Journal of Naval Architecture and Marine Engineering
June, 2021
http://doi.org/10.3329/jname.v18i1.53193 *http://www.banglajol.info*

MODAL ANALYSIS OF COMPOSITE NOZZLE FOR AN OPTIMAL DESIGN OF A TIDAL CURRENT TURBINE

H. Laaouidi[1]*, M. Tarfaoui [2], M. Nachtane [2], M. Trihi[1], O. Lagdani[1]**
[1]FSAC - UH2C, Laboratory for Renewable Energy and Dynamic Systems, Morocco
[2]ENSTA Bretagne, IRDL UMR CNRS 6027, F-29200 Brest, France

Abstract:

Monitoring of structural vibrations and operational modal analysis are clearly essential to effectively control structural safety and the operational behavior of tidal current turbines. In order to satisfy industrial requirements, generally related to a mass gain problem, hybridization provides an excellent method to improve the breaking strength of composite materials, while keeping adequate mechanical performance for marine renewable energy applications. In this context, this work aims to study the structural modal analysis of a tidal turbine nozzle and the effect of hybrid materials (carbon/Glass) on the natural frequencies and corresponding mode shapes of the three laminates. The modal analysis was calculated by the Finite Element Method using ABAQUS software. According to the results, the stacking sequence has a considerable impact on the natural frequency of the nozzle. Furthermore, it is also found that the resonance effect does not appear for the three laminates under investigation.

Keywords: Tidal current turbine, hybrid fibers composite, stacking sequence, natural frequencies of vibration, global stability, resonance, finite element analysis

NOMENCLATURE

$\bar{u},\bar{v}$	velocity components
ρ	Density
E_1, E_2, G_{12}	Undamaged material moduli
$N_{1,2}$	Undamaged material Poisson's ratios
F_r	The loading frequency
$F_{0,n}$	The n-th natural frequency of the
U	Displacement

Greek symbols

CCC	Carbon/Carbon/Carbon
GGG	Glass/Glass/Glass
CGG	Carbon/Glass/Glass
FEM	Finite Element Method
RME	Renewable Marine Energy
TCT	Tidal Current Turbine
BEMT	Blade Element Moment Theory
FRP	fiber-reinforced polymer

1. Introduction

Due to the fast growth of the global economy, energy consumption has greatly increased in recent years. The enormous consumption of fossil fuels leads to serious greenhouse gas emissions and climate change; all this poses some challenges for the protection of the environment (Tarfaoui et *al*., 2018). Renewable Marine Energies (RME) are attracting increasing attention worldwide due to the problem of the greenhouse effect, and the energy crisis (Nachtane et *al*., 2020). The production of energy from marine currents has taken a big step forward, moving from conservative-type systems to large-scale machines. The utilisation of marine current turbines offers an exciting proposition for the extraction of energy from marine currents. Several industries are now working to develop various forms of devices to exploit the energy resources of ocean currents throughout the world (El-Shahat et *al*., 2020). Recently, Tidal Current Turbines (TCTs) have been implemented as systems to convert marine currents into electrical energy. They have received particular attention as a highly attractive renewable energy resource, predictable with high energy flux density (Nachtane et *al*., 2017). Indeed, the TCTs are subject to high loads due to marine currents and waves, which must be correctly predicted. These stresses lead to an acceleration of fatigue, which results in the failure of the turbine (El-Shahat et *al*., 2020). Therefore, this technology must be constructed in the most secure way possible to resist different loadings. In this context, composite materials perform a crucial part in the development of marine renewable energy conversion technologies under difficult environmental conditions (Nachtane et *al*., 2018). These composite materials are very promising for various technical applications as they offer excellent performance in terms of high specific

1813-8535 (Print), 2070-8998 (Online) © 2021 ANAME Publication. All rights reserved. Received on: April, 2021

stiffness and strength, good dynamic and static properties, and good corrosion resistance (Santos et *al*., 2020). They are therefore the ideal choice for hydrokinetic turbine designers.

In recent years, the control of the behavior of composite turbines has improved extremely well. Porter et *al*. (2020) analyzed experimentally the behavior of a horizontal axis turbine with three blades under conditions of co-directional wave current. The turbine was evaluated with both composite blades and rigid aluminium blades to describe, by comparison, the torsion-curve response under these flow conditions. Fagan et *al*. (2016) analyzed the loads affecting the blades of a tidal turbine employing a hydrodynamic model that uses Blade Element Moment Theory (BEMT). Furthermore, using sub-modelling methods in Abaqus, a stress-strain and failure analysis was carried out. The materials used in this study were glass and carbon fiber-reinforced composites. Nachtane et *al*. (2020) studied the effect of environmental impacts on the mechanical properties of a tidal turbine composed of glass fiber-reinforced polymer composite. The results obtained showed that damage was observed in different areas of the structure. According to the literature, the stratified structure of fiber-reinforced composites and the characteristics of their constituent properties (fiber and matrix) frequently make their structural performance susceptible to transverse impact loading. For example, according to Santhanam et *al*. (2020) composite materials made from a single reinforcing fiber tend to absorb moisture in a marine environment, which results in a weakening of the composite. For this reason, much research has been conducted to ameliorate the impact resistance and damage resistance of fiber-reinforced composite laminates. Recourse of laminate hybridisation has demonstrated that it is possible to reduce impact damage and improve the structural characteristics of damaged stratified (Damghani et *al*., 2019). In general, hybrid laminates consist of different fiber layers as for example carbon and glass fibers in a single polymer matrix. Indeed, an analysis of the literature reveals a total absence of studies on the application of hybrid composites in tidal current turbines.

The conception of a horizontal axis tidal current turbine involves many important factors in terms of strength, cost, and stability. Vibration reduction is an important step for a suitable rotor blade structure. To minimize vibration, a good conception consists of separating the natural frequencies of the structure from the harmonics of the rotor speed. This prevents resonances when high vibration amplitudes could seriously destroy the structure (Tarfaoui et *al*., 2013). Following the rising application of Fiber-Reinforced Polymers (FRPs) in modern engineering structures such as wind and tidal turbines, the problem of FRP fatigue is attracting particular attention. During the fatigue process of composite materials, stiffness evidently diminishes, and the calculation of the natural frequency of the structure is only dependent to rigidity. Thus, the variation of the natural frequency can be used as a way to explain the fatigue damage of composite materials (Wu et *al*., 2020).

Currently, no investigations on the attenuation of the natural frequency of tidal current turbines have been carried out. In contrast, much research has been conducted on the stability problems of offshore wind turbine structures because of the trend towards bigger and more flexible structures. However, comprehensive knowledge of the natural frequencies ensures and guarantees ideal dynamic behavior of the wind turbine, when it is exposed to aerodynamic forces. For example, a study was conducted by Dong et *al*. (2018) on structural vibration monitoring and operational modal analysis of the structure of offshore wind turbines. It was reported in their article that the increase in modal frequency and damping ratio progressively rise with wind speed and blade rotation velocity. On the other hand, the works conducted in this article (Thomas et *al*., 2017*)* shown that by using the spar caps, the blade mass can be decreased and the stiffness at the edge can be improved. Moreover, defining natural mode shapes and frequencies of the blade are of great interest, particularly for the first four-five modes, where the frequencies are the smallest (Cai et *al*., 2013). In this context, Tarfaoui et *al*. (2013) studied the modal analysis of a wind turbine blade and the influence of the spar shape by determining the natural frequencies for various spars and for the complete blade. The study demonstrated that the resonance phenomenon did not happen for the rotor blade.

Two research works (Laaouidi et *al*., 2021, Laaouidi et *al*., 2020) have been conducted to analyze the response of a hybrid composite nozzle under impact during a maintenance operation. This can lead to complex damage modes in the nozzle, capable of harming their structural integrity. In this context, a numerical simulation of progressive damage based on the Hashin criterion was conducted to predict failure modes. According to the literature, no studies have been conducted on tidal turbines made of hybrid composite materials in order to determine mode shapes and natural frequencies using the modal analysis technique. Indeed, the Investigation on vibration behavior and modal analysis of tidal current turbines (TCTs) offers technological support for the assessment of operational safety and the practical basis for the conception and maintenance of tidal turbine designs (Tarfaoui et *al*., 2013). Base on this motivation, this work aims to examine the structural modal analysis of a tidal turbine nozzle and the effect of hybrid materials (carbon/carbon/carbon, glass/glass/glass, and carbon/glass/glass) by identifying the natural frequencies and characterizing the vibration mode shapes of the three laminates. The model was evaluated numerically using ABAQUS software that uses the finite element approach to identify all significant behavioural and stability issues. The numerical results showed that the stacking sequence has a significant impact on the natural frequency, displacement and resonance of the structure. This study could subsequently contribute as a reference for a more detailed study of the tidal current turbine's vibrations, structural dynamics, and other problems. First, this paper presents a description of the structure, the hybrid materials and the boundary conditions studied. Then, a presentation of the numerical model and a study on the convergence of the mesh were conducted. At the end, some results and discussions have been presented.

2. Structure and Mechanical Properties of Composites

2.1. Nozzle design

To estimate the natural frequencies of the ducted tidal turbine and the vibration mode shapes, the numerical model is developed in Abaqus software using finite element method. The hydrodynamic profile of the nozzle was obtained using Heliciel software as shown in Fig. 1. Fig. 2 represents the 3D nozzle of the tidal current turbine. Indeed, the total diameter of the nozzle is about 20 meters.

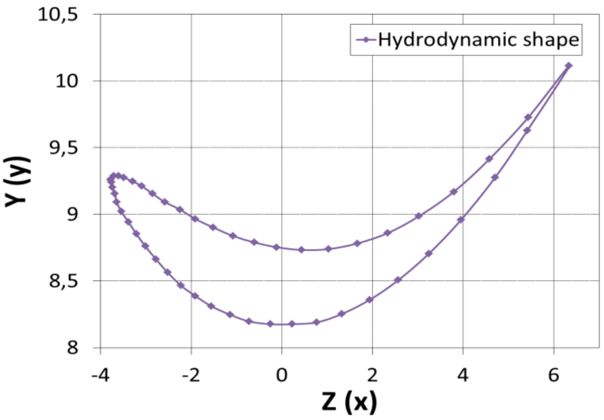
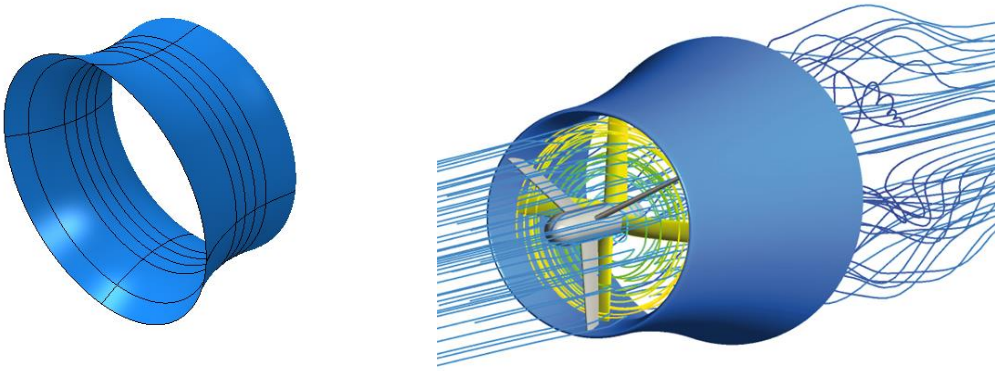


Fig. 1: Hydrodynamic profile of the ducted tidal turbine

(a) Commissioning/ installation of the tidal turbine

Fig. 2: 3D structure of a tidal current (contd.)



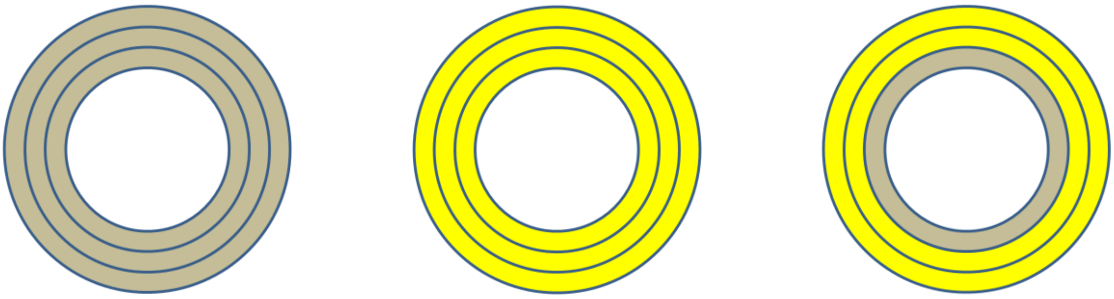
(b) CAO model

(c) Tidal current turbine in service

Fig. 2: 3D structure of a tidal current

2.2. Materials and properties

Because of the high density of seawater, marine turbines are exposed to several loads during their operation (Nachtane et *al*., 2017). In order to satisfy industrial requirements, generally related to a mass gain problem, hybridization provides an excellent method to improve the breaking strength of composite materials, while keeping adequate mechanical performance for marine renewable energy applications (Wu et *al*., 2020). In this context, the composite used in this study is a hybrid laminate immersed in an epoxy resin 0.64 mm thick per layer (Gemi et *al*., 2018). The stacking sequence configurations have been described as follows: carbon/carbon/carbon (CCC), glass/glass/glass (GGG), and carbon/glass/glass (CGG) extending from the internal to the external surface as shown in Fig. 3. The total thickness of the laminate is 9.6 mm and the composite structure layup is [0/45/90/45/0], with n=15 as shown in Fig. 4. The mechanical properties of the composites investigated in this study are illustrated in Table 1.



(a) CCC

(b) GGG

(c) CGG

Fig. 3: The stacking sequence configurations

Table 1: Properties of Glass-Epoxy and Carbon-Epoxy [3]

Properties	**Glass-Epoxy**	**Carbon-Epoxy**
ρ (kg/m^3)	1659	1238
E_1 (MPa)	26705	1928
E_2 (MPa)	7495	4598
Nu_{12}	0.28	0.32
$G_{12}=G_{13}=G_{23}$ (MPa)	2833	1729

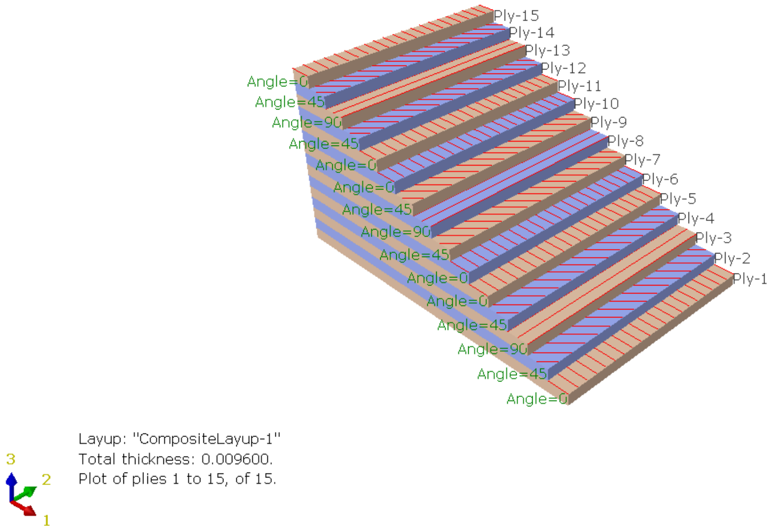
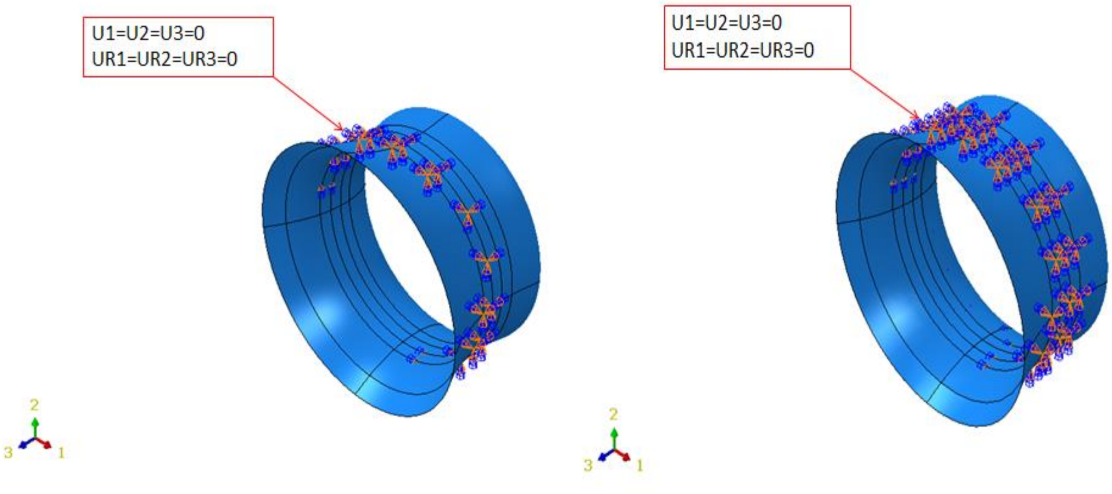


Fig. 4: Distribution of materials



(a) Case 1

(b) Case 2

(c) Real turbine

(d) Final design

Fig. 5: Boundary conditions

3. Boundary Conditions

To properly investigate the operational and environmental impacts on the mechanical properties of the tidal current turbine, similar boundary conditions of Encastre type were introduced at different locations of the nozzle as shown in Figs. 5(a) and 5(b).

In our investigation, we have adopted a mechanical joint constraint as a type of boundary conditions where the blades are embedded on a rotor that is itself attached to the stator. Figs. 5(c) and 5(d) present the fixed part of the structure.

$U1 = U2 = U3 = UR1 = UR2 = UR3 = 0$

4. Numerical Investigation

In order to study the overall behavior related to, for instance, global stress/strain levels, tip deflection, and Eigen-Frequencies. The Finite Element Method (FEM) is highly practical and has historically been successfully deployed in the development of tidal turbine blades (Luo et *al*., 2020). No publications have been conducted previously on finite element (FE) modeling using ABAQUS software to investigate all pertinent behavioral aspects and stability problems of tidal turbines. This field of research is increasingly important; given this technology is progressively becoming large enough to induce flutter instability. In this regard, the finite element modeling was developed in the Abaqus software to estimate the natural frequencies and mode shapes of the structure. In this numerical model, the composite hybrid nozzle was modeled with the shell quadrilateral S4R type element.

To reduce the calculation time and optimize the mesh model without impacting the accuracy of the simulation results, a mesh sensitivity analysis was conducted. This strategy is focused on defining an optimal mesh by analyzing the convergence of the numerical model. The evolution of the maximum deflection and stress versus the number of elements is presented in Fig. 6. The results of the various calculations are converging starting from 129490 elements with mesh size of 100 mm length. The convergence is determined from a ratio "mesh size / total size of the structure" equal to 0.005. It can be seen that the more the mesh is refined, the maximum stress increases and the maximum displacement decreases.

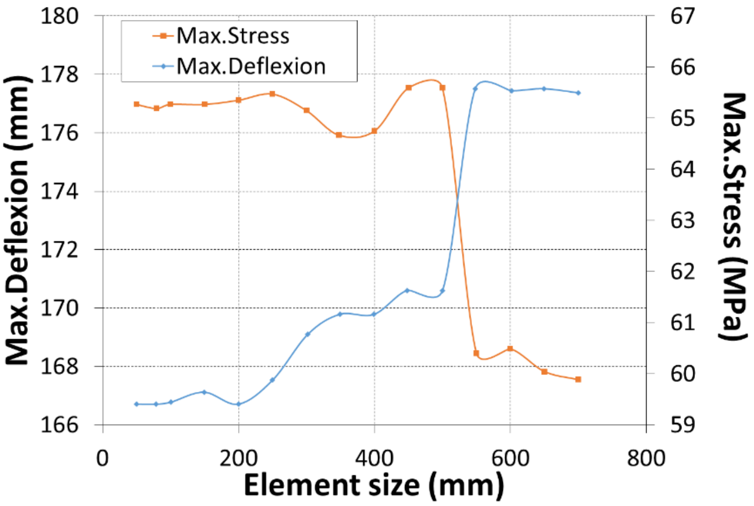


Fig. 6: Mesh convergence

5. Results and Discussion

5.1. Modal analysis

The development of modern measurement technologies has led this study to focus on understanding the vibration characteristics of tidal turbines and to increasing attention to the problems of instability given that tidal current turbines have become increasingly larger than before. In this context, it is essential to perform vibration characteristics in the design and development process of the structure.

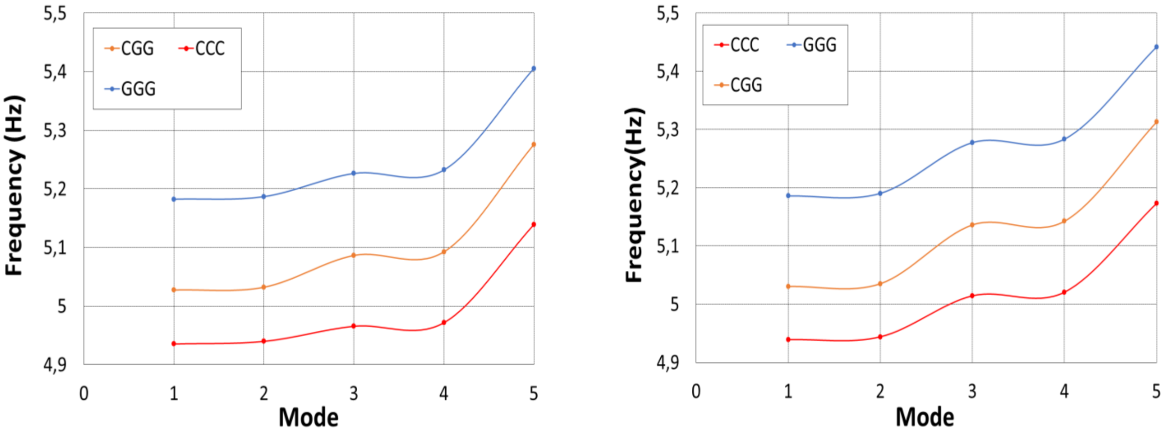
Evidently, structural vibration control and modal analysis are essential tools to effectively monitoring the operational behavior and ensure the structural security of offshore wind turbines (Alaoui et *al*., 2019). In this regard, in our study, a modal analysis was calculated by the finite element method using ABAQUS software to identify the natural frequencies and modal shapes of a hybrid composite nozzle at different modes. Indeed, the modal will specify in which frequency range the nozzle will be more sensitive to vibrations.

5.1.1. Effect of the staking sequence

This paper focuses on the investigation of the effects of reinforcing carbon/glass fiber hybridization on behavioural aspects and stability issues of tidal turbine nozzle. The modal analysis method performed in ABAQUS led to identifying the first five natural frequency modes of the tidal turbine nozzle. Fig. 7 illustrates the natural frequency of the three composite hybrids. According to the results, the natural frequency for the three materials under investigation increases from mode 1 to 3, decreases from mode 3 to 4, and then increases from mode 4 to 5. In addition, Fig. 7 indicates that the natural frequency of the CCC configuration is the smallest and that of the GGG laminate is the highest for the two cases studied.

For the CCC configuration, the natural frequency for mode 1 is 4.9355 Hz and for mode 5 is 5.1392; and for the GGG configuration, it is equal to 5.1825 Hz in mode 1 and 5.4057 Hz in mode 5 (see Table 2). This result is evident since the mass of GGG laminate is 18.57 tons and that of CCC laminate is approximately 13.85 tons (see Table 3). Thus, we can conclude that when the material is less heavy the natural frequency will not be important.

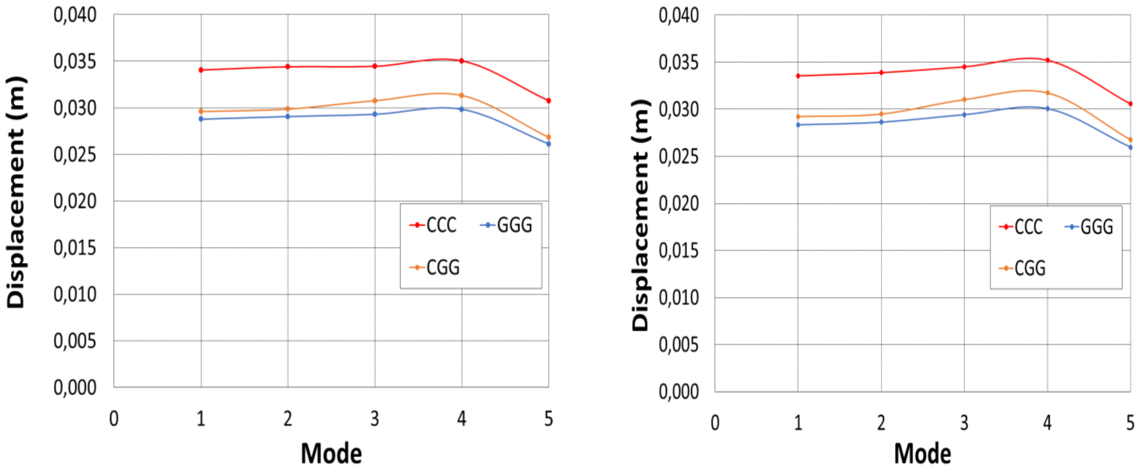
In the first and second mode of vibration, the natural frequencies in cases 1 and 2 are nearly identical to each other (see Table 2). However, in the last three modes, the natural frequencies in case 2 are higher than case 1. So, it can be concluded that the change in boundary conditions of the "Encastre" type has an influence on the natural frequency of the structure.



(a) Case 1 (b) Case 2

Fig. 7: The natural frequency of different stratified for the two cases studied

From Fig. 8, the behavior of the graph for all hybrid composite materials is the same. It can be seen that the configuration GGG has the smallest displacement, which could be explained by the high weight of this laminate. The displacements for the five first modes of the three laminates CCC, CGG, and GGG are illustrated respectively in Figs. 9, 10, and 11. According to the results, we can conclude that the stacking sequence has a considerable impact on the natural frequency of the structure.



(a) Case 1 (b) Case 2

Fig. 8: The displacement results of different stratified

Table 2: Frequencies and displacement for the first five modes of the three laminates

	Natural Frequency (Hz)					
	Case 1			**Case 2**		
	CCC	**GGG**	**CGG**	**CCC**	**GGG**	**CGG**
Mode 1	4.9355	5.1825	5.0276	4.9394	5.1859	5.0306
Mode 2	4.9399	5.1869	5.0323	4.9441	5.1904	5.0353
Mode 3	4.9658	5.2265	5.0866	5.0146	5.2776	5.1363
Mode 4	4.9718	5.2324	5.0927	5.0208	5.2836	5.1426
Mode 5	5.1392	5.4057	5.2759	5.1732	5.4419	5.3129
	Displacement (mm)					
Mode 1	34.06	28.78	29.6	33.55	28.35	29.23
Mode 2	34.41	29.07	29.87	33.89	28.63	29.49
Mode 3	34.46	29.31	30.77	34.51	29.43	31.02
Mode 4	35.04	29.85	31.33	35.21	30.07	31.74
Mode 5	30.76	26.13	26.83	30.57	25.97	26.76

Table 3: Mass of laminates

Configurations	**Mass (tons)**
CCC	13.85
CGG	16.99
GGG	18.57

5.1.2. Resonance

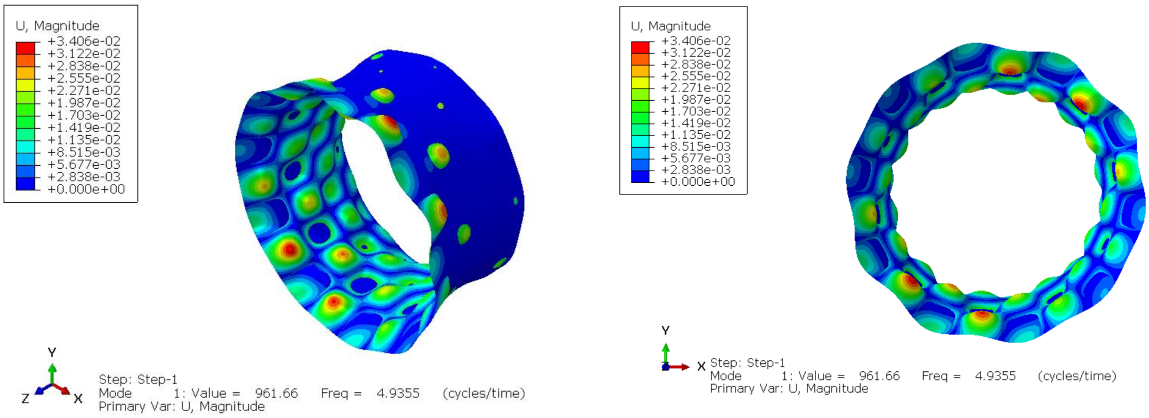
The knowledge of natural frequencies is primordial to overcome the undesired resonance phenomena impacts and unwanted structural elastic mechanisms on the tidal current turbines. The resonance is a condition that can be present in mechanical structures and could be described as sensitivity to a specific vibration frequency. Resonance happens when a natural frequency is equal or close to a forcing frequency (Tartibu et *al.*, 2012).

To avoid the resonance phenomenon, the condition mentioned below must be respected conforming to the GL Wind2003 standard (Germanischer Lloyd Wind Energy GMBH, 2005) (Tarfaoui et *al*., 2013):

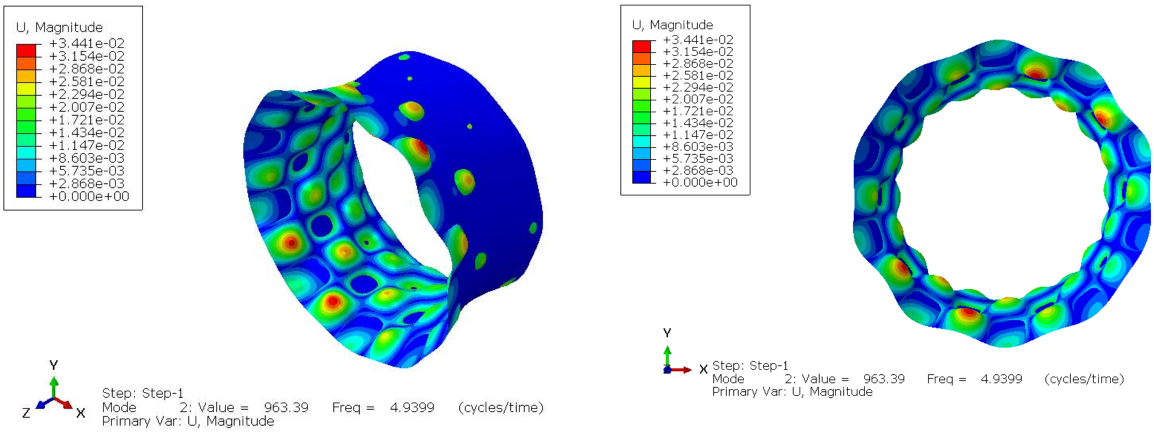
$$\frac{F_r}{F_{0,n}} \leq 0.95 \tag{1}$$

With Fr=0.26 Hz

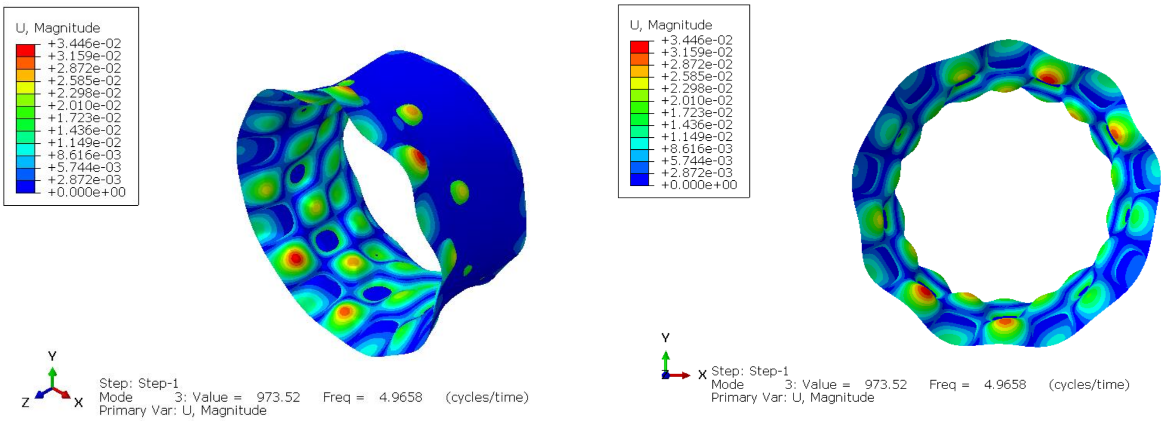
Where, Fr: The loading frequency and F0, n: The n-th natural frequency of the structure



Mode 1

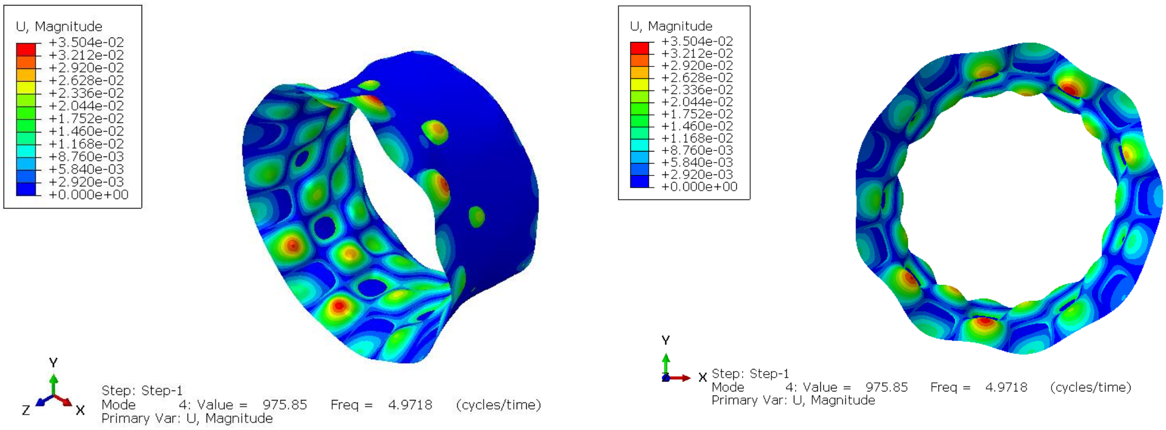


Mode 2

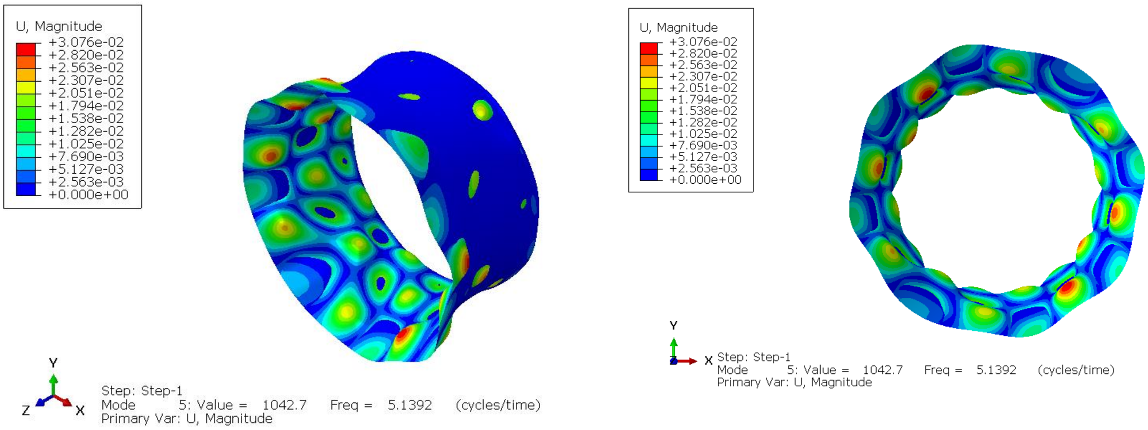


Mode 3

Fig. 9: Natural frequency modes of CCC laminate (contd.)

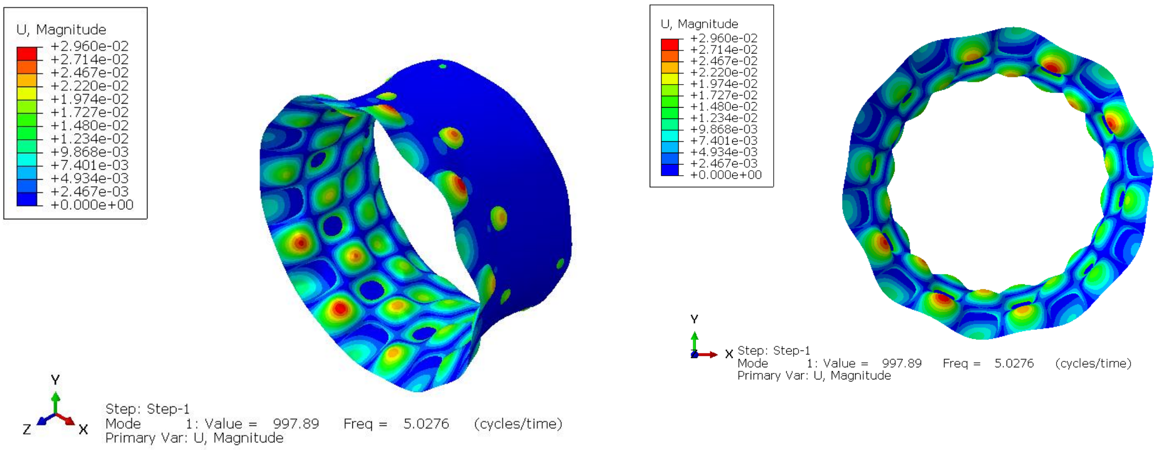


Mode 4



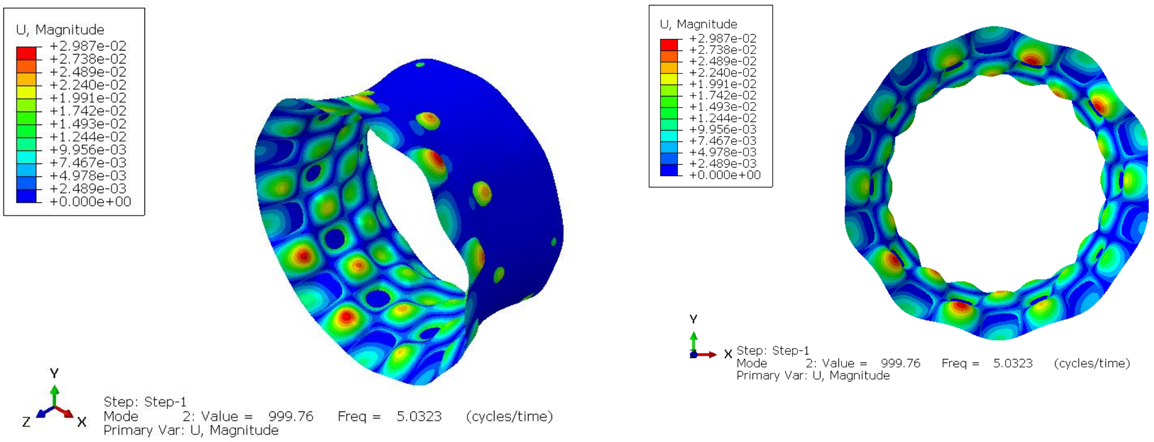
Mode 5

Fig. 9: Natural frequency modes of CCC laminate

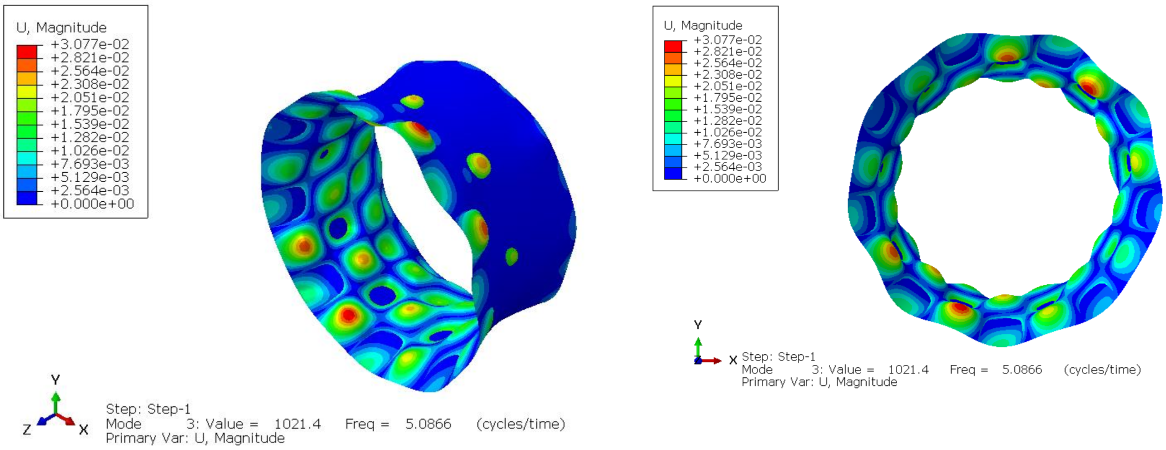


Mode 1

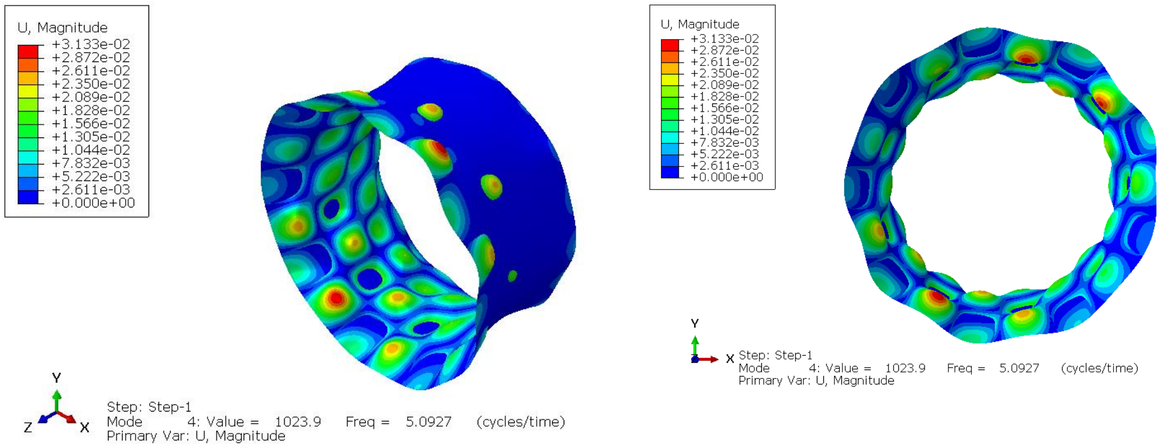
Fig. 10: Natural frequency mode of CGG laminate (contd.)



Mode 2

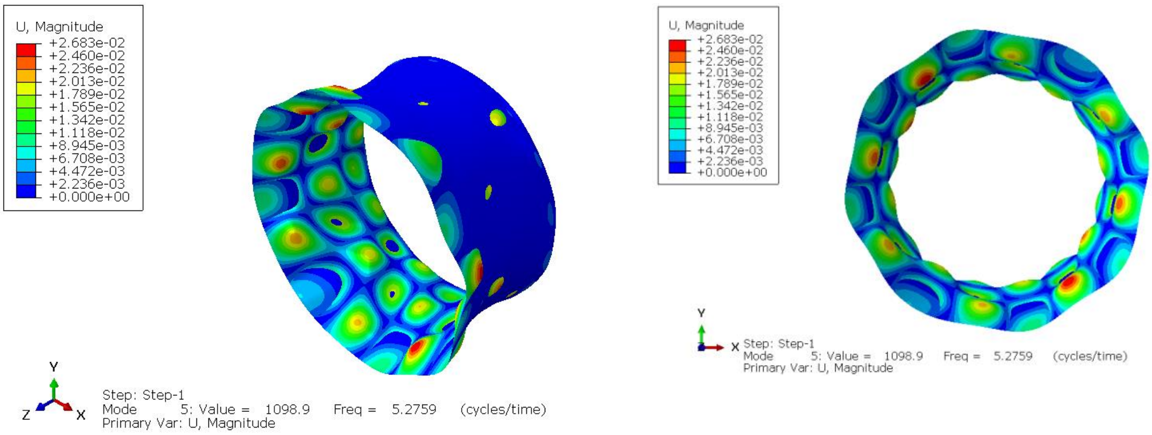


Mode 3



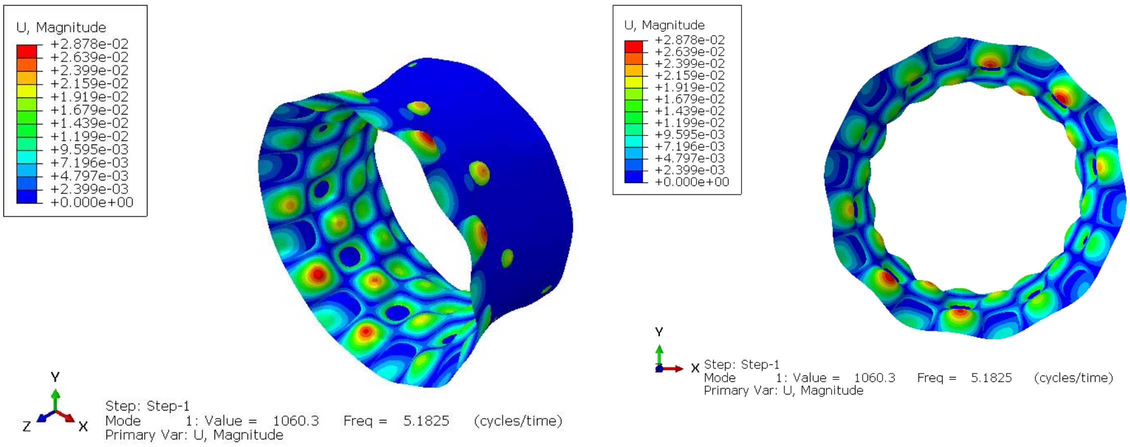
Mode 4

Fig. 10: Natural frequency modes of CGG laminate (contd.)

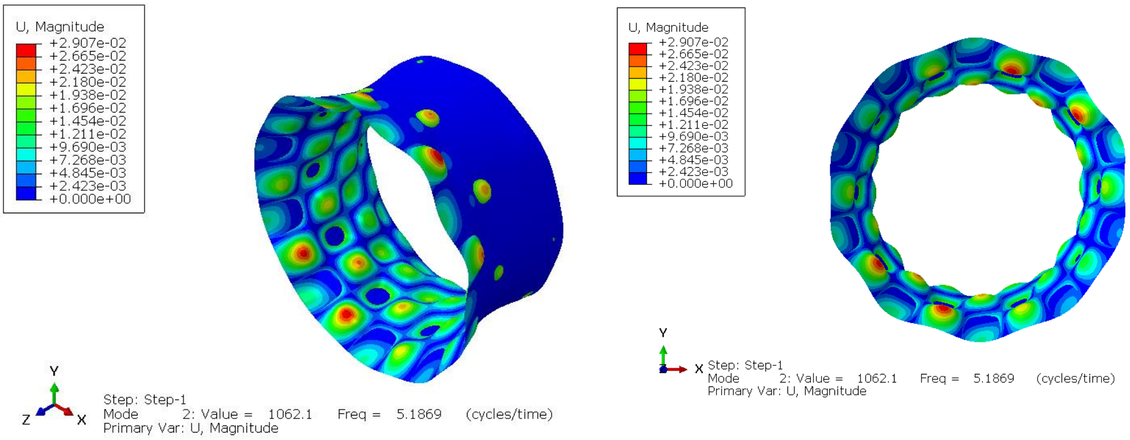


Mode 5

Fig. 10: Natural frequency mode of CGG laminate

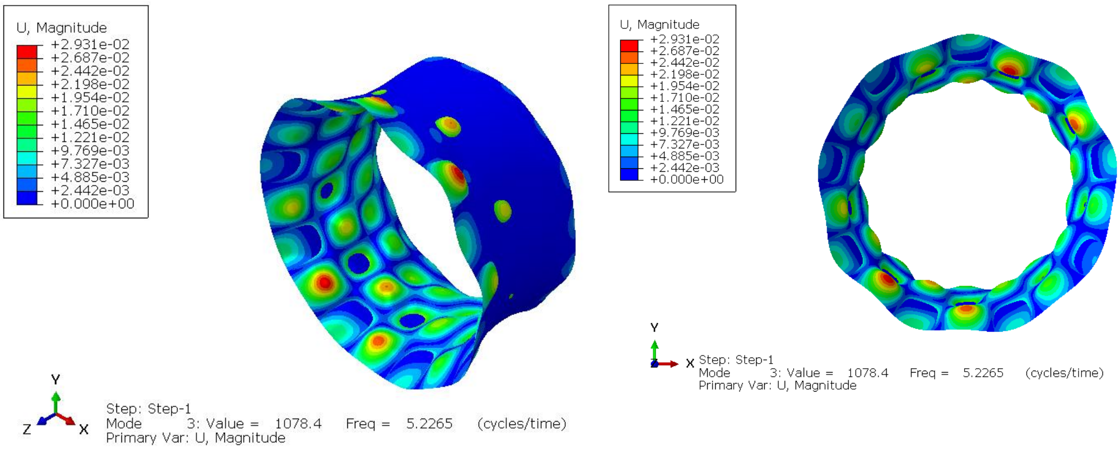


Mode 1

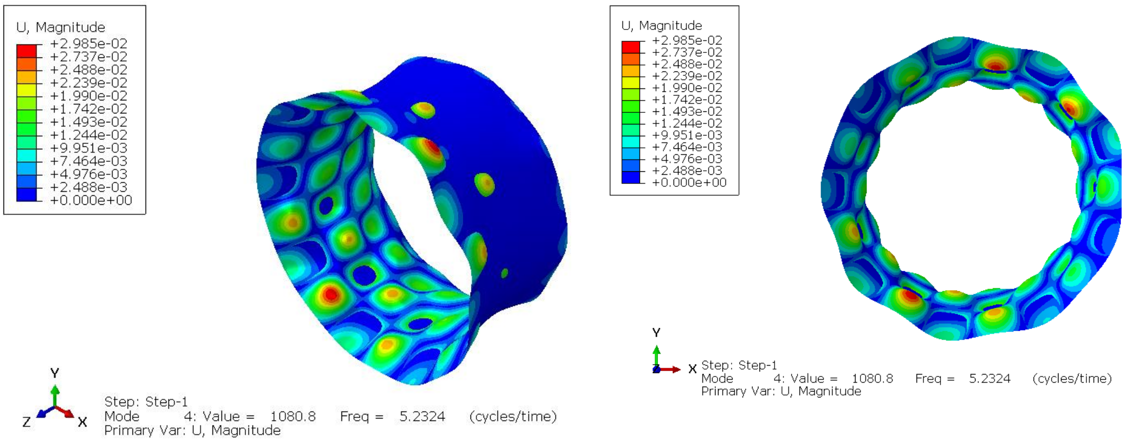


Mode 2

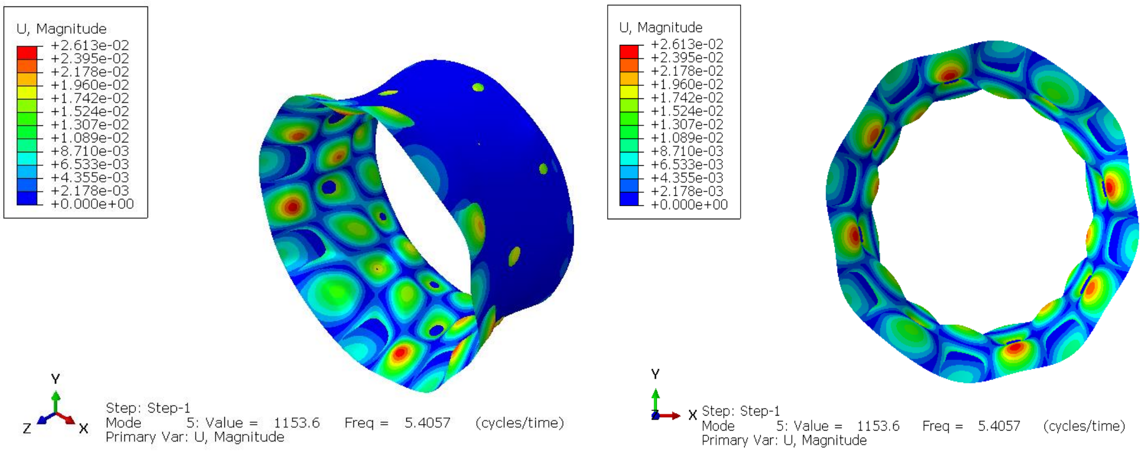
Fig. 11: Natural frequency modes of GGG laminate (contd.)



Mode 3



Mode 4

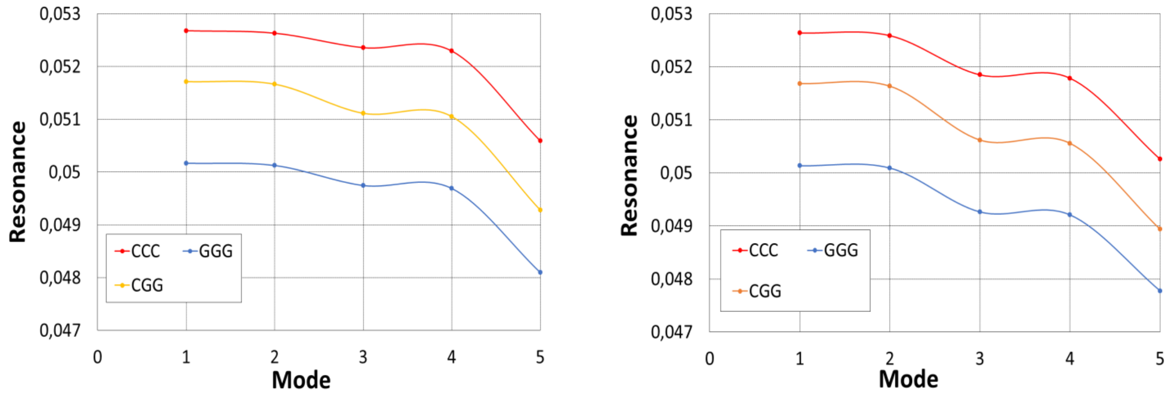


Mode 5

Fig. 11: Natural frequency modes of GGG laminate

After this condition was applied for the five modes, we observed that the resonance phenomena effect did not appear for the three hybrid composites, Table 4. Fig. 12 illustrates the resonance as a function of the modes for the two cases under study. It can be observed from this figure that the resonance of GGG configuration is the lowest and that of the CCC is the highest for the two cases studied.

After comparing the three laminates, we conclude that the GGG laminate had lower resonance as well as lower displacement than other laminates.



(a) Case 1 (b) Case 2

Fig. 12: Resonance versus modes for the three laminates

Table 4: Results of the resonance phenomenon for the three configurations

	Case 1					Case 2				
	$\frac{F_r}{F_{0,1}}$	$\frac{F_r}{F_{0,2}}$	$\frac{F_r}{F_{0,3}}$	$\frac{F_r}{F_{0,4}}$	$\frac{F_r}{F_{0,5}}$	$\frac{F_r}{F_{0,1}}$	$\frac{F_r}{F_{0,2}}$	$\frac{F_r}{F_{0,3}}$	$\frac{F_r}{F_{0,4}}$	$\frac{F_r}{F_{0,5}}$
CCC	0.05267	0.05263	0.0523	0.0522	0.0505	0.0526	0.0525	0.0518	0.0517	0.0502
GGG	0.05016	0.05012	0.0497	0.0496	0.0480	0.0501	0.05	0.0492	0.0492	0.0477
CGG	0.0517	0.0516	0.0511	0.0510	0.0492	0.0516	0.0516	0.0506	0.0505	0.0489

6. Conclusion

Research on structural vibration characteristics and operational modal analysis of tidal current turbines offers technological support for the assessment of operational safety and the practical basis for the conception of the tidal turbine structures. A modal analysis was developed in Abaqus software using finite element method (FEM) to evaluate the vibration mode shapes and natural frequencies of the ducted tidal turbine. The effects of the reinforcement of the carbon/glass fiber hybridization of the behavioral aspects and stability issues of the tidal turbine nozzle were studied. Furthermore, to properly investigate the operational and environmental impacts on the mechanical properties of the nozzle, two cases of boundary conditions of Encastre type were investigated. The comparison of the results of the three laminates showed that the stacking sequence has a meaningful impact on the natural frequency, displacement, and resonance of the structure. Thus, it was observed that the GGG laminate had a lower resonance as well as lower displacement than other laminates. On the other hand, it was found that the change in boundary conditions type has an influence on the natural frequency of the structure.

The next work consists of performing a 3D modeling using the technique of sub-modeling in the case of a low speed impact. This technique makes it possible to focus on the area at risk and, to model the intralaminar damage (cracking of the matrix, rupture of the fibres) via a Vumat and interlaminar (delamination, rupture of the bonding zones) via the method of the cohesive zones.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Cai, X., Pan, P., Zhu, J., and Gu, R. (2013): The analysis of the aerodynamic character and structural response of large-scale wind turbine blades, Energies, Vol. 6, No. 7, pp. 3134–3148. https://doi.org/10.3390/en6073134.

Dong, X., Lian, J., Wang, H., Yu, T., and Zhao, Y. (2018): Structural vibration monitoring and operational modal analysis of offshore wind turbine structure, Ocean Engineering, Vol. 150, pp. 280-297. https://doi.org/10.1016/j.oceaneng.2017.12.052.

Damghani, M., Ersoy, N., Piorkowski, M., and Murphy, A. (2019): Experimental evaluation of residual tensile strength of hybrid composite aerospace materials after low velocity impact, Composites Part B Engineering., Vol. 179, pp. 10753. https://doi.org/10.1016/j.compositesb.2019.107537.

El-Shahat, S. A., Li, G., and Fu, L. (2020): Dynamic loading characterization of a horizontal axis tidal current turbine, Ocean Engineering., Vol. 211, pp. 107561. https://doi.org/10.1016/j.oceaneng.2020.107561.

El-Shahat, S. A., Li, G., Lai, F., and Fu, L. (2020): Investigation of parameters affecting horizontal axis tidal current turbines modeling by blade element momentum theory, Ocean Engineering., Vol. 202, pp. 107176. https://doi.org/10.1016/j.oceaneng.2020.107176.

El Alaoui, R., Mounir, H., El Marjani, A., and El Mostapha, B. (2019): Investigation and analysis of static and dynamic behaviour of a new natural composite material of a wind turbine blade using the finite element method, International Journal of. Renewable Energy Research, Vol. 9, No. 1.

Fagan, E.M., Kennedy, C.R., Leen, S.B., and Goggins, J. (2016): Damage mechanics-based design methodology for tidal current turbine composite blades, Renewable Energy, Vol. 97, pp. 358–372. https://doi.org/10.1016/j.renene.2016.05.093.

Gemi, L. (2018): Investigation of the effect of stacking sequence on low velocity impact response and damage formation in hybrid composite pipes under internal pressure. A comparative study, Composites Part B: Engineering, Vol. 153, pp. 217-232. https://doi.org/10.1016/j.compositesb.2018.07.056.

Laaouidi, H., Tarfaoui, M., Nachtane, M., and Trihi, M. (2021): Energy absorption characteristics in hybrid composite materials for marine applications under impact loading: Case of tidal current turbine, International Journal of Energy Research, Vol 45, No 4, pp. 5894-5911. https://doi.org/10.1002/er.6210.

Laaouidi, H., Tarfaoui, M., Nachtane, M., Trihi, M., and Lagdani, O. (2020): A Comprehensive Numerical Investigation on the Mechanical Performance of Hybrid Composite Tidal Current Turbine under Accidental Impact, International Journal of Automotive and Mechanical Engineering, Vol. 17, No. 4, pp. 8338-8350. https://doi.org/10.15282/ijame.17.4.2020.10.0630.

Luo, Y., Presas, A., Wang, Z., Xiao, Y., Wang, H., and Jiang, X. (2020): Operating conditions leading to crack propagation in turbine blades of tidal barrages. Influence of head and operating mode, Engineering Failure Analysis, Vol. 108, pp. 104254. https://doi.org/10.1016/j.engfailanal.2019.104254.

Nachtane, M., Tarfaoui, M., Goda, I., and Rouway, M. (2020): A review on the technologies, design considerations and numerical models of tidal current turbines, Renewable Energy, Vol 175, pp. 1274-1288. https://doi.org/10.1016/j.rerene.2020.04.155.

Nachtane, M., Tarfaoui, M., and Saifaoui, D. (2017): Composite materials for marine renewable energy. European University Editions.

Nachtane, M., Tarfaoui, M., Saifaoui, D., El Moumen, A., Hassoon, O.H., and Benyahia, H. (2018): Evaluation of durability of composite materials applied to renewable marine energy: Case of ducted tidal turbine, Energy Reports, Vol 4, pp. 31-40. https://doi.org/10.1016/j.egyr.2018.01.002.

Nachtane, M., Tarfaoui, M., Ait Mohammed, M., Saifaoui, D., and El Moumen, A. (2020): Effects of environmental exposure on the mechanical properties of composite tidal current turbine, Renewable Energy, Vol. 156, pp. 1132-1145. https://doi.org/10.1016/j.renene.2020.04.126.

Nachtane, M., Tarfaoui, M., El Moumen, A., and Saifaoui, D. (2017): Damage prediction of horizontal axis marine current turbines under hydrodynamic, hydrostatic and impacts loads, Composite Structures, Vol. 170, pp. 146-157. https://doi.org/10.1016/j.compstruct.2017.03.015.

Porter, K.E., Stephanie, E.O.S. et al., (2020): Flume testing of passively adaptive composite tidal turbine blades under combined wave and current loading, Journal of Fluids Structures., Vol. 93, pp. 102825. https://doi.org/10.1016/j.jfluidstructs.2019.102825.

Santhanam, V., Dhanaraj, R., Chandrasekaran, M., Venkateshwaran, N., and Baskar, S. (2020): Experimental investigation on the mechanical properties of woven hybrid fiber reinforced epoxy composite, Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2020.07.444.

Santos, P., Parente, J.P., Valvez, S., Silva, M.P., and Reis, P.N.B. (2020): Hybridization effect on the bending properties of flax composites, in Procedia Structural Integrity, Vol 25, pp. 370–377. https://doi.org/10.1016/j.prostr.2020.04.042.

Tarfaoui, M., Nachtane, M., Khadimallah, H., and Saifaoui, D. (2018): Simulation of Mechanical Behavior and Damage of a Large Composite Wind Turbine Blade under Critical Loads, Applied Composite Material., Vol. 25, No. 2, pp. 237-254. https://doi.org/10.1007/s10443-017-9612-x.

Tarfaoui, M., and Shah, O.R. (2013): Spar Shape Optimization of a Multi Megawatt Composite Wind Turbine Blade: Modal Analysis, Recent Advances in Composite Materials for Wind Turbine Blades, xxx, Chapter 6, pp 93-104.

Tarfaoui, M., Khadimallah, H., Shah, O., and J. Y. Pradillon, J.Y. (2013): Effect of spars cross-section design on dynamic behavior of composite wind turbine blade: Modal analysis. 4th International Conference on Power Engineering, Energy and Electrical Drives. https://doi.org/10.1109/PowerEng.2013.6635748

Tartibu, L. K., Kilfoil, M., and Der Merwe, V. (2012): Vibration Analysis of a Variable Length Blade Wind Turbine, International Journal of Advances in Engineering & Technology, Vol. 4, No. 1, pp. 2231-1963. https://doi.org/10.7323/ijaet/v4_iss1.

Thomas, T.T., Narkhede, M.M., Patil, B.S., and Mogra, A. (2017): Analysis of Wind Turbine Blade Having I Shaped Spar Using Both Epoxy Fiber and Carbon Fiber Using FEM, in Materials Today: Proceedings, Vol 4, No 2, pp. 2573-2579. https://doi.org/10.1016/j.matpr.2017.02.111.

Wu, L., Wang, W., Jiang, O., Lin, J. H., and Tang, Y. (2020): Illustrating hybrid effect and damage evolution of carbon/aramid braided composite under low-velocity impact, Composite Structures, Vol. 245, pp. 112372. https://doi.org/10.1016/j.compstruct.2020.112372.

Wu, T., Yao, W., Xu, C., and Li, P. (2020): A natural frequency degradation model for very high cycle fatigue of woven fiber reinforced composite, International Journal of Fatigue, Vol. 134, pp. 105398. https://doi.org/10.1016/j.ijfatigue.2019.105398.