OPTIMIZATION OF SPLIT REACTION WATER TURBINE WITH GUIDE CONE USING GENETIC ALGORITHM

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ABSTRACT: *With the increasing demand for renewable energy in most countries including the Philippines, hydropower has introduced its great potential for electricity generation. This study introduced an improved split reaction water turbine with the implementation of a guide cone that reduces the stagnation effect experienced in the conventional split reaction water turbine. A Genetic Algorithm (GA) was used as the optimization method to identify the optimum radius and height of the guide cone to achieve the maximum torque. The improved turbine model and flow simulation using the Solidworks tool were conducted to calculate the torque output. MatLab was used for the GA to generate feasible dimensions. The generated torque value of the Solidworks was evaluated in MatLab's GA for the possible next-generation process of design parameters until convergence is achieved. The studied optimization of the guide cone of the SRWT has improved at around 5.22% compared to SRWT-H300 (with predesigned cone) and at 66.44% compared to SRWT-H000 (without cone). The optimum cone guide dimension was observed at the height of 116.084 mm and the radius of about 28.3182 mm with an achieved torque value of around 0.189813N-m.*

Keywords: MatLab, Solidworks, Guide Cone, Split Reaction Water Turbine, Genetic Algorithm

1. INTRODUCTION

Economic growth is rapidly changing which causes an increase in energy consumption particularly in developing countries. This increasing global energy consumption directly affects the resources used to fuel power plants [1]. At present, the majority of the electricity is produced from thermal power plants which use coal, gas, oil as the energy source [2]. With the continuous usage of power plants, global warming has been of great concern because of its carbon dioxide emissions. This challenge has led to the need to explore technologies utilizing renewable energy as alternative source to meet the increasing demand for electricity in the future. A renewable energy system is a mechanism that uses energy that comes from unlimited natural resources such as the wind, rain, waves, sunlight, and geothermal heat [3]. There are already several renewable energy systems that are being used throughout the world including those in the Philippines such as hydropower, geothermal power, wind, ocean power, solar power, and biomass [4]. Hydropower is stated to be the largest renewable energy resource in the world; in 2009 it produced 3,329 TWh of electricity representing a share around 16.5 % of the world's electricity [5]. In the Philippines setting, there is a large potential of hydropower waiting to be exploited [6]. Most hydropower technologies were focused on large hydropower sites and have already been explored as a significant source of renewable energy [7]. Philippines potential for hydropower development could be an alternative to strengthen the exploration of renewable energy resources and could also have mitigation effects on frequent floods in flat, low-lying downstream areas [8]. However, many potential small hydro sites are still available for exploitation but are limited in terms of technological development.

A reaction turbine is a machine that produces power by expanding a continuously flowing fluid to a lower pressure or head. Under a high static head, its pressure energy is transformed into kinetic energy in a nozzle, which in itself forms a part of the rotor. In reaction turbines, the water completely fills all the runner passages where the impeller is located. The change in pressure drop occurs in the impeller [9]. The fluid flow of the reaction water turbine is opposite to a pump wherein the water enters at the larger passage and exit from a smaller gap releasing pressure energy in the rotating wheel. In simple reaction turbines like the Hero's steam turbine and Barker's Mill or the Segner's turbine, the water enters the turbine axially and exits tangentially through the nozzles located at the outer periphery and producing jets of fluid which then spin the entire assembly. One of the present technologies developed is the low head simple reaction split-type water turbine studied by Akbarzadeh and Date shown in figure 1 [10]. The designed turbine is a progeny of Hero's turbine and Barker's mill but with an innovative concept of using a split pipe turbine which achieves an estimated efficiency of around 71% [10]. The challenge is how to modify this turbine to increase its performance.

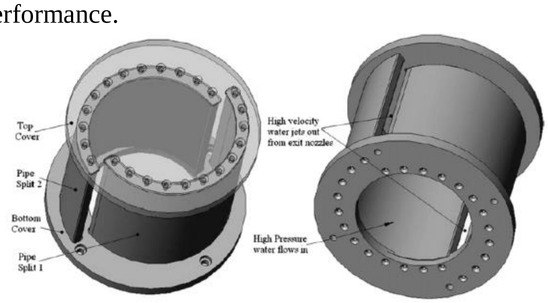

Figure 1. Simple Reaction Water Turbine of Date and Akbarzadeh [10]

In the study of split water reaction turbine conducted by Akbarzadeh and Date [10], the path of moving fluid particles relative to a surface of the solid body located at the upper portion of the turbine assembly is moving in with turbulence. This characteristic was shown in figure 2 when simulated using the Solidworks tool. It is observed that the exit velocity in the nozzle was close to zero. This is probably due to the stagnation effect created at the top portion of the turbine assembly. This stagnation effect that occurs in the turbine must be minimized to further increase the performance of the turbine such as increasing its torque characteristic, thus improve its power generation

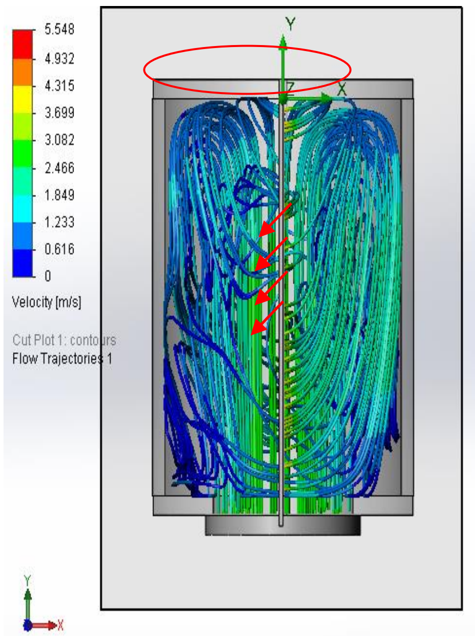

Figure 2. Velocity Flow Trajectories of Water without Guide Cone with stagnation effect observed in the upper portion and with a very low velocity at the exit nozzle of the turbine

In the development of mechanical systems such as split reaction water turbine, optimization methods is necessary to ensure optimum design for better performance. With the aid of computing technologies, several studies already explored optimization methods to evaluate the system design and performance. The hydro turbine design by Kawajiri, Enomoto, and Kurosawa employed the Particle Swarm Optimization for blade profile to maximize turbine efficiency by minimizing the hydraulic loss which the latter is defined by the difference of total pressure between inlet and outlet. The optimization model utilizes 23 design parameters covering from blade camber line and profile, inner diameter, outer diameter and etc. The study significantly improves the water turbine performance by achieving significant improvement in its efficiency [11].

Recently, genetic algorithm has found many applications in power system operation and control as a robust and flexible optimization tool. A study by Wei Wang et al. of 2014 implemented an optimization methodology on the design of thermal power and wind power turbines. In their study, they aimed to minimize the consumption of coal, emission of pollutants, and power consumption based on different power generation performances [12]. Also, Tommaso et al. or 2012 presented the concept of optimization in their study on small wind turbine power. They introduced the Modular Multiple Blade Fixed Pitch Wind Turbine (MMBFPWT) designs [13]. The goal of their study was to maximize the power generation by efficiently turning the turbine blade at various wind speeds. Their system was tested and validated using the MPPT (Maximum Power Point Tracking) algorithm. Moreover, Kantor, Chalupa, Souček, Bílková, and Nowak also conducted a study about and application of Genetic Algorithm to a Kaplan turbine hydraulic profile for optimum 3-blade shape to increase hydraulic efficiency and improve cavitation properties. The geometric model of the whole turbine is created in the CAESES environment and the process of virtual verification of hydraulic parameters was automatically conducted by numerical flow simulation (CFD) performed in ANSYS CFZ environment [14].

This study addresses the problem of stagnation effect experienced in the study of Akbarzadeh and Date of 2012 by introducing a modified split water reaction turbine with a guide cone. Specifically, this study will find the optimum design of the guide cone by using a Genetic Algorithm that could improve the torque performance of the water reaction turbine.

2. MATERIALS AND METHODS

This study introduced a guide cone operably placed inside the upper portion of the turbine that will streamline the inside flow and will in turn reduce the stagnation phenomena experienced in the conventional split reaction water turbine (SRWT) as illustrated in figure 3. The convex-shaped cone was modeled using a parabolic profile embedded in the Solidworks tool. The turbine model and flow simulation are also done through Solidworks and a Genetic Algorithm optimization method through MatLab was implemented to achieve an optimum dimension of the guide cone. The goal of this study is to achieve optimal performance by increasing the torque characteristic.

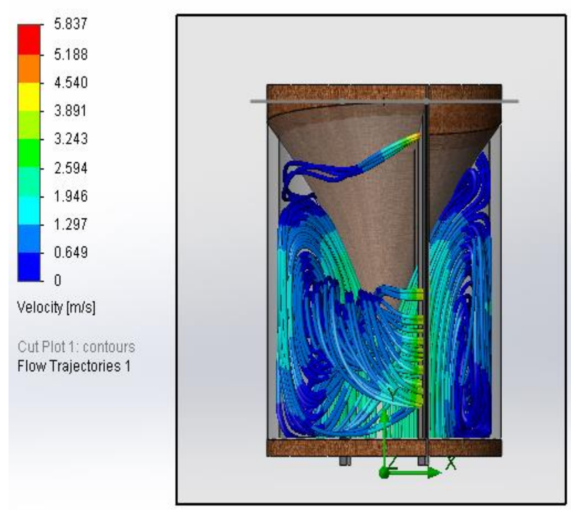

Figure 3. Velocity Flow Trajectories of Water with Guide Cone Embedded in the Turbine

With the optimization concept, the goal is to maximize the torque of the SRWT design through designing the optimum radius (*r*) and height (*h*) of the guide cone shown in fig 4.

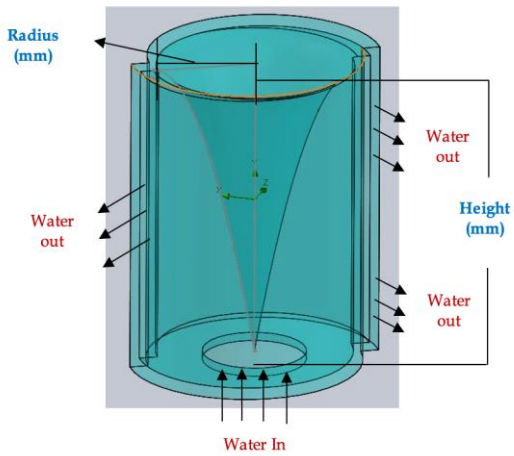

Figure 4. Design Parameters (height in mm and radius in mm) of the Guide Cone embedded in the Turbine with Water In and Out Direction

The optimization equation or model is illustrated below which is a function of torque (*T*). This torque is dependent on the radius and height of the guide cone. The optimization goal is to maximize the torque generation by finding the optimum radius and height values of the cone. In the constraints section, the radius and height allowable ranges were defined which aligns with the dimension of the cylindrical turbine model. The angular velocity of the turbine which is around 20.944 rad/s or 200 revolutions per minute (RPM) and with a 50 m^3/hr is the volume of the water that will pass and enter in the inlet every hour was set in the design.

Objective: Maximize = T{r,h}
Constraints:

10 mm <= r <= 90 mm	*(cone radius)*
10 mm <= h <= 150 mm	*(cone height)*
$Q = 50\ m^3/hr$	*(volumetric flow rate)*
$\rho = 101.325\ kPa$	*(pressure)*
$\omega = 20.944\ rad/s$	*(angular velocity)*

The physical constraint s an improved design from the study of Date and Akbarzadeh. The turbine is developed from an 8-inch PVC pipe split into two halves. The splits halves are offset to 8 mm and this offset length would serve as the turbine nozzles. At the bottom portion of the assembly, the bottom cover plate will serve as water inlet. The diameter of the hole for water inlet is set to 90 mm. The height is based from their study which has 150 mm exit nozzle length [10].

A genetic algorithm (GA) is a type of optimization algorithm, which is used to find the maximum or minimum of the above function. Unlike other optimization methods, GA is one of the most popular methods because of its nature wherein it works on a population of possible solutions, while other heuristic methods use a single solution in their iterations. It possesses a probabilistic approach in finding the optimum of a function and is not deterministic in nature. This algorithm is initiated by a certain number of individuals and each individual in the GA population represents a feasible solution to the problem. The suggested solution is coded into the "genes" of the individual. The values and their position in the "gene string" tell the genetic algorithm what solution the individual represents. By applying the rules of evolution to the individuals, it is possible to find one set of individuals, which can be combined with new individuals. Using this method iteratively, a particular population will progress to good solutions or that possess the fittest value. Specifically, the elements of a GA are selection (according to some measure of fitness), cross-over (a method of reproduction, "mating" (the individuals into new individuals), and mutation (adding a bit of random noise to the off-spring, changing their "genes").

The optimization problem considered in this study is solved using the Genetic Algorithm method with the probabilistic generation of design points. The design variables or parameters are the radius (mm) and height (mm) of the guide cone, and the fitness parameter is the maximum torque (N-m). The algorithm initializes by randomly selecting the values of the design variables (input candidates) but then again subject to the defined constraints. These two design variables referred to as the radius and height of the guide cone, shown in figure 4, were constrained with the acceptable values ranging from 10 to 90 mm and 10 to 150 mm, respectively. The "equations" feature of the Solidworks was implemented to assign equations for radius and height specified in the turbine assembly model.

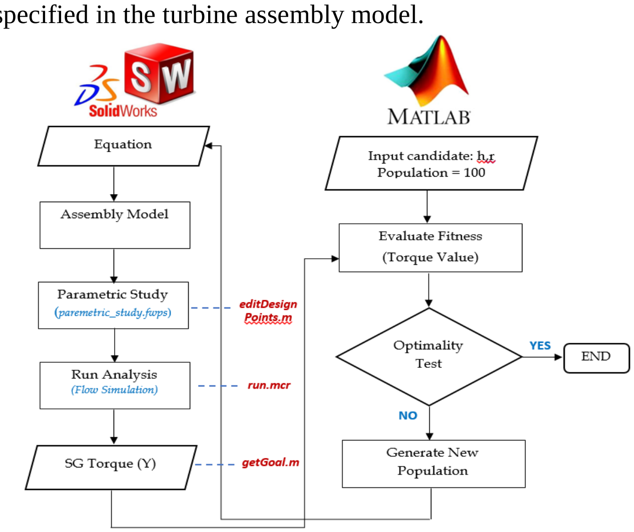

Figure 5. Design Implementation: MatLab and Solidworks Integration

Figure 5 shows the entire algorithm of integrating MatLab and Solidworks to implement the optimization process. Initially, at generation=0, the algorithm generates a random population comprising 100 individuals for each of the parameters or candidates (*h* and *r*). The generation of the design paramater values are prepared in MatLab and are resolved using the Genetic Algorithm. The GA will choose the fittest design points (*h* and *r*) based on the performance of the previous population by evaluating its fitness values which in this study is the torque performance. The generated design points will be automatically defined in the parametric_study.fwps (.xml file) using the *editDesignPoints.m* program. A macro recorder tool was also used to automate the iterative process of Solidworks, starting from loading the parametric study (parametric.wfps) up until running the flow simulation using the *run.mcr*. Once the flow simulation is completed, the generated torque value, referred to as the fitness goal of the flow simulation, is then passed on to MatLab using the *getGoal.m* program for fitness evaluation. In every generation, an optimality test is conducted to assess if convergence was accomplished. The entire process is iterative wherein the turbine design assembly model will also be updated accordingly until the generated torque value converged and is evaluated as maximum.

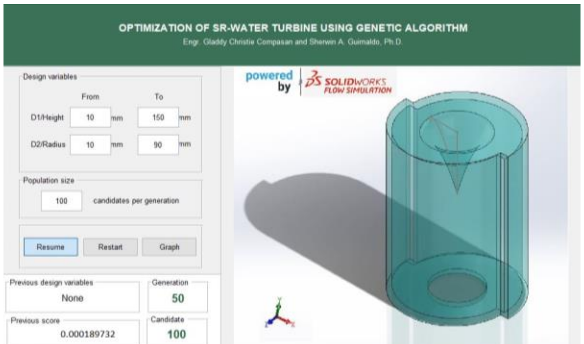

Figure 6. Graphical User Interface of the Optimization Platform

A Graphical User Interface shown in figure 6 was employed for easy inputting and visualization of all significant data such as the lower and upper limits of the design parameters (radius and height of the cone), population size, generation, candidate values, and fitness scores. The plot or graph pushbutton was also implemented to visualize the graphical behavior of the simulation as a way of assessing convergence. Another good feature of the implemented system is that in the advent of uncontrolled interruption of the simulation, the user may choose to restart or resume the operation as needed.

3. RESULTS AND DISCUSSION

With the simulated conventional split reaction water turbine without a guide cone and some predesigned guide cones following a convex shape, below is the result of torque calculation with its velocity performance shown in Table 1. With the three predesigned guide cones with dimensions shown in the table, the SRWT-H300 achieved by far the best torque and velocity performance. These predesigned guide cones have not undergone optimization.

Table 1. Torque of SRWT without guide cone and Predesigned SRWT with Guide Cone simulated at an average volume flow rate Q = 50m^3/hr

Torque Performance in N-m				
RPM	SRWT-H000 (without guide cone)	SRWT-H275 (h=2.75 in) (r=0.625 in)	SRWT-H300 (h=3.00 in) (r=1.625 in)	SRWT-H350 (h=3.50 in) (r=1.325 in)
200	0.11404	0.142198	0.180384	0.177129

In this study, the optimization model was implemented for fifty (50) generations wherein each generation consists of 100 population or 100 different design parameters (height and radius in mm). As represented in the graph of figure 7, in each generation, the best or fittest torque value was chosen and referred to as the fittest candidate or fittest torque value with some corresponding fittest height and radius dimension of the guide cone for selected generations (0, 24, 45, 47, 48, and 50).

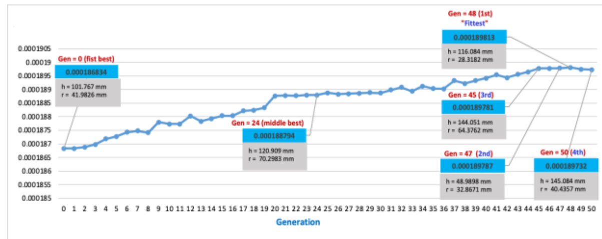

Figure 7. Torque with Cone Height and Cone Radius Data of (Fittest Candidates)

From figure 7, four of the best generations were illustrated: the fittest candidates were found at 48th generation with maximum torque value achieved to be 0.000189813kN-m or 0.189813 N-m, with its corresponding optimum height of 116.084 mm and optimum radius at 28.3182 mm; the second-best generation is at 47th with torque value of 0.000189787 kN-m at height of 48.9898 mm and radius 32.8671 mm; the third-best generation is at 45th with torque value of 0.000189781 kN-m at height 144.051 mm and 64.3762 mm, and fourth best generation is found at 46th with torque value of 0.00018978 kN-m at height 47.8412 mm and 89.0734 mm.

In the concept of maximization optimization problem, it is expected that the optimum value converges at its maximum Generation = 50point until no significant change of the fitness was observed. In the graph also, with the simulation set to 50 generations, the fittest torque value or best candidate was found at the 48th generation in terms of velocity and torque achieving a torque value of 0.000189813 kN-m or 0.189813N-m and is shown in figure 8.

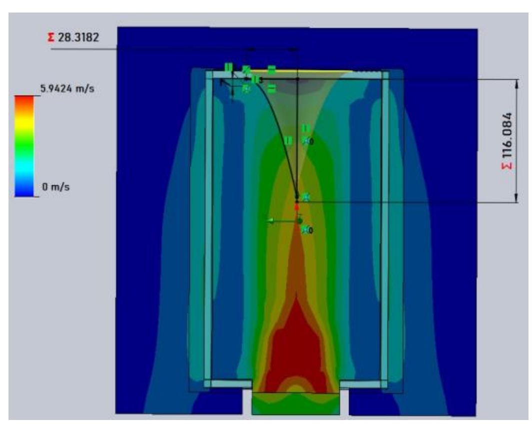

Figure 8. Velocity Cut plots and Torque values of the Generation 48 @ Q= 50m^3/hr. and RPM=200

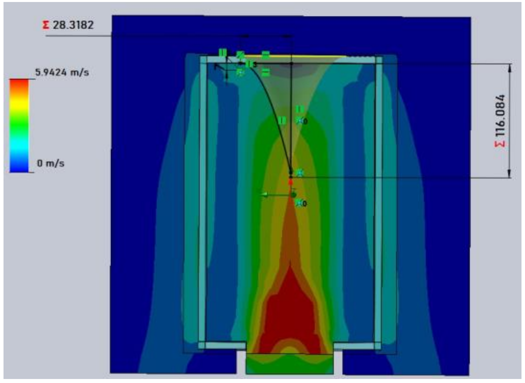

Figure 9. Velocity Cut plots and Torque values of the Generation 48 @ Q= 50m^3/hr. and RPM=200

4. CONCLUSION

The optimization introduced in the study is finding the maximum torque performance through identifying the optimum design variables, which are the guide cone height (*h* in *mm*) and radius (*r* in *mm*) embedded in the conventional split reaction water turbine. From the results gathered, it was observed that with the simulated 50 generations, the latest fittest design was found to be at generation 48th, achieving a torque value of 0.000189813 kN-m or 0.189813N-m, which correspondingly happens when the height of the guide cone is 116.084 mm and at radius of about 28.3182 mm. From the fittest torque value which was identified to be in the 48th generation's best candidates, and with the aid of optimizing the dimension of the guide cone (height and radius) using GA, it was observed that the torque generation has improved its performance with an average of 5.22% compared to the pre-designed guide cone with SRWT-H3000 (with guide cone height of 3.00 in), where the design was not yet optimized. Moreover, from the optimized model, an improved torque performance of around 66.44% compared to SRWT-H000 (without guide cone) was also perceived. In the implementation of integrating MatLab and Solidworks, the simulation has significantly simplified the process in assessing the optimality of the design.

5. RECOMMENDATIONS

As a recommendation, it is suggested to examine the same design utilizing another optimization technique such as Particle Swarm Optimization. Moreover, it is also reasonable to explore adding the RPM as another design variable to assess the optimum RPM to which the improved turbine model can best operate in relation to power generation.

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