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FEA-Based Simulation of a Small Water Turbine for Waterfall

Werayoot Lahamornchaiyakul*

Department of Mechanical Engineering Faculty of Engineering, Rajamangala University of Technology Lanna, Phitsanulok 65000, Thailand

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ABSTRACT

The purposes of this study were to analyze and compare the results of structural strength for small water turbines, which were designed to address problems in the production of electricity for communities and small villages in the mountains, and fix the problem of water turbine structure damage due to water force on the principle of engineering. The small water turbines for the waterfall system were designed and simulated in the laboratory of the Rajamangala University of Technology Lanna. The goal of this work was to introduce a new vertical water turbine structure that can support the force acting on water speed, as well as to develop an optimal design for both types of water turbines for the waterfall. The main structure of the horizontal axis small water turbine is 560 mm long, 540 mm wide, and 270 mm high, and the main structure of the vertical axis small water turbine is 560 mm long, 540 mm wide, and 370 mm high. Stress analysis for the main structure was carried out using the Autodesk Inventor Professional 2014 software. The maximum net force of water velocities was 1,087 N. The maximum von Mises stress observed in the horizontal axis small water turbine was 15.74 MPa, while a maximum von Mises stress of 23.30 MPa was observed in the vertical axis small water turbine. The result of FEA prediction led to the creation of an optimum small prototype and the results may be compared to actual testing of both the water turbines for installation on waterfalls in the future.

Keywords: Finite Element Analysis (FEA); Numerical Simulation; Stress Analysis; Small Water Turbine generator for Installation on the Waterfall

1. Introduction

Renewable energy is the world's most important clean energy source today. At present, Thailand has begun to focus more on renewable energy sources, consisting of wind and water energy, because it is clean and inexhaustible energy. Hydropower offers an advantage over fossil fuels because we currently use water as a renewable fuel source. Furthermore, it is considered one of the most desirable sources of electrical energy [1]. Water is a clean fuel

***Corresponding author:** werayootrmutl@gmail.com
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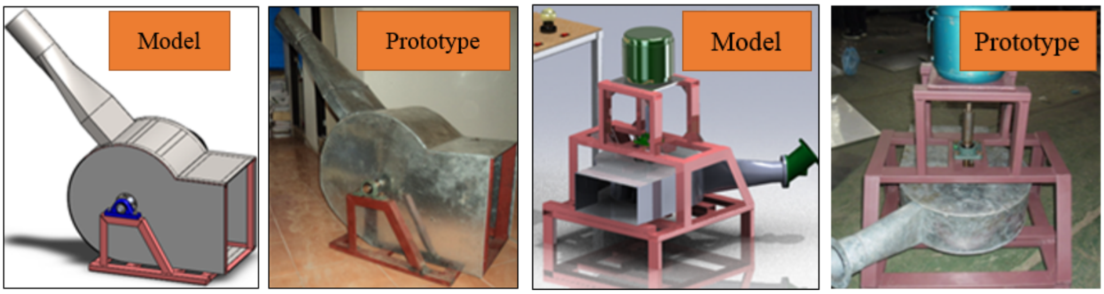
and does not release any particulates into the air [2]. Small hydropower units provide renewable energy, and they have large potential with a low cost of installation [3]. Water is considered a renewable fuel because of the important hydrological cycle for Thailand. In Thailand, hydropower is one of the most important energy sources in the domestic economy. Moreover, hydropower is an important energy source in the countryside. The present investigations on waterpower technology are progressing rapidly. In Thailand, this is especially the case in remote and rural areas in Nan province, where many of the people are still deprived from electricity access. Decentralized solutions as a whole are the least-cost way to provide power to more than half of the population to gain access to electricity. In a small water turbine for waterfalls, a nozzle is the main part for regulating the flow of water quantity. The water nozzle is a circular guide mechanism. A small water turbine for the waterfalls system for remote areas in Nan province of Thailand is mainly classified into the running of the waterfalls type and the brook type. The major parts of the small water turbine system for waterfalls are the wheel and the water nozzle. The wheel of the water turbine is a circular section of a turbine on which the curved blades are supported at the ends. The height of the waterfall head affects the water speed and force acting on the main structure of the small water turbine generator. The main structure is one of the main components in horizontal and vertical axis small water turbine generator construction. An analysis of the main structure fabrication design needs to be done to determine the accuracy and quality of the main structure that is designed in order to determine the material compatibility, construction model, and type of the water force [4]. In this study, the frame of the horizontal and vertical axis small water turbine generator was designed to support the force acting of water speed on the main structure, namely the wheel rotor, shaft, and volute body. In the design of the water turbine structure, the finite element analysis principle was applied. The design and analysis of the horizontal and vertical axis small water turbine generator structure construction was carried out using the 2014 Autodesk Inventor Professional software.

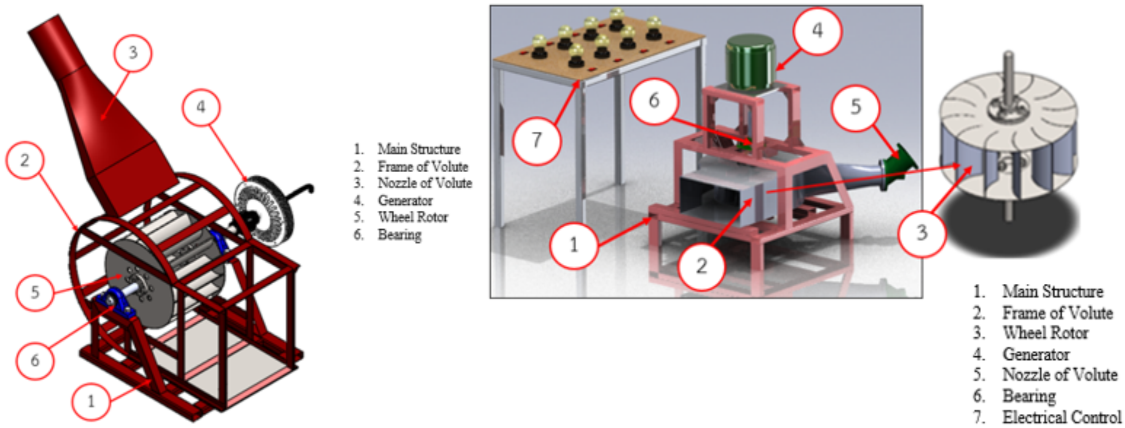
The goal of this study was to design, analyze and compare the results of the stress distribution on structural strength and to improve the main structure of a horizontal and vertical axis small water turbine generator for waterfalls by carrying out the main structure analysis of both types of turbines by using the parameters of material and water force calculated. The design and system analysis in this research employed the stress analysis module on Autodesk Inventor Professional software version 2014. Mechanical strength analysis of the material or construction was also carried out by loading, which can be in the form of axial loading, loading with bending moment (bending moment), and loading with torque [4, 5]. Stress and strain analysis is essential in measuring strength and rigidity. Both strength and rigidity are consequences that cannot be separated from the working of a load on a structural material [4, 6, 10]. This paper presents the development and comparison of the horizontal and vertical axis small water turbine generators for waterfalls in Nan province of Thailand to fix the problem of water turbine structure damage due to water force. It also investigates the effects that loading approximation has on deflection and stress distribution results. Modification of the main structure of water turbines is also presented in this paper. The prototype of both types of turbines before the analysis in this research can be seen in Fig. 1.



a. Horizontal axis small water turbine b. Vertical axis small water turbine

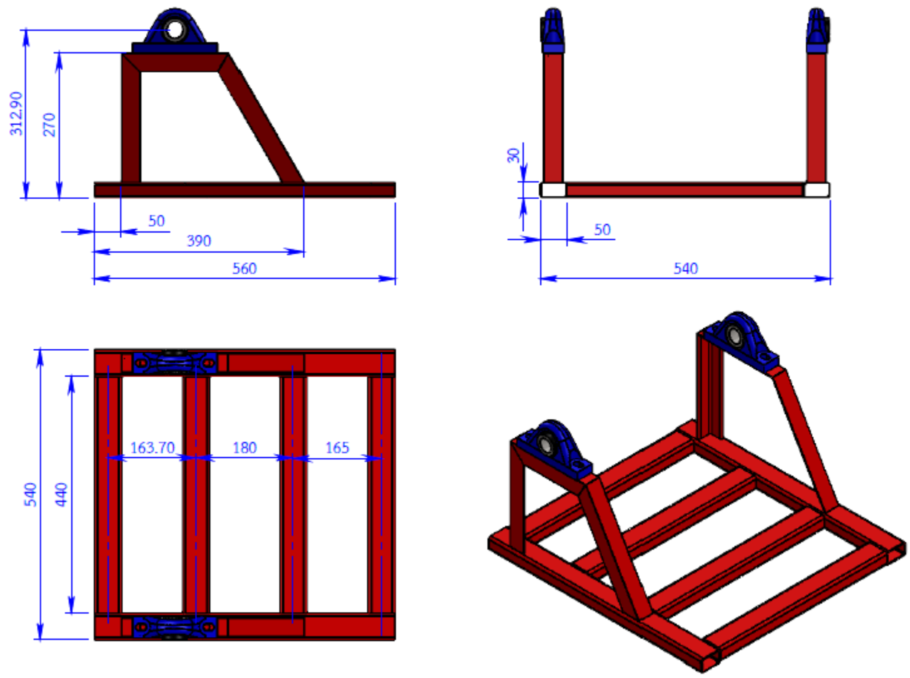
Fig. 1. Prototype of the both types water turbine for the waterfall [7, 8, 16].

The details of the horizontal and vertical axis small water turbine generator for the waterfall are shown in Fig. 2. The main structure of the horizontal axis small water turbine is 560 mm long, 540 mm wide, and 270 mm high, and the vertical axis small water turbine is 560 mm long, 540 mm wide, and 370 mm high as shown in Fig. 3.

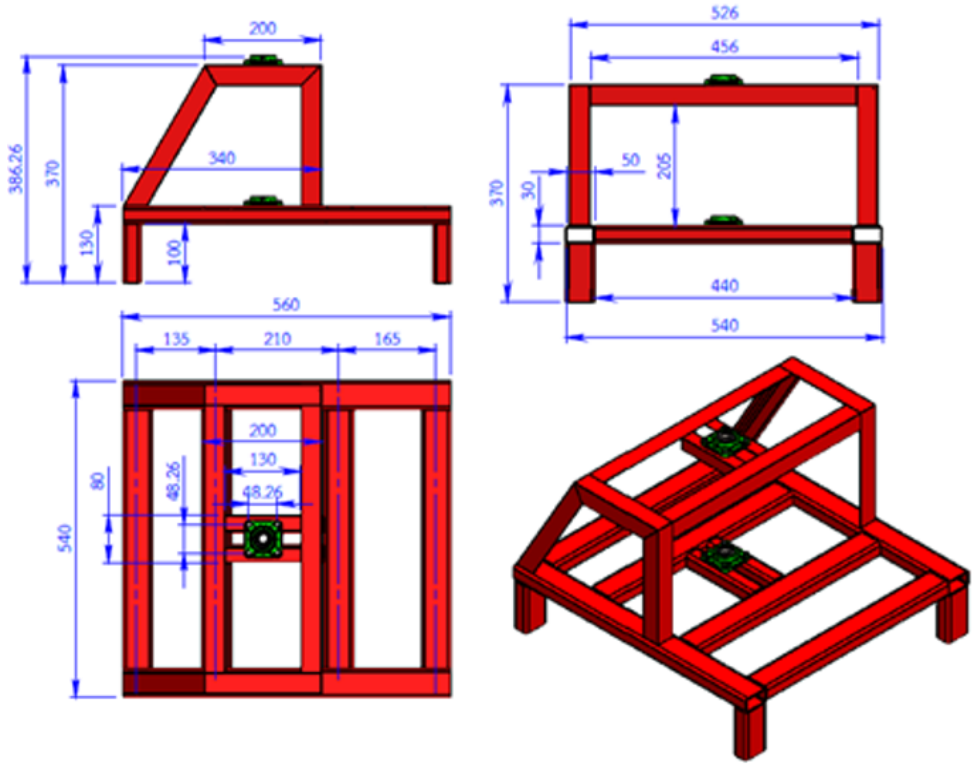


a. Horizontal axis small water turbine b. Vertical axis small water turbine

Fig. 2. Details of both types of small water turbine systems [7, 8, 11, 16].



a. Horizontal axis small water turbine



b. Vertical axis small water turbine

Fig. 3. The main structure and wheel of both types of water turbine generators [7, 8].

2. Theoretical Analysis

2.1 Principle of finite element analysis

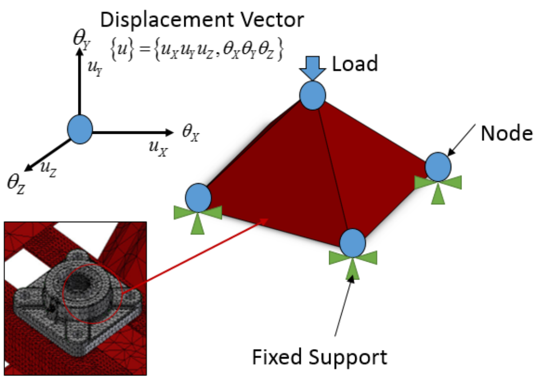


Fig. 4. Details of mesh element.

Fig. 4 shows the finite element structure consisting of a node and element. The element, considering only one node, found that degree of freedom has a maximum of 6 independent variables. The degree of freedom employed in most cases is shown below.

$$\text{Tree Translations } (u_X u_Y u_Z). \quad (2.1)$$

$$\text{Tree rotations } (\theta_X \theta_Y \theta_Z), \quad (2.2)$$

when $\{u\} = displacement\ vector,$

$$\{u_X u_Y u_Z, \theta_X \theta_Y \theta_Z\}. \quad (2.3)$$

2.2 Numerical simulation model

The processing of numerical simulation in this research applied the basic theoretical principles of engineering calculations. These concepts can be formulated into matrix equations that are suitable for analysis by using the FEM technique. For the structural analysis of both types of the designed water turbines can be seen that the displacement, stiffness, and loads are related. The stress analysis module in Autodesk Inventor Professional is used for the finite element analysis. The governing equation of the linear static finite element analysis is given below.

$$[K]\{q\}=\{F\}, \quad (2.4)$$

where $[K]$ is structural stiffness. $\{q\}$ is Nodal displacement. $\{F\}$ is load matrix.

In the solution phase we really end up with governing equations for each element. By solving these equations at each node, we obtain the degrees of freedom, which would give the approximate behavior of the complete model [3, 10].

2.3 Force of the water speed

In this study, the conceptual design and development of both new types of turbines were generated and determined. The force of the water speed from different water heads was calculated. Force can be calculated by the measurement of the squared velocity of water, a cross-section area, and the density of the fluid. The force of the water speed can be calculated as [9]:

$$F_{Water} = \rho A V_1^2 (1-\cos\theta). \quad (2.5)$$

The water speed was determine using Eq. (2.6).

$$V_1 = kv \times \sqrt{2gh}, \quad (2.6)$$

where F_{Water} is Force of water speed (N), ρ is Fluid density (kg/m^3), A is Cross-section area (m^2), V_1 is Velocity of water (m/s), θ is Degree of water attack to the turbine volute, h is Head water (m), kv is Coefficient of velocity.

The angular velocity and the rotation speed of a small water turbine can be calculated by using Eq. (2.7) and (2.8), respectively.

$$\omega = \frac{V_{operate}}{R}, \quad (2.7)$$

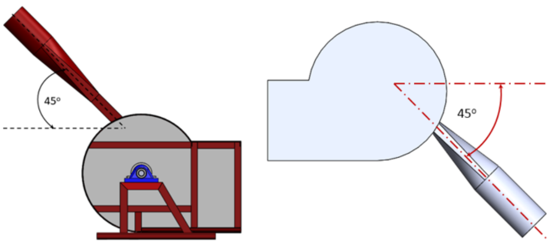
$$N = \frac{\sqrt{h}\times 38}{D}, \quad (2.8)$$

where ω is angular velocity (rad/s), R is Radius of diameter (m), R is Diameter of wheel (m), N is Rotation speed (rpm), $V_{operate}$ is Velocity of water (m/s).

3. Methodology

3.1 Force calculation

The research was carried out in the laboratory of the Mechanical Engineering Department of the Rajamangala University of Technology Lanna, Phitsanulok campus. The research used a prototype of a horizontal and vertical axis small water turbine generator for investigation and design by Computer-Aided Design (CAD) and Computer Aided Engineering (CAE). The stress and displacement distribution of the main structure with varied loads can be determined by using the version 2014 Autodesk Inventor Professional software. Both types of turbines were installed in the water nozzle of the size 0.055×0.3 meters. The height of the water head is set at 2, 4, 6, 8, 10, and 12 meters, respectively. The water was discharged from the water tank at a velocity of between 6.14, 8.68, 10.63, 12.28, 13.73, and 15.00 meters per second, respectively. In this study, Eq. (2.5) was then used to determine the force of the water speed from different water heads. And body load parameter for setup to the boundary condition of the wheel turbine can be used in Eqs. (2.7) and (2.8). Fig. 4 shows the angle degree of the water attack to the turbine volute for horizontal and vertical axis small water turbine generators. The force of water speed is shown in Table 1.



a. Horizontal axis b. Vertical axis

Fig. 4. The degree angle of water attack to the turbine volute [7, 8, 16].

In both types of water turbine, we can define the volute angle as 45° as shown in Fig. 4. The researcher selected an angle of 45 degrees for installing the water nozzle set because it is the angle at which the speed of the water can run into the blade on the water turbine wheel. The force transferred by the nozzle to the blade, angular velocity, and rotation speed are presented in this section.

Define: h = 2 m.

$$V_1 = 0.98 \times \sqrt{2 \times 9.81 \times 2} \ , \ \therefore V_1 = 6.14 m/s,$$

$$\omega = \frac{6.14 m/s}{0.125 m} = 49 rad/s,$$

$$N = \frac{\sqrt{2} \times 38}{0.25} = 215 rpm,$$

$$F_{Water} = 1{,}000 kg/m^3 \times 0.0165 m^2 \times \left(6.139^2\right) m/s \times \left(1 - \cos 45^o\right) = 182 N.$$

Table 1. Force calculation.

Head (m)	Velocity (m/s)	Rotation speed (rpm)	Force (N)
2	6.14	215	182
4	8.68	304	364
6	10.63	372	546
8	12.28	430	729
10	13.73	481	911
12	15.00	527	1,087

Table 1 shows the force calculation using a math equation. Computational Fluid Dynamics (CFD) can also be used to calculate the pressure force of water speed. After that, the pressure load can be transferred to the FEA simulation [3]. In this work, the researcher used force values from Table 1 for FEA boundary conditions. The researcher chose a height of 2–12 m due to the research area for the installation of both types of water turbines. The waterfall has different heights. So, the height of the aforementioned water head was chosen and used in the design.

3.2 Material of analysis

In this work, the researcher simulated and designed the turbine structure for analysis, namely a horizontal axis small water turbine, a vertical axis small water turbine, and the bearing. Both types of turbines were made of the AISI 304 material. The standard model of the bearing was made of alloy steel, as shown in Fig. 3. The materials and parameters used in this research were AISI 304 and alloy steel, as shown in Tables 2 and 3. The process of FEA simulation in this research consisted of modeling the geometry on Autodesk Inventor Professional software; meshing the geometry on the Stress Analysis Module on Autodesk Inventor Professional; and solving the equations and post-processing to obtain the FEA simulation results.

Table 2. AISI 304 parameters.

Parameters of AISI304:	Value	Unit
Elastic modulus	210,000	N/mm^2
Poisson's ratio	0.28	N/A
Shear modulus	79,000	N/mm^2
Mass density	7,800	Kg/m^3
Tensile strength	399.83	N/mm^2
Yield strength	220.60	N/mm^2

Table 3. Alloy steel parameters.

Parameters of alloy steel:	Value	Unit
Elastic modulus	210,000	N/mm^2
Poisson's ratio	0.28	N/A
Shear modulus	79,000	N/mm^2
Mass density	7,700	Kg/m^3
Tensile strength	723.83	N/mm^2
Yield strength	620.42	N/mm^2

3.4 Procedures for FEA Simulation

3.4.1 Preprocessing [3].

- Select the geometric domain of the problem for FEA analysis.
- Select the mesh element type.
- Select the material properties.
- Select the geometric properties.
- Select the element connectivity (mesh the model).
- Select the physical constraints (boundary conditions).
- Select the loadings and fixed support.

3.4.2 Solution

- Compute the unknown values of the primary field variable.
- Computed values are then used by back substitution to compute additional, derived variables, such as reaction forces, element stresses, heat flow and pressure force.

3.4.3 post-processing

Postprocessor software contains sophisticated routines, and it is used for sorting, printing, and plotting selected results from a finite element solution [3, 12-15].

3.5 FEA Simulation setup

Both types of small water turbines were previously as shown in Fig. 1. Installation simulation of the working system at different water heads is shown in Fig. 5.

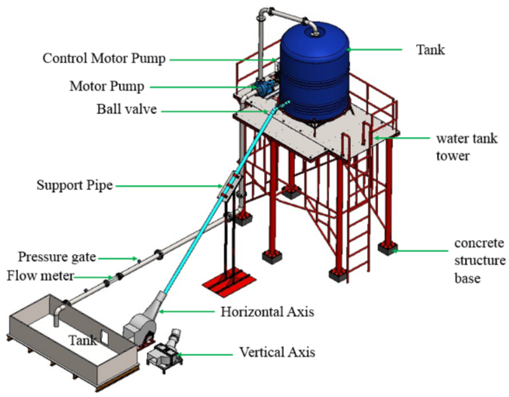
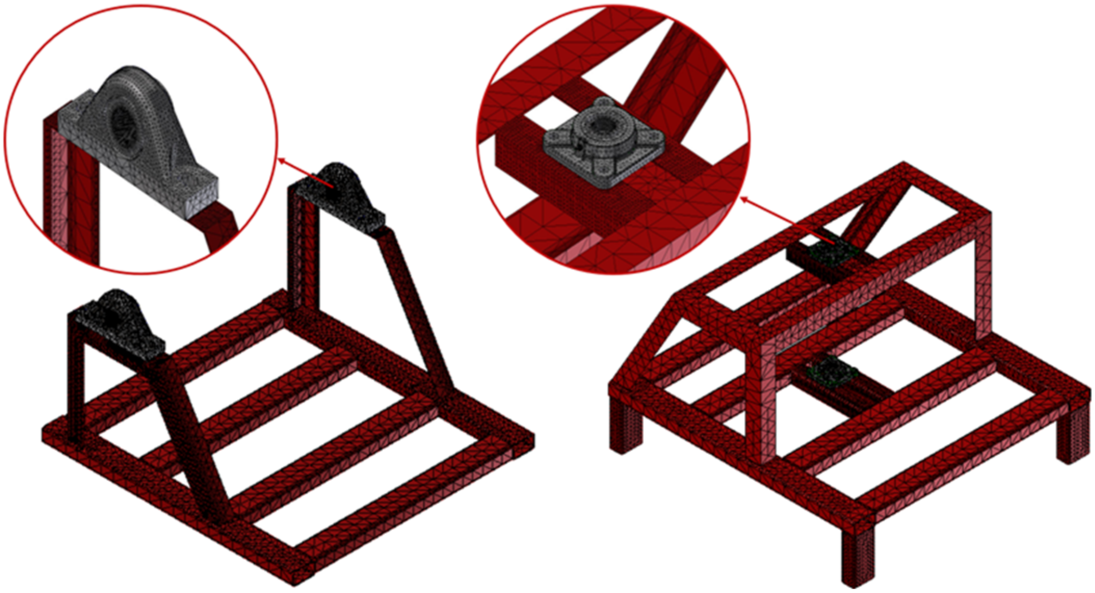


Fig. 5. Installation simulation of the working system [7, 8, 11, 16].

Fig. 5 shows the installation of the working system of both types of turbines in the laboratory. The designed system was analyzed by focusing on the main structure of both types of water turbines. The analysis was generally to check whether it was sustainable or not in the working environment. Based on the calculated force, the analysis of the main structure was done by using AISI 304 material. Moreover, the standardized model of the bearing was done by using steel alloy as the main structural material. FEA meshing of the geometry of both types of turbines in this research was done in the Stress Analysis Module of Autodesk Inventor Professional version 2014 software. The details of the settings for creating a mesh are as follows:

- Type of element is triangular.
- Elements of the horizontal axis are 312,177, and the elements of the vertical axis are 256,353.
- Nodes of the horizontal axis are 181,294, and nodes of the vertical axis are 144,821.
- Creating the curve mesh element for both types of water turbines. The creation of the FEA meshing, as detailed above, is shown in Fig. 6.

To analyze the problem in this research, the researchers chose the MSI version of the computer and the following computer features: RAM: 12 GB Intel (R) Core (TM) i7.

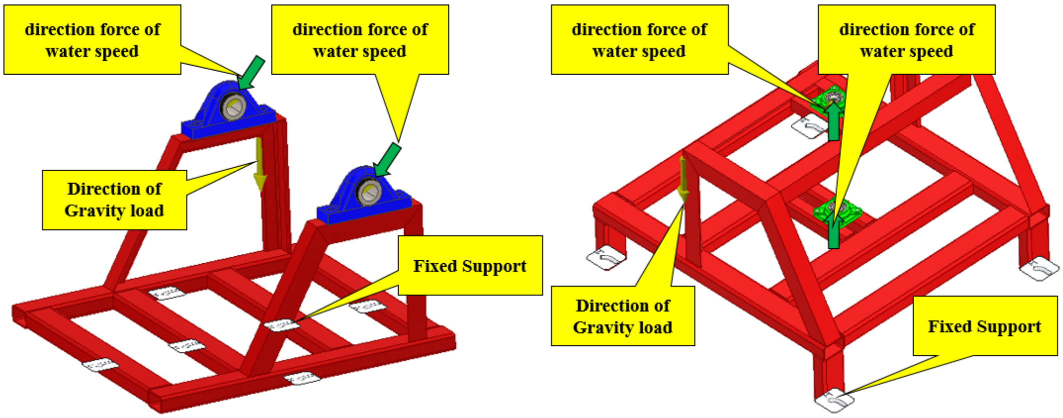


a. Horizontal axis small water turbine

b. Vertical axis small water turbine

Fig. 6. Estimation of FEA meshing for both types of turbines.

The boundary conditions in this research were fixed support and application of a gravity load in the Z direction of the domain of both types of water turbines, which was 9.81 m/s^2. The defined boundary conditions of the water force setup were 182, 364, 546, 729, 911, and 1,087 N, as shown in Fig. 7. Materials incorporated in the analysis are shown in Tables 2 and 3.



a. Horizontal axis small water turbine b. Vertical axis small water turbine

Fig. 7. FEA boundary conditions for both types of turbines in this research.

4. Results and discussion

FEA simulation of both types of water turbines is presented in this section. The analysis and simulation were carried out using the commercial software of the Autodesk Inventor Professional 2014 program.

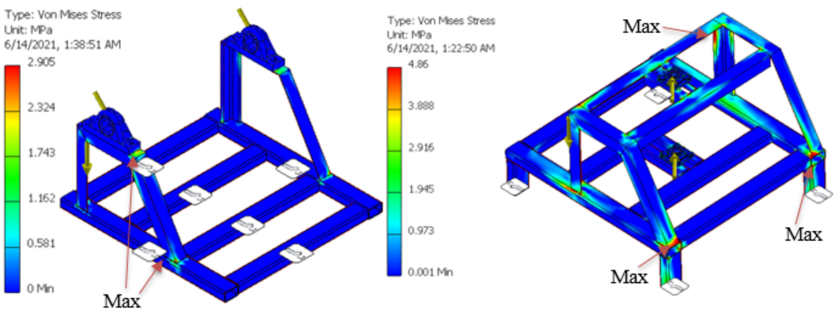
1) The following assumptions were incorporated with the FEA simulation:

- Design objective analysis is a single point.
- Contact type is bonded
- Contact tolerance is 0.100 mm.

2) Solution parameters for analysis

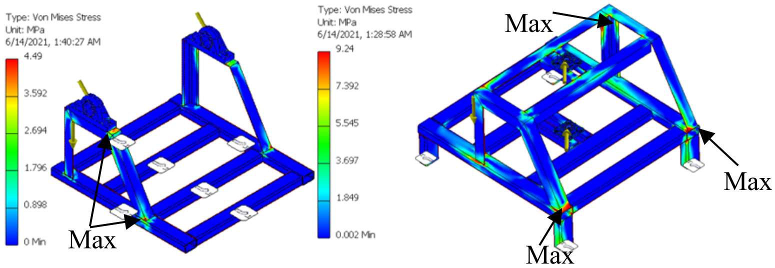
- The convergence criterion for continuity and parameters were set to 10 percent.
-The defined value of h Refinement parameters was set to 1.
- The defined direction of the force under the water velocity conditions is shown in Table 1.

The main structure of both types of water turbines in this research are shown in Fig. 3. The meshing of the main structure of both types of water turbines is shown in Fig. 6. The maximum von Mises stresses at a water force of 1,087 N for the horizontal and vertical axis of small water turbines were 15.74 and 23.3 MPa, respectively, as shown in Fig. 12. The total deformation when the water jet impacts the main structure of both types of water turbines was maximum at a joint of the structure. The maximum value of the total deformation at a water force of 1,087 N was 0.06757 and 0.3582 mm, as shown in Fig. 18.



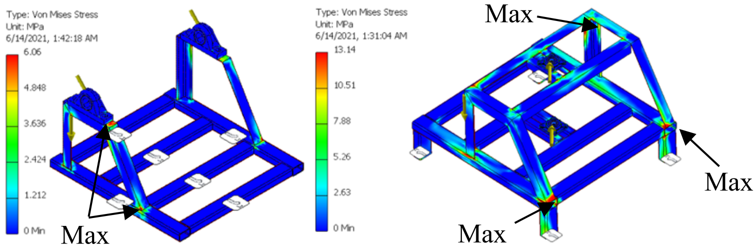
(a) Horizontal axis (b) Vertical axis

Fig. 8. The maximum von Mises stress at a force of 182 N.



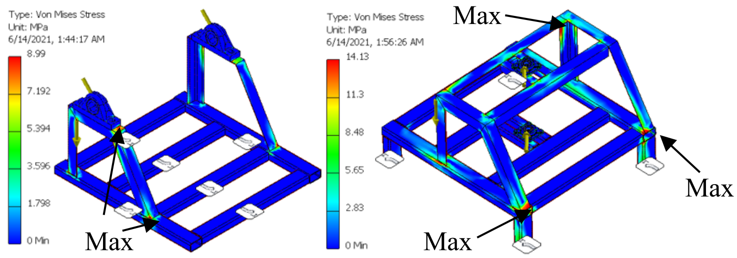
(a) Horizontal axis (b) Vertical axis

Fig. 9. The maximum von Mises stress at a force of 364 N.



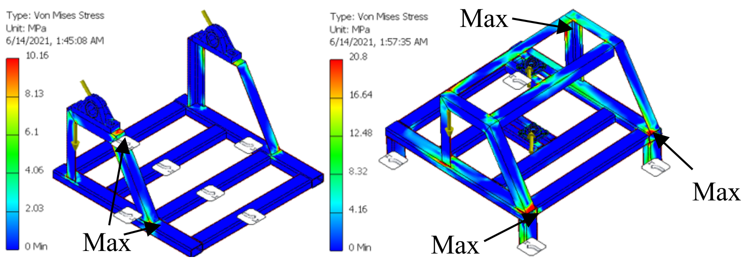
(a) Horizontal axis (b) Vertical axis

Fig. 10. The maximum von Mises stress at a force of 546 N.



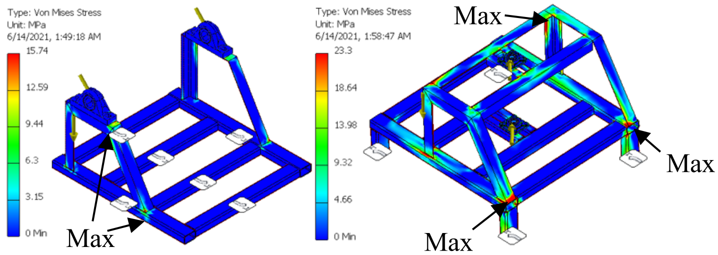
(a) Horizontal axis (b) Vertical axis

Fig. 11. The maximum von Mises stress at a force of 729 N.



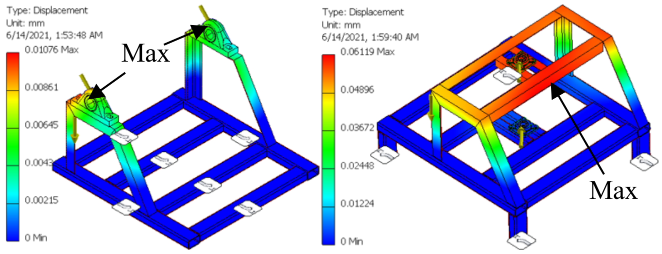
(a) Horizontal axis (b) Vertical axis

Fig. 11. The maximum von Mises stress at a force of 911 N.



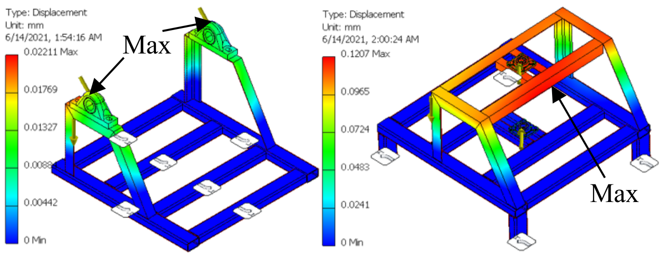
(a) Horizontal axis (b) Vertical axis

Fig. 12. The maximum von Mises stress at a force of 1,087 N.



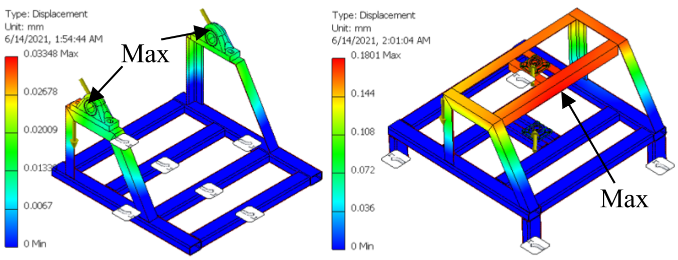
(a) Horizontal axis (b) Vertical axis

Fig. 13. The maximum displacement at a force of 182 N.



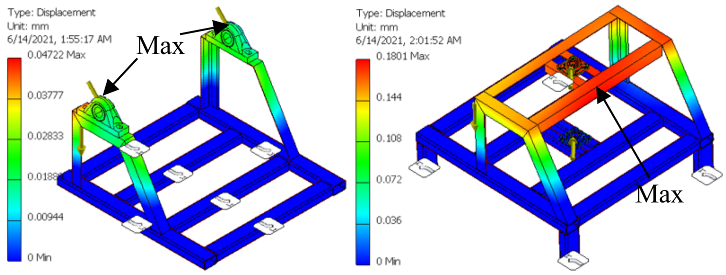
(a) Horizontal axis (b) Vertical axis

Fig. 14. The maximum displacement at a force of 364 N.



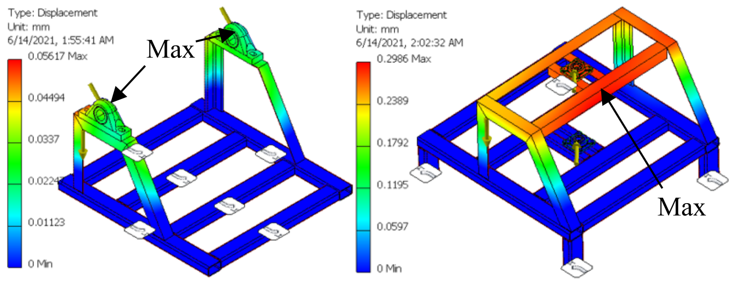
(a) Horizontal axis (b) Vertical axis

Fig. 15. The maximum displacement at a force of 546 N.



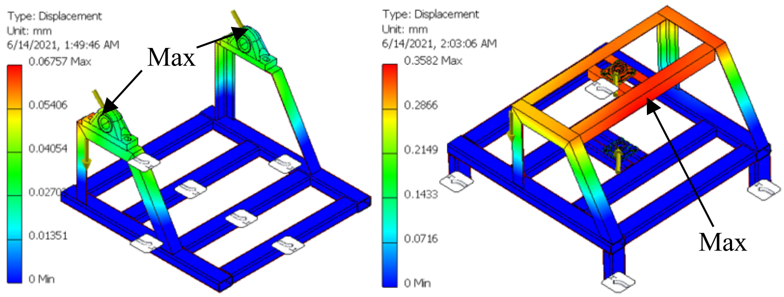
(a) Horizontal axis (b) Vertical axis

Fig. 16. The maximum displacement at a force of 729 N.



(a) Horizontal axis (b) Vertical axis

Fig. 17. The maximum displacement at a force of 911 N.



(a) Horizontal axis (b) Vertical axis

Fig. 18. The maximum displacement at a force of 1,087 N.

Table 4. FEA simulation results of the horizontal axis small water turbine.

Result	**Water force**					
	182 N		**364 N**		**546 N**	
	Max	**Min**	**Max**	**Min**	**Max**	**Min**
Von misses stress (MPa)	2.095	0.00	4.490	0.00	6.060	0.00
Displacement (mm.)	0.01076	0.00	0.02211	0.00	0.03348	0.00
1st Principal stress (MPa)	4.439	-3.206	9.790	-6.199	15.13	-9.19
3rd Principal stress (MPa)	0.612	-8.716	1.54	-16.88	2.48	-25.03

Table 5. FEA simulation results of the horizontal axis small water turbine.

Result	Water force 729 N		911 N		1,087 N	
	Max	Min	Max	Min	Max	Min
Von misses stress (MPa)	8.990	0.00	10.16	0.00	15.74	0.00
Displacement (mm.)	0.04722	0.00	0.05617	0.00	0.06757	0.00
1st Principal stress (MPa)	21.58	-12.79	25.79	-15.14	31.14	-18.13
3rd Principal stress (MPa)	3.62	-34.87	4.36	-41.29	5.30	-49.45

Table 6. FEA simulation results of the vertical axis small water turbine.

Result	Water force 182 N		364 N		546 N	
	Max	Min	Max	Min	Max	Min
Von misses stress (MPa)	4.860	0.001	9.240	0.002	13.14	0.00
Displacement (mm.)	0.06119	0.00	0.1207	0.00	0.1801	0.00
1st Principal stress (MPa)	19.83	-6.39	40.85	-11.93	61.8	-17.45
3rd Principal stress (MPa)	4.44	-26.48	9.07	-51.56	13.68	-76.58

Table 7. FEA simulation results of the vertical axis small water turbine.

Result	Water force 729 N		911 N		1,087 N	
	Max	Min	Max	Min	Max	Min
Von misses stress (MPa)	14.13	0.00	20.80	0.0	23.30	0.0
Displacement (mm.)	0.1801	0.00	0.2986	0.0	0.3582	0.0
1st Principal stress (MPa)	61.83	-17.44	103.7	-28.5	124.7	-34.0
3rd Principal stress (MPa)	13.68	-76.58	22.90	-126.5	27.5	-151.6

Figs. 8-18 show the results of von Mises stress and the displacement at different water speeds of both turbines. The results are summarized in Tables 4-7. And Tables 4-7 show the employment of different forces that aim to find the maximum strength of the horizontal and vertical-axis small water turbine structures. The results of the analysis included von Mises stress and deflections. The numerical simulation revealed that the higher the water force got, the higher the von Mises stress, and the deflection were. The comparison of the maximum von Mises stress results and displacement for both types of water turbines are shown in Figs. 19-20.

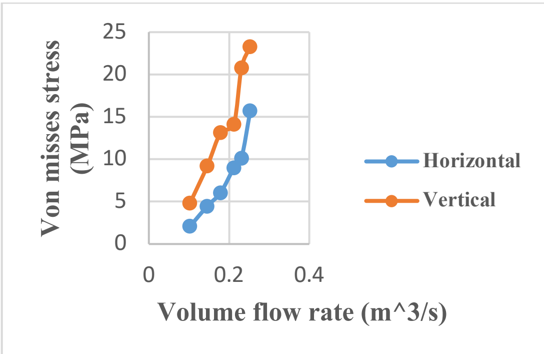


Fig. 19. Comparison of maximum von miss stress for both types of small water turbines.

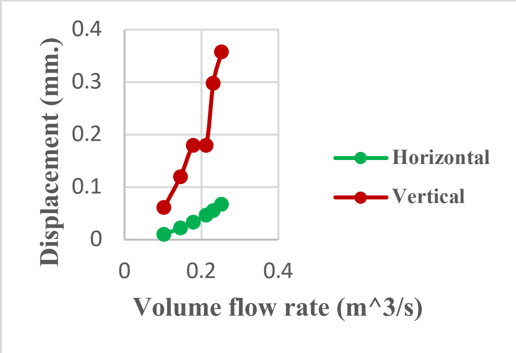
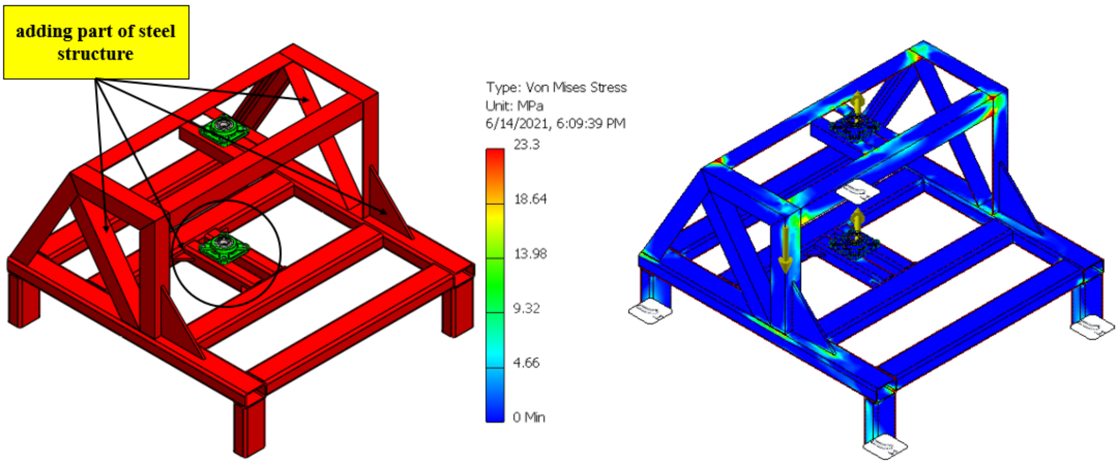


Fig. 20. Comparison of displacement for both types of small water turbines.

The mechanical stress analysis and deformation of both types of small water turbines were carried out by using a stress analysis module in Autodesk Inventor Professional software 2014. In this study, the varying water head range and water speed range were from 6.14, 8.68, 10.63, 12.28, 13.73, and 15.00 m/s, respectively. Figs. 14 and 19 compare the maximum von Mises stresses and the maximum value of the total deformation obtained from both types of turbines at a water force ranging from 182, 364, 546, 729, 911, and 1,087 N. The maximum von Mises stress observed in the horizontal axis small water turbine was 15.74 Mpa. On the other hand, the maximum von Mises stress of 23.30 Mpa was observed in the vertical axis small water turbine. The total maximum value observed in the horizontal axis small water turbine was 0.06757 mm. In contrast, the maximum value of total deformations of 0.3582 mm was observed in the vertical axis small water turbine. Based on the research results, it was found that the horizontal axis water turbine can bear the force of the water velocity better than the vertical axis water turbine. The researcher modified the main structure of the vertical axis small water turbine by adding part of the steel structure for reinforcement, as shown in Fig. 21a. After that, the new results were obtained and showed that it could help to reduce the maximum von Mises stress value as well as the total deformation of the structure, as shown in Fig. 21b. The comparison of the maximum von Mises stress and displacement for both types of water turbines was made. The modification of the main structure of the vertical axis small water turbine was then initiated. Figs. 22 and 23 illustrate the main structure of the vertical axis small water turbine before and after improvement, respectively.



(a) adding part of steel structure (b) Result of new analysis

Fig. 21. New case of vertical axis water turbine.

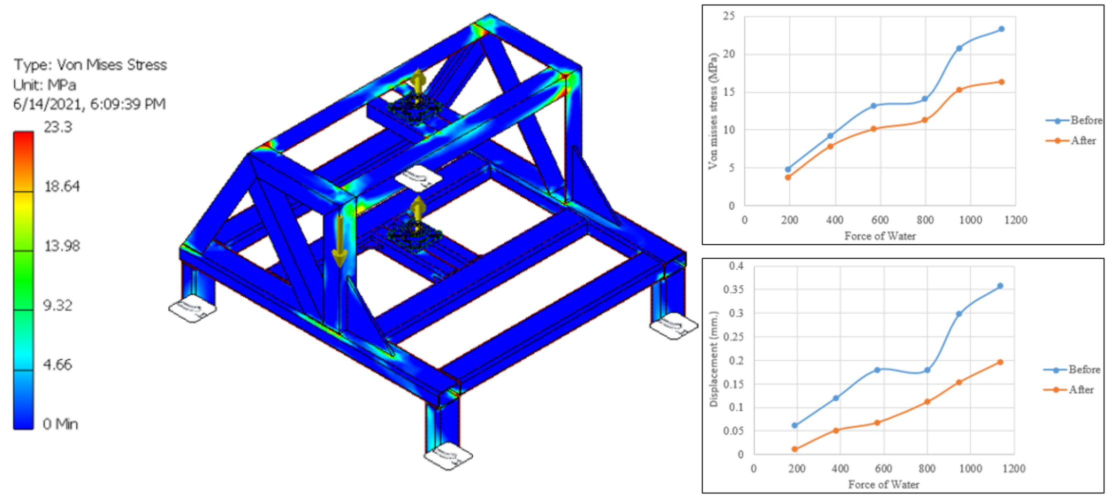


Fig. 22. The maximum von Mises stress and displacement results for new case of vertical water turbine.

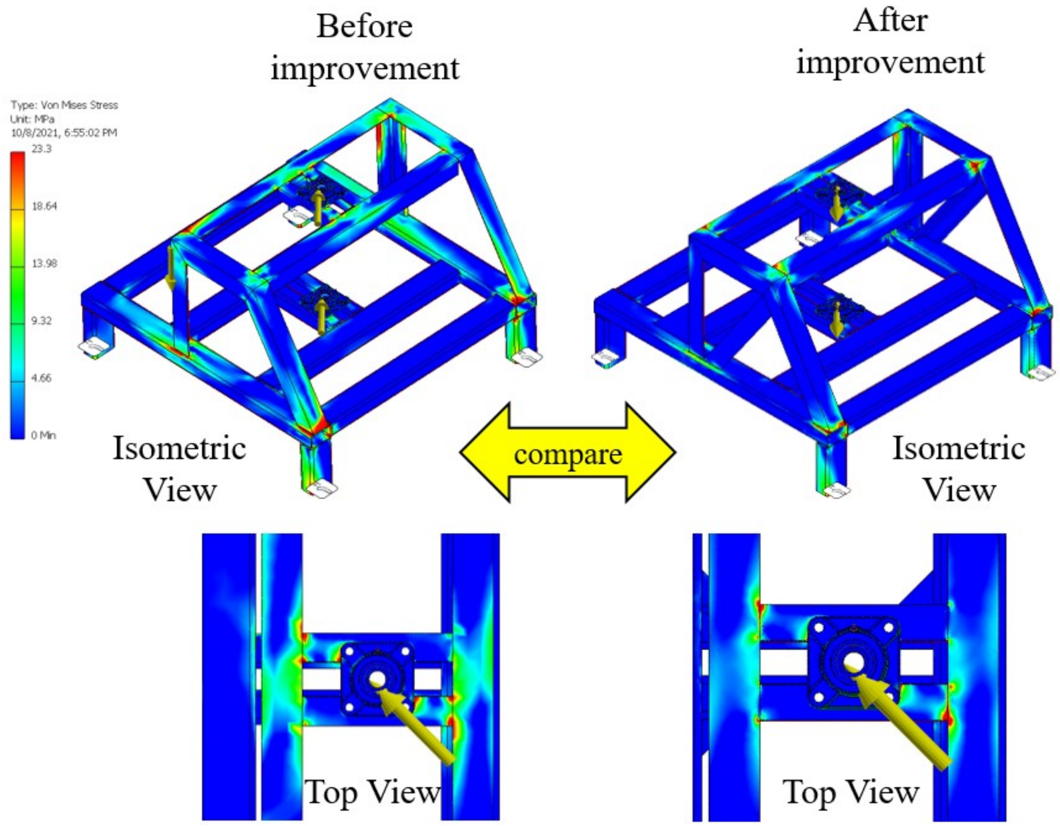


Fig. 23. The compare of vertical axis small water turbine generator.

The current research initiated the experimental installation and numerical simulation of the main structure of the horizontal and vertical axis small water turbine generators for waterfalls. It also compared the results of different water heads, which affect the main structure of the two types of turbines using finite element analysis. The result of a reanalysis of the construction strength of the structure of the vertical axis water turbine shows that the construction of the vertical axis small water turbine can withstand a maximum load of 4000 Newton by using AISI 304. Moreover, the part of the horizontal axis small water turbine can withstand a maximum load of 6000 Newton by using AISI 304. Based on the test results of the horizontal and vertical axis water turbines, it can be concluded that the horizontal axis turbine is more appropriate for use than the vertical axis water turbine. The horizontal axis water turbine handles most of the forces generated by compression force and gravity force; on the other hand, the vertical axis water turbine is water volute installation in the horizontal axis direction. As a result, it receives more shear force, gravity force, and compression force than the horizontal axis water turbine. This result FEA simulation of can be calculated from the parameters mathematical from a design program for the development of a main structure of the both types of water turbine for waterfall and modeled of low head water turbine wheel for the community for high efficiency. From various design parameters, the best combination will give an efficient horizontal and vertical axis micro water turbine generator, and successful implementation will help in eradicating power demands with some installation cost and negligible maintenance. This will be a lifelong clean source of energy in Thailand.

5. Conclusion

Based on the simulation results of the analysis of the construction strength of the horizontal and the vertical-axis small water turbine generators for installation on the waterfall using the Autodesk inventor professional software 2014, it can be concluded that

1. The construction of the vertical axis small water turbine can withstand a maximum load of 4,000 N by using AISI 304.

2. The horizontal axis small water turbine can withstand a maximum load of 6,000 N by using AISI 304.

3. The horizontal axis turbine is more appropriate for use than the vertical axis water turbine.

4. The horizontal axis water turbine handles most of the forces generated by compression force and gravity force; on the other hand, the vertical axis water turbine is a water volute installation in the horizontal axis direction. As a result, it receives more shear force, gravity force, and compression force than the horizontal axis water turbine.

The stress analysis simulation result may be generated using the mathematical parameters of a design program for the construction of the main structure of both types of tiny water turbine generators for the high-efficiency community. The optimal combination of diverse design factors will result in efficient and effective implementation, allowing the energy industry in Thailand to satisfy the demands for tiny water turbines with low installation costs.

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