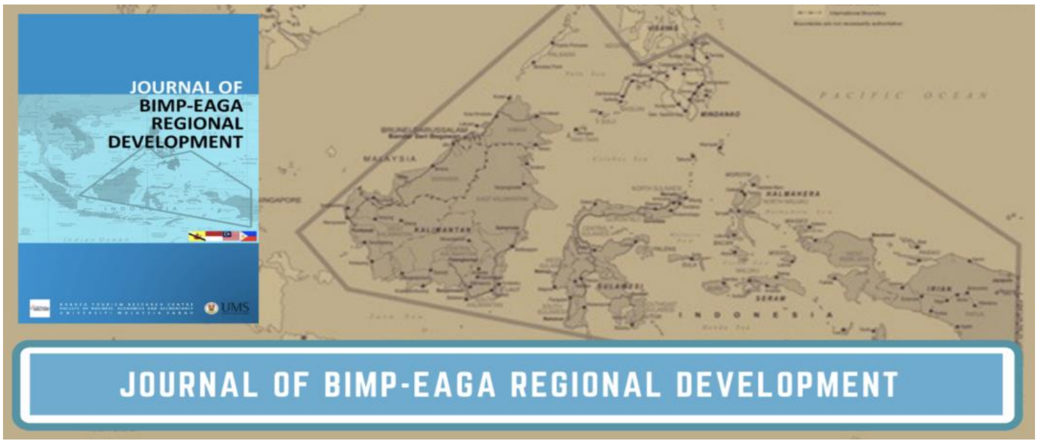

Fabrication and Characterization of Floating Small Hydroelectric Power Generator using Spiral Water Wheel

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Abstract

For the practical application of small hydroelectric power generation, the authors designed a floating small hydroelectric power generation system equipped with a float, and fabricated and measured the system using a spiral turbine. The authors also designed and fabricated a cylinder as a mechanism to prevent water divergence. This paper describes the number of blades of the spiral turbine and the effect of the mechanism designed and fabricated by the authors on the measurement results.

A three-phase AC generator with a rated voltage of AC 220 [V], a rated power of 30 [W], a rated speed of 900 [rpm], and a winding resistance per phase of 32.5 [Ω] was used as the generator. The three-phase AC output of the generator was converted to DC by a three-phase bridge diode. The rotation of the spiral turbine is transmitted to the generator by a gear box with bevel gears and a gear ratio of 2. The float was made of SPF material, which is moderately soft and easy to process, and a two-body float was fabricated. The total length of the float was set at 1200 [mm], taking into account the buoyancy and total weight of the device. The water wheel was made from a commercially available product and one made by the authors using a 3D printer. Based on the measurement results, firstly, the mechanism (cylinder) for preventing water divergence is considered to be effective in a state where there is little braking by the load current, that is, in a region where the load resistance is sufficiently larger than the value of the winding resistance per phase. Measurements under a flow velocity of 1.18 [m/s] and the winding resistance per phase 32.5 [Ω] of the generator used showed that the power output and efficiency were better with the cylinder attached in the region where the load resistance was 200 [Ω] or higher. Next is the number of blades. The same can be said for the number of vanes as for the choice of whether or not to install a cylinder. In the region where the load resistance is small, the rotation of the generator is braked by the large load current, so increasing the number of blades requires a larger force to rotate the generator, making it ineffective. The authors expect that determining the number of blades and the inner diameter of the cylinder from a composite point of view, according to the load current, will increase the power and efficiency. In the measurements with a winding resistance of 32.5 [Ω] per phase and a flow velocity of 1.18 [m/s], both power and efficiency peaked in the range of load resistances between 90 [Ω] and 200 [Ω], with and without cylinders. The average power and efficiency in this range were 3.3 [W] and 8.9 [%], respectively.

For the practical application of small hydroelectric power generation, the effectiveness of auxiliary mechanisms such as floats and cylinders fabricated by the authors, as well as the characteristics of the number of blades, can be utilized.

Keywords: Renewable Energy, Small Hydroelectric Power Generator, Spiral Turbine, Power Generation Characteristics, Charging Performance

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1. Introduction

Efforts to achieve carbon neutrality are accelerating in order to mitigate climate change and build a sustainable society. The Seventh Basic Energy Plan (draft) published in Japan in December 2024 indicates that the power source composition in FY2040 is expected to be 40-50 [%] renewable energy, 30-40 [%] thermal power, and 20 [%] nuclear power. In the current Sixth Basic Energy Plan, the power source composition in FY2030 is about 41 [%] thermal power, 36-38 [%] renewable energy, and 20-22 [%] nuclear power, and in the Seventh Basic Energy Plan, renewable energy surpasses thermal power for the first time to become the largest share in the power source composition.

In the SDGs (Sustainable Development Goals), the seventh goal is to "significantly increase the share of renewable energy in the global energy mix by 2030". Renewable energy is an important part of the solution to the problems of global warming and energy resources.

Among renewable energy sources, small hydroelectric power, which can be generated in rivers and irrigation canals, has attracted attention in recent years. Small hydroelectric power is a type of hydroelectric power. Hydroelectric power generation uses the potential energy of water flowing from a high point to a low point. Small hydroelectric power has not been specifically defined, but the Japanese power industry has traditionally defined small hydroelectric power as "hydroelectric power with an output of up to 10,000 [kW]. Small hydroelectric power generation is classified into two types: run-of-the-river and canal, both of which utilize the flow of water without storing it in rivers. Small hydroelectric power turbines include Pelton turbines, Francis turbines, cross-flow turbines, Kaplan turbines, siphon turbines, top-hung open turbines, bottom-hung open turbines, and spiral turbines. While there is some literature on cross-flow turbines that performs numerical fluid dynamics analysis of the turbine blades, there is little literature on other types of turbines, and the reality is that they are far from being practical for small hydroelectric power generation. In order to move towards practical application, it is essential to design a system that is suitable for the river or irrigation canal in which it will be introduced, and a multifaceted approach that is not limited to the blade shape alone is required. To the best of the authors' knowledge, there are no specific examples of research on small hydroelectric power generation working on such a practical approach.

The authors have independently designed a floating small hydroelectric power device with a float mechanism, manufactured and measured the device with a bottom-hung turbine, a kind of open-type turbine, and aimed at its practical application as a kind of multifaceted approach to the practical application of small hydroelectric power generation. The float mechanism allows the device to float and does not require the device to be fixed. This has the following two advantages. First, it can respond to fluctuations in water level. Second, it is portable and can generate power anywhere. In addition to underwater turbines, the authors have also been focusing on spiral turbines since FY2020 and have begun research on them. The spiral turbine has a wide flow path between the blades, so there is no risk of contamination by trash, fish, etc., and depending on the degree of submersion, it can obtain more input energy than a bottom-hung turbine. This paper describes the outline and characteristics of a unique floating small hydroelectric power generation system using a spiral turbine newly fabricated by the authors. The authors also designed and fabricated an original water diversion prevention mechanism to allow water to flow efficiently into the turbine. The number of blades of the spiral turbine and the effect of the mechanism designed and fabricated by the authors on the measurement results are also discussed.

2. Overview of the Fabricated Generator

This chapter describes the small hydroelectric power generation system built by the authors. The generator is described in Section 2.1, the water wheel in Section 2.2, the power transmission mechanism in Section 2.3, the float in Section 2.4, the water diversion mechanism in Section 2.5, and the small hydroelectric power generator fabricated by the authors in Section 2.6.

2.1. Three Phase AC Generator

A three-phase AC generator was used to obtain high voltages even at low speeds. The actual three-phase AC generator used was model number DR-9538-709 (CHZXDZ), rated voltage: 310 [V] DC (220 [V] AC), rated power: 30 [W], rated speed: 900 [rpm], winding resistance per phase: 32.5 [Ω], Number of field poles: 8, Inductance per phase: 0.140 [H].

Since the output voltage of a three-phase AC generator is AC, a three-phase bridge rectifier is used to convert the output voltage from AC to DC. This circuit consists of two diodes in series and three diodes in parallel (see Figure 1).

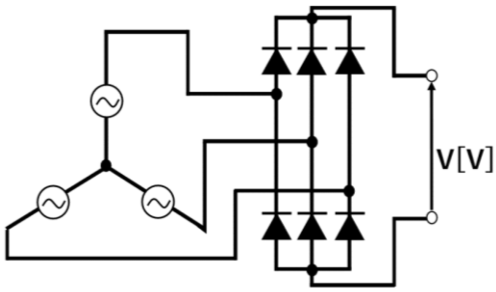


Figure 1: Three phase AC generator

2.2. Water Wheel

2.2.1. Commercial spiral water wheel and its mounting

A spiral turbine with a total length of 218 [mm], a mass of 0.75 [kg], a pitch of 205 [mm], and a blade cross-sectional area of 0.044 [m^2] per revolution was selected. Figure 2 shows the appearance of the spiral turbine and its mounting. In a previous study by the authors, it was found that the number of turns of the spiral turbine does not affect the power output and efficiency when the turbine is not covered with a pipe or the like, so a single-turn spiral turbine was used.

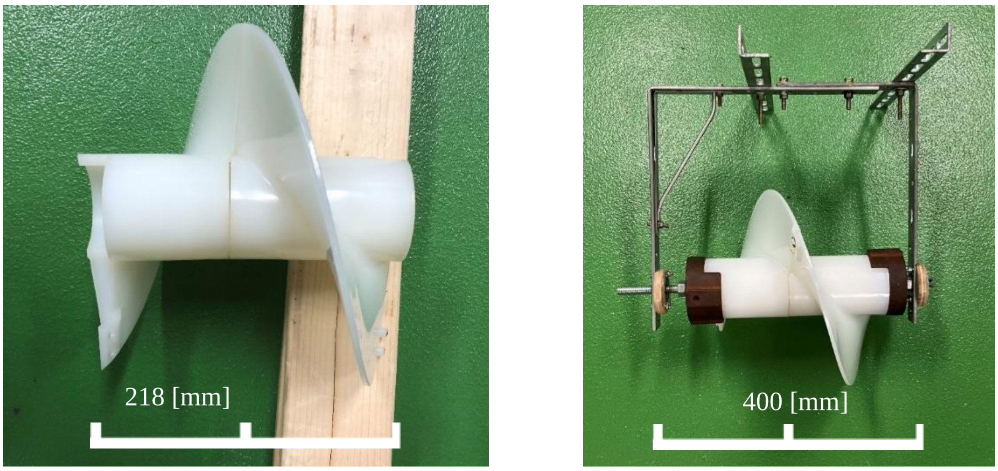
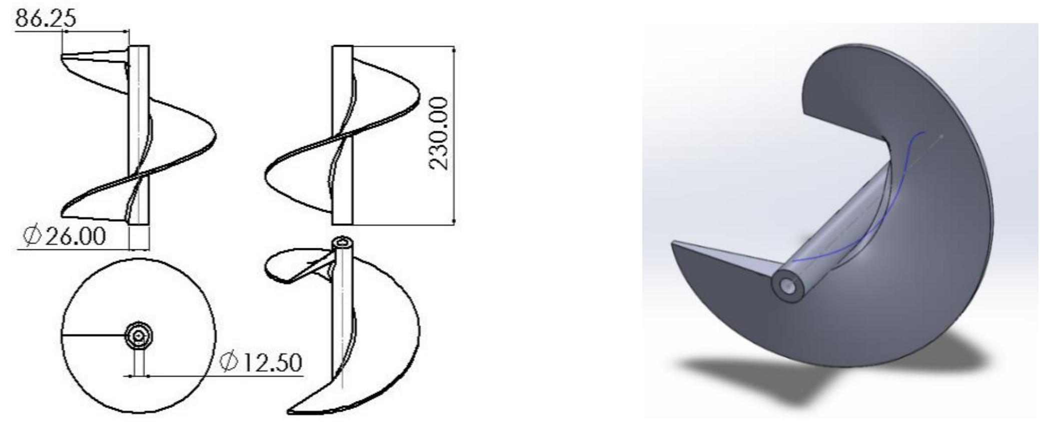


Figure 2: Appearance of the spiral water wheel and its fixing

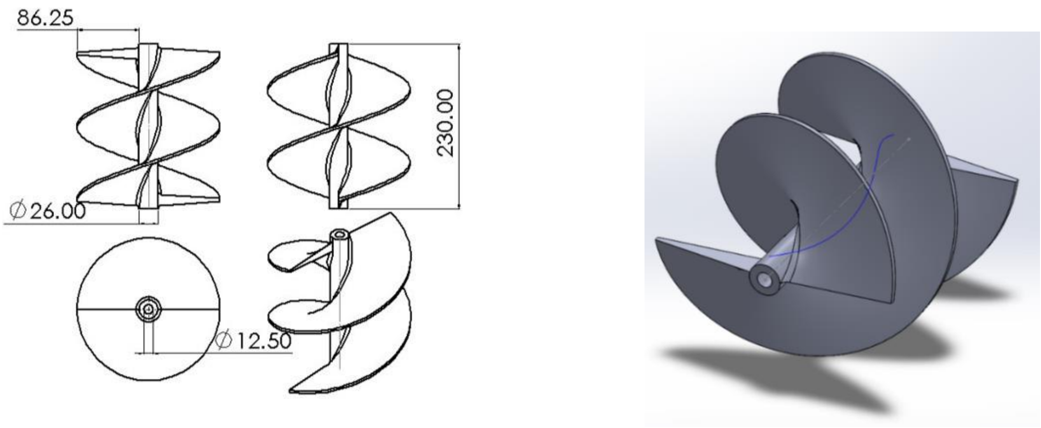
2.2.2. Spiral water wheel fabricated by the authors using a 3D printer

The authors independently built a spiral turbine to confirm the effect of the number of blades (pitch) on the characteristics of the turbine. It is known that the number of blades has an effect in semi-submerged water, and that the output of a water turbine with two or three blades increases compared to that with one blade. The authors envisioned a fully submerged installation of small hydroelectric power devices to effectively utilize the hydraulic energy of rivers and irrigation canals, and fabricated a spiral turbine to see if the number of blades would make an effective contribution. The spiral turbine was fabricated using a 3D printer (Raise3D Pro3). ABS resin: Thermoplastic resin (Hyper Speed ABS V2) composed of acrylonitrile (A), butadiene (B), and styrene (S) was used as the modeling material, considering impact resistance, processability, and cost. SOLIDWORKS 2024 was used to design the spiral turbine. Figures 3 to 5 show the design drawings of the water turbines fabricated by the authors, and Figure 6 shows the actual turbine.



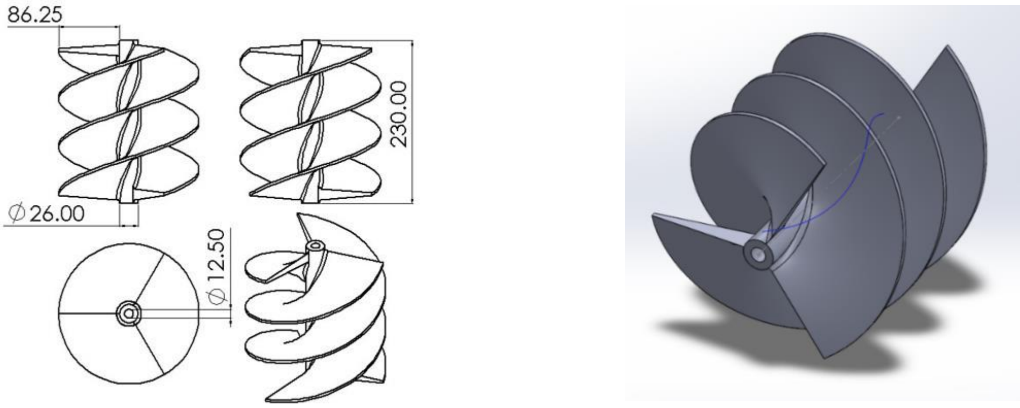
(a) Three-view drawing (Unit: [mm]) (b) 3D model

Figure 3: Single blade spiral water wheel



(a) Three-view drawing (Unit: [mm]) (b) 3D model

Figure 4: Two-blade spiral water wheel



(a) Three-view drawing (Unit: [mm]) (b) 3D model

Figure 5: Three-blade spiral water wheel

Figure 6: The spiral waterwheel actually built by the authors

2.3. Power Transmission Mechanism

A gearbox with bevel gears is installed between the spiral turbine and the generator to make the direction of power transmission orthogonal. The base to which the gear unit is fixed is pointed at the upstream end to reduce the resistance to flowing water. The gear unit is fixed to the base as shown in Figure 7 to prevent it from being displaced to the left or right by the water flow, and the base is fixed to the float by an L-shaped bracket. The flexible coupling is inserted into the shaft from the generator to the gearbox. The function of the flexible coupling is to provide mechanical clearance for power transmission. This prevents shaft misalignment during manufacturing and shaft deflection due to water flow.

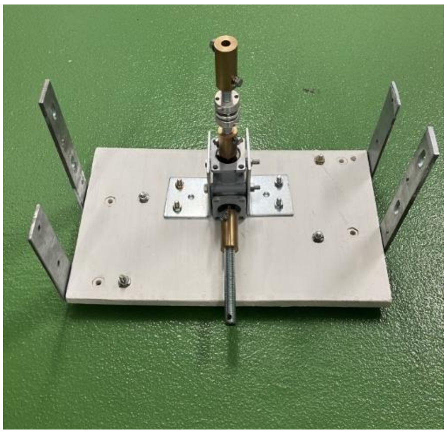


Figure 7: Appearance of the right-angle connector

2.4. Float

The float was made of moderately soft and easy to work with SPF lumber (wood harvested and processed from trees grown in mixed forests (spruce, pine, and fir) on the North American continent) and was two-piece. The dimensions of commercially available SPF lumber are 1.828 [m] long × 0.038 [m] thick × 0.235 [m] wide. The float length was calculated by considering the following three conditions.

- The thickness and width were set to y = 0.038 [m] and z = 0.235 [m], respectively.
- Both ends of the float were sharply cut to reduce the resistance to water flow (x' = 0.100 [m], y' = 0.019 [m]).
- The immersion depth of the float was set at d = 0.225 [mm] to keep the length from the top of the float to the water surface at about 0.010 [m] to prevent the generator from being submerged in the water.

Figure 8 shows the approximate shape of the float after machining. The relationship between the buoyancy of the float and the total weight of the device parts and the float is shown in equation (1). The specific gravity of the float material is ρ_w = 382.87 [kg/m^3], the density of water is ρ = 997 [kg/m^3], and the acceleration of gravity is g = 9.8 [m/s^2]. x [m], y [m], z [m], x' [m], y' [m] are the dimensions of the float after processing, and d [m] is the depth to which the float sinks.

The left side represents the buoyancy of the float when the difference between the top of the float and the water surface is 0.010 [m], and the right side represents the sum of the weight of the float and the weight of the device components. Using these values to solve for x, we find that the generator can float if the length of the float is approximately 1180 [mm] or more. Therefore, we considered an additional margin and manufactured the float with a length of 1200 [mm].

$$\rho\,(xy - 2x'y')dg = \rho_W(xy - 2x'y')zg + Mg \qquad (1)$$

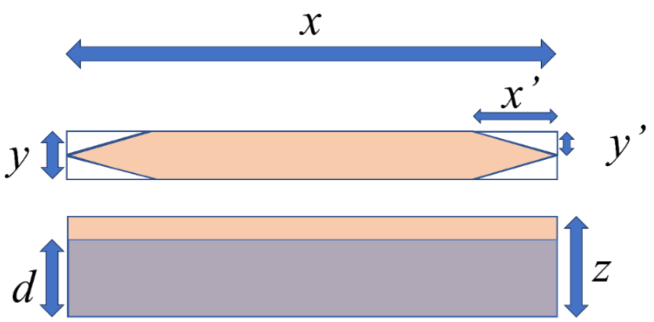


Figure 8: Approximate shape after float machining

2.5. Water diversion prevention mechanism

The authors developed the use of commercially available polyvinyl chloride pipe sockets to prevent water diversion with the goal of efficiently directing water into the turbine. The cylinder was mounted to cover the spiral water wheel. L-shaped fittings, wood screws, bolts, nuts, washers, spring washers and other fasteners were used for mounting. The inner diameter is 268.6 [mm], the outer diameter is 280 [mm], the weight is 2.50 [kg], and the difference between the cross-sectional radius of the spiral turbine and the inner radius of the cylindrical mechanism used by the authors is 10 [mm]. As a result, the inner surface of the cylinder does not come into contact with the spiral water wheel during rotation. Figure 9 shows the appearance of the attached cylinder.

Figure 9: Water diversion prevention mechanism

2.6. Small hydroelectric power generator fabricated by the authors

Figure 10 shows the appearance of the unit. A flexible coupling was used between the gearbox and the generator, and a universal joint was used between the gearbox and the spiral turbine to reduce the effects of shaft misalignment during manufacturing and shaft deflection due to water flow. The total weight of the generator was 19.05 [kg].

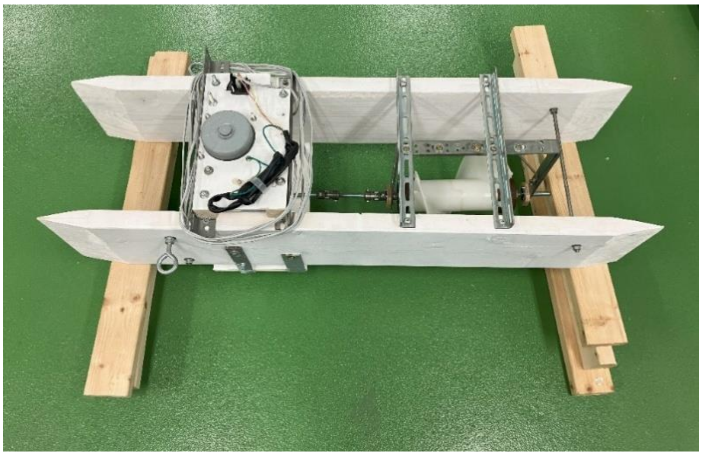


Figure 10: Appearance of the Small hydroelectric power generator fabricated by the authors

3. Measurement Ⅰ

This section describes experiments conducted by the authors to confirm the effectiveness of the mechanism they devised and fabricated to prevent water dissipation.

3.1. Overview - Location, Method and Equipment Used

Measurements were taken at Ogawaesuji in Taira Shimohirakubo, Iwaki City, Fukushima Prefecture. Since the waterway at the measurement site is straight, the generator was stable without swinging from side to side. The following procedure was used for the measurements. These measurements were made both with and without a mechanism to prevent water diversion.

(1) Measure the flow velocity in the irrigation canal for 20 seconds using an anemometer.

(2) Float the small hydroelectric power device in the canal and measure the terminal voltage and frequency of the generator's line voltage for 20 seconds under no load.

Connect a load resistor of 10 [Ω] to 270 [Ω]. Measure the voltage at the load terminals and the frequency of the line voltage of the alternator for 20 seconds.

A current meter (KENEK VR-301) was used to measure the flow rate, and a data logger (Graphtec midi LOGGER GL240) was used to measure the voltage. A combination of enamel resistors (rated power: 5 [W]) and cement resistors (rated power: 100, 300 [W]) were used as loads. Figure 11 shows the measurement circuit diagram.

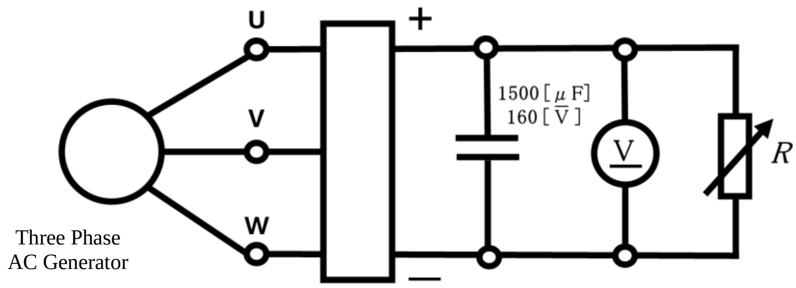


Figure 11: Measurement circuit

3.2. Measurement Result

The power and efficiency were calculated using equations (2) and (3), respectively. The average value of the measured data for 20 seconds was used for the voltage and flow velocity. The flow velocity was v = 1.18 [m/s]. The density of water ρ = 997 [kg/m^3] and the cross-sectional area of the spiral turbine blades S = 0.044 [m^2] were used for the calculations. V [V] is the terminal voltage of the load and R [Ω] is the resistance of the connected load. Figure 12 shows the comparison of characteristics with and without cylinders. Figure 13 shows the photos of the experiment. The ropes were attached to three points on the small hydroelectric generator, and the other end of the rope was tied to the bridge to secure it.

$$P = \frac{V^2}{R} \qquad (2)$$

$$\eta = \frac{\frac{V^2}{R}}{\frac{1}{2}\rho S v^3} \times 100 \qquad (3)$$

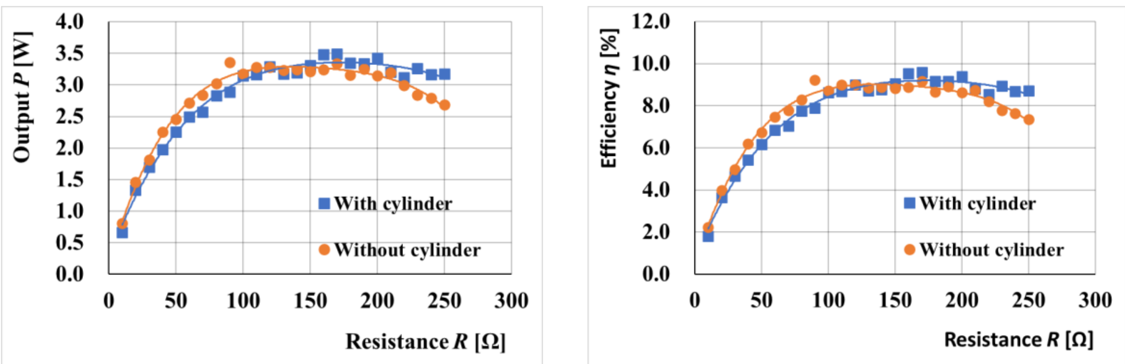


Figure 12: Comparison of characteristics with and without cylinders

Figure 13: Photos of the experiment

3.3. Consideration

In general, when load current flows, the generator rotor is braked and the speed of the spiral turbine is reduced. This is more pronounced when the value of the load resistance is less than the value of the winding resistance per phase. If there is a cylinder surrounding the turbine, the water flowing into the cylinder hits the spiral turbine, which pushes the water back to the inlet and reduces the speed inside. In the region where the load resistance is less than 90 [Ω], the turbine is strongly affected by these factors.

In the load resistance range between 90 [Ω] and 200 [Ω], where both power and efficiency are at their peak, there was almost no change in power and efficiency with or without the cylinders. Within this range, the average output power and efficiency for each resistance value were 3.3 [W] and 8.9 [%], respectively, without the cylinder, and 3.3 [W] and 8.9 [%], respectively, with the cylinder.

In the range where the load resistance is 200 [Ω] or higher, the output power and efficiency are higher with the cylinder than without it. It can be inferred that this is because the braking effect of the load current on the generator rotor becomes smaller in this region. The no-load terminal voltage was 48.2 [V] without the cylinders and 52.1 [V] with the cylinders. The effect of the cylinders designed by the authors is considered to be effective when the braking by the load current is small.

4. Measurement Ⅱ

Here we describe an experiment conducted by the authors to confirm the effect of the difference in the number of blades.

4.1. Overview - Location, Method and Equipment Used

Measurements were taken on the Yoshima River in Watado, Miwa-machi, Iwaki City, Fukushima Prefecture. At this measurement site, water from upstream flowed at a right angle under a stone bridge. As a result, the device floating in the canal directly under the stone bridge oscillated from side to side. The measurement procedure is the same as in section 3.1.

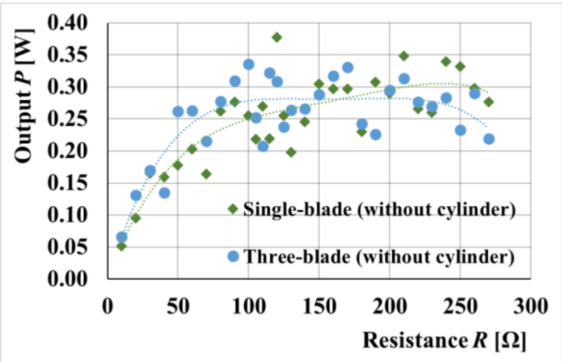
This was done both with a single-blade spiral turbine and with a three-blade spiral turbine attached. The same experiment was also performed with and without the cylinders used in the comparison of power generation characteristics with and without the cylinders attached to each spiral turbine. Ropes were attached to three points on the apparatus, and the ropes were secured by tying them to stakes driven around the stone bridge.

The measuring equipment and load resistance are the same as in section 3.1. A digital multimeter (CUSTOM M-03FBM) was used to measure the frequency of the line voltage of the three-phase alternator used in the generator, and an LCR meter (CUSTOM ELC-121D) was used to measure the inductance at rest.

4.2. Measurement Result

As in section 3.2, the power was calculated using equation (2) and the efficiency was calculated using equation (3). The flow velocity was $v = 0.77$ [m/s]. The impedance per phase of the three-phase AC generator during rotation was calculated using equation (4), where Z [Ω] is the impedance per phase during rotation, R_a [Ω] is the winding resistance per phase, f [Hz] is the frequency between phases of the generator, and L [H] is the inductance of one phase. The inductance of one phase L was measured with an LCR meter at no rotation and was 0.14 [H]. Figure 14 shows the comparison of power output by number of blades in a spiral turbine. Figure 15 shows the comparison of power output by number of blades in a spiral turbine (with cylinders).

$$Z = \sqrt{R_a{}^2 + (2\pi f L)^2} \qquad (4)$$



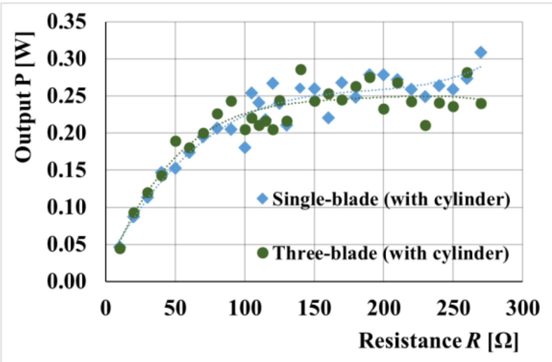


Figure 14: Comparison of power output by number of blades in a spiral turbine
(Left: without cylinder, Right: with cylinder)

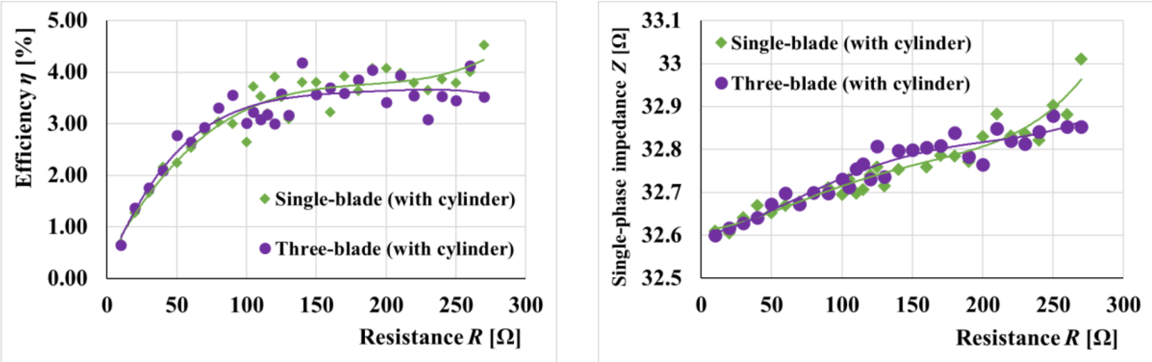


Figure 15: Comparison of power output by number of blades in a spiral turbine (with cylinders)

4.3. Consideration

In the absence of cylinders, both the power and efficiency of the three-blade spiral turbine were greater than that of the single-blade spiral turbine in the range where the load resistance was less than 150 [Ω]. This is believed to be due to an increase in the torque applied to the spiral turbine as the number of blades increases. In the low load resistance region, the generator rotation is braked by the large load current, so more force is required to rotate the turbine than when the load resistance is high.

In the presence of the cylinder, both the power output and the efficiency of the three-blade spiral turbine were greater than that of the single-blade spiral turbine in the range where the load resistance was less than 100 [Ω]. This factor is considered to be the same as in the case without cylinders. These results suggest that the three-blade spiral turbine should be used when the braking by the load current is large.

The power and efficiency values for the state without the cylinder were higher than those for the state with the cylinder. The difference between the cross-sectional radius of the spiral turbine and the internal radius of the cylinder used by the authors is 10 [mm], which is expected to be due to the fact that the three blades would reduce water drainage. The authors believe that the radius of the cylinder can be improved by using a larger size.

Over the speed range of the generator, the impedance per phase varies less than 0.4 [Ω] with the cylinder and less than 0.3 [Ω] without the cylinder, with no significant changes observed.

The variations in power and efficiency in Figures 14 and 15 are due to the fact that the water flow under the stone bridge at the measurement point was uneven, causing the generator to sway from side to side. This uneven water flow is also the reason for the variability and the low average efficiency. By the way, the maximum average efficiency during measurement I was 8.9 [%]. The reason why the power is lower than in Measurement I is that "the average efficiency was significantly lower" and "the flow velocity was lower". For example, in the case of a single-blade spiral turbine with one cylinder, the output power was 3.17 [W] and the efficiency was 8.68 [%] when the load resistance was 110 [Ω] in Measurement I. In Measurement II, the output power was 0.24 [W] and the efficiency was 3.53 [%] when the load resistance was 110 [Ω]. In measurement II, when the load resistance was 110 [Ω], the output power was 0.24 [W] and the efficiency was 3.53 [%]. The efficiency ratio was 2.46. The flow velocity in Measurement I was $v = 1.18$ [m/s]. In Measurement II, $v = 0.77$ [m/s]. The flow velocity ratio was 1.53, and the effect on the input energy was 3.60 times the cube of the flow velocity ratio. Based on the known facts, the effect on the output power is calculated as: efficiency ratio 2.46 × speed ratio cubed 3.60 = 8.86 times. 0.27 [W] is the output power when the load resistance is 110 [Ω] in measurement I with a single-blade spiral turbine cylinder, and multiplying it by 8.86 gives 2.39 [W]. The output power of the single-blade spiral water turbine is 0.27 [W]. This is 0.89 [W] lower than the output of 3.28 [W] when the load resistance is 110 [Ω] in Measurement II with the single-blade spiral turbine cylinder. The authors speculate that this is due to the effect on the rotation of the turbine caused by the swaying of the device from side to side in measurement II, that is a mechanical loss.

5. Conclusions

For the practical application of small hydroelectric power generation, a floating small hydroelectric power device with floats was designed, and the device using a spiral turbine was fabricated and measured. In addition, a water diversion mechanism was originally designed and fabricated to allow water to flow efficiently into the turbine. This paper describes how the number of blades of the spiral turbine and the mechanism designed and fabricated by the authors affected the measurement results.

First, the water divergence prevention cylinder is considered to be effective when the braking by the load current is small, that is when the load resistance is sufficiently larger than the value of the generator winding resistance per phase. Measurements under a flow velocity of 1.18 [m/s] and the winding resistance per phase 32.5 [Ω] of the generator used showed that the output and efficiency without the cylinder were better in the range where the load resistance was less than 90 [Ω]. Conversely, the output and efficiency with the cylinder were better in the range where the load resistance was greater than 200 [Ω]. Therefore, it is concluded that it is desirable to choose the installation of the cylinder designed by the authors to prevent divergence of the water flow according to the size of the load current.

The same can be said for the number of vanes as for the choice of whether or not to install a cylinder. In a region where the load resistance is small, the generator rotation is braked by a large load current, so increasing the number of blades requires a larger force to rotate the generator, which does not work effectively. It is expected that the effect of increasing the number of blades will be effective if the inner diameter of the cylinder is set appropriately. In other words, we conclude that it is desirable to select the number of blades according to the load current as well as the choice of whether or not to install a cylinder.

In the measurement with a winding resistance of 32.5 [Ω] per phase of the generator and a flow velocity of 1.18 [m/s], both output power and efficiency peaked in the range between 90 [Ω] and 200 [Ω] of load resistance (results of Measurement I). The values were almost the same with and without the cylinder. The average power and efficiency in this range were 3.3 [W] and 8.9 [%], respectively.

Much remains to be done for the practical application of small hydraulic power generation. In this process, the effectiveness of auxiliary mechanisms such as floats and cylinders designed and fabricated by the authors, as well as the characteristics of the number of blades, are most likely to be utilized. Small hydroelectric power generation systems using spiral turbines have great potential for use in lighting around irrigation canals and charging smartphones and other devices. The authors will continue their research in order to establish small hydroelectric power as one of the methods of supplying electricity in an increasingly carbon-neutral society.

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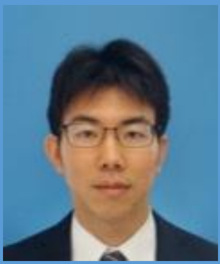
Authors' Biographies

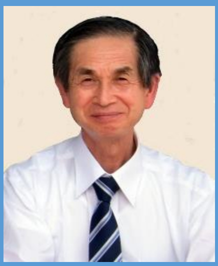
Shinya HASHIMOTO received his Ph.D. in engineering from the University of Tsukuba in 2012. I joined Fukushima National College of Technology in 2014 as an assistant professor. In 2020, I became an associate professor, which is his current position title. My field of research is renewable energy. I work daily to develop equipment for solar, wind, and small hydroelectric power generation, as well as energy education activities for elementary and junior high school students.



Yuta YOSHINO graduated from the Department of Electrical and Electronic System Engineering, Fukushima National College of Technology in 2023. In 2025, I will complete Advanced Courses Program at Fukushima National College of Technology. In 2025 I will start working for Tohoku Electric Power Co., Inc. I conducted research on The Study on Practical Realization of Floating Small Hydroelectric Power Generator using Spiral Water Wheel at Fukushima National College of Technology.

Kyosuke HIRUTA graduated from the Department of Electrical and Electronic System Engineering, Fukushima National College of Technology in 2023. In 2025, I will complete Advanced Courses Program at Fukushima National College of Technology. I will be working for Nippon Koei Energy Solutions Co., Inc. starting in 2025. I was conducting research on the study on Practical Realization of Floating Small Hydroelectric Power Generator using Water Wheel at Fukushima National College of Technology

Mizuyasu KOIDE 2002 received his Ph.D. in engineering from the Nagaoka University of Technology in 2002. I was appointed as lecturer at the Niigata Sangyo University in 2003, and then joined National Institute of Technology, Fukushima College in 2013. In 2022, I became a professor. My research areas are vortex induced vibration, vibration power generation, and wind turbines in fluid engineering. I am also engaged in engineering education activities for elementary and junior high school students, focusing on manufacturing.



Toshikazu Yamamoto received Ph.D. in engineering from Gunma University in 1998. I joined Fukushima National College of Technology in 1998 as an assistant professor. In 2016 I was promoted to professor. And I retired National Institute of Technology (KOSEN), Fukushima College in 2020. Currently, I am collaborating with Dr. Hashimoto on his renewable energy research.