INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
El Alaoui R. et al., Vol.8, No.4, 2018

Investigation and Analysis of Static and Dynamic Behaviour of a New Natural Composite Material of a Wind Turbine Blade Using the Finite Element Method

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Received: 04.11.2018 Accepted:27.12.2018

Abstract-A wind turbine blades modeling study is so critical because of their design, as we all know, domestic wind turbine blades are usually designed using aluminum alloy and glass fiber. In this paper, we are going to study the resistance of a new natural composite material based on hemp fiber and an Epoxy matrix, for that we had conceived a three-dimensional model of the blade using aerodynamic profile parameters and geometric parameters on SolidWorks modeling software. Then, the model was imported into the ANSYS to perform a static, modal and harmonic analysis using FEM. The results were compared between the three materials; this comparative study shows that there is a good agreement between the three materials under stress. In addition, for natural frequencies, the hemp fiber composite blade has higher natural frequencies than the aluminum alloy blade and the glass composite blade with a large standard deviation. For the harmonic response, results show that the blade operates stably under resonance conditions, resonance does not occur and the composite hemp blade functions safely.

Keyword: Wind turbine; Materials; Hemp; Static analysis; Modal analysis; harmonic; FEM.

1. Introduction

The constant growth of energy consumption in all its forms and the associated polluting effects[1]–[3], mainly caused by the combustion of fossil fuels[4]–[6], are at the heart of the issue of sustainable development and environmental care in a discussion about the future of the planet[7], [8].

Supplied by the sun, wind, earth's heat, waterfalls, tides or plant growth, renewable energies generate little or no waste or polluting emissions[9]–[11], and are an encouraging alternative to conventional energies that have caused a lot of ecological damage, and which are in all cases limited and exhaustible resources[12]–[16].

As a clean and green renewable energy, wind energy is the most promising energy compared to a traditional one[17]–[23], and it will surely become one of the most important sources of energy [24], [25]. The blades are the centerpiece and the most critical part of the realization of the turbine; they represent about 20% of the wind turbine design cost [26]–[31]. Their role consists to recover the kinetic energy of the wind and to transform it into mechanical energy [32], [33]. The life cycle of the wind turbine is directly related to the methods adopted to design and realized the blades, as well as the quality of the materials, used [34]–[40]. To ensure the smooth operation of the wind turbine safely in different aerodynamic conditions, generally, a performance analysis of the blade's resistance must be performed to provide a reliable and efficient basis to improve the mechanical performance and optimization of the blade's structure [41]. Many studies have been carried out in this field, including the structural analysis of the blade's composite material structure, based on the numerical analysis obtained from ANSYS. [42]. Song et al. Presenting a modeling method, they use two software SolidWorks and ANSYS, then study the dynamic behavior of the blade using the finite element method[43]. Nitin et al. used the finite element method to analyze the blade with the ANSYS software and the results were compared with the experimental results [44]. Abdelkader et al carried out a study to evaluate the behaviour of a different material blade under an aerodynamic load by the finite element method, and also studied the transient behaviour that allowed determining the vibratory responses due to the imbalance and different excitation modes [45]. A. Gangele and S. Ahmed, investigate the behaviour and dynamic characteristics of a 1.5 MW wind turbine, taking into account different geometric and material parameters, using the finite element method in ANSYS [46].

Generally, large blades are made from composite materials, carbon fiber, glass fiber... [18], [47] and small blades that are used on domestic wind turbines are made from aluminum alloy, wood and glass fiber [48], In this article we will study the possibility to use a new composite material which is based on natural fibers of hemp, instead of the different advantages that give this new material, among all natural materials, hemp has a low density, cost's low and its mechanical characteristic allow it to be a good composite material [49]. This present work will show the three-dimensional model of the blade using the SolidWorks software, and how the 3D model will be imported into ANSYS for exploring some analysis, but before importing the model, the file's format must be converted to IGS format.

This study was based on the study that was performed by Kakumani Sureka [50] which had for goals to find the best material adapted to make flight wing. In his study, he used the CAD model of the A300 wing modeled with the CATIA V5 R20 software and the modeling and ANSYS had realized structural analysis on the wing structure

2. Methodology

*2.1. Description of m*aterials

The main goal of this project is to reduce the cost and weight of the wind turbine blade by using another form of material. For that, we are going to design the geometry of the blade in the 3D model with SolidWorks, and then a FEM analysis has been executed in ANSYS Workbench figure 1. The results that we have got after simulation are compared with those obtained using Aluminum alloy and glass fiber composite to determine if the new natural composite material (hemp fiber) is qualified to be used in domestic wind turbine considering the different environmental conditions.

The characteristics of glass fiber and hemp fiber are the results of a tensile test on specimens already carried out on both materials. The mechanical characteristics of the three materials are summarized in table 1.

Table 1. Mechanical property of materials for study[50]

Properties	Aluminum alloy	Hemp fiber composite	Glass fiber composite
Density kg/m³	2700	1271	1775
Young's modulus (MPa)	58000	33496.7	33027.09
Tensile Strength (MPa)	310	398.5	1118.5

2.2. MODELING

The study of the dynamic behavior of blades is a fundamental task in the wind turbine design due to the applied wind forces at this part of the machine. Hence, the calculation of the dynamic stresses is necessary[51].

There are two methods that can be carried out for the stress analysis of the blade. The first one is the resolution of the coupled analytical equation (flexion - torsion); in this method, the blade is considered as a continuous system. This equation is characterized by particular difficulties of resolution. The second one is a finite element modeling applied for a blade of complex shape using simulation software.[46], [52]

In this work, the blade is considered as a continuous system.

- Bending case

The calculation of normal displacements and stresses is based on the resolution of the bending motion equation given by:[47]

$$\frac{\partial^2}{\partial x^2}\left(EI\frac{\partial^2 Z}{\partial x^2}\right)-\frac{\partial}{\partial x}\left(G\frac{\partial Z}{\partial x}\right)+m\frac{\partial^2 Z}{\partial t^2}=\frac{\partial F}{\partial x} \qquad (1)$$

Where:
T: The weather;
F: The aerodynamic effort;
G: The centrifugal force;
E: The modulus of elasticity;
I: The moment of inertia

- Torsion case

The calculation of the angular displacements and shear stresses is based on the resolution of the torsional motion equation given by:[47]

$$\frac{\partial}{\partial x}\left(GJ\frac{\partial\theta}{\partial x}\right)-C\frac{\partial^2\theta}{\partial t^2}-C\Omega^2\theta=-\frac{\partial M_A}{\partial x} \qquad (2)$$

Where:
[illegible]: The moment of inertia per unit length;
[illegible]: The angular velocity;
[illegible]: The torsion angle;
[illegible] The aerodynamic moment;
[illegible]: Torsional rigidity

- Bending-torsion case:

The computation of the displacements and constraints is based on the resolution of the equation of flexion-torsion.

First, the analytical equations for both bending and twisting cases are presented in a divided manner. However, in reality, both movements are mutually dependent on each other, since one has an effect on the other. The torsional movement changes the center of gravity of the profile section; thereby it generates a change in the bending moment and the cutting forces. Therefore, they are proposed an equation that makes it possible to calculate the bending-torsion torque by adding new terms to the bending equation as a function of the torsion angle[53][47][54]. The solution of this equation makes it possible to calculate the stresses and the displacements applied to the blade.[47]

$$\frac{\partial^2}{\partial x^2}\left(EI\frac{\partial^2 Z}{\partial x^2}\right)-\frac{\partial}{\partial x}\left(G\frac{\partial Z}{\partial x}\right)+m\frac{\partial^2 Z}{\partial t^2}+Ft\left(X,\theta,\frac{\partial^2\theta}{\partial t^2}\right)=\frac{\partial F}{\partial x} \qquad (3)$$

Where: [illegible]: is a given function.

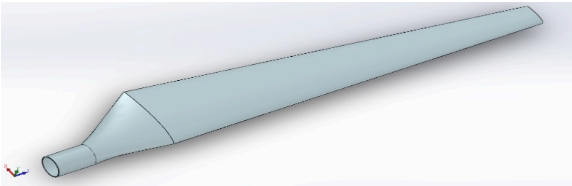
The analytical resolution of this equation is impossible. Therefore, the method of the finite elements is used to solve the equation.

3. Simulation

3.1. blade design procedure

In this work, a NACA 4412 profile figure 1. was selected as the best and most appropriate profile[55]

(a)



(b)

Fig. 1. (a): Airfoil of NACA 4412, (b). Three-dimensional model of Wind turbine blade SolidWorks

Table 2. Propriety of geometry

Length following X	4.2 m
Length following Y	0.69165 m
Length following Z	0.23484 m

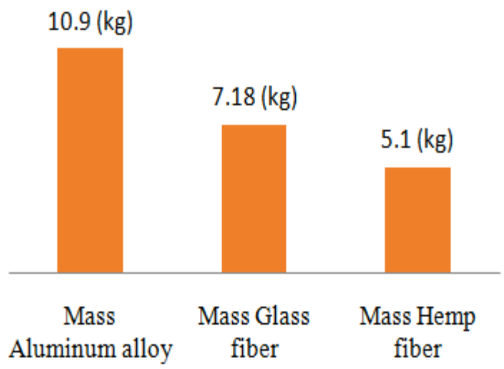


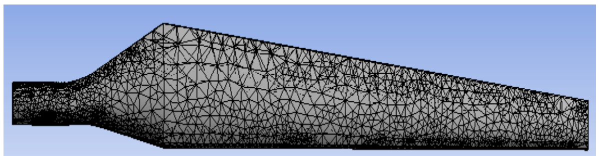
Fig. 2. Weight of wind turbine blade (in Kg)

Figure 2, shows the difference in weight of the wind turbine blade in terms of the materials used by the simulation, and it is clear that the blade made of hemp composite material, is less heavy than the blade in Aluminum Alloy by 53.2%, and blade in glass fiber composite by 29%, and this gives more advantage to the hemp fiber composite blade.

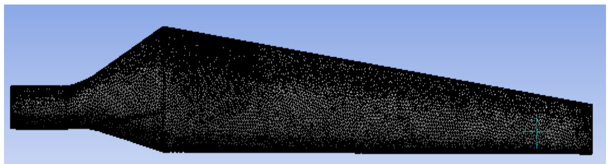
3.2. Meshing of parts

The mesh of different sections in a wind turbine blade was-made using ANSYS Workbench software figure 3. the main role of the mesh is to divide the geometry of the wind turbine blade into small elements [56]. Each one of those elements will have a set of parameters such as pressure and wind speed on their location. For that, a small elements of tetrahedral shape have been used [57]. More the mesh is fine, more the size elements are smaller, and the result will be favorable. However, if the mesh is too thin, some problems has been detected such as : a long computing times or convergence problems [58].

The choice of mesh size is the most important step in the calculation process[59]. An analysis of the mesh influence on the solution convergence is carried out.



(a) : 0.1



(b): 0.001

Fig. 3. Full Blade with different size of Mesh

The finite element method is based on a blade division according to the type of mesh. when the mesh is fine, the solution by the MEF will be higher and precise [59], The two figures (a) and (b) are modeled by a three-dimensional mesh with tetrahedral elements at 10 nodes with a different mesh element size. The latter was obtained automatically using the ANSYS Workbench options. The results of the mesh are presented in Table 3 and Figures 8 (a) and (b).

Table 3. Statistics of mesh calculated by ANSYS for coarse and fine mesh

	COARSE	FINE
Size of the elements	0.1	0.001
Number of elements	30878	102510
Number of nodes	60811	205977

3.3. boundary condition

When we use some numerical methods to perform simulations, the boundary conditions are a way to set some parameters for having the right equations number to solve the problem. So, for our study it was appropriate to add into some boundary conditions to the blade on the software which is responsible for calculations to determine their dynamic behavior.

Among the different possibilities of boundary conditions, we choose the most direct one that allowed us to obtain optimum performances of the blade. For that, a pressure on the extrados surface of the blade has been fixed figure 4, and then we have embedded the blade on the end. The unknown elements identified by the software using the pressure on the blade will be consider as: constraints, deformation and blade's displacement figure 5.

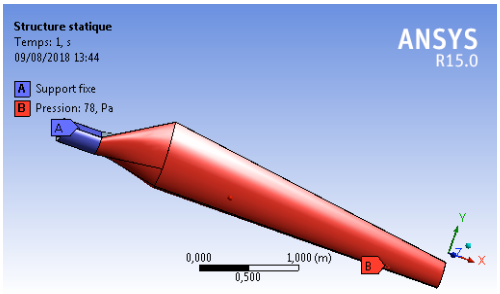


Fig. 4. Fixed support and Applied load

When calculating, the ANSYS Workbench software must solve some complex equations that cannot be solved otherwise than using a numerical method such us finite element's method for ANSYS Workbench. This method allows approximating the partial differential equations to describe real physical behavior. In such a case, the equations that must be solved are those whose related to the motion and stresses.

4. Results

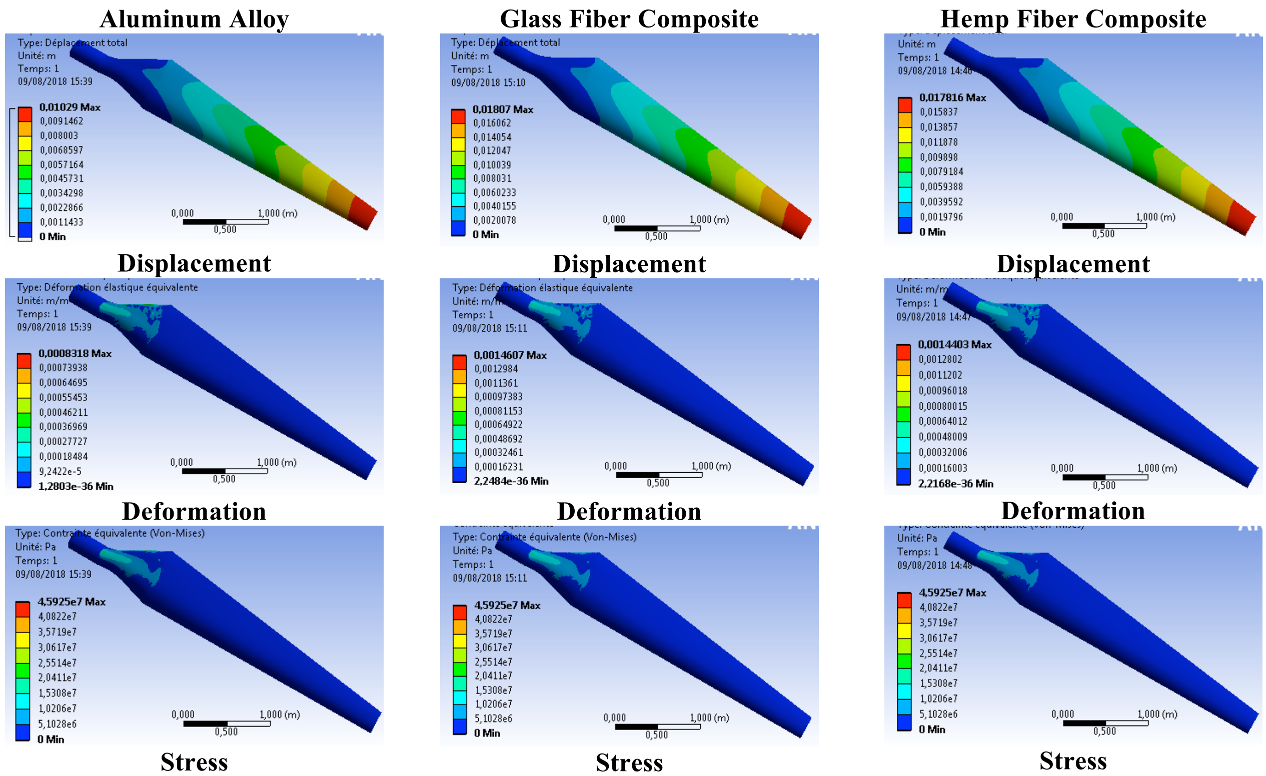


Fig. 5. Mechanical behavior of the blade for Aluminum Alloy, Glass Fiber Composite and Hemp Fiber Composite

Figure 5 shows the extreme behavior distribution of the blade with an aluminum alloy, glass fiber composite and hemp fiber composite at a wind speed of 11m / s. We fixed the blade at the end; the results show that the maximum value of the stress Von Misses is 45.92 MPa for three materials, and the value of the displacement is 0.01 m for Aluminum Alloy, 0.02 m for Glass fiber composite and 0.02 m for hemp fiber composite. According to the properties of the three materials, these results have no impact on the blade geometry

Table 4. Static result of the three materials

	Type	Displacement (m)	Deformation (m/m)	Stress (MPa)
Aluminum Alloy	Min	0	1.2803e-036	0
	Max	0.01	8.318e-004	45.92
Glass Fiber	Min	0	2.2484e-036	0
	Max	0.02	1.4607e-003	45.92
Hemp Fiber	Min	0	2.2168e-036	0
	Max	0.02	1.4403e-003	45.92

From the above tables, we conclude that the Von-Mises stress induced in the wind turbine blade for all three materials is 45.92 MPa. This maximum stress value is lower than the permissible stress of the three materials and meets the design requirements. Therefore, the use of a hemp fiber composite material is more beneficial than aluminum alloy and glass fiber composite due to its low weight and its less expensive material

5. Modal analysis of the blade

Modal analysis is an approach to analyze the natural vibration characteristics of the blade and their dynamic characteristics, each frequency mode has a damping ratio and a shape mode[60].

Natural frequency and main vibration mode

Equations of motion[61]:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(z,t)\} \quad (1)$$

With,

M: The quality of the structure,

C: The Damping ratio,

K: The stiffness matrix;

X: Structure downwind displacement,

[illegible]: Velocity;

[illegible]: Acceleration vector;

F (z, t) is the fluctuating wind load vector or earthquake.

Rayleigh damping is generally used on vibration analysis method when processing damping.

The Rayleigh damping matrix is:

$$[C] = \alpha[M] + \beta[K] \quad (2)$$

The vibration equation is:

$$[K]\{\Phi\}_j = \omega_j^2 \, M \, \{\Phi\}_j \quad (3)$$

With,

[illegible] is mode shape vector of the structure

w is Eigen-value.

Modes and natural vibration frequency vectors can be obtained from the Jacobi method using the equation above

[illegible] (4)

With:

[illegible] Are the natural frequencies of the corresponding main modes.

The generalized eigenvector equation of the vibration problems of the blade can be obtained by

[illegible] (5)

With,

[illegible] Is the natural frequency

[illegible] Is modal values

6. Results of modal analysis

The following table 5. Shows the first six natural frequencies and shape's mode for the all materials

Table 5. Sixth-order natural frequencies of the blade

	Aluminum alloy		Glass Fiber Composite		Hemp fiber composite	
Mode	Frequency [Hz]	Displacement (m)	Frequency [Hz]	Displacement (m)	Frequency [Hz]	Displacement (m)
1	9.5214	0.70929	8.8537	0.8745	10.537	1.0334
2	19.892	0.60448	18.485	0.74537	21.999	0.88084
3	38.86	0.84161	36.145	1.0381	43.017	1.2267
4	74.693	0.67911	69.368	0.83508	82.556	0.98685
5	95.891	0.90828	89.232	1.1177	106.2	1.3209
6	136.44	0.84837	127.02	1.0463	151.17	1.2364

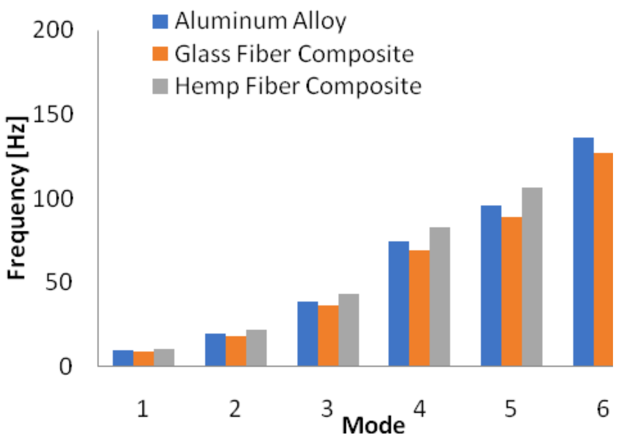


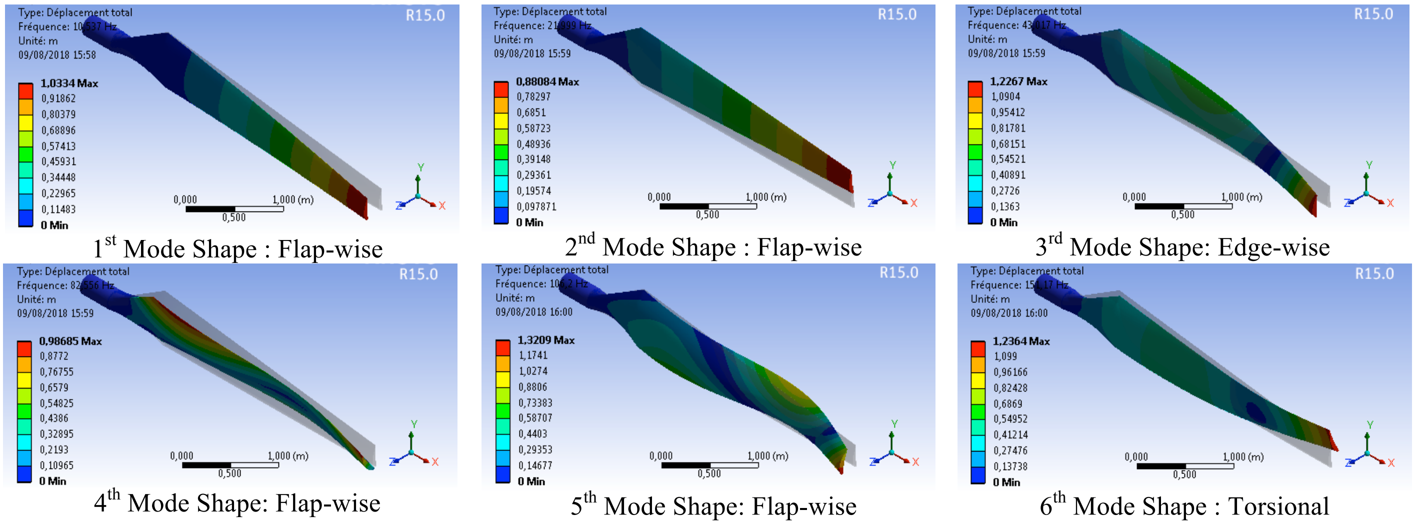
Fig. 6. Comparison of the blade frequency variation according to the mode for the three materials

Figure 6 shows that the hemp fiber composite blade has higher natural frequencies than the aluminum alloy blade and the glass composite blade with a large standard deviation table 6. This gives more advantages to our new natural composite material hemp fiber to be used in the design of wind turbine blades.

Table. 6. Represents the standard deviation between the hemp fiber composite blade and the other blades as function of natural frequencies

Mode	standard deviation between (Hemp/Glass)	standard deviation between (Hemp/Aluminum)
1	15.98	9.64
2	15.97	9.58
3	15.98	9.66
4	15.97	9.52
5	15.98	9.71
6	15.98	9.74

For the blade shapes modes, we have the same operating mode for the three materials



1st Mode Shape : Flap-wise — 2nd Mode Shape : Flap-wise — 3rd Mode Shape: Edge-wise
4th Mode Shape: Flap-wise — 5th Mode Shape: Flap-wise — 6th Mode Shape : Torsional

Fig. 7. The sixth mode shapes of the blade for Aluminum Alloy.

The figures 7 shows the results of the modal analysis of blade according to the three materials with the same mode of operation for the natural frequencies, we notice that in the first, second, fourth and fifth mode an Flap- wise vibration, on the third mode an edge-wise vibration and on the sixth mode we perform a torsion vibration mode.

7. Harmonic Analysis

The harmonic response analysis gives the ability to predict the sustained dynamic behavior of the blade, allowing us to verify if the designs will successfully overcome the resonance, the fatigue and also other distress effects causing by forced vibration. We are going to use this harmonic response analysis to identify the steady-state response of wind turbine blade on some loads that vary sinusoidally over time[62]–[66].

7.1. Results and Discussions:

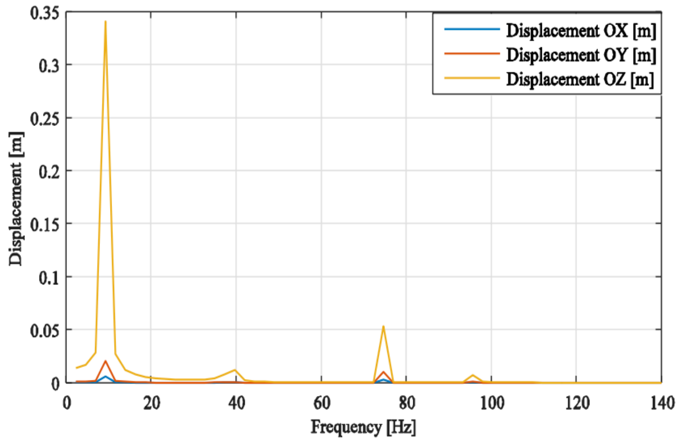
We had calculated the response of the blade exposed to a wind speed for several frequencies, which allow us to obtain some graphs of stress and displacement according to these frequencies.

The Harmonic analysis results are represented on a graph form generally known by the term FRF[66]: frequency response function. For this analysis, The FRF is revealed in the following figures, which showed the most aggressive behavior on a cyclic load, Figure 8 shows the variation of displacement according to operating frequency and Figure 9 shows the variation of Von-misses stress.

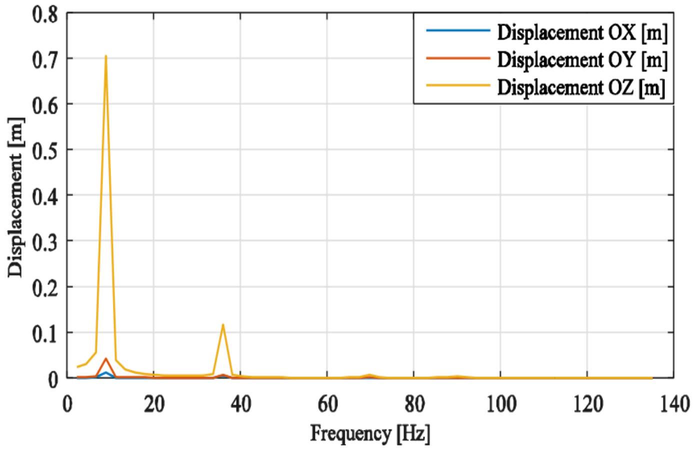
7.2. Harmonic analysis of all materials:

7.2.1. Displacement

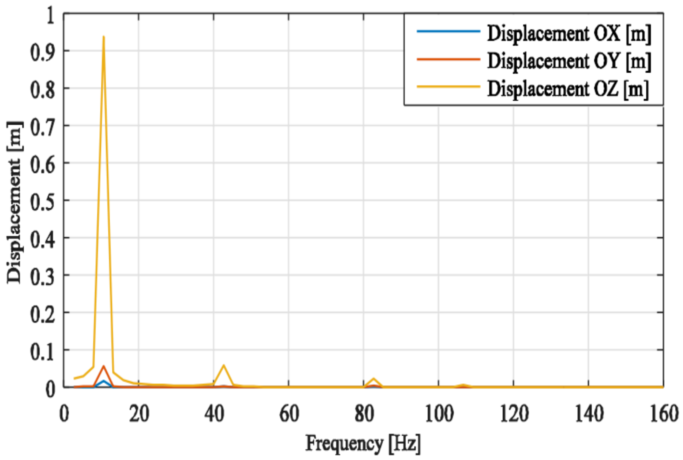
From the harmonic analysis, the displacements of various nodes over the entire frequency range 0 to 140 Hz with amplitude were obtained for Aluminum Alloy and glass fiber composite, and over the entire frequency range 0 to 160 Hz with amplitude were obtained for hemp fiber composite, based on the results of the natural frequencies. The observed peaks in the frequency response graphs were plotted. Figure 8 (a, b, c) shows the variation of displacement in X, Y and Z directions with frequency at node 9.33 for aluminum Alloy, 9 for Glass fiber composite and 10.667 for hemp fiber composite. The maximum component displacement of the X, Y and Z directions obtained in the harmonic analysis for the aluminum blade, the glass fiber composite blade and the hemp fiber composite blade due to the ANSYS pressures are given in Table No 7.



(a)



(b)



(c)

Fig. 8. Component of Displacement versus Frequency response graph; (a) Displacement Aluminum Alloy, (b) Displacement Glass fiber composite, (c) Displacement Hemp fiber composite

Table 7. Maximum Displacement in all three directions

	Aluminum Alloy	
	Max (m)	Frequency [Hz]
Displacement X-Component	0.006	9.3333
Displacement Y-Component	0.020	9.3333
Displacement Z-Component	0.3407	9.3333

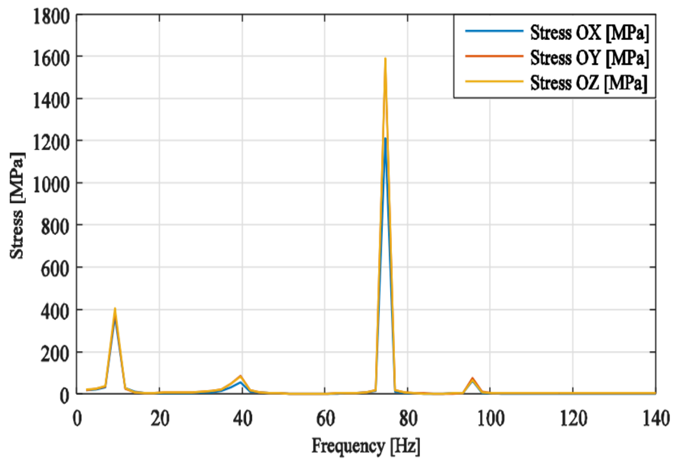
	Glass Fiber	
	Max (m)	Frequency [Hz]
Displacement X-Component	0.012	9
Displacement Y-Component	0.042	9
Displacement Z-Component	0.70559	9

	Hemp Fiber	
	Max (m)	Frequency [Hz]
Displacement X-Component	0.016	10.667
Displacement Y-Component	0.056	10.667
Displacement Z-Component	0.93583	10.667

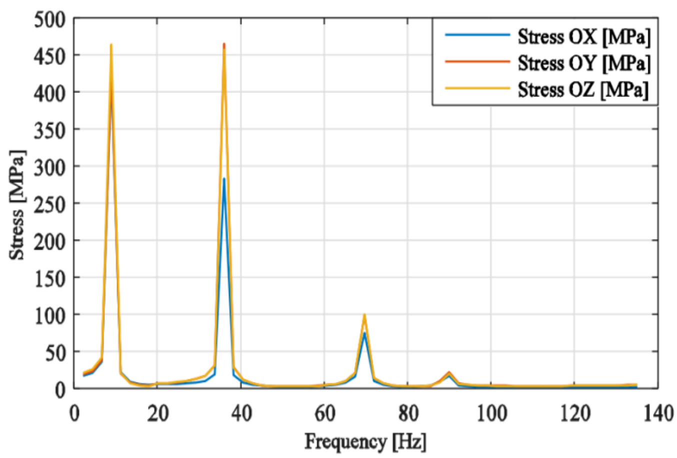
Figure 8, shows that the displacement curve represents the vibration amplitude defined as a maximum displacement along the X, Y and Z directions for all materials used. All graphs clearly show the spectrum that represents the resonance frequency is similar for all three materials over the entire frequency range. These spectra show the presence of a dominant amplitude component in the frequency of the blades. This is the answer to aerodynamic forces, it means that our blade works in all three modes flap, Edge and torsional, safely.

7.2.2. Stress

As a result of the harmonic analysis, the stresses of the different elements over the entire frequency range from 0 to 140 Hz with amplitude were obtained for Aluminum Alloy and glass fiber composite, and over the entire frequency range from 0 to 160 Hz with amplitude were obtained for hemp fiber composite. The peaks observed in the frequency response graphs were plotted. Figure 9 (a, b, c) shows the stress variation in X, Y and Z directions with a knot frequency of 74,667 for Aluminum Alloy, (9 in direction (x, z) and 36 in direction (y)) for glass fiber composite and 10.667 for Hemp fiber composite. The maximum stress of the components of the X, Y and Z directions obtained in the harmonic analysis for the aluminum blade, the glass fiber composite blade and the hemp fiber composite blade due to ANSYS pressures is given in Table No 8.



(a)



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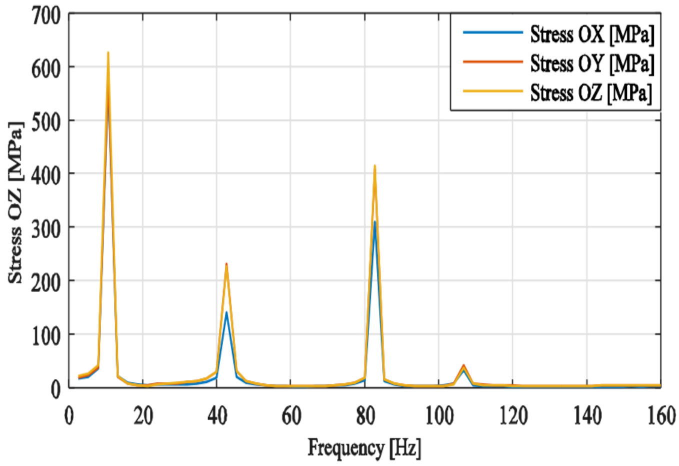

(c)

Fig. 9. Component of Stress versus Frequency response graph; (a) Stress Aluminum Alloy, (b) Stress Glass fiber composite, (c) Stress Hemp fiber composite

Table. 8. Maximum stress in all three directions

	Aluminum Alloy	
	Max (MPa)	Frequency [Hz]
Stress X-Component	1.21E+03	74.667
Stress Y-Component	1.58E+03	74.667
Stress Z-Component	1.59E+03	74.667

	Glass Fiber	
	Max (MPa)	Frequency [Hz]
Stress X-Component	4.23E+02	9
Stress Y-Component	4.65E+02	36
Stress Z-Component	4.65E+02	9

	Hemp Fiber	
	Max (MPa)	Frequency [Hz]
Stress X-Component	5.69E+02	10.667
Stress Y-Component	5.81E+02	10.667
Stress Z-Component	6.26E+02	10.667

- From to the results of the harmonic analysis, the hemp composite blade is protected from resonance phenomena.
- The harmonic analysis is performed on the aluminum, glass composite and hemp composite blades, it has been observed that the maximum stress of the composite blade is lower than that of the aluminum blade.
- The weight of the hemp fiber composite blade is 29% less than that of the glass fiber composite and 53.2 % less than that of the aluminum blade.
- The hemp composite can replace glass composite and aluminum wicking in the design of wind turbine blades in all safety.
- This study helps predict the frequency of blade operation.

8. Conclusion

Based on the structural analysis, we conclude that the Von-Misses stress induced in the wind turbine blade is 45.92 (MPa). This maximum stress value is less than the permissible stress of the material and meets the design requirements.

Modal analysis and harmonic analysis show that the blade operates stably under resonance conditions, resonance does not occur, which clearly indicates that the blade is sheltered from resonance phenomena for all three materials. A harmonic response within a specified range is also acceptable because the maximum value of the stress is much less than the static stress.

The results show that there are good agreements between the three materials in terms of strength, but the hemp fiber composite blade has higher natural frequencies than the aluminum alloy blade and the glass composite blade.

This study concluded that hemp fiber composite blades have advantages over other blades (aluminum alloy blade and the glass fiber composite blade) because hemp is a natural, recyclable, available and less expensive material.

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