World Journal of Environmental Research

Volume 8, Issue 1, (2018) 026-036

www.wjer.eu

Investigation of modal analysis of new materials for wind turbine blade

Rabie Elalaoui*, Equipe Energetic, Mechanical and Industrial Systems (EMISys) Research Team, Engineering Smart and Sustainable Systems (Engineering 3S) Research Center, Mohammadia School of Engineers, University Mohammed V in Rabat, Rabat 8007, Morocco

Hamid Mounir, Equipe Energetic, Mechanical and Industrial Systems (EMISys) Research Team, Engineering Smart and Sustainable Systems (Engineering 3S) Research Center, Mohammadia School of Engineers, University Mohammed V in Rabat, Rabat 8007, Morocco

Boudi Elmostapha, Equipe Energetic, Mechanical and Industrial Systems (EMISys) Research Team, Engineering Smart and Sustainable Systems (Engineering 3S) Research Center, Mohammadia School of Engineers, University Mohammed V in Rabat, Rabat 8007, Morocco

Abdellatif Elmarjani, Equipe Energetic, Mechanical and Industrial Systems (EMISys) Research Team, Engineering Smart and Sustainable Systems (Engineering 3S) Research Center, Mohammadia School of Engineers, University Mohammed V in Rabat, Rabat 8007, Morocco

Suggested Citation:

Elalaoui, R., Mounir, H., Elmostapha, B. & Elmarjani, A. (2018). Investigation of modal analysis of new materials for wind turbine blade. *World Journal of Environmental Research*. *8*(1), 026–036.

Received from December 18, 2017; revised from February 21, 2018; accepted from March 10, 2018;
Selection and peer review under responsibility of Prof. Dr. Haluk Soran, Near East University, Cyprus.

* ADDRESS FOR CORRESPONDENCE: **Rabie Elalaoui**, Equipe Energetic, Mechanical and Industrial Systems (EMISys) Research Team, Engineering Smart and Sustainable Systems (Engineering 3S) Research Center, Mohammadia School of Engineers, University Mohammed V in Rabat, Rabat 8007, Morocco. *E-mail address*: elalaoui.rabie@gmail.com / Tel.: +223 71 99 02 82

Abstract

The aim of this study is the search for new material for the manufacture of wind turbine blades in order to improve its performance and to reduce its cost. A composite material based on hemp natural fibres is studied. A numerical simulation using the finite element method is developed and a comparison of the performances of the new material with the usual composite of carbon fibres and glass is performed. The simulation allows us to calculate the proper values and the Eigenmodes of a wind turbine blade in the rotation. The results showed that the epoxy matrix allows to reduce the weight of composite hemp/epoxy relative to other matrix. It is almost 4.6% lighter than hemp/phenolic and 1.9% that hemp/polyester, so the blades hemp/epoxy has several advantages over the blades hemp/phenolic or over the blades hemp/polyester: this new material is characterised by lower weight and lower cost and has better mechanical features.

Keywords: Eigenmode, proper values, new material, blade, rotation.

1. Introduction

Renewable clean energy investigations have been increased rapidly, owing to critical issues such as high oil price, finite fossil fuels and pollution. Thus, among the different sources of renewable clean energy, wind energy is one of the fastest growing forms (Aye, 2011; Jureczko & Pawlak, 2005; Lilia, 2012; Ottmar, Edenhofer, Ramon, Pichs-Madruga & Youba, 2011; Quang, n. d.).

The emerging demand for energy stimulates researchers to design wind turbines with highly efficient blades. These latter are critical components of turbines and they are susceptible to failure due to stresses arising primarily from bending forces. A concentrated study was done by Xiong and et al. Liu (2010) used experimental and theoretical methods to study the analysis of the dynamic response of the rotating blade of the turbine with horizontal axis wind solving structural dynamic equation using the Newmark method and dynamic response global blade is obtained based on the principle of modal superposition, and Tartibu (2013) used experimental modal analysis that was performed on a uniform and stepped mild steel beam to extract the first five natural frequencies, the results were compared. In order to design a highly effective composite, it is essential to consider the blade material that satisfies the complex design constraints of Attaf (2010): high strength, lower weight and high resistance to the fatigue phenomenon (Mahri & Rouabah, 2002). If we desire to obtain a proper wind turbine, firstly, we have to design the blade structure theoretically. Then, we can do some calculation and analysis to verify the results of the blade design. Indeed, it is essential to inspect the vibration characteristic of the blade structure.

The present investigation focused on simulation predictions of the performance of a new material blade turbine. Our objectives are to 1) define the proper values and the eigenmodes of the blade in rotation; 2) establish the natural frequencies. This paper is organised as follows. Theoretical methods are described initially. The results are then presented and discussed. Finally, concluding remarks are provided.

2. Blade description

2.1. Blade wind turbine

Table 1. The characteristics of the wind turbine blade

Property	
Length (m)	2.54
Mass (kg)	10.624
Volume (m^3)	0.008
Area (m^2)	0.670

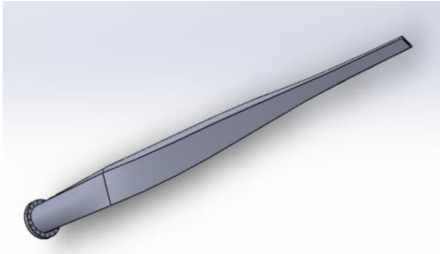

Figure 1. Geometry of the wind turbine blade (SolidWorks)

2.2. Hemp fibre

Hemp is an easy resource to grow and renewable just waiting to be used. This plant contains a truly revolutionary potential (Figure 2) because it could effectively replace a large number of practical and industrial products, and the benefits of this beautiful plant are easily observable. Hemp has vast practical applications as a renewable and sustainable resource in almost all major areas of the economy (Rabie, Mounir, Boudi & Marjani, 2015). However, due to decades of propaganda and disinformation, hemp is still not receiving the attention it deserves, because it is a light material with good strength (Table 2; Rabie et al., 2015).

Table 2. The characteristics of the hemp fibre (Ringuette, 2011)

	Hemp
Density (g/m3)	1.48
Tensile modulus (E, GPa)	70
Resistance to traction (σr, MPa)	389
Elongation at break (%)	1.6
Price (€/kg)	0.60–1.30

Figure 2. Hemp plant (Rabie et al., 2015)

3. Modelling

From the perspective of modelling, properties such as mass and stiffness distributions have great importance for the dynamic behaviour of the wind turbine blade (Rominger & Nepf, 2014). This latter can be considered as a beam structure of type mass-spring. There are several types of beam elements which can be used. The most common type is based on the Euler–Bernoulli because of the thin nature of the structure (Bot, 1994) which makes low shear effects.

3.1. Law of mixtures for laminated composites

The deformations of homogeneous and isotropic materials can be described by using the modulus of elasticity and deformation stresses, which are the basic properties of the gross materials. In the case of composites, each element has a different role and it is the combination of these properties that gives the final material of its own characteristics. Although these final characteristics are the result of complex interactions between the reinforcement and the matrix, it is possible to give a simple estimation using the mixtures law of stratified composites (Busignies, 2005; Cayer-Barrioz & Smerdova, 2011):

The estimation parameters are as follows:

f_f = volume fraction of the fibre

f_m = volume fraction of the matrix

P_C = estimated property of the composite

P_f = property of the fibre

P_m = matrix property

These are theoretical values, in fact, the presence of voids that $f_f + f_m \leq f$. For example, the tensile modulus of elasticity can be estimated based on the respective modulus of the fibre and the matrix. This equation can be modelled by a system of springs associated in parallel (Habib, Abdellah, Ouinas & Ahmed, 2014).

$$E_C = (E_f f_f + E_m f_m)$$

where

E_C = tensile module of the composite felt

E_f = module of elasticity in traction of the fibre

E_m = module of elasticity in traction of the matrix

f_f = volume fraction of fibre

f_m = volume fraction of matrix

However, the rule of mixtures to the constraints applied is (Rouby, 2005):

$$\sigma_C = \sigma_f f_f + \sigma_m f_m \quad (1)$$

Young's modulus of the composite:

$$E_C = E_f f_f + E_m f_m \quad (2)$$

Law of mixtures on the modulus is:

- well (if there are no empty): $f_f + f_m = 1$,
- in the L direction (direction of fibres), if the composite works optimally.

The density of the composite material is derived based on the following volume fractions

$$\rho_c = \rho_f f_f + f_m \rho_m \tag{3}$$

3.2. General information about hemp fibre

Cannabis is more commonly known as hemp; it is a plant of the family Cannabaceae. The historic market fibres from these cultures are stationery. Its rapid growth and the fact that most of the time it does not require the use of pesticides make it as a very interesting plant economically and ecologically. Its strength allows it to grow in a climate less specific than flax. The percentage of cellulose and hemicelluloses content in hemp fibres is as high enough for flax, also the proportion of lignin is higher. Lignin is playing a chief role in the structuring of cellulose fibrils, this difference could explain the higher rigidity of hemp fibre (Ringuette, 2011).

3.3. Calculation of composites

Table 3. Property of the matrix epoxy, phenolic, polyester and hemp fibre (Nguyen, 2008)

	Epoxy	Phenolic	Polyester	Hemp
Density (g/m3)	1.5	1.20	1.14	1.48
Tensile modulus (E, GPa)	4.5	4	3.45	35
Resistance to traction (σr, MPa)	75	40	70	389

Applying the formulas (1), (2) and (3)

- For 40% of the fibre

Table 4. Hemp fibre properties according to the three matrixes

	Hemp/epoxy	Hemp/phenolic	Hemp/polyester
Density (g/m^3)	1.252	1.312	1.276
Tensile modulus (*E*, GPa)	17	17	16.16
Resistance to traction (*σr*, MPa)	203.6	179.6	206.6
Elongation at break (%)	1.84	2.14	1.84

3.4. Dynamic study

An excitation frequency of the rotating system is integer multiples of the speed of rotation.

The designer must ensure that the resonant frequencies are not too excited, although the dynamic loads on the blades (Chelirem, 2010).

The rotating blade subjected to aerodynamic forces is considered an embedded length L of a transversely vibrating straight beam (Carrera, Filippi & Zappino, 2013). The model of the blade was made from a beam Bernoulli model. It is equated to a blade beam of homogeneous mass M of length L and an equivalent section S rotating about a fixed point O with a ω turnover, the beam is cut into N segments of length $l = L/N$, and mass $m = M/N$. Each section is modelled by the spring-mass model as discussed previously.

For a beam element dl and mass $dm = \rho \cdot S \cdot \mathrm{d}l$, spring stiffness '$k$' is a function of Young's modulus E (Chelirem, 2010): $k = \frac{ES}{dl}$

Also, the mass *m* is evenly distributed to the two ends.

Continuous model: $\frac{\partial}{\partial r}\left(ES\frac{\partial u}{\partial r}\right)=\rho S\omega^2 r+C\cdot L$

$$u(r=0)=0$$

$$ES\frac{\partial u}{\partial r}(r=R)=0$$

Discrete model: $\begin{bmatrix} k & -k \\ -k & k \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}=\begin{bmatrix} f_1 \\ f_2 \end{bmatrix}$ (4)

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & k_1+k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2+k_3 & -k_3 \\ 0 & 0 & k_3 & k_3 \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix}=\begin{bmatrix} 0 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \quad (5)$$

To define the modes of vibration in traction compression pale, we consider a system of *N* 'mass/spring' and the static equilibrium is obtained by solving the following linear system:

$$\boldsymbol{K}\{\bar{U}\}=\{F\}$$

where ***K*** is the stiffness matrix of dimension $(N+1)^2$; $\{\bar{\boldsymbol{U}}\}$ is the vector of displacements at the nodes (*N* dimensional); {*F*} is the vector of forces applied to the nodes (*N* dimensional).

By putting aside the system from its equilibrium position, it starts to oscillate. The vector of shifting at the nodes $\{\boldsymbol{U}(t)\}$ is dependent of time and also is a solution of the following:

$$M\left\{\frac{d^2U}{dt^2}\right\}=\{\boldsymbol{F}\}-\boldsymbol{K}\{\boldsymbol{U}\}$$

or by introducing the vector of {***u***} oscillations around the static equilibrium position:

$$M\left\{\frac{d^2\boldsymbol{U}}{dt^2}\right\}=-\boldsymbol{K}\{\boldsymbol{u}\} \quad (6)$$

We obtain a system of *N* + 1 linear differential equations of second order by giving the amplitude of movement relative to the balance at the initial time (the system is released without initial velocity).

$$\{\boldsymbol{u}(t=0)\}_{i=1,\ N+1}=\{\boldsymbol{u}_0\}, \left\{\frac{d\boldsymbol{u}}{dt}\right\}_{i=1,\ N+1}=\{0\}$$

Then, Eq. (6) has a unique solution. This solution is a linear combination of the modes of natural vibration, which are basic solutions of Eq. (6). Equation (6) can be rewritten as:

$$\left\{\frac{d^2\boldsymbol{U}}{dt^2}\right\} = -\mathrm{A}\left\{\boldsymbol{u}\right\} avec \mathrm{A} = M^{-1}\boldsymbol{K} \quad (7)$$

where A is a symmetric positive that define matrix if $X^t \mathrm{A} X > 0 \forall X \neq 0$

This matrix is diagonalised and has (N + 1) positive eigenvalues $\left\{\lambda_k\right\}_{k=1,\ N+1}$

Each λ_k values is associated with an eigen vector Λ^k, satisfying: $\mathrm{A}\left\{\Lambda^k\right\} = \lambda_k\left\{\Lambda^k\right\}$

An elementary solution of Eq. (7) can be written: $\left\{\boldsymbol{u}^k\right\} = \left\{\Lambda^k\right\} e^{j\sqrt{\lambda_k t}}$

As:

$$\mathrm{A}\left\{u^k\right\} = (\mathrm{A}\left\{\Lambda^k\right\})e^{j\sqrt{\lambda_k t}} = \lambda_k\left\{\Lambda^k\right\} e^{j\sqrt{\lambda_k t}}$$

$$\left\{\frac{d^2\boldsymbol{u}^k}{dt^2}\right\} = \left\{\Lambda^k\right\}\frac{d^2 e^{j\sqrt{\lambda_k t}}}{dt^2} = j^2\lambda_k\left\{\Lambda^k\right\} e^{j\sqrt{\lambda_k t}} = -\lambda_k\left\{u^k\right\}$$

These basic solutions are independent and form a basis of solutions (Eq. (7)).The general solution of Eq. (7) is a linear combination of these elementary solutions that check the initial condition: $\left\{\boldsymbol{u}\right\} = \sum_{k=1}^{N+1}\alpha_k\left\{\Lambda^k\right\} e^{j\sqrt{\lambda_k t}}$ These basic solutions $\boldsymbol{u}_k$ are the modes of natural vibrations of the system, associated with natural frequencies $f_k = \frac{\sqrt{\lambda_k}}{2\pi}$.

3.5. Calculating a wind turbine blade

3.5.1. Idling frequency

The lambda value (λ) characterises the relationship between the speed blade tip and wind speed.

$$\lambda = \frac{V_{\text{blade}}}{V_{\text{wind}}} \quad (8)$$

Depending on the rotor diameter, tip speed of the blade follows the rotational frequency *N*. Therefore, λ directly affects the rotation frequency for a given wind speed.

The specific speed or the speed parameter noted λ is the ratio between the tip speed of the blades and the wind speed. The machines can be classified according to the following parameters:

If λ is less than 3, then the turbine is called slow

If λ is greater than 3, then the turbine is said to be fast

For $\lambda = 7$, rotation frequency = 263 tr/minute = 4 tr/second

3.5.2. Support rotation frequency

A blade running on empty by definition produces nothing. To produce energy, you have to load the curb. The recovered energy is converted into electricity by an alternator.

Betz's law states that energy can be recovered conveniently when $C_p = 16/27$ of the wind power provided that $V_{downstream} = V_{uphill}/3$. But whether the equation is true for any sliding?

In other words, the calculation we consider that the page is in charge when its speed is two-third (33% of sliding) its idle speed, to check.

$$V_{blade} = V_{wind} * \lambda * (100de)/100 \quad (9)$$

'g = sliding in %' = 33%

Rotation frequency = 176 tr/minute = 3 tr/second

4. Results and discussion

The traction modes obtained by solving the differential equation are represented in Figures 2–4.

Characteristic of the blade are as follows:

Length $L = 2.54$;

Equivalent section $S = M/(\rho * L)$;

Total stiffness $k = E * S/L$;

Revolutions per minute $\omega = 176$;

$N = 100$.

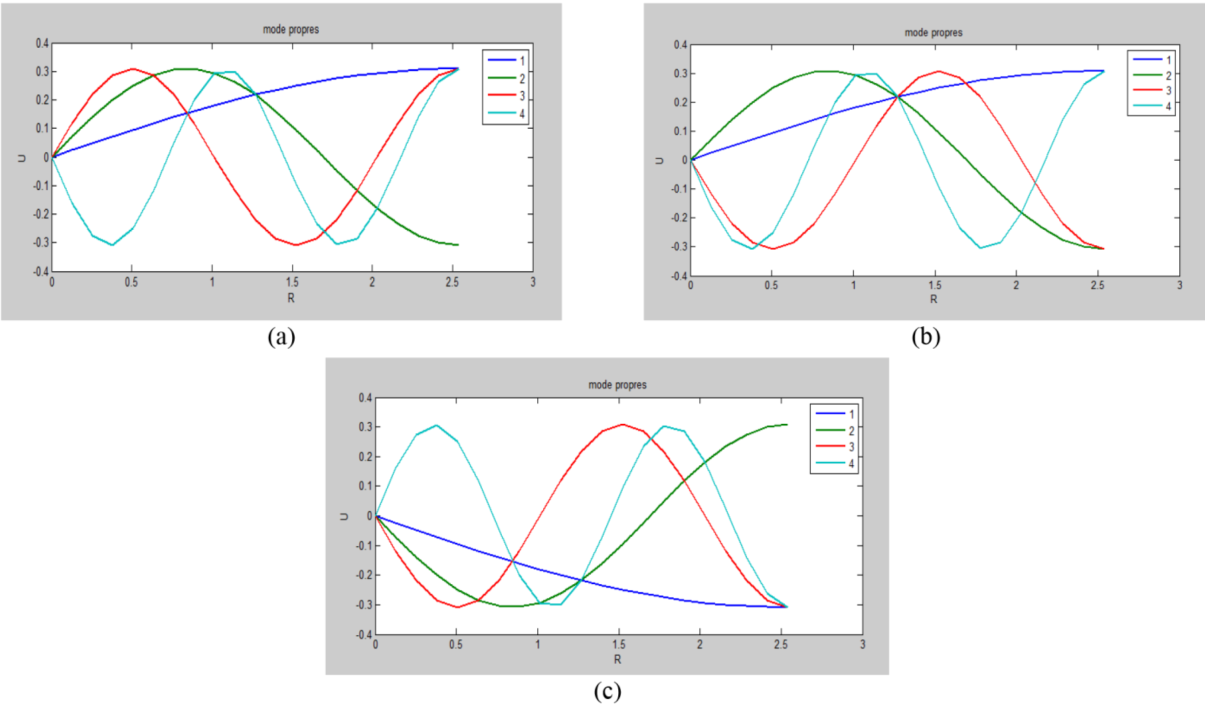

Figure 3. (a) Mode proper for hemp/epoxy. (b) Mode proper for hemp/phenolic. (c) Mode proper for hemp/polyester

The MATLAB program was used to compute the natural frequencies. The results found using MATLAB program were compared. The first four natural frequencies of the blade are calculated successively for three different materials. Figures 2–4 show the results obtained for materials 1 to 3. Comparison of results for the materials is presented in Table 3.

Table 5. Frequencies of blade

	Hemp/epoxy	Hemp/phenolic	Hemp/polyester
Reference pulse	2.06e + 03	2.01e + 03	1.98e + 03
Mode 1	2.29e + 03	2.23e + 03	2.20e + 03
Mode 2	6.82e + 03	6.66e + 03	6.59e + 03
Mode 3	1.13e + 04	1.11e + 04	1.09e + 04
Mode 4	1.58e + 04	1.54e + 04	1.52e + 04
Rotation speed		18.325957	

The results show that the first natural frequencies of the blade of the first material are higher than a material of the other blade; this demonstrates improved flexibility of the blade hemp/epoxy materials.

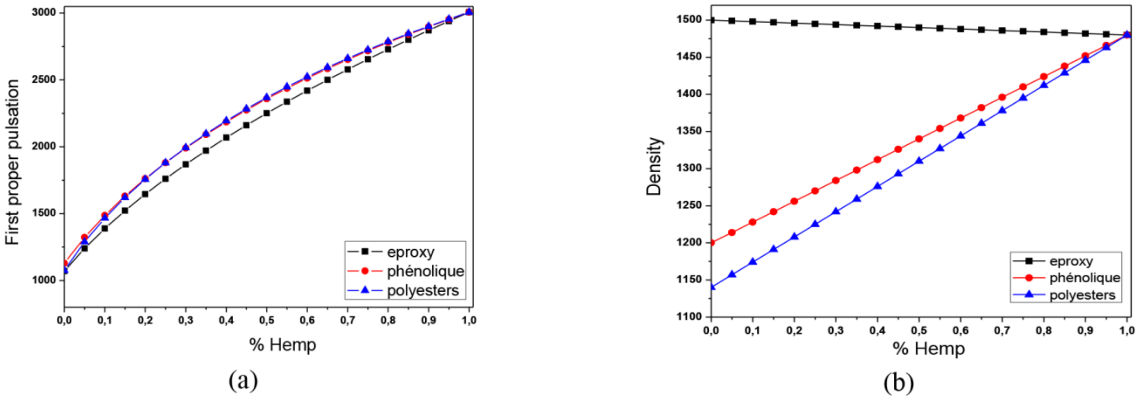

Figure 4. (a) The first natural frequency changing the blade against the three matrices. (b) The development of the hemp material density based on the three matrices.

Blades designed in turbines are composed principally of fibre composite materials so that the design is lightweight, rigid and with a high fatigue endurance and life is achieved. Indeed, in order to get better insights into the pulsation characteristics of the three materials, we plot the first pulsation as a function of the portion of hemp. As shown in Figure 3(a), the first pulsation increases with the increase in the portion of hemp for the three matrices which indicate that the hemp material has a better performance. Also, we note that the epoxy matrix has a small pulsation than that of phenolic and polyesters matrices that have an equal pulsation. This result can be understood by looking at Figure 3(b); we can see that both blades designed with the phenolic and polyesters matrices have the small density which is good for a blade. It is interesting to point out that the blade made with polyesters matrix is the best due to its small density.

In the following, we examine the effect of the blade length on the first pulsation. For this purpose, we plot the first pulsation as a function of the portion of hemp for different blade length (Figure 4). We can have inferred from this figure that as the length of the blade decreases as the first pulsation increases. Furthermore, it is clear that even if the blade length is changed the density still constant. Indeed, the shorter blade is, the higher pulsation and performance are.

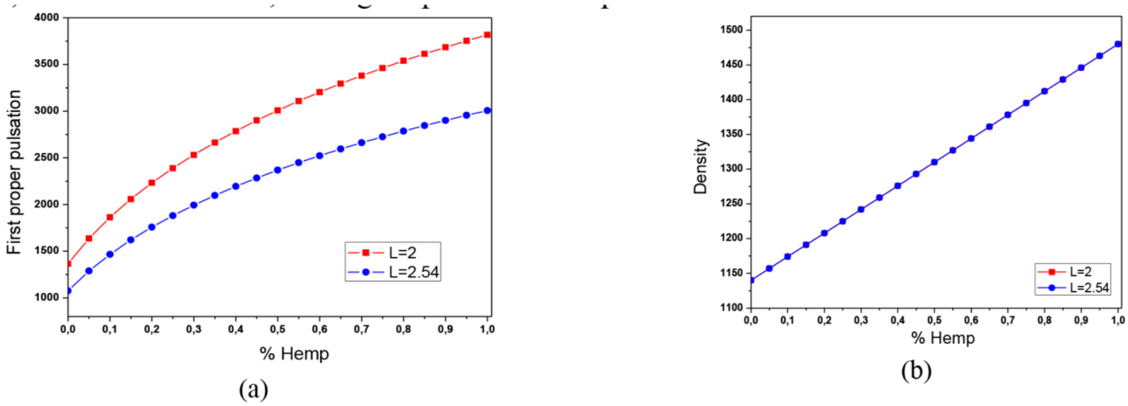

Figure 5. (a) The first natural frequency changing the blade according to the blade length. (b) The change in the density of the blade as a function of the percentage of hemp fibre. The blade is made with polyesters matrix.

5. Conclusion

The main objective of this study is to investigate the performances of new composite material based on hemp natural fibres for a blade wind turbine. A numerical simulation was developed and the equations describing the pulling movement are processed using the method of Bernoulli. The results were compared with the performance of the usual composite material. The results showed that the blades hemp/epoxy have several advantages over the blades hemp/phenolic or blades hemp/polyester. The epoxy matrix allows reducing the weight of composite hemp/epoxy relative to another matrix. It is almost 4.6% lighter than hemp/phenolic and 1.9% that hemp/polyester.

We demonstrated that the first natural frequencies of the blade of the first material are higher than a material of the other blade, this shows improved flexibility of the blade hemp/epoxy materials.

As prospects for future work, the development of a comprehensive model is suggested to consider other modes of lateral deformations, the results of this modelling can be used to calculate the dynamic stresses, in order to estimate the fatigue of the pale thereafter.

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