Lightweight optimal rotor design of a 10MW-scale wind turbine using passive load control methods

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Abstract. The present paper investigates the potential to reduce the mass of the blade of the 10MW DTU Reference Wind Turbine through build-in, material bend-twist coupling (BTC). It is materialized by introducing an offset angle on the plies of the uni-directional material over the spar caps of the blade. Optimum BTC designs are obtained on the basis of an integrated optimization framework combining an aeroelastic solver for the calculation of the structural loads of the blade and a cross-sectional tool that provides beam-like structural properties of the blade and stresses distributions. The derived designs are verified based on a subset of representative fatigue and ultimate design loads cases of IEC 61400-1. Reduction of the combined bending moment at the root of the blade by 5\% and reduction of the blade mass by 10\% is achieved with a hybrid model consisting of three span-wise segments having different constant ply offset angles.

1. Introduction
Up-scaling of modern turbines to ratings up to or even beyond 20MW, requires technological breakthroughs and innovative turbine concepts that combine new advanced materials, hybrid manufacturing methods, new inner structure designs beyond the standard spar concept, new high performance thick airfoils and active or passive aero-elastic control techniques. Among the above options, passive control methods have attracted a lot of attention and they have been proven very efficient in reducing loads \cite{1}. Such passive methods of controlling loads have been described by the wind scientific community through the term “Aero-elastic Tailoring”. Aero-elastic Tailoring is a design technique through which geometric and/or stiffness properties of an aerodynamic structure are matched with its aerodynamic characteristics in such a way that overall structural loads are reduced. In wind turbine engineering it appears as a passive control design option based for example on Bend-Twist-Coupling (BTC) and aims to reduce blade loading.

By the term BTC we describe the behavior of a structure designed to undergo torsion deformation under the action of bending loads (Figure 1). The resulting change of sectional angle will affect the aerodynamic loading through change in the angle of attack. Modern approach to BTC is to twist the blade sections and decrease the angle of attack, which corresponds to the so call twist-to-feather concept. BTC can be either material based, by introducing an offset angle on the plies of the uni-
directional (UD) material over the spar caps of the blade (Figure 2), or geometry based, by sweeping the elastic axis of the blade with respect to the pitch axis.

The focus of the present paper is on material based BTC. Lobitz and Veers from the SANDIA laboratories group [2], [3] were the first who investigated the possibility to passively reduce loads through material BTC. They reported fatigue load reduction of 10-20% for the coupled blades and a slight decrease in the annual energy production (AEP) of the turbine, which was compensated by re-twisting the blade. Extensive work on material BTC has been also performed by the Technical University of Denmark (DTU). Fedorov [4] experimentally and numerically investigated the possibility to use material based BTC on commercial wind turbine blades, while Stäblein [5] numerically assessed fatigue load reduction levels on BTC blades, reporting an annual reduction of blade root flapwise moment of about 15% but also a small penalty in energy output.

Recently, substantial effort has been put by the wind research community in developing integrated, aeroelastic design optimization tools for wind turbine blades. Using such tools, different passive control methods can be integrated into the design of the blade in an optimal manner. Integrated optimization of material BTC blades was first tackled by Bottasso et al [6]. In their work, optimization of the inner structure was performed for different fiber angles on the skin and the spar caps and for different starting spanwise positions wherefrom ply angle re-orientation is performed (partially coupled blades). Croce et al. [7] in addition to fibers’ rotation have also enhanced the coupling between flapwise and edgewise bending directions through the displacement of the spar caps in opposite directions. The authors arrived to the conclusion that if the rotor is resized in order to achieve the same loads as those of the baseline rotor then the levelized cost of energy can be reduced by about 3%. Integrated optimization work on BTC blades has been also performed by DTU. Zahle et al [8] developed an integrated design environment based on open source optimization tools and performed concurrent optimization of the blade external shape and inner geometry. Significant passive load alleviation is reported by the authors that allows for a 9% longer blade with an increase in AEP of 8.7%.

BTC load reduction capabilities have been assessed in [9] and [10] considering the DTU 10MW reference wind turbine (RWT) [11]. In [9], material BTC through ply angle re-orientation was addressed without considering any modification on the blade mass. In addition, modeling of the material BTC in the in-house aero-elastic code hGAST [12] was verified based on existing experimental and numerical data. Load reduction of 7–10% and 6–8% of the fatigue and ultimate blade flapwise moments respectively was obtained with moderate ply offset angles (~9-12.5°). In [10], the material BTC was combined with blade sweep and active individual (cyclic) pitch or flap control to assess the reduction capabilities of their concurrent application. Blade mass was slightly increased.
in order to restore flapwise bending stiffness loss due to material BTC but also due to the increased arc-length of the blade in geometric BTC (sweeping). The abovementioned studies focused exclusively on the assessment of the BTC resultant load reduction capabilities (internal structural moments), without investigating their impact on the stresses and in turn on the reduction of the blade mass.

The present work is a follow up of [9] and [10] in which the potential to reduce the mass of a baseline blade by using BTC is assessed. The analysis is again performed for the reference DTU 10MW Wind Turbine (RWT). The optimal design parameters of the BTC blades (i.e. spanwise ply angle distribution) are determined by employing an integrated optimization framework. The maximum mass reduction level is estimated while maintaining maximum stresses along the blade span at the same levels as in the reference blade.

2. Numerical tools

2.1. Multibody servo-aero-elastic analysis tool hGAST

Ultimate load distributions along the span of the blades are obtained through nonlinear time domain aeroelastic simulations of the coupled wind turbine system using the in-house, multibody, FEM, servo-aero-elastic tool hGAST [12]. In hGAST solver, the full wind turbine is considered as a multi-component dynamic system having as components the blades, the drive train and the tower, all approximated as Timoshenko beam structures. Assembly of the above components into the full system is carried out in the framework of the so-call multibody approach. It consists of considering each component separately from the others, but subjected to specific free-body kinematic and loading conditions imposed at the connection points of the components. hGAST can handle BTC beam structures as it can accommodate full 6x6 stiffness matrices. Verification of hGAST code in test conditions that require definition of a fully populated stiffness matrix is performed in [9].

The multibody formulation in hGAST is extended up to the component level. Highly flexible components such as the blades are divided into a number of interconnected “sub-bodies” considered as an assembly of linear beam elements. Large deflections and rotations gradually build up and nonlinear dynamics are introduced by imposing to each sub-body the deflections and rotations of preceding sub-bodies as rigid body – nonlinear – motions. The approach allows capturing the geometrical nonlinear effects due to large deflections and rotations using linear beam theory at the finite element level, but considering nonlinear effects at the sub-body level. Rotor aerodynamics in hGAST are simulated using an elaborated Blade Element Momentum model that accounts for dynamic inflow, yaw misalignment and dynamic stall effect through the ONERA dynamic stall model [13].

2.2. Cross-sectional analysis tool

An in-house cross-sectional analysis tool based on thin lamination theory [14] is adopted for the calculation of the structural cross-sectional properties along the blade span. The tool provides the equivalent beam stiffness and mass characteristics of cross sections with laminated composite skins and shear webs and it is capable of treating the anisotropic behavior of material plies. Therefore it provides fully populated stiffness matrices, taking into account all material driven coupling effects and it can be used for the modeling of BTC blades through ply angle re-orientation. Furthermore, the above cross sectional analysis tool provides stress distributions and values of the Tsai-Wu failure criterion [15] over the different cross-sections of the blade by taking as input structural resultant loads calculated by the aeroelastic analysis tool.

2.3. Optimization framework

The open-source multidisciplinary design analysis and optimization (OpenMDAO) framework [16] is employed. It is a flexible and versatile environment based on Python, which provides necessary interface and tools to set-up multidisciplinary design analysis and optimization problems. In the present work, a gradient-free optimizer has been employed based on genetic algorithms. Genetic
algorithms allow for a wide scanning of the design space and by that ensure that the solution is not trapped in local minima. Furthermore, they are well suited for interdisciplinary problems as they can easier handle non-conventional types of design variables (e.g. string type variables like the code name of an airfoil or a ply sequence).

3. Methodology
The procedure for obtaining maximum mass reduction is divided into two loops, in order to reduce the number of optimization variables and the computational cost:

a) The outer loop which is exclusively handled by the optimizer. It specifies the values of the primary design variables and evaluates the cost function. In the present work, the primary design variables of the optimization problem are the geometric parameters of BTC (i.e. ply angle distribution along the span), while the cost function of the optimization problem is chosen to be the percentage of the blade mass reduction with respect to the baseline blade mass.

b) The inner loop within which an iterative procedure is established that determines the secondary design variables of the optimization problem. Secondary design variables are the laminate thicknesses along the blade span. The inner loop seeks for the minimum thickness values for which the minimum values of the Tsai-Wu failure criterion are at the same level as those of the reference blade. Currently a uniform thickness reduction ratio is considered at every cross section of the blade.

![Flowchart](image)

**Figure 3:** Flowchart presenting the procedure for estimating the optimal BTC distribution in terms of maximum blade mass reduction while maintaining the same minimum Tsai-Wu values with the baseline blade. The dashed box contains the steps of the inner loop.
Every step of the inner iterative procedure consists of the following sub-steps; i) the beam properties of the blade are determined based on the primary BTC design parameters and the secondary laminate thicknesses, ii) the ultimate resultant loads along the blade span are computed and iii) stresses distributions and Tsai-Wu failure criterion values over every cross section of the blade are evaluated. Calculations of steps i) and iii) are performed using the cross sectional analysis tool, while calculation of ultimate loads is based on simulations performed with hGAST aero-elastic solver. When the iteration is concluded, the values of the failure criterion are compared with those of the reference blade and if they are found different a new iteration is initiated considering new thicknesses. The procedure is repeated until convergence in the thickness reduction ratios is achieved. It is noted that before calculating loads, the BTC blades are re-twisted in order to restore power losses due to non-optimum twist distribution (see [9] for more details). The above steps are schematically shown in the flowchart of Figure 3.

The most time consuming part of the optimization process is the estimation of the design loads through the time domain aeroelastic analysis. Thus, in the present work the IEC 61400-1 [17] design load case (DLC) 1.3 (extreme turbulent wind conditions in normal operation), at the wind speed of 13m/s, is only simulated within the optimization loop with the aim to retain the computational cost low. In [9] and [10] the above DLC was found to result in maximum flapwise blade loads. In addition, and in order to further reduce computational cost, every simulation is performed for only 25 s duration. The above 25 s duration is centered around the time instant that ultimate load of the reference blade occurs. Given that the overall blade shape is not altered, peak loads are expected to occur at neighboring time instants. Even though this might not be the ultimate load of the new design it will definitely correspond to a peak load. Hence, reduction of a peak load is already a strong indication that overall the new design exhibits lower loads. The above assumption is verified in the numerical results of section 4 (see the minimum Tsai-Wu value obtained in DLC1.3 at 13m/s in the upper left plot of Figure 9, being almost the same for the three tested blade designs).

4. Numerical Results and Discussion

4.1. Design optimization

Assessment of the mass reduction capabilities through ply angle re-orientation based on the above described methodology is performed considering the DTU 10MW RWT [11]. It is a 3-blade, IEC [17] class IA, pitch regulated, variable speed wind turbine. Its rated power is 10MW, produced at the rated wind speed of 11.4 m/s with the nominal rotational speed of 9.6 rpm. The hub height is 119 m and the diameter of the rotor is 178.3 m. The baseline configuration employs no passive (or active) control.

![Figure 4: Mass reduction of BTC blades as a function of the ply angle (i.e. 5°, 7.5° and 10°) and ply angle offset starting positions (points on the curves correspond to different values of starting positions) (left). Convergence of the inner optimization loop for ply angle offset starting position=0.3 (right). Mass reduction is estimated for given BTC blade parameters (ply angle & starting position) to maintain the Tsai-Wu value of the baseline blade.]
A first estimation of the mass reduction capabilities of the BTC blades is shown in the left plot of Figure 4, obtained by considering fixed values of the ply angles equal to 5°, 7.5° and 10°. In addition, to assess the effect of the ply angle offset starting position (partially coupled blades) ply angle re-orientation is applied at various starting radial positions from the blade root up to about the 2/3 of the span. Every point on the left plot corresponds to a different value of the ply angle offset starting radius. The presented results are derived within the inner optimization loop of the above described procedure, for fixed values of the BTC blades. They correspond to 60 different design points (3 ply angles x 20 starting positions). The maximum mass reduction of the blades is about 8%, obtained for ply angle of 7.5° and starting positions spanning from 25-40% of the blade span. It is noted that positive relative differences correspond to increase of the blade mass, as for example seen in the 10° ply angle case, for ply angle offset starting positions near the blade root. Because the flapwise bending stiffness of the BTC blades decreases for increasing ply angles, the thickness must be increased to maintain the Tsai-Wu value at the same level as compared to the reference blade. The right plot of Figure 4 demonstrates the convergence of the blade mass reduction with the number of the 25s aeroelastic simulations performed. It is found that 4-5 iterations of the inner optimization loop (sets of aeroelastic simulations) are required for convergence.

Next, to obtain the optimum BTC configuration in terms of mass reduction, the full optimization methodology is employed (i.e. the outer loop is activated as well). Four cases are considered regarding the spanwise distribution of the ply angles. In the first three cases the blade is divided into 2, 3 or 4 parts respectively (symbol N denotes the number of parts) of constant ply angle. In every case the ply angle of the first part is set to zero. The forth case considers a theoretical, continuous ply angle distribution given by the following 3-parameter space function,

\[ ply(r; ply_{tip}, r_5, \gamma) = ply_{tip} \left[ 1 - \left( 1 - \frac{r-r_5}{1-r_5} \right)^{\gamma} \right] \]  

where \( r \) is the independent variable denoting the non-dimensional with the blade radius radial position and the three parameters \( ply_{tip}, r_5, \gamma \) denote the ply angle at the tip, the non-dimensional with the blade radius starting position of ply angle offset and the order of the function respectively. Design variables in the first three cases are the values of ply angle and starting positions of the N-1 last parts, while in the latter case the three parameters of the space function.

Figure 5 shows the converged (optimum) values of the design variables and of the corresponding cost function. Specifically, the left plot provides the optimum ply angle distribution along the blade span (design variables), while the right plot presents the corresponding maximum mass reduction percentage of the considered BTC blade configurations (cost function). For \( N=2 \), maximum mass reduction is 8.3% for 6° offset ply angle starting at 25% of the blade span. For \( N=3 \), maximum mass reduction
reduction increases to 10% for offset ply angles of 5° and 7.8° starting at 20% and 50% of the blade span respectively. For N=4 no further significant improvement is obtained. Furthermore, the continuous theoretical distribution defines the upper mass reduction limit with BTC blades. The maximum mass reduction achieved is 10.5%, while the estimated optimum values of the parameters of equation (1) are ply_{tip} = 8.36°, r_s = 6.9% and y = 2.50. It is thus concluded that the configuration with N=3 approaches the maximum theoretical limit. It is also remarkable that the optimum ply angle values of the first three cases are more or less piecewise constant approximations of the continuous function of case 4 as shown in the left plot of Figure 5. The layout of the optimized BTC blade for the case N=3 is shown in Figure 6.

Figure 7 shows the optimum spanwise distribution of the wall thickness ratio which specifies the reduction of the BTC blades mass, for which the Tsai-Wu minimum value of the baseline configuration are maintained. It is noted that cases N=3, N=4 are almost identical with the continuous theoretical one. In Figure 8 the convergence of the outer optimization loop is shown for the case N=3. The values of the design variables and cost function are presented versus the performed optimization iterations. For the case N=3, 35 optimization iterations are required to obtain the optimum design parameters, while for N=2 about 25 iterations given that the number of the design variables is reduced.

4.2. Design verification

The BTC designs with N=2 and N=3 are verified in this section through aeroelastic simulations of a
representative subset of IEC 61400-1 [17]. The first (N=2) is the standard BTC option addressed in the existing literature, with a uniform ply angle offset starting at 25% of the span. The second (N=3) is a slightly more complex design with lower ply offset angle at the blade inner part and higher at the outer (see Figure 6), which however allows for almost 2% additional mass reduction. Manufacturing of both designs is considered feasible.

Verification of the derived designs is performed through IEC DLC simulations using the aeroelastic code hGAST. A representative subset of the IEC DLCs shown in Table 1 is considered. Three realizations of 10 minutes are simulated for each wind speed bin. DLC 1.2 (normal turbulence conditions in normal operation) is considered for assessing fatigue, while DLC 1.3 (extreme turbulence conditions in normal operation) and DLC 6.1, DLC 6.2 (storm conditions in idling) are performed for ultimate load analysis. In stress analysis the safety factors of Table 1 are applied to the maximum resultant loads.

Before proceeding with the time domain analysis the first eight natural frequencies of the coupled DTU 10MW RWT at stand still are checked for the different BTC configurations considered (see Table 2). Frequencies of the baseline configuration and of the two BTC designs (with N=2 and N=3) are compared in the table. For the BTC designs, the percentage relative frequency difference with respect to the baseline turbine is also provided. Tower side-to-side and fore-aft frequencies slightly increase due to the lower rotor mass. The increase in the frequencies of the first tower modes is of the order of 1%. As concerns rotor modes, the frequency of the symmetric edgewise mode increases by 5% and 6.2%, while the frequency of the symmetric flap-wise mode increases by 2.7% and 2.8% for N=2 and N=3 respectively. Rotor asymmetric flapwise modes increase by 3.3%-4.6% and asymmetric edgewise modes by 3.3%-4.1%. It is concluded that the change of the laminate thicknesses and the ply angle re-orientation does not significantly alter the dynamic behaviour of the turbine.

Figure 9 presents the results of the ultimate loads assessment. Comparisons between the baseline DTU 10MW RWT and the BTC configurations with N=2 and N=3 are presented. Plots on the left correspond to IEC DLC 1.3, while plots on the right to DLC 6.1 and DLC 6.2 respectively. The minimum Tsai-Wu values (failure occurs for values <1) of the blade are shown in the upper plots, the maximum combined bending moment at the blade root in the middle plots and the maximum combined bending moment at the base of the tower in the lower plots. Minimum Tsai-Wu values are obtained for DLC 1.3 at 13m/s for all designs, corresponding to the case considered in the optimization process. The minimum Tsai-Wu value along the whole blade span is shown in the plots.

| Table 1: DLCs definition for BTC blades design verification |
|----------------------------------|----------------|-------------------|--------------|
| DLC | Conditions | Wind speeds [m/s] | Yaw angle [°] | Safety factor [-] |
| 1.2 | NTM | 5-25, step 2 | 0 | |
| 1.3 | ETM | 5-25, step 2 | 0 | 1.35 |
| 6.1 | EWM | 50 | -8, 0, 8 | 1.35 |
| 6.2 | EWM | 50 | ±60, ±45, ±50, ±15 | 1.10 |

| Table 2: Standstill natural frequencies of the baseline DTU 10MW RWT and the BTC designs with N=2 and N=3. Relative percentage differences with respect to the baseline configuration are also provided. |
|----------------------------------|---------------|----------------|--------------|
| Modeshape | Baseline Freq. [Hz] | N=2 Freq. [Hz] | Diff. [%] | N=3 Freq. [Hz] | Diff. [%] |
| 1st tower bending side-side | 0.249 | 0.252 | 1.2 | 0.253 | 1.6 |
| 1st tower bending fore-aft | 0.252 | 0.254 | 0.8 | 0.255 | 1.2 |
| 1st symmetric rotor edgewise/drive-train | 0.515 | 0.541 | 5.0 | 0.547 | 6.2 |
| 1st asymmetric rotor flapwise (yaw) | 0.539 | 0.560 | 3.9 | 0.564 | 4.6 |
| 1st asymmetric rotor flapwise (tilt) | 0.580 | 0.599 | 3.3 | 0.601 | 3.6 |
| 1st symmetric rotor flapwise | 0.633 | 0.650 | 2.7 | 0.651 | 2.8 |
| 1st asymmetric rotor edgewise (vertical) | 0.958 | 0.991 | 3.4 | 0.997 | 4.1 |
| 1st asymmetric rotor edgewise (horizontal) | 0.972 | 1.004 | 3.3 | 1.010 | 3.8 |
All designs depict the same Tsai-Wu value levels at the above conditions, providing a verification of the optimization process. Low Tsai-Wu values close to 1 are also obtained for the BTC blades at DLC 6.2 and wind yaw ±30°. BTC mechanism is not expected to reduce blade loads in idling because flapwise deflections are small when the blades are pitched to feather. It is noted that DLC 6.2 can be also included in the optimization loop in case lower Tsai-Wu values are obtained for BTC blades (not in the present case). Maximum blade root combined moment is obtained for DLC 1.3 at 13m/s for all designs. BTC blades reduce the combined moment by about 5%. Maximum tower base combined moment is obtained in DLC 6.2 at wind yaw ±30°. BTC designs reduce the combined moment of the tower by about 6.6-8.1%.

**Figure 9**: Ultimate load assessment of the baseline DTU 10MW RWT and the BTC configurations with N=2 and N=3 considering the DLC 1.3 (left) and DLC 6.1 and DLC 6.2 (right). Blade minimum Tsai-Wu values (upper plot), maximum combined bending moment at blade root (middle plot) and maximum combined bending moment at tower base (lower plot).

**Figure 10**: Fatigue load assessment of the baseline DTU 10MW RWT and the BTC configurations with N=2 and N=3 considering the DLC 1.2. DELs spanwise distribution of the spar cap mean normal stress (left) and of the blade moments (right).
Fatigue loads are assessed based on the Damage Equivalent Loads (DELs) calculated assuming 20 years lifetime, Weibull parameters $C=11\text{m/s}$ and $k=2$, $10^7$ reference cycles and Wöhler coefficients $m=10$ for the blades and $m=4$ for the steel tower. Figure 10 presents the results of the fatigue load assessment, providing comparisons between the baseline DTU 10MW RWT and the BTC configurations with $N=2$ and $N=3$. The left plot corresponds to the DELs of the spar cap mean normal stress along the span, while the right plot to the DELs of the three blade moments along the span. In Table 3, the DELs of the tower base moments are shown. BTC designs reduce tower DELs by 0.8% and blade DELs by up to 10% (reduction increases towards the root). On the contrary, DEL of the mean stress increases up to 14% at the 75% of the blade span due to the thickness reduction, while near the root it increases by only 2.7%.

5. Conclusions
In the present work, assessment of mass reduction capabilities for BTC blades is performed on the basis of an integrated optimization framework, combining the in-house aero-elastic analysis tool hGAST and a cross-sectional tool based on thin lamination theory. It is found that for the DTU 10MW RWT blades, ply angle in the range of 5°-7.5° starting at 15-30% of blade span can provide overall mass reduction of about 8%. Moreover, a hybrid BTC design in which the ply angles gradually increase toward the tip is addressed (max ply angle ~8deg). Mass reduction of 10% is obtained for the above hybrid configuration. In addition, BTC blades reduce the combined bending moment at the root of the blade by 5% and at the tower base by 6.6-8.1%.

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References
[1] Veers P, Bir G and Lobitz D 1998 Aeroelastic tailoring in wind turbine blade applications, Windpower ’98 AWE association meeting and exhibition, Sandia National Laboratories, Bakersfield, California, USA
[2] Lobitz D and Laino D 1999 Load mitigation with twist-coupled HAWT blades, ASME/AIAA Wind Energy Symposium, Reno, NV, pp. 124–134, DOI: 10.2514/6.1999-33
[3] Lobitz D and Veers P 2003 Load mitigation with bending/twist-coupled blades on rotors using modern control strategies, Wind Energy, vol. 6, no. 2, pp. 105–117, DOI:10.1002/we.74
[4] Fedorov V 2012 Bend-twist coupling effects in wind turbine blades, Technical University of Denmark, Kgs. Lyngby, Denmark
[5] Stäblein A and Hansen M 2016 Effect of turbulence on power for bend-twist coupled blades J. Phys.: Conf. Ser. 753 (2016) 042018, DOI: 10.1088/1742-6596/753/4/042018
[6] Bottasso C, Campagnolo F, Croce A, and Tibaldi C 2012 Optimization-based study of bend–twist coupled rotor blades for passive and integrated passive/active load alleviation, Wind Energy, 2003 16:1149–1166 Milano Italy, DOI: 10.1002/we.1543
[7] Croce A, Sartori L, Lunghini M, Clozza L, Bortolotti P, and Bottasso C 2016 Lightweight rotor design by optimal spar cap offset J. Phys.: Conf. Ser. 753 (2016) 062003, DOI:10.1088/1742-6596/753/6/062003
[8] Zahle F, Tibaldi C, Pavese C, McWilliam M, Blasques J and Hansen M 2016 Design of an
aeroelastically tailored 10 MW wind turbine rotor. J. Phys.: Conf. Ser. 753 (2016) 062008, DOI: 10.1088/1742-6596/753/6/062008

[9] Bagherpour T, Li X, Manolas D and Riziotis V 2017 Modeling of material bend-twist coupling on wind turbine blades. J. Composite Structures 193 (2018) 237-246 (http://dx.doi.org/10.1016/j.compstruct.2018.03.071)

[10] Manolas D, Serafeim G, Chaviopoulos P, Riziotis V and Voutsinas S 2018 Assessment of load reduction capabilities using passive and active control methods on a 10MW-scale wind turbine. J. Phys.: Conf. Ser. 1037 (2018) 032042 DOI:10.1088/1742-6596/1037/3/032042

[11] Bak C, Zahle F, Bitsche R, Kim T, Yde A, Henriksen L, Hansen H, Blasques J, Mac G and Natarajan A 2013 Description of the DTU 10MW reference wind turbine, DTU Wind Energy Report I-0092 (https://dtu-10mw-rwt.vindenergi.dtu.dk)

[12] Manolas D, Riziotis V and Voutsinas S 2015 Assessing the importance of geometric nonlinear effects in the prediction of wind turbine blade loads. J. Computational and Nonlinear Dynamics, DOI: 10.1115/1.4027684

[13] Petot D 1989 Differential equation modelling of dynamic stall La Recherche Aerospatiale paper no. 5, pp:59-72

[14] Saravanos D, Varelis D, Plagianakos T and Chrysochoidis N 2006 A shear beam finite element for the damping analysis of turbulent laminated composite beams. J. of Sound and Vibration 291 (2006) 802-823, DOI: 10.1016/j.jsv.2005.06.045

[15] Tsai S and Wu M 1971 A general theory of strength for anisotropic materials. J. of Composite Materials, vol 5, 58-80, DOI: 10.1177/002199837100500106

[16] Gray J, Hwang J, Martins J, Moore K and Naylor B 2019 OpenMDAO: an open-source framework for multidisciplinary design, analysis and optimization. J. Structural and Multidisciplinary Optimization (2019) 59 1075-1104 (https://doi.org/10.1007/s00158-019-02211-z)

[17] IEC 61400-1, IEC 2003, 188184CDV, edited by TC88-MT1, 25-26 May 2004, pp.26-29, 3rd edition