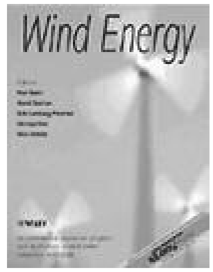

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Performance Prediction of Wind Turbines Utilising Passive Smart Blades: Approaches and Evaluation

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Abstract
The induced deformation, due to the presence of elastic coupling in the structure of passive smart blades, is the key parameter that affects the wind turbine performance. Therefore, when predicting the aerodynamic performance of these turbines, a structural analyser is also required to bring the effect of the induced deformation into account. This diverts the numerical simulation of wind turbines utilising passive smart blades from the simulation of wind turbines with traditional blades. In performance prediction, additional complexity arises when the blades are bend-twist-coupled. In this case an iterative coupled-aero-structure analysis must be carried out. Further difficulties in simulation of these turbines are posed by the fact that the current analytical models for analysis of structures made of anisotropic composite materials are not accurate enough. Different strategies have been proposed and followed by investigators to embark upon the above highlighted problems. The present paper describes, evaluates and compares these approaches.

Keywords: Adaptive Blade, Smart Blade, Aero-structure Simulation, Wind Turbine Simulation, Wind Turbine Design

1 Introduction

In wind turbines a passive control system without any traditional mechanical parts, employs the blade itself as the controller to sense the wind velocity or rotor speed variations and adjust its aerodynamic characteristics to affect the wind turbine performance. These blades are known as adaptive or smart blades. These blades can be structurally categorised as either (i) extrinsically smart (active), where the embedded actuators in the material generate and control the elastic deformation of the blade or (ii) intrinsically smart (passive), where only the symmetry and balance of the composite fibre plies produce and control the elastic deformation of the blade.

In intrinsically smart blades, integrating anisotropic composite materials into the wind turbine blade structure and taking the advantage of the directionality of anisotropic composite material is used to produce a controlled twist in the blade.

Various elastic couplings, which are the result of the specific lay-up and fibre orientations, can be induced in a structure constructed of fibre reinforced composites. Figure (1) is a simplified illustration showing how using unbalanced composite laminates in a blade skin makes the internal loads elastically coupled. Normal force f_n on the blade cross section, due to the bending moment or axial load, is the resultant of normal and shear stresses in the matrix σ_m and τ_m, and normal stress in the fibres σ_f. This normal-shear coupling is the source of elastic couplings in the structure. Different lay-ups can be used to achieve different types of couplings. A mirror lay-up generates bend-twist coupling in which the bending moment also produces the torsional moment. A helical lay-up makes the blade a stretch-twist-coupled structure in which the axial load produces the torsional moment. Different levels of elastic coupling can be achieved in the blade by changing the ply angle θ in the layers that comprise such material, the shell thickness as well as the fibre and matrix mechanical properties.

These structural couplings can have favourable influences on the aeroelastic behaviour of the blades. These blades can be classified as either bend-twist (BT) or stretch-twist (ST) smart blades.

The concept of using intrinsically smart blades in wind turbines was introduced by Karaolis et al [1, 2] and Kooijman [3] and subsequently studied by other investigators. There are a number of possible uses of aeroelastic tailoring in wind turbine applications, including improving the average energy capture, regulating the output power, blade load alleviation and improving the start up torque in order to reduce the cut-in speed.

If the implemented elastic coupling in a blade is of the form of stretch-twist coupling, the blade twist will be a function of the blade axial force, which is mainly due to the centrifugal forces. In this case the magnitude of the induced twist depends on the rotor speed. That is the induced twist in a stretch-twist (ST) blade has the potential of being used as a controlling parameter only when the rotor speed is variable, i.e. variable-speed rotors or starting-up situation in constant-speed rotors.

Using bend-twist (BT) blades gives more flexibility in controlling of the wind turbine performance. The blade twist due to the bend-twist elastic coupling is a function of the bending moment in the blade, which in turn depends on the blade aerodynamic loading. The applied aerodynamic force on the blade varies with the variations of the wind speed and rotor speed. That is BT blades react to both wind speed and rotor speed variations.

Figure (2) compares BT and ST passive smart blades in terms of their source load for generating the induced deformation as the controlling parameters.

The magnitude and direction of the aerodynamic forces applied on the blade and consequently the blade and wind turbine performance strongly depend on the blade angle of attack. Angle of attack depends on the inflow angle and twist angle of the blade. Wind velocity and rotor angular velocity define the inflow angle. Blade twist angle is a combination of three angles: pre-twist, pitch angle and elastic torsional deformation of the blade. Equation (1) expresses the angle of attack in terms of other angles.

$$\alpha = \varphi + \beta_e - \beta_0 - p \qquad (1)$$

In the above equation α, φ and β_e stand for the angle of attack, the inflow angle and the elastic torsional deformation respectively, measured positive toward stall, β_0 and p are the blade pre-twist and pitch angle respectively, measured positive toward feather.

In wind turbines with conventional blades, twist angle of the blade is a combination of known parameters of pre-twist and pitch angle while the elastic torsional deformation is neglected. Knowing topology and aerodynamic characteristics of the blades together with the wind turbine operating condition, an aerodynamic code can be employed as a wind turbine simulator to predict the wind turbine performance. For wind turbines with ordinary blades, Equation (1) reduces to the following equation.

$$\alpha = \varphi - \beta_0 - p \tag{2}$$

In the case of wind turbines with adaptive blades, neglecting the torsion due to off-axis aerodynamic loading, the elastic torsional deformation term β_e, reduces to the torsion due to elastic coupling or induced twist β. Blade twist angle is a combination of pre-twist, pitch angle and induced twist and Equation (1) changes to Equation (3).

$$\alpha = \varphi + \beta - \beta_0 - p \tag{3}$$

Induced twist is a variable parameter which depends on wind turbine operating condition (wind speed, rotor speed and pitch angle in case of having a pitch control system); blade unloaded topology (pre-twist, chord and aerofoil distributions) and size; and material and structural characteristics of the blade.

Different methods have been employed in simulation of wind turbines utilising passive smart blades. These methods can be distinguished by the adopted approach in treating the induced twist β in Equation (3). In these studies, as explained in the rest of the paper, the induced twist has been predicted, planned, or a combination of the two.

2 Predicted induced twist

Anisotropic composite materials have inherent unusual behaviour like large torsional warping, coupled in-plane and out-of-plane warping, transverse shear strain, 3-dimensional strain effects and non-uniform shear stiffness. These unusual effects make anisotropic materials difficult to be modelled analytically. During the past two decades a vast amount of research on analytical modelling of thin and thick walled beams made of anisotropic composites has been carried out, but they have been limited to either simple geometries, or they account for only some of the effects; see for example [4 to 8]. The fact that the required accuracy for predicting the induced twist is very high, (e.g. a twist angle of about one degree can affect the energy capture capability of the unit or the blade loading significantly [9]), together with the current deficiencies in the available analytical models, have placed the finite element (FE) techniques to the fore with respect to analysis of the induced twist in adaptive blades.

In ST blades, the source load for the induced twist is centrifugal force which depends upon the rotor angular velocity and blade mass distribution. In these blades the source load affects the induced twist but the induced twist does not affect the source load directly. Having the blade material and structural characteristics and the wind turbine operating condition, a blade centrifugal load predictor gives the source load and a structural analyser finds the induced twist at that operating conditions. Applying the effect of the induced twist in the blade topology, through Equation (3), the aerodynamic characteristics of the blade will be known. Here, the same simulator as used for the wind turbines with ordinary blades can be employed to simulate the wind turbine with ST blades. Since in this approach each set of unknowns can be determined by a single-step calculation this approach has been called a single-step (SS) simulation. Figure (3) shows a schematic diagram of a single-step simulation.

In BT smart blades the source load for the induced twist is the aerodynamic force which depends upon both the rotor angular velocity and wind velocity and also the blade topology and its aerodynamic characteristics. In these blades the source load affects the induced twist and the induced twist affects the source load. In other words there is an interaction between the induced twist and the source load. This interaction makes simulation of wind turbines with BT blades an iterative coupled aero-structure (CAS) process. In a CAS simulation, the effect of the induced twist on the initial loading situation is taken into account. Correcting the load, induced twist will be re-calculated. This sequence repeats until a converged solution is achieved. A schematic description of a CAS simulation is shown in Figure (4).

By assigning a zero initial value to the induced twist, Box “a” in Figure (4) can be considered as a starting point in the correction loop.

Many difficulties arise for a CAS simulation by linking available commercial codes. Using a commercial FE code, running in a loop, could be very cumbersome and inefficient. An interface is also necessary to convert the blade aerodynamic loading, calculated by the aerodynamic code, to a proper load file for the FE solver. In a coupled aero-structure code, the mesh must be efficient. Generating a mesh based on an automatic algorithm does not necessarily yield an efficient mesh, suitable for an iterative code. All of these factors make linking commercial codes inefficient and cumbersome and developing a code especially designed for this purpose a necessity [10]. WTAB is a coupled aero-structure code developed for simulating wind turbines with BT smart blades [11], which is a combination of an aerodynamic code, an adaptive mesh generator and a finite element solver, all developed especially for this purpose. Many unique features of this code, i.e. using an in-loop force-adaptive semi-automatic mesh generator [12], applying a convergence accelerator in its BEMT-based aerodynamic load predictor [13] and employing a sophisticated element based on natural mode FE formulation, have made it fast, accurate and therefore an efficient tool for CAS simulation of wind turbines with BT blades. Employing WTAB, a FE-based CAS simulation takes of about 20-30 seconds CPU- time on a 3 GHz computer.

Since smart blades are employed to control one or more aspects of the unit performance, therefore in design process of these blades the wind turbine must be simulated over a range of operating conditions. For example, when a smart blade is designed to enhance the power yield of the unit, a power curve between cut-in and cut-out velocities is required to calculate the unit average power. On the other hand, in an optimum design process, depending on the size of the design space and the employed algorithm, the number of objective evaluations can be of the order of hundreds or even thousands. Although WTAB is an efficient tool for simulation of wind turbines with BT, the iterative nature of a CAS simulation and the presence of a FE-based structural analyser make it far too slow to be useful for optimal design of blades.

2.1 Robust predicted induced twist

Knowing that in simulation of wind turbines with BT blades only an iterative CAS process gives accurate results, in order to reduce the computational time of a series of simulations over a range of operating conditions, a robust method utilises a FE-based CAS simulation to predict the induced twist at a reference operating condition and then employs a model to find the induced twist at other operating conditions.

The robust approach reported in Reference [14], aims at increasing the simulation efficiency over a range of operating condition via by-passing the FE-based structural analyser. They showed that the effects of variation of wind turbine operating conditions on the induced twist can be represented by the magnitude of flap bending at the hub of the blade and then developed an analytical model that relates the induced twist to the flap bending at the hub. In this method once the induced twist $\beta(r)$ is predicted through a FE-based CAS simulation at a reference operating condition, it can be used for prediction of $\beta(r)$ at other operating conditions through the following model:

$$\beta(r,V,\Omega,p) = M_{hub}(V,\Omega,p)\frac{\beta(r)_{ref}}{M_{hub,ref}} \tag{4}$$

In the above equation, $\beta(r)_{ref} = \beta(r,V_{ref},\Omega_{ref},p_{ref})$ is the reference induced twist and $M_{hub,ref} = M_{hub}(V_{ref},\Omega_{ref},p_{ref})$ is the reference flap bending at the hub, both obtained from a FE-based CAS simulation of the wind turbine at a reference operating condition, whilst $M_{hub}(V,\Omega,p)$ is determined only through an aerodynamic analysis without involvement of a structural analyser. This method is presented schematically in Figure (5)

Comparing this approach with the fully CAS simulation of Figure (4), this method is still an iterative CAS process in which the FE analysis of the blade has been replaced by the model of Equation (4), Box “a”. Box “b”, the results of a FE-based CAS simulation at a reference operating condition is however required as an input data for this approach.

To compare the performance of this method with a fully CAS simulation a constant-speed stall-regulated AWT-27 was adopted as the test case. The reference operating condition was selected as: $V_{ref} = 10m/s$, $\Omega_{ref} = 53.3rpm$ and $p_{ref} = 1.2^{\circ}$. Here the wind speed is the only variable operating condition. The reference induced twist distribution had been obtained from a CAS simulation at this reference operating condition.

Figure (6) shows the predicted tip induced twists by this method at different wind velocities and compares them with the results of FE-based CAS simulation. Figure (7) compares the power curves obtained by the two different methods of simulation. The maximum relative difference (RD) in the predicted tip induced twist is about 7% corresponding to the wind velocity of $V = 24m/s$.

Referring to Figure (7) the robust simulation yields excellent results with a maximum RD of less than 1.5% with respect to a complete FE-based CAS simulation for all wind velocities, while for this particular case study the computation time is less than 5% of a fully CAS simulation. This significant reduction in the computational time of simulation makes the optimal aerodynamic design of bend-twist adaptive blades practical [15]. Maheri et al performed a design case study aiming at converting the ordinary blades of an AWT-27 to BT smart ones. The assumed material properties of the blade make it a BT coupled blade in which flap bending generates an induced twist towards feather. The optimisation objective was maximising the annual energy capture capability of the unit. Working with only four design parameters, namely pre-twist, rotor radius, shell thickness and ply angle and only one constraint: limiting the output power to the original rated power; and having no other constraints on blade loading or structural behaviour of the blade, their designed blade could increase the power yield by 15.5% to 8% corresponding to site average velocities of 5.6 to 9m/s respectively.

Another attempt to develop a robust approach aiming at the iterative nature of the CAS simulation has been reported in Reference [16]. Knowing that in simulation of wind turbines with BT blades using SS, at best, gives only approximated results with expecting large amounts of errors, the goal was to find out if there existed any correlation between the results of a SS and a CAS simulation. If such a correlation could be found then the results of a CAS simulation at a reference operating condition could be used to correct the results obtained by a SS simulation at other operating conditions.

A 2-blade AWT-27 wind turbine was selected as the test case. CAS simulation of the modelled wind turbine has been carried out by using the computer code WTAB. SS simulation of the modelled wind turbine has been also carried out by using WTAB code while the correction loop runs only once.

Figure (8) and (9) show the results of SS and CAS simulations and the relative differences between them. Figure (8) shows that the two different simulation approaches give different predicted tip induced twist with a difference of about 4% to 52%. The over-prediction of induced twist is the reason for under prediction of the power by SS simulation as shown in Figure (9).

Since there was no predictable relation between the RD and wind velocity, it was concluded that in simulation of wind turbines with BT blades the results of SS simulations cannot be corrected through a model.

3 Planned induced twist

In this approach, as illustrated schematically in Figure (10), span-wise distribution of the induced twist and its variation with the wind turbine operating condition is planned. This approach can be very efficient in the early stages of an adaptive blade design process only if the planned distribution and variation of the induced twist are achievable and realistic. This method detaches the cumbersome task of material selection from the optimal aerodynamic design process.

Eisler and Veers [17] applied this approach to model a variable-speed HAWT with stretch-twist adaptive blades. They assumed a constant full span twist that varies quadratically with the rotor speed, both assumptions achievable and realistic. A constant induced twist can be achieved in the outer parts of the blade by using elastic coupled material only in the inner parts. Since in ST blades the centrifugal source load varies quadratically with the rotor speed, the assumed variation of the induced twist with rotor speed is also realistic.

Work of Lobitz et al [9] is another example of using this approach. In their work two options have been provided for twist as a function of blade position: constant with span and linear with span. For constant twist with span, the twisting is assumed to take place locally near the hub in a specially designed blade segment. For linear twist, the blade is assumed to be designed so that under the action of the various loadings it twists in a linear fashion from the hub to the tip. For each of the above span-wise twisting strategies, three options have been investigated. For the first two, the maximum blade twist at the blade tip varies with wind speed, linearly and quadratically, whilst in the third option the blade tip twists linearly with the output power of the turbine. They used these planned induced twist distributions and variations, in order to show the potential of using the adaptive blades in enhancing the power yield for a typical stall-regulated wind turbine.

4 Semi-planned induced twist

Maheri et al [18, 19 and 20] proposed another approach, more accurate and still efficient enough to be used for design of BT blades. In their approach, like Eisler and Lobitz approach, the induced twist $\beta(r)$ is described by its maximum value, β_T the induced twist at the tip of the blade and its span-wise trend, $\beta^*(r)$ normalised induced twist.

$$\beta(r) = \beta_T \beta^*(r) \tag{5}$$

Unlike the Lobitz approach, the tip induced twist variation is not taken as a function of wind turbine operating condition or output power. Here the source load, the flap bending moment as expressed by Equation (6), gives the tip induced twist.

$$\beta(r,V,\Omega,p) = M_{hub}(V,\Omega,p)\frac{\beta_{T,ref}}{M_{hub,ref}}\beta^*(r) \tag{6}$$

Another difference between their approach and the Lobitz approach, making this method of simulation more accurate, is that the normalised induced twist is only partially planned.

Using experimental and numerical data they showed that, it is the span-wise distributions of the dimensionless effective stiffness and flap bending that dictate the distribution of the normalised induced twist, not the actual values of them, as expressed in the following equation:

$$\beta^*(r) = \frac{\beta(r)}{\beta_T} = \frac{\int_0^r \frac{M^*(r)}{K^*(r)}dr}{\int_0^R \frac{M^*(r)}{K^*(r)}dr}, \tag{7}$$

in which R stands for the rotor radius, $M^* = M / M_{hub}$ stands for normalised flap bending and K^* represents the dimensionless effective torsional stiffness. Using Equation (7), if only the material lay-up configuration is decided then the normalised induced twist can be predicted accurately based on a closed form model. Since the normalised induced twist is defined based on dimensionless parameters rather than the actual mechanical properties of the material, driving a closed form model out of Equation (7), as exemplified in Reference [19], is not difficult.

They also showed that the wind turbine operating condition has negligible effects on the normalised flap bending moment, leading to this conclusion that once the normalised induced twist is calculated at a wind turbine operating condition, it can be used at other operating conditions.

Figure (11) shows a schematic description of simulation of a wind turbine using this approach, which is still iterative but no FE analysis is involved. One can observe two loops in this figure. Iteration loop “1” is due to the presence of the normalised flap bending M^* in Equation (7), which is originally unknown, and loop “2” is the normal CAS correction loop. Iteration loop “1” runs only once at a reference operating condition.

This method can be used for simulation of a wind turbine utilising the BT blades with unknown material, suitable for aerodynamic design of blades. The reference tip induced twist can be determined from an optimisation algorithm along with other aerodynamic design parameters. Structural design takes place after the aerodynamic design. In the structural design phase material selection must be carried out such that the blade experiences the obtained optimal tip induced twist at the reference operating condition.

For a constant lay-up configuration, (uniform shell thickness, ply angle and material through the span of the blade), Equation (7) can be approximated by the simple model of Equation (8) [19]:

$$\beta^*(r) = \frac{\int_0^r \frac{M^*(r)}{t_{\max}^3(r)} dr}{\int_0^R \frac{M^*(r)}{t_{\max}^3(r)} dr} \ , \qquad (8)$$

in which $t_{\max}$ stands for the maximum aerofoil thickness. They also performed a case study to demonstrate the efficiency of the method. Using the same AWT-27 test case, in the case study a $\beta_T = 4.9^\circ$ at $V_{ref} = 10m/s$ (obtained from a CAS simulation) was selected as the reference tip induced twist. Figure (12) shows the power curve obtained from a simulation based on this method when the simplified model of Equation (8) has been used to predict the normalised induced twist. Comparing this power curve against the predicted power curve from a fully CAS simulation results, with a maximum relative difference of less than 2% for this case study, highlights the accuracy of this method.

Design case studies based on this approach can be found in the literature [18], [19] and [20]. The chief advantage of this method is that it decouples the aerodynamic design from the structural design.

5 Summary and conclusion

To investigate the potential benefits of utilising bend-twist and stretch twist smart blades in wind turbines, and to design such blades new tools and methods are required. Simulation of wind turbines with passive smart blades is quite different from the simulation of wind turbines using conventional blades. A simulation tool, as a part of a design tool, must be both efficient and accurate.

Employing the available analytical models for predicting the induced twist in structures made of anisotropic composite materials does not yield results with the required level of accuracy. Linking commercial codes makes an accurate prediction of the wind turbine attainable but is not an efficient approach. A FE-based simulation tool especially developed and customised for this purpose predicts the output power and blade loading at a single operating condition efficiently, but still is not efficient enough to be used as an objective evaluation tool in a design process.

A robust method, targeting the efficiency of the structural analyser by replacing the FE-based structural analyser by a model, significantly reduces the time required for predicting the performance over a range of operating conditions. Since the model used in this method is still based on the FE-based results, this method has also a good level of accuracy.

An attempt to target the iterative nature of the simulation process has been failed since no correlation between the results of a single step simulation and a coupled aero-structure simulation could be found.

In pursuit of the aerodynamic design of bend-twist smart blades two approaches can be adopted. In the first approach the structural/material design parameters (e.g. fibre orientation, mechanical properties of composite, shell thickness, etc) are decided along the aerodynamic parameters (e.g. pre-twist, aerofoil and chord distributions, etc). Here to perform the aerodynamic objective evaluation, a CAS simulation, like methods summarised above, is required. Since the efficiency of design objective evaluation and the accuracy of the results highly affect the success and quality of a design, none of the above methods are the ideal choice for design of BT blade.

In the second approach the induced twist is decided along with the other aerodynamic parameters. Once the optimal value for the induced twist is obtained, the structural/material parameters must be selected such that to produce the decided (planned) induced twist. This approach is valid only if the planned distribution of the induced twist is achievable, and it is accurate only if the variation of the induced twist with operating conditions is predicted realistic.

The planned approach performs well for ST blades, where a realistic model accurately predicts the tip induced twist as a function of operating condition. This method has two main drawbacks. Planning the span-wise trend of the induced twist (e.g. as a linear or quadratic function of blade position) seeks a lot of effort and care on the selection of a proper span-wise material distribution and fibre angle variation. Another shortcoming is highlighted when utilising this method for BT blades. Assumption of the variation of the tip induced twist by simple linear or quadric functions of wind speed or output power, as assumed by Lobitz et al [9] may lead to unrealistic results. The behaviour of this variation is complicated. It depends on the aerodynamic behaviour of the blade which varies itself when the wind turbine operating condition changes. As a matter of fact the designer cannot plan a particular variation for the tip induced twist.

The semi-planned approach, on the other hand, uses the same basics of the Eisler/Lobitz's planned approach but has two chief distinctions, aiming at removing the two drawbacks of the that approach. Deciding the normalised induced twist at the aerodynamic design phase, removes the first drawback of a fully planned approach and makes the search for the set of material/structural design parameters easier. Reducing the structural design space is carried out by deciding the material/structural configurations of the aero-structure prior to commencing the aerodynamic design. Another drawback of a planned approach has been removed by representing the induced twist in terms of the bending moment rather than a direct function of operating conditions.

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Nomenclature

f_n	Normal force on the blade cross section
K	Effective torsional stiffness
M	Flap bending moment
$pitch$	Pitch angle
R	Rotor radius
r	Radial axis along blade span
$t_{\max}$	Aerofoil maximum thickness
V	Wind speed
α	Angle of attack
β	Induced twist due to elastic coupling
β_0	Blade pre-twist
β_e	Elastic torsional deformation in the blade
θ	Ply angle
σ	Normal stress
τ	Shear stress
φ	Inflow angle
Ω	Rotor speed

Subscripts

f	Fibre
hub	Hub
I	Cut-in
O	Cut-out
m	Matrix
ref	Reference
T	Tip

Superscripts

*	Normalised, dimensionless

Abbreviations and Acronyms

BEMT	Blade Element Momentum Theory
BT	Bend-Twist
CAS	Coupled Aero-Structure
FE	Finite Element
HAWT	Horizontal Axis Wind Turbine
RD	Relative Difference
SS	Single Step
ST	Stretch-Twist

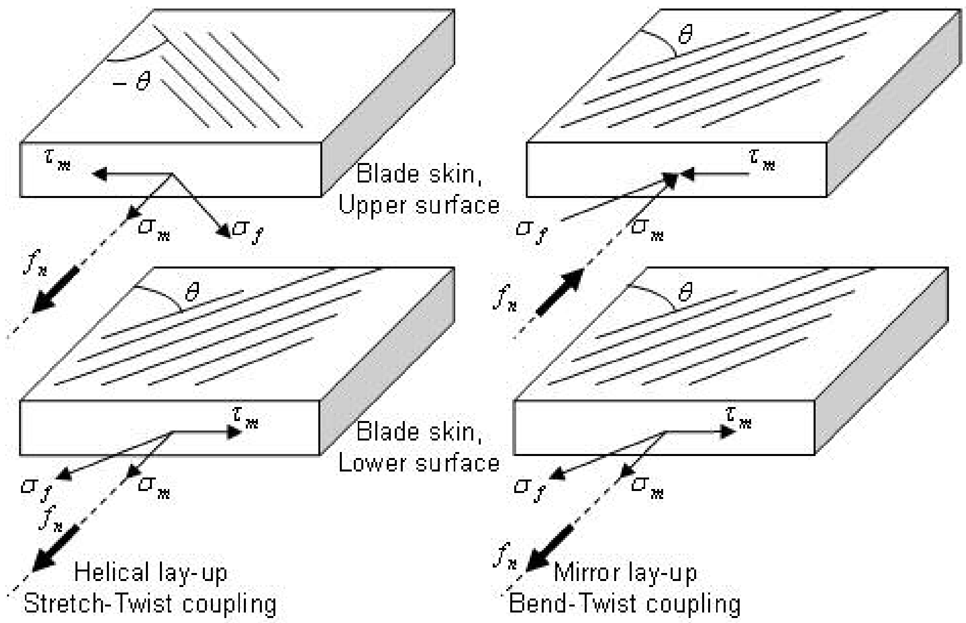

Figure 1- Elastic coupling
135x88mm (96 x 96 DPI)

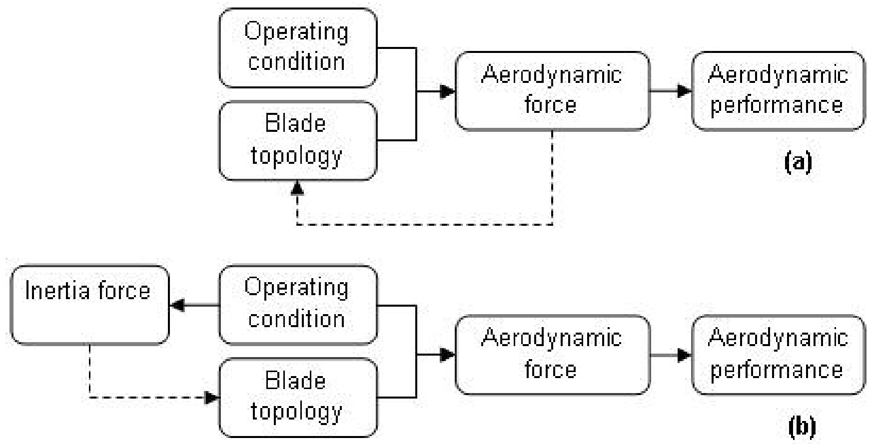

Figure 2-Control of wind turbine aerodynamic performance by utilising: (a) bend-twist coupled smart blades; (b) stretch-twist coupled smart blades
140x70mm (96 x 96 DPI)

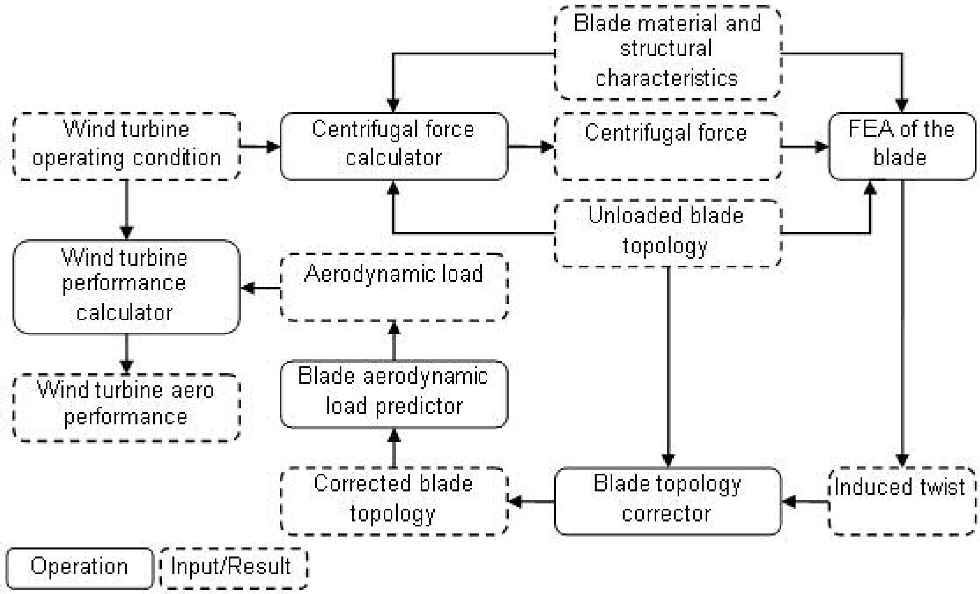

Figure 3-Single-step simulation of a wind turbine with ST blades
150x90mm (96 x 96 DPI)

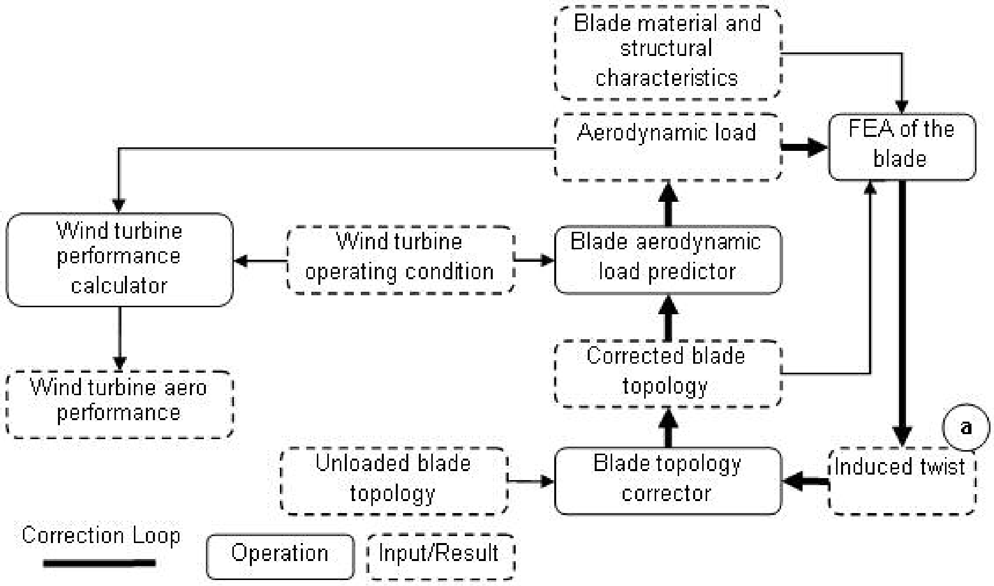

Figure 4-Coupled aero-structure simulation of a wind turbine with BT blades
150x90mm (96 x 96 DPI)

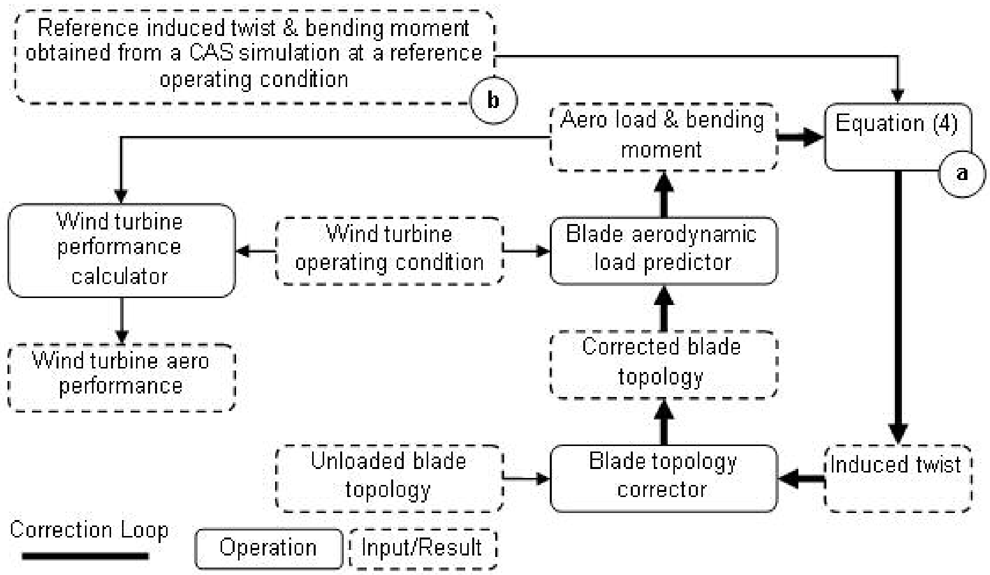

Figure 5- Simulation over a range of operating conditions using the Robust method
150x90mm (96 x 96 DPI)

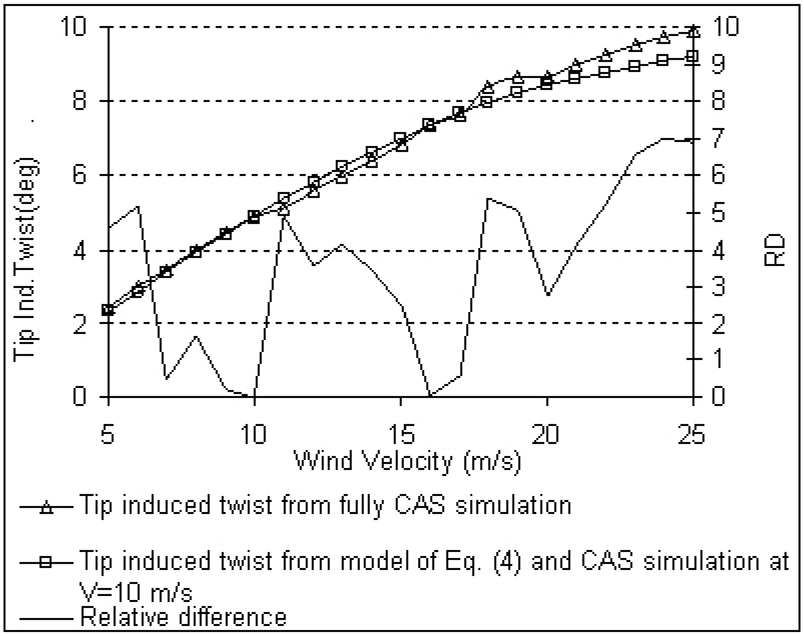

Figure 6- Tip induced twist predicted by fully CAS simulation and The Robust method
108x85mm (96 x 96 DPI)

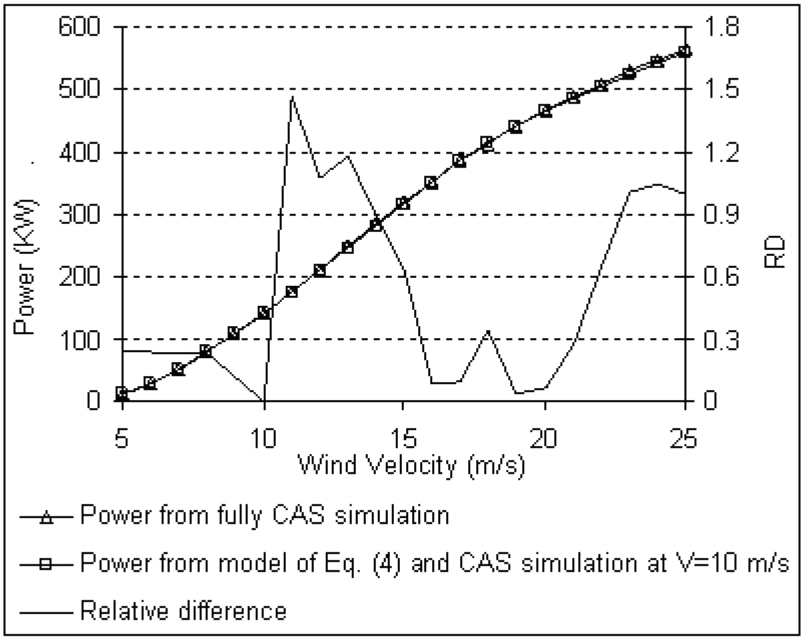

Figure 7- Mechanical power obtained from fully CAS simulation and robust method
108x86mm (96 x 96 DPI)

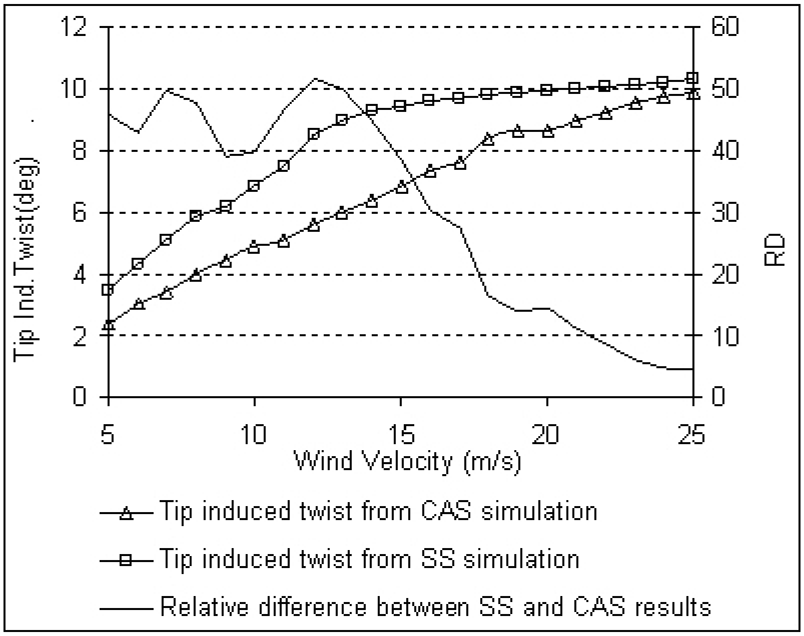

Figure 8-Tip induced twist obtained from SS and CAS simulations versus wind velocity
108x86mm (96 x 96 DPI)

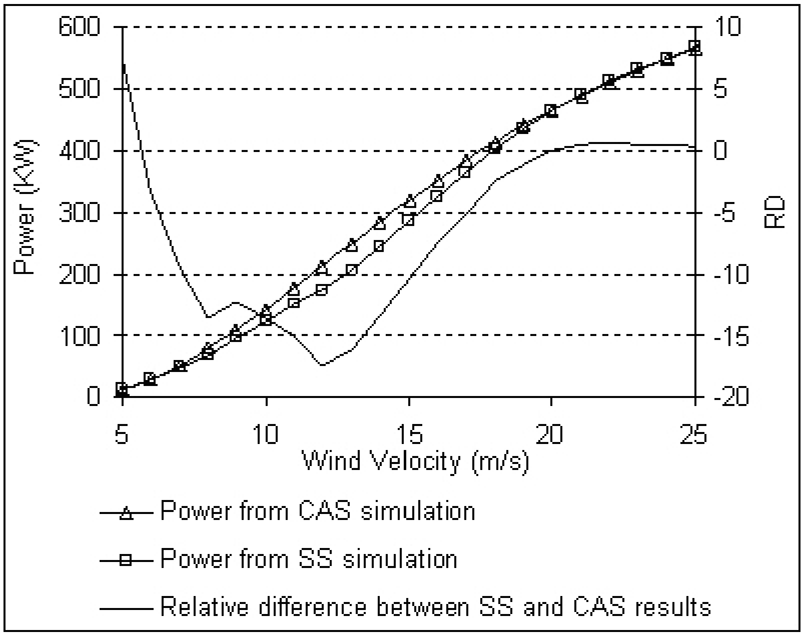

Figure 9-Mechanical power predicted by SS and CAS simulations versus wind velocity
108x85mm (96 x 96 DPI)

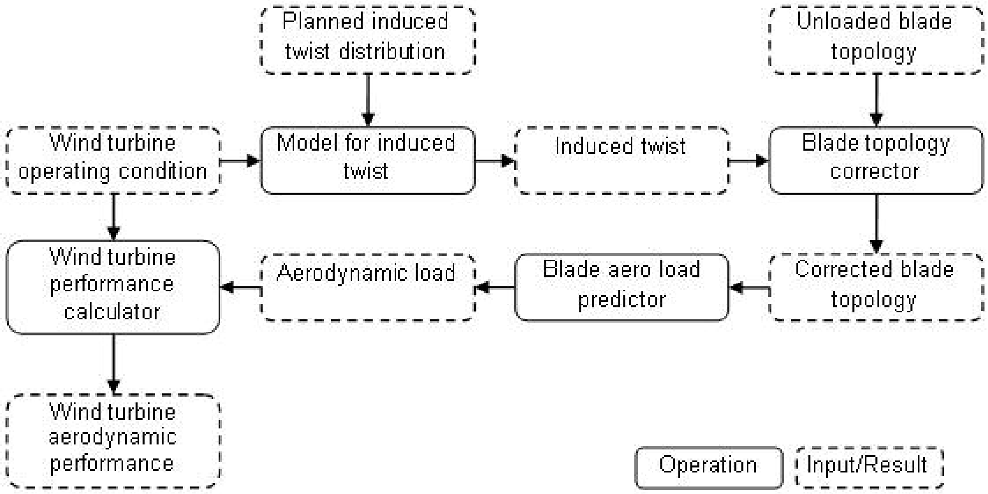

Figure 10- Simulation of a wind turbine with smart blades using planned distribution and variation of the induced twist
150x80mm (96 x 96 DPI)

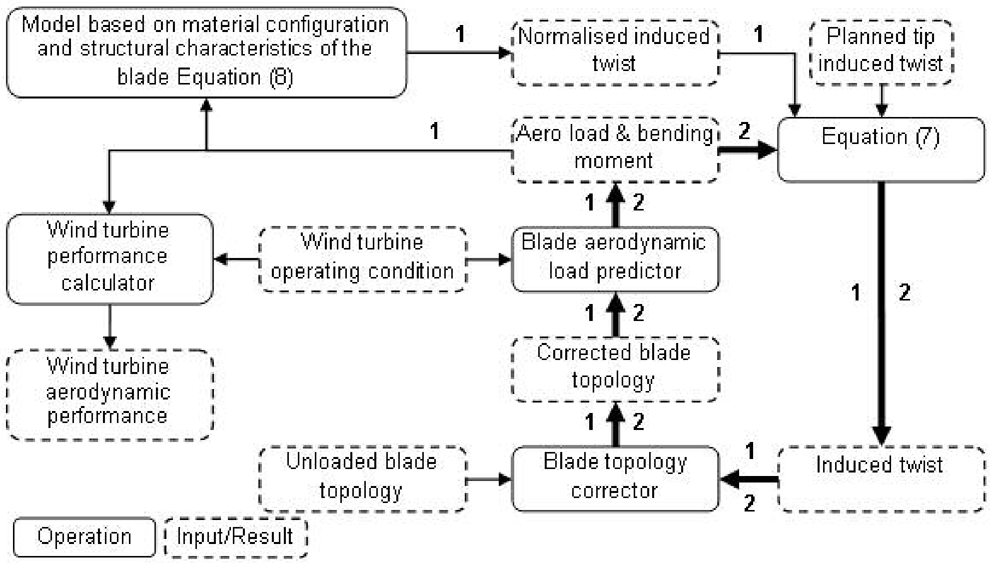

Figure 11-Simulation of a wind turbine with BT blades based on semi planned induced twist method
155x90mm (96 x 96 DPI)

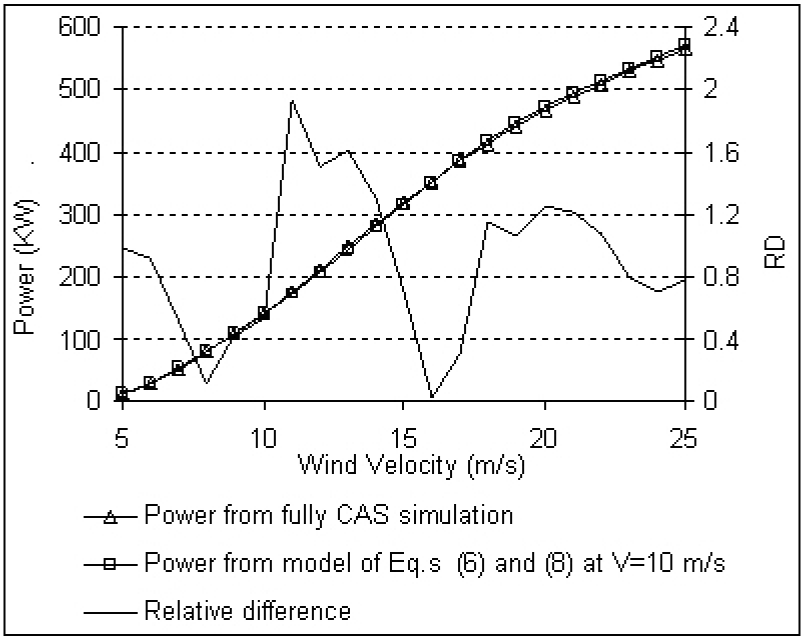

Figure 12-Power curve from models of Equations (6) and (8) versus predicted power curve from a fully CAS simulation
108x86mm (96 x 96 DPI)