Design and Development of a Smart Vortex Turbine

Moid Khan¹, Haseeb Ul Hassan¹, Kamran Mehmood¹, Taqi Ahmed Cheema², Arsalan Arif²

¹Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Faculty of Mechanical Engineering, Topi, Pakistan
²Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Faculty of Mechanical Engineering, Topi, Pakistan

Abstract. The growing demand for clean energy has led many engineers and scientists to find a way to effectively generate and distribute electricity without any carbon footprints. One of the most prominent and widely known methods of generating electricity is Hydropower. One of the leading researches in harvesting energy from low-head water sources is through a gravitational vortex turbine. Gravitational vortex turbine is special type of micro-hydro turbine that relies on the rotational energy of a water vortex. This research delves into techniques required to increase the efficiency of vortex turbines. This project bolsters an extensive design methodology used to finalize a system of smart vortex turbine. It includes a section on CAD modelling and governing equations followed by an ANSYS simulation to predict and study the vortex generated in main tank. The main goal of this project is to achieve a water tight sealing to ensure that generator does not gets damaged. In addition, reducing mechanical losses due to vibrations by using a smaller shaft is one of the set targets of this project. Our mission is to prove that electricity can be generated in off the grid communities with low-head water sources by using 3D printing as Pakistan does not have the modern expensive fabrication techniques to manufacture complex geometries. There is a need to look for a cost effective, efficient and green manufacturing method.

1 Introduction

1.1 Background and Motivation

The days of fossil-fuel-based electricity are declining in the modern world, and the need for cleaner, greener, and more efficient energy is increasing. Societies have been relying mainly on the use of fossil fuels for a very long time, but their rapid depletion will affect people’s lifestyle to a great extent. Studies indicate that by 2040, global energy demands increase increases by 30%, while the population of the world is projected to grow from 8 billion to 9 billion [4]. 70% of the Global energy needs are currently supplied using nonrenewable sources. On the top of that Non-renewable energy resources release harmful greenhouse gases into the atmosphere, creating the greenhouse effect which causes global warming. Non-renewable energy sources are also responsible to produce harmful pollutants which can lead
to habitat destruction. The world must prepare to supply the demand for clean, more sustainable future energy.

There are many alternatives to produce energy from renewable sources; one of them is the use of water energy. Hydropower can respond to increasing demand rapidly, as it requires much less time to construct and assemble, making it one of the most flexible energy sources available [5]. Water energy being a clean, cheap and environmentally friendly source of power generation is of great importance for a sustainable future. On a large scale, hydropower has a limited scope for expansion. On a smaller scale, the generation of small hydropower can be a valuable green energy source for hilly regions and places near rivers and lakes all over the world. Among the new technologies to produce electricity in hydropower electricity are the gravitational water vortex turbines.

A water vortex turbine is a low head impulse micro hydro turbine which utilizes gravity to cause water to flow downstream [6]. Water is flown through a straight inclined path into a round basin where a water vortex is created, and a pre-installed turbine collects the rotational energy from this vortex and it gets converted into electrical energy. In many rural areas of Pakistan, there are adequate river flows for electricity generation at such a scale. It is hoped that by exploiting the available potential hydro energy, the need of electricity for the people in rural areas can be met [7]. The benefits of using an artificially induced vortex above gravity-accelerated water are numerous including high efficiency, low cost and easier maintenance [8]. This turbine not only lowers the negative impact on the environment but improves the sustainability and health of the river.

1.2 Problem Statement

Designing and manufacturing of smart vortex turbine is such that, it generates clean, cost-effective, and renewable electricity that is even accessible to remote areas. The incentive of smart vortex turbine is also proposed to provide a passive source of renewable electricity which promotes reduced use of electricity through nonrenewable means. Instead of mounting the generator on the top of the rotor shaft, it is mounted inside a sealed generator assembly along the flow of water to overcome losses and increase efficiency. This inclines toward 3D printing to manufacture rotor in response to the unavailability of modern fabrication techniques to produce complex geometries.

2 Design and Analysis

2.1 Design Methodology

The first and most significant step in the design methodology of Smart Vortex Turbine is to select the most suitable structural design considering all the design parameters. Next, the geometry of the rotor and assembly of the entire setup of electricity generation are carried out on a CAD software. This step is directly followed by simulation and analysis of the turbine on ANSYS to validate the model; specifically, to determine the output torque, rpm, and mechanical power at a specified efficiency. The next step is to 3D-print the rotor, construct the entire structure of water passage and tank, procure a suitable generator, and achieve a water tight casing. The last step is to test the model under different flow conditions and capture resulting data.

Fig. 1. Design Methodology
2.2 Concept Generation

The first design of the impeller consists of five blades attached to a cylindrical hub. To attach a that needs to be coupled with the generator, the hub has a hole where the shaft can fit. The second design focuses more on the blade geometry than the size of rotor. This rotor also has five blades attached to a hub with a hole on the bottom. The main difference between the two rotors is that the first rotor has vertical blades and is a radial flow reaction turbine (Francis). Whereas the second rotor is designed as an axial flow turbine (Kaplan) as it is the most efficient type of turbine for very low heads [1].

![Fig. 2. (a) Vertical rotor blades (b) Curved rotor blades](image)

2.3 Governing Equations

The governing equations for water vortex turbine are consistent with Kaplan turbine’s equations as Kaplan turbine is most suitable for power output to be generated from low pressure heads [2]. To meet large power demands a very large volume flow rate needs to be accommodated in our turbine. The total flow configuration for vortex turbine is from radial to axial. Water enters from an upstream channel into the runner’s inlet which imparts a degree of swirl. The flow leaving the runner is forced by the shape of the passage into an axial direction and the swirl becomes essentially a free vortex.

Let α1 and α2 be the absolute flow angles at inlet and exit, β1 and β2 be relative flow angles (blade angles) from inlet and exit of the runner. Vf, Vr and Vw are flow velocity, relative velocity, and whirl velocity of turbine respectively. The total output torque for the turbine is given as:

\[
\tau = \dot{m} \times R \times (V_{w2} - V_{w1})
\]  

(1)

Where \(\dot{m}\) is the mass flow rate, R is the average radius of hub and runner. As the flow is radial. So, the total output torque will become:

\[V_{w1} = 0\]

So, the total output torque will become:

\[\tau = \dot{m} \times R \times V_{w}\]  

(2)

Where:

\[V_{w2} = V_{w}\]

To find whirl velocity, following relationship can be utilized:

\[V_{w} = V_{a} \times \cot(\alpha_{2})\]  

(3)

\(V_{a}\) is the axial velocity of turbine. In order to calculate axial velocity of turbine following relationship is required:

\[V_{a} = \frac{Q}{\pi(R_{b}^{2} - R_{o}^{2})}\]  

(4)

Where Q is the volume flow rate (discharge) of water, \(R_{b}\) and \(R_{o}\) are radius of hub and runner respectively. The discharge can be calculated from mass flow rate using following relationship:
\[ Q = \frac{\dot{m}}{\rho} \]  

Using equation (3), (4), (5) the total output torque can be calculated from (2). Next, we calculate the maximum power the vortex can generate for a known value of head. The total output power of turbine can be calculated using following relationship:

\[ P_{out} = \rho * g * H * Q * \eta_H \]  

Where \( \rho \) is the density of water, \( g \) is the acceleration due to gravity, \( H \) is the total head size, and \( \eta_H \) is the hydraulic efficiency of turbine [2]. To calculate hydraulic efficiency following relationship is utilized:

\[ \eta_H = \frac{\nu w * u}{g * H} \]  

\( u \) is the blade velocity of turbine and can be determined by using following relationship:

\[ u = \frac{\pi * N * R_O}{30} \]  

\( N \) is the rotational velocity of the runner of turbine and \( R_O \) is the radius of runner. By using equation (5), (7) and (8) total output power of turbine can be calculated by equation (6). Consequently, the overall performance of turbine can be calculated by following relationship:

\[ \eta = \frac{P_{out}}{P_{in}} * 100\% \]  

Where \( P_{in} \) is the input power of turbine and can be calculated by following relationship:

\[ P_{in} = \rho * g * H * Q \]  

By using equation (6), and (10) total efficiency of turbine can be calculated by equation (9).

### 2.4 CAD Modelling and Simulation

1. First the rotor was designed in SOLIDWORKS according to the optimum blade angle of 44° [3][9][10][11]. The diameter of rotor was set to 30 cm, the hub was set close to 10 cm and the height of the hub was 13.33 cm (figure 2(a)).
2. Water Canal guides the water towards the tank.
3. Next a strainer was made by the using the revolve feature. It helps in guiding water towards the blades of the rotor.
4. A hollow cylinder was made to provide a housing for the generator assembly. At, the end all of these parts.
5. The figure below shows all the parts.

![Fig. 3. Exploded view of smart vortex turbine](image-url)
The Computational Fluid Dynamics analysis is performed on vortex turbine to calculate output torque and output power. ANSYS Fluent is used to complete the analysis. First, the original geometry created by SOLIDWORKS is uploaded in Fluent’s Design Modeler and all the interfaces are merged using Boolean command to get accurate results. After the geometry is complete, mesh is defined to generate solution. The purpose of mesh is to divide whole geometry into much smaller finite parts of equal sizes. All the inlet, outlet and boundary conditions are specified during this stage. The result at every part is calculated in the form of streamlines and surface contours in the later stages.

The mesh is more refined near the runner to get more accurate results. The mesh size is considered 80mm based on hit and trial method. There are 164554 nodes and 809077 elements created based on the mesh size. After mesh generation is complete all the inputs and constraints are specified during setup stage. Water is used as a fluid while Aluminum is used as a material. Steady state conditions are assumed for the sake of simplicity. Mass flow rate at inlet and exit is 15kg/s. From previous literature, it is noted that runner will rotate at 300rpm for selected value of mass flow rate.

After completing the setup procedure, all the results, plots and contours can be determined using CFD post.

Fig. 4. Velocity streamlines and pressure contours of vortex generated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh size</td>
<td>80 mm</td>
</tr>
<tr>
<td>Iterations</td>
<td>200</td>
</tr>
<tr>
<td>Rotational velocity</td>
<td>300rpm</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>15kg/s</td>
</tr>
</tbody>
</table>

### 3 Physical Model

The testing of the smart vortex turbine is first carried out on a scaled-down prototype to have a general idea of working around the turbine setup and reduce the cost of experimentation. The prototype model consists of the following components: a rotor, a tank with a hole at its base- the ratio of the diameter of the tank to the diameter of the hole is 5.44:1, a steel frame to hold the entire structure, and a flexible silicon rubber tube (figure 5).
3.1 Results and Discussion

The prototype of the smart vortex turbine employed a 12V DC motor with its shaft coupled with the shaft of turbine using a 4 mm stud. The purpose was to use the motor as a generator and prove that electrical energy could be generated by harvesting rotational energy of a water vortex. The data was captured and tabulated as shown below:

From the data obtained, we can observe that by increasing the flow rate the value of RPM increases and as a response we can get a higher value of generated voltage and power. We can also observe that the increase in flow rate has resulted higher current values which will also contribute to the higher power values.
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4 Conclusion

This paper presents a cost-effective and environmentally friendly smart vortex turbine for generating electricity from low-head water sources. The design methodology involved concept generation, CAD modeling, ANSYS simulation, and 3D printing, which were presented systematically. The proposed design incorporates water-tight sealing for generator protection and a smaller shaft to mitigate mechanical losses resulting from vibrations. 3D printing was suggested as an economical approach to manufacturing complex rotor geometries. Testing the model under varying flow conditions has generated invaluable data, which can be used to further enhance the design of smart vortex turbines. This innovation holds promise for future implementation, providing a sustainable source of electricity for off-grid communities.

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References


