International Journal on Emerging Technologies **12**(1): 19-24(2021)

ISSN No. (Print): 0975-8364
ISSN No. (Online): 2249-3255

One Way Fluid-structure Interaction Analysis of Vertical Axis Hydrokinetic Turbine

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(Received 06 October 2020, Revised 20 November 2020, Accepted 11 December 2020)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: The straight blade Darrieus turbine is simple, easy to manufacture, maintain and install, despite of that its use is limited due to poor self-starting characteristics and lack of structural understanding. In this this connection present study aims to predict the stresses and deformation produced in vertical axis hydrokinetic turbine during operation at different free stream velocity values. In order to predict stresses and deformation one-way fluid-structure interaction is carried out in ANSYS workbench environment. Initially, fluid flow analysis of the turbine at different free stream velocity values was conducted. Once fluid flow analysis is performed those fluid loads are transferred to ANSYS structural module for stress and deformation prediction. Finite Element Method (FEM) is used to analyze turbine structural behavior under varying water free stream velocity. Stress analysis results revealed that stresses produced in turbine are highly non-uniform in nature. The stresses produced in turbine are lower than material yield strength therefore turbine remains safe under all the operating conditions. Moreover, study results also reveal that stresses and deformation produced in turbine increase with increase in water upstream velocity.

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

I. INTRODUCTION

Straight blade Darrieus turbine comes under the category of cross-flow turbines. The Darrieus turbine is widely used machine to harness kinetic energy from wind, tides and river water. The Darrieus turbine offers great advantages due to its simple construction, ease of installation and requires lower maintenance. Furthermore, it can be used as an isolated system at micro scale power generation. In contrast to this H-type Darrieus turbine have poor self-starting capability, lack of detail structural analysis as well as low power performance has limited its use [1].

At present, the number of attempts was made to enhance turbine performance [2-6]. However, most of efforts were made for wind power applications through considering effect of turbine tip speed ratio, solidity, pitch angle and airfoil geometry [2-6]. Moreover, due to different properties of air, undefined wind direction and distinction in operating conditions, similar design of turbine profile and structural strength will not be able to provide desired output performance. In recent years use of Darrieus turbine increased beyond wind to harness kinetic energy of water [1]. Due to increased number of application of Darrieus turbine in river and tidal power generation, performance enhancement became an agile research area. To investigate pitch angle and airfoil thickness effect Ali, I. *et al.*, [16] performed CFD analysis. The CFD analysis results indicated that 0o pitch angle and thicker airfoil turbine gives better performance than the turbine with higher pitch angle [7].

Recently an experimental study was conducted to analyze H-type Darrieus hydrokinetic turbine by using three different airfoils namely NACA0015, NACA0018 and NACA4415 at various solidities. Experimental results found that NACA0015 and NACA0018 airfoil achieved higher power coefficient than cambered airfoil NACA4415 at solidity of around 0.382 [8]. Li and Calisal [9] conducted research to analyze arm shape effect along with 3D effects on the performance of Darrieus turbine for tidal applications. They concluded that the arm shape has negligible effects, also, it was also found that 3D effect decreases with increase in turbine aspect ratio. During recent years few studies were conducted 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 [10-12]. Another study investigated effect of duct augmentation system on the overall performance of H-type Darrieus hydrokinetic turbine through one-way FSI. Study result reveal that use of duct augmentation system increase power performance two times whereas it also increase stresses and the deformation produced within turbine due to fluid loads. But the major limitation of the study was that authors neglected the effect of centrifugal force produced as a result of turbine rotation [13]. 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 than the straight blade Darrieus hydrokinetic turbine [14].

From the above literature it observed that most of the studies conducted on Darrieus vertical axis turbine are related to its power performance and to improve turbine self-starting characteristics. However, the one major limitation in the use of Darrieus turbine for wind and hydrokinetic power extraction is the lack of turbine structural analysis. The turbine structural behavior is investigated by various research studies but most of the studies analyzed various turbine parts separately. Moreover, the previous studies conducted on the structural integrity of the Darrieus vertical axis turbine for wind power applications however, the density of water is 1000 times higher than the density of the wind, thus the structural analysis of the vertical axis turbine for hydrokinetic application is yet be explored.

II. COMPUTATIONAL METHODOLOGY

To analyze the structural behavior of the vertical axis turbine initially the turbine model is imported to ANSYS workbench and the computational fluid dynamic (CFD) technique was used to compute pressure and shear stress distribution on the turbine blade, turbine connecting arms and the shaft. Once the CFD analysis is conducted then those fluid loads were transferred to static structural module in order to determine stresses and the deformation produced within complete turbine under operating conditions. Moreover, the process is repeated at all the velocity values in order to predict variation in stress and deformation with fluid velocity.

III. TURBINE GEOMETRY

The 3D model of Darrieus hydro-kinetic turbine was developed in Pro-Engineer software, for which airfoil coordinates were obtained from University of Illinois at Urbana–Champaign website. Once 2D airfoil is produced then, three dimensional blades will be generated. For turbine blade airfoil NACA0020 were selected. A three-dimensional model, of Struts and turbine shaft were developed separately and then assembled in Pro-Engineer assembly module to generate complete 3D turbine model. Turbine design specification were obtained from [15]and given in Table 1. Additionally, 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 [15].

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

Table 2: Properties of Aluminum & structural steel.

Material property	Aluminum	structural steel
Density	2700kg/m^3	7850kg/m^3
Young's modulus	70 GPa	210 GPa
poisons ratio	0.33	0.3

IV. MESHING AND FLUID FLOW SIMULATIONS

In order to perform, one-way fluid structure interaction initially the pressure and the shear stress distribution is computed through CFD technique. The turbine model is imported in ANSYS Design modeler where the fluid domain is created around the turbine. Domain consists of two zones rotating zone and the stationary zone. Once geometry is completed than the model is meshed in order to divide domain into small elements and apply discretization technique. Moreover, the tetrahedral mesh elements were used, and the patch conforming algorithm is applied to create fine mesh in high pressure gradient regions.

The different sections of the fluid domain were named in order to assign boundary conditions. Once the mesh is completed the next step in CFD simulation is setting the solver according to the physics of the physical problem. The pressure-based solver is used because fluid i.e water is used and is incompressible. The steady state simulation performed and the turbulence present within the fluid was modeled through k-ω Shear stress Transport model. Moreover, the pressure velocity coupling is used and simulation is carried out through moving frame of reference.

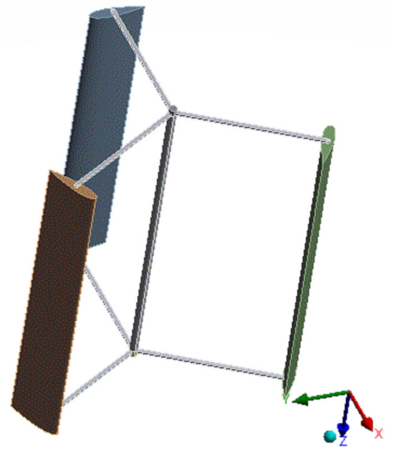

Fig. 1 (a) Three Dimensional model of H-type Darrieus turbine.

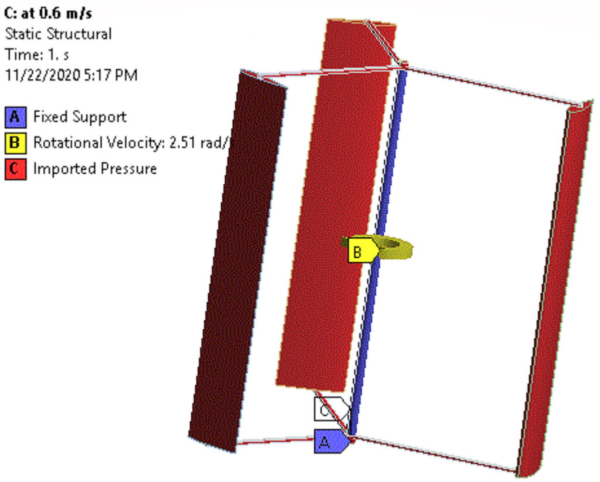

Fig. 1 (b) Boundary conditions applied on the turbine.

V. GOVERNING EQUATION& TURBULENCE MODELING

The governing RANS equation for the fluid flow analysis of hydrokinetic turbine using water (incompressible, viscous) as working fluid can be written as follow.

$$\frac{\partial}{\partial x_i}(u_i)=0 \tag{1}$$

$$u_j \frac{\partial}{\partial x_j}(u_i) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + v\frac{\partial}{\partial x_j}\left(\frac{\partial}{\partial x_j}(u_i)\right) + \frac{\partial}{\partial x_j}\left(-\rho \overline{u_i' u_j'}\right) + \chi \tag{2}$$

The Eqn. (1) & (2) are known as Reynolds Average Navier-Stokes (RANS) equations. The term$(-\rho\,\overline{u_i u_j})$ of Eqn. (2) is known as Reynolds stress that takes into account the effect of turbulence present in flow. It is modeled through appropriate turbulence model for accurate result prediction [16]. Number of studies was conducted to select turbulence model that provide results very near to experimental work. Their results reveal that $(k-\omega)$ model showed better accuracy as compared to $(k-\varepsilon)$model in case of near wall problems [3, 17, 18]. But the problem still remained in modeling of flow away from the wall. Sometime later Menter's introduced $(k-\omega)$Shear Stress Transport (SST) model that combine the merits of both discussed models [19, 20]. In case of separated flows $(k-\omega)$ (SST) model provides good results. Furthermore, lot of studies found $(k-\omega)$ (SST) model more suitable for vertical axis turbine fluid flow analysis [4, 21-24]. Present study model 3D dimensional turbulent flow through$(k-\omega)$the SST model with fully resolved turbulent boundary layer by employing inflation layers. The$(k-\omega)$ SST model has been used successfully in similar studies [25-35].The Transport equations of$(k-\omega)$SST model are given below.

$$\frac{\partial(ku_i)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\Gamma_k}{\rho}\frac{\partial k}{\partial x_j}\right) + P + Y_k \tag{3}$$

$$\frac{\partial(\omega u_i)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\Gamma_\omega}{\rho}\frac{\partial \omega}{\partial x_j}\right) + \tilde{G}_\omega - Y_\omega + D_\omega \tag{4}$$

The above Eq. (1-4) were solved by using the Fluent TM through employing the finite volume method. Multiphysics 5.0, there design is constructed, and simulation is done.

VI. BOUNDARY CONDITIONS

In order to validate the results of numerical simulation, boundary conditions of current study should be same as of the used in the experimental work. In 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 form is kept as

u1=0.2-1.4m/s u2=0 u3=0

VII. STRUCTURAL SIMULATIONS

The structural behavior of the Straight blade Darrieus hydrokinetic turbine, the ANSYS workbench framework is used. Where the real time fluid loads were computed through CFD analysis and the fluid loads were then transferred to the ANSYS structural module for Stress and deformation prediction. Once the pressure loads due to fluid are imported to the ANSYS structural module, meshing is performed tetrahedral elements were used to develop mesh. Moreover, the patch conforming algorithm is applied in order to create non-uniform mesh over the turbine blade.

In this study hydrodynamic forces produced as result of fluid flow and the centrifugal force produced due to rotation of the turbine has been considered. Moreover, the fixed support is applied at the central shaft of the turbine and the fluid loads are applied over the entire turbine geometry. Once the all the boundary conditions were applied then the next step is to solve.

The structural steel and the Aluminum were selected as material, in which shaft and struts were being considered made of structural steel and the blades were made of Aluminum. The mechanical properties of both the materials are given in Table 2 [36].

VIII. RESULTS AND DISCUSSION

In this section result of one-way fluid structure interaction is discussed in terms of stresses produced within turbine at different freestream velocity values and the deformation experienced by the turbine. Stresses and the deformation predicted through one-way FSI is very close to the real results because real-time fluid loads were transferred for the turbine structural analysis.

IX. VARIATION OF VON-MISES STRESS WITH FREESTREAM VELOCITY

In this section stresses produced within turbine at different water velocity values is presented. Stress distribution is shown in Fig. 2 for three different water velocity values. Moreover, from the stress distribution throughout the turbine it is observed that stress distribution is highly non-uniform in nature in all the cases.

From the Fig. 2 it noticed that stresses produced within turbine at different freestream velocity values increase with increase in fluid freestream velocity.

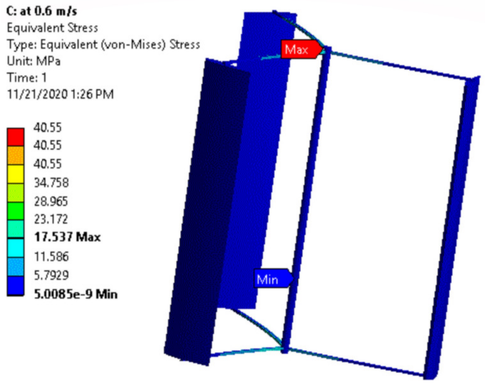

Fig. 2 (a) Von-Mises stress distribution throughout the turbine at top & bottom freestream velocity values.

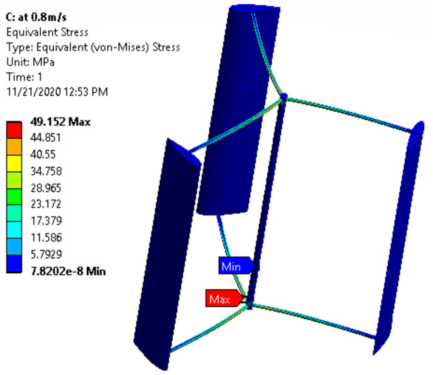

Fig. 2(b). Von-Mises stress distribution throughout the turbine at bottom freestream velocity values.

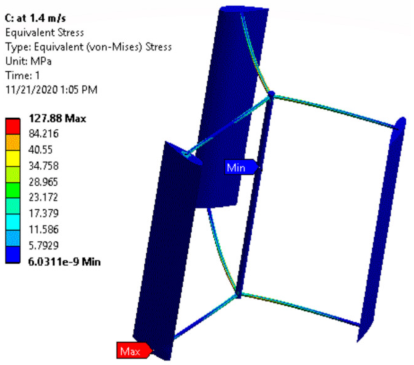

Fig. 2 (c) Von-Mises stress distribution throughout the turbine at side & mid freestream velocity values.

Moreover, it is also observed that very small magnitude stresses were produced within turbine blades in all the cases. In addition to this, it is also found that maximum stresses were produced within arm connecting turbine blades with central shaft

X. DEFORMATION AT DIFFERENT FREESTREAM VELOCITY VALUES

The deformation experienced by the turbine at different freestream velocity values is determined through FEM; the deformation produced within turbine was due to fluid loads and centrifugal force acting on the turbine. Whereas the fluid loads were transferred CFD analysis. The deformation produced within turbine at 0.6m/s and 1.4m/s is shown in Fig. 3. From the Fig. 3 it is observed that deformation produced within turbine is highly non-uniform in nature and maximum deformation is produced within turbine arms.

The deformation produced is minimum at the central shaft of the turbine for all the freestream velocity values. Moreover, the deformation of 2.12mm and 6.09mm is produced at the freestream velocity values of 0.6m/s and 1.4m/s respectively. From deformation produced within turbine at all the freestream velocity values it is observed deformation increase non-linearly with freestream water velocity.

In addition to this it is also found that deformation produced at all the considered freestream velocity values is within elastic limit because stresses produced in all the cases are lower than the yield strength of the material.

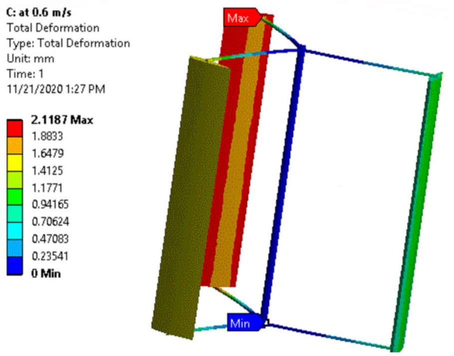

Fig. 3(a) Von-Mises stress distribution throughout the turbine at top and bottom freestream velocity values.

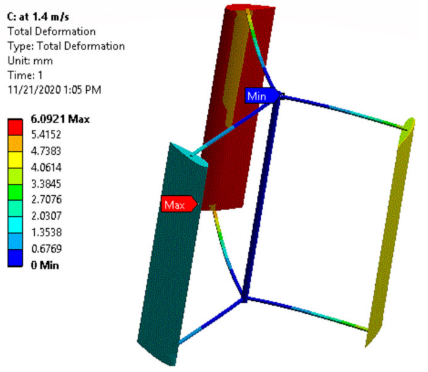

Fig. 3(b) Von-Mises stress distribution throughout the turbine at top center & top side freestream velocity values.

XI. CONCLUSION

In this research, stresses and the deformation experienced by the Darrieus vertical axis hydrokinetic turbine was analyzed through one-way FSI. The one-way FSI enable predict real-time stresses and the deformation produced within turbine under operating conditions because FSI utilize the real time hydraulic loads. Structural analysis results revealed that stress distribution is highly non-uniform in throughout the turbine.

Results also indicated that turbine blade experiences lower stresses whereas connecting arms experience highest stresses. Moreover, results also found that stresses increase with increase in freestream velocity non-linearly, however, the maximum stresses produced within turbine are lower than the material yield strength and thus turbine is safe from strength point of view. Moreover, very low deformation is produced within turbine under elastic limit.

XII. FUTURE SCOPE

The findings of the study will be help in understanding the structural behavior of the Darrieus hydrokinetic turbine at different upstream water velocity values. The findings of the study will lay down some technical foundation in designing of future H-type Darrieus turbines because results clearly highlighted the critical locations that require careful design considerations. Moreover, study results also help designers to reduce the weight of the turbine through reduction material usage at low stress areas.

Conflict of Interest. This is to certify that research with title “One way fluid-structure interaction analysis of vertical axis hydrokinetic turbine” is being attested by authors that they have no conflict of interests, regarding financial concerns and other kind of related disagreements with any organization, institutes, research labs and educational grants.

ACKNOWLEDGMENT

The authors are thankful to Mehran University of Engineering & Technology, Jamshoro for providing computational resources required to complete this research work.

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How to cite this article: Sangi, M. J., Samo, S., Shaikh, S. A., Ali, I. and Hussain, T. (2021). One Way Fluid-structure Interaction Analysis of Vertical Axis Hydrokinetic Turbine. *International Journal on Emerging Technologies, 12*(1): 19–24.