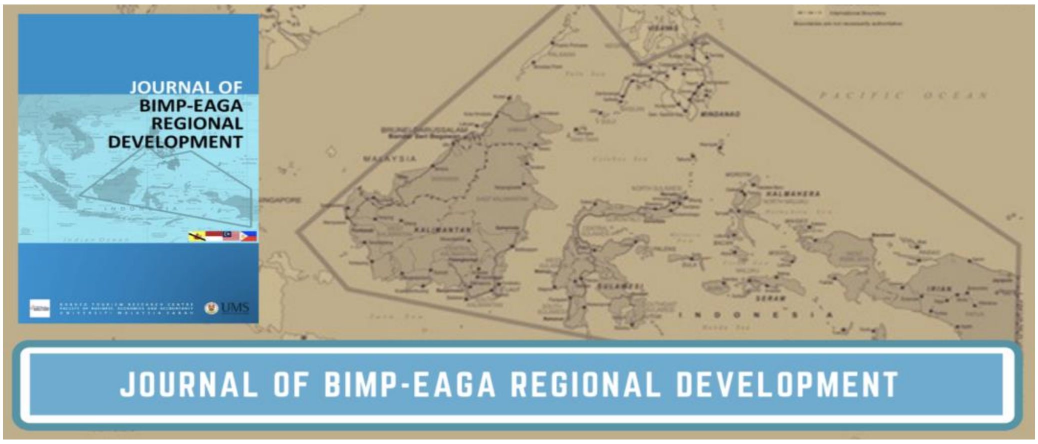

Introduction of Automatic Braking System and auxiliary starting mechanism using wave force for Small Vertical Axis Wind Turbine

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Abstract

Recently, wind power has become an energy source that is expected to increase installation in Japan as wind power prices decrease internationally. However, wind power generation in Japan is still low compared to international standards, and the cost of power generation is high. Therefore, we have been working on small-scale power generation, especially small vertical-axis wind turbines, to adapt the wind turbines to the wind conditions in Japan.

In this study, (1) an auxiliary starting mechanism using wave force was installed in the device, (2) designed and fabricated to compare with drag and lift types, and (3) a rotational speed detection mechanism to introduce a braking system into the system. The drag-type wind turbine was tested in a simple wind tunnel. As a starting aid mechanism, a float attached to the bottom of the float support is floated on the surface of the water, and its vertical movement is converted into horizontal rotation by a combination of gears to turn the wind turbine shaft. The size of the wind turbine is 0.58 [m] in diameter, 0.73 × 0.23 [m] in blades, and 6.70 [kg] in total weight. As a result of the characteristic test of the drag-type wind turbine, it was confirmed that the cut-in wind speed was 3.7 [m/s], the sustained wind speed was 3.3 [m/s], and the maximum power was 0.50 [W] at a load resistance value of 150 [Ω]. For the brake system, a torque of approximately 0.06 to 0.12 [N-m] was obtained to determine the braking strength. A rotation speed detection program was then developed. The mechanism consists of a gear attached to the shaft of a wind turbine and a mechanism that determines the rotation speed based on the number of times the teeth pass between an infrared sensor and a phototransistor facing each other. The program counts each time a tooth passes and calculates the rpm for each specified number of passes using an Arduino. Experimental results with gears on 2, 4, 15, and 21 teeth showed that the measured values were within the permissible error. We investigated the minimum size of an object that blocks the light of the infrared sensor and can be received by the phototransistor and found it to be 4.1 [mm]. In the future, we will work on installing a brake on the generator. We are considering a braking method that connects a load to the generator and aims to activate the brake when the rpm value exceeds 100.

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1. Introduction

Amid the global trend towards decarbonization, there are high expectations for wind power generation. The IEA report estimates that Japan's energy supply from wind power generation is 9,074 TWh/year. In addition, the scale of offshore wind power generation that various organizations are considering is said to be between 159GW and 1,621GW by 2050. The mainstream wind power generators currently used commercially are horizontal-axis wind power generators, where the rotor shaft is horizontal to the ground. There are also vertical-axis wind power generators, where the rotor shaft is vertical to the ground. Compared to horizontal axis wind turbines, vertical axis wind turbines generally have a lower power generation efficiency, but they have many advantages, such as being less sensitive to wind direction. They also have an advantage over horizontal axis wind turbines in offshore wind power generation, and their research has been reevaluated recently.

This research project focuses on vertical-axis wind turbines and is conducting research into the development of unique wind turbines and improvements in their functionality. In this paper, we report on the development of a mechanism that uses wave power to improve start-up characteristics, as well as the development of a rotational speed detection mechanism that activates the braking system. We will supplement our research on the braking system. There are two types of auxiliary mechanisms for improving start-up characteristics: those that use electrical power and those that use mechanical power. In our research on electrical power assistance, we are using a generator as a motor to improve start-up characteristics. The advantage of this method is that it can improve the starting characteristics without making any structural changes to the mechanical structure. On the other hand, excessive assistance can increase energy consumption and may result in a decrease in the overall power generation performance of the system. Many braking systems use rotational speed as a trigger, and the authors are also conducting research on introducing a braking mechanism that detects the rotational speed in the wind turbine generator they are developing. In this paper, we report on the results of creating a sensor that detects the rotational speed and verifies the validity of its functions.

2. Purpose

The authors' ultimate goal is to effectively utilize vertical-axis wind turbines as small-scale power generators, with the development of wind turbines tailored to Japan's wind conditions. To achieve this goal, the authors have considered two perspectives: The first is “self-startability capability.” The second is “shape.” The authors designed and fabricated two vertical-axis wind turbines, a drag type and a lift type, to be attached to a power generation system using wave power. A braking system was developed and installed to safely stop a rotating wind turbine like an ordinary wind turbine. The goal is to test the characteristics of wind turbines equipped with these features.

3. Initiatives for this research

3.1. Waving power

The purpose of this study is “Using Sea Energy”. The authors have created renewable energy like solar, wind, and water. However, the authors had no generators that used sea energy at the time. The actual starting point is something like that.

There are large-scale facilities in the world that use ocean power. However, the authors can use only waves as accessible energy sources. When searching how to use wave, found the “skwid” hybrid generator combined with tide and wind. That’s where we got the idea. The authors decided to use the vertical movement of the sea level as the accessible energy source. By using energy as an auxiliary power, the study aims to improve the poor starting characteristics of lift-type vertical axis wind turbines.

Please find a Figure. 3.1 and explain how to generate production with waves and wind below i~iii.

i: Receive vertical movement of the sea level using float. The float attaches to the extension bar with the chain. The chain baits sprocket changes the vertical force to rotate the horizontal shaft.

ii: Considering the wind turbine’s rotating direction, the sprocket torque must be in one direction only. The cam-clutch inside the sprocket performs that function. The spiral bevel gear attached to the end of the horizontal shaft carries the torque to the secondary gear on the axial main shaft.

iii: Those bevel gears make the torque high to provide the starting torque to the axial main shaft. If the shaft is rotating faster than the bevel gear, it’s possible to disconnect by using the cam-clutch inside the bevel gear.

In conclusion of that system, only while the wind turbine is stopping (near 0 rpm), the mechanical system provides the Starting torque from the sea continuously. So, this wind turbine never stops.

The authors would say this system will be a valuable method for increasing the availability of “Lift-type vertical axis wind turbines” by eliminating the presence of cut-in wind speed. Furthermore, the sea power is strong, so even a small system can perform for bigger wind turbines.

The production of renewable energy must constantly vibrate due to environmental factors. Sometimes, those plants act as consumers. The aim is always to perform as a generator using different renewable resources as auxiliary or combined power.

This system is one example of this.

An experiment at a wharf confirmed that the wind turbine rotates under wave force at wind speeds as low as 0~3 [m/s].

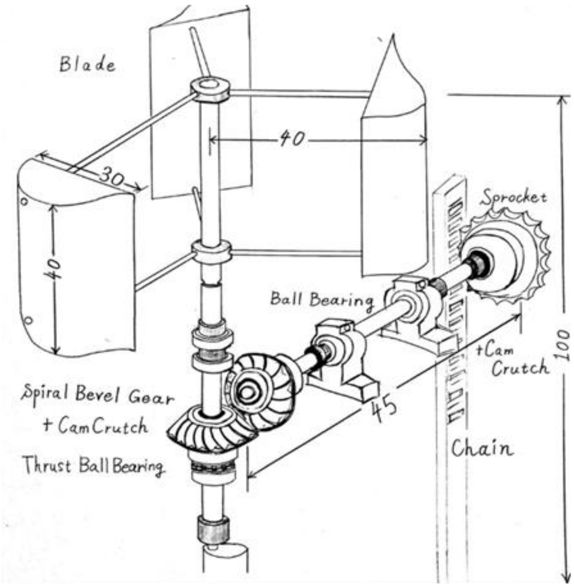


Figure. 3.1 Conceptual diagram of the generator

Figure. 3.2 Wave force experiment

3.2. Design and production of wind turbines

The authors will design a drag-type and a lift-type wind turbine to be attached to a vertical axis wind turbine. The purpose is to see whether the drag or lift type is more suitable for installation on the wave power system. In designing the wind turbine, the authors decided to match the number and shape of the blades to compare the performance of the two types. The wind turbine design is shown in Figure. 3.3.

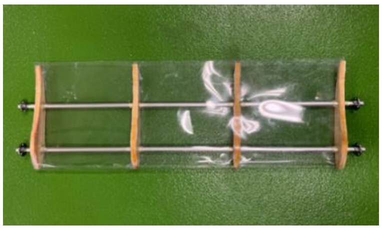
The designed wind turbine was fabricated. The blade materials were wood for the framework, aluminum pipe for the strut, and vinyl chloride for the sheathing. Epoxy resin was used to glue the framework and strut. A pipe holder was attached to the end of the support pole for fixing. A heat gun was used to bend the vinyl chloride to fit the framework when attaching the vinyl chloride to the framework.

The upper and lower disks of the wind turbine were then fabricated. The design was adapted to the size of the power generator. From the standpoint of cost and portability, the drag and lift types were designed to be interchangeable. To fix the blades to the disk, holes were drilled in the upper and lower disks, and the blades could be replaced to allow for the drag and lift types. Pipe holders for fixing the blades to the disk were bolted to the blade posts by drilling holes. In addition, fittings were attached to the upper and lower disks to secure the wind turbine shaft to the wind turbine body.

The actual appearance of the assembled wind turbine is shown.

Diameter: 290 [mm]
Thickness: 10 [mm]

Figure. 3.3 Design of wind turbine



Over-All Length (the Vertical): 73.4 [cm]
Over-All Length (Side): 23.2 [cm]
Pillar Spacing: 9.55 [cm]
Wind Receiving Area: 1515 [cm^2]
Vinyl Chloride Thickness: 0.5 [mm]

Figure. 3.4 Design of Brade

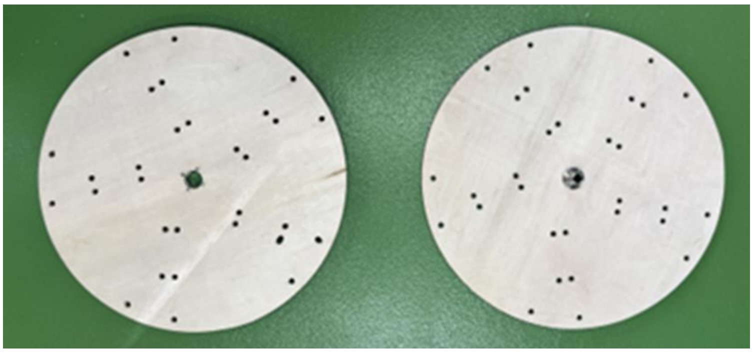


Figure. 3.5 Design of Disks

Over-All Length: 840 [mm]
Gross Weight: 6.70 [kg]

Figure. 3.6 Wind Turbine

3.3. Test of wind turbine

The authors borrowed the wind tunnel building at the Fukushima Robot Test Field to obtain accurate wind turbine characteristics and conducted experiments.

Experiment location: Fukushima Robot Test Field Wind Tunnel Building
Wind Tunnel Equipment Catalog Values
Measurement section: 3 [m]×3 [m]
Maximum wind speed: 20 [m/s].
Wind velocity distribution: ±15 [%] or less above 10 [m/s] (at the outlet)
Turbulence value: ±10 [%] or less at 10 [m/s] or more (near the center of the outlet)

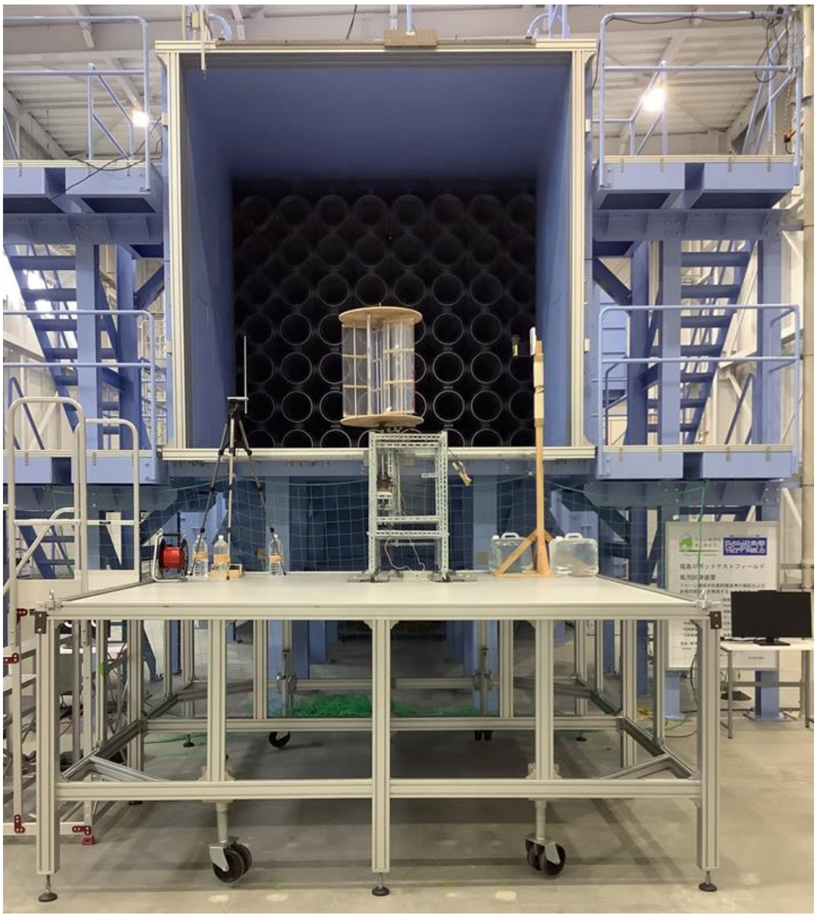


Figure. 3.7 Exterior view of the wind tunnel building

・Equipment used
Sliding resistors (0~190 [Ω]): YAMABISHI ELECTRIC CO.
Switching resistor 1 (0~800 [Ω])
Switching resistor 2 (0~100 [Ω])
Data logger: GRPHTEC, midi LOGGER GL240
PC for measurement

3.4. Characteristic Tests

3.4.1. Experimental Methods

Here, the cut-in wind speed is the wind speed at which the wind turbine starts rotating, and the sustained rotation wind speed is the minimum wind speed at which the wind turbine does not stop rotating. These two wind speeds are measured for drag and lift types, respectively. For the wind speed values, the data from the thermoelectric anemometer installed in the wind tunnel is used as a reference.

・Measurement of cut-in wind speed
From a stationary state, increase the wind speed from 0 [m/s] to 1.0 [m/s] every 1.0 [m/s], and record the wind speed at which the wind turbine begins to rotate. From there, the wind speed is lowered every 0.5 [m/s] to determine the wind speed at which the wind turbine begins to rotate.

・Measurement of sustained rotation wind speed
The wind turbine is rotated at the cut-in wind speed, and the wind speed is lowered little by little from there, and the minimum wind speed at which the wind turbine does not stop rotating is recorded.

・Load characteristics test
Rotate a drag-type wind turbine at a set wind speed of 6.5 [m/s], and after confirming that the rotation speed remains constant, the switch resistor 10 to 250 [Ω] connected to the generator in 10 [Ω] increments. Measure the terminal voltage of the load with a data logger for 30 seconds. The sampling interval shall be 0.1 [s]. Calculate the average power from the average of the recorded voltage and resistance. At the same time, a mark was placed on one of the blades to measure the rotational speed, and the rotation was photographed. A program of rotational speeds was also run for comparison.

3.4.2. Experimental Results

Cut-in and sustained rotational wind speeds for drag and lift types are shown below.

Table. 3.1 Rotational Characteristics Results

Cut-in Wind Speed [m/s]	6.0
Sustained Rotation Wind Speed [m/s]	4.5

Table 3.1 shows that the drag type results in a cut-in wind speed of 6.0 [m/s] and a sustained rotation wind speed of 4.5 [m/s]. However, it initially rotated at 6.5 [m/s] when measuring the cut-in wind speed. The wind turbine rotated several times at that wind speed to see if it was the cut-in wind speed, but sometimes it rotated and did not.

Then, based on the idea that the initial position of the blades might have affected the rotation, the authors tried several patterns and found that there was only one place where the rotation started. The measured value of 6.0 [m/s] was also obtained when the blade position was adjusted.

However, it was confirmed that the rotation was unstable depending on the initial position of the blades. The factors that contributed to the results were

1. uniform wind conditions in the wind tunnel
2. the wind hitting the entire surface of the wind turbine
3. the wind speed was higher than the previous year
4. The blades were not uniform.

The following factors are considered.

・Load resistance – Power

The results for load resistance-power are shown in Figure. 3.8.

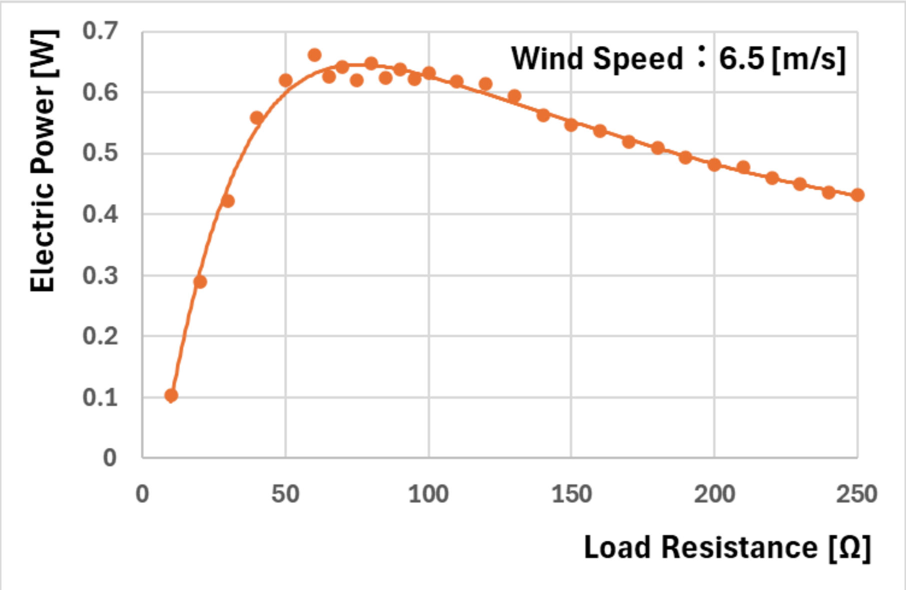


Figure. 3.8 Load Resistance - Electrical Characteristics

In this graph, wind speed is the set wind speed of the airflow system, resistance is the load resistance used, and power is the average of the 30 second measurements. The power graph shows that output power increases with increasing load resistance and decreases with increasing resistance. The approximate curve shows that the peak value of output voltage is around 60 [Ω]. This coefficient may be the same as the rotational speed.

3.5. Introduction of Auto braking systems

Most commonly used wind turbines are equipped with brakes for safety reasons. Therefore, two types of brakes, mechanical and electric, were installed. These two brakes were introduced because mechanical brakes alone accelerate the deterioration of the brake pads and structurally cannot apply a strong force. In contrast, electric brakes alone cannot stop the turbine completely. The electric brake uses a cement resistance of 5 [Ω]. Mechanical brakes are applied by clamping a brass cylinder attached to a rotating shaft with brake shoes used on the front wheel of a bicycle. In use, the blade is first slowed down by applying the electric brake, and then the rotation is completely stopped using the mechanical brake. The circuit diagram of the electric brake mechanism is shown in the Figure. 3.9, the mechanical brake in Figure. 3.10.

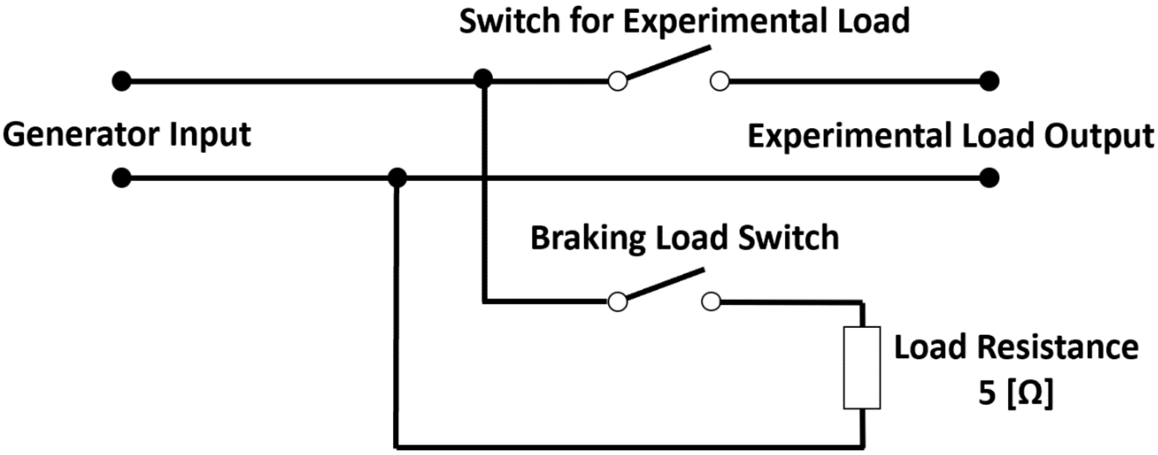


Figure. 3.9 Electric Brake Mechanism

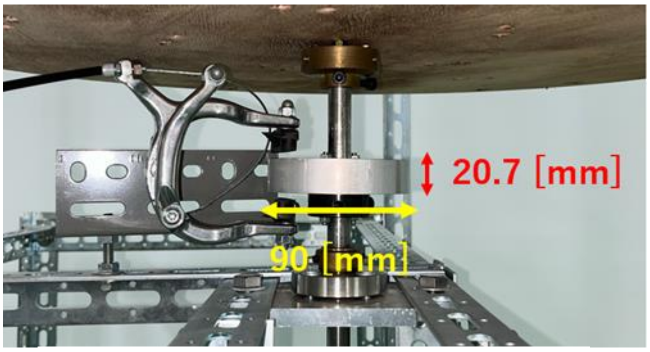


Figure. 3.10 Mechanical Brake

The authors confirmed that the brake system the authors fabricated could apply to the brakes. However, a problem arose regarding safety, as they eventually had to stop the car by themselves. Therefore, it was decided to change the break from manual to automatic. For automatic braking, the goal is to create a control circuit based on the rotational speed as the parameter for applying the brake. There are various methods for detecting rotational speed, including reflective, sensor, and encoder methods, but for this study, an infrared LED (940 nm OSI5FU5113A-40) and a phototransistor (940 nm L-51ROPT1D1) were used. The mechanism devised is shown in Figure. 3.11.

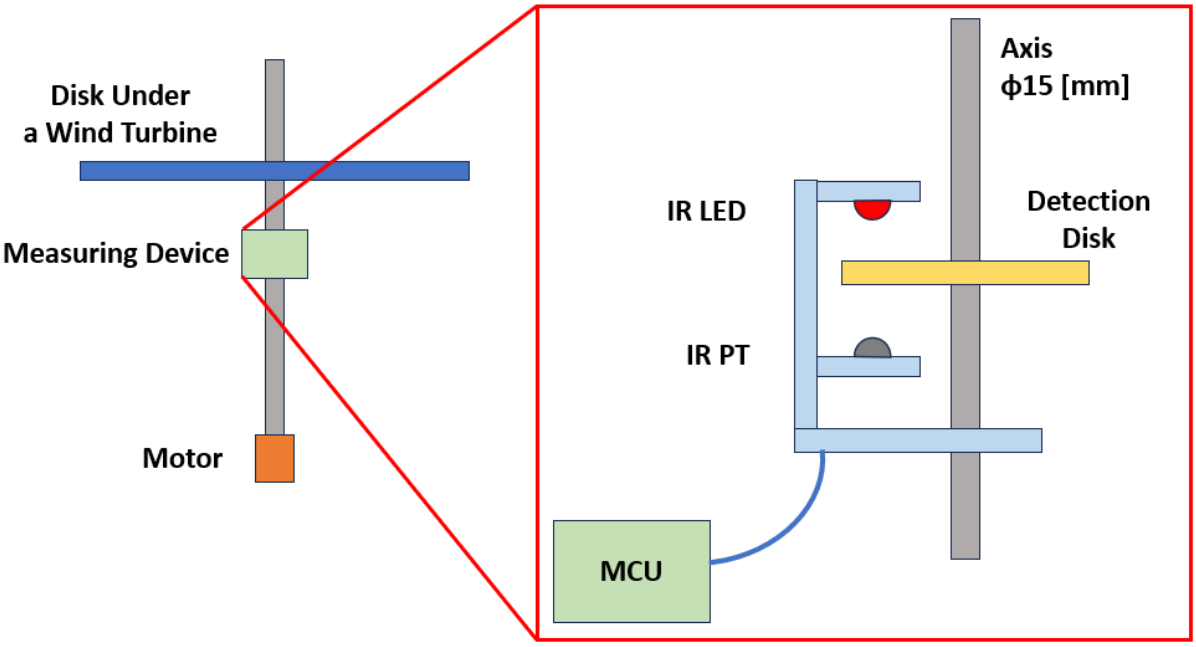


Figure. 3.11 Detecting Rotational Speed

First, an infrared LED and a phototransistor are fixed facing each other on the shaft of a wind turbine. In between, a disk with a hole in its circumference is fixed to the shaft. The infrared light from the infrared LED reaches the phototransistor. Still, it is intercepted by the disk so that each time a hole passes through the disk, the rotation speed is calculated every second from the signal value obtained and the total number of holes in the disk.

The program is written using an Arduino.

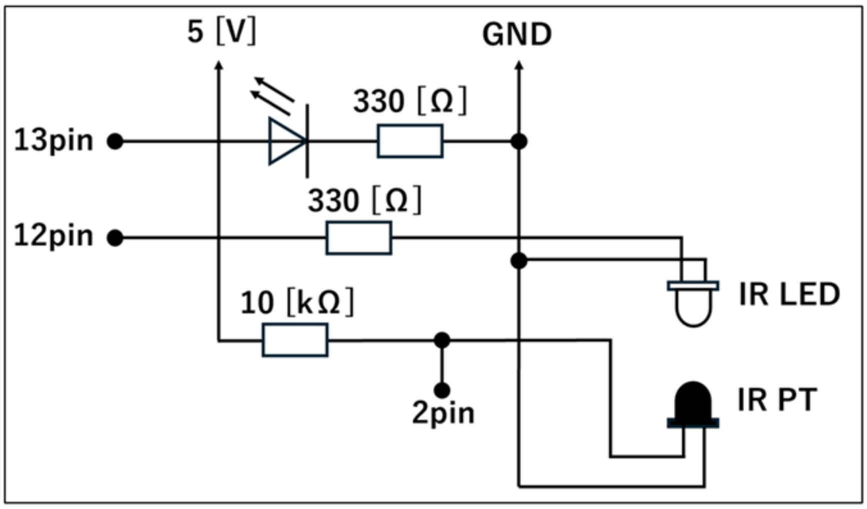


Figure. 3.12 Circuit Diagram

To determine the accuracy of the program, the following formula is used to set the tolerance.

The visual measurement here is the number of revolutions of the gear actually rotating, which is captured on video for one minute and counted. The error that can be considered from this and the number of teeth on the gear is calculated and added to or subtracted from the number of revolutions measured, and this is the allowable error.

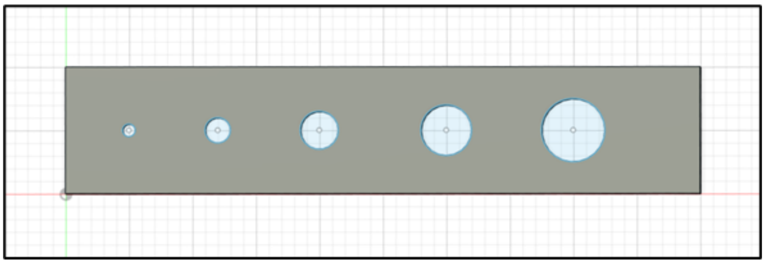
$$\text{Allowable Error [rpm]} = \frac{1}{T} \times N \cdot \cdot \cdot \cdot (1)$$

T：Number of Teeth　N：Visual Measurement [rpm]

3.6. Disk design

Since the preliminary experiments confirmed the program's operation, the gears were designed for actual installation in the mechanism. However, a problem was brought to light: increasing the number of teeth to increase resolution would make the gears physically larger. Therefore, the previous attempt to calculate by blocking infrared light by the gear teeth was changed to a mechanism in which a hole is drilled on the circumference of the disk, and infrared light passes through the hole when it passes through the hole.

A 3D printer was used to fabricate a plate with holes of 1 to 5 [mm] in diameter to determine the appropriate size of the holes and the spacing between them. The holes were passed through the sensor section facing each other to see if they responded.



The Vertical：10 [mm]
Side：50 [mm]
Thickness：2 [mm]

Figure. 3.13 Board produced by printer

The authors experimented, but at first, the program did not respond. The authors thought the infrared light might penetrate through the thin disk. We tried to solve this problem by painting the board black. When we let the disk pass through again, the program worked, and the infrared light passed through to a hole of 1 [mm] in diameter. Next, objects of different thicknesses were passed between the sensors to determine the distance between the holes. As a result, the infrared light was blocked up to 4.1 [mm], so the thickness of the infrared light is 4.1 [mm].

Next, consider the number of holes. From the tolerance formula, you can determine the number of holes by determining the tolerance you wish to set. Now, consider how often the rotational speed should be reached before the brake is applied. In this study, the authors aim to apply the brake when the rotational speed reaches 100 [rpm]. Regarding the allowable error rate, commonly used wind turbines have a braking error rate of about 0.01 [%]. However, if the authors tried to reproduce this error rate with the method, the authors adopted this time, it would result in many holes. Therefore, the authors initially set a goal of allowing a rotational speed of 98 to 102 [rpm] and found that the number of holes needed to be 50 when calculated with an error rate of 2 [%]. The authors would like to reduce the error rate more based on the experiment results.

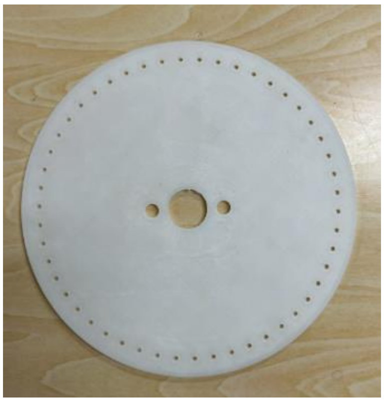
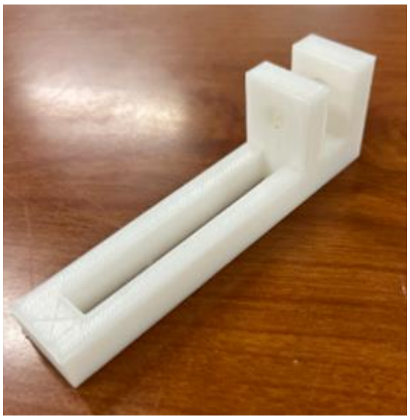


Figure. 3.14 Disk (Before Painting)

Figure. 3.15 Disk (After Painting)

Diameter: 290 [mm]
Thickness: 10 [mm]
Hole Diameter: 2 [mm]
Hole Spacing: 5.2 [mm]
Number of Hole: 50

Outer Diameter: 40 [mm]
Inside Diameter: 15 [mm]
Figure. 3.16 Shaft Holder



Long Side: 100 [mm]
Short Side: 20 [mm]
Figure. 3.17 Sensor fixing device

Auto desk Fusion was used to fabricate the 3D printer. The design was slightly larger than 1 [mm], which allows infrared light to pass through, and 4.1 [mm], which allows infrared light to be blocked. This is because when printed by a 3D printer, it is slightly smaller than the designed value. A fixture was also made to hold the infrared LED and phototransistor facing each other.

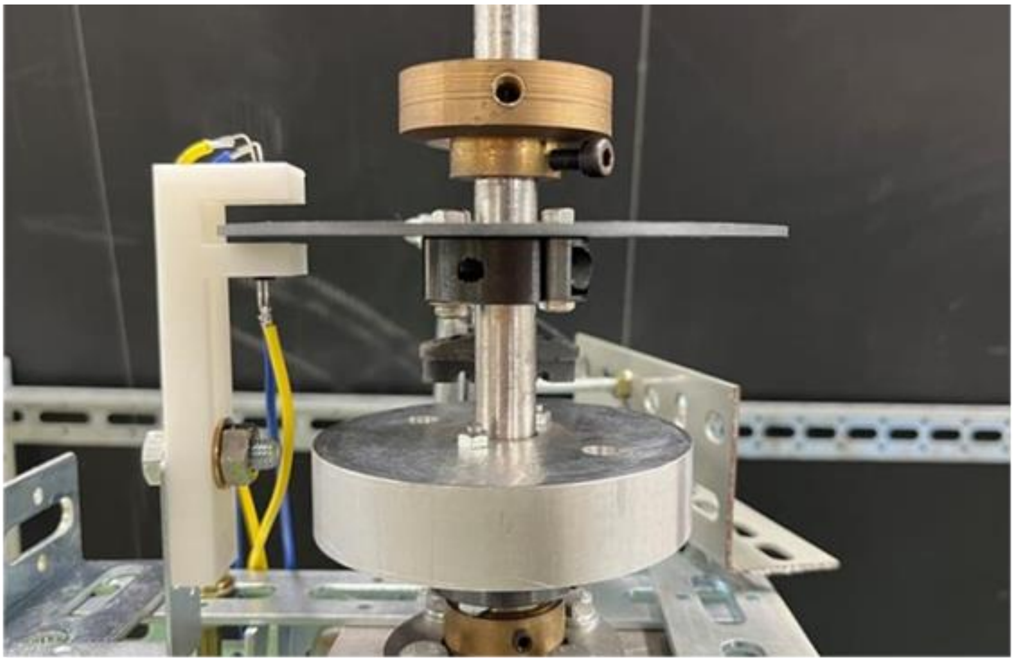


Figure. 3.18 Rotation speed detection mechanism

3.7. Measurement by rotation speed program

Using the fabricated rotation speed detection mechanism, confirm the operation by applying wind.

3.7.1. Experimental method

In a drag-type wind turbine, wind speeds of 0.5~7.5 [m/s] were increased in increments of 1.0 [m/s], and rotation was made for 1 minute at each speed and recorded by the program. At the same time, the video was taken and compared. When the speed reaches 7.5 [m/s], lower the speed in 1.0 [m/s] increments from 7.0 [m/s] and measure in the same manner.

3.7.2. Experimental method

The measurement results are shown in Table In addition, a comparison with visual measurement and the relationship with tolerance is obtained.

Table. 3.2 Results of rotational speed program

Wind Speed [m/s]	6.0	6.5	7.0	7.5
Program [rpm]	62	76	91	102
Visual Measurement [rpm]	66	76	90	100
Allowable Error [rpm]	1.32	1.52	1.8	2
Allowable Error Range [rpm]	64.7～67.3	74.5～77.5	88.2～91.8	98～102

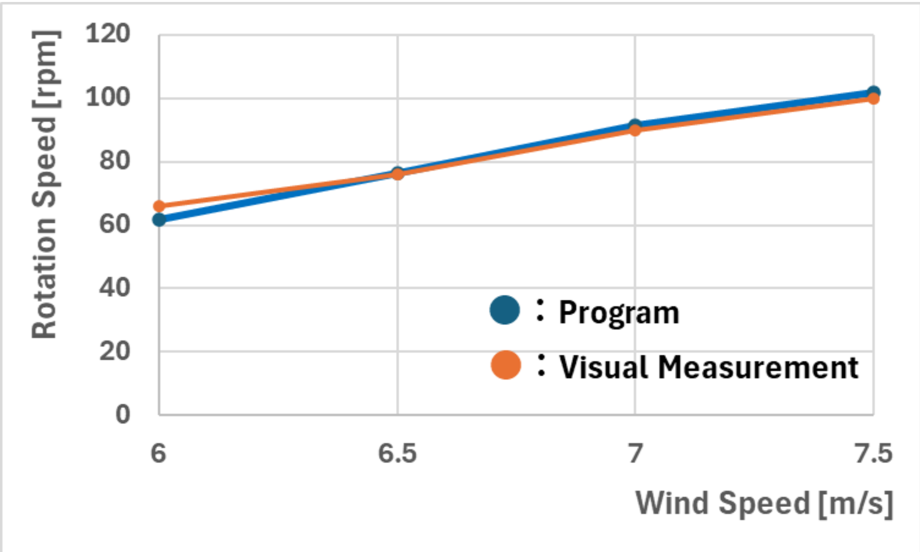


Figure. 3.19 Results of rotational speed program

Here the visual measurements were recorded as in the experiment in 3.4, taken with a tablet. The program values are the average values at the time the pictures were taken. Table 3.2 shows that the initial plan was to measure in 1.0 [m/s] increments from 0 [m/s], but since the drag-type cut-in wind speed was 6.0 [m/s], measurements were made from 6.0 [m/s] to 7.5 [m/s] in 0.5 [m/s] increments. The results showed that all values except for 6.0 [m/s] were within the permissible error range, according to the tolerance equation (1). The results confirmed that the measurement of 100 [rpm], which was the target of the measurement, was performed accurately within the error.

4. Conclusions

The purpose of this research is to effectively utilize vertical axis wind turbines as small-scale generators. Specifically, we fabricated a vertical axis wind turbine generator using wave force, designed, fabricated, and tested a drag-type wind turbine to be attached to the vertical axis wind turbine using wave force, and installed a braking device on the generator.

The vertical axis wind turbine generator using wave energy is composed of: 1. a float attached to the bottom of the float support moves up and down, and a chain attached to the float moves up and down; 2. this vertical motion is converted to horizontal shaft rotation by a sprocket and to vertical shaft rotation by a spiral bevel gear; 3. this rotation is transmitted to a shaft, and the shaft is used as a starting torque aid; and 4. the chain is attached to the float support, and the chain is attached to the float, and the float support is used as a starting torque aid, This rotation is transmitted to the shaft to assist in the starting torque. The above mechanism was fabricated and tested on the wharf to confirm rotation.

The wind turbine was designed, fabricated, and tested for characteristics. As a result, the cut-in wind speed was 6.0[m/s], sustained wind speed was 4.5[m/s], maximum output was 0.66[W] (with a load resistance of 60[Ω]), and maximum efficiency was about 2.46[%]. However, when the wind was applied from the front, some areas of weak rotational force were observed depending on the position of the blades. This may be due to the bent shaft of the wind turbine and the inappropriate shape of the blades.

Two types of brakes were initially installed, a mechanical brake and an electric brake, with the goal of stopping at 100 [rpm]. The mechanical brake consists of an aluminum disk mounted on a rotating shaft and sandwiched between bicycle brake shoes. The electric brake was to be connected to the generator with a 5[ohm] cement resistance. The problem with this braking system, however, was that the final stop had to be made by hand. Therefore, an automatic braking system that could completely stop the wind turbine was devised as a first step. To create an automatic brake system, it was necessary to accurately determine the rotational speed, so a disk with a hole in it was attached to the wind turbine's rotating shaft, and an infrared sensor and phototransistor were placed opposite each other to create a system that would determine the rotational speed based on the number of times the hole passed through the disk. The disk was designed to block the light of the infrared sensor, and the minimum size of an object that could be received by the phototransistor was found to be 4.1[mm]. The fabricated mechanism was incorporated into a power generator, and it was confirmed that the rotation speed could be measured correctly at around 100 [rpm], which was the target.

Prospects from this study are as follows. First, the shaft of the wind turbine should be improved. The second is to review the blade geometry. The part of the blade that provides drag should be curved more and the part that provides lift should be enlarged to design a blade that is confirmed to be omni-directional. Third is the completion of automatic braking. We would like to create a system in which the RPM detection mechanism is connected to the brake system, and at a set RPM the generator is properly loaded, and the brakes are activated.

As for first, we will conduct experiments at the wharf and in the wind tunnel building to observe changes in the blades as they rotate.

For the second, we will conduct experiments at cut-in wind speeds as in the main experiment to confirm the insect configuration and to confirm that the system will rotate at even lower wind speeds.

Third, we would like to conduct the same experiment in the wind tunnel building to check the operation of the brake system at various rotation speeds, not only at 100 [rpm] but also before and after that.

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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.

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.

Toshihito NAKATSUKA received his BS from the Tokyo University of Agriculture and Technology in 2021. I joined the maintenance company of wind turbine after graduation. In 2022, I joined ENEOS Renewable Energy Management Corp. (former JRE Operations Corp.). The job involves asset management, operation and maintenance of onshore wind farm. I started this research while I was in Fukushima National College of Technology and developed the base model. I've been involved in it bit by bit ever since.

IIDA holds Ph. D. from the Graduate School Engineering at the University of Tokyo. He was a readership for the Mechanical Engineering after graduation in 2001. He currently teaches as a associate professor at the Research Center for Advanced Science and Technology (RCAST) at the University of Tokyo after a readership for the Electrical Information, a lecturer for the Institute of Engineering Innovation School of Engineering and an associate professor. His professions are development of a small wind turbine, acoustic model, CFD model around wind turbines.