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Structural Strength Analysis and Fabrication of a Straight Blade of an H-Darrieus Wind Turbine

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Abstract. Small H-Darrieus wind turbines have become popular in the wind power market because of their many advantages, which include simplicity of design, low construction costs, and they are thought to represent an adequate solution even in unconventional installation regions. The blade is generally considered as the most important component of the wind turbine system because it controls the efficiency of the turbine. The blade structure must be designed to support the difficult environmental conditions (e.g., wind, and snow) encountered during the operational life of the wind turbine. This current study uses three-dimensional (3D) modeling and structural strength analysis to fabricate two straight blades (aluminum and galvanized steel) for a small H-Darrieus wind turbine. The 3D modeling of the blade structure is performed using SolidWorks, a computer-aided design (CAD) software package, and the structural strength analysis uses the Finite Element Analysis (FEA) technique to identify the stiffness, resistance, and reliability of the blade structure. The simulation results obtained indicate that no structural failures are predicted for either of the two structures tested because the factors of safety are larger than one, and the all maximum deflections are within the allowable deformation limits for the materials. Manufacturing processes for the two structures are described.

Keywords: H-Darrieus wind turbine, Strength analysis, Centrifugal load, SolidWorks simulation.

1. Introduction

Algeria has set the ambitious objective of installing up to 22,000 MW installed capacity from renewable and alternative energy sources to supply the country's domestic power market by 2030 while maintaining the option to export as a strategic goal if market conditions allow. Wind energy is one of the most competitive and major contributors to the growing renewable energy needs of the global community [1]. As a result, global installed capacity is constantly evolving and reached more than 591,000 MW at the end of 2018, an increase of 9.4% compared to 540,000 MW in 2017 [2]. The overall wind power target of the Algerian government is to install 5,000 MW by 2030. At present, there is only one wind farm a power 10.2 MW of installed capacity at the Kabertene site in Adrar city [3].

Compared to horizontal axis wind turbines (HAWTs), vertical axis wind turbines (VAWTs) have received more attention because they can be installed in urban areas, and isolated sites. They can be used at any location, independent of the wind direction (without yawing), and are low-noise, simple to manufacture, and easy to install. Vertical axis wind turbine types include Darrieus, Savonius, and combined Darrieus-Savonius rotors. Due to its simpler manufacturing features and straight blade design, the H-Darrieus rotor has become popular [4-5].

The blade is a key structural element of the turbine, and its quality determines the reliability of the turbine because the blade converts the kinetic energy of the atmosphere into mechanical energy, which is then converted into electrical energy in the generator [6]. During operation, the blade structure may experience major aerodynamic loads and subsidiary loads due to gravity, centrifugal forces, and thermal effects when in service. Analyzing these loads is a complex task because they are all inter. In this paper, we analyze the effects of gravity, extreme winds, and centrifugal forces acting on the blade structure [6-7].

The blades have usually been optimized by experimental tests and simplified analytical methods and. However, finite element (FE) simulation tools are gaining wider acceptance because they are used to improve and accelerate the design process and offer ways to reduce the product development cycle (lower system costs) [8].

In this work, we use 3D modeling and structural strength analysis to fabricate a straight blade for a 2.5-kW combined Darrieus-Savonius wind turbine (shown in Fig. 1) using the SolidWorks simulation software package [9]. Structural strength analysis of the blade structures for two different types of materials (aluminum and galvanized steel) is used to determine the von Mises stresses, deflections, and factors of safety for loads that include extreme winds and centrifugal and gravitational loads. The analysis results confirmed the structural safety. Finally, we describe the manufacturing processes for two blade structures.

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Fig. 1. Wind turbine prototype in URER/MS, Adrar site [5].

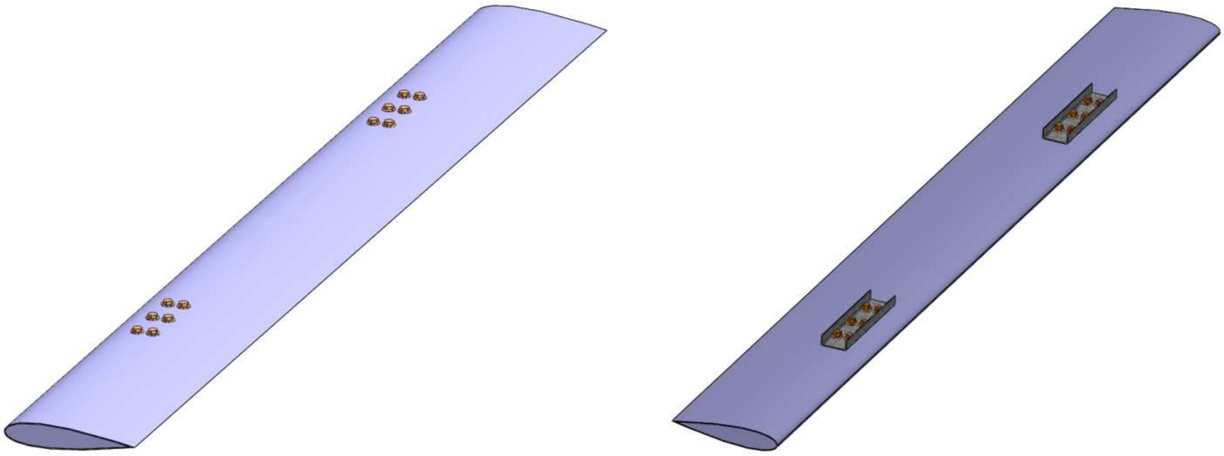

Fig. 2. CAD model of the blade.

2. Structure of the Blade

The blade used in this present study is a straight blade for a 2.5-kW combined Darrieus-Savonius wind turbine located in Adrar in South-west Algeria (shown in Fig. 1) [5]. The details of this turbine are presented in Table 1. The nominal power of 2.5 kW was calculated at a wind speed of 15 m/sec and a tip-speed ratio (TSR) of 3, corresponding to a rotational speed of 430 rpm. Two different material types (aluminum and galvanized steel) were considered for the blade structures. Due to its superior aerodynamic performance, the blade profile is a NACA0018 symmetric airfoil shape (National Advisory Committee for Aeronautics) [10]. The blades have a total height (span) of 2 m and a chord length (c) of 0.2 m. A CAD model is used to produce the design before manufacture. Fig. 2 shows the FE modeling of the proposed blades designs produced with the SolidWorks CAD software package.

3. Finite Element Analysis of the Blades

The numerical simulations for strength analysis of the structure of the blades were run using the SolidWorks simulation software, which is included with the SolidWorks package. FEA proceeds in the following five steps: (i) modeling of the geometric model; (ii) definition of the material properties; (iii) definition of the boundary conditions; (iv) mesh generation, and (v) results.

3.1 Blade material

The selection of the blade material is among the most crucial design parameters for reliable wind turbine design and to reduce costs [1]. Most small vertical axis wind turbines (rotor diameter of less than 5 m) use aluminum and fiber-reinforced plastic as the blade material. Due to manufacturing problems and cost constraints, our turbine blades were designed and manufactured from aluminum, which has the following benefits: it is 100% recyclable (perhaps most importantly), low price, long life, light weight, lower fatigue level and is easy to work with and from galvanized steel (low price, high inertia) [11-12]. The properties of the two materials are listed in Table 2.

3.2 Loading and boundary conditions

The optimal design of the blade structure depends on the different loading conditions. During in-field operation, the structure of the blade is reduced because it is due to subject to aerodynamic, gravitational, centrifugal, and seismic loads and inertial forces. Analysis of these loads is complex because they are all interrelated. With the rotational movement of the turbine rotor, the aerodynamic and centrifugal forces acting on the blade are generally the major design concern, even under normal conditions [13-14]. This study looks at the effects of gravity, extreme winds (thrust), and centrifugal loads on the blades.

Table 1. Characteristics of the wind turbine (2.5-kW).

Parameters	Unit	Value
Rotor diameter D	[mm]	2000
Rotor height H	[mm]	2000
Airfoil type	[---]	NACA0018
Blades number N	[---]	3
Rotor area $(A = DH)$	[m²]	4
Chord length c	[mm]	200
Solidity factor ($\sigma = \frac{Nc}{D}$)	[---]	0.3

Table 2. Material properties used for blade structures.

Property	Unit	Material	
		galvanized steel	aluminum
Elastic modulus	GPa	200	70
Poisson ration	---	0.29	0.33
Yield strength	MPa	203.94	180
Density	kg.m^{-3}	7870	2690

Table 3. Details mesh of the blade models.

Property	Type of the material	
	aluminum	galvanized steel
Element size	0.839 – 16.781 mm	1.429 – 28.598 mm
Number of elements	21273	14834
Number of nodes	42909	4060
Number of DoFs	126135	11559

3.2.1 Extreme wind loads

When wind passes the wind turbine, it generates a thrust force on the rotor and the tower. The extreme wind velocity (V_{e50}) given in Eq. (1) increases with the height above the ground (z) as presented to the IEC 61400-2 profile [15]:

$$V_{e50}(z) = 1.4V_{ref}(z/z_{hub})^{0.11} \tag{1}$$

In Equation (1), the reference wind velocity was taken as $V_{ref} = 28$ m/sec for the site at Adrar, Algeria (Wind Zone II) [16], and the hub height as $z_{hub} = 12$ m.
The relationship between the extreme wind velocity and the wind pressure P_x acting on the structure can be defined by Equation (2):

$$P_x = \frac{1}{2}C_T\rho_{air}V_{e50}^2 \tag{2}$$

where $C_T = 0.5$ is the thrust coefficient and $\rho_{air} = 1.225$ kg/m^3 is the mass density of the air,

3.2.2 Centrifugal loads

The centrifugal force associated with the rotation of the blade can be calculated simply from the Equation (3) [14]:

$$F_c = m\omega_{max}^2 R \tag{3}$$

This force depends on the rotor mass m, and the rotor radius R, where ω_{max} is the maximum possible angular speed of the rotor calculated at the reference wind velocity of V_{ref} [15].

3.2.3 Gravitational loads

The effect of gravity loading on the blade is taken into consideration. In the structural model, the self-weight of the structure is estimated directly by the SolidWorks simulation software for the given dimensions and density of the material. The blade structure weights for aluminum and galvanized steel are 4.2 kg and 6.5 kg, respectively.

3.2.4 Boundary conditions

Boundary conditions of the turbine blade model, its root (strut attachment) was fixed at a distance of 0.5 m (H/4) from both ends using a fixed constraint (zero all translations and rotations). Also, the joining and welding areas were replaced by suitable connections (fixtures). The loading and boundary conditions are shown in Fig. 3.

3.3 Mesh generation

Meshing is a fundamental component of FEA tools like the SolidWorks simulation and is the most important task in the structural design analysis because it has a large effect on the accuracy of the results and the computing time [17]. In the SolidWorks simulation, the meshing is generated by three fundamental element types: 1D beam and truss mesh (suitable for structural members), 2D triangular shell mesh (appropriate for thin-walled parts), and 3D solid mesh (suitable for bulky or complex models). Our two-blade structures were meshed by 3D parabolic tetrahedral solid elements (higher-order elements). In general, this element type, which is defined by ten nodes (with three degrees of freedom (DOF) at each node) and six edges, yields more accurate results than linear elements [18]. The size of this element is chosen based on the geometrical size of the smallest part of each structure of the blade. Because it is especially efficient for solving large problems (over 100,000 DOF), the FFEPlus solver (iterative) was used for numerical solution. The total number and size of elements, nodes and DOFs of the mesh of the blade models are given in Table 3.

4. Results and Discussion

For the FE models of the structure of the blade, SolidWorks simulation software was used to calculate the maximum stresses, deflections (displacements), and factors of safety.

Von-Mises (or effective) stress is based on the Hencky-Huber theory (maximum distortion energy theory) and is widely used by design engineers to present their results. The information is used to evaluate the safety of the design for several engineering materials. It has been experimentally proven that for materials showing elastoplastic properties (for example, aluminum alloy or steel), the Max von Mises stress criterion provides more accurate results than the Max Shear stress (Tresca criterion) [19, 20].

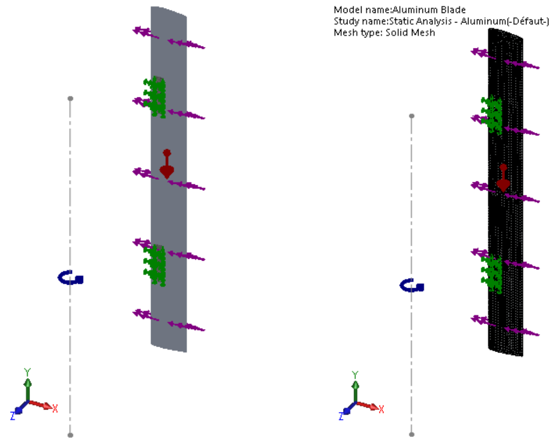

Fig. 3. Illustration of 3D FE aluminum blade, load application, and boundary conditions. Pink, blue and red areas represent the extreme winds, centrifugal and gravity loads, respectively, and green area is assumed as fixed as boundary conditions.

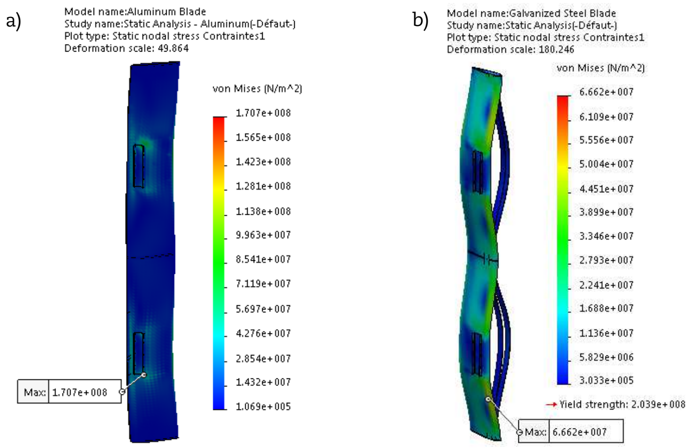

Fig. 4. von Mises stress in the blade. a) aluminum; b) galvanized steel.

If the principal stresses are given as σ_x, σ_y and σ_z, the von-Mises stress is defined by Equation (4) [21]:

$$\sigma_{vonMises} = \left\{\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_x - \sigma_z)^2\right]/2\right\}^{1/2} \tag{4}$$

According to this theory, the failure of ductile material will occur when the von-Mises stress value is equal to the yield strength, which is used in most cases as a stress limit (σ_{limit}). The factor of safety at a location is defined as (Equation (5)) [22]:

$$S_F = \sigma_{limit}/\sigma_{vonMises} \tag{5}$$

The FEA simulation results obtained for the blade structures are shown in Figs. 4 to 7 and Table 4.

Fig. 4 shows the von Mises stress distributions in the structure of the blade for both materials. It can be seen that the maximum concentration of the stresses was located in the end region of the blade attachment piece (U-shaped) for the aluminum blade and in the flat-iron region for the galvanized steel blade. The maximum stress values for aluminum and galvanized steel are 170.7 and 66.62 MPa, respectively. Based on these values, there is no need for any constructive changes in the appearance of the blade structures because the maximum stresses induced are lower than the yield strengths of the materials.

The maximum horizontal (transverse) deflections are shown in Fig. 5. They occur at the end of the blade attachment piece (U-shaped) in the aluminum blade and the free end region of the galvanized steel blade. The maximum values were 0.052 mm (aluminum) and 0.059 mm (galvanized steel), which are negligible compared to the chord length and are within materials the allowable deformation limits for the materials. Vertical (longitudinal) deflections (see Fig. 6) were recorded at 0.09 mm (aluminum) and 0.027 mm (galvanized steel), which are small compared to the total blade height and are still within the allowable deformation limits of the materials. These maximum values appear in the free end region of the aluminum blade and the region near the attachment piece (U-shaped) of the aluminum blade.

Based on the strength analysis results, neither of the structures will undergo structural failure (the design is safe) during different phases of the wind turbine operation because the minimum values for the factor of safety (weak area of the structure) are approximately 1.18 for the aluminum blade and 1.79 for the galvanized steel blade (greater than 1) (see Fig. 7).

Table 4. Results of simulation for two blade structures (maximum values).

Property	The material of the blade	
	aluminum	galvanized steel
Von Mises stress (MPa)	170.7	66.62
Horizontal deflection (mm)	0.052	0.059
Vertical deflection (mm)	0.090	0.027
Factor of safety (---)	1.117	1.792

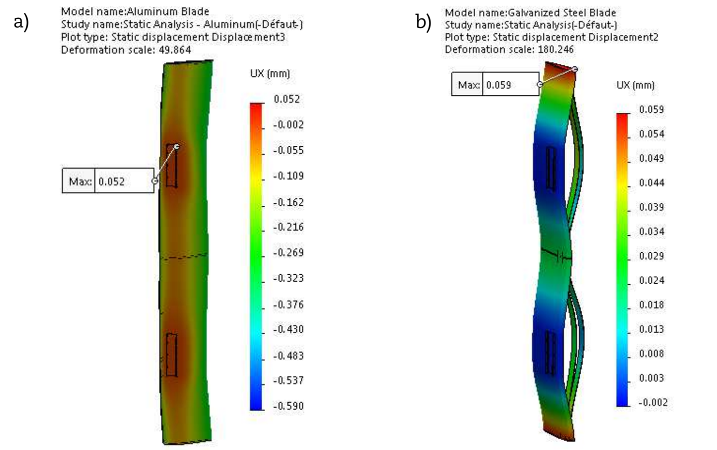

Fig. 5. Horizontal deflections (transverse) in the blade. a) aluminum; b) galvanized steel.

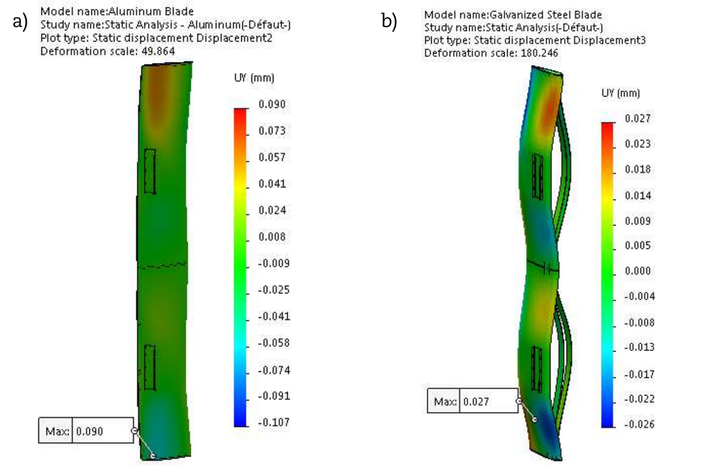

Fig. 6. Vertical deflections (longitudinal) in the blade. a) aluminum; b) galvanized steel.

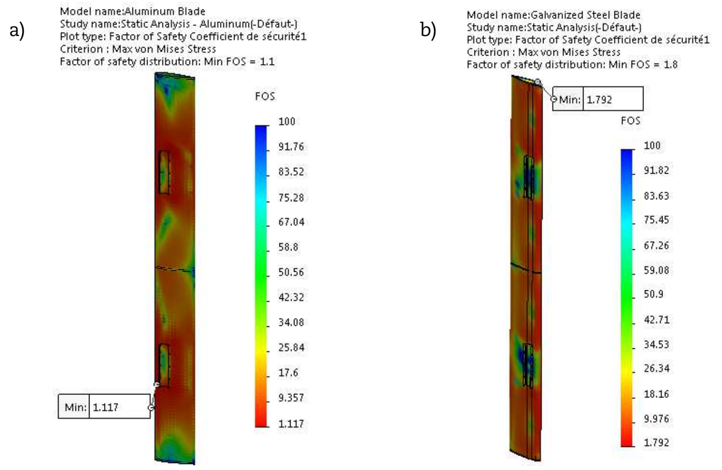

Fig. 7. The factor of safety in the blade. a) aluminum; b) galvanized steel.

5. Fabrication of the Blades

The structure of the blade is made up of two parts: (i) an internal part (frame), which consists of three profile pieces (NACA0018), and two flat irons (3×40×2000 mm), and (ii) an external part made up of a covering metal sheet. The profile pieces and flat irons were fabricated from 2D sketches. A high-power laser was used to cut the outline of the NACA0018 shape (200mm in the chord). The profile pieces were manufactured from aluminum and galvanized steel, as shown in Fig. 8a. Then the flat irons were welded to the profile pieces (two profiles at the ends and one in the center). Once the frame was complete, a covering metal sheet 2000 mm in length and 500 mm in width was fabricated—1.2 mm thick for the aluminum blade, and 0.4 mm thick for the galvanized steel blade. Finally, the sheet was wrapped around the frame and riveted onto it to give the final of the blade (see Fig. 8b).

(a)

(b)

Fig. 8. Fabrication two considered blades types, a) Pieces of the profile NACA0018 b) External part.

6. Conclusion

This study used finite element analysis to carry out a structural strength analysis and fabrication of a straight blade for an H-Darrieus wind turbine with a rated power of 2.5-kW. The SolidWorks software package was used to create 3D models of the blade structures. Strength analysis of the blade structures for two different materials (aluminum and galvanized steel) subjected to extreme winds and centrifugal and gravitational loads was carried out using SolidWorks simulation to determine the stiffness, resistance, and reliability of structure of the blades. The analysis revealed that the structure of the blades will not be subjected to structural failure during different phases of the wind turbine operation. This is because the maximum stresses induced are lower than the yield strength of the two materials (lowest factor of safety is 1.11), and all maximum structural deflections are within the allowable deformation limits of the materials.

Author Contributions

All authors planned the scheme, initiated the project, suggested the fabrications, and conducted the analyzed the empirical results. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed and approved the final version of the manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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Nomenclature

TSR	Tip-speed ratio [---]	$z,\ z_{hub}$	Height above the ground, Hub height [m]
$NACA$	National Advisory Committee for Aeronautics	P_x	Wind pressure [N/m²]
D	Rotor diameter [mm]	C_T	Thrust coefficient [---]
H	Rotor height [mm]	ρ_{air}	Mass density of the air [kg/m³]
N	Blades number [---]	F_c	Centrifugal force [N]
A	Rotor area [m²]	m	Mass rotor [kg]
R	Rotor radius [mm]	ω_{max}	Maximum angular speed of the rotor [m/sec]
c	Chord length [mm]		

σ	Solidity factor [---]	$\sigma_x, \sigma_y, \sigma_z$	Principal stresses [MPa]
V_{e50}	Extreme wind velocity [m/sec]	$\sigma_{vonMises}$	Von-Mises stress [MPa]
V_{ref}	Reference wind velocity [m/sec]	σ_{limit}	Stress limit [MPa]
		S_F	Factor of safety [---]

References

[1] Veers, P., et al. Grand Challenges in the Science of Wind Energy, *Science*, 366(6464), 2019, 2027.
[2] REN21, *Renewables 2019 Global Status Report-2019* (Paris: REN21 Secretariat), 2019, ISBN 978-3-9818911-7-1.
[3] Bailek, N., Bouchouicha, K., EL-Shimy, M., Slimani, A., Updated Status of Renewable and Sustainable Energy Projects in Algeria, In EL-Shimy M., editor. *Economics of Variable Renewable Sources for Electric Power Production*. Lambert Academic Publishing, Germany, 2017.
[4] Kumar, R., Raahemifar, K., Fung A.S., A Critical Review of Vertical Axis Wind Turbines for Urban Applications, *Renewable and Sustainable Energy Reviews*, 89, 2018, 281-291.
[5] Ferroudji, F., Khelifi C., Meguellati F., Koussa K., Design and Static Structural Analysis of a 2.5 kW Combined Darrieus-Savonius Wind Turbine, *International Journal of Engineering Research in Africa*, 30, 2017, 94-99.
[6] Konga, C., Banga J., Sugiyama, Y., Structural Investigation of Composite wind Turbine Blade Considering Various Load Cases and Fatigue Life, *Energy*, 30, 2005, 2101-2114.
[7] Jamieson, P., *Innovation in Wind Turbine Design*, Second Edition, John Wiley & Sons, UK, 2018.
[8] Jensen, F.M., Structural Testing and Numerical Simulation of a 34 m Composite Wind Turbine Blade, *Composite Structures,* 76, 2006, 52-61.
[9] SolidWorks, 2016, SolidWorks Corporation, 300 Baker Avenue, Concord, MA 01742. Available at: <http://www.solidworks.com/> [accessed 20.7.2016].
[10] Hameed, S.M., Afaq, S.K., Design and Analysis of a Straight Bladed Vertical Axis wind Turbine Blade using Analytical and Numerical Techniques, *Ocean Engineering*, 57, 2013, 248-255.
[11] Cousins, D. S., Suzuki, Y., Murray, R. E., Samaniuk, J. R., Stebner, A. P., Recycling Glass Fiber Thermoplastic Composites from Wind Turbine Blades. *Journal of Cleaner Production*, 209, 2019, 1252–1263.
[12] Babu, K.S., Raju, N.V.S., Reddy, M.S., Rao, D.N., The Material Selection for Typical Wind Turbine Blades using a MCDM Approach and Analysis of Blades, *Proceedings of 18th International Conference on Multiple Criteria Decision Making*, Chania, Greece, June 19–23, 2006.
[13] Bel Mabrouk, I., El Hami, A., Walha, L., Zghal, B., Haddar, M., Dynamic Vibrations in Wind Energy Systems: Application to Vertical Axis Wind Turbine, *Mechanical Systems and Signal Processing,* 85, 2017, 396-414.
[14] Liu, W., Xiao, Q., Investigation on Darrieus Type Straight Blade Vertical Axis Wind Turbine with Flexible Blade, *Ocean Engineering*, 110, 2015, 339-356.
[15] IEC, 2006. *Wind Turbines—Part 2: Design Requirements for Small Wind Turbines*, International Electrotechnical Commission, Geneva, Switzerland, Standard No. IEC 61400-2.
[16] Document Technique Réglementaire, *Règlement neige et vent* "R.N.V.1999", 2000, ISBN: 9961-845-03-X. 2000.
[17] Ferroudji, F., Khelifi, C., Outtas, T., Structural dynamics analysis of three-dimensional bi-axial sun-tracking system structure determined by numerical modal analysis, *Journal of Solar Energy Engineering*, 140, 2018, 031004-1-11.
[18] Steffen, J.R., Nudehi, S.S., *Analysis of Machine Elements Using SolidWorks Simulation 2017*, SDC Publications, United States of America, 2017.
[19] Kurowski, P.M., *Engineering Analysis with SolidWorks Simulation 2018*, SDC Publications, United States of America, 2018.
[20] Petrova, R.V., *Introduction to Static Analysis using SolidWorks Simulation,* CRC Press, Taylor & Francis Group, New York, USA, 2015.
[21] Khelifi, C., Ferroudji, F., Stress and Fatigue Analyses under Wind Loading of the Dual Axis Sun Tracking System via Finite Element Analysis, *Journal of Mechanical Engineering and Sciences*, 10, 2016, 2008-15.
[22] Ferroudji, F., Khelifi, C., Design, Modeling and Finite Element Static Analysis of a New Two Axis Solar Tracker using SolidWorks/COSMOSWorks, *Applied Mechanics and Materials*, 446-447, 2014, 738-743.

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