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Structural Analysis of a Composite Wind Turbine Blade

C. Amer, M. Sahin

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***Abstract*—**The design of an optimised horizontal axis 5-meter-long wind turbine rotor blade in according with IEC 61400-2 standard is a research and development project in order to fulfil the requirements of high efficiency of torque from wind production and to optimise the structural components to the lightest and strongest way possible. For this purpose, a research study is presented here by focusing on the structural characteristics of a composite wind turbine blade via finite element modelling and analysis tools. In this work, first, the required data regarding the general geometrical parts are gathered. Then, the airfoil geometries are created at various sections along the span of the blade by using CATIA software to obtain the two surfaces, namely; the suction and the pressure side of the blade in which there is a hat shaped fibre reinforced plastic spar beam, so-called chassis starting at 0.5m from the root of the blade and extends up to 4 m and filled with a foam core. The root part connecting the blade to the main rotor differential metallic hub having twelve hollow threaded studs is then modelled. The materials are assigned as two different types of glass fabrics, polymeric foam core material and the steel-balsa wood combination for the root connection parts. The glass fabrics are applied using hand wet lay-up lamination with epoxy resin as METYX L600E10C-0, is the unidirectional continuous fibres and METYX XL800E10F having a tri-axial architecture with fibres in the 0,+45,-45 degree orientations in a ratio of 2:1:1. Divinycell H45 is used as the polymeric foam. The finite element modelling of the blade is performed via MSC PATRAN software with various meshes created on each structural part considering shell type for all surface geometries, and lumped mass were added to simulate extra adhesive locations. For the static analysis, the boundary conditions are assigned as fixed at the root through aforementioned bolts, where for dynamic analysis both fixed-free and free-free boundary conditions are made. By also taking the mesh independency into account, MSC NASTRAN is used as a solver for both analyses. The static analysis aims the tip deflection of the blade under its own weight and the dynamic analysis comprises normal mode dynamic analysis performed in order to obtain the natural frequencies and corresponding mode shapes focusing the first five in and out-of-plane bending and the torsional modes of the blade. The analyses results of this study are then used as a benchmark prior to modal testing, where the experiments over the produced wind turbine rotor blade has approved the analytical calculations.

***Keywords*—**Dynamic analysis,Fiber Reinforced Composites, Horizontal axis wind turbine blade, Hand-wet layup, Modal Testing.

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C. Amer, Graduate Student, is with the Dept. of Aerospace Engineering, METU, Ankara, 06800 Turkey (phone: +90-543-245-27-38, Fax: +90-312-210-4250, e-mail: e1989086@metu.edu.tr).

M. Şahin, Assoc. Prof. Dr. is with the Dept. of Aerospace Engineering, METU, Ankara, 06800 Turkey (phone: +90-312-210-4256, Fax: +90-312-210-4250, e-mail: msahin@metu.edu.tr).

I. Introduction

IN the project of METUWIND - Center For Wind Energy, the design of aerodynamically optimized and structurally light and reliable rotor blade is the primary aim. For this purpose, a blade is designed according to IEC 61400-2 [1], which includes an internal hat shaped spar beam structure, a joint design at the hub as well as composite shells. In this particular research study, modal analysis and linear static analysis are performed analytically on a 5-m long horizontal axis composite wind turbine blade by using MSC Patran/Nastran commercial finite element software as a tool. First, the required data regarding the general geometrical parts are gathered and then the airfoil geometries are created at various sections along the span of the blade by using CATIA software to obtain the suction and the pressure side of the blade. Following the material property selection, the finite element modelling of the blade is performed via MSC Patran software with various meshes created on each structural part considering 2-D shell type for all the blade surfaces. The boundary conditions are assigned as both fixed at the root - free and free-free for the normal mode dynamic analyses which are aiming to find the first five out-of-plane bending and the torsional natural frequencies and corresponding mode shapes of the blade are performed. In addition to these analyses, blade's mass centre of gravity coordinates, as well as its tip deflection under its own weight is obtained.

II. Analysis Procedures

In this section, the modelling details of the blade including all its surfaces, selection of materials regarding positioning of different staking laminates, as well as the analysis details and the corresponding results are discussed.

A. Geometric Modeling

The geometric modelling of the blade is performed in CATIA environment with the airfoils of the type NACA 23014 (Fig. 1) [2] which are the basis of the drawings provided by the aerodynamic design having each different cord length and twist angle along the blade span of the blade. They start from a pitch down angle (20.6°) at (0.5 m) from the root until reaching the horizontal position at the tip (5 m) and are located at around 10 stations along the span after a cylindrical geometry of diameter (0.289 m) at the root (0-0.2 m). Then, the transition surfaces between the airfoils are designed via "multi-sections surface" tool. After drawing each airfoil in its related position, hat shaped spar position is located for each airfoil cross-section where two shear webs starting from 0.5 m from the root and extending up to 4 m are

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the main load carriers. These two shear webs are also perpendicular to the chord of each airfoil and located at 50% and 85% of the airfoil from the trailing edge chord, respectively. Following this, the width of each of the suction flanges are designated at 7% of the airfoil cord, which is shown in Fig. 2 [3], and all the surfaces of the blade are finalised.

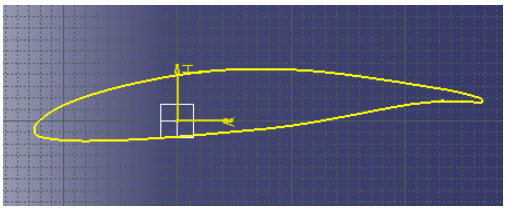


Fig. 1 NACA 23014 airfoil at 3.0 m from the root

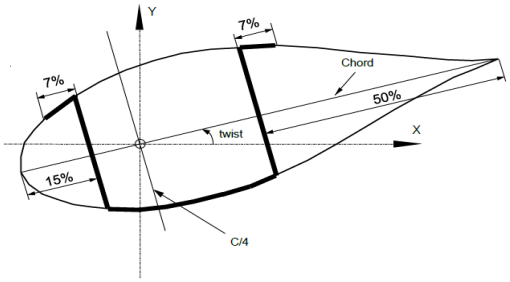
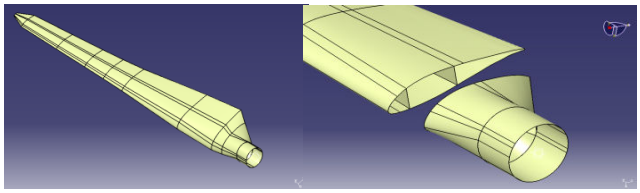


Fig. 2 Spars Positioning

1. Blade Solid Modelling

The modelling of the blade is obtained as mentioned by using surface geometries following the airfoil drawings at different sections and the transition areas in between. Each surface section of the design has its specific material lamination properties. By taking this in consideration, the airfoil positions are chosen precisely to divide the areas as desired and shown in Fig. 3. In other word, the area at the root part, including the skin and the shear webs, has a thicker and stronger cross-section to handle a bigger moment at this particular station. This layer staking sequences is decreased gradually until having a relatively thinner thickness at the blade tip, in order to prevent delamination due to thickness discontinuity in composite materials and to conserve an optimum engineering stiffness, elastic stability, strength, and natural frequencies in the design.



(a) (b)

Fig. 3 Blade Solid Model (a) Isometric view (b) Cross-sectional zoom view

2. Root Part Solid Modelling

At the root, inside the composite cylindrical part, there exists a hub joint steel frame having an outside diameter of 273 mm and 12 hollow studs located at a diameter of 245 mm. The studs are of length of 200 mm and 24 mm in diameters with internal thread that are held equidistant by means of two steel perforated annular disks. They are of M16x1.5 type quality 8.8 and they are distributed along the bolt hole circle of the hub as seen in the (Fig. 4) The steel frame structure after its placement in the blade root is covered with adhesive putty, balsa wood and glass fibre reinforced plastic unidirectional (UD) strips.

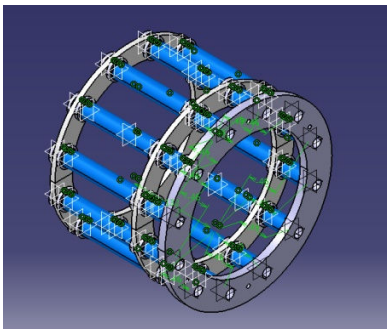


Fig. 4 The Hub Joint Steel Frame

B. Material Modeling

The basic materials that are used are in the analyses comprise; Two glass fabrics which are to be applied using hand lay-up wet lamination with Epoxy resin, namely; METYX L600E10C-0 of 623 g/m^2, is unidirectional with parallel continuous fibres and METYX XL800E10F-[0/45/-45] of 835 g/m^2, is a tri-axial architecture with fibres in the 0, +45° and -45° directions in a ratio of 2:1:1. Polymeric foam, is the commercial Divinycell H45 of DIAB group as core material in sandwich constructions, and steel. For the surface finishing two protection materials are used; transparent gel coat and a layer of chopped strand mat, 300 g/m^2 CSM 300. The properties of each are shown in Table 1 [4].

TABLE I
BASIC MATERIAL PROPERTIES

Property	(UD)	Divinycell H45	Steel	Gel Coat	CSM 300
ρ [kg/m^3]	1896	48	7850	1200	1896
E_1 [GPa]	24.84	55.10^{-3}	210	3.98	9.14
E_2 [GPa]	9.14	55.10^{-3}	-	-	-
G_{12} [GPa]	2.83	15.10^{-3}	-	-	-
ν_{12}	0.29	0.4	0.3	0.34	0.29

The symbols chosen are defined as follows; ρ = density, E_1 = Young Modulus in direction 1, E_2 = Young Modulus in direction 2, G_{12} = Shear Modulus, ν_{12}= Poisson ratio, UD = unidirectional.

A surface section in the interval labeled as D3 (Fig. 5) is chosen as an example for a lamination stacking sequence (Figs. 6, 7) at the blade upper surface where all section properties and dimensions are given in meters [2].

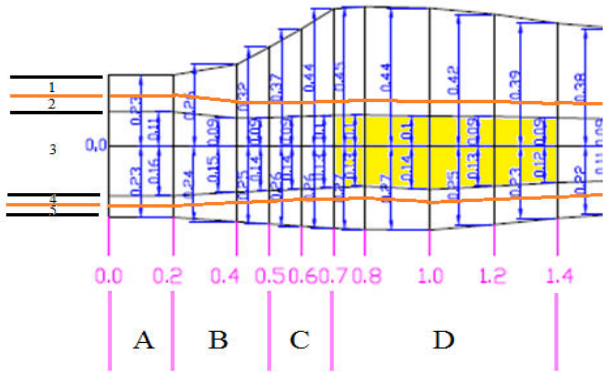
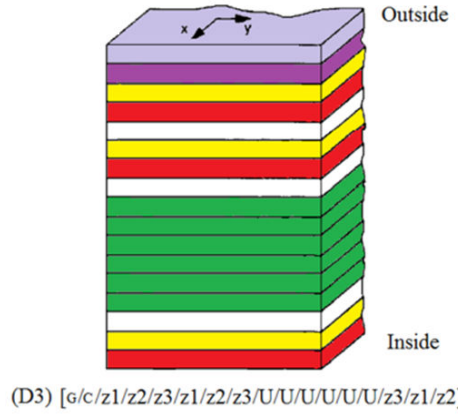


Fig. 5 The Blade Upper Surface Sections

G	gel coat		
C	csm300		
z1	45	(METYx 835g/m2)	
z2	-45	(METYx 835g/m2)	
z3	0	(METYx 835g/m2)	
U	unidirectional	(METY 623g/m2)	
M	metalic		
F5	foam 5mm		
F10	foam 10mm		

Fig.6 Color Symbols Corresponding to Materials of Each Layer



(D3) [G/C/z1/z2/z3/z1/z2/z3/U/U/U/U/U/U/z3/z1/z2]

Fig. 7 A Lamination Staking Sequence at the Blade Upper Surface in Interval D3

C. Finite Element Modeling

The design is then imported to MSC Patran/Nastran finite element modelling and analysis tool [5], [6]. Defining the dimension as metric, materials are created as isotropic for steel, gel coat and CSM300 and orthotropic for the fiber glass and foam core as mentioned. For the composite part of the model, linear layered structural shell elements are selected which are defined by four nodes with six degrees of freedom in each. The complicated steel frame structure (Fig. 4) is then modelled as a simplified hollow cylindrical section (i.e. hubjoint steel frame simplified model shown in Fig. 8.) of equal stiffness to be a part of the root laminate for the sake of the simplicity in the finite element modelling and analysis. The blade mass and centre of gravity coordinates are then deduced from the final model as tabulated in Table II.

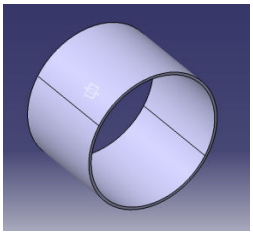


Fig. 8 The Hub Joint Steel Frame Simplified Model

To each surface section, a corresponding composite material laminate is created by using the 2-D shell elements. Hybrid mesh using QUAD4 elements are then constructed, for three different mesh densities one coarse, other fine, and a finer one are tabulated in Table III.

TABLE II
BLADE PHYSICAL PROPERTIES

Properties	Values
Mass [kg]	75
CG_x [m]	0.019
CG_y [m]	0.039
CG_z [m]	1.580

CG=Centre of gravity and its corresponding location

The finest mesh density is shown in Fig. 9 where the boundary condition (Fig. 10) is made as fixed at the root by fixing all degree of freedom to the external circle line. The three-dimensional view of the blade is also shown in Fig. 11.

TABLE III
MESH DENSITY AND RELATED PROPERTIES

	Coarse Mesh	Fine Mesh	Finest Mesh
Element Size	0.089	0.045	0.01
Number of Elements	921	2949	57299
Number of Nodes	814	2787	56614
Degree of Freedom	4884	16722	339684

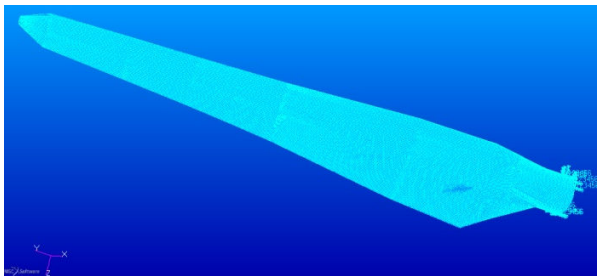


Fig. 9 The Finest Mesh of the Blade

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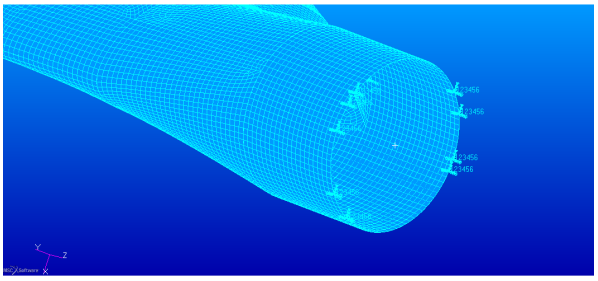


Fig. 10 Zoomed View over the Root

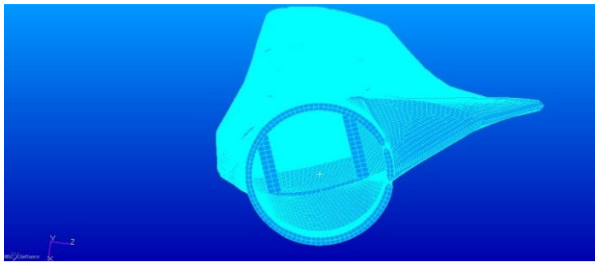


Fig. 11 Three-dimensional View of the Blade

D.Normal Mode Dynamic Analysis

1. Fixed-Free Case

In order to obtain the natural frequencies and corresponding mode shapes focusing on the first three out-of-plane bending, two in-plane bending and the torsional modes of the blade, 'normal modes' analysis type is performed in MSC Patran/Nastran environment. The results are tabulated in Table IV and shown in Figs. 12–16.

TABLE IV
NATURAL FREQUENCIES FOR THREE DIFFERENT MESH DENSITIES
(FIXED – FREE CASE)

Mode Shapes	Natural Frequencies[Hz]		
	Coarse Mesh	Fine Mesh	Finest Mesh (Original)
1st Out-of-plane Bending	5.02	5.06	5.09
2nd Out-of-plane Bending & 1st In-plane Bending Coupling	13.66	13.70	13.80
2nd Out-of-plane Bending	17.33	17.56	17.71
3rd Out-of-plane Bending	36.37	37.16	37.44
2nd In-plane Bending & 1st Torsion Coupling	51.71	51.89	52.17

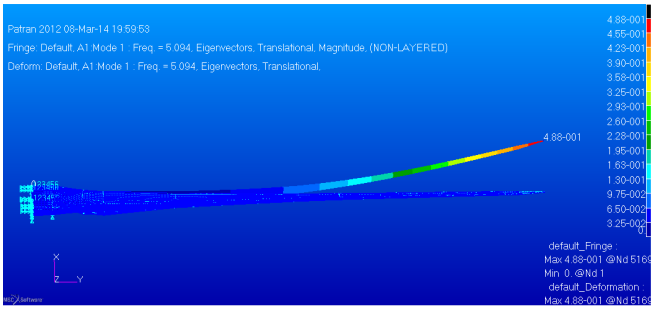
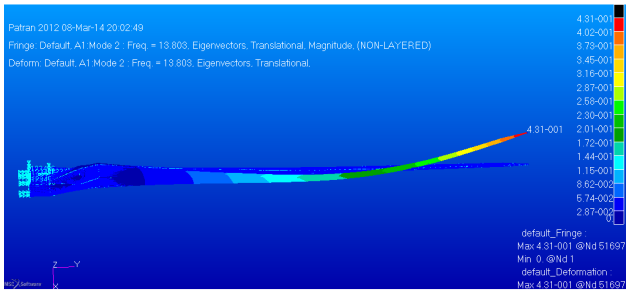
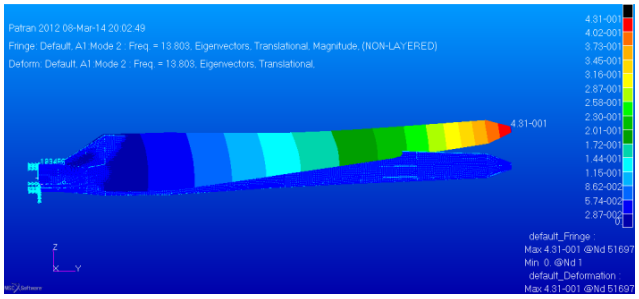


Fig. 12 1st Out-of-plane Bending [5.09 Hz]



(a)



(b)

Fig. 13 2nd Out-of-plane Bending & 1st In-plane Bending Coupling [13.80 Hz] (a) Side view (b) Top view

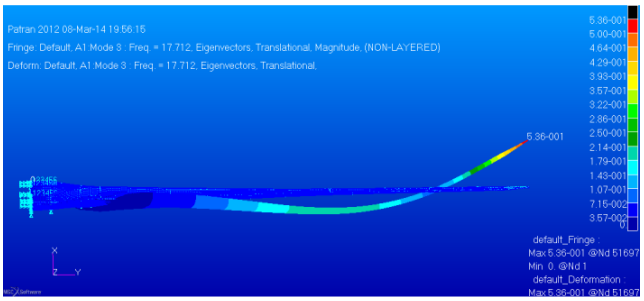


Fig. 14 2nd Out-of-plane Bending [17.71 Hz]

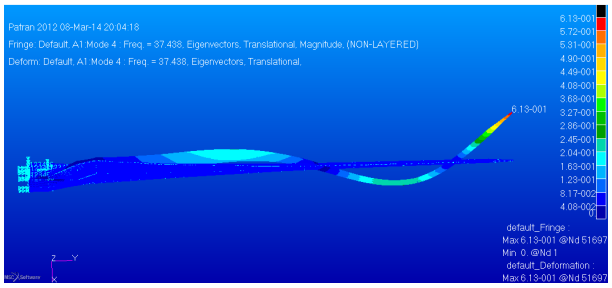
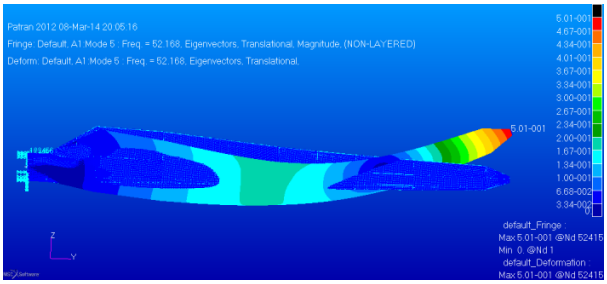
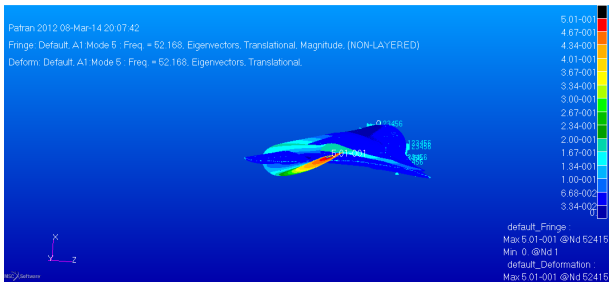


Fig. 15 3rd Out-of-plane Bending [37.44 Hz]

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(a)



(b)

Fig. 16 2nd In-plane Bending & 1st Torsion Coupling [52.17 Hz] (a) Side view (b) Top view

A comparative study with the original configuration (Figs. 6 and 7) in dynamic analysis on blades having different layer orientations in fixed-free boundary condition are performed by keeping the same material properties by also considering he finest mesh density only. Table V presents the results of the dynamic analyses and Fig. 17 shows the change in natural frequencies for different orientations.

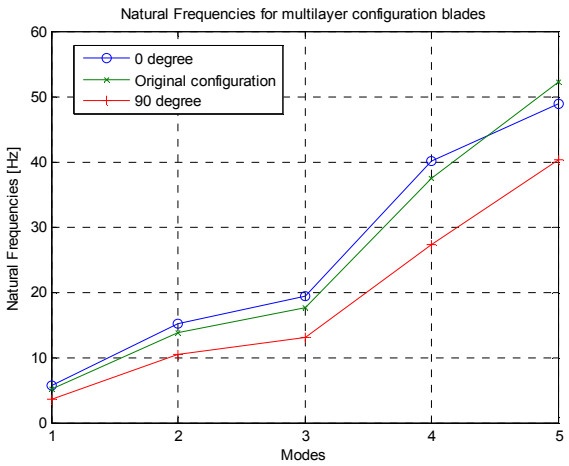


Fig. 17 Change in Natural Frequencies for Different Orientations in Fixed-Free Case

TABLE V
NATURAL FREQUENCIES FOR BLADES HAVING LAYER ORIENTATION IN FIXED – FREE CASE

Natural Frequencies[Hz]	Original	0 Degree	90 Degree
1st Out-of-plane Bending	5.09	5.70	3.65
2nd Out-of-plane Bending	13.80	15.17	10.43
2nd Out-of-plane Bending& 1st In-plane Bending Coupling	17.71	19.43	13.12
3rd Out-of-plane Bending	37.44	40.00	27.20
2nd In-plane Bending &1st Torsion Coupling	52.17	48.20 (1st Torsion)	40.31 (2nd In-plane Bending)

2. Free-Free Case

In order to find the natural frequencies and corresponding mode shapes, 'normal modes' analysis type is performed in MSCPatran/Nastran environment for the free-free boundary condition. The results are tabulated in Table VI and shown in Figs. 18–22.

TABLE VI
NATURAL FREQUENCIES FOR THREE DIFFERENT MESH DENSITIES (FREE – FREE CASE)

Mode Shapes	Natural Frequencies[Hz]		
	Coarse Mesh	Fine Mesh	Finest Mesh (Original)
1st Out-of-plane Bending	10.92	11.13	11.20
2nd Out-of-plane Bending	29.37	30.11	30.28
2nd Out-of-plane Bending& 1st In-plane Bending Coupling	47.20	47.38	47.55
3rd Out-of-plane Bending	56.14	56.91	57.18
1st Torsion	62.47	67.33	68.44

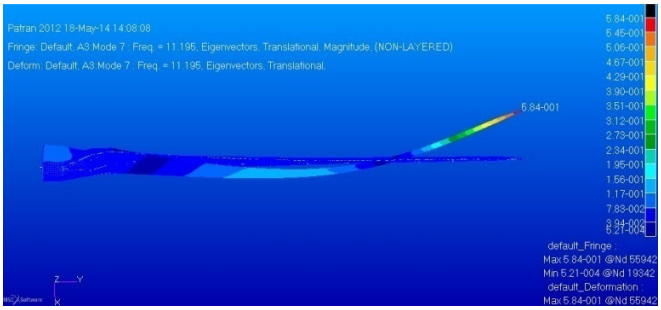


Fig. 18 1st Out-of-plane Bending [11.20 Hz]

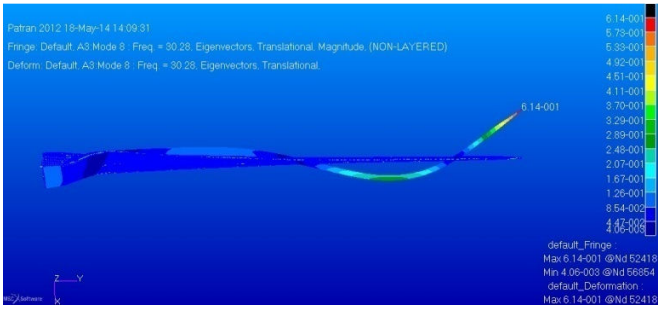
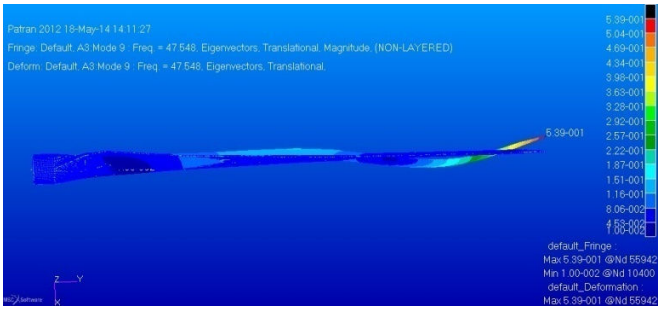
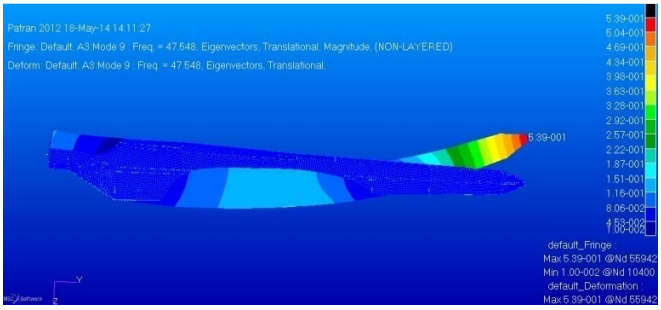


Fig. 19 2nd Out-of-plane Bending [30.28 Hz]

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(a)



(b)

Fig. 20 2nd Out-of-plane Bending & 1st In-Plane Bending Coupling [47.55 Hz]



Fig. 21 3rd Out-of-plane Bending [57.18 Hz]

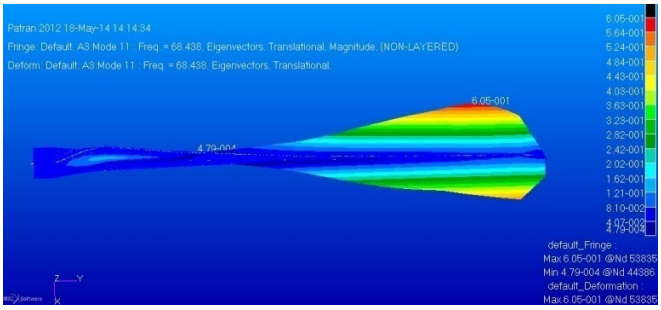


Fig. 22 1st Torsion [68.44 Hz]

A comparative study with the original configuration (Figs. 6 and 7) in dynamic analysis on blades having different layer orientations in fixed-free boundary condition are performed by keeping the same material properties by also considering the finest mesh density only. Table VII presents the results of the dynamic analyses and Fig. 23 shows the change in natural frequencies for different orientations.

TABLE VIII
TIP DEFLECTIONS FOR THREE DIFFERENT LAYER ORIENTED BLADES

Direction of deflection [m]	Original	0 Degree	90 Degree
Out-of-Plane	0.0193	0.0148	0.0363
In-Plane	0.0037	0.0032	0.0073

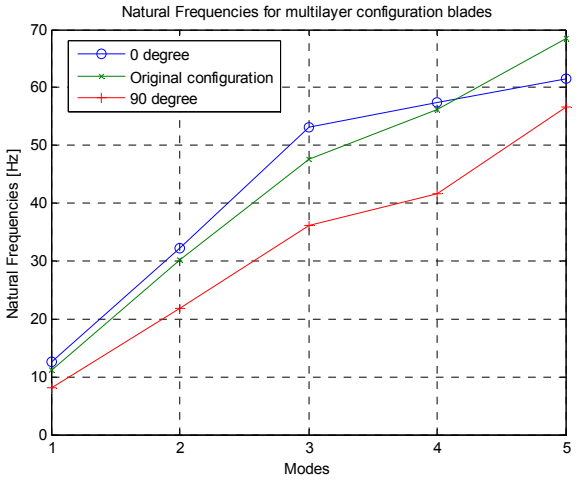


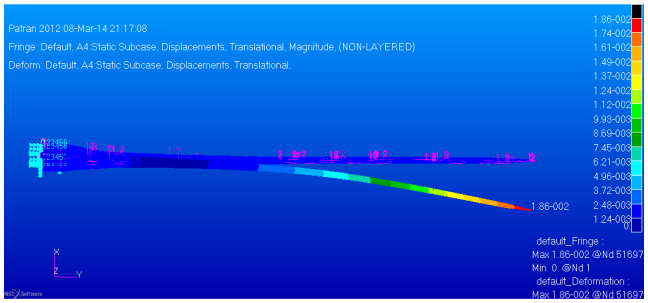
Fig. 23 Change in Natural Frequencies for Different Orientations in Free-Free Case

E. Linear Static Analysis

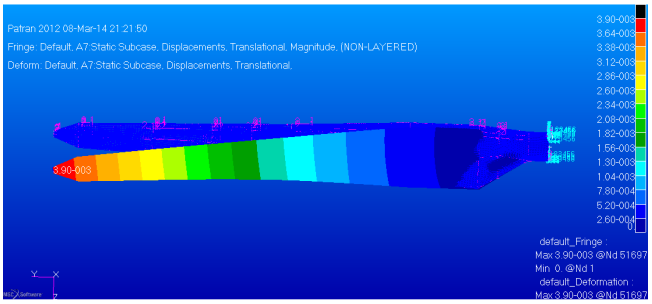
MSC Patran/Nastran 'linear static' type analysis is performed by applying one "g" in two different directions; namely flap-wise and edge-wise. The tip deflections are found as 0.0186 m and 0.0039 m respectively and shown in Fig. 24 and tabulated in Table VIII.

TABLE VII
NATURAL FREQUENCIES FOR BLADES HAVING LAYER ORIENTATION IN FREE – FREE CASE

Natural Frequencies[Hz]	Original	0 Degree	90 Degree
1st Out-of-plane Bending	11.20	12.54	8.06
2nd Out-of-plane Bending	30.28	33.16	21.86
2nd Out-of-plane Bending & 1st In-plane Bending Coupling	47.55	53.17	36.05
3rd Out-of-plane Bending	56.18	57.46 (1st Torsion)	41.69
1st Torsion	68.44	61.52 (3rd Out-of-plane Bending)	56.64



(a)



(b)

Fig. 24 Tip Deflection of the Blade under its own Weight (a) Out-of-Plane (b) In-Plane

III. Conclusions

In this work, an optimised horizontal axis 5-meter-long wind turbine rotor blade is modelled by using the airfoil geometries created at various sections along the span of the blade. The obtained geometry is then transferred to finite element modelling environment and the material properties are assigned. For the investigation of both the dynamic and static behaviour of the blade, various analyses are performed regarding the finite element mesh independency check, for diversity of boundary conditions and layer orientations configuration. Regarding the effect of the layer orientation both on modal and static analyses, the original configuration could be made stiffer by applying all layers in the 0-degree direction. Some changes are observed in the order of appearance of the normal modes regarding the new layer orientations (i.e. 0 and 90 degrees) with respect to that of the original one. The obtained analysis results of this particular research study show that the normal modes are highly coupled and needed to be investigated in details. This requires an experimental modal testing which is an on-going process.

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C. Amer is a Lebanese citizen born in Beirut, 1990. In 2012, he was graduated from the Aeronautical Engineering Department of Istanbul Technical University in Istanbul, Turkey. Currently, he is working on his graduate studies, as Master of Science in Aerospace Engineering, in Middle East Technical University, Ankara, Turkey. He has worked for short periods for many companies mainly related in conferences organization and translation in Turkey. Adding to that, he accomplished a training in Middle East Airlines, Lebanese Airlines as a maintenance engineer and few months of research in Turkish Airlines at the maintenance management department, namely HABOM.Mr. Ameris currently studying in the domain of composites and mechanical of wind turbine blades.

M. Sahin is a graduate of Middle East Technical University, Turkey (BSc, 1996, Aeronautical Engineering; MSc, 1999, Aeronautical Engineering) and University of Southampton, UK (PhD, 2004, School of Engineering Sciences). His specializations are structural dynamics and experimental analysis of vibrating structures, smart structure applications and active vibration control, light-weight structures and composite applications, analysis and design of mission adaptive wings and morphing concepts, structural health monitoring and damage identification. He is an Associate Professor at Middle East Technical University in the Department of Aerospace Engineering.

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