



OPTIMAL DESIGN OF WIND TURBINE BLADES EQUIPPED WITH FLAPS

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ABSTRACT

As a result of the significant growth of wind turbines in size, blade load control has become the main challenge for large wind turbines. Many advanced techniques have been investigated aiming at developing control devices to ease blade loading. Amongst them, trailing edge flaps have been proven as effective devices for load alleviation. The present study aims at investigating the potential benefits of flaps in enhancing the energy capture capabilities rather than blade load alleviation. A software tool is especially developed for the aerodynamic simulation of wind turbines utilising blades equipped with flaps. As part of the aerodynamic simulation of these wind turbines, the control system must be also simulated. The simulation of the control system is carried out via solving an optimisation problem which gives the best value for the controlling parameter at each wind turbine run condition. Developing a genetic algorithm optimisation tool which is especially designed for wind turbine blades and integrating it with the aerodynamic performance evaluator, a design optimisation tool for blades equipped with flaps is constructed. The design optimisation tool is employed to carry out design case studies. The results of design case studies on wind turbine AWT-27 (Aerodynamic Wind Turbine-27) reveal that, as expected, the location of flap is a key parameter influencing the amount of improvement in the power extraction. The best location for placing a flap is at about 70% of the blade span from the root of the blade. The size of the flap has also significant effect on the amount of enhancement in the average power. This effect, however, reduces dramatically as the size increases. For constant speed rotors, adding flaps without re-designing the topology of the blade can improve the power extraction capability as high as of about 5%. However, with re-designing the blade pretwist the overall improvement can be reached as high as 12%.

Keywords: flaps, design blade, optimisation, simulation, genetic algorithm, WTAero.

INTRODUCTION

Trailing edge flaps are aerodynamic control surfaces, borrowed from aerospace industry and mainly used for wind turbine blade load alleviation and rotor power regulation [1]-[4].

As wind turbine blades become longer and more complex, new design and optimisation methods and tools have been developed for design of wind turbine blades. When designing a wind turbine, the goal is to attain the highest possible power output under specified atmospheric conditions. From the technical point of view, this depends on the shape of the blade. As mentioned in [5, 6], Jureczko developed a computer programme package that would enable optimisation of wind turbine blades with regard to a number of criteria and Mendes developed a method to obtain optimal chord and twist distributions in wind turbine blades by using genetic algorithms (GA). More efficient blade designs via integrated design (structure and aerodynamics considered simultaneously) also investigated and reported by [7]. [8], [9] developed an alternative approach for design of adaptive blades using the concept of variable state design parameters. Using the new concept they developed a design tool for adaptive blades [10].

As mentioned in [11], they investigated shape optimisation of wind turbine blade using an aerodynamic/aeroelastic code incorporating structural dynamics of the blades. The present study aims at investigating the potential benefits of flaps in enhancing

the energy capture capabilities while considering redesigning and optimising the baseline blade.

DESIGN PROBLEM

The blade topology and size are defined through the aerodynamic design phase of blades. In this phase the design variables are chord distribution $c(r)$, pretwist distribution $\beta_0(r)$ and aerofoil distribution $AF(r)$ as well as the exact rotor radius R . These parameters are normally obtained via a search-based optimisation process. In a search-based design the objective of the optimisation is normally to maximise the annual energy production rather than, for example, maximising the power coefficient at a certain wind speed. The annual energy production of a wind turbine is influenced by the wind characteristics of the site at which the unit is installed as well as the wind turbine capability of generating power. Wind density probability function is a model giving information on the magnitude and likelihood of wind in a site. Power curve, on the other hand, provides information on the capability of a wind turbine in producing power at various wind speeds. Annual average power, P_{av} , is defined as:

$$P_{av} = \int_{v_i}^{v_0} P(V)R(V)dV \quad (1)$$

where, $R(V)$ is wind speed probability density function (PDF), P is the wind turbine power and v_i and v_0 are the



cut-in and cut-out velocities, respectively. In this study, a Rayleigh PDF represented by:

$$R(V) = \frac{2}{V} \frac{\pi}{4} \left(\frac{V}{V_{av}} \right)^2 \exp \left[-\frac{\pi}{4} \left(\frac{V}{V_{av}} \right)^2 \right] \quad (2)$$

is used to calculate average power. Parameter V_{av} stands for the site average wind speed.

The optimisation problem, therefore, can be summarised as maximise P_{av} subject to main constraint

$$P \leq P_{rated} \quad (3)$$

and possibly other constraints on, for example, blade maximum bending moment, weight of the blade, etc:

$$M_{max} \leq M_{allowable} \quad (4)$$

OPTIMISATION METHOD

The optimisation module employs a genetic algorithm (GA) as explained below:

Chromosome: A real number encoding is used. Depending on the number of design points (n_{dp}) considered for distributed design variables and the number of design variables included in the optimisation problem, the maximum length of the chromosome (for three distributed and one singular design variables) is $3n_{dp} + 1$.

In the developed optimisation code in MATLAB, the user sets n_{dp} and selects the design variables to be included in the optimisation problem. For each design variable selected for optimisation a realistic range is also required to be set. For those design parameters not selected for optimisation, a fixed value or distribution is considered.

Initial Population Generation: The initial population in most of GAs is generated randomly. A random initial population generation method can generate both feasible and infeasible solutions. In highly constrained problems and problems in which the constraints are very sensitive to the design variables, generating feasible initial population can be very time consuming due to high number of failed attempts. In our case here, the output power (constraint of Eqn. (3)), is highly sensitive to the blade pretwist and chord length distribution as well as the rotor radius. Particularly, random generation of initial population becomes very time consuming when all these design variables are included in the optimisation process. To overcome this problem, a new design candidate is produced by a random deviation of an initial design rather than a randomly generated blade from scratch. This method is applicable when the design variable is distributed (e.g. pretwist and chord). In this method, one of the design points is randomly selected and the rest have the same value as the baseline design.

Crossover: The purpose of the crossover operation is to exploit the search area via creating new solutions from existing solutions in the current population.

Two types of crossover have been coded and implemented in the optimisation module. The first type is classical arithmetic or weighted average crossover. The second type is the geometric crossover recently proposed by [12]. In both arithmetic and geometric crossover, a roulette wheel based on the fitness is used to select the parents.

The fitness is defined as the average power:

$$fitness = P_{av} \quad (5)$$

Mutation: A random gene in the chromosome of a randomly selected individual is selected for mutation. This gene will be replaced by a randomly selected new value within the range of the corresponding design variable.

Constraint Handling: After each crossover or mutation operator the feasibility of the offspring is checked. If all constraints are satisfied, the offspring is added to the population. Infeasible solutions will be discarded.

Regeneration: At the end of each generation, after n_{CO} crossover and n_{Mute} mutation operations, the population size increase from n_{pop} to a maximum of $n_{pop} + n_{CO} + n_{Mute}$. At this point, all individuals will be sorted based on their fitness. The first fittest n_{pop} individuals are passed to the next generation.

Termination: Genetic algorithm continues until the generation number reaches the set maximum number of generations, n_{gen} or when the maximum fitness in a generation becomes the same as the average fitness (converged solution).

DESIGN CODE

WTAero (Wind Turbine Aerodynamic), a BEMT-based aerodynamic software tool, was modified to incorporate the effect of flaps into the aerodynamic characteristics of the blade [13]. The aerodynamic simulator code calculates the wind turbine aerodynamic performance (blade and rotor loads and rotor mechanical power) between cut-in and cut-out velocities and using a Rayleigh PDF and finds the average annual power P_{av} at a given site average wind speed V_{av} .

The aerodynamic performance of a wind turbine depends on the characteristics of the control system in place (type, response time, controlling parameter, controllable parameter, etc) as well as the wind turbine rotor characteristics (e.g. blade topology and size, number of blades and rotor angular speed) and the operating condition (e.g. mean wind speed at hub elevation, wind direction and turbulence level). Therefore, to be able to simulate a wind turbine, the behaviour of the control system is also to be simulated along with the aerodynamic behaviour of the wind turbine. This, however, is not practical as it requires having the control system designed prior to the blade. An alternative solution to this is to assume that the controller is capable of delivering the



expected functions perfectly. This implies that the controlling parameter is always adjusted at its best possible value which leads to the best (goal) performance. Adapting this approach, the optimum (best possible) controlling parameter, which optimises the performance measure(s) can be found via solving an optimisation problem formulated as follows:

$$\max P(q_i); i = \{1, 2, \dots, n_q\} \quad (6)$$

subject to

$$P \leq P_{rated} \quad (7)$$

$$q_{i,l} \leq q_i \leq q_{i,u}; i = \{1, 2, \dots, n_q\} \quad (8)$$

In Eqn. (6), P is the rotor mechanical power at a given wind speed, q_i stands for the i -th controlling parameter limited to the interval $[q_{i,l}, q_{i,u}]$. Number of independent controlling parameters, n_q depends on the type of the blade and the rotor speed (constant speed or variable speed). For blades utilising flap the number of controlling parameters is 1 for constant speed rotors and 2 for variable speed rotors.

Hill-climbing and pattern search methods are used to solved the optimisation problem above. These methods find a local optimum in the neighbourhood of the initial point. If the initial point is selected wisely, a hill-climbing search finds the global optima. Hill-climbing and pattern search methods are very efficient for problems with small number of variables. It should be noted that the optimisation problem (6) is part of the aerodynamic performance evaluation and is different from the design optimisation problem (3).

The modified WTAero, as objective evaluator, is integrated with the GA optimisation module to form the blade design optimisation tool. That is, each produced design candidate at the stage of initial population generation or as a result of crossover and mutation operations is evaluated using modified WTAero.

CASE STUDY

In design optimisation of blades equipped with trailing edge flap three parameters, namely, blade pretwist, flap length $(R_{F,e} - R_{F,s})$ and flap location $0.5(R_{F,e} + R_{F,s})$, are considered as design variables. Parameter $R_{F,s}$ and $R_{F,e}$ stand for the span location of the start and the end of flap respectively. The optimal design is carried out for different cases: (i) original AWT-27 without installing flap, (ii) original AWT-27 blades equipped with flap (with original pretwist) in different percent length of flap, and (iii) optimised AWT-27 blades equipped with flap in different percent length of flap. In all cases the width of the flap d_F is considered as 10% of the local chord $C_F (d_F = 0.1C_F)$, where $C_F = \text{chord} @ r = 0.5(R_{F,e} + R_{F,s})$. The deployment angle

of the flap is assumed to be limited to the interval $[\delta_{F,l} = -20^\circ, \delta_{F,u} = 20^\circ]$.

The amount of enhancement in the average power due to equipping blades with flap is shown in Figure-1 and Figure-2. The calculations for the average power are based on a site average wind speed of 5.7m/s and Rayleigh probability density function. In this Figure, results are shown for original blades without flap, original blades with flap and optimised blades with flap.

Using the data shown in Figure-2, share of installing flap and optimisation in the power enhancement are shown separately in Figure-3. Figure-4 shows the effect of the flap size on the power enhancement.

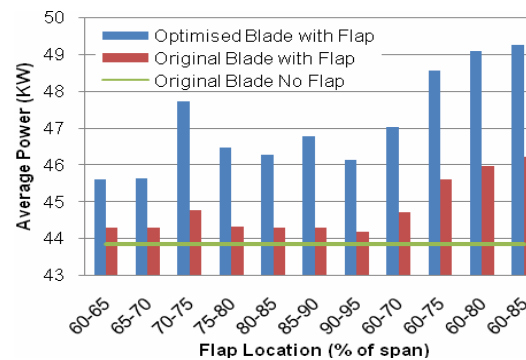


Figure-1. Effect of flap size and location on power enhancement.

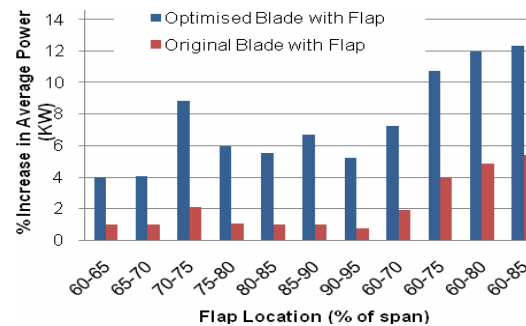


Figure-2. Percent increase in the average power versus flap size and location.

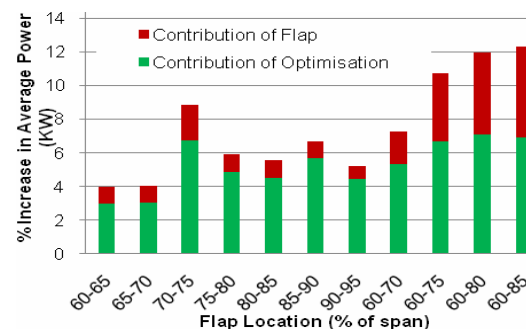


Figure-3. Percent improvement in the average power due to blade optimization.

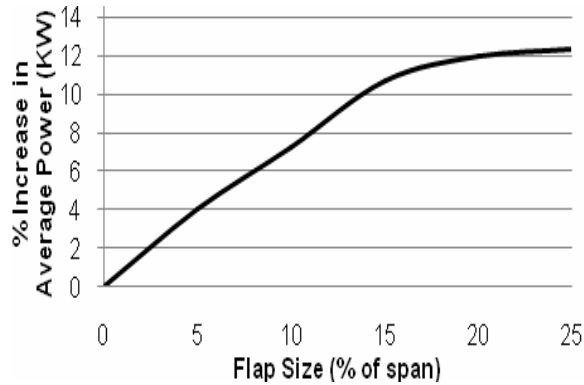


Figure-4. Effect of flap size on the power extraction enhancement.

Figure-5 through Figure-10 show the effect of flap size and location on power curves, power coefficient and maximum flap bending moment for all examined cases for which the blade has been optimised.

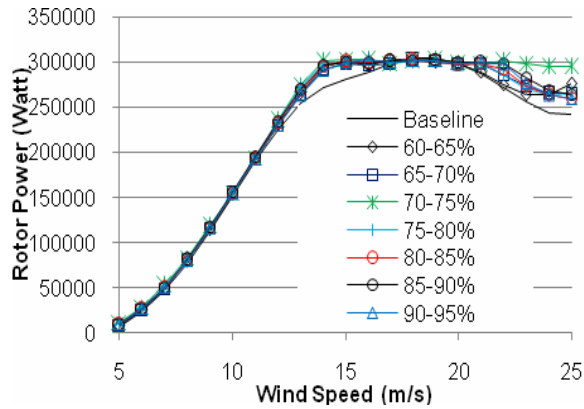


Figure-5. Effect of flap location on power.

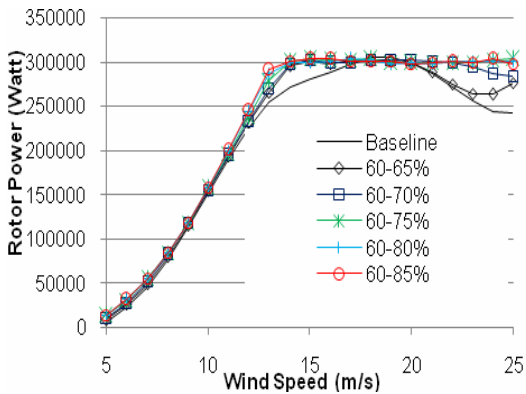


Figure-6. Effect of flap size on power.

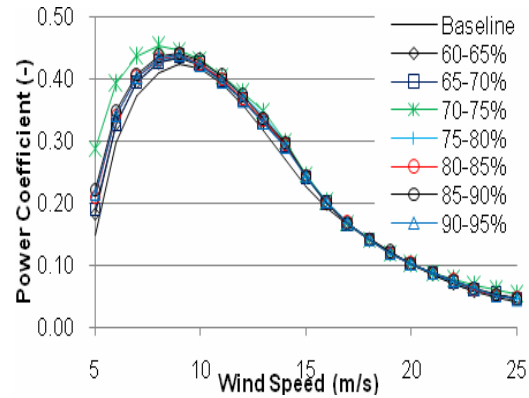


Figure-7. Effect of flap location on power coefficient.

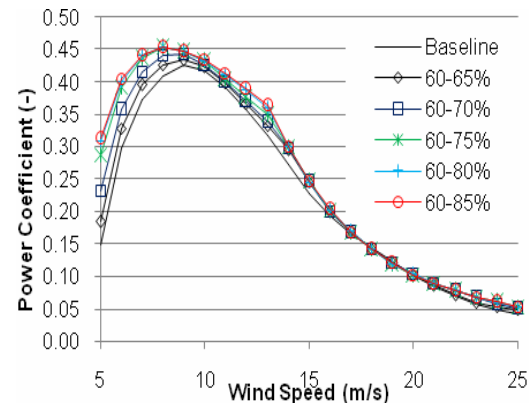


Figure-8. Effect of flap size on power coefficient.

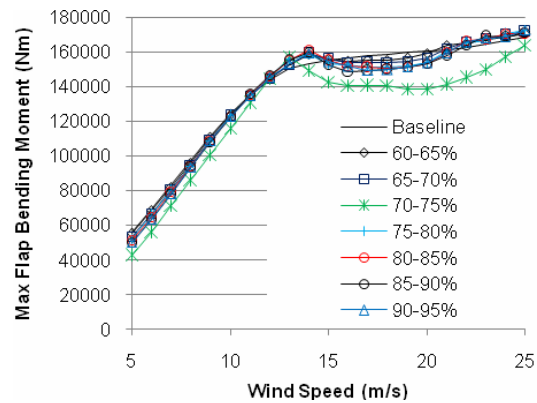


Figure-9. Effect of flap location on flap bending moment at the root of the blade.

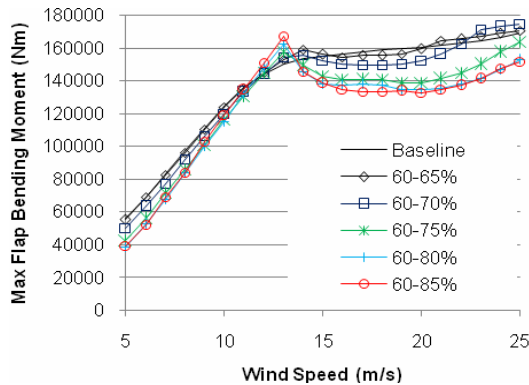


Figure-10. Effect of flap size on flap bending moment at the root of the blade.

CONCLUSIONS

- According to the above figures the following conclusion can be drawn:
- Adding flap without optimisation improve the power extraction capability as high as of about 5% for the case of flap located between 60-85% of span. However, optimisation of the blade is required to obtain the highest power improvement. Improvement as a result of optimisation can be as high as 7% (for case of 60-80%). The overall improvement can be reached as high as 12%.
- Location of flap is a key parameter influencing the amount of improvement in the power extraction. The best location for placing a flap is at about 70% of the blade span from the root of the blade.
- The size of the flap has also significant effect on the amount of enhancement in the average power. This effect, however, reduces dramatically as the size increases.

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