustrates the flowchart of the optimization process.

248 **DESIGN OBJECTIVE**

249 It is important and difficult to estimate the total cost of the power production. It may not only
250 include the price of each component of the wind turbine but also the costs from operation and
251 maintenance. There are different kinds of characteristics taking into account of the cost evaluation
252 for different types of wind turbine. Normally the magnitude of the design loads is important for the
253 wind turbine components choosing and design. For small wind turbines, good starting performance
254 is generally more critical than for large wind turbines. For large wind turbines, shorter diameters
255 and lower weights are important for the rotor design. As shown in the study of Ref [49], with the
256 increasing of the diameter of wind turbines, the fatigue loads has become to the critical load cases
257 instead of loads from extreme wind model. In the present paper, the extreme loads are not used for
258 the cost model. In the present work the thrust of the rotor and the AEP are selected as the objective
259 functions for the blade shape optimization.

$$\begin{aligned} f_1(thrust) &= \frac{N^{opt}}{N^{ref}} \\ f_2(AEP) &= \frac{AEP^{opt}}{AEP^{ref}} \end{aligned} \quad (1)$$

where N^{opt} is the thrust of the optimum rotor and N^{ref} is the thrust of the reference rotor and AEP^{opt} is the AEP of the optimum rotor and $AEP^{reference}$ is the AEP of the reference rotor.

The AEP is determined by the wind velocity of the wind site and the power curve of the wind turbine. The power curve is calculated by the lifting surface model in present paper. The wind speed frequency distribution function is [50]:

$$f(V_\infty) = (8760 / C) k (V_\infty / C)^{k-1} \exp[-(V_\infty / C)^k] \quad (1)$$

where C is the empirical Weibull scale factor (m/s), the Weibull shape factor k is set to 2 corresponding to the Rayleigh distribution. The Weibull scale factor [50] is calculated from the average wind speed:

$$V_a = C \Gamma(1 + 1 / k) \quad (2)$$

where V_a is the average wind speed.

The AEP is evaluated as shown in the following equation [50]:

$$AEP = \int_{V_{in}}^{V_{out}} p(V_\infty) f(V_\infty) dV_\infty \quad (3)$$

where $p(V_\infty)$ is the wind turbine power output at the wind speed of V_∞ .

The thrust of the rotor is calculated as [51]:

$$N = \sum_{i=1}^n \int_{r_1}^R N(r) dr \quad (4)$$

where r_1 is the radius of the blade root and $N(r)$ is the normal force of the blade section at the radius of r .

DESIGN VARIABLES

Choosing the design variables is another important task for the optimization design. The key is using as few variables as possible while the chosen variables have to represent as much geometry detail and as many rotor working conditions as possible. Increasing the number of the variables will certainly increase the computation time of the optimization process. The chord, twist, rotor diameter are often use for the description of blade. Because lifting surface method can be used to predict the aerodynamic performance of rotor with 3d geometry shape, a curved and swept blade is used in this paper. In order to show whether the improvements from the 3D shape of the blade, the same chord and twist distribution is used in the present work.

The variables used in the paper are: the variables for blade sweep and curve description.

Blade sweep and bend (Fig. 6): The blade is defined as a backward-swept (the inflow direction is not perpendicular to the span-wise direction) and upper dihedral blade (the blade surface is not normal to the hub). A power law function is used to describe the sweep and bend along the blade. The blade section is shifted to a new position according to the power law function given below:

$$\begin{aligned} z_{bend}(\bar{r}) &= h_1(\bar{r})^{a_1} \\ y_{sweep}(\bar{r}) &= h_2(\bar{r})^{a_2} \end{aligned} \tag{5}$$

h_1 and h_2 are the maximum distance shifted which is the distance shifted at the tip of the blade.

The changes of sweep and bend is governed by a_1 and a_2 where

$$\bar{r} = r / R \tag{6}$$

DESIGN RESULTS

The primary intention of this section was to demonstrate the capabilities of the design method. The NREL PHASE VI rotor is chosen as the test of the optimize model. Throughout the NREL PHASE VI rotor design process[52], the AEP (assuming a 100% generator efficiency) was computed based on a Rayleigh wind-speed distribution having an average wind speed of 7.2 m/s (16 mph), which is representative of the windy months at NREL. In the present work, in order to compare the results of the optimum design of the rotor with the original type of the NREL PHASE VI rotor, we use the same wind velocity distribution.

In order to show the improvements from the 3D shape of the blade, the chord and twist distribution remain the same in the optimized process as explained before. 4 design variables are used for the definition of backward sweep and upper leaned blades. The AEP and blade root flap moment are calculated according Eq.(3) and Eq.(4). The design space and baseline values are listed in Table 1.. It is important to provide proper design space constituted by the upper and lower limits of the design variables to reduce the computation time during the optimization process.

The Pareto-front shown in Fig. 7 is obtained by using NSGA II with two objective discussed in the previous section, the rotor thrust $f_1(thrust)$ and the AEP $f_2(AEP)$. The performances of NREL PHASE VI rotor are used for the comparison with the results of the optimization as reference. During the simulation, a population size of 60 is used and calculation is stopped after 157 generation. The multi-objective optimization algorithm is the compromise of both objectives. All the results obtain by the optimization process are better than the original NREL PHASE VI rotor. The Pareto-front presents a set of solutions to the designers for choosing according to their own

design needs. The rotor thrust increases with the growth of the AEP as can be seen in the figure. Due to the 3D geometry of the blade (sweep and lean), nearly half of the solutions reduce the rotor thrust and all of the solutions have higher AEP than the original rotor. The AEP of the optimized rotor increases 9% while the rotor thrust remains lower than the original rotor. The AEP of the optimized rotor can increase more than 11.82% with the rotor thrust increases less than 2% present. Obviously the Pareto-front gives an improvement of these objectives from the reference blade.

Fig. 8 presents the distribution of the design variables at the AEP. It has been notice the gradual increase of the a_l which govern the shape of dihedral with the increase of the AEP. The maximum distant shift of dihedral h_l reaches to the upper limit of the design space for most of the optimized solutions. When blade generates aerodynamic lift fluids are forced to flow from high to low pressure and the air below the blade (the pressure side of blade) tends to migrate toward the top of the blade via blade tip. The tip vortex trails from the tip of the blade which is associated with induced drag. The induced drag is an essentially unavoidable side effect of the blade generation lift and decreases the power output of the wind turbine. Increasing h_l can move the tip vortex further downstream the of the rotor plan and reduce the contribution of the induced drag to the blade caused by the tip vortex. The increasing of the power exponent a_l can force more portion of the blade near the tip away from the influence of the tip vortex. Most of the solutions have barely the minimum distant shift of sweep h_2 until the $f_2(AEP)$ larger than 1.1 which means that the AEP increases 10%. Then with the increase of the AEP the distant shift of sweep h_2 increases dramatically to about 0.05 when the optimization proccession gets the maximum AEP solution. It is interesting to note that the swept shift of the tip only helps the rotor with an improvement of less

than 1.7% of AEP and with an increasing of more than 1.5% of rotor thrust. Another important aspect is that, from the structural point of view, the swept shape of the blade introduces extra pitching moment to the blade and forces the blade a change of twist angle distribution span-wise at different wind speeds.

Among the solutions 2 designs are chosen as shown in Table 2. for detailed study and compare with the reference blade.

The maximal AEP design (type I) can increase AEP 11.82% with the rotor thrust increases less than 2% while the minimal thrust design (type II) reduce the thrust 1.48% with the AEP increases 5.87%. The optimized blade with maximal AEP has both sweep and significant dihedral at the tip. The optimized blade with minimal thrust also has combination of sweep and dihedral at the tip and the offset at the sweep direction is relative small which is only 0.0015R. This leads to the interest that the sweep and dihedral have different effects to the aerodynamics performance of wind turbine blade and needs further investigated.

Fig. 9 and Fig. 10 give the power coefficient and aerodynamic thrust of the NREL PHASE VI rotor (original rotor) and the optimized rotors. It is seen that the power coefficient of type I rotor is larger than the original rotor at most of the wind speeds except from tip speed ratio λ 3.447 to 4.461. The power coefficient of type II rotor is smaller than the original rotor from λ 3.447 to 5.056. The thrust of type I rotor is larger than the other rotors at all the wind speeds. Type II rotor and the original rotor has almost the same thrust as most of the wind speeds. The original rotor has a slightly larger thrust compare to the type II rotor at low λ (2.917 to 4.740).

It is of interest to investigate the detailed effects of the sweep and dihedral on the aerodynamic performance of wind turbine. Two more rotors (type III and type IV) as shown in Table 3. have been analyzed based on the optimized type I and compared to the original rotor and type I rotor. Type III rotor has the same sweep geometry as type I rotor but no dihedral. Type IV rotor has the same dihedral geometry as type I rotor but no sweep.

Both rotor (type III and type IV) have an increase in AEP and nearly the same thrust level compared to the original rotor. As it can be seen in Fig. 7 the value of objectives of type III rotor are located at extreme ends of the Pareto front and the value of objectives of type IV are at the Pareto front. The type IV rotor has a large increase in AEP (9.88%) only 1.4% less than type I rotor (the optimized design with maximum AEP) and a relatively small associated increases in thrust (0.28%) which is 1.55% less than type I rotor. The type III rotor also has an increase in AEP (3.42%) and even decrease in thrust (0.65%). The geometric shape of the type I rotor is the combination of type III and IV rotors; however the effects of the 3D shape to the aerodynamic performance cannot be simply combined.

The aerodynamic performance of the optimized blade, the effective angle of attack (Fig. 12 and Fig. 13) distribution along the blade at λ 5.417. The forces on the airfoil are illustrated in the Fig. 11 where blade geometric angle of attack is represented as α_g , the effective angle of attack is represented as α_e , Φ is the angle between the plane of rotation and the relative velocity V_{rel} and θ is the pitch angle. For the sake of convenience from now on the angle of attack means the effective angle of attack. There are increase in angle of attack for both type I and II rotor almost all along the blade compared to the original rotor. Type I and II rotor has nearly the same angle of attack

distribution at the inboard of 60% radius. It is seen that there is a large increase of angle of attack at the tip of the blade (80% radius) for type I rotor. Type IV has nearly the same angle of attack distribution as type I at the inboard of the blade and the same angle of attack distribution as type III at the outboard of the blade. For fixed wing, the tip vortex only affects the portion of the wing closest to the tip. While the fundamental process of the blade tip vortex formation is similar to that of a fixed wing, it will be appreciated that a complication with rotors is that the tip vortices from other blades can lie close to the plane of blade rotation and can have a large induced effects on the blade lift distribution [53]. Type I, II and IV rotor have their blades bent towards the suction side and it is consequently move the tip vortices further to the downstream of the rotor plane. The helical tip vortices have overall influence on the whole blade by reducing the induced velocity at the blades especially at the tip of the blades. The blade of type III rotor only bent on the rotor rotating plan (sweep), consequently the tip vortices can only affect the tip region of the blade. As it can be seen from **Error! Reference source not found.** the angle of attack of type III rotor is only larger than the original rotor at the tip of the blade.

Fig. 14, Fig. 15, Fig. 16 and Fig. 17 give the tangential and normal force distribution along the blade of the rotors at λ 5.417. The tangential force and normal force distributions of type I, II, III and IV have the same character as their angle of attack distributions. The change blade geometry gives an additional driving force (tangential force) on the outer approximately 80% radius of the blade and the undesired thrust (normal force) has also increased. Among all the four rotors with 3D shape blade, type II rotor has the smallest thrust which even smaller than the original NREL PHASE VI rotor. At the tip of the blade of type II rotor ($0.93 < r/R < 1$), the blade has a smaller thrust

distribution than the blade of NREL PHASE VI rotor as can be seen from Fig.16. The tip of the blade of type II bends towards the dihedral direction and the direction of the normal force is not perpendicular to the rotor rotation plane which leads to a smaller thrust distribution at the tip. Type I, II and IV rotor have the same tip shift distant at the dihedral direction, but differs their bending curvature. Type I and IV rotor have much steeper curvature at the tip and move more portion of the blade away from the tip at inflow direction and reduce the influence of the tip vortex to the blade which makes the type I and IV rotor produce more tangential force at the tip of the blade ($r/R > 80$) than type II rotor. Extra driven force can also be attained through sweep. However since the position of swept blade's tip has only changed in the rotor rotating plane, the tip vortex of swept blade only affects the portion of the blade close to the tip as it can be seen from Fig. 14, Fig. 16 and Fig. 17.

CONCLUSION

This paper has proposed a general procedure of multi-objective optimization of wind turbine blades with sweep and dihedral 3-D shape with the help of lifting surface method as the aerodynamic model and NSGA-II as the optimization algorithm. The NSGA-II algorithm provides the Pareto optimal front of conflicting objectives by searching compromised solutions which give enhanced results of both objectives. Two objectives the AEP and the thrust of the rotor are optimized with 4 variables by controlling the 3-D shape of the blade (sweep and dihedral). The multi-objective optimization procedure presents a set of solutions improving each objective instead of providing a single solution obtained by single-objective optimization. It is seen that the solutions

414 provide rotors with 3-D shape which not only increase the power output of the rotor but also keep
 415 the thrust of rotor under control. With the help of multi-objective optimization method, we gain an
 416 improvement of AEP up to 11.82% with only 2.11% increasing of rotor thrust or a reduction of
 417 thrust of rotor up to 1.48% with an improvement of 5.87% in AEP compared with the original
 418 NREL PHASE VI rotor. The aerodynamic results analysis show that the tip vortex of the dihedral
 419 blade has an overall influence all along the blade. The tip vortex of swept blade only affects the
 420 portion of the blade close to the tip.

421 **NOMENCLATURE**

a_1	Chord position function parameter
a_2	Chord position function parameter
F_N	Normal force on blade
F_t	Tangential force on blade
h_1	Chord position function parameter
h_2	Chord position function parameter
m_{chord}	Number of segments along chord-wise of the blade
M_{Flap}	Blade root flap wise moment
n	Blade number
N	Rotor thrust
r	Position of vortex control point

$\bar{r}$	Relative position of vortex control point
R	Diameter of the rotor
$\vec{V}_B$	The induced velocity from blade
$\vec{V}_{FW}$	the induced velocity from far wake
$\vec{V}_{NW}$	The induced velocity from near wake
V_∞	free stream velocity
$\bar{w}$	The induced velocity on the blade

Greek Letters

θ_p	Blade pitch angle
ψ	Azimuth angle
Ω	Rotor rotational speed
ψ_b	Blade azimuthal angle
ζ	Vortex age

Abbreviations

AEP	Annual energy production
COE	Cost of energy
MOEA	Multi-objective evolutionary algorithm
MOPSO	Multi objective particle swarm optimization
NREL	U.S. National Renewable Energy Laboratory
NSGA II	Non-dominated sorting genetic algorithm II

PSO	Particle swarm optimization
SQP	Sequential quadratic programming

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Fig. 1 Schematic of rotor coordinates and the aerodynamic blade model

Fig. 2 Normalized CPU time and normalized predicted C_T for difference number of panels placed along the chord-wise of the blade

Fig. 3 The comparison of the predicted and measured thrust coefficient

Fig. 4 (a) $\lambda=8, \theta_p=0^\circ$

Fig. 4 (b) $\lambda=8, \theta_p=2^\circ$

Fig. 4 (b) $\lambda=8, \theta_p=4^\circ$

Fig. 4 The comparison of the predicted and measured tip wake structure for different θ_p , $\lambda=8$

Fig. 5 Flow chart of the optimization design process

Fig. 6 Schematic of the swept-curved blade

Fig. 7 The Pareto optimal solution

Fig. 8 (a) Distribution of h_1 and a_1 at AEP

Fig. 8 (b) Distribution of h_2 and a_2 at AEP

Fig. 8 The distribution of the design variables

Fig. 9 Power coefficient performance of the original and optimized rotors

Fig. 10 Aerodynamic thrust of the original and optimized rotors

Fig. 11 Schematic of velocity and force decompositions a blade element

Fig. 12 Angle of attack distribution of the original and optimized type I and II blades

Fig. 13 Angle of attack distribution of the original and optimized type I, III and IV blades

Fig. 14 Tangential force distribution of the original and optimized type I and II blades

Fig. 15 Tangential force distribution of the original and optimized type I, III and IV blades

Fig. 16 Normal force distribution of the original and optimized type I and II blades

Fig. 17 Normal force distribution of the original and optimized type I, III and IV blades

Fig. 1 Schematic of rotor coordinates and the aerodynamic blade model

Fig. 2 Normalized CPU time and normalized predicted C_T from the lifting surface method with difference number of panels place along the chord-wise of the blade

Fig. 3 The comparison of the predicted and measured thrust coefficient

Fig. 4 (a) $\lambda=8, \theta_p=0^\circ$

Fig. 4 The comparison of the predicted and measured tip wake structure for different θ_p , $\lambda=8$

Fig. 4 (b) $\lambda=8, \theta_p=2^\circ$

Fig. 4 The comparison of the predicted and measured tip wake structure for different θ_p , $\lambda=8$

Fig. 4 (c) $\lambda=8, \theta_p=4^\circ$

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Table 1. The design space for the rotor

	h_1	a_1	h_2	a_2
Reference blade	0	1	0	1
Lower limit	0	1	0	1
Upper limit	0.1	99	0.1	99

Table 2. The optimization results

	h_1	a_1	h_2	a_2	$f_1(thrust)$	$f_2(AEP)$
NREL PHASE VI rotor	0	0	0	0	1	1
Design with maximal AEP	0.0989	83.5437	0.0967	9.9686	1.0183	1.1182
Design with minimal thrust	0.0992	18.0904	0.0021	1.6577	0.9852	1.0587

Table 3. Overview of the studied rotors

	h_1	a_1	h_2	a_2	$f_1(thrust)$	$f_2(AEP)$
Type I rotor	0.0989	83.5437	0.0967	9.9686	1.0183	1.1182
Type II rotor	0.0992	18.0904	0.0021	1.6577	0.9852	1.0587
Type III rotor	0	0	0.0967	9.9686	0.9935	1.0342
Type IV rotor	0.0989	83.5437	0	0	1.0028	1.0988