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STRESS AND FATIGUE LIFE PREDICTION OF THE H-TYPE DARRIEUS VERTICAL AXIS TURBINE FOR MICRO-HYDROPOWER APPLICATIONS

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Abstract

The present study aims to analyze the structural behavior of the Darrieus Hydro-kinetic turbine at different upstream velocity values and rotational rates. For that purpose, one-way fluid-structure interaction is performed to predict stresses, deformation and fatigue life of the turbine. To determine real-time fluid loads three-dimensional fluid flow simulations were performed, and the obtained fluid loads were transferred to the structural finite element analysis model. CFD simulation results were validated with experimental results from literature where the close agreement was noticed. Structural analysis results revealed that the highest stresses are produced in the struts and at the joint where the shaft is connected with struts. Moreover, it was also found that the stress produced in the turbine is highly non-linear against Tip Speed Ratio (TSR) i.e inflow water velocity. Finite Element Analysis (FEA) results showed that maximum values of stresses were found in the turbine strut having a value 131.99MPa, which is lower than the yield strength of the material, the fatigue life of 117520 cycles and the factor of safety 1.89. The study also found that increased inflow velocity results increase in stress and deformation produced in the turbine. Additionally, the study assumed Aluminum Alloy as turbine blade material, further; it was found that the blade which confronts flow, experiences higher stresses. Moreover, the study concluded that strut, blade-strut joint and strut-shaft joint are the critical parts of the turbine, requiring careful design consideration. Furthermore, the study also suggests that the turbine blade may be kept hollow to reduce turbine weight; hence inertia and turbine struts and shaft should be made of steel or a material having higher stiffness and strength.

Keywords: Structural loading; Hydrokinetic turbine; Turbine stress analysis; deflection; fatigue life; Factor of safety

I. Introduction

Vertical axis turbine offers several advantages over the horizontal axis turbine, such as power produced by vertical axis turbine is insensitive to flow direction and its auxiliary parts (i.e drive train and generator) remain at the water surface. Moreover, H-type Darrieus Hydrokinetic Turbine (DHT) is simply easy to manufacture and install. It can be used as an isolated system due to its simple design and having a generator on the ground. In contrast to this H-type Darrieus turbine have the poor self-starting capability, lack of detail structural analysis, as well as low power performance, which has limited its use [I]. In this regards several studies were performed to improve turbine power coefficient through modifying its hydrodynamic design of blade and struts. These studies investigated the effect of pitch angle, blade profile, solidity and strut geometry profile [II], [III], [IV]. However, the aforementioned research has either performed experimentation or two-dimensional numerical simulation. However, later studies found that 2D numerical simulation enables to provide accurate power estimation hence fluid loads. These studies most of the time over predict power coefficient because they don't capture 3D effects of blade tip losses and strut [V], [VII], [VIII], [IX], [X], [XI]. Another study showed that three-dimensional numerical simulation is an efficient method of computing hydraulic loads [XI], [XII]. By comparing the hydraulic load experienced by for Francis turbine through experimentation were in close agreement with the hydraulic loads obtained through three-dimensional fluid flow analysis [XI], [XIII], [XIV], [XVII], [XVII], [XVIX], [XIV], [XXI], [XXI], [XXIII], [XXIV], [XXIV]. It is observed from the above-mentioned literature that most studies have focused on the Darrieus turbine power performance rather than on its structural integrity. However, to design safe, reliable and long-lasting turbines for hydro-kinetic applications, detail structural behavior understanding is required. Furthermore, a very limited, experimental study has been carried to measure stresses and deformation by employing strain gauges. But nowadays with the use of high-speed computers actual hydrodynamic loads may be predicted and real-time stresses, deformation and fatigue behavior may be analyzed.

During recent years few studies were conducted a structural analysis of Darrieus turbine for the application of wind and hydropower production, but among them, most of the studies investigated structural behavior of each turbine component like the blade, shaft and struts separately and not considered the effect of turbine rotation, however, blade-strut and strut-shaft areas are the regions of high-stress concentration [XXVI], [XXVII], [XXVIII], [XXVIX]. The recent study compared the hydrodynamic and structural behavior of helical and Darrieus hydro-kinetic turbine through employing numerical methods. It was that straight blade turbine has a higher hydrodynamic efficiency than the helical turbine. However, it experiences 13% more stresses [XXX], [XXXI]. In this connection present study aims to predict stress, deformation and fatigue life of complete straight blade Darrieus hydrokinetic turbine, to enhance more understanding regarding turbine structural behavior.

The present study aims to estimate real-time hydraulic loads over a complete turbines for different fluid velocities and also predict stresses, deformation and the fatigue life of the turbine through considering 3D effects. The study also provides detail structural analysis at different points such as at the blade-strut joint and shaft-strut joint location. In addition to this, using two different materials such steel for turbine shaft and strut, whereas Aluminum for the turbine blades.

II. Computational Methodology

In this research structural behavior of the Darrieus hydrokinetic turbine is analyzed, by employing a one-way FSI, analysis methodology, where real-time hydrodynamic loads were estimated through CFD analysis. These loads are then transferred to ANSYS static structural module for stress analysis. The turbine three-dimensional model is developed in Pro-Engineer and simulated in the ANSYS workbench framework. Aluminum and structural steel are used to carry out the structural analysis of hydrokinetic turbines and to compute deformation and fatigue life.

(A) Turbine Geometry

The 3D model of the Darrieus hydro-kinetic turbine was developed in Pro-Engineer software, for which airfoil coordinates were obtained from the *University of Illinois* at Urbana–Champaign website. Once 2D airfoil is produced then, three-dimensional blades will be generated. For turbine blade airfoil NACA0020 was selected. A three-dimensional model, of Struts and turbine shaft, were developed separately and then assembled in a Pro-Engineer assembly module to generate a complete 3D turbine model. Turbine design specifications were obtained from [VII] and given in Table 1. Additionally, the turbine 3D model is presented in Fig. 1(a) along with its complete design specifications. Moreover, stress concentration regions have been reduced by employing fillet or round command.

Table 1. Geometric parameters of designed Darrieus turbine [VII]

The geometry of the turbine	Dimensions
Blade pitch angles	0^o
Blade length	1.5m
Turbine diameter	1.5m
Number of blades	3
Airfoil	NACA0020

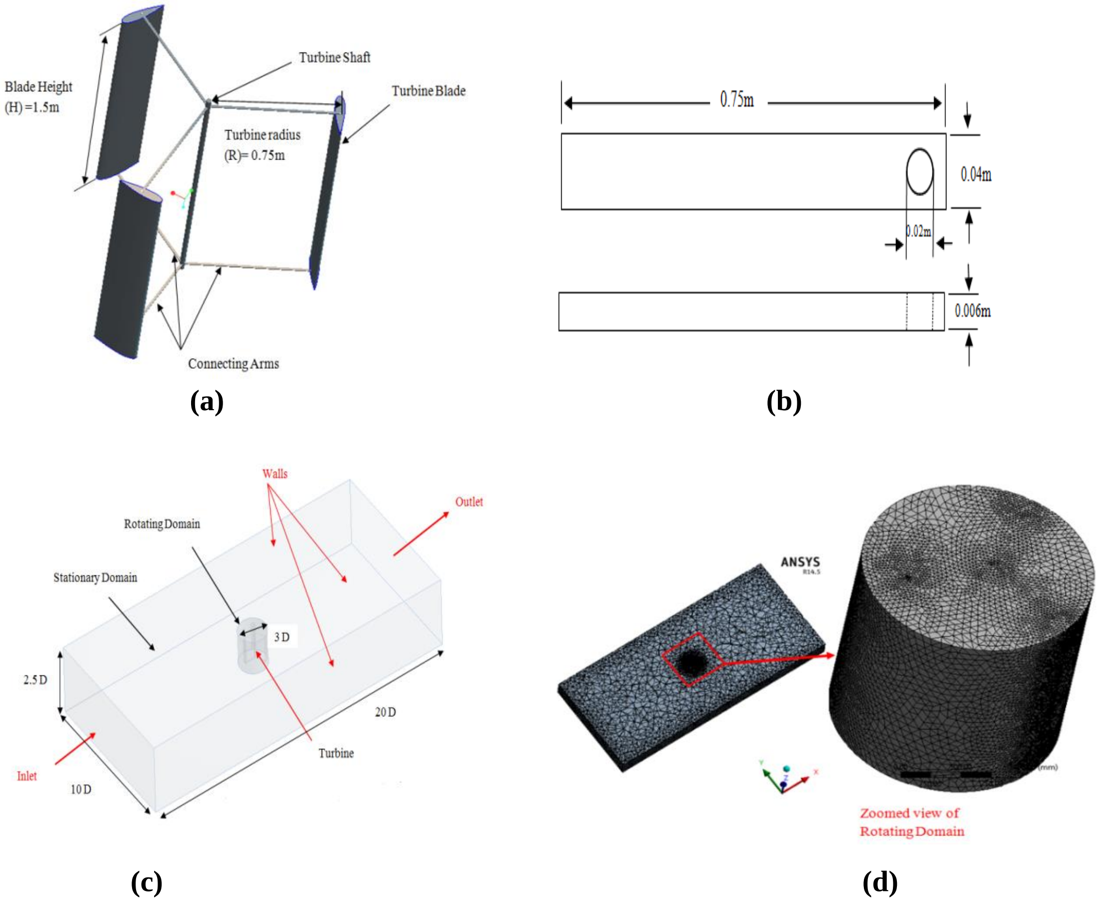

Fig. 1(a) Three Dimensional model of H-type Darrieus turbine (b) Dimensions of blade strut (c) Fluid Domain containing stationary and rotating Domain, size is specified in terms of turbine diameters (D) (d) Meshed model of the fluid domain with a zoomed view of rotating domain

(B) Hydrodynamic Simulations

To perform fluid flow analysis, three-dimensional models of the turbine are imported to ANSYS Design Modeler, once the imported model is generated fluid domain is created around the solid turbine. The fluid domain consists of the rotating and stationary domain because turbine simulation is performed through the moving frame of reference technique. Then meshing is performed and names were assigned to the various face of the fluid domain. Detail of fluid domain is shown in Fig. 1(c) along with its main features. The size of the fluid domain is expressed in terms of turbine diameter (D). Additionally, the rotating domain is cylindrical in shape having a diameter as 3D and height as 2D. Meshing is performed by employing tetrahedral mesh elements, where a patch confirming algorithm is used to generate non-uniform mesh within the fluid domain, by keeping small element size in high-pressure gradient regions. The meshed of the turbine along with a zoomed view of the rotating region is shown in Fig. (d).

(C) Validation Of CFD Model

The fluid flow analysis results were compared with experimental work [VIII] from literature, to enhance the confidence in the simulated results. The experimental results in the form of power produced at various upstream velocity values are compared with the simulation results. The values of power produced at different inflow velocity values through experimental and computational methods are compared and presented in Fig.2. By comparing the values of power produced in both of the cases it was noticed that power estimated through CFD simulation is higher than predicted by experimental methods. However the difference between the results obtained through both of the methods showing close agreement. Additionally, it was found that the maximum error is about 14% at an inflow velocity of 1m/s.

(D) Boundary conditions

To validate the results of numerical simulation, boundary conditions of the current study should be the same as the used in the experimental work. In the present study, the free-stream velocity of water varies from 0.2m/s to 1.4m/s, the angular velocity of the turbine also varies correspondingly. By using these conditions TSR is calculated.
At the inlet that is located 10D in upstream from the front side blade, the velocity of water in three Cartesian coordinate forms is kept as

$$u_1=0.2\text{-}1.4\,m/s \qquad u_2=0 \qquad u_3=0$$

(E) Structural Simulations

The structural behavior of the Darrieus hydrokinetic turbine is analyzed in ANSYS static structural through finite element analysis, hydraulic loads were mapped to the turbine surfaces through Octree mapping as shown in Fig. 3. As a result of flow fluid force the turbine experience centrifugal as well as hydrodynamic loads. The centrifugal forces are developed due to the angular velocity of the turbine and the hydrodynamics loads were due to the kinetic energy of the flowing water. Moreover, turbine rotational velocity is assigned at each inflow velocity value. In the static structural module, the only solid model of the turbine is used to evaluate its structural behavior. Turbine design specifications are provided in Table.1, material selection is the next step, in this study turbine is designed by using two different materials such as structural steel and Aluminum alloy. The turbine shaft and struts were assumed to be made of structural steel, whereas turbine blades were made by using Aluminum, this significantly reduces the turbine weight. The mechanical properties of structural steel and Aluminum are given in Table. 2 [V]. The turbine shaft is assumed to be fixed, to determine stress, deflection and fatigue life. The patch conforming algorithm is used to generate the unstructured mesh. The tetrahedral meshed elements were used to generate a mesh of the turbine for the structural in static structural, to have the accurate mapping of fluid forces. The Goodman fatigue theory is employed to predict the fatigue life of the turbine by applying fully reversed loading conditions. Since the turbine experiences highly time-varying dynamic loads thus the fatigue life prediction is highly important for safe and reliable turbine design. The fatigue stress concentration factor (K_f) is used to encounter the effect of local discontinuities and is defined as follow:

K_f= *Maximum stress in specimen/Stress in notch-free specimen* fatigue stress

In the present study fatigue stress concentration factor (K_f) is taken as K_f=1, It shows that material doesn't exhibit notch sensitivity.

Table.2 Properties of Aluminum& structural steel [V]

Material property	Aluminum	structural steel
Density	2700kg/m3	7850kg/m3
Young's modulus	70 GPa	210 GPa
poisons ratio	0.33	0.3

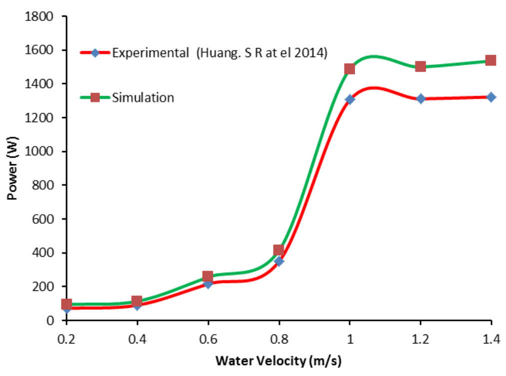

Fig. 2 Computational model validation with published experimental at different values of TSR [VIII]

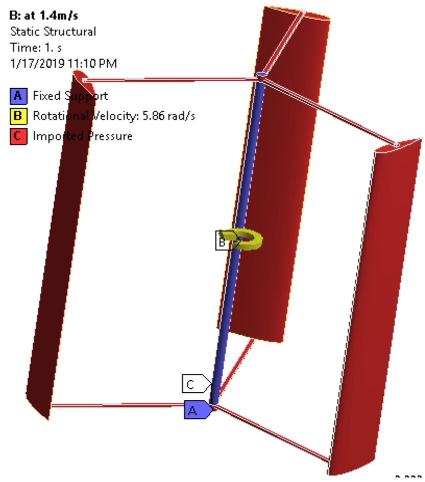

Fig. 3 Constrained and loads applied to the turbine

III. Results and Discussion

In this section, results are presented in terms of stresses, deflection and the fatigue life of the turbine at different inflow velocities. In Fig.4 (a) & Fig. 4(b) stress and deflection have been plotted against TSR. From Fig. 4(a) it is observed that stress increase with an increase in TSR; however it is also noticed that stress variation against TSR is highly non-uniform. The maximum stress experienced by the turbine is very close to the yield strength of the material. The magnitude of maximum stress produced in the turbine is 131.99MPa. In Fig. 4(b) the deflection produced in the turbine at different values of TSR is presented. From Fig. 4(b) it is observed that deflection is highly non-linear against the tip speed ratios. Moreover, the deflection graph showed the drastic increase in deformation between the TSR 4 and 8. The similar trend was also noticed in power produced and stresses experienced by the turbine. From the deflection graph, it is found that the magnitude of minimum and maximum deformation is about 1.76 mm and 15.0 mm respectively.

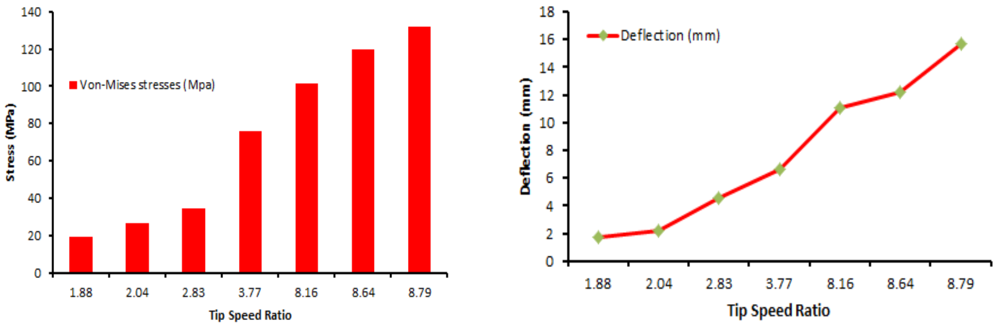

Fig. 4 (a) stress experienced by the turbine at different TSR (b) deflection produced at various TSR

In Fig. 5(a) the three-dimensional model of the turbine is presented, showing highlighted location. Moreover, in Fig. 5(b) the stress at those locations has been plotted and presented. On the vertical axis of the graph, stress is plotted and highlighted locations have been placed on the horizontal axis. Two vertical axes are shown in graph one having the values in stress magnitude in kPa and the other in MPa. The values of stress in the graph have been placed on two axes, due to the very stress magnitude at the location A, D and E. Moreover, from Fig. 5(b) it is observed that very low stresses are produced at turbine blades, however; the highest stresses were experienced in strut and shaft-strut joint location. Stresses in the strut very near to shaft reached a maximum value of 132MPa at an inflow water velocity of 1.4m/s. furthermore, the second-highest stress location is at shaft-strut connection and the third-highest stress was found at the blade strut joint.

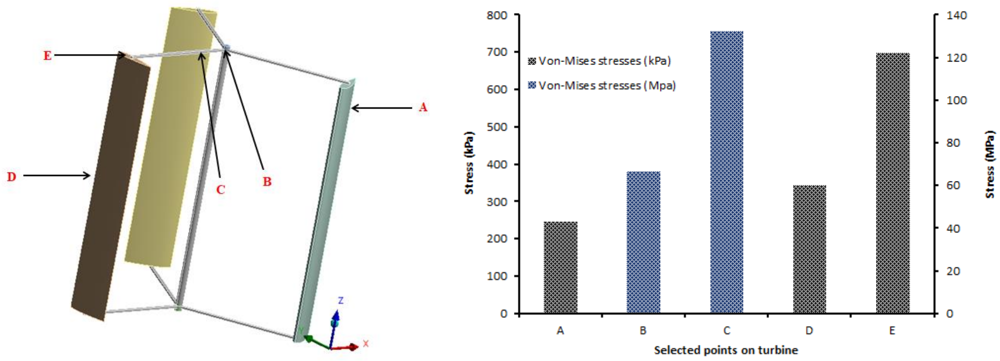

Fig. 5 (a) selected locations on turbine (b) stress against the selected location

In Fig. 6(a) & 6(b) deformations and stress distribution is presented on turbine. From deformation contour, it was found that maximum deformation was produced in the blade that is in front of the flow, but the actual situation is that turbine strut experience huge deformation and blade is attached to it and the deformation produced in the blade is very low along the blade length. However, minimum deformation was produced in the turbine shaft were noticed. In addition to that, the stress distribution in the turbine is presented in Fig. 6(b). From Fig 6(b) it is observed that maximum stresses were experienced by turbine strut and at the strut-shaft joint and strut-blade joint. It was also found that bending stresses were produced in the turbine strut. From Fig.6(b) it is found that the turbine strut and its joints with shaft and blade are the critical parts of the turbine. Moreover, the fatigue life of the turbine was determined through employing Goodman theory by considering fully reversed loads and it was found that at maximum stress level, hence inflow velocity of 1.4m/s current turbine design will have fatigue life of about 117520 cycles, however the with a decrease in inflow velocity results in higher fatigue life.

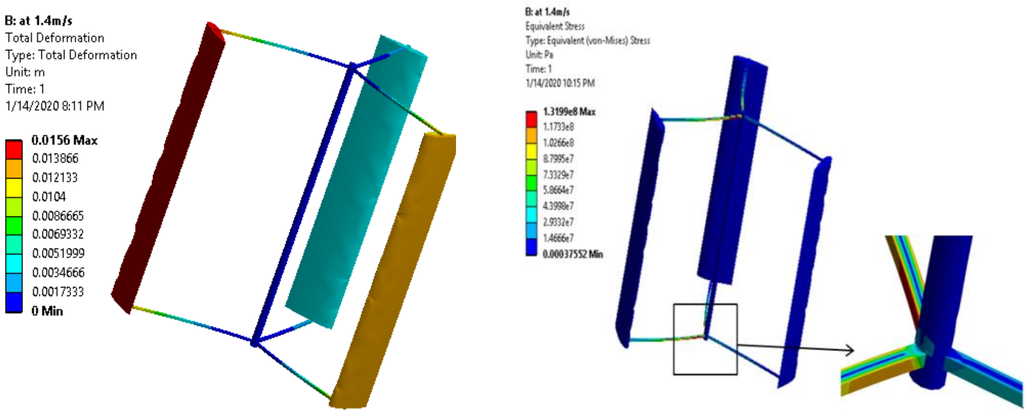

Fig. 6 (a) Deformation produced in the turbine (b) stress and zoomed view of high-stress concentration region

IV. Conclusion

In this research, stress, deformation and the fatigue life of the Darrieus hydrokinetic turbine were evaluated by employing one-way FSI analysis. The study aim, to acquire in-depth structural behavior of the turbine at different free-stream velocity values and turbine rotational rates. Stress analysis results reveal that the stress produced in the turbine is highly non-linear against (TSR) i.e inflow water velocity. Finite element analysis results predicted that maximum stresses produced in the turbine strut are 131.99MPa, which are lower than the yield strength of the material, thus the turbine is safe. The fatigue life of the turbine was found to be 117520 cycles and the factor of safety is 1.89. It was also found that increase inflow velocity results in higher stress and deformation in the turbine. Additionally, the study assumed that turbine blades are made of Aluminum, whereas turbine shaft and strut were made of steel. Moreover, it was found that blade that confronts flow experience higher stresses. The study concluded that strut, blade-strut joint and strut-shaft joint are the critical parts of the turbine, require careful design consideration. Furthermore, the study also suggests that the turbine blade may be kept hollow to reduce turbine weight; hence inertia and turbine struts and shaft should be made of steel or the material having higher stiffness and strength. Authors expect that these findings will lay down some technical foundations in designing future H-type Darrieus turbines.

Conflicts of Interest:

The authors declare that they have no conflicts of interest to report regarding the present study.

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