Experimental Investigation and Optimization of Floating Blade Water Wheel Turbine Performance Using Taguchi Method and Analysis of Variance (ANOVA)

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Abstract. Floating blade water wheel turbine is a development design of goose leg turbine which has been studied in the previous year. This water turbine has a specialty on its blade ability that can open and close like a goose leg. This study employed the Taguchi method to obtain the optimum design parameters on the floating blade water wheel turbine. There were 3 factors used, they are water flow rate with 4 levels (35; 40; 45; 50 ℓ/min), number of buckets with 2 levels (4 and 6 units), and the shape of the blade with 2 levels (concave and flat) which was predicted to affect the turbine performance. The response or dependent variable used was the turbine efficiency. According to factors and levels that have been determined, orthogonal array used in this study is L16. Orthogonal Array is a matrix that used in Taguchi method to determine the minimum number of experiments that can provide information about factors which affect the parameter response. According to ANOVA results, they indicated the factors affecting the optimum quality characteristics of the turbine performance are the number of buckets with the contribution of 68.13%, the blade shape with the contribution of 23.28%, water flow rate with the contribution of 7.35%, and the 1, 25% is the other factors. According to Taguchi method, the optimum parameter design was a turbine with 6 blades, convex blade shape, and water flow rate at 50 ℓ/m that yielded turbine efficiency as much as 3.999%.

Keywords: Floating blade, wheel water turbine, Taguchi method, ANOVA, efficiency

1. Introduction

Floating blade water wheel turbine is one example of a water turbine in Indonesia. The principal work of this water turbine is inspired by the work of goose leg while swimming. The floating blade water wheel is significantly appropriate to extract the kinetic energy of free water flow because of the ability of the blade which can open and close. However, the floating blade water wheel has not been widely used as a power plant. The water turbine itself has the disadvantage of having the part of blades not submerged in water, so the blades clash during closing. The clash resulted in the occurrence of vibrations which causing the components will be damaged easily. The floating blade water wheel has not been assessed scientifically, so its efficiency and appropriate construction reliability have not been known. Moreover, its appropriate technology transfer mechanisms should be designed so that this water turbine
is acceptable and beneficial among society. Minimizing the weaknesses in water turbine can be performed by conducting variation on the turbine design. Thus, the water turbine works more optimally. Variations in turbine design can be performed by testing a few parameters such as the shape of the blade, the large of steering blade, and the number of buckets which these parameters can affect the amount of power produced by turbine generator, efficiency, and performance of the resulting water turbine [1].

Few numbers of buckets have a wider distance between the blades than the more number of buckets. This distance will affect the flow in the crevices of the blade. The wider distance between the blades, the flow passing through the blades will be filled by the air so that the energy of the water cannot be accepted, then the rotation of the wheel will be slow, the narrower the distance between the blades also resulted in the rotation of the wheel path which is not optimal. This is because the blades have a thickness that can impede the flow of water through the crack of the blade. Besides that, the size of the opening angle of steering blade can also affect the optimization of the flow of water through the crack of the blade to turn the wheels will be more maximal.

Several studies have been conducted as attempts to improve the workability of a water turbine include the number of buckets and blade profile. The performance generated by the waterwheel undercurrent with bowl-shaped blade indicated that the highest efficiency of the waterwheel various blade contained in a water mill with a number of 6 blades, i.e., 57.8491% [2]. Accordingly, it can be concluded that the waterwheel with spoon bowl shape can be used in the manufacture of small-scale power generation. The profile of the blade was also affected the ability of a water turbine. The data from the research conducted by the previous researcher showed that there was an effect of the blade profile against the power coefficient of Gorlov turbine. It was stated that the best result was performed by blade profile type of NACA00017 with twist angle at 300 and power coefficient average at 17.3% [3].

The design of experiment Taguchi method is essential equipment which is used for robust design to produce products with high quality and low cost. Taguchi method is based on an evaluation of the dependent variable of independent variables which have been determined based on orthogonal arrays to obtain the optimum design parameters [4]. Orthogonal arrays provide a design with a minimum number of experiments. S/N ratio is a log function of the desired output which serves as the objective function for optimization, helps in analyzing the data, and predicts the optimal results. In general, the response characteristics can be grouped into 3 parts, they are smaller-the-better, nominal-the-better, and larger-the-better specified to obtain the optimum response [5].

Based on the research background and also several previous studies, the researcher conducted the research related to the effect of water flow rate, the shape of the blade, and the number of buckets on floating blade waterwheel turbine against the efficiency turbine and to obtain optimum design parameters using the Taguchi method.

2. Methods
2.1. Material and method
The floating blade water wheel was a part of the water turbine that works based on the push of water. When the turbine was pushed by water, the blades would open and close. This turbine was adopted from water turbine goose leg as reported in previous work [6]. This water turbine was fitted to extract the kinetic energy of the free water wheel, because of the ability of each blade can open and close [7].

In this study, the independent variables used were the flow rate (35; 40; 45; 50 ℓ/min), number of buckets (4 and 6 buckets), and the blade shape (convex and flat). The response variable used to view the performance of the turbine was efficiency turbine. The performance of the water turbine depended on the turbine shaft power generated and the mechanical efficiency of the turbine. Table 1 and Figure 1 show the specifications of the water turbine and blade design used in this study.
Table 1. Specifications Pelton Turbine Laboratory Scale

| Specification                        | Value   |
|--------------------------------------|---------|
| The length of the blade              | 150 mm  |
| Blade width                          | 45 mm   |
| The distance of the blade to the shaft| 15 mm   |
| Diameter of shaft                    | 4.5 mm  |
| Number of buckets                    | 5 pieces|

Figure 1. Floating blade free water wheel design

The characteristic of water turbine performance had an interaction between the main variables that affect the performance of the water turbine. The equations used were as follows. The torque produced by the turbine could be obtained using the following equations:

\[ T = F \cdot L \text{ (Nm)} \]  
\[ F = m \cdot g \cdot sin\theta \]  

The tangential speed of the turbine runner was obtained using this equation:

\[ \omega = \frac{2 \cdot \pi \cdot n}{60} \text{ (Rad / s)} \]  

Water power into the turbine:

\[ P_w = \rho \cdot g \cdot H \cdot Q \text{ (watt)} \]  

The yielded power of turbine shaft:

\[ P_s = \omega \times T \text{ (watt)} \]  

Mechanical efficiency of the turbine:

\[ \eta_m = \frac{P_s}{P_w} \% \]
The purpose of this study was to obtain a new parameter in the optimization of the design performance of the turbine. According to this research, it obtained the optimum turbine design parameters such as the number of buckets, water flow, and the shape of the turbine blades to obtain the best efficiency. The Taguchi method was an optimization method that used to solve optimization problems in this study.

2.2. Design of experiment by Taguchi method
Taguchi method was the technique used to reverse or improve productivity during research and development, in order to obtain a high-quality product with low cost and short time. Taguchi method was a design method with the principle of improving quality by minimizing the variations without removing the causes. If the quality of the product was getting close to the target value, then the resulting quality would be better. Quality characteristics used were the larger, the better with the response of the turbine efficiency. Quality characteristics of the experimental results were analyzed by Signal to Noise Ratio (S/N) to determine the factors and the level of the most influential on the quality of the product. Table 2 describes the factors that were expected to affect the value of the response. These experiments used three factors with the multilevel design. Based on the number of levels and factors, they determined the number of rows and the orthogonal matrix was 16, which showed the number of trials was 16 times. The L16 orthogonal matrix is shown in Table 3.

| Table 2. The levels of the variables (control factor) used in the experiment |
|---|---|---|---|---|
| Factor | Levels | Unit |
| Flow Rate | 35 | 40 | 45 | 50 | ℓ/ m |
| Number of Bucket | 4 | 6 | - | - | Pieces |
| Blade Shape | Convex | Flat | - | - |

| Table 3. The L16 Taguchi orthogonal array |
|---|---|---|---|---|---|
| Run | Coded Level | Uncoded Level |
| | A | B | C | Flow Rate | Number of Bucket | Blade Shape |
| 1 | 1 | 1 | 1 | 35 | 4 | Concave |
| 2 | 1 | 1 | 1 | 35 | 4 | Concave |
| 3 | 1 | 2 | 2 | 35 | 6 | Flat |
| 4 | 1 | 2 | 2 | 35 | 6 | Flat |
| 5 | 2 | 1 | 1 | 40 | 4 | Concave |
| 6 | 2 | 1 | 1 | 40 | 4 | Concave |
| 7 | 2 | 2 | 2 | 40 | 6 | Flat |
| 8 | 2 | 2 | 2 | 40 | 6 | Flat |
| 9 | 3 | 1 | 2 | 45 | 4 | Flat |
| 10 | 3 | 1 | 2 | 45 | 4 | Flat |
| 11 | 3 | 2 | 1 | 45 | 6 | Concave |
| 12 | 3 | 2 | 1 | 45 | 6 | Concave |
| 13 | 4 | 1 | 2 | 50 | 4 | Flat |
| 14 | 4 | 1 | 2 | 50 | 4 | Flat |
| 15 | 4 | 2 | 1 | 50 | 6 | Concave |
| 16 | 4 | 2 | 1 | 50 | 6 | Concave |
3. Results and Discussion

3.1. Experimental analysis for turbine efficiency

The efficiency graph was affected by the power generated by the shaft and the amount of energy into the water wheel. The energy which works into water wheel is kinetic energy that is available on the free-flow of water that flows in accordance with the predetermined flow. Figure 2 shows that the highest efficiency obtained by using water flow of 50 liters/minute of 3.999% with the number of buckets of 6 pieces and the shape of the blade was concave, followed by 3.955% with the number of buckets of 6 pieces and the shape of the blades was flat, then 2.876% with the number of buckets of 4 pieces and the shape of blades was concave and 2.581% with the number of buckets of 4 pieces with the shape of blades was flat. According to the graph, it can be concluded that the shape of blades affected the performance of the water wheel. The shape of the convex blades generated greater efficiency compared to the flat one.

![Figure 2. The correlation between efficiency, flow rate, number of buckets, and blade shape of the floating blade water wheel turbine](image)

The same study used by Anurat Tevata and Luther Sule shows the number and shape of bucket affected the performance of turbine, particularly, its power and its efficiency. According to the results of their study, they explained that the highest performance had been achieved by using 6 buckets [1]. While the study results of Luther Sule explained that the concave blade improved the performance of turbine [8]. The concave blade had a wider surface compared with the flat one. This statement in line with the momentum equation which explained that the momentum value was the mass multiplied with the velocity, where the mass obtained from surface area multiplied with the water velocity. Thus, the wider surface area, the bigger momentum yielded by the water crashing the blade.

3.2. Taguchi analysis for turbine efficiency

Taguchi analysis performed using MINITAB 16 statistical software. The experimental results for the actual efficiency of the water wheel and the predicted one are presented in Table 4. The value of the actual water wheel efficiency derived from the experimental results was compared with the predicted efficiency value of the mathematical equations obtained from the regression analysis were presented in Figure 3. The value of predicted efficiency was very close to the actual efficiency values so that the
mathematical equations which resulted by regression analysis was able to be used to find the value of response without performing actual experiments.

Figure 4 shows the analysis of the effect of control (the flow rate, number of bucket, blade shape) in response (efficiency) obtained from the main effect plot of SN ratio that showed factors and levels that had a significant effect on the response. Table 5 shows the effect of the main results of the SN ratio, which provided the effect of control factor significantly to the efficiency of the water wheel was the number of buckets, followed by the blade shape, and flow rate. Level optimum parameters are shown in Table 6 with bucket number of 6 pieces, the water flow of 50 ℓ/min, and the concave shape of the blade. The greater value for the S/N ratio, the better quality result [9], [10].

Table 4. The experimental results for the efficiency of floating blade water wheel

| Exp. Run | Coded Level | Uncoded Level | Response |
|----------|-------------|---------------|-----------|
|          | A  B  C     | Flow Rate (ℓ/minute) | Number of Buckets (pieces) | Blade Shape | Efficiency of Water Wheel (Actual-%) | Efficiency of Water Wheel (Predicted-%) |
| 1        | 1  1  1    | 35             | 4          | Concave    | 2.359                          | 2.697                          |
| 2        | 1  1  1    | 35             | 4          | Concave    | 2.326                          | 2.697                          |
| 3        | 1  2  2    | 35             | 6          | Flat       | 3.006                          | 2.996                          |
| 4        | 1  2  2    | 35             | 6          | Flat       | 3.014                          | 2.996                          |
| 5        | 2  1  1    | 40             | 4          | Concave    | 2.876                          | 2.827                          |
| 6        | 2  1  1    | 40             | 4          | Concave    | 2.862                          | 2.827                          |
| 7        | 2  2  2    | 40             | 6          | Flat       | 3.136                          | 3.126                          |
| 8        | 2  2  2    | 40             | 6          | Flat       | 3.129                          | 3.126                          |
| 9        | 3  1  2    | 45             | 4          | Flat       | 2.803                          | 2.495                          |
| 10       | 3  1  2    | 45             | 4          | Flat       | 2.811                          | 2.495                          |
| 11       | 3  2  1    | 45             | 6          | Concave    | 3.555                          | 3.179                          |
| 12       | 3  2  1    | 45             | 6          | Concave    | 3.561                          | 3.179                          |
| 13       | 4  1  2    | 50             | 4          | Flat       | 2.528                          | 2.625                          |
| 14       | 4  1  2    | 50             | 4          | Flat       | 2.519                          | 2.625                          |
| 15       | 4  2  1    | 50             | 6          | Concave    | 3.999                          | 3.849                          |
| 16       | 4  2  1    | 50             | 6          | Concave    | 3.984                          | 3.849                          |
Figure 3. Timescale graph for efficiency (actual) and efficiency (predicted)

Table 5. Response Table for the signal to noise ratios

| Level | Flow Rate | Number of Buckets | Blade Shape |
|-------|-----------|-------------------|-------------|
| 1     | 9.167     | 8.495             | 10.19       |
| 2     | 9.434     | 10.634            | 8.94        |
| 3     | 9.53      | -                 | -           |
| 4     | 10.128    | -                 | -           |

Delta 0.961 2.139 1.25

Rank 3 1 2
3.3. **ANOVA (analysis of variance)**

The purpose of using ANOVA statistical analysis was to determine the design parameters which had a significant effect on the response (efficiency of water wheel). The analysis was performed with an error rate of 5% and a confidence level of 95%. Based on the ANOVA table, it can be seen that the number of buckets provided the largest contribution of 68.13%, the blade shape provided the contribution of 23.28%, while the flow rate provided the contribution of 7.35% and the residual error of 1.25%. Besides the view of percentage contribution, it also can be seen from the P-value for each factor. The smaller of the P values (less than 0.05), the control factors had a significant effect on the response. The R² showed 98.75% which close to 100% where the flow rate, the number of the bucket, and the blade shape provided the most significant effect on the efficiency of the water wheel, while the rest of 1.25% was affected by other variables besides predetermined control factor [3,11]. The results of ANOVA analysis can be seen in Table 7.

**Table 6. Optimum response parametric**

| Factor            | Level         |
|-------------------|---------------|
| Flow Rate         | 50 ℓ / m     |
| Number of Bucket  | 6             |
| Blade Shape       | Concave       |

**Table 7. Analysis of variance for SN ratio**

| Source              | DF  | seq SS  | adj SS   | adj MS  | F    | P     | % Contribution |
|---------------------|-----|---------|----------|---------|------|-------|----------------|
| Flow Rate           | 3   | 0.9868  | 0.9868   | 0.32894 | 3.93 | 0.21  | 7.35%          |
| Number of Bucket    | 1   | 9.1488  | 9.1488   | 9.14877 | 109.26 | 0.009 | 68.13%         |
| Blade Shape         | 1   | 3.1257  | 3.1257   | 3.12568 | 37.33 | 0.026 | 23.28%         |
| Residual Error      | 2   | 0.1675  | 0.1675   | 0.08373 | -    | -     | 1.25%          |
| Total               | 7   | 13.4287 | -        | -       | -    | -     | 100%           |

R-sq = 98.75%        
R-sq (adj) = 95%
In addition, to examine the adequacy of the model, the residual analysis contained in Figure 5 was employed. While the normal distribution graph in Figure 5 (a), the form of plot approached the straight line (normal line). Heteroscedasticity testing was used to test whether the regression model which had homogenous residual variance. According to the result shown in Figure 5 (c), it can be seen that the points are scattered randomly or not patterned either above or below the zero on the X-axis, so that we can conclude the range of homogeneous residuals (assumptions fulfilled). The histogram plot can be seen in Figure 5 (c), it shows that the experimental data results visually above had a normal distribution. Figure 5 (d) shows the graph versus order in the form of the plot does not form a specific pattern, it can be visually indicated that the experimental results on the residuals were independent.

3.4. Regression analysis of floating blade water wheel
Regression analysis was a statistical process used to estimate the correlation between the dependent and independent variables. This was a method to model the different variables, which helped in understanding how the dependent variable diverges when one independent variable changes. The regression analysis was performed on the efficiency of the water wheel as the dependent variable against the water flow, the number of bucket, and the blade shape as independent variables [3,12]. Based on the above data analysis, in order to obtain a mathematical model is shown as follows:

\[
\text{Turbine Efficiency} = 0.726 + 0.02603*\text{flow rate} + 0.3806*\text{number of bucket} - 0.4623*\text{blade shape}
\]

![Figure 5. Graphs of (a) Normal probability of the turbine efficiency (b) Histogram (c) Versus fits (d) Versus order](image)

4. Conclusion
Based on the results and discussion of study which have been described previously on a floating blade water wheel turbine performance with variations of water flow, the number of buckets and the blade shape, it can be concluded that the turbine efficiency that can be yielded in this study was 3.999% with total bucket of 6 pieces, concave shape, and water flow at 50 ℓ/m. According to the ANOVA results, the factors that most affected the turbine efficiency were the number of buckets, followed by the blade shape, and the water flow.
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