European Association for the Development of Renewable Energies, Environment and Power Quality

International Conference on Renewable Energies and Power Quality (ICREPQ'09)

Valencia (Spain), 15th to 17th April, 2009

Design Blades of a Wind Turbine Using Flexible Multibody Modelling

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Abstract. A methodology for the application of structural optimization to find the optimal layouts of composite blades, based on a multibody model of a wind turbine, is presented. VABS (Variational Asymptotic Beam Section) is used to compute the sectional constants for a generalized Timoshenko beam model. The gravity and inertia effects are taken into account as well as the aerodynamic force, which are calculated by the aerodynamic coefficients and transferred to the corresponding finite element nodes. The minimum lateral moment component at the blade root is found by using an optimization methodology that finds the optimal values for the fiber orientation of the composite spar of the blade. The computational efficiency and robustness of the optimal process relies on the accurate evaluation of the system sensitivities. In this work a general formulation for the computation of the first order analytical sensitivities based on the direct method is used. The direct method for sensitivity calculation is obtained by differentiating the equations defining the response of the structure with respect to the design variables. The equations of motion and sensitivities of the flexible multibody system are solved simultaneously and therefore the accelerations and velocities of the system and the sensitivities of the accelerations and of the velocities are integrated in time using a multi-step multi-order integration algorithm.

Keywords

Composite material; Rotor blade, flexible multibody systems, mode component synthesis, automatic differentiation, design sensitivity, variational asymptotic beam section.

1. Introduction

Composite blades are the type of structures encountered in helicopter rotor blades and wind turbines blades [1]. The design of composite rotor blades in modern industrial environments requires complex and accurate computational models, which are difficult to build, thus restricting the design exploration and making it hard for designers to try novel lay-ups and cross-sectional configurations. Therefore, the variations of the cross-sectional layouts across the wide range of modern rotor blades are remarkable small compared to the wealth of possibilities provided by the use of composite materials [2].

The wind turbine modeling complexity is related with the tools used in the construction of the models of individual and coupled components of the system. Because of the special cross-sectional geometric features of blades, the use of computational tools that provide fast and accurate mean of assessing the blade properties opens opportunities to improve the design cycle of composite blades. The computer program VABS (Variational Asymptotic

Beam Section analysis) allows modeling heterogeneous anisotropic beams with arbitrary cross section geometries through a finite element discretization of the cross section and, therefore, permits a high-fidelity representation of the blade structure in terms of an equivalent beam model [3]. Once the blade properties are obtained, various types of blade analyses, including the multibody dynamic simulation of the entire wind turbine system, become possible. The outline of the blade used in this work is a SERI-8 aerofoil with the chord length of 0.594 m [4].

The wind turbine is a typical mechatronic system consisting of mechanical, electrical and control subsystems interacting with each other [5]. Regardless the importance of the electrical and control subsystems on the performance of the wind power generator, the mechanical subsystem is the focus of this work, in which a three-bladed wind turbine is investigated. The use of the flexible multibody dynamics approach to describe the large motion of complex systems that have flexible components is advantageous compared to standard nonlinear finite element methodologies because it deals very efficiently with the very large rotations, relative kinematics of the different system components and with the deformation of the structural members including the inertia coupling between large gross motion and the structural elastodynamics. The application of flexible multibody dynamics formulation allows the use of reduction techniques to obtain simpler models while preserving the ability to represent the large rotations of the components with respect to each other or with respect to an inertial reference frame [6,7]. For efficient modeling and accurate dynamic analysis of a wind turbine, a rigid-flexible multibody system methodology is recommended since it combines the rigid body motion and elastodynamics allowing to capture all the rigid and elastic components, couplings and important motions that result from the nonlinear kinematics [5].

With the objective of reducing the transient loads of wind turbine blades, the aeroelastic tailoring concept has been used since the late 1980s. Using this concept the blade geometry and its structure are designed in such a way that when the blade undergoes flapwise deflection during operation it inherently undergoes twist as well. Two basic approaches used either (1) sweep the blade in the plane of rotation, allowing that the aerodynamic loading to act on the outboard portions of the blade producing a substantial torque about the blade elastic axis, or (2) rotate some of the structural laminate fibers away from the spanwise direction inducing, in this way, a twist-flap coupling in the structure [8]. For a comprehensive review of prior research on aeroelastic tailoring of blades the interested reader is referred to Lobitz et al. [9] Several works sponsored by the Sandia National Laboratories have been focusing the structural details of various blade designs to achieve twist-flap coupling [10,11,8]. All of these studies are conducted by performing a set of static analysis in which the fiber angle of the spar cap is modified in a discrete form changing from 5 to 20 or to 25 degrees.

In this work, the optimization of the composite blade is carried out using a flexible multibody dynamics model of a wind turbine. The ply orientations of the laminate used to make up the spar cap of the blade are taking as continuous design variables. The multibody dynamic and sensitivities analysis code is linked with general optimization algorithms included in the package DOT/DOC [12].

2. Sensitivity Design in Flexible Multibody Dynamics

The finite element method is used to represent the flexible body being the body reference frame coincident with a coordinate system rigidly attached to a point on the flexible component. The kinetic energy of a flexible body is defined by assuming that the distributed mass of the flexible body is replaced by particle masses and lumped inertias in the nodal positions of the finite elements [13]. The local body reference frame is aligned with the body principal inertia directions and it is fixed to its center of mass. The sensitivity design is necessary for deterministic optimization algorithms because one needs to know how a change in the design variables changes the system performance. The calculation of these sensitivities can be carried out analytically or numerically. In this work only the analytical sensitivities are obtained by using automatic differentiation.

The sensitivities of the equations of motion are obtained by differentiating the equations of motion of a rigid-flexible multibody system with respect to the design variables **b**,

$$\begin{bmatrix} \mathbf{M}_{rr} & \bar{\mathbf{M}}_{rf} & \mathbf{\Phi}_{\mathbf{q}_r}^T \\ \bar{\mathbf{M}}_{fr} & \bar{\mathbf{M}}_{ff} & \mathbf{\Phi}_{\mathbf{w}}^T \\ \mathbf{\Phi}_{\mathbf{q}_r} & \mathbf{\Phi}_{\mathbf{w}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}_{r_\mathbf{b}} \\ \ddot{\mathbf{w}}_\mathbf{b} \\ \boldsymbol{\lambda}_\mathbf{b} \end{bmatrix} = \begin{bmatrix} \bar{\mathbf{Q}}_\mathbf{b}^* \\ \bar{\mathbf{R}}_\mathbf{b}^* \\ \bar{\boldsymbol{\gamma}}_\mathbf{b}^* \end{bmatrix} \quad (1)$$

where the notation used is the following $\bar{\mathbf{M}}_{ff} = \mathbf{X}^T \mathbf{M}_{ff} \mathbf{X} = \mathbf{I}$, $\bar{\mathbf{M}}_{rf} = \mathbf{M}_{rf} \mathbf{X}$, $\bar{\mathbf{M}}_{fr} = \mathbf{X}^T \mathbf{M}_{fr}$, $\mathbf{\Phi}_\mathbf{w} = \mathbf{\Phi}_{\mathbf{q}_f} \mathbf{X}$ and $\mathbf{\Phi}_\mathbf{w}^T = \mathbf{X}^T \mathbf{\Phi}_{\mathbf{q}_f}^T$. In equation (1) $(\cdot)_\mathbf{b}$ denotes the sensitivity of quantity $(\cdot)$ with respect to **b** and the sensitivities $\bar{\mathbf{Q}}_\mathbf{b}^*$, $\bar{\mathbf{R}}_\mathbf{b}^*$ and $\bar{\boldsymbol{\gamma}}_\mathbf{b}^*$ are defined according to Ambrósio et al.[14].

For the laminate optimization problem the design variables used are the lay-up orientations, denoted by vector $(\mathbf{b}=\boldsymbol{\theta})$. Therefore, the derivative of the stiffness matrix of the composite flexible body with respect to the lay-up orientations has to be accounted for. The sensitivity of the stiffness matrix of the composite beam element is such that the matrix **D** is the only matrix that depends on the design variables. Thus, the sensitivity of this equation is given by

$$\frac{\partial \mathbf{K}_{ff}^{(e)}}{\partial \boldsymbol{\theta}} = \int_{-1}^{1} \left(\mathbf{B}^{T} \frac{\partial \mathbf{D}}{\partial \mathbf{b}} \quad \mathbf{B} \right)^{(e)} \left| \boldsymbol{J} \right| d\xi \quad (2)$$

The partial derivative of matrix **D** is obtained by using the VABS code, which is extended to consider this computation. In the generalized Timoshenko theory. The partial derivative of the **D** matrix with respect to the design variables, is

$$\frac{\partial \mathbf{D}}{\partial \boldsymbol{\theta}} = \begin{bmatrix} \dfrac{\partial \mathbf{X}}{\partial \boldsymbol{\theta}} & \dfrac{\partial \mathbf{F}}{\partial \boldsymbol{\theta}} \\ \left(\dfrac{\partial \mathbf{F}}{\partial \boldsymbol{\theta}} \right)^{T} & \dfrac{\partial \mathbf{G}}{\partial \boldsymbol{\theta}} \end{bmatrix} \quad (3)$$

More details on the evaluation of the derivatives of the sub matrices **X, F** and **G** are found in Neto et al. [15´,16]

3. Optimization of Composite Rotor Blades of a Wind Turbine

The methodology for the optimal design of flexible multibody systems made with composite beam components is applied to the design of a three-bladed wind turbine. Several models of the wind turbine are given in references by Stol et al. [17], Bauchau and Wang [18] and Hodges and Yu [1].

The solution of the optimization problem can be obtained by either deterministic or stochastic optimization methods. In this work a deterministic optimization method, the Modified Method of Feasible Directions (MMFD), as implemented in DOT program [12], is used.

A. Description of the Wind Turbine

This application deals with the modeling of the three-bladed wind turbine depicted in Figure 1. The physical properties of the system are presented in Stol et al. [17] and are not be repeated here. The full multibody model considers the tower that is connected to a flexible bed plate, the shaft that is connected to the bed plate, by means of a revolute joint, and the tip of the shaft is attached to the hub, which is modeled as a rigid body. Finally, the three flexible blades, each modeled by ten cubic composite beam elements, are attached to the hub by revolute joints, called "pitch hinges", allowing for the relative motion of the blade with respect to the hub, which is normal to the plane of rotation of the rotor. Flexible root retention beams, each modeled as a single cubic beam element, are connected to the assemblies on the back of the hub [18].

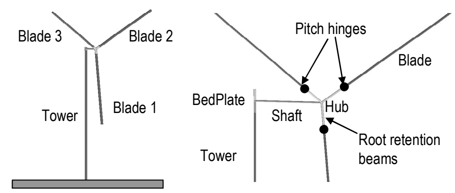

Fig. 1. Schematic configuration of the wind turbine.

The outline of the blade is a SERI-8 aerofoil with chord length of 0.594 m being the shear web located 30% of the chord length from the leading edge, as sketched in Figure 2 [4]. The rotor diameter is of 20.52 m. The layer orientations used, to make the different components of this blade, are listed in Table I. The material properties, including density and elastic constants, are given in Table II. The blade cross section finite element model is meshed with 1030 nine-node quadratic elements in order to be used in the computer code VABS.

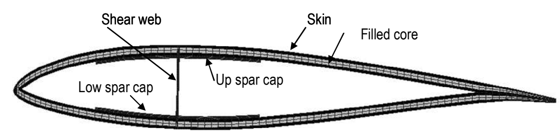

Fig. 2. Blade cross-section of the S805A/S807 aerofoil.

TABLE I. - Laminated used in the blade of the wind turbine.

Component	Material	Total thickness (mm)	Laminate orientations
Skin	Graphite/epoxy	2.877	0^0
Fill core	Graphite/epoxy	5.754	$0^0/0^0$
Up spar cap	Graphite/epoxy	2.877	$15^0/15^0/15^0/15^0$
Low spar cap	Graphite/epoxy	2.877	$15^0/15^0/15^0/15^0$
Shear web	Graphite/epoxy	1.869	$45^0/-45^0/45^0/-45^0$

TABLE II. – Material properties of the composites used on the blade.

Material	Density (Kg/m^3)	Elastic properties
Graph-ite/epoxy	1600	$E_1 = 184.556 GPa \quad \upsilon_{12} = \upsilon_{13} = 0.28$ $E_2 = E_3 = 10.503 GPa \quad \upsilon_{23} = 0.33$ $G_{12} = G_{13} = 7.312 GPa \quad G_{23} = 3.9 GPa$

The induced wind forces are computed according to the combined blade element and momentum theories, being defined as [19]

$$\text{Lift} = \int_{x_1}^{R} \frac{1}{2} \rho v^2 c C_l dr \quad (4)$$

$$\text{Drag} = \int_{x_1}^{R} \frac{1}{2} \rho v^2 c C_d dr \quad (5)$$

where v is the apparent wind speed, c is the chord length, ρ is air density, C_l is the lift coefficient and C_d is the drag coefficient. Lift and Drag forces depend on the coefficients C_l and C_d, which in turn depend on the cross section of the blade that is being used, and on the angle with which the wind strikes the blade. The lift force acts perpendicularly to the direction of wind flow and the drag force acts parallel to the direction of wind flow. Because the chord of the blade cross-section is constant throughout the blade span, the finite element model computes the drag and lift forces as distributed throughout the blade span.

The projection of the drag and lift forces over the cross-section coordinate system is depend on the angle between the apparent wind direction and the chord line, α, and on the twist blade angle, β. Because the blade is not twisted initially, the multibody model of the wind turbine accounts for the flexible twist of the cross section only. Therefore, the thrust and the driving forces that acts on the blade cross section are evaluated, as presented in Figure 3. Actually, the flexible twist allows to adjust the local angle of attack which in turn leads to different coefficients C_l and C_d.

The flexible twist is evaluated for all nodes of the 1-D finite element model of the blade, being time dependent. The aerodynamic forces are transferred to the corresponding finite element nodes and are used at the next time step, thus a direct aeroelastic coupling is taking into account.

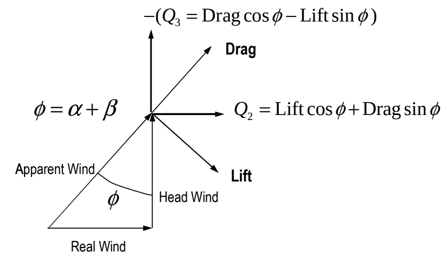

Fig. 3. Aerodynamic forces acting on the cross section of the blade.

B. Multibody simulation of the wind turbine

For the purpose of demonstrating the proposed methodology the wind turbine model depicted in Figure 1 is used. For simplicity the tower and the bed plate are not considered in this simulation. Modeling of these components would be easily done, but they do not affect significantly the optimization goal related with the lateral moment component at the root blade.

The initial angular velocity of the shaft is 5 rad/s and a constant resistant moment is applied on the shaft during all period of simulation. Others parameters considered are the air density 1.2 Kg/m [3], the wind speed 10 m/s and the span of the blades 10.26 m, which corresponds to a wind turbine diameter of 2×10.26 m. Because the aerodynamic characteristics for the S805A/S807l airfoil profile are not available, the lift and the drag coefficients are selected from Wolfe and Ochs [20]. For a mixed laminar/turbulent calculations and an angle of attack between 0 and 9.22 degrees the experimental drag coefficient is about 0.007, thus in these simulations the drag coefficient is assumed constant with a value of 0.007. Nevertheless, the value of the lift coefficient experience significant modifications as the angle of attack changes. Therefore, in this work the least square minimization method is used for fit the experimental values [20] of the lift coefficient to a linear equation, defined as

$$C_l = 0.177249 + 0.098172\phi \quad (6)$$

where ϕ is defined in Figure 3. It is assumed that the angle of attack is about 5.13^0.

When using the modal superposition technique, four vibration modes corresponding to the first four frequencies of each flexible component are selected. These modes of vibration are obtained by performing a modal analysis on each component of the flexible multibody system. The structural attachment conditions used in the eigenproblem are the same used to fix the body coordinate system to the flexible body, i.e., the node in the centre of mass is fixed to the body fixed frame. The simulation of the wind turbine is carried out for 10 seconds being the time histories of displacement, force and moment obtained as the results of the analysis. In Figures 4, 5, 6 and 7 the wind turbine response is presented in terms of the rotor angular velocity, the transverse elastic displacement component at the tip of the blade and the sectional force and moment components at the blade root, respectively.

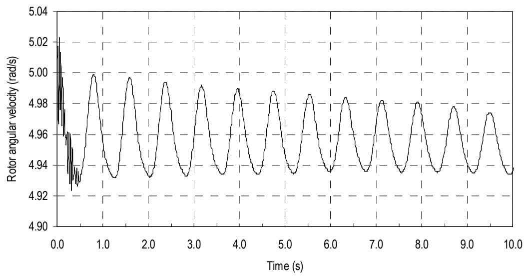

Fig. 4. Rotor angular velocity of the wind turbine.

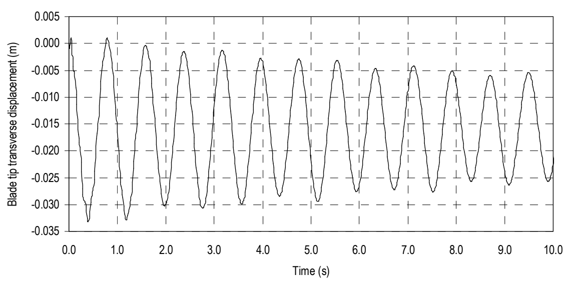

Fig. 5. Time history of transverse blade tip displacement.

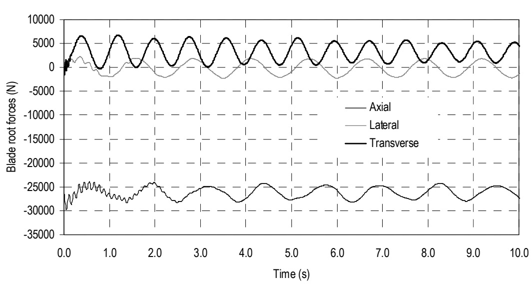

Fig. 6. Time history of blade root forces.

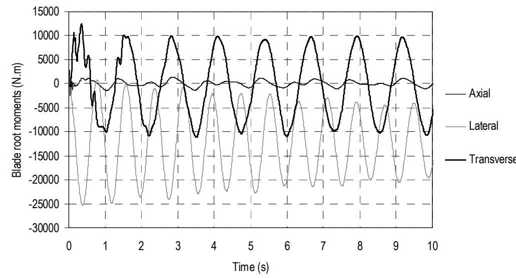

Fig. 7. Time history of blade root moments.

C. Wind turbine blade optimization

The use of composite materials in wind turbine blades allows taking advantage of particular effects associated with the design of the blade material, namely the twist-flap coupling that makes the blades intrinsically smart. This coupling effect acts as a passive mechanism within the blade structure to enhance their static and dynamic behavior [21]. Besides the twist-flap coupling, general improvements are achieved when the moment components at the blade root are minimized.

In this work the magnitude of the minimization of the lateral moment, $\chi(t)$, at the root of blades is the objective of the optimization procedure. The problem is formulated as the minimization of the objective function

$$\Psi_0 = \int_{t_i}^{t_e} f_0(t)dt = \frac{1}{(t_e - t_i)} \int_{t_i}^{t_e} \left[\chi_0 - e^{(-\chi(t)/\chi_1)} \right]^2 dt \quad (7)$$

where χ_0 and χ_1 are the reference value and a scaling factor, respectively. The simulation period is of ten seconds but equation (7) is only computed in the simulation period of $t_i = 1.2\,s \le t \le t_e = 10\,s$ to avoid accounting for the transient period of the start of the analysis. The reference value, χ_0, is defined as being the average value of function $e^{(-\chi(t)/\chi_1)}$ through the simulation period. Figure 8 shows the time history of function f_0 for the simulation described in the previous section.

The objective function defined by equation (7) is equivalent to the area under the curve f_0 between the limits $t_i = 1.2$ to $t_e = 10$. With this objective function the fluctuation of the lateral moment around the average value χ_0 should be minimized, which may imply an improvement of the blade damping. To verify this idea, the time history of the blade lateral moment for the initial and for the optimum design is fitted to the function defined as

$$\chi_f(t) = \chi_m + \chi_a e^{(\mu t)} \cos(\chi_\omega t + \theta) \quad (8)$$

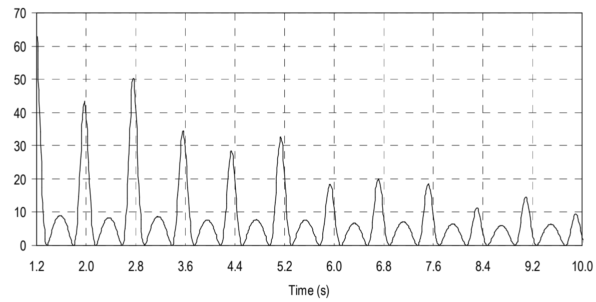

Fig. 8. Time history of function f_0.

Due to the nonlinear nature of this function the use of least square minimization methods to obtain the constants χ_m, χ_a, μ, χ_ω and θ used in equation (8) leads to the solution of a nonlinear least square optimization problem. Thus, in this work, the constants χ_m, χ_a, μ, χ_ω and θ are evaluated by solving a second minimization problem defined as

$$\begin{aligned} &\text{minimize } \sum_{k=1}^{n}\left[\chi_f(t) - \chi(t)\right]^2 \quad \text{(objective function)} \\ &\text{Subject to} \quad (\chi_m)_L \le \chi_m \le (\chi_m)_U \quad \text{(Side constraints)} \\ &\qquad (\chi_a)_L \le \chi_a \le (\chi_a)_U \\ &\qquad (\chi_\omega)_L \le \chi_\omega \le (\chi_\omega)_U \\ &\qquad (\mu)_L \le \mu \le (\mu)_U \\ &\qquad (\theta)_L \le \theta \le (\theta)_U \end{aligned} \quad (9)$$

where the indices *U* and *L* refer to the upper and lower limit constraints of the design variables. The optimization problem expressed by equation (9) is solved using a genetic algorithm, specially recommended for the solution of curve fitting problems [22].

The laminate used to model blades 1, 2 and 3 is the material used in the previous section. The first design variable used in the optimization process corresponds to the lay-up orientation of the laminate used in the upper spar cap, and the second design variable corresponds to the lay-up orientation of the laminate used in the lower spar cap. The initial laminate design of the blades is defined in Table I.

The optimization results are summarized in Table III. The convergence to the optimum solution is very fast, reducing the objective function in the order of 22%. Figure 9 shows the time history of the lateral moment, χ_f at the blade root for the initial and the optimal design.

TABLE III. – Summary of the optimization of the wind turbine.

	Upper spar cap	Lower spar cap
Optimum Layer orientations	$70^0/70^0/70^0/70^0$	$90^0/90^0/90^0/90^0$
Normalized Initial objective function	1.00	
Normalized Optimum objective function	0.78	
Reduction of objective function	22%	
Function calls	15	
Gradient calls	2	
Number of iterations	3	

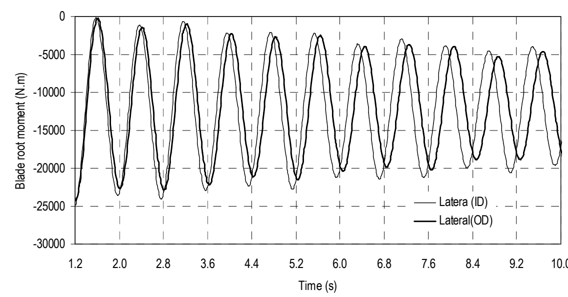

Fig. 9. Lateral moment at the root blade for the initial and optimal designs.

The solution of the optimization problem formulated by equations (8) and (9) for the initial and optimized designs are presented in Table IV. The optimum design allows improving the damping coefficient of about 40% of its initial value. The representation of function $\chi_f(t)$ for the initial and optimum designs is made on Figure 10.

TABLE IV. – Summary of the curve fitting problem for the second optimization scenario.

Constants	Initial design	Optimum design
χ_m	-1.2357×10^4	-1.1981×10^4
χ_a	-1.2934×10^4	-1.31478×10^4
χ_ω	8.007	7.855

θ	3.037	3.036
μ (damping)	-0.05	-0.07

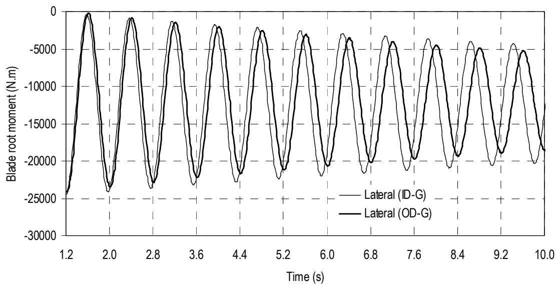

Fig. 10. $\chi_f(t)$ given by equation (8), for the initial and optimized designs.

The comparison of the initial design with the corresponding optimum design allows concluding that the major improvement of the optimum design is obtained for the maximum value of the lateral moment rather than for its minimum value. Moreover, if the value of the constant χ_m of the initial design is compared with the corresponding optimum design it is observed that the optimum design show smaller mean lateral moments than the initial design.

Note that the present manufacturing technology limits the accuracy at which layer orientations can be set to increments of about 5^0. This fact, more than constituting a constraint in the optimization process, enforces the use of optimization methods such as those based on evolution strategies. However, such methods usually require several hundreds or even thousands of expensive simulation runs [23], being too costly to be considered in this work at this time.

4 Conclusions

A general method for the design optimization of flexible multibody systems made of composite materials has been presented in this work for the optimal design of wind turbine blades. The emphasis of the proposed methodology is on a flexible multibody formulation involving composite beams and efficient evaluation of the design sensitivities. The sensitivities computation of the 6×6 cross-sectional stiffness matrix of the beam element is obtained by extending the VABS code to include the evaluation of the design sensitivities for anisotropic, heterogeneous materials and to represent general cross-sectional geometries. In the process the use of a costly 3-D finite element discretization is avoided without any loss of accuracy, inherent in the simplified representations of the cross section [3]. The incorporation of such beam analysis into the flexible multibody code has been showed to be a powerful approach to the modeling of realistic engineering systems with slender composite components.

The optimization of wind turbine blades has been achieved using the formulation proposed. The results show a feasible design for the wind turbine in which an improvement on damping coefficient of the lateral moment component at the blade root is observed. Although an improved design of the turbine blade was obtained there is no assurance that it is a global optimal design.

Acknowledgement

This study was supported by the Portuguese Foundation for the Science and Technology and FSE under a post doc scholarship. The views and the findings contained herein are those of the author and should not be interpreted as necessarily representing the theoretical policies or endorsement, either expressed or implied, of the Portuguese Foundation for the Science and Technology.

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