Eigenfrequency Optimization of a Wind Turbine Blade Based on Material and Fiber Orientation

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ABSTRACT

This study presents a framework to design eigenfrequencies of wind turbine blades with material constraints for avoiding resonance in a given interval. To this end, the spar caps and webs of the 10 MW DTU blade design is selected to optimize using Decoupled Discrete Material Optimization (DDMO). The optimization objective is designing of the eigenfrequencies of the wind turbine blade. The framework can be used to maximize the fundamental or higher order eigenfrequencies. The design variables are piecewise patch orientations and material properties of the fiber reinforced composites for the spar caps and webs as the load-carrying component. In the design process, a volume constraint of carbon fiber reinforced polymer (CFRP) can be imposed on composite laminates of the spar caps and webs. To overcome the non-differentiability issues of the eigenfrequencies, the Kreisselmeier–Steinhauser function is used in the optimization framework. The framework is able to use non-convex and convex sequential approximation optimization to reduce the computational cost. The numerical results show that the proposed framework is suitable for material and fiber orientation optimization of composite laminates structures with eigenfrequency objective.

KEYWORDS: *Decoupled Discrete Material Optimization (DDMO), Wind turbine blade, Variable stiffness composite structures, Material and fiber orientation Optimization.*

1 INTRODUCTION

One of the key parts of the wind turbine is the blade to absorb wind energy. The blade should be light to harvest wind energy in low wind speed, in addition it should withstand extreme environmental conditions. Wind turbine blades are primarily made of Glass Fiber Reinforced Polymer (GFRP). Nowadays, the use of Carbon Fiber Reinforced Polymer (CFRP) is increasing due to interest of larger blades, where this leads to higher cost compared to GFRP. The structural performance of a wind turbine blade can be improved using the hybrid composite which is a combination of GFRP and CFRP. The hybrid composite is a type of Variable Stiffness Composite Laminates (VSCL) that allows tailoring the stiffness in a structure [1,2]. This stiffness variation may be discrete described by several patches with different fiber angle orientation or/and material properties. Therefore, CFRP can be only allocated to parts of a structure where it needs high stiffness properties. However, an optimization framework is required to tailor stiffness of a structure carefully to maximize the structural performance. Metaheuristic methods are limited to low number of design variables. Gradient based optimization methods are commonly used when there are high number of design variables. Ghiasi et al. (Ghiasi et al., 2009, Ghiasi et al., 2010) published a review of the state of the art on the optimization of laminated composite structures. Discrete Material Optimization (DMO) is an efficient method to design material and fiber orientation of composite structures. This method is a generalization of multi-phase topology optimization problems (Sorensen and Lund, 2013) introduced in (Stegmann and Lund, 2005). In this method, the discrete design variables are converted into continuous design variables to be used for gradient-based optimization approaches. A set of discrete candidate materials is defined over a structural domain by means of material interpolation techniques. The candidate materials can be fiber reinforced composite materials with different orientations or different material properties in the optimization process. DMO is computationally expensive in the optimization problem with the high number of design variables. This problem is more critical when the design variables of the optimization are material, orientation and topology optimization, simultaneously. In (Sohouli et al., 2017b, Sohouli et al., 2017a), a Decoupled DMO (DDMO) approach was introduced to obviate simultaneous optimization of material, orientation and topology. The material optimization step is separated from fiber orientation step in each optimization loop in this approach. This leads to decrease the number of design variables and improve the convergence problem in DMO.

In the present work, the application of the framework is tested on optimization of a wind turbine blade. The objective function is the maximization of the first eigenfrequency of the blade. Variable stiffness composite laminates have been achieved through putting unidirectional patches with different fiber orientation and material. The approach can be also used for higher order eigenfrequencies.

2 DECOUPLED DISCRETE MATERIAL OPTIMIZATION

The Discrete Material Optimization (DMO) is inspired from structural topology optimization. This approach increase a binary selection between solid and void to a number of distinct materials for the design domain. The design variable can be defined for each patch which it may cover a number of elements in a structure. In DMO schemes, the formulation of the constitutive matrix E_p for each patch is given as:

$$E_p = E_0 + \sum_{c=1}^{nc} w_{c,p}\left(E_{c,p} - E_0\right) \qquad \forall p \tag{1}$$

Here E_0 is a low stiffness material to ensure positive definiteness for E_p. $E_{c,p}$ is the constitutive tensor for the c^{th} candidate material and the p^{th} patch, nc is the number of design variables or materials for each patch. $w_{c,p}$ is the weights of the c^{th} candidate material and the p^{th} patch. The objective of the DMO technique is set to one for a single weight and to zero for all other weights for each patch.

A new formulation is defined in Decoupled Discrete Material Optimization (DDMO) that the optimization step is implemented at two levels. Thus, the number of design variables nc is divided into the number of candidate fiber orientations no and the number of candidate materials nm. Two types of weight functions are required according to this definition. In the material optimization step, the formulation of the constitutive matrix E_p for each patch is given as:

$$E_p = E_0 + \sum_{m=1}^{nm} \varrho_{m,p}\left(\Delta E_{m,p}\right) \qquad \forall p \tag{2}$$

$$\Delta E_{m,p} = \begin{cases} \sum_{o=1}^{no} \widetilde{w}_{o,p}\left(E_{m,o,p} - E_0\right) & for \quad m \in \boldsymbol{M}_A \\ E_{m,p} - E_0 & Otherwise \end{cases} \tag{3}$$

Here $\varrho_{m,p}$ is the material weight of the m^{th} candidate material and the p^{th} patch. $E_{m,o,p}$ is the constitutive tensor for the m^{th} candidate material, the o^{th} candidate fiber orientation and the p^{th} patch. $\boldsymbol{M}_A$ is set of materials that its fiber orientation should be also optimized in the orientation optimization step, the rest of materials are in the set of $\boldsymbol{M}_I$. The constitutive tensor in the set of $\boldsymbol{M}_I$ for the m^{th} candidate material and the p^{th} patch is represented by $E_{m,p}$. $\widetilde{w}_{o,p}$ is the rescaled fiber orientation weight of the o^{th} candidate orientation and the p^{th} patch and given by:

$$\widetilde{w}_{o,p} = \frac{w_{o,p}}{\sum_{o=1}^{no} w_{o,p}} \tag{4}$$

Where $w_{o,p}$ is the fiber orientation weight of the o^{th} candidate orientation and the p^{th}patch. The rescaled fiber orientation weights are considered constant in the material optimization phase, and the material optimization weights are optimized in this step. In the orientation optimization of DDMO, the constitutive matrix E_p for each patch is represented as:

$$E_p = E_0 + \zeta_p \sum_{o=1}^{no} w_{o,p}\left(E_{o,p} - E_0\right) \qquad \forall p \tag{5}$$

$$\zeta_p = \frac{\sum_{m \epsilon M_A} \varrho_{m,p}}{\sum_{m=1}^{nm} \varrho_{m,p}} \tag{6}$$

Here ζ_p is the rescaled material weight of the p^{th} patch. $E_{o,p}$is the constitutive tensor of one of the candidate materials in the set of M_A, the o^{th} candidate fiber orientation and the p^{th} patch. In the orientation optimization step, the fiber orientation weights are optimized by considering rescaled material weight as constant values.

3 PROBLEM FORMULATION

The objective function is the maximization of the minimum eigenfrequency of composite structures. The finite element formulation of the eigenvalue problem is defined as:

$$(\boldsymbol{K} - \omega_s^2 \boldsymbol{M})\boldsymbol{\Phi}_s = \boldsymbol{0}, \qquad \forall s = 1, \cdots, n_f \tag{7}$$

Where $\boldsymbol{K}$ and $\boldsymbol{M}$ are the stiffness and mass global matrices. The number of degrees of freedom is represented by n_f. In the above equation, the eigenfrequencies $\boldsymbol{\omega} = \{\omega_1, \ldots, \omega_{n_f}\}$ has the corresponding eigenvectors $\boldsymbol{\Phi} = \{\Phi_1, \ldots, \Phi_{n_f}\}$. The Solid Isotropic Material with Penalization (SIMP) scheme reported in (Bendsoe and Sigmund, 1999) is used to interpolate the mass density. In the material optimization step, the mass density ρ_p for each patch is given as:

$$\rho_p = \sum_{m=1}^{nm} x_{m,p} \rho_{m,p} \qquad \forall p \tag{8}$$

here $\rho_{m,p}$ is the mass density of the m^{th} candidate material in the p^{th}patch. In the orientation optimization step, the mass density for each patch is calculated as:

$$\rho_p = \rho_{o,p} \sum\nolimits_{m \epsilon M_A} x_{m,p}, \qquad \forall p \tag{9}$$

Where $\rho_{o,p}$is the mass density of one of the candidate materials in the set of M_A, the o^{th} candidate fiber orientation and the p^{th} patch. It is assumed that the eigenfrequencies are ordered such that $\omega_1 \leq \cdots \leq \omega_{n_f}$. The optimization problem can be stated through the Kreisselmeier–Steinhauser (KS) function described in (G. and R., 1979) for the material optimization step as:

$$Objective: \quad \max \ \underline{KS}(x)$$

Subject to:

$$f_1(x) = \sum_{p=1}^{np} v_p \sum_{m=1}^{nm} \varrho_{m,p} \mu_c \leq \overline{m} \tag{10}$$

$$\sum_{j=1}^{np} f_j(x) = \sum_{p=1}^{np} \sum_{m=1}^{nm} x_{m,p} = 1; \quad \forall (p)$$
$$x_{m,p} \in [0; 1]; \quad \forall (m, p)$$

The optimization problem at the orientation level is defined as follows:

$$Objective: \quad \max \ \underline{KS}(x)$$

Subject to:

$$\sum_{j=1}^{np} f_j(x) = \sum_{p=1}^{np} \sum_{o=1}^{no} x_{o,p} = 1; \quad \forall (p) \qquad (11)$$
$$x_{o,p} \in [0; 1]; \quad \forall (o, p)$$

$\underline{KS}(x)$ is the Kreisselmeier–Steinhauser (KS) function to optimize the eigenfrequencies of the composite structures. The KS function is used as a differentiable function. $\underline{\boldsymbol{\omega}} = \{\omega_1, \ldots, \omega_{ng}\}$. is defined as a subset of $\boldsymbol{\omega}$, which is also in ascending order as $\omega_1 \leq \cdots \leq \omega_{ng}$. The subset of $\underline{\boldsymbol{\omega}}$ is a group of ng eigenfrequencies to maximize. Thus, the KS function may be defined by:

$$\underline{KS}(x) = \omega_{ng}(x) - \frac{1}{\beta_s} ln\left(\sum_{g=1}^{ng} e^{-\beta_s(\omega_g(x) - \omega_{ng}(x))}\right) \qquad (12)$$

Where the value of the parameter β_s is chosen one.

The Sequential Approximate Optimization (SAO) technique is used to assure a reasonably fast optimization. The convex exponential approximation is used to approximate the primal sub-problem. The optimization solver is L-BFGS-B (Byrd et al., 1995), which is a limited-memory quasi-Newton code for bound-constrained optimization.

4 WIND TURBINE BLADE DESIGN

In this study, the DTU 10MW RWT blade is chosen as the reference blade (Bak et al., 2013). During the optimization process, the material and fiber orientation of a selected part of the caps and the webs are designed while the material and fiber orientation of other parts have the same designs as the DTU 10MW RWT blade. The selected part of the spar caps and the webs are shown in Figure 1. The webs and caps are divided into 70 patches along the Z-direction.

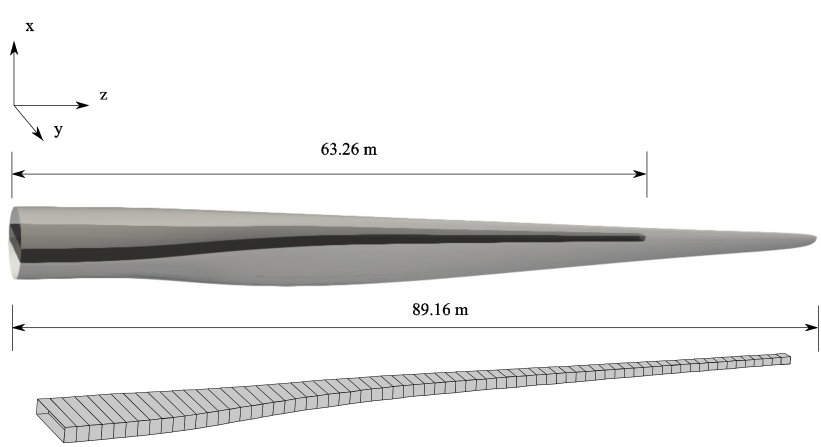

Figure 1: Design domain of the blade in the deterministic optimization analysis.

One of the spar caps is selected to be designed and the second spar cap follows the Circumferentially Uniform Stiffness (CUS) configuration. The selected caps are divided into 8 layers with the same thickness of the caps of the DTU 10MW RWT blade. The 8 layers is assumed to be symmetrical as depicted in Figure 2. The webs of the reference blade have a core layer which is balsa wood. The total thickness and the core thickness are considered to have the same thicknesses as the reference blade and the remained thickness is divided into 8 layers symmetrically as shown in Figure 2. Since the layers of the spar caps and the webs are symmetrical, the number of patches in the optimization process is 840 for all layers of the caps and the webs.

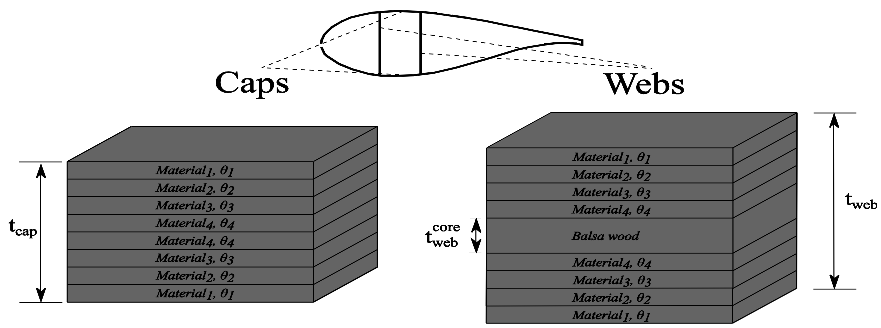

Figure 2: Description of the layers of caps and webs for the selected design space.

In this study, the composite materials of the design domain are unidirectional Carbon Fiber Reinforced Polymer (CFRP) and unidirectional Glass Fiber Reinforced Polymer (GFRP) given in Table 1. The non-design domain of the blade has the same material as the reference blade in (Bak et al., 2013).

Table 1: Material Properties of the blade.

Property	Unit	Candidate materials of the design domain	
		CFRP	GFRP
Longitudinal modulus E_1	GPa	123.13	42.01
Transverse modulus E_2	GPa	8.45	13.38
In-plane shear modulus G_{12}	GPa	3.89	5.02
Transverse shear modulus G_{23}	GPa	3.04	5.02
Major Poisson's ratio υ_{12}	-	0.27	0.28
Minor Poisson's ratio υ_{23}	-	0.39	0.33
Mass density ρ	kg/m^3	1486	1882

5 RESULTS

The optimal materials and fiber orientations of the wind turbine blade are designed to maximize the first eigenvalue. The candidate materials are CFRP and GFRP in the material optimization step. The candidate orientations are four fiber orientations, $\theta = \{-45^\circ, 0^\circ, 45^\circ, 90^\circ\}$ in the orientation step. In the material optimization step, the number of design variables is 1680, while the number of design variables in the orientation optimization step is 3360. The allowable CFRP volume should be 20% of the total volume of the design domain. Figure 3, Figure 4, and Figure 5 show the optimal design of the blade with the volume constraint of 20%. It can be seen from the figures that the orientations of the caps are mostly aligned along the blade direction. The orientations of the caps are only aligned to the normal direction of the blade at the sections close to the root. CFRP as the stiffer candidate material is mostly distributed in the spar caps of the blade. The webs of the blade tend to be ±45° angles with CFRP close to the tip location. The optimization history of the first and second frequencies are shown in Figure 6.

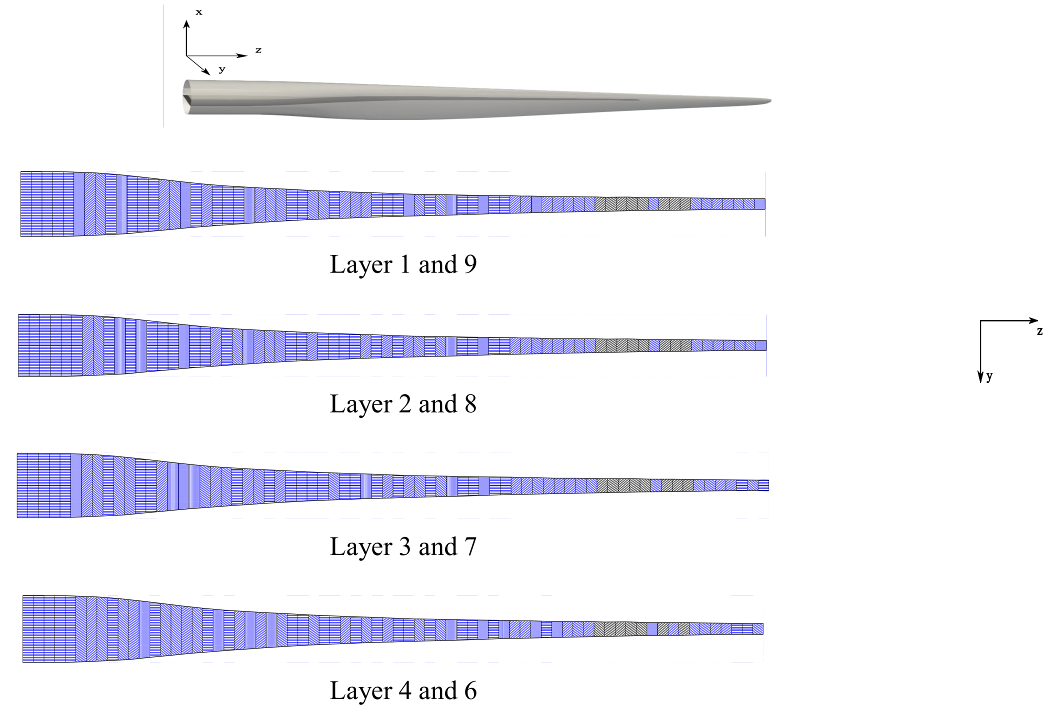

Figure 3: Optimal layout of the web A.

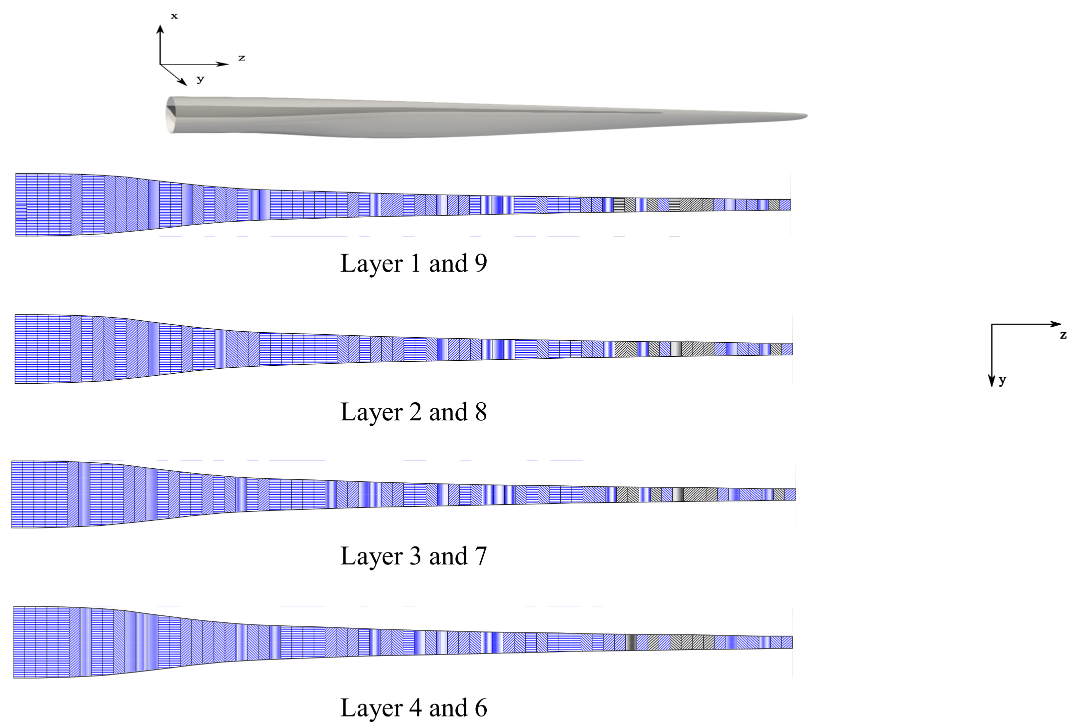

Figure 4: Optimal layout of the web B.

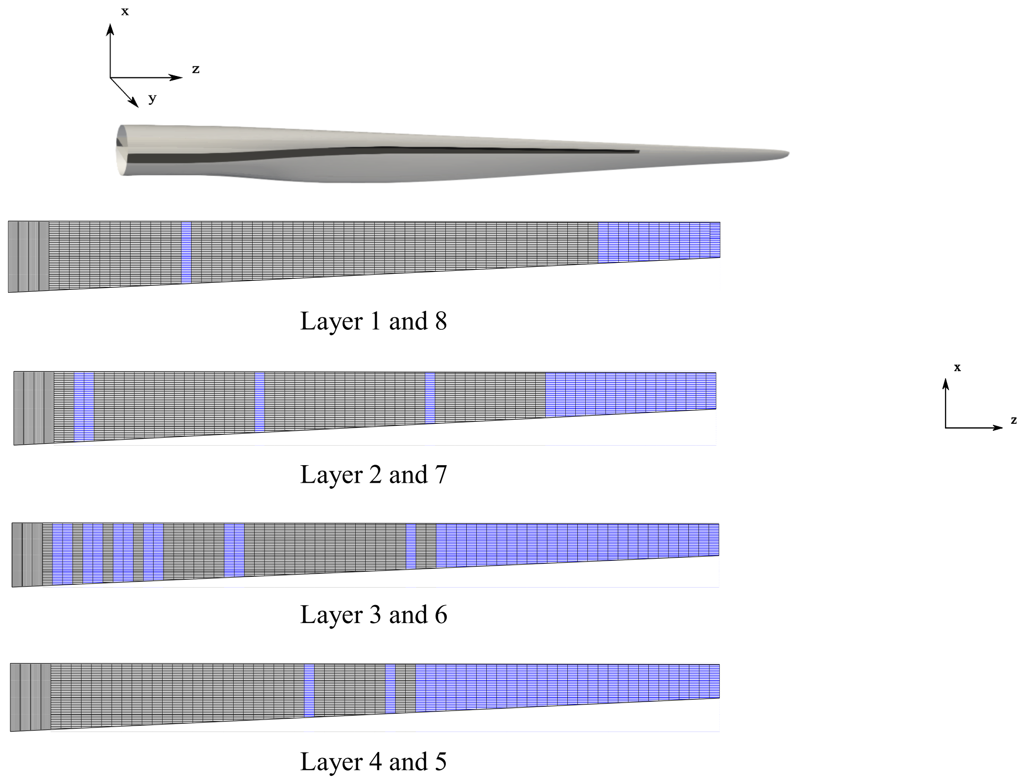

Figure 5: Optimal layout of the spar caps.

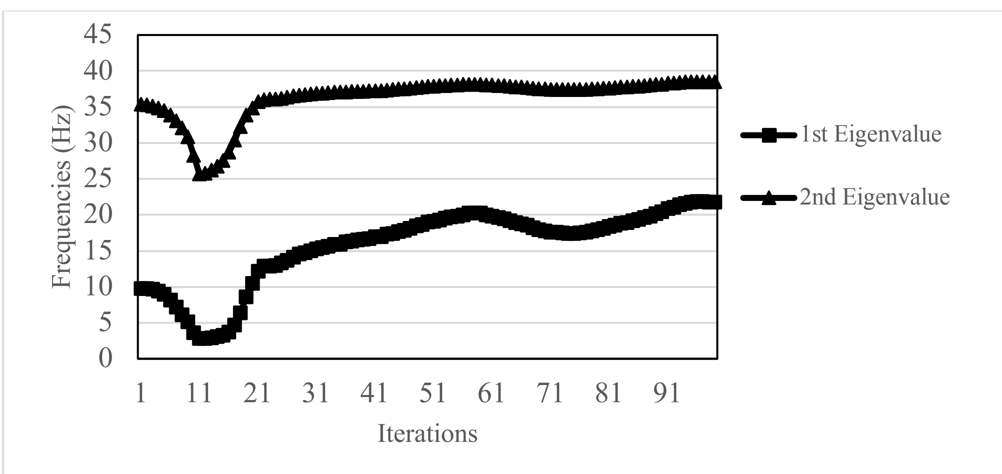

Figure 6: The optimization history of the first and second eigenvalues.

6 CONCLUSION

In this study, a computational framework employing Decoupled Discrete Material Optimization was used to design the material and fiber orientation of a blade. The 10 MW DTU blade was chosen as the case study. The framework has been used to maximize the fundamental eigenfrequency of laminated hybrid composite structures. The Kreisselmeier–Steinhauser function was employed to overcome multiple eigenfrequencies. The results show that the structural performance could be improved significantly by distributing the stiffer material in some load-carrying sections of the wind turbine blade. Also, it was shown that the optimization framework can be an efficient design tool to optimize material and orientation of fibers in composite structures for automated patch placement machine.

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