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Characterization of Tidal Current Turbine Dynamics Using Fluid Structure Interaction (FSI)

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Abstract-Global climate change is one of the greatest challenges faced by the humanity. There is a growing awareness among the world population about the need of reducing the greenhouse gas emissions. This in fact, has led to an increase in power generation from renewable sources. The tidal current energy has the potential to play a vital role in a sustainable energy future if the applicable technologies are developed. The main objective of this paper is to investigate the horizontal axis tidal current turbine (HATCT) dynamics using fluid structure interaction (FSI) modeling. Vibration in tidal current turbine is produced due to hydrodynamic forces. The vibration causes resonance and dynamic loads on the structures which leads to failure of the structures. To prevent the TCT from failure and to increase the annual energy production its dynamic analysis is important. In order to achieve this aim a number of key steps were performed. Using computational fluid dynamics (CFD), flow passing through the turbine rotating in a rectangular channel was modelled. The National Renewable Energy Laboratory (NREL) developed code HARP_Opt (Horizontal Axis Rotor Performance Optimization) was used for Blade element momentum (BEM) Design of turbine in support of CFD. The pressure exerted on the turbine blade modelled in CFD was transferred to finite element model (FEM) through Fluid structure interaction (FSI) module in Ansys. Transient structural analysis module of the Ansys work bench was used to investigate the structural response of tidal current turbine. The modal analysis, pre-stressed vibration analysis and forced vibration analysis were performed for the structural response of tidal current turbine. The performance curves obtained from CFD and BEM showed a very good match. The modal analysis showed that neither of the natural frequency is critical and it is expected that the structure of the designed turbine is not prone to resonance. The techniques used in the research provided excellent results that will be crucial in understanding the physics governing the operation of Tidal current turbine (TCT) in tidal currents.

Keywords-Tidal Current Turbine, CFD, BEM, HARP_Opt, Finite Element Model.

I. INTRODUCTION

The tidal current energy is a form of hydropower extracted from tides. The tides are produced due to relative motion of earth and moon. The sun also contributes to the generation of tides. Because of the proximity to the earth, the lunar gravity is the primary driver for the generation of tides [i].

Several turbine design concepts for the extraction of tidal current energy have been studied during the past decade [ii]. However, the Horizontal Axis and Vertical Axis turbines have attracted most of the research focus. The shape of rotor of horizontal axis turbine is of propeller type [iii].

Tidal Current Turbines (TCT) must be designed in a way to provide reliable electrical energy production in a subsea environment with minimal maintenance [iv]. Blades are one of the major component of this system. The two blades turbine have lower cost, easy to install and required small size gear box but creates higher wake [v]. Three blades turbine satisfies the minimum number of wings required to be stable. Three blades turbine can run at low flow velocity and reduce the chances of cavitation [vi]. Some of the prototype tests of TCT have showed early blade failures [vii-viii]. It is therefore very important to understand the behavior of TCT against the complex loading imposed by tidal currents. The Failures related to the TCT, especially turbine blades, will have a significant impact on the overall cost-effectiveness and reliability of developed technology [ix]. Extensive research have been carried out for investigating the effects of structural loads on turbine blades [x]. Experimental approaches were developed by Liu et. al for the modal/vibrational analysis of TCT, that produces the Edgewise mode shapes of the blade on the basis of blade vibration and time [xi]. Along with experimental techniques, numerical modeling techniques have also been widely used to study the dynamic response of the turbine structure. One way FSI model was used to study the interaction between the rotating blade and pressure on the surface of the turbine rotor [xii-xiii]. The pressure around the turbine blade was investigated by considering the accurate motion of vibrating blade. The study revealed that there is no significant deviation of pressure between the casing surface and blade tip. A similar numerical study [xiv], was conducted on the dynamic analysis of different configuration of wind turbine. The results revealed that the effect of elastic foundation and hydro-dynamic plays vital role in highlighting the dynamic response of the structure. Blades of the turbine are continuously under the influence of repeated hydrodynamics loads that causes resonance and ultimately lead to failure of the blades [xv].

The current study is conducted for the characterization of tidal current turbine dynamics by using the numerical technique of fluid structure interaction (FSI). The vibration parameters are determined that shows the efficiency as well as the structural reliability of TCT and is the novelty of the current work. The main focus of current research work is to analyze the behavior of tidal current turbine rotor against dynamic loads. Natural frequencies and mode shapes will be analysed for the modal response of tidal current turbine.

II. COMPUTATIONAL FLUID DYNAMICS

A 3-bladed turbine based on the work of [ix] was modelled. This was a 0.50 m turbine modelled in autodesk inventor as in Fig.1, according to the design sequence available in the original work.

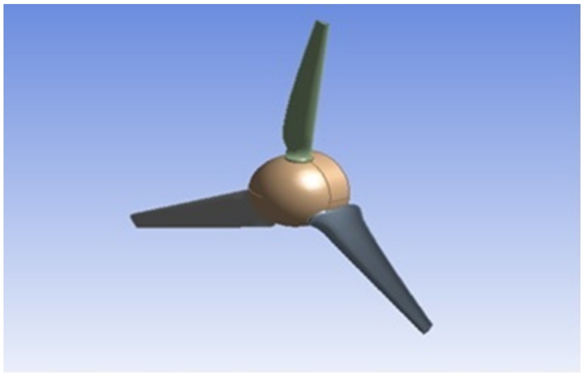

Fig.1. Solid 3D Model of TCT (ISO View)

The geometry was meshed in ansys ICEM CFD using tetra meshing as shown in Fig. 2. The overall mesh consisted of 4.7 Million tetrahedral elements. A dense prism-layer consisting of 197474 elements and 99266 nodes was generated around the blade in order to predict the torque on blade. Unstructured mesh having 3979481 elements and 1312011 nodes for the inner and 541280 elements and 102214 nodes was selected for the outer domain as shown in Fig. 2.

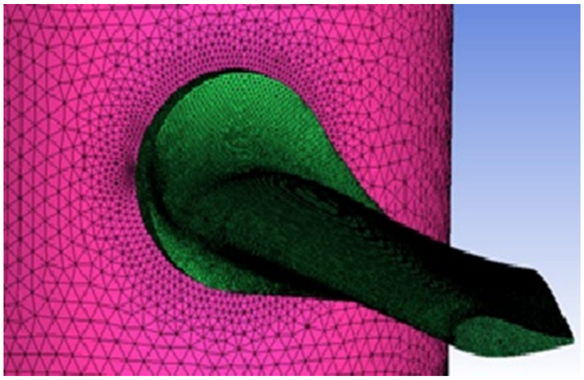

Fig. 2. Grid system of the rotor

The unstructured mesh was selected for this study because complex geometries like TCT can be meshed easily by this method. Also the unstructured mesh reduced the computational cost and has faster convergence. And more accurate solution can be obtained easily by using this method.

For CFD analysis of TCT the flow field is divided into a rotating and a stationary domain. The external stationary domain where the fluid flows is modeled in a rectangular shape having length of 5.0 meter, width 1.0 m and height of 0.80 meter which are also the dimensions of the experimental circulating water channel. The internal rotating domain where the turbine rotates is a cylindrical shape having diameter of 0.6 meter and height of 0.11 meter as shown in Fig 3.

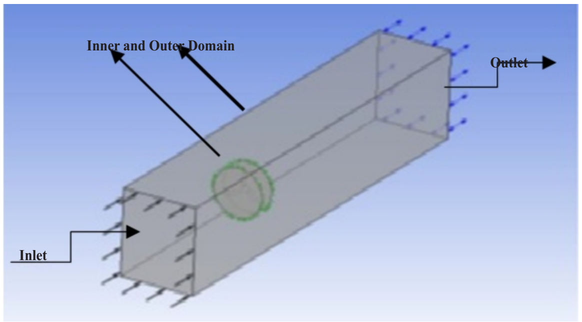

Fig. 3. Specification of external and internal domain

Condition at the inlet of external domain was normal speed condition with incoming velocity of 1.0 m/s, which is also the design velocity. An opening condition was used at the outlet area of the external domain so that according to the flux change due to the turbine it can be calculated. The wall conditions that were similar to the environment of the circulating water channel were used at the walls and floors of the external domain. Free slip condition was used for the channel top. Meeting part of the internal rotating area and the external area used the general connect - frozen rotor as the interface condition, while the mesh connect method used the GGI condition. No slip wall condition was used on the blade. Steady state CFD analysis was carried out with a rotating reference frame (RFR) with medium intensity. The shear stress transport (SST) model was selected. In solver control setting, maximum number of iterations was set to 300 with auto time scale. For residuals, the criteria for convergence was set to 1.0 E^-04. And ANSYS CFX Postprocessor was used to calculate the torque. The analysis in the proposed work was performed on the Dual core CPU with 64-bit operating system with 8 GB RAM. And a single simulation takes 3 to 4 hours to complete.

III. HYDRODYNAMICS OF TIDAL CURRENT TURBINE

In this research work BEM and CFD methods were used to analyse the full rotor comprising of three blades and hub in order to predict the torque generated by the turbine at different tip speed ratios (TSR). The performance curve using a design velocity of 1.0 m/s is shown in Fig.4 Using function calculator of ANSYS-CFX torque values were calculated for eight repetitive analysis. These analysis were performed for TSR 2 to 8.

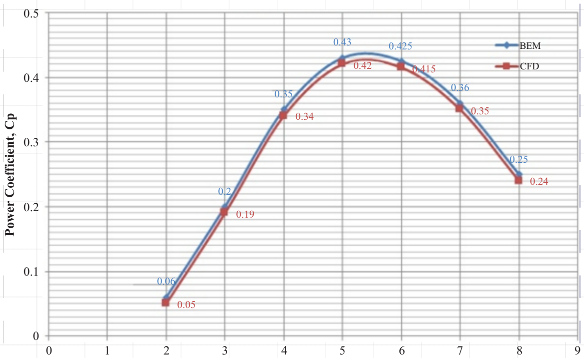

Fig. 4. Performance Curve of TCT

The Fig 3 shows both BEM and CFD analysis. The values of power coefficient increasing linearly at TSR 2 - 4. The maximum power coefficient (Cp) 0.43 occurs at a TSR 5 in BEM analysis, while maximum Cp 0.42 occurs at TSR 5 in CFD analysis. Further increase in TSR decreases the Cp value in both cases. The CFD and BEM analysis are in good agreement and produce reasonable estimates of power output.

IV. FSI MODELS

When the flowing fluid comes in contact with a deformable structure, it will exert some forces on structure and the structure will deform, as a result this deform structure will influence the flow. Such type of interaction is called fluid structure interaction. Advancement in the computational field has made it possible to analyse the complex fluid structure interaction problems. This approach is widely used in wind turbine industry to study the response of structure to wind. TCT installed in a flowing fluid can be regarded as fluid structure interaction problem.

When the fluid forces act on the blade surface it produce the torque due to which the turbine rotate. The blades of the turbine also deform when the fluid exerts pressure on the blade. This Deformation of turbine blades will change flow field around the blades. In order to find out the resulting variation in hydrodynamic forces and deformation of turbine blades the CFD models were coupled with finite element model.

FEA is a numerical technique used for the solution of complicated problems and used for structural analysis. The accuracy and physical response of this method is based upon discretization and boundary conditions. The method has ability to handle complex and irregular geometries simply. Handle the static and transient loading condition easily, they have the ability to handle large number of boundary condition.

The equation of motion for the structural response used in ANSYS are given as [xvi]:

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+[K]\{u(t)\}=\{F(t)\}$$

Where:
$[M]$ = Structural mass matrix
$[C]$ = Structural damping matrix
$[K]$ = Structural stiffness matrix
$\{\ddot{u}(t)\}$ = Nodal acceleration vector
$\{\dot{u}(t)\}$ = Nodal velocity vector
$\{u(t)\}$ = Nodal displacement vector
$\{F(t)\}$ = Applied load vector

In above equation, the $[M]$, $[C]$ and $[K]$ matrices are the properties of the system, $\{u\}$ is the behavior and $\{F(t)\}$ is the action or applied force.

V. MODAL ANALYSIS OF TCT

The phenomenon of resonance due to excessive vibratory motion arises in many structures. It is necessary to find out the quantity and quality of the frequency to analyze the vibration related problems. The response of the structure can be investigated using the Modal analysis by applying the boundary conditions to the structure. The mode shapes and natural frequencies of the structure are simulated for analyzing the vibration response.

For Modal analysis of rotor, the constraints are applied on back side of the rotor in all degrees of freedom and the rotor are analyzed in static conditions. First six mode shapes and natural frequencies are calculated by using ANSYS workbench, shown in Table I and in Fig. 5 to 10.

TABLE I
MODE SHAPES AND NATURAL FREQUENCIES

Modes	Natural Frequency [Hz]
1	126.04
2	171.93
3	177.02
4	460.02
5	548.92
6	550.41

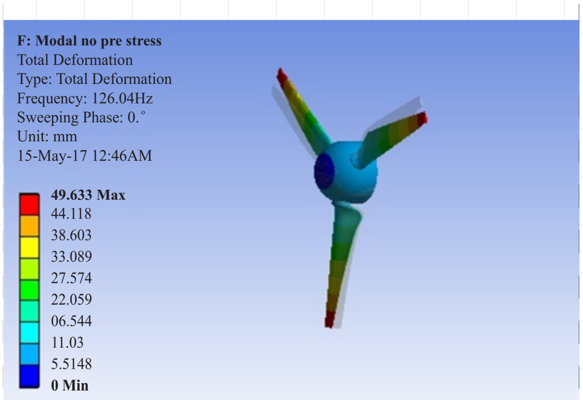
F: Modal no pre stress
Total Deformation
Type: Total Deformation
Frequency: 126.04Hz
Sweeping Phase: 0.°
Unit: mm
15-May-17 12:46AM

Fig. 5. Modes Shapes For Frequency 126.04 Hz

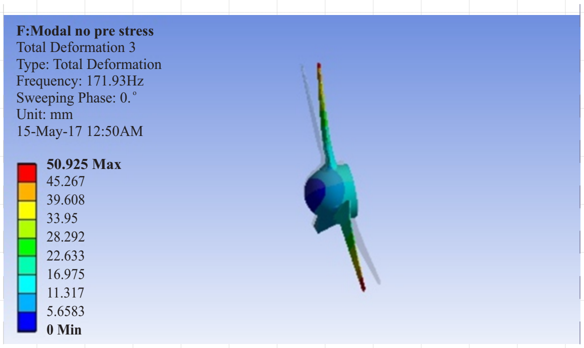
F:Modal no pre stress
Total Deformation 3
Type: Total Deformation
Frequency: 171.93Hz
Sweeping Phase: 0.°
Unit: mm
15-May-17 12:50AM

Fig. 6. Modes Shapes For Frequency 171.93 Hz

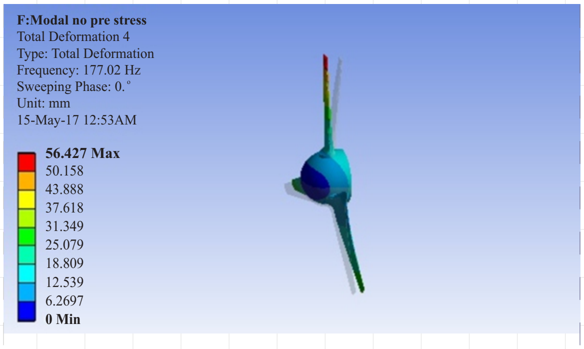
F:Modal no pre stress
Total Deformation 4
Type: Total Deformation
Frequency: 177.02 Hz
Sweeping Phase: 0.°
Unit: mm
15-May-17 12:53AM

Fig. 7. Modes Shapes For Frequency 177.02 Hz

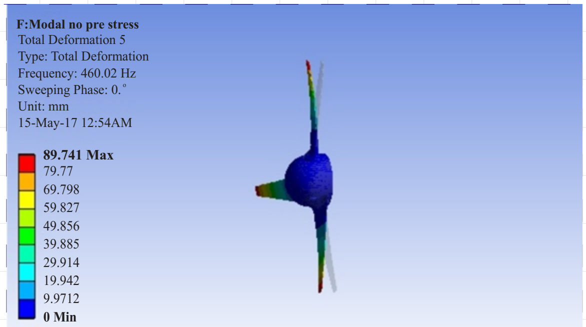
F:Modal no pre stress
Total Deformation 5
Type: Total Deformation
Frequency: 460.02 Hz
Sweeping Phase: 0.°
Unit: mm
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Fig. 8. Modes Shapes For Frequency 460.02 Hz

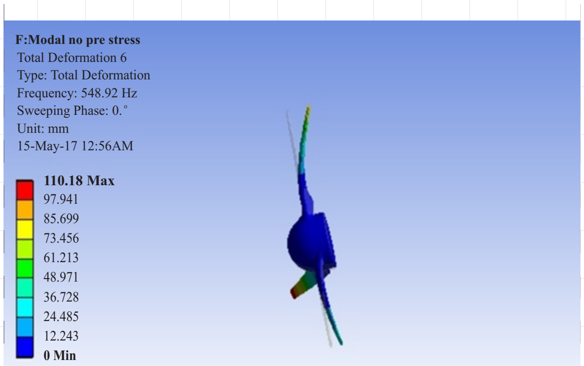
F:Modal no pre stress
Total Deformation 6
Type: Total Deformation
Frequency: 548.92 Hz
Sweeping Phase: 0.°
Unit: mm
15-May-17 12:56AM

Fig. 9. Modes Shapes For Frequency 548.92 Hz

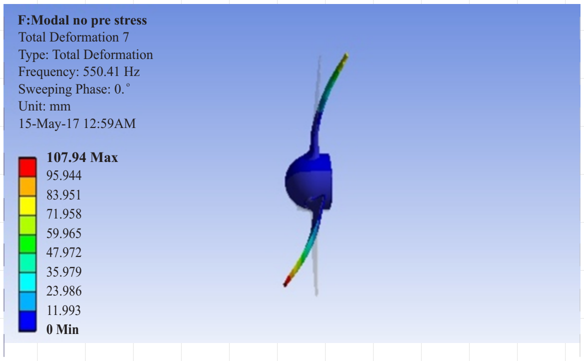
F:Modal no pre stress
Total Deformation 7
Type: Total Deformation
Frequency: 550.41 Hz
Sweeping Phase: 0.°
Unit: mm
15-May-17 12:59AM

Fig. 10. Modes Shapes For Frequency 550.41 Hz

The full rotor is simulated at an RPM of 191resulting the forcing frequency of 20 Hz at rotor. The natural frequency and forcing frequency of the rotor should not match. If this forcing frequency of the rotor matches the natural frequency, then the structure of the rotor will resonate causing the increase in amplitude of vibration, which may leads to the failure of the structure. By comparing the values of the natural frequencies in Table I with 20 Hz forcing frequency, no matching of natural and forcing frequencies are observed. Satisfying that the rotor will not resonate and also there is no potential failure observed in the structure of the rotor in modal analysis of TCT.

VI. FORCED VIBRATION ANALYSIS

For forced vibration the Transient analysis was carried out in ANSYS workbench to analyze the structural response of TCT due to influence of the hydrodynamic loads. This analysis was performed for a time duration of 0-3 seconds. The transient analysis results for forced vibration are shown in Table II, III and Fig. 11-12.

TABLE II
DIRECTIONAL DEFORMATION OF TCT

Directional Deformation (Transient Structural Analysis)		
Time (S).	Minimum(mm).	Maximum(mm).
0.20	-7.281E-02	2.910E-02
0.40	-7.302E-02	2.920E-02
0.60	-7.303E-02	2.920E-02
0.80	-7.305E-02	2.920E-02
1.0	-7.306E-02	2.920E-02
1.20	-7.308E-02	2.920E-02
1.40	-7.309E-02	2.920E-02
1.60	-7.309E-02	2.920E-02
1.80	-7.309E-02	2.920E-02
2.0	-7.300E-02	2.920E-02
2.20	-7.300E-02	2.920E-02
2.40	-7.300E-02	2.920E-02
2.60	-7.300E-02	2.920E-02
2.80	-7.300E-02	2.920E-02

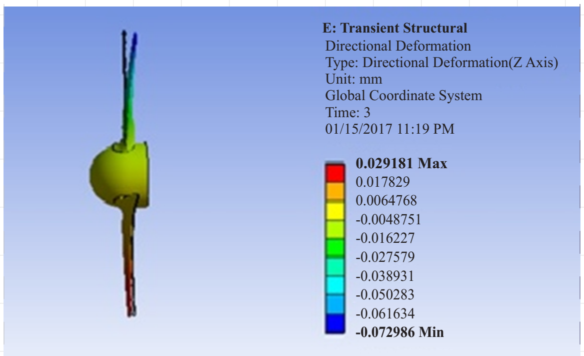

Fig. 11. Directional deformation of TCT

TABLE III
TOTAL DEFORMATION OF TCT

Total Deformation obtained from Transient Structural Analysis		
Time (S).	Minimum(mm)	Maximum(mm)
0.20	0.00	7.48E-02
0.40	0.00	7.50E-02
0.60	0.00	7.50E-02
1.0	0.00	7.50E-02
1.20	0.00	7.50E-02
1.40	0.00	7.50E-02
1.60	0.00	7.50E-02
2.0	0.00	7.50E-02
2.20	0.00	7.50E-02
2.40	0.00	7.50E-02
2.60	0.00	7.50E-02
2.80	0.00	7.50E-02
3.0	0.00	7.50E-02

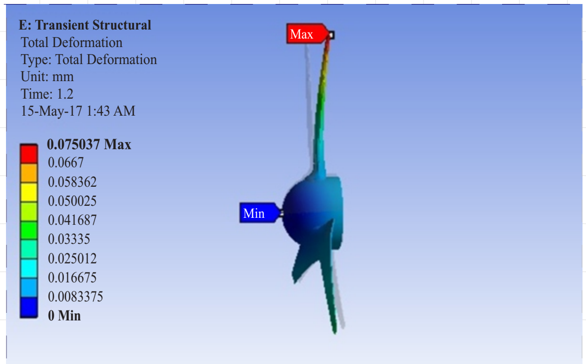

Fig. 12. Total Deformation of TCT Rotor

The above performed analysis showed that TCT blade has low natural frequency for natural mode excitation. To suppress the vibration, flexible joints are recommended and in this manner the TCT can be prevented from failure. It must have damped vibrations earlier before any natural modes can activate.

VII. CONCLUSION AND FUTURE RECOMMENDATIONS

The performance curves obtained from CFD and BEM showed a very good match. They showed an error of 1% for TSR 2 to 8. The modal analysis showed that neither of the natural frequency is critical and it is expected that the structure of the designed turbine is not prone to resonance. The one way analysis showed that deformation caused by the vibration is not critical to cause any power loss or failure to turbine blades. The techniques used in the research work proved to be very efficient and the results produced were quite good.

It is recommended that a full model of the TCT including the Nacelle and tower structure may be studied for its dynamics properties using fluid structure interaction. Moreover, a transient flow model may be used instead of a steady state rotating frame of reference model to more accurately capture the behavior of the flow. A two way FSI model may be used to investigate the effect of fluid pressure on the turbine and at the same time the effect of the vibration produced in the turbine on the wake of the turbine. The study of the effect of the vibration on the wake will be important for the design of tidal arrays. The real sea condition like randomness of the current, wave current interaction and velocity shear etc., may be included in the future model to get a more realistic understanding of the physics governing the operation of a tidal turbine in tidal currents.

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