Vibration Analysis of an Ocean Current Turbine Blade

M. Imran[1] and S.Badshah[2]
Department of Mechanical Engineering, International Islamic university
New Campus, H-10, Islamabad, Pakistan
[1]muhammad.imran@iiu.edu.pk, [2]saeed.badshah@iiu.edu.pk

Abstract- Vibration characteristics of an ocean current turbine blade have been analyzed using Design foil, BET tool, Pro/Engineer and Finite Element Package ANSYS. Natural frequencies and mode shapes of a turbine blade can be evaluated by Vibration Analysis. It can also serve as a starting base for another, dynamic analysis, such as a transient dynamic analysis, or a spectrum analysis. The natural frequencies and mode shapes are important parameter in the design and analysis of an ocean current turbine blade. Modal analysis can also be performed on a pre-stressed spinning turbine blade. It has been investigated that the blade would not fail in an ocean current of 2.3 to 2.5 m/s that can produce power production up to 151 KW. The blade is of Composite structure with carbon fibers and foam core. It is also facilitated with two webs of carbon fibers to add shear rigidity.
Eight design cases of blade were analyzed involving the differences in geometry, material properties and internal structures. Results from the vibration analysis revealed that the recommended blade design have adequate frequency difference than the frequency of other components of turbine like rotor, assembly to produce proposed power of 151 KW without any resonance or structural failure. Deflection analysis and Principal stress analysis have been conducted that showed the proposed blade design have adequate strength.

Keywords: blade, energy, oceans, mechanical, vibrations, design

INTRODUCTION

Renewable energy technologies have become a well-liked matter in this “go green” era. Wind energy has been very well focused and has been added to many stations and grids. Pakistan has large potential of Ocean currents Power in Arabian Stream. Karachi is the closest center to a large ocean current of Pakistan in Arabian Sea. The Ocean Potential of Arabian Sea can fulfill the whole power requirements of Karachi. Department of Mechanical Engineering has planned to grab this ocean energy by installing ocean currents turbines in the future.

The issue with the variety of alternative energy sources is that they are intermittent and on based on expectations. Sun or the wind can be trusted to provide a constant power production output, and people can only able to predict. On the other hand, Ocean currents, are moving continuously and steadily, and could provide us with huge amounts of energy while being consistent [2]. Due to an increase in conventional energy prices and environmental effects, such as air pollution, global heating, decreasing of the ozone layer, effects of greenhouse; the usage of ocean energy has improved, following the energy disaster in recent years [3]. Wing turbine Blades used are designed hollow in order to reduce their weight and give maximum output but in this case of an ocean, hollow blades should not be considered in oceans because if blade is made hollow and water gets within the blade shell by means of a micro crack then not only the blade would fail but whole system would damaged.

Following factors shows the Ocean Current Energy privileges over the other energies in many ways

- Ocean Current water has density of 835 times than of air results that ocean current turbine can produce much power than a windmill of the same rotor diameter.
- For a given area: solar resources produce power in kW, wind MW and ocean current resources produce GW [1].
- 71% of the earth’s surface is covered by oceans as opposed to the limited sites for conventional resources [1].
- Ocean current resources have been estimated over 80,000MW [1].

The focus of this research is to design and analyze efficient ocean current turbine blade. Much work has been conducted on wind turbine blades and the area of Ocean current turbine has been targeted to grab self-sustained power production in Pakistan

It is most important that ocean turbines should be designed and analyzed in a way to assure fault-free operation in ocean premises. Failure of Ocean turbines can be costly for both the end user and the manufacturers. Turbo machinery components, especially blades, are exposed to loads and pressures that can cause failure to operation, designing trustworthy components require in-depth vibration and stress analysis [12].
Natural frequency is the frequency at which a body vibrates when excited by external or internal force. At this natural frequency, the structure offers the smallest amount of resistance to a force and if left uncontrolled, failure can occur. Mode shape is the deflection of an object at a given specific natural frequency. A guitar string is a good example of natural frequency and mode shapes. When excited, the string vibrates at a specific frequency and gains a deflected shape. The eigenvalue (natural frequency) and the accompanying eigenvector (mode shape) are considered to define the dynamics of a structure. Understanding of natural frequencies and periodic forces helps explain the phenomenon of resonance. Resonance is a condition where response or amplitude of vibration is at peak value and resistance to an oscillating force is at minimum. At this state, the shape and frequency of a force must match the natural frequency and mode shape of the structure. An example of resonance is the Tacoma-Narrows bridge failure [13]. The bridge, as any structure, had inherent natural frequencies and associated mode shapes. When the wind blew at a specific speed, it created a forcing function that matched one of the bridge’s natural frequencies and mode shapes, the bridge started to vibrate. Vibration amplitudes became so huge that consequently lead to bridge’s structure failure.

HYDRODYNAMICS OF BLADE DESIGN

Design Foil was used to create Aerofoil geometry and Blade Element Theory (BET) was used to verify the hydrodynamics of blade structure and Pro Engineer was used to model an ocean current turbine blade involving the geometry variations.

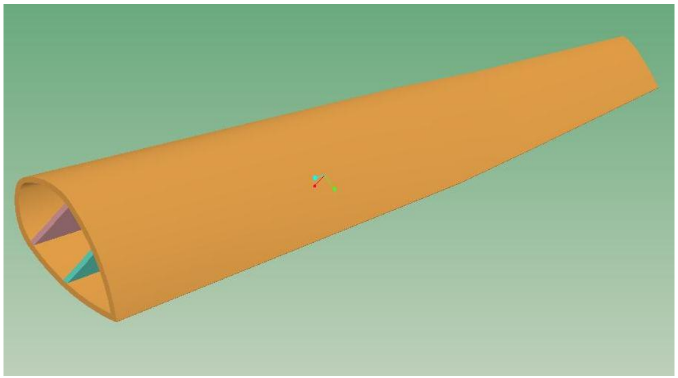

Fig 1 Pro/E model of blade

Fig. 1 Illustration of the blade analyzed. Area towards the hub was left untouched for future work. Each blade design case has nine stations and eight hydrodynamic sections

For simplicity, tip losses were not considered for in the algorithm, but the provided references can be used to further analyze the occurrence by making use of Prandtl's tip loss factor, or Goldstein's momentum averaging factor [4, 5].

The NACA 4 series has a more round leading edge and a thicker trailing edge than most of the foils used in the wind and marine energy industry. This allows it to distribute in-plane loads more consistently; loads that can result from traveling ocean debris. The thicker trailing edge is also easy to fabricate and makes the usage of a trailing edge webs possible. The following figure illustrates that the webs were also integrated into the blade to increase shear rigidity.

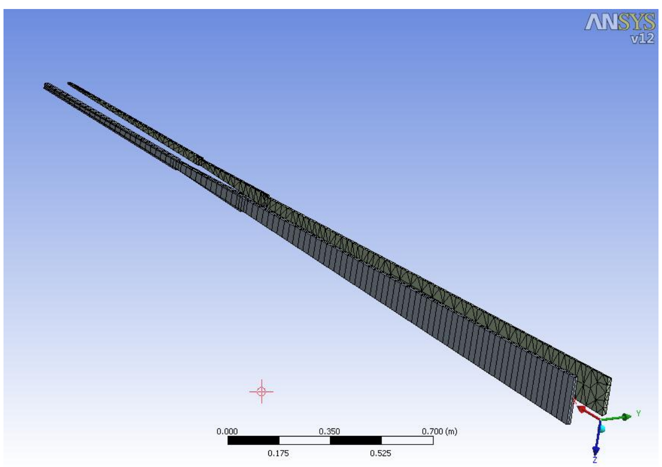

Fig 2 Pictorial view of webs

Composites are ideal materials for structures and applications in the ocean environment due to their high strength to weight ratio, excellent resistance to corrosion, and capability to tailor a design compatible with loads. By optimization of the different materials used, the number of plies of a certain material, and/or the direction of fiber/ply orientation, one can tailor the design [7]. Along the fiber directions, composites offer high strength values than of metals. Weaves may be avoided where possible as they can decrease the value of fatigue resistance because of their interlocked structure. At comparatively low tensile loads the fibers lean to straighten out, generating larger stresses in the matrix, also possibly initiate micro cracks [8]. The skin will be a symmetric and balanced laminate. By balancing of the laminate inline to the principal, span wise axis, the in-plane shear coupling stiffness would be zero. Then, by arrangement of any angle plies, +θ and –θ pairs, so that they are balanced and symmetrical about the center of the principal axis, the bending or twisting coupling stiffness will be zero [7, 9]. This is very significant in order to keep the pitched blade away from twisting because of the high lift force acting along it. If the blade were to twist, the angle of attack would be changed, that caused the blade section to be exposed to an increase the value of torque, or the vice versa. Temperature is also important parameter but in this case effects of temperature in ocean on material properties were ignored since the operational depth will be approximately 75 m (246 ft). At this depth, the testing environment would face seasonal temperature variation between 21^0 and 29^o C (70 to 84^o F), providing ignorable temperature effects on material properties considering under ocean operations. The skin thickness of the blade was reduced along the length to permit the webs and core to be regular and smooth. Otherwise each sectional termination would cause a stress concentration. The flap wise tapered design also permitted the design to keep its neutral buoyancy and would reduce the cost of material. The angle plies offer the skins tensional stiffness and soak up transverse stresses [9]. Without the usage of angle plies, a blade would fail pre-maturely due to matrix cracking [5]. The 0^o layers give the ocean current turbine blade its flap wise stiffness and in-plane bending stiffness [9]. The upper pressure sides and low pressure sides provide the flap wise stiffness and the leading edge and trailing edge provide the in-plane stiffness. Small constants in plane loads are predictable due to drag, but the leading edge remains thick for structural solidity and impact resistance. The webs hold angle plies seeing as out-of-plane shear and flexural stiffness is required [8]. Similarly stacking sequence was used [9-10]. The ply thicknesses were 1 mm for the finite element (FEM) model strictly for convenience and to less keep computational time. Since stresses are considered at the top and at the bottom of each layer, the stacking sequence and layer thicknesses can be defined and analyzed depending on how critical through the thickness results are [11].

Table 1 Ocean Turbine Rotor Characteristics

	Design 1-4	Design 5-8
Rotor diameter (m)	6.75	6.75
Blade Length (m)	3	3
Number of Blades	3	3
Twist	11	12
Swept Area (m²)	35.3	35.3
Design Flow Speed (m/s)	1.7	1.7
Design RPM (rpm)	25	24
Max Flow Speed (m/s)	2.5	2.5
Max RPM (rpm)	36.5	35.25
Foil Type	NACA 44xx	NACA 44xx
Design TSR	5	5
Power Coefficient	0.475	0.5

Table 2 Rotor Design and Maximum Power

Design 1-4	Design 5-8

ISSN 2229-5518

	Design Flow	Max Flow	Design Flow	Max Flow
Flow Speed (m/s)	1.7	2.5	1.7	2.5
RPM (rpm)	25	36.5	24	35.25
Lift (N)	38733	84610	41150	88790
Drag (N)	516	1041	506	1092
Thrust (N)	37934	82806	40251	86845
Torque (Nm)	16140	35644	17730	38305
Power (kW)	42.28	136.31	44.58	141.47

Table 3 BET Parameters for Design 1

length (m)	chord (mm)	pitch (o)	inflow angle (o)	α (o)	Re	NACA 44xx	CL	CD
0.6	477	12.0	24.7	12.7	1085335	4428	1.077	0.021
0.9	427	7.6	18.3	10.7	1178600	4424	1.132	0.017
1.2	377	3.6	14.0	10.4	1222523	4421	1.183	0.017
1.5	328	2.7	11.7	9.0	1243150	4418	1.232	0.015
1.8	278	1.7	10.7	9.0	1194643	4417	1.247	0.015
2.1	229	1.4	10.4	9.0	1094601	4417	1.244	0.016
2.4	179	1.2	10.2	9.0	954720	4416	1.284	0.016
2.7	129	0.9	9.9	9.0	761196	4415	1.294	0.017
3.0	80	0.5	9.5	9.0	513503	4415	1.288	0.018

Table 4 BET Parameters for Design 2-4

length (m)	chord (mm)	pitch (o)	inflow angle (o)	α (o)	Re	NACA 44xx	CL	CD
0.6	500	16.5	26.4	9.9	1106100	4441	0.868	0.017
0.9	480	11.0	20.0	9.9	1282165	4438	0.904	0.017
1.2	460	7.0	16.8	9.8	1438808	4434	0.954	0.016
1.5	430	5.5	13.5	8.0	1565234	4431	0.965	0.014
1.8	390	5.0	10.2	5.2	1623068	4427	0.946	0.011
2.1	330	4.5	9.9	5.4	1533421	4423	1.003	0.011
2.4	260	4.5	9.9	5.4	1333776	4418	1.075	0.011
2.7	200	4.5	9.4	4.9	1130972	4416	1.064	0.011
3.0	180	4.5	9.3	4.8	1112705	4416	1.064	0.011

Finite element Modeling using ANSYS

Models created in Pro Engineer were saved as IGES and then imported to ANSYS Workbench. All design cases can be analyzed using the bottom-up solid modeling method in ANSYS Classic but in this case, ANSYS workbench has been used while in ANSYS Workbench Element selection is by default. The webs and skin material properties were entered as orthotropic as we are using Composite materials. The elements used in ANSYS which are capable of modeling composite materials are: SOLID186, SHELL91, SHELL99, SHELL181, SHELL281, SOLID185, SOLSH190, SOLID46, and SOLID191. [6]

Commercial software Packages such as NASTRAN and ANSYS are capable to handle linear, nonlinear static and dynamic analyses. ANSYS Workbench has the capability of vibration and modal analysis on any type of structures. Natural frequencies and mode shapes can be extracted from ANSYS. It is also capable of performing modal analysis on pre-stressed models to include stiffening and thermal effects from static loading conditions. Any nonlinearity, such as plasticity and contact (gap) elements in this case, are ignored even if they were defined. The general process for modal analysis consists of five steps: Build the FEM model (or import model as in this case), define the engineering materials used and their corresponding properties, apply the boundary conditions and generate the mesh of the model and solve the problem. In this paper we will investigate model for modal analysis to predict the natural frequencies and mode shapes of the turbine blade. [12]

Mesh generation is one of the most critical and important aspects of engineering simulations in ANSYS. Too many numbers of meshed elements cause too much time to solve and few cells cause inaccurate results in ANSYS workbench. ANSYS Workbench Meshing provides an adequate way to overcome these difficulties and generate mesh in standard form that meets the mesh skewness criteria. Consistent consumer controls make switching methods very easily and multiple methods can be used within the same model. Mesh connectivity is maintained automatically. Different structural problems require different meshing techniques. CFD simulations require very higher quality meshes in both the element shapes and softness of size changes.

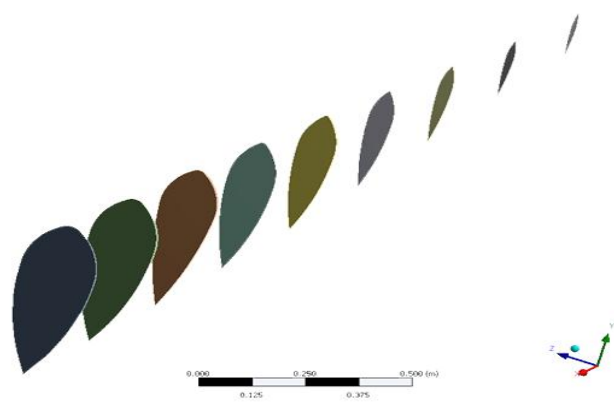

Fig. 3 Section wise distribution of blade

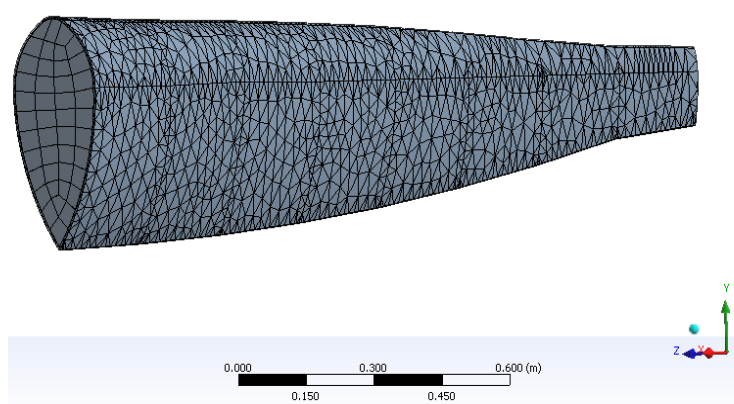

Fig 4 Mesh Generated using Ansys

Results and Discussion

The following bar chart indicates the frequency at each calculated mode of case 3-b

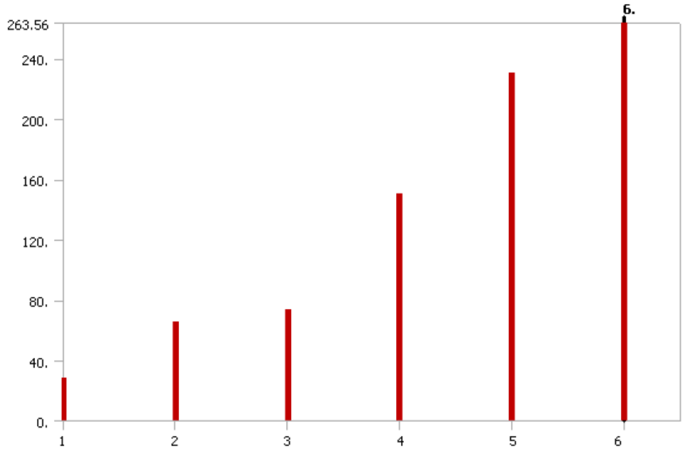

Table 5 shows Modal behavior of design case 3-b

Model	Pre-stress vibration, Hz	Free vibration, Hz	Deflection, m	Max principal Stresses, Pa	Type of Model	Skin	Webs
1a	28.664	68.786	0.35368	2.15E+08	Shell	As4	As4
1b	0.0283	0.0651	0.45767	1.78E+08	Shell	S2glass	S2glass
1c	28.779	69.096	0.856758	1.65E+08	Shell	Al	Al
2a	44.872	104.87	0.13701	9.47E+01	Solid	As4	As4
2b	24.236	57.685	0.09575	6.27E+01	Solid	S2glass	S2glass
2c	24.307	58.179	0.924365	9.16E+01	Solid	Al	Al
3a	48.833	114.05	0.04783	1.50E+08	Shell with Webs	As4	S2glass
3b	29.245	72.587	0.08902	1.49E+08	Shell with Webs	Al	S2glass

Table 6 Illustration of Materials used, natural frequencies and deflection produced

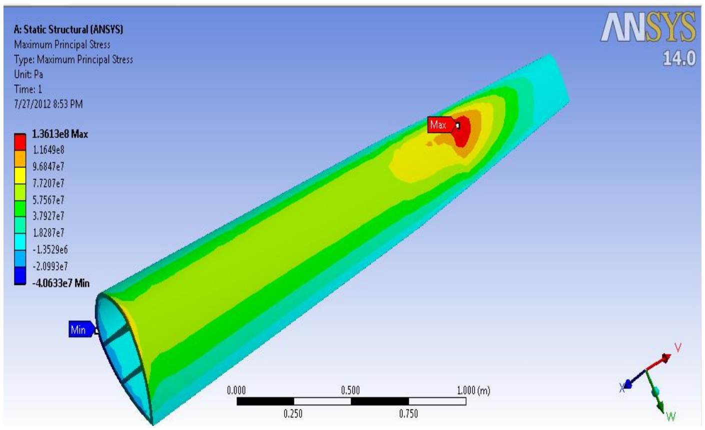

Fig 5 shows Maximum Principal stresses in Case 3b

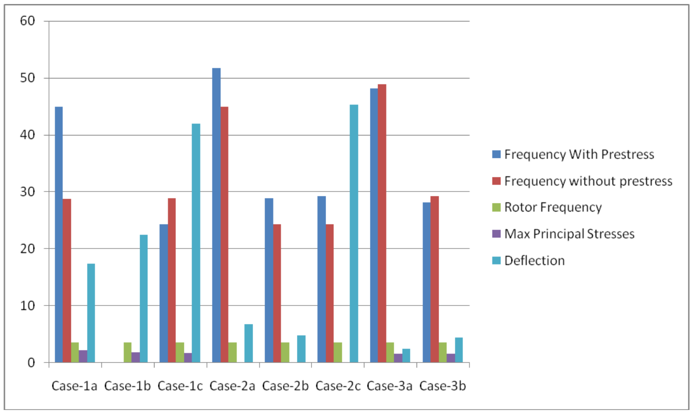

Table 7 explains the graphical view of Pre-stress vibration, Free-stress vibration and deflection of different blades with respect to Material Variations

Eight design cases have been simulated involving the shape and material variations.

Case 1-a has deflection of 0.35368 meter and frequency of 44.0 Hz, following the case 2-a which has maximum deflection of 0.13701 meter.

Designs 2-b and 2-c have same geometry that resulted in equivalent values of frequencies but different materials. Design 2-c showed maximum deflection than design 2-b

Case-2a has similar values of pre stress and free stresses to that of case 3-a but 3-b has higher value of deflection produced as compared to case 3-a

In Designs 3-a and 3-b only skin materials were changed from AS4 to aluminum and have same material (S2 glass) of webs but design case 3-b produced much deflection than that of 3-a. Carbon Fiber is not necessary for the Webs, as S2-glass showed parallel performance and would permit for a much cheaper design.

If we want to deduce feasible solution out of those all eight cases, one can suggest that design case 3-a is feasible than any other case because case-1b is not feasible due to its higher deflection and case-2a has a disadvantage of heavy weight due to its solid structure, so case-3a supersede all analyzed models on the basis of less resonance chances and weight.

Acknowledgement

Mechanical Engineering Department, International Islamic University, supported this research work.

Conclusion

To Analyze, address and assess vibration problems; understanding of the concepts of vibration, the basic theoretical models, time and frequency domain analysis, measurement techniques and instrumentation, vibration suppression techniques, and modal analysis play a major role. In this research thesis, eight cases were analyzed involving the differences in shape, geometry and materials. Results showed that design 3-a has best suited not only for vibration but also for deflection, and maximum principal stresses.

References

[1] Dr. Darwish M. K. Al Gobaisi "OCEAN CURRENT'S ENERGY" Nov 11, 2010 < http://www.exergy.se/goran/hig/re/08/ocean.pdf >

[2] The Wind Power, the green optimistic, 23 February 2012 <http://www.greenoptimistic.com/category/wave-power/>
[3] “Design and Finite element analysis of ocean current turbine blades.” August 2009 by Nicholas S Youseff
[4] Hansen, Martin. Aerodynamics of Wind Turbines. 2nd ed. London and Virginia: Earthscan, 2008.
[5] Batten, W.M.J., Bahaj, A.S., Molland, A.F., Chaplin, J.R., “The prediction of the hydrodynamic performance of marine current turbines,” Renewable Energy Volume 33, Issue 5, May 2008, Pages 1085-1096.
[6] ANSYS, Inc. Release 11.0. “Structural Guide.” Chapter 13. Composites. 2007.
[7] Daniel, Isaac, Ishai, Ori. Engineering Mechanics of Composite Materials. 2nd ed. New York: Oxford University Press, Inc., 1996.
[8] de Goeij, W. C., van Tooren, M. J. L., Beukers, A. “Implementation of bending-torsion coupling in the design of a wind-turbine rotor-blade,” Applied Energy Volume 63, Issue 3, July 1999, Pages 191-207, ISSN 0306-2619, DOI: 10.1016/S0306-2619(99)00016-1.
[9] Barbero, Ever. Introduction to Composite Materials Design. New York: Taylor & Francis Group, 1999.
[10] Shokrieh, Mahmood M., Rafiee, Roham. 2006. “Simulation of fatigue failure in a full composite wind turbine blade,” Composite Structures, Volume 74, Issue 3, (August), Pages 332-342, ISSN 0263-8223, DOI: 10.1016/j.compstruct.2005.04.027.
[11] ANSYS, Inc. Release 11.0. “Elements Reference.” Part 1. Element Library. 2007.
[12] “Vibratory Analysis of Turbomachinery Blades” December 2008 by Mohamed Hassan
[13] William J. Palm “Mechanical Vibration” Wiley ISBN 0-471-34555-5, 2004.