XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

A layup optimization approach of laminated composite wind turbine blade for improved power efficiency

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Abstract. Wind turbine blades are usually made of composite materials. Their stiffness and behavior affect the turbine performance, on the other hand, the material and layup orientation influence the blade stiffness. By taking advantage of the bend-twist coupling that is a consequence of layup sequence, it is possible to produce a passive control of the pitch angle which aims to improve the blade performance. The purpose of this work is finding the best layup sequence of a wind turbine blade made of laminate composite materials using metamodeling based optimization. For this, the finite element method is used to obtain the structural response of the wind turbine blade. From this numerical simulation responses, a surrogate model based on Kriging approach is generated. Ply orientations are adopted as input parameters, and the power coefficient of the wind turbine as output. Then, an optimization process is carried out. The optimized layup sequence is compared with other layup configurations and the surrogate model responses with the finite element model itself. Using this methodology is possible to reach a significant improvement in turbine power coefficient. For instance, at wind speed of 20 m/s, the power coefficient between layups achieves 8.2% of variation.

Keywords: wind turbine blade, laminate composites, optimization, Kriging, finite element method.

1 Introduction

Wind turbines are responsible for converting wind energy into electricity. Aerodynamic forces produce torque in the turbine shaft, resulting in mechanical energy which is transformed into electricity by a generator. Although most of wind turbines are basically made up of the same subsystems, the ones with small generation capacity are simpler and do not have, for example, the active control of the blade's pitch angle (see Figure 1). This control allows the blade position adjustment according to the wind direction and speed, improving the turbine efficiency [1].

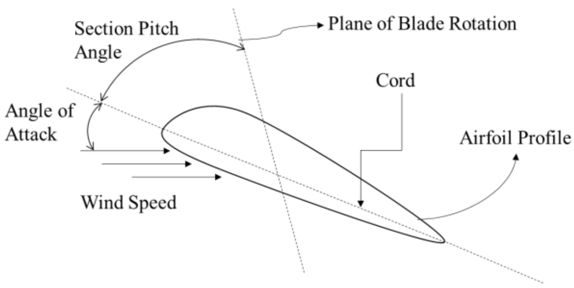

Figure 1. Blade section representation

The active control of the pitch angle demands mechanisms and control systems and, due to this, its application is counter-productive in low energy capacity turbines. As an alternative, it is possible to perform this control in a passive way taking advantage of the intrinsic deformation of the turbine blade. This concept, also known as aeroelastic tailoring, takes advantage of bend-twist coupling inherent in anisotropic materials and has been an important tool for the optimization of wind turbine blades that are often made of laminate composite materials [2].

The evaluation of laminate composite structures designs is complex and has high computational cost. For this reason, its optimization is usually made using surrogate models. Surrogate models (also called metamodels) are simplified models that approximate, with a relatively good accuracy, a more detailed model of a phenomenon, therefore, they can be used as substitute for high computational cost functions in the optimization process. The surrogate model construction requires, initially, a design of experiments (DoE). The DoE is a technique that assists in determining the value of design variables that are used in the surrogate model construction [3].

Thus, combining the following techniques: finite element simulation, DoE, surrogate model and optimization, it is possible to reach a higher performance and efficiency of laminate structures [4]. Within this context, the objective of this work is to develop, apply and evaluate an optimization methodology with low computational cost aiming to increase the power coefficient of composite wind turbine blades. This methodology uses metamodeling, specifically Kriging (KRG).

2 Methodology

The metamodeling-based optimization usually follows the sequence of steps proposed by Wang and Shan [5] which are shown in Figure 2. The details of each step is explained in the sections 2.1 to 2.5.

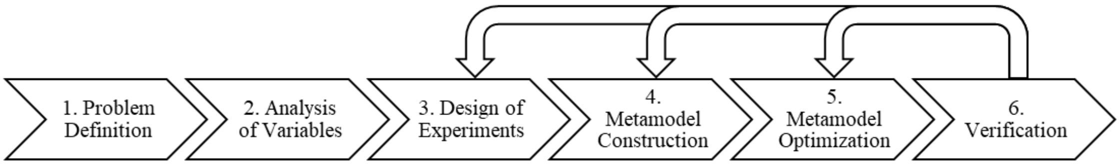

Figure 2. Flowchart of metamodeling-based optimization process

2.1 Problem definition

In this work, a wind turbine blade model developed by Leite and Ferreira [6] is used as a reference and a corresponding finite element model is generated using the commercial software Abaqus. The four node shell finite element model (S4R) is used and static analysis is performed, considering the material within the linear elastic regime, but the structure can undergo large displacements (geometric non-linear analysis). The numerical technique used the nonlinear system of equations is the Newton's method. This finite element model is then used to simulate the torsion generated in the wind turbine blade for different layup configurations.

The lamina material is an unidirectional carbon-epoxy prepreg with the elastic modulus in the fiber direction (E_1) equals to 121 GPa; the elastic modulus in the transversal direction of the fibers (E_2) equals to 8.6 GPa; the shear modulus in the 1-2 plane (G_{12}) equals to 4.7 GPa and the Poisson ratio (ν) equals to 0.27.

The wind turbine blade has the NACA 23018 airfoil profile as a reference. Only the chamber line of the profile is used as a thin airfoil blade and seven plies of 0.57mm thickness were added to it. In order to ensure a better bend strength, the three central plies are oriented with the fibers in the longitudinal direction of the turbine blade. The orientation of the two upper and lower plies are the input variables of this analysis. The turbine blade has 750 mm length, although the useful area starts from a radial distance of 150 mm. Table 1 shows the chord length and the geometric torsion angle in relation to the radial position.

Two simultaneous loads are applied to the wind turbine blade. A centrifugal load generated by the turbine blade's rotation that is calculated by:

$$F_c = dm\Omega^2\, r \tag{1}$$

where dm is the mass differential, Ω is the angular speed calculated by [6]:

$$\Omega = \sqrt{1467{,}95U + 387.67)} - 19.69. \tag{2}$$

And the second one is the aerodynamic load that enables to calculate the torque generated by the turbine using the blade element momentum theory (BEMT), so, the turbine blade is divided in N sections and the torque in each of those sections is obtained by the equation:

$$dQ = \sigma'\pi\rho\frac{U^2(1-a)^2}{sen^2\varphi}(C_l cos\varphi + C_d sin\varphi)r^2dr \quad (3)$$

where σ' is the chord solidity of the aerofoil, ρ is the fluid density, U is the speed flow, a is the axial induction factor, C_l the lift coefficient, C_d is the drag coefficient, r is the rotor radius and $\varphi = \beta + \alpha$, where β is the inclination angle of the turbine blade and α is the blade´s element angle of attack [1].

Table 1. Geometric characteristics of the wind turbine blade

Radial position (m)	Chord length (m)	Geometric torsion angle (º)
0.15	0.16	20.1
0.2	0.14	14.7
0.26	0.12	10.0
0.32	0.10	6.7
0.38	0.09	4.3
0.45	0.08	2.5
0.51	0.07	1.0
0.57	0.06	-0.1
0.63	0.05	-1.0
0.69	0.05	-1.8
0.75	0.05	-2.5

In Equation (3), in addition to the angle φ being directly proportional to the angle of attack, the variables C_l e C_d are directly affected by the angle of attack either, their values are obtained through aerodynamic simulations and are also affected by the Reynolds number of the flow. Figure 3 shows the finite element model generated for the mechanical analysis of the wind turbine blade.

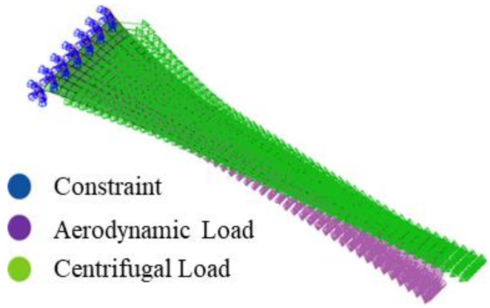

Figure 3. Finite element model

Through BEMT it is possible to obtain the turbine power either:

$$P = \int_r^R \Omega\, dQ \quad (4)$$

where r is the internal radius and R the external radius of the wind turbine blade.

Dividing Equation (4) by the flow power, the power coefficient of the turbine is obtained (C_p):

$$C_p = \frac{P}{P_{esc}} = \frac{\int_r^R \Omega\, dQ}{\frac{1}{2}\rho\pi R^2 U^3}\,. \quad (5)$$

According to the Betz theory [5], the maximum possible value for C_p is 0.593.

2.2 Analysis of variables

Wind turbine blades are made mostly of reinforced fiber laminated composite materials. In these materials, layers with fibers in different orientations are stacked and bonded to generate high mechanical strength and stiffness in different directions. Then, in order to obtain the desired properties for a given loading, a suitable stacking sequence of plies can be chosen [7].

The equation that represents the relation of the normal loads to the plane (**N**) and moments (**M**), with the normal displacement (**ε**) and the medium plane curvature (**κ**) of a laminate composite material is given by:

$$\begin{Bmatrix} \mathbf{N} \\ \mathbf{M} \end{Bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\varepsilon} \\ \boldsymbol{\kappa} \end{Bmatrix} \tag{6}$$

where the submatrices **A**, **B** e **D** form the stiffness matrix of a laminate, also known as ABD matrix. The components of this matrix depend on the elastic properties of the plies, their thickness, the amount of plies and the stacking sequence (sequence and ply orientation). Each term of the matrix represents a deformation mode of the laminate, and the component that allows to apply the aeroelastic tailoring technique are the bend-twist terms (D_{16} and D_{26}) [7].

Thus, for the same loading, different laminate configurations generate different torsion angles. This torsion obtained through the finite element model, changes the angle of attack of each wind turbine blade section, which is used in the calculation of turbine C_p. This way, in order to assess the blade behavior over its application range, the output variable is defined to be the sum of C_p of three different speeds above the nominal speed of the wind turbine blade, in this study case, the nominal wind speed is 10 m/s. So, the wind speeds used to evaluate the sum are 13, 15 and 20 m/s. Figure 4 represents the analysis in the form of an optimization problem.

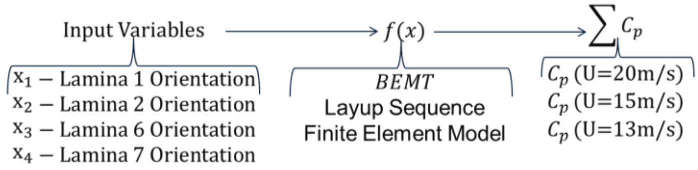

Figure 4. Objective function detail

2.3 Design of experiments (DoE)

The DoE aims to obtain as much information as possible using a limited number of experiments. In projects where several variables are evaluated and a complex metamodel shall be constructed, it is recommended that the DoE also include points inside the domain. This is important when the metamodel is complex and unknown. This type of approach is widely used in non-parametric metamodels [8].

In the Latin hypercube, technique used in this work, each input variable is divided in n non overlapping intervals of equal probability, where n is to total amount of samples desired. A value within each interval is selected in a random way. The n values of the first variable are associated with n values of the second variable. These n pairs are randomly combined with n values of third variable to form n trebles, and so on [9]. This work adopted 8 samples as an initial set of points.

2.4 Metamodel construction

In situations where the function to be optimized have high complexity and considerable evaluation time, the optimization can be unfeasible, even by computational resources or due to the time. In this cases, an alternative is to use a surrogate model to replace the original function. A surrogate model generates an approximate function, which gives a result very close to the original model. The relation between the original function, surrogate model and the approximation error can be given by:

$$f(\boldsymbol{x}) = \hat{f}(\boldsymbol{x}) + \delta(\boldsymbol{x}) \tag{7}$$

where $f(\mathbf{x})$ is the response of the function or original model for a certain point within the project domain, $\hat{f}(\mathbf{x})$ is the surrogate model response and $\delta(\mathbf{x})$ is the error [9].

There exists several techniques that could be used to build a metamodel. This work adopt the KRG, which build the surrogate model through the interpolation of a database and a stochastic component that is explored in global optimization processes.

The KRG models consists in two components. The first one is a simple model that captures the data tendency, the second one measures the deviation between the model and the original function. The KRG can be written as:

$$\hat{f}\,(\boldsymbol{x}) = \mathrm{F}(\boldsymbol{x}) + z(\boldsymbol{x}) \tag{8}$$

where $\mathrm{F}(\boldsymbol{x})$ is a regression model and $\mathrm{z}(\mathbf{x})$ represents a deterministic response to the input vector $\boldsymbol{x}$. More details about the KRG are described in literature by several authors [10-13].

2.5 Metamodel optimization and verification

After the construction of the surrogate model, new points are added in the most promising regions to find the global optimum of the function, thus, improving the surrogate model accuracy in these regions, these points are known as infill points. Several methods can be used to determine these additional points. The present work uses the expected improvement method described by Forrester, Sóbester e Keane [10]. In this method the infill points are selected through the expected improvement function, where the improvement for a vector $\boldsymbol{x}$ for a Gaussian function is given by:

$$E[I(\boldsymbol{x})] = \left(y_{min} - \hat{y}\,(\boldsymbol{x})\right)\Phi\left(\frac{(y_{min}-\hat{y}\,(x))}{s(x)}\right) + s\phi\left(\frac{(y_{min}-\hat{y}\,(x))}{s(x)}\right) \tag{9}$$

where $\Phi(.)$ and $\phi(.)$ represent the cumulative distribution of the function and the probability function respectively; y_{min} is the optimum point so far; $\hat{y}\,(\mathbf{x})$ is the predicted value in $\mathbf{x}$ and s the predicted error of the surrogate model. At each iteration several candidate points different from the original dataset are generated, the value of Equation (9) of these points is then evaluated and the point with the highest value is selected as the next infill point. This point checked with the original model and the surrogate model is successively updated until the maximum number of accesses allowed to the experiment is reached. The technique has some particularities that avoid the assessment in regions outside of the domain. Details of the methodology can be found in [10].

3 Results and discussion

The combined application of the techniques described in Section 2 allows to obtain a proposal of a layup sequence for wind turbine blade with optimum power coefficient. Figure 5 presents the result of the objective function per iteration. The first 8 dots are originated by the simulations of the samples generated by the DoE and the other dots are results of the sequential refinement. The best value of the objective function obtained for the DoE points is 1.510. In the sequential refinement and optimization phase, the maximum value found is 1.519.

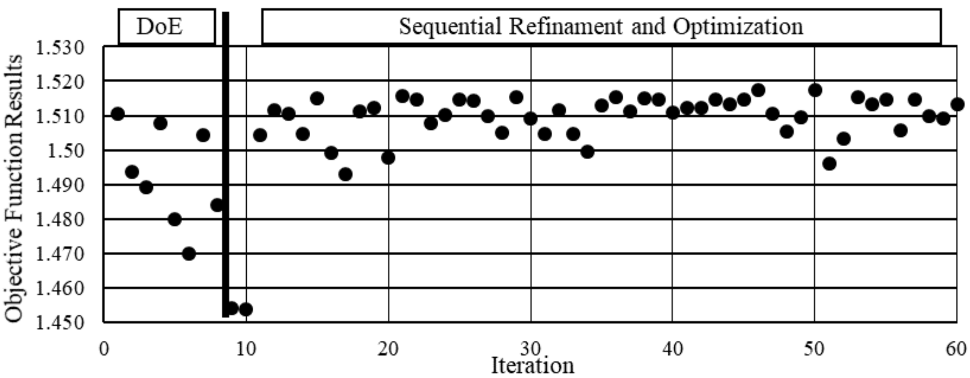

Figure 5. Response of the objective function in each iteration

In order to verify the surrogate model accuracy, the difference between the predicted value of the metamodel and the observed value in each iteration of the sequential refinement phase is calculated, these values are represented in Figure 6. It is possible to notice that absolute errors are very close to zero. Adding to that the fact that the proportional mean error of the iterations is 0.41%, indicating a high accuracy of the surrogate model.

The mean square error is also evaluated and represented in Figure 6. It is possible to notice the convergence to the value of 0.0001 after 50 iterations. Therefore, after iteration number 50 the addition of new assessments of the experiment no longer contributes significantly to improve the metamodel accuracy.

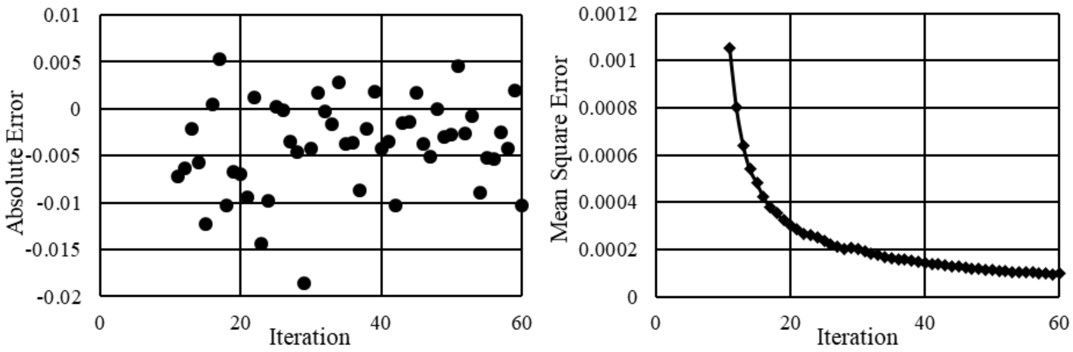

Figure 6. Absolute error and mean square error per iteration

The speed and accuracy of KRG surrogate model in the optimization of composite structures is also verified in the works of Lanzi and Giavotto [12] and Nik et al. [13]. In these analysis the feasibility of representing structural problems of laminate composite structures through KRG technique with high reliability is observed.

The efficiency of the sequential refinement and optimization through the expected improvement technique are verified in [11], where the best point of a composite structure was found after about 30 iterations. Thus, the values obtained in the present work of absolute error, mean square error and the low number of iteration to achieve the optimum value of the function confirm the method efficiency also obtained in the works [11-13].

In order to evaluate the efficiency of the proposed methodology, it is applied ten times consecutively to the proposed problem, in each application a new set of starting points (DoE) is generated. Thus, it is possible to verify the real gain of using the methodology proposed in this work. The mean improvement obtained compared to best value found in the DoE was 0.41% in the power coefficient. Therefore, a wind turbine blade with an optimum laminate configuration generates, on average, 0.41% more energy only by having their layup sequence changed.

Among the 10 analyses carried out, the laminate configuration that presented the lowest and highest values of $\sum C_p$ were selected, named Laminate 1 and Laminate 2, respectively. The C_p curves of these laminates are represented in Figure 7, it is possible to notice that the proper application of the aeroelastic tailoring can give considerable gains in the design of a laminate wind turbine blade for wind speeds above the design nominal speed (10 m/s). Considering the wind speed of 13 m/s the difference can reach 2.2%, at a wind speed of 15 m/s this difference is 3.4%, finally, considering 20 m/s this difference can reach 8.2% between laminates. Therefore, this justify the need of applying and developing a methodology that speeds up the optimization design of composite wind turbine blades.

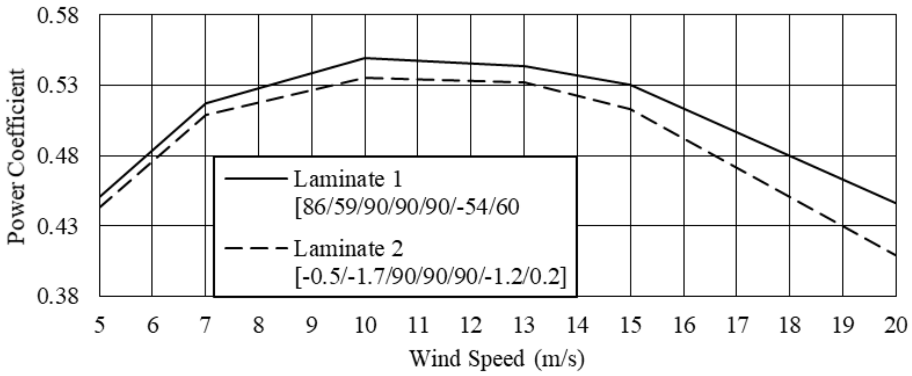

Figure 7. C_p curves in relation to wind speed of the best and worst laminate configuration

The increase in the power coefficient obtained using the aeroelastic tailoring concepts support the results of the work of Maheri, Noroozi e Vinney [14]. In this work, a similar methodology was applied seeking to take advantage of the benefits provided by bend-twist coupling in wind turbine blades, the analysis goal was to relieve the maximum load with the passive control in order to be able to increase the rotor diameter thus increasing the power generated. The improvement in the average power generated by the turbine reached 15.5%, supporting the potential for gain that exists when applying the aeroelastic tailoring.

4 Conclusion

The methodology proposed by Wang and Shan [3] was adapted here and applied to optimize the layup sequence of a composite wind turbine blade. The results were considered satisfactory. One of the main issues to find optimal layup sequences of wind turbine blades is the high computational cost, however, the proposed methodology seems to have overcome this issue allowing to obtain the optimum sequence after about 50 computational experiments (simulations).

Moreover, the KRG proved to be a quite suitable method for this application, presenting good accuracy in predicting the results of the finite element model, thus a fast and accurate assessment of the finite element model over the entire domain is possible with high reliability.

Finally, it is noted that the application of the aeroelastic tailoring concepts can generate C_p gains at wind speeds higher than the nominal design speed. This value grows continuously as the wind speed increases, the difference between applying the aeroelastic tailoring concepts and a wind turbine blade with an inefficient layup sequence can reaches 8.2% at higher wind speeds.

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