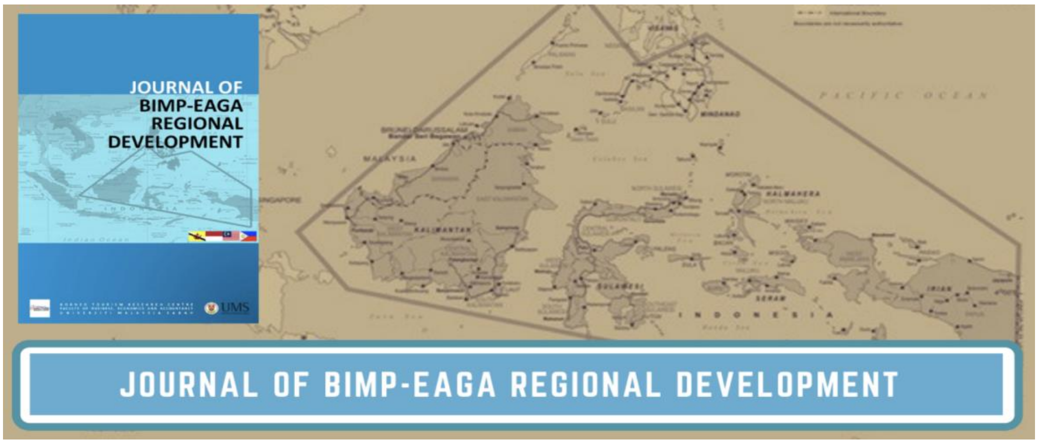

Analysis of the Operating Mechanism of the Hybrid Vertical-Axis Wind Turbine Using a Linkage Mechanism

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Abstract

Vertical-axis wind turbines are classified into lift and drag-based types. Currently, the issues facing the spread of vertical-axis wind turbines are that lift-based types have poor starting characteristics, while drag-based types produce low output at low speeds. To address these issues, we have proposed a linkage wind turbine that combines both types using a linkage mechanism. In the linkage wind turbine, the leading edges of the blades are attached evenly to the upper and lower disks, while the trailing edges are connected to the rods. These rods are connected at a location offset from the centre of rotation (rod centre), and the rod centre and rotational axis are linked by a small rod, forming a significant linkage mechanism. This mechanism enables the turbine to obtain rotational force in the same direction from both the left and right sides, as the left blade approaches a perpendicular angle to the wind direction and the right blade approaches a parallel angle.

To optimise the linkage wind turbine design, we aimed to predict the performance of all possible configurations and compare them. We have established a method to obtain arbitrary linkage wind turbines' starting and output characteristics. However, to realize this method, it is necessary to grasp each blade's position and pitch angle at any given moment, i.e., the trajectories of the blades. As a result of consideration, we decided to hypothesise the conditions that determine the trajectories of the blades by performing rotational experiments on various types of linkage wind turbines and comparing their rotational behaviour.

Therefore, we are conducting rotational experiments on a "flat plate blade linkage wind turbine (FPB wind turbine)" first, which has a flat plate airfoil, one of the most basic airfoils. We stopped the turbine in various linkage mechanism configurations, measured the minimum wind speed required to start the rotation in each "initial configuration," and observed the rotation when it began. Additionally, we continued to blow the maximum wind speed the blower can produce to the turbine in each initial configuration and observed the rotation for enough time.

The results suggest that the FPB wind turbine is essentially omnidirectional unless the initial blade position of the linkage mechanism satisfies special conditions. However, the results are influenced by the unintended presence of a cam clutch on the rotational axis, which prevents reverse rotation. In addition, if the initial configuration of the linkage mechanism was capable of starting, regardless of its specific configuration, the behaviour of the linkage mechanism of the FPB wind turbine inevitably converged and stabilised when sufficient time and wind were applied. In this stable state, it can be inferred that the FPB wind turbine can automatically maintain a pitch angle close to the ideal without a generally used active pitch control system.

Corresponding author: Yuki Sekiuchi
Received: 2/03/2025
Accepted: 14/03/2025
Revised: 13/04/2025
Published: 15/04/2025
DOI: 10.51200/jberd.v11i2.6322

Keywords: vertical-axis wind turbine; hybrid vertical-axis wind turbine; linkage wind turbine; linkage mechanism;

1. Introduction

In the global move towards carbon neutrality, expectations for wind energy are high, with the International Energy Agency [IEA] report (2019) estimating Japan's offshore wind energy potential at 9,074 TWh/year and the potential scale of offshore wind installations being considered by various organisations at 159 GW~1,621 GW in 2050 (Ishii & Sugiyama, 2023; Saito, 2023). The current commercial mainstream of wind turbines is the horizontal-axis wind turbine, a large wind turbine with a diameter of over 100 m. In contrast to horizontal-axis wind turbines, vertical-axis wind turbines generally have disadvantages regarding power generation efficiency. Still, they also have many advantages due to their negligible effect on wind direction. Moreover, vertical-axis wind turbines can be broadly categorised into two types: lift-based types and drag-based types. The drawbacks for lift-based kinds are their poor starting characteristics, while drag-based types produce smaller outputs at low rotational speeds. Overcoming these issues is essential for vertical-axis wind turbines to be widely adopted.

This research focuses on vertical-axis wind turbines and aims to develop a Hybrid Vertical-Axis Wind Turbine that compensates for and enhances the drawbacks and advantages of lift and drag-based Vertical-Axis Wind Turbines. This paper reports on developing a unique hybrid wind turbine with a linkage mechanism called the "linkage wind turbine".

There have been many studies of hybrid vertical-axis wind turbines. Much of the relevant research can be categorised as improving the self-starting characteristics, improving the structure, and even improving power generation efficiency (Shen, Gong, Xie, Lu, & Guo, 2024; Shen, Gong, Zuo, Chen, & Guo, 2024; Zhao et al., 2022). Recent developments suggest that the current performance improvements of Darius vertical-axis wind turbines mainly focus on blade and wind turbine structural optimisation and innovation of hybrid vertical-axis wind turbines. Cheng et al. (Chen, 2022; Cheng & Yao, 2022, 2023) have identified an increasing trend in studying optimal design methods for complex wind power systems, including research on machine learning-based optimal geometry design methods. Research on optimal design methods for complex wind power systems is also increasing.

To optimise the linkage wind turbine design, we aim to predict the performance of all possible variations of the turbine and compare them. So far, a method has been established to obtain any linkage wind turbine's starting and output characteristics. However, to implement this method, it is necessary to get each blade's position and pitch angle at a given moment, which is the trajectories of the blades. Therefore, this paper provides an analysis of the operating mechanism of the linkage wind turbine to derive the blade trajectory for any linkage wind turbine.

2. Overview of the linkage wind turbine

This section explains the linkage wind turbine developed in this study. This wind turbine was conceived under the idea of creating a wind turbine that can more efficiently utilise both lift and drag by combining lift and drag-based types, which was achieved by introducing a mechanism that changes the blade angle while rotating through a linkage system. Figure 1 shows the operational state of the linkage wind turbine.

In the turbine, the leading edges of the blades are evenly attached to the upper and lower discs, enabling each blade to rotate around its leading edge as the axis. On the other hand, the trailing edges are connected to rods. The node of the total five rods connected to each blade (hereafter referred to as the rod centre) are linked by a single short rod (small rod), which connects to the overall rotational axis of the turbine, forming a significant linkage mechanism. However, the rotational axis of the turbine is not continuous inside the turbine, allowing both the blades and rods to move inside the turbine without contacting the rotational axis.

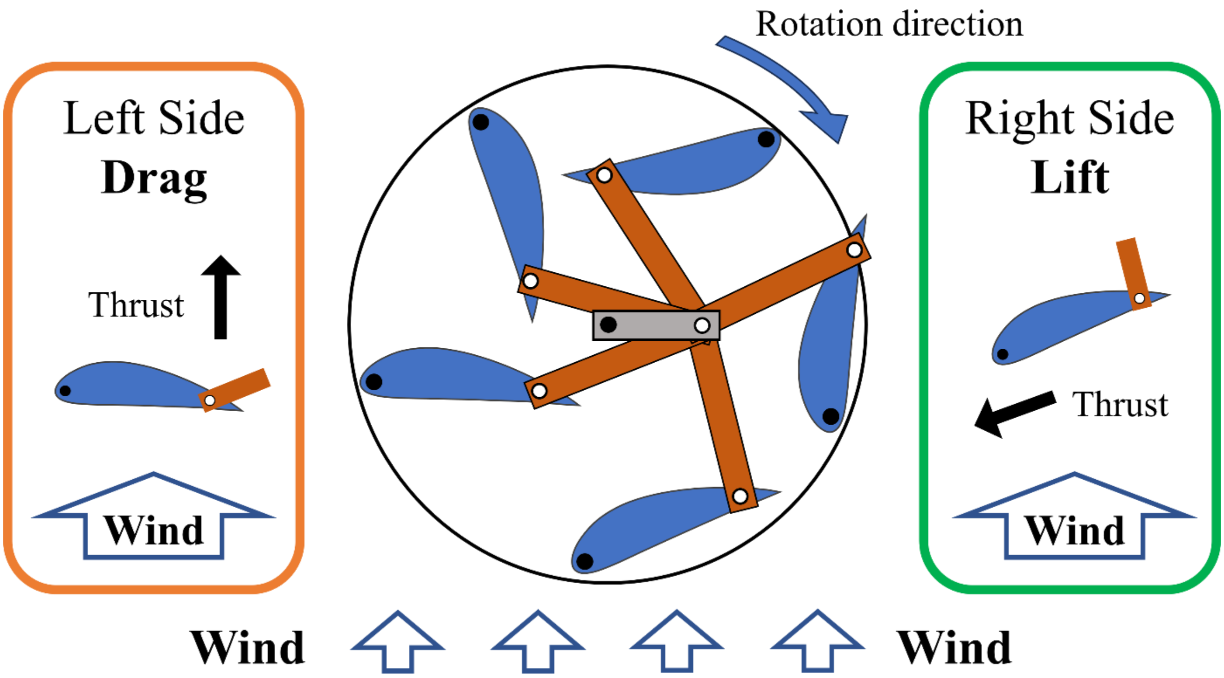

Figure 1: Operational state of the linkage wind turbine

So far, two types of linkage wind turbines with identical linkage mechanisms but different airfoil shapes have been fabricated, and no-load, load, and output tests were conducted on them. During these tests, the following behaviours were observed as the turbines rotated:

First, when exposed to the sufficiently strong wind, the prototype linkage wind turbine transitioned through the following states with increasing angular velocity:

- "Stopped State"
  The turbine is not rotating.
- "Rod Centre Rotating State"
  The state where the rod centre rotates around the axis at the same angular velocity as the turbine.
- "Rod Centre Transitional State"
  The state where the rod centre repeats rotation and subtle oscillations, is positioned between the front and the rear.
- "Rod Centre Slight Movement State"
  The state where the rod centre continues to try to remain in a fixed position.

Additionally, concerning both types of wind turbines, in the "Rod Centre Slight Movement State," the rod centre and small rod attempted to stay on the right side of the turbine from the perspective of the wind, perpendicular to the wind direction. The angles of the blades changed asymmetrically, with the blades entering from the right side to the left side, becoming closer to being perpendicular to the airflow. In contrast, those entering from the left side moved closer to being parallel to the airflow. Furthermore, although there were differences in degree depending on the airfoil types, even after reaching the "Rod Centre Slight Movement State," the rotational angular velocity of these linkage wind turbines continued to increase.

Moreover, no-load and load tests showed that the prototype linkage wind turbines exhibited better starting characteristics than lift-based types and higher rotational speeds than drag-based ones at moderate wind speeds of around 5.0 m/s (Haga, 2021). Drag-based types of vertical-axis wind turbines are known for good starting characteristics but small output at low rotational speeds. In contrast, lift-based types have higher output at high speeds but poor starting characteristics.

Based on the above, it can be considered that the prototype linkage wind turbine generates drag on the left side and lift on the right side, creating rotational forces in the same direction on both sides of the turbine. It is believed that the linkage wind turbines show better starting characteristics than lift-based turbines because they can generate enough drag on the left side of the turbine during startup. Also, it is believed that the prototype linkage wind turbines can generate some lift on the right side of the turbine. Drag-based types experience drag that inhibits rotation, but the turbine generates regular rotational forces from the lift. Even in this section, the small output typical of drag-based types improves.

In this way, a wind turbine with the linkage mechanism described above, which reaches the "Rod Centre Slight Movement State" when exposed to sufficiently strong wind from any one of directions, is defined in this paper as a linkage-type hybrid vertical-axis wind turbine, abbreviated as a linkage wind turbine.

Many aspects of the linkage wind turbine remain unclear, such as the precise conditions required for its operation and whether it can reach the "Rod Centre Slight Movement State" from any wind direction. Additionally, the reasons for the occurrence of the "Rod Centre Slight Movement State," and whether it always transitions through the "Rod Centre Rotating State" and "Rod Centre Transitional State" are yet to be fully understood.

3. Definitions

The following are newly defined terms specific to the linkage wind turbine. These terms refer to positions, distances, and angles on the horizontal plane; height is disregarded.

The terms are listed in the order of the term, the variable used, and a description of the term when necessary.

- Blade Attached End (-)
  The location where the blade is attached to the upper and lower disks.

- Blade Rod Connection Point (-)
  The location where the blade and rod are connected.

- Rod Centre (-)

- Small Rod (-)

- Wind Turbine Radius (Radius) R
  The distance from the rotation axis to the blade attached end.

- Rod Connection Distance C'
  The straight-line distance between the blade attached end and the rod connection point.

- Rod Length L
  The distance from the blade rod connection point to the rod centre.
- Small Rod Length ℓ
  The distance from the rod centre to the rotation axis.

- Blade Moveable Angle θ ($-180° \leq \theta < 180°$)
  The angle between the blade's leading edge (starting line) and the radial line is measured from the blade's attached end. The leading edge is the starting line, and the turbine radius is the radial line. The moveable angle increases when the radial line moves counterclockwise.

- Small Rod Angle φ_1 ($0° \leq \varphi_1 < 360°$)
  The angle between the small rod and the wind direction. When the small rod is perpendicular to the wind and located on the right side of the turbine from the perspective of the wind, $\varphi_1 = 0°$. With the wind direction held constant, when the small rod rotates counterclockwise as viewed from above, the magnitude of φ_1 increases.

- Small Rod - Blade Attached End Angle φ_2 ($0° \leq \varphi_2 < 72°$)
  The angle between the small rod and the first of the five radii connects the attached end of the blade and the rotation axis when the small rod moves counterclockwise while the radii remain attached.

Figure 2 summarises these terms in a single diagram. For example, in Figure 2, $R = 275$, $C' = 195$, $L = 190$, $\ell = 105$, $\varphi_1 = 210°$, and $\varphi_2 = 54°$. In Addition, define θ_f as the Blade Moveable Angle of the blade located at the central front from the perspective of the wind, $\theta_f = 30.7°$.

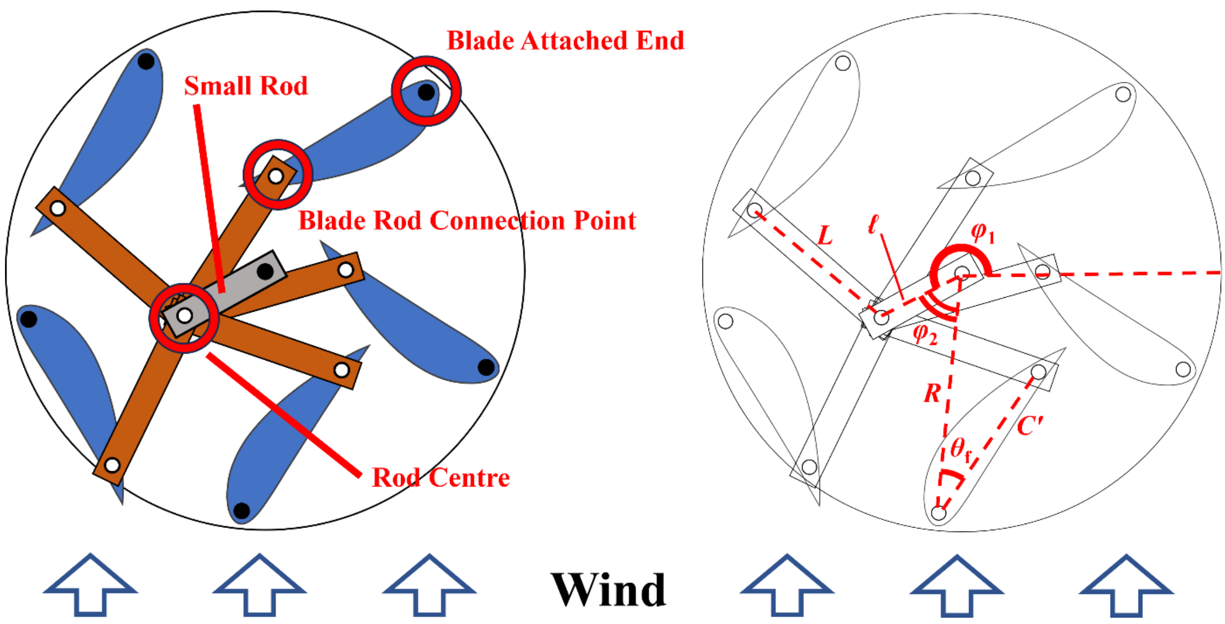

Figure 2: Diagram to explain the terms

4. Optimization Method of the linkage wind turbine

We first considered methods to optimise the airfoil and linkage mechanism of the linkage wind turbine. Since the linkage mechanism constantly changes the angle of the blades, optimising the turbine requires a different approach than the conventional vertical-axis wind turbines, where the blades remain stationary. After careful consideration, we decided to predict and compare the starting and output characteristics of all possible linkage wind turbines.

To efficiently advance the research, we decided to use existing simulation software to predict the starting and output characteristics of the linkage wind turbine. Based on our investigation, we chose QBlade, which can quickly analyse the airfoil, and SOLIDWORKS Flow Simulation and Ansys, which might allow direct dynamic analysis and can visualize the wind flow and pressure distribution.

We have developed a method to obtain any linkage wind turbine's starting and output characteristics. The process involves calculating the turbine's starting and output torque based on the blades' lift and drag coefficients and the trajectory of each blade when exposed to the wind. To begin with, I will explain how to analyse the output characteristic λ-P at any tip-speed ratio λ and wind speed V. First, we obtain the blade trajectory and lift and drag coefficients. The α-Cl and α-Cd curves necessary to get the lift and drag coefficients can be easily obtained using QBlade. Second, the lift and drag acting on the blade at any given moment are calculated based on the direction and strength of the wind hitting the blade at that time and the lift and drag coefficients. Finally, it is possible to estimate the turbine output by calculating the torque generated by the entire wind turbine at that moment. Similarly, when analysing the starting characteristics, we calculate the lift and drag acting on the blade based on the pitch angle, lift coefficient, and drag coefficient at the start-up time and then calculate the torque generated by the turbine. In the future, the power calculation method described above will be verified by comparing it with the actual measured results of the starting and output characteristics.

Another method involves performing direct dynamic analysis using SOLIDWORKS Flow Simulation or Ansys. However, it is known that 3D dynamic analysis generally takes a long time. Therefore, the previously mentioned method is more promising.

To carry out these two methods, we will first perform the following two preparatory tasks:

1. Clarify the operating mechanism of the linkage mechanism and numerically grasp each blade's position and pitch angle changes during the linkage wind turbine's rotation. This is essential for calculating the starting and output torque of the turbine from the lift and drag coefficients and the blade trajectory. Furthermore, the results of this analysis of the operating mechanism may reduce the scope of direct dynamic analysis using SOLIDWORKS Flow Simulation or Ansys.

2. Visualize the wind flow and pressure distribution inside the turbine. The direct dynamic analysis using SOLIDWORKS Flow Simulation or Ansys will be a 3D analysis. Still, the wind flow and pressure distribution will be visualised in 2D on the cross-section of the turbine perpendicular to the axis, so it is expected to be less complex. Depending on the airfoil's shape and the linkage mechanism, the wake generated by the blade when it interferes with another blade may prevent the second blade from receiving the wind it should have received, causing the turbine to fail to perform as expected. By visualising the wind flow and pressure distribution inside the turbine, we can determine whether the wake is hindering the rotation of the turbine. Additionally, suppose we can predict the trends of wind turbine parameters that cause improper wakes. In that case, we can prevent unnecessary lift, drag, torque calculations and dynamic analysis in advance.

It is believed that the analysis of the operating mechanism of the linkage mechanism and the analysis of the wind flow inside the turbine will influence each other. By clarifying the blade trajectory and researching the operating mechanism, we can better understand the wind flow and pressure distribution inside the turbine. Conversely, if we can more precisely analyse the wind flow and pressure distribution inside the turbine, the blade trajectory will also become more explicit. These analyses will also help determine the superiority or inferiority of the starting characteristics.

5. Establishing a Method for Obtaining Blade Trajectories.

Next, we considered methods to numerically grasp each blade's position and pitch angle changes in any linkage wind turbine. As a result, we decided to hypothesise the conditions that determine the trajectories of the blades by performing rotational experiments on various types of linkage wind turbines and comparing their rotational behaviour. In the rotational experiments on the linkage wind turbines, we will not only observe the rotation but also investigate the basic properties and principles common to all linkage wind turbines (such as the requirements for the existence and operating mechanism of the linkage wind turbine) and their unique properties (such as the presence of directional control).

Specifically, the method will be carried out as follows:

First, we will conduct rotational experiments on one of the prototype linkage wind turbines manufactured in 2022, which has a flat plate airfoil, one of the most basic airfoils. From this point forward, this wind turbine will be referred to as the "Flat Plate Blade Linkage Wind Turbine," hereafter abbreviated as the FPB Wind Turbine.

Second, we will manufacture several wind turbines with the linkage mechanism, all having the same radius of the FPB wind turbine, and conduct rotational experiments on each. To obtain the conditions that must be satisfied when the blades of the linkage wind turbine rotate, we need to understand how the rotation changes when parameters such as the airfoil, the small rod length/radius ratio, and the rod length/radius ratio are modified. Therefore, after manufacturing the reference linkage wind turbines that differ only in the airfoil from the FPB wind turbine, we will manufacture wind turbines modified only by one factor, such as the number of blades or the rod length, from the reference wind turbines. Since the FPB wind turbine can be disassembled into parts such as blades and rods, we need to manufacture the rods if we want to change the rod length. Thus, it is expected that new wind turbines can be fabricated in a short period, except in case of modifying the airfoil.

Finally, based on the information gathered, we will compare the rotational behaviour of all these wind turbines, including the FPB wind turbine, and predict the trajectories of the blades of any linkage wind turbine. Additional wind turbine manufacturing and rotational experiments will be conducted as necessary.

Regarding the method of manufacturing the linkage wind turbines for the rotational behaviour comparison experiments, the use of 3D printers was also discussed. The advantages of using a 3D printer include improved precision and uniformity in manufacturing wind turbines. However, since we need to create the entire wind turbine, including the base, from scratch, the total fabrication time required for the experiments is expected to be much longer than the above method. Therefore, we will use the already fabricated FPB wind turbine for the experiments.

In addition to the rotational experiments, we may conduct further analyses using SOLIDWORKS Flow Simulation or Ansys while determining the blade trajectories of the linkage wind turbines. The details are undecided, but we plan to proceed with the analysis after trialling this simulation software and reviewing the results.

6. Rotational experiments on the FPB wind turbine

To investigate the conditions determining the blade trajectory of a linkage wind turbine, we are currently conducting rotational experiments on the FPB wind turbine, which has a flat plate airfoil. This paper reports on the behaviour of the FPB wind turbine during startup and in the "Rod Centre Slight Movement State," among its rotation. In addition, we will report on the presence or absence of directional characteristics of the FPB wind turbine and discuss various aspects such as the principle behind the occurrence of the "Rod Centre Slight Movement State."

6.1. Experimental Content and Methodology

The FPB wind turbine was rotated without load using a blower, and rotational experiments were conducted. The experimental environment is shown in the following Figure 3. In these experiments, the distance from the front of the FPB wind turbine to the blower outlet is 1.5 m, and the blower base height is 1.4 m.

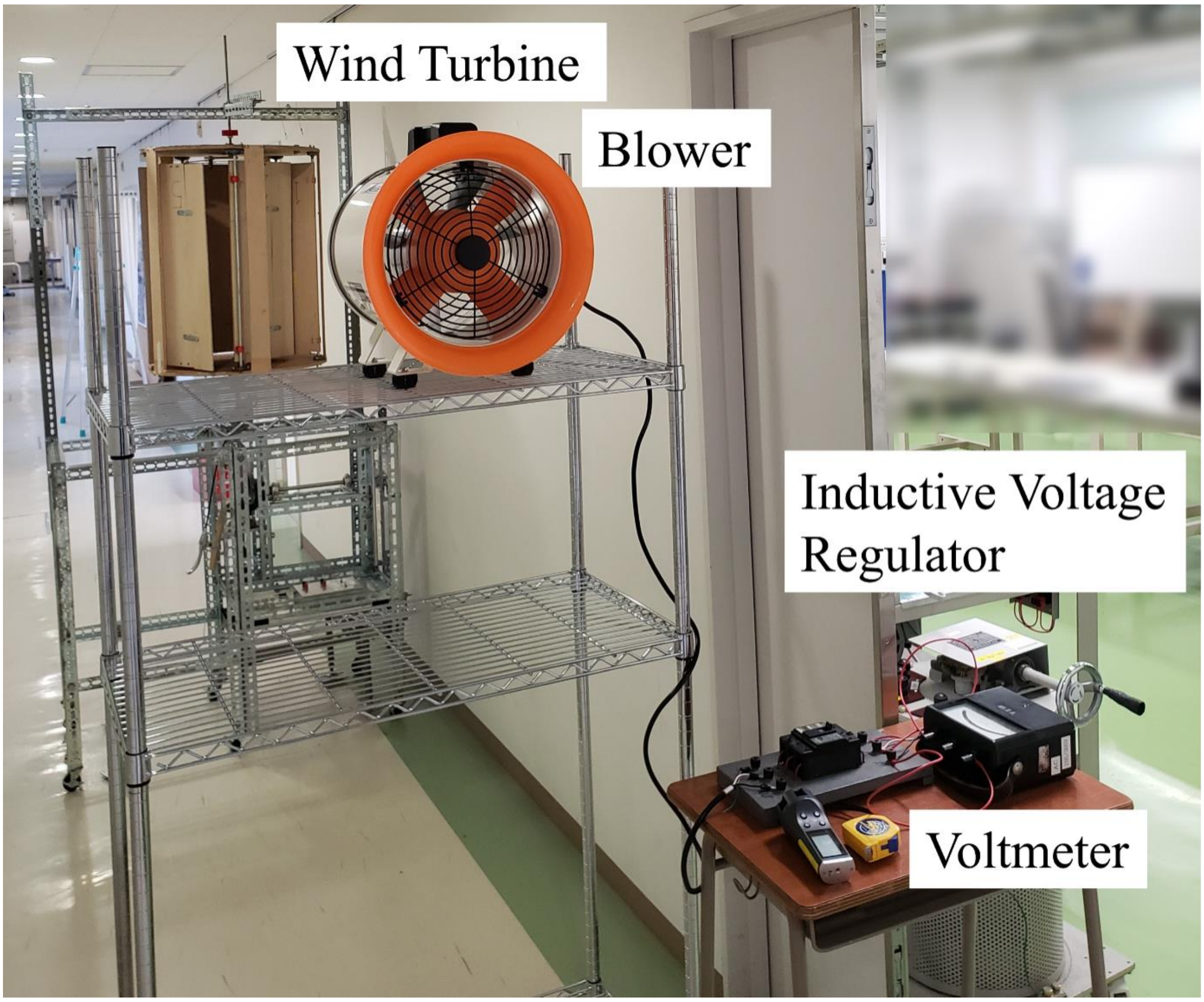

Figure 3: Experimental Environment of FPB Wind Turbine Rotation

Without using a wind tunnel, the blower was positioned so that the centre of the FPB wind turbine and the centre of the blower's air outlet were at the same height, allowing the wind from the blower to hit the turbine directly. Wind speed adjustments were made using a voltage regulator to adjust the blower voltage in increments of 10 V. Wind speed measurements were taken after the rotational experiments using a hot-wire (thermal type) anemometer. Instead of placing the turbine, the anemometer was positioned at the frontmost and central part of the turbine from the perspective of the wind, and wind speeds were measured as the voltage was increased in 10 V increments.

It has been known that the blade's movable angle of the FPB wind turbine is always positive. Therefore, by specifying φ_1 and φ_2, the positions of all the blades are uniquely determined. Thus, we can cover all possible link mechanism configurations by varying φ_1 and φ_2. φ_1 was varied in 30° increments, and φ_2 was varied in 18° increments during the experiments.

We stopped the FPB wind turbine in various link mechanism configurations, measured the minimum wind speed required to start the rotation in each “Stopped State,” and observed the rotation when it began. Additionally, we continued to blow the maximum wind speed the blower could produce to the turbine in each “Stopped State,” observing the rotation until the "Rod Centre Slight Movement State" was maintained for a certain period.

The FPB wind turbine and equipment used are as follows:

Flat plate blade linkage wind turbine

Figure 4: The appearance of FPB Wind Turbine

- External dimensions:
  590 mm (width) × 590 mm (depth)
  × 735 mm (height)
- Wind turbine radius R: 275 mm
- Chord length C: 300 mm
- Rod connection distance C': 195 mm
- Rod length L: 190 mm
- Small rod length ℓ: 105 mm
- Total weight: 11.0 kg
- Blade area: 198,000 mm²

Blower

- Manufacturer: Suiden Co., Ltd.
- Model: SJF-300RS-3
- Motor power output: 550 W
- Maximum air volume: 50 m³/min
- External dimensions: 390 mm (width) × 332 mm (depth) × 432 mm (height)
- Blade outer diameter: Φ288

Three-Phase Induction Voltage Regulator

- Manufacturer: Yamabishi Electric Co., Ltd.
- Standard: JEC-2201
- Capacity: 5 kVA
- Primary voltage: 200 V
- Adjustable voltage: 200±200 V

Voltmeter

- Manufacturer: Yokogawa Electric Corporation
- Standard: JIS C1102
- Usage terminal: 300 V
- Minimum scale: 2 V
- Allowable error range: CLASS 0.5

Anemometer

- Manufacturer: Custom Co., Ltd.
- Model: CW-60
- Range: 0.2 m/s to 20.0 m/s
- Resolution: 0.1 m/s
- Measurement accuracy: ± (5% reading + 1 digit) or 1% FS + 1 digit

6.2. Results of the rotational experiments

The experimental results are as follows:

(a). The relationship between φ_1, φ_2, and the wind speed at which the FPB wind turbine starts rotation is shown in Table 1. When (φ_1, φ_2) = (270°, 18°) or (270°, 36°), the FPB wind turbine does not rotate despite a wind speed of 13.2 m/s, which is the maximum wind speed that the fan can produce when 200 V is applied.

(b). During the startup of the FPB wind turbine, in many initial configurations of the linkage mechanism, the blade located at the left front of the perspective of the wind is pushed toward the left rear by the wind. Subsequently, the turbine starts rotating clockwise, which is the expected direction. However, for initial configurations near the region where the turbine does not start rotating, including (φ_1, φ_2) = (270°, 18°) and (270°, 36°), the turbine slightly rotates counterclockwise and then immediately stops. Thereafter, as the blade at the left front is pushed back, the rod centre moves, and the turbine starts rotating clockwise.

(c). When sufficiently strong wind is continuously applied, all FPB wind turbine except for (φ_1, φ_2) = (270°, 18°) or (270°, 36°) reach the "Rod Centre Slight Movement State," and the rod centre always attempt to stay on the right side of the turbine, perpendicular to the wind direction. In addition, even after reaching the "Rod Centre Slight Movement State," the rotational speed continues to increase.

Table 1: The relationship between φ_1, φ_2, and the wind speed at which the FPB wind turbine starts rotation

		φ_2			
		0°	18°	36°	54°
φ_1	0°	9.6	8.5	8.5	9.6
	30°	9.6	8.5	9.6	8.5
	60°	9.6	8.5	8.5	8.5
	90°	8.5	9.6	10.5	10.5
	120°	10.5	11.1	11.1	10.5
	150°	10.5	11.5	11.5	10.5
	180°	11.1	11.8	11.1	11.5
	210°	10.5	11.5	11.1	11.1
	240°	11.5	11.5	11.5	10.5
	270°	11.1	N/D	N/D	11.1
	300°	10.5	12.7	11.1	9.6
	330°	9.6	9.6	9.6	9.6

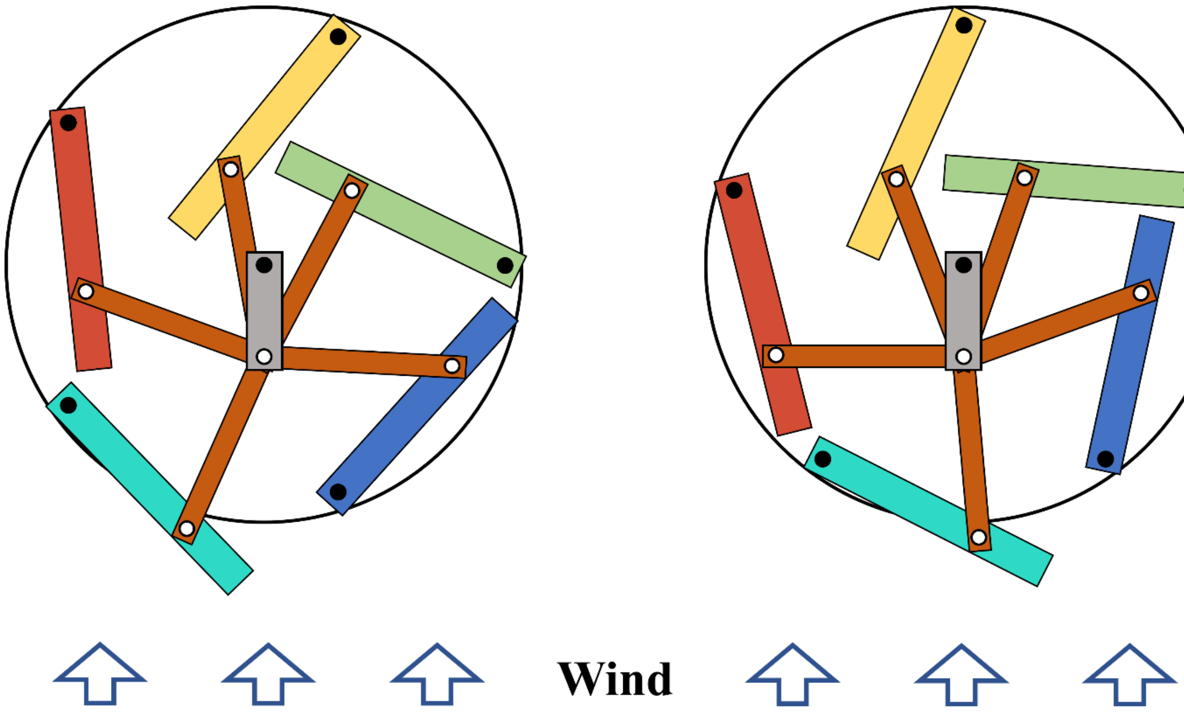

Figure 5: The FPB wind turbine appearance when (φ_1, φ_2) = (270°, 18°) and (270°, 36°)

(d). In the "Rod Centre Slight Movement State," the following sequence is likely repeating:

1. Clockwise rotation of the FPB wind turbine causes the new blade to move from the right front to the left front from the perspective of the wind.
2. As the wind pushes the blade toward the left rear, the rod centre moves toward the right rear.
3. The entire wind turbine rotates, the new blade moves to the left front, and the rod centre moves toward the right front.
4. The wind pushes the blade toward the left rear again, and the rod centre moves toward the right rear.
5. The entire wind turbine rotates, the new blade moves to the left front again, and the rod centre moves toward the right front.

6.3. Discussion

From result (a), it is found that the FPB wind turbine cannot start when the small rod is facing the wind direction and is nearly aligned with the rod located closer to the wind direction, but in most other cases, it can start.

Additionally, it is found that the cam clutch inside the wave power transmission mechanism, which is connected to the rotational axis of the flat plate blade wind turbine, influences both results (a) and (b).

Our laboratory is also studying to improve the self-starting capability of vertical-axis wind turbines by transmitting the up-and-down motion of waves to them for startup. Therefore, the turbine's base is equipped with a mechanism that transmits the up-and-down motion of the waves to its shaft. In this mechanism, the up-and-down motion of the waves is first converted into the up-and-down motion of a vertically mounted chain, which is then converted into the rotation of a horizontal axis by a sprocket, and finally into the rotation of a vertical axis by a spiral bevel gear. This spiral bevel gear is equipped with a cam clutch to disconnect the mechanism from the shaft when the turbine's rotational speed exceeds that of the spiral bevel gear, preventing the mechanism from becoming a load on the rotation of the turbine.

However, this cam clutch unintentionally prevents the reverse rotation of the FPB wind turbine. In result (a), the reason the FPB wind turbine do not rotate when $(\varphi_1, \varphi_2) = (270°, 18°)$ or $(270°, 36°)$ is likely that the cam clutch prevents the reverse rotation, and the forces attempting to rotate the rod centre counterclockwise and clockwise are in equilibrium, causing the linkage mechanism being unable to move. Furthermore, in result (b), the FPB wind turbine slightly rotates in the reverse direction because the cam clutch cannot prevent the reverse rotation by only one roller inside it but can do so afterwards.

Based on the above, when a cam clutch that prevents reverse rotation is equipped on the rotational axis, the FPB wind turbine is essentially omnidirectional. Moreover, it is unclear if all linkage wind turbines are like this, but at least the FPB wind turbine can be inferred that it rotates in clockwise and counterclockwise directions depending on the configuration of the link mechanism in the "Stopped State."

Suppose we are to operate this wind turbine without a cam clutch. In that case, a mechanism which can generate power even during reverse rotation must be incorporated into the foundation. It is necessary to develop airfoils that efficiently create drag and lift even when reversing. However, we can expect to improve the starting characteristics because of that. These experiments highlighted whether we should equip the linkage wind turbine’s axis with the cam clutch, an essential issue in studying linkage wind turbines.

Regarding result (c) and (d), the following considerations are made:

When rotation begins, each FPB wind turbine airfoil exerts force on the linkage mechanism, causing the rod centre to move actively. Although, after enough time has passed, the behaviour of the linkage mechanism converges on the "Rod Centre Slight Movement State" and continues stabilising. Given this result, it is considered that in the "Rod Centre Slight Movement State," only the essential minimum forces required to maintain the rod center in a specific position are applied, with any excess forces being eliminated.

In other words, before the "Rod Centre Slight Movement State," forces that airfoils generate are consumed to operate the linkage mechanism. However, in the "Rod Centre Slight Movement State," some forces are stably converted into torque and thrust. As can be inferred from the fact that the rotational speed continues to increase even after reaching the state, the "Rod Centre Slight Movement State" is probably sufficiently ideal.

Moreover, wind turbines generally require mechanical or electrical pitch control. In contrast, once the "Rod Centre Slight Movement State" is reached, it can be inferred that the FPB wind turbine can automatically maintain a pitch angle close to the ideal without such control. This can be considered a significant advantage of the FPB wind turbine and linkage wind turbines.

7. Conclusions

We have proposed a Linkage Wind Turbine as a new type of vertical-axis wind turbine. By introducing a linkage mechanism that changes the blade angle while rotating, we aim to compensate for the drawbacks and enhance the advantages of both lift and drag-type vertical-axis wind turbines, efficiently capturing both drag and lift. We attempted to calculate the output and starting torque of arbitrary linkage wind turbines to optimise the linkage wind turbine. However, we found that the blade trajectory was required for these calculations. Therefore, to determine the trajectories of the blades of any linkage wind turbine, we are trying to analyse how it operates. As the first step, we observed the rotation of a FPB wind turbine which has a flat plate airfoil, one of the most basic types of airfoils.

The following findings were made:

- When sufficiently strong wind is exposed to the FPB wind turbine equipped with a cam clutch that prevents reverse rotation at the rotational axis, the turbine starts rotating unless the initial configuration of the linkage mechanism satisfies special conditions. Thus, the FPB wind turbine with a cam clutch is essentially omnidirectional.

- If sufficiently strong wind is exposed to the FPB wind turbine without a cam clutch, the turbine will likely rotate in both standard and reverse directions, depending on the initial configuration of the link mechanism at “Stopped State.”

- If the initial configuration of the linkage mechanism can start, regardless of its specific configuration, the FPB wind turbine will inevitably reach the "Rod Centre Slight Movement State" when sufficient time and wind are applied.

- In "Rod Centre Slight Movement State," the behaviour of the linkage mechanism of the FPB wind turbine is converging and stabilising.

- In "Rod Centre Slight Movement State," it can be inferred that the FPB wind turbine can automatically maintain a pitch angle close to the ideal without a generally used active pitch control system.

We will continue analysing the rotation of the FPB wind turbine and aim to understand the process of reaching the "Rod Centre Slight Movement State." In addition, we analyse other linkage wind turbines with different parameters and compare their rotational behaviours. Moreover, we will investigate the impact of the presence or absence of the cam clutch on the linkage wind turbine. Ultimately, we will clarify the conditions that determine blade trajectories, calculate the starting and output characteristics of various linkage wind turbines based on these conditions, and optimise the linkage wind turbine design.

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Authors' Biographies

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Mizuyasu KOIDE 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.

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.

Makoto 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 an 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.