Type of contribution:
Editorial
▶ Research Paper
Case Study
Review Paper
Scientific Data
Report of Tech. Application

mesi
e-issn. 2798-5245

Mechanical Engineering for Society and Industry
Vol. 4, No. 1 (2024) pp 82-91
https://doi.org/10.31603/mesi.10837

Improving cross-axis wind turbine performance: A Lab-scale investigation of rotor size and blades number

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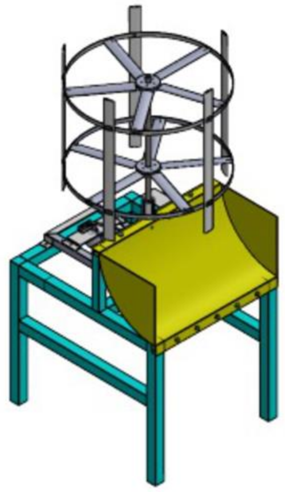

Highlights:

- Cross-axis turbines to capture wind flow from horizontal and vertical directions around multi-storey buildings have been studied.
- Performance analysis was carried out using a wind tunnel in a laboratory that was conditioned both under loading and without loading conditions.
- The time required to move from a non-rotating speed to a constant speed is affected by the wind speed and the blade pitch angle.
- The maximum power coefficient of the wind turbine was obtained at 5.2% at a wind speed of 7.6 m/s, blade pitch angle of 25°, and tip speed ratio of 0.5.

Abstract

Horizontal and vertical-axis wind turbines have long been used to generate electricity in open areas by utilizing horizontal wind flow. Under certain conditions, for example in multi-storey building areas, wind flows not only from horizontal but also vertical directions. Therefore, this research aims to develop a new turbine model known as a cross-axis to capture wind flow from horizontal and vertical directions around multi-storey buildings. Design, production, testing, and performance analysis are carried out in this project. The model is designed with a rotor diameter of 700 mm which has 5 vertical blades and 10 horizontal blades with a total height of 600 mm which is divided into two configurations, upper and lower. Performance analysis was carried out using a wind tunnel in a conditioned laboratory both in loaded and unloaded conditions. The output power of the wind turbine is measured using an electric dynamometer. The no-load test was applied to determine the time required to move from non-rotating to constant rotation at different speeds and horizontal blade angles. Meanwhile, the load test is used to determine the power coefficient at various speeds, horizontal blade pitch angles, and loads. The research results show that the time required to move from a non-rotating speed to a constant speed is influenced by the wind speed and the blade pitch angle. The power coefficient was also observed to be influenced by wind speed, blade pitch angle, and load. Furthermore, the shortest time to reach a constant rotation speed is around 20 seconds at a wind speed of 7.6 m/s and a blade pitch angle of 25°. The maximum power coefficient of the wind turbine was obtained at 5.2% at a wind speed of 7.6 m/s, blade pitch angle of 25°, and tip speed ratio of 0.5.

Keywords: Wind speed; Blade pitch angle; Wind turbine power; Power coefficient

Article info
Submitted: 2024-01-11
Revised: 2024-02-22
Accepted: 2022-02-24

Publisher
Universitas Muhammadiyah Magelang

1. Introduction

The electrical power demand in Indonesia is generally supplied by fossil fuel-powered plants. The fossil fuel resources used in these plants are reducing continuously and the consumption also has a significant negative impact on environmental sustainability. The future demand for electricity in Indonesia has been projected to increase steadily due to the advancement in industrial activities and population growth. Therefore, the use of renewable energy in electricity generation is necessary now and in the future. Indonesia has a large potential source of wind renewable energy. Utilization of wind energy into electrical energy using wind turbines [2]–[7]. The most popular types turbines are horizontal and vertical axes as presented in **Figure 1** and are both designed to transform wind energy in an open area with a horizontal flow of wind [8]. One of the problems observed is the need for heavy and complex foundation structures during their installation [8]. Moreover, the direction of wind can be reflected by the high-rise buildings in cities [2], [3], showing the need to have a wind turbine design for this type of structure.

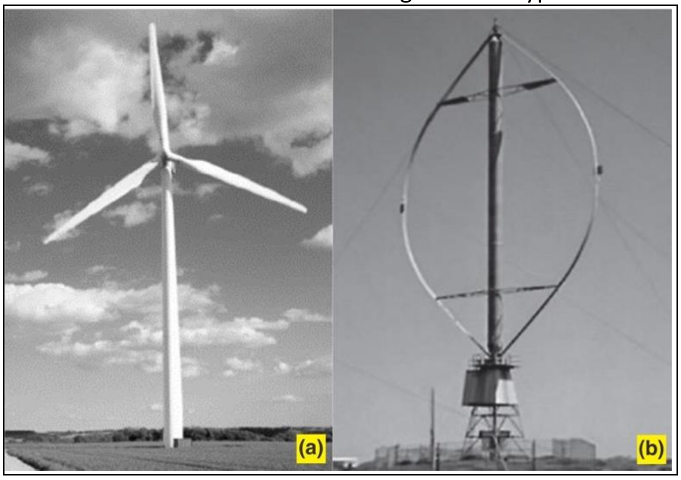

Figure 1. Popular wind turbine: (a) Horizontal axis [1]; (b) Vertical axis [2]

A new wind turbine design known as the cross axis is designed for this purpose [1] with a focus on absorbing wind energy from two directions, horizontal and vertical, based on the conditions around high-rise buildings [1], [9]–[11]. This model can be implemented through a light and simple foundation structure. It was designed with 3 vertical and 6 horizontal blades divided into two configurations including 3 at the top and another 3 at the bottom area. Moreover, the dimensions of the blade rotor was 350 mm in diameter and 350 mm in height. The turbine design has been tested in a laboratory at a wind speed of 4.5 m/s from a fan configuration and generated a maximum coefficient estimated at 2% [1]. Meanwhile, the test conducted on an integrated model produced a maximum power coefficient approximated at 26.6% [1], [12].

Therefore, this research was conducted to improve the performance of the cross-axis wind turbine model by modifying the blade area, rotor size, and deflector [13]–[15]. The process focused on having additional blades and changing the type of airfoil [16], [17]. Furthermore, the diameter and height of the rotor were increased, and the same trend was applied to the deflector component through a plate curve form. The performance of the model was tested in the educational laboratory using a wind tunnel to generate wind and the aim was to improve the coefficient.

2. Ideal Wind Turbine Performance

The ideal wind turbine model was simulated using one propeller without friction in **Figure 2** [18] and the performance was previously predicted by A. Bets in 1920. Non-friction propeller was used as the actuator disk to form the surface tracking with A used to represent the section area and V1 for the local speed. Wind pressure on the tracking surface was not continuous with those around the disk observed to have increased to pb while those behind the disk reduced to P_a and returned to free flow pressure P_∞.

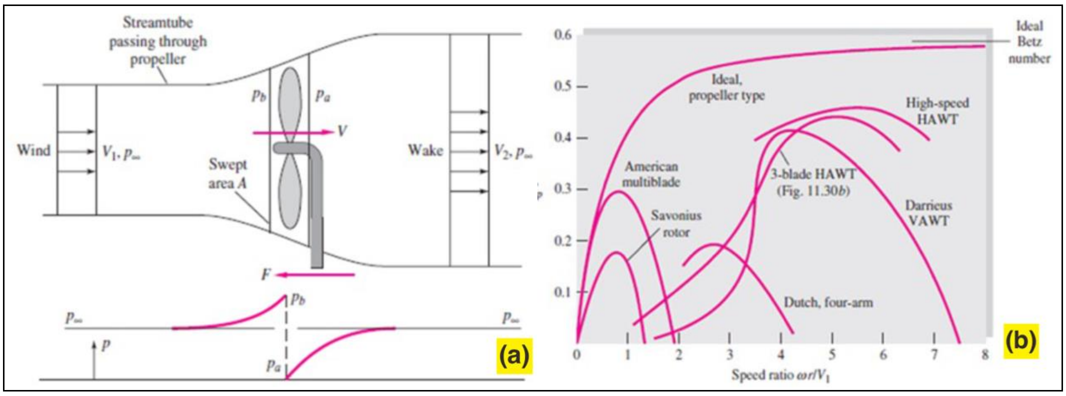

Figure 2. (a) Simulation of ideal wind turbine and (b) Performance estimation of several wind turbine to tip speed ratio [18]

Momentum and Bernoulli equations were applied to the horizontal direction based on the volume sides 1 and 2 to produce the maximum ideal wind turbine model power as follows Eq. (1) [7], [18].

$$P_{max} = \frac{8}{27} \rho A V_1{}^3 \tag{1}$$

Wind power that actually penetrated the ideal wind turbine was determined based on the total rate of wind kinetic energy in the disk section area as stated in the following Eq. (2) [18].

$$P_W = \frac{1}{2} \rho A V_1{}^3 \tag{2}$$

The maximum power coefficient probably achieved by the ideal wind turbine was determined as follows Eq. (3).

$$C_{Pmax} = \frac{P_{max}}{P_W} = 0{,}593 \tag{3}$$

Eq. (3) was based on the number or Betz limit applied to compare the ideal performance of the model with the actual wind turbine. Moreover, the performance coefficient of the ideal model and other designs is presented in **Figure 2b** [19]. The power coefficient of the actual condition was determined through the independent variable of the tip speed ratio.

3. Development of Wind Turbine

The cross-axis wind turbine model developed was designed using a rotor with 700 mm diameter and 600 mm height as shown in **Figure 3**. The rotor had 15 blades consisting of 5 in the vertical and 10 in the horizontal orientation which were further divided into two configurations including 5 in the top area and 5 in the bottom area. All the outer tip blades were connected using two circular connectors at the top and bottom areas. Meanwhile, the inner horizontal blades were connected through a threaded joint in the two-axis hubs at the top and bottom areas with an adjustable pitch angle [20]–[25].

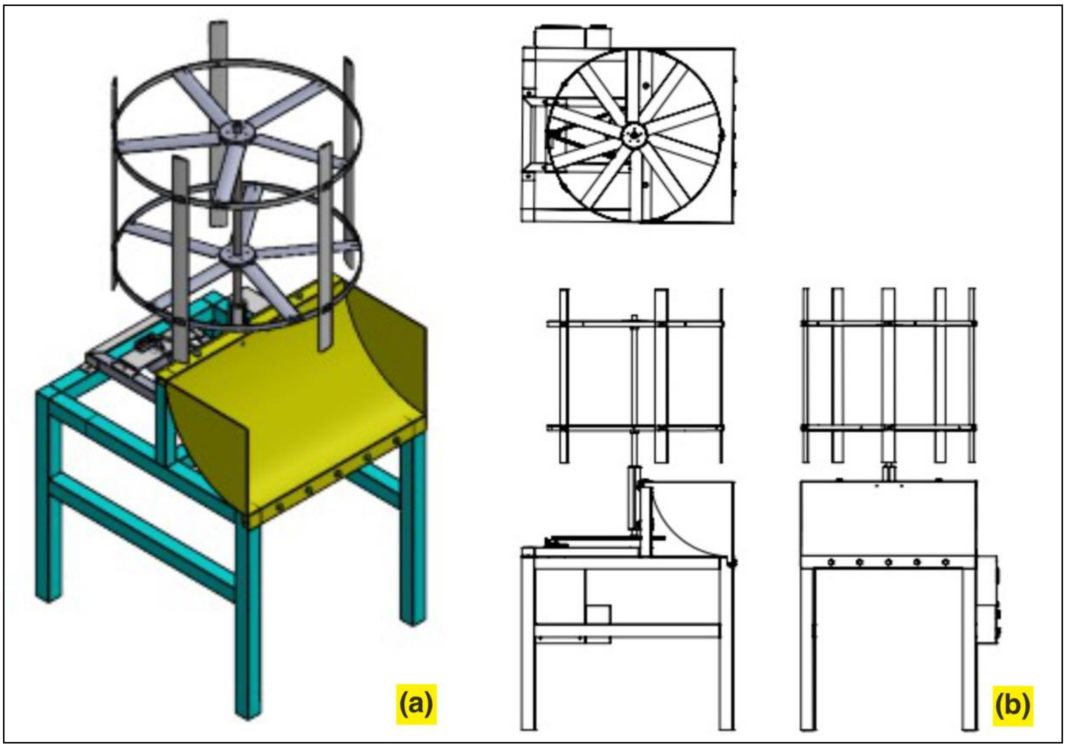

Figure 3. Cross axis wind turbine model design drawing consisting of: (a) assembly drawing and (b) view drawing

The vertical and horizontal blades were selected by considering the widely accepted airfoil standard practice [17], [19], [26]–[34]. This was indicated by the application o of 4412 NACA (National Advisory Committee of Nation Aeronautics) airfoil with a 50 mm chord line for the horizontal blades and 0015 NACA airfoil with a 50 mm chord line for the vertical blades [31], [33], [35]. All the blades were fiberglass materials considered to be lightweight, inherently strong, and cheap [34], [36], [37]. Moreover, the curved deflector attached to the bottom area as wind entrance into the turbine had a radius of 300 mm.

The rotor axis for wind turbine was supported by a steel frame construction with a square profile having two bearings. Moreover, the sprocket chain power transmission attached to the bottom tip of wind turbine to the electrical generator served as part of the dynamometer measurement tool. The dynamometer was applied to measure the electrical power generated from the shaft.

4. Facility Test Setup

The laboratory facility used to test wind turbine model is presented in **Figure 4**. The wind tunnel used in this test is an open forced type. The tunnel is about 4 m long and about 1.7 m high. The cross section of the tunnel is square with a length of 1 m and a width of 1 m. At the end of the outer side of the tunnel is installed flow straightener. The maximum wind speed generated by this wind tunnel reaches about 8.0 m/s. Wind flow rate inside the tunnel blower was regulated by an inverter. A flow straightener was also incorporated in the tunnel to ensure uniform wind speed distribution, reduce turbulence, and create a consistent pattern [14], [16], [18]. Moreover, wind speed affecting the model was measured using a calibrated Pitot tube meter as shown in **Figure 5a** and **Figure 5b**. The power generated by the shaft of the turbine was transmitted to the electrical generator through the sprocket chain operating with a speed ratio estimated at 10. This caused the rotation speed of the generator to be approximately 10 times the value for the wind turbine as confirmed through the contact tachometer in **Figure 5c**.

The output power was in the form of direct current from the electrical generator which was part of the dynamometer measurement tool. The tool had a multimeter to measure the voltage and electrical current recorded through an Arduino microcontroller device in addition to the rotation speed of the electrical generator determined based on a rotational sensor.

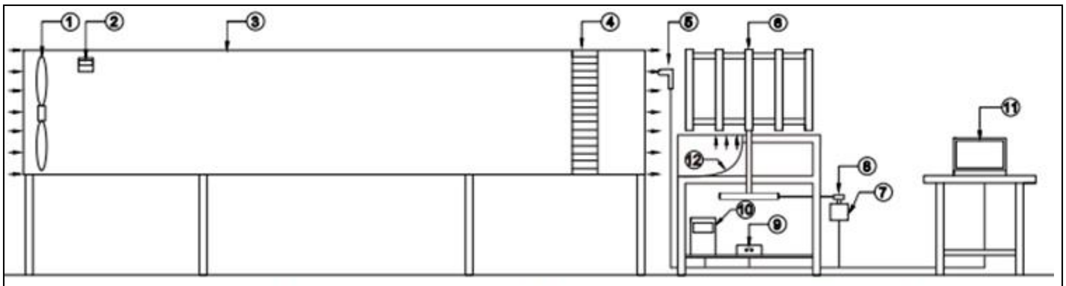

Figure 4. Testing setup

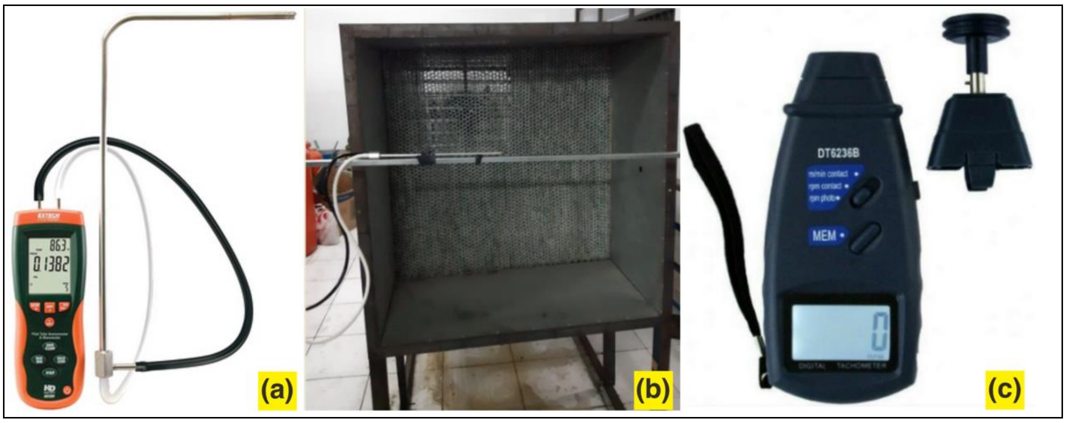

Figure 5. (a) Pitot tube, (b) Application of pitot tube during the test, and (c) Tachometer

5. Testing

The Cross-axis wind turbine model was tested in the laboratory using the tool setup presented in **Figure 4**. The performance was determined based on wind speed, blade pitch angle, and load variation. Wind speed in the tunnel was changed by adjusting the blower motor using the frequency inverter and measured through the Pitot tube meter. Meanwhile, the horizontal blade pitch angle was changed by rotating against the rotated axial line and the pitch blade was measured using a graduated arch tool.

The generator dynamometer was loaded using an electrical resistor and the load was adjusted to provide 11 different levels of workload. Under unloaded conditions, the change in wind turbine rotation from a standstill to a consistent speed was observed. Moreover, the unloading and loading observations were performed at 5 m/s and 8 m/s wind speed with the blade pitch angle varied between 10° and 45°. The loading test was conducted by varying from light to heavy load at constant wind speed and specific blade pitch angle. The increase in the load was observed to have led to a reduction in the rotation speed. The data from the test was recorded and stored one time at every 4 seconds by the Arduino microcontroller device.

6. Data Processing

The data was processed to evaluate model performance of the pitch angle, wind speed, rotation speed, wind power, electrical voltage, electrical current, and electrical power. Attention was also placed on the duration required to move from unrotated conditions to constant rotation speed, tip speed ratio, and performance coefficient using the following equations.
Rotation speed of wind turbine [18]:

$$n = in_G \tag{4}$$

Where, *i* is the speed ratio of the sprocket chain and n_G is the generator rotation speed in rpm.
Turbine shaft angle speed [18]:

$$\omega = \frac{2\pi n}{60} \tag{5}$$

ω unit is in rad/s and n is the speed rotation of wind turbine in rpm.
Tip speed ratio [18]:

$$TSR = \frac{\omega R}{U} \tag{6}$$

R is the radius of wind turbine rotor and U is wind speed.
Electrical power generated from the direct current generator [18]:

$$P = VI \tag{7}$$

V is the electrical voltage in volts and I is the electrical current in amperes.
Incoming wind power entering wind turbine [18]:

$$P_w = \frac{1}{2}\rho A U^3 \tag{8}$$

Power coefficient of wind turbine [18]:

$$C_P = \frac{P}{P_w} \tag{9}$$

The results from these tests were presented in graphical form with a focus on wind speed based on the variation of the blade pitch angle. It was applied to the change in the turbine rotation speed per time and power coefficient to tip speed ratio. The tip speed ratio expresses the change in rotational speed resulting from the load exerted on the wind turbine model at a given wind speed that is kept constant with a variable blade pitch angle. The tip speed ratio decreases as the load applied to the wind turbine model increases. The change in rotational speed of the cross-axis wind turbine model over time from rest to reaching a constant rotating speed at the lowest wind speed in the test, which is 5.0 m/s with some variation in blade pitch angle is shown in **Figure 6**. While the change in rotational speed at the highest wind speed, which is 7.6 m/s is shown in **Figure 7**.

The power coefficient of the cross axis wind turbine model to tip speed ratio at the lowest wind speed of 5.0 m/s with some variation in blade pitch angle is shown in **Figure 8** and at the highest wind speed of 7.6 m/s is shown in **Figure 9**.

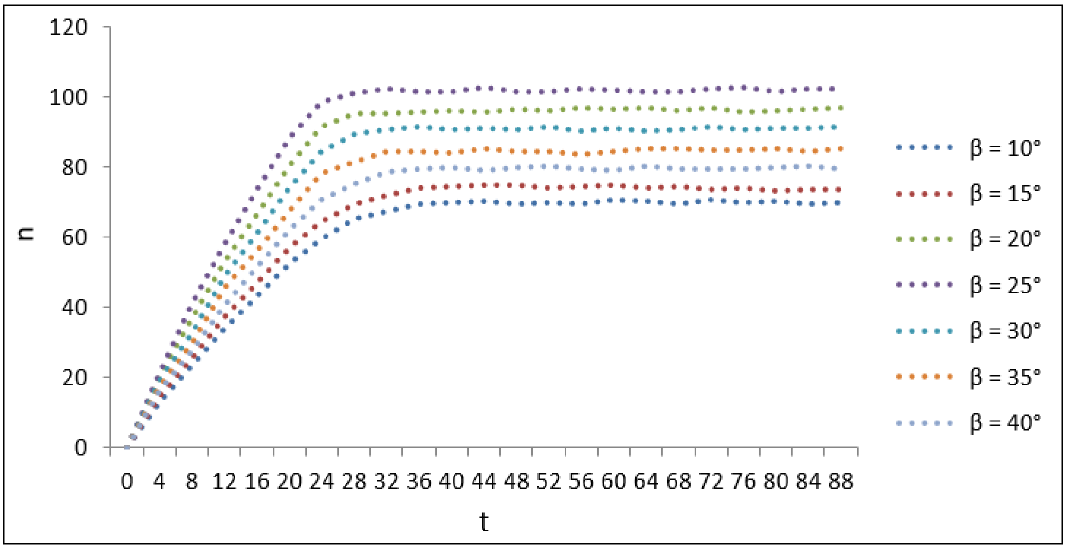

Figure 6. Change in wind turbine rotation speed per time at a wind speed of 5.0 m/s and variations in the blade pitch angle

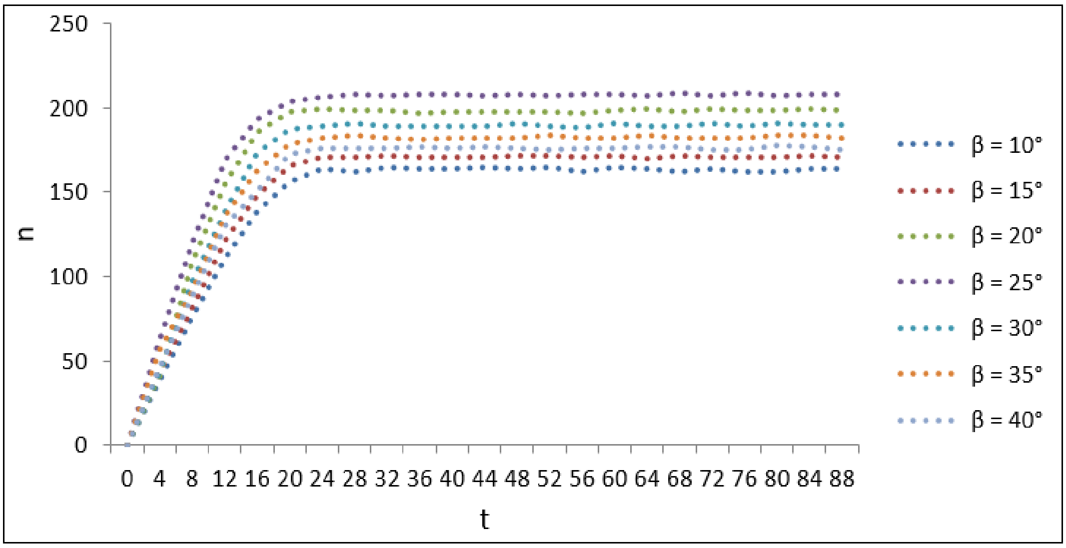

Figure 7. Change in wind turbine rotation speed per time at a wind speed of 7.6 m/s and variations in the blade pitch angle

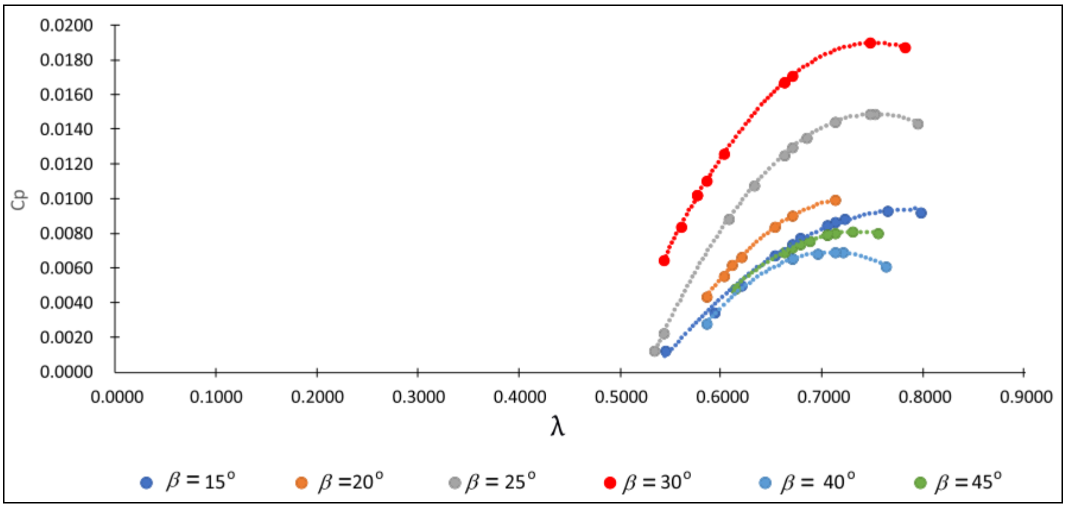

Figure 8. Power coefficient to tip speed ratio at a wind speed of 5.0 m/s and variations in the blade pitch angle

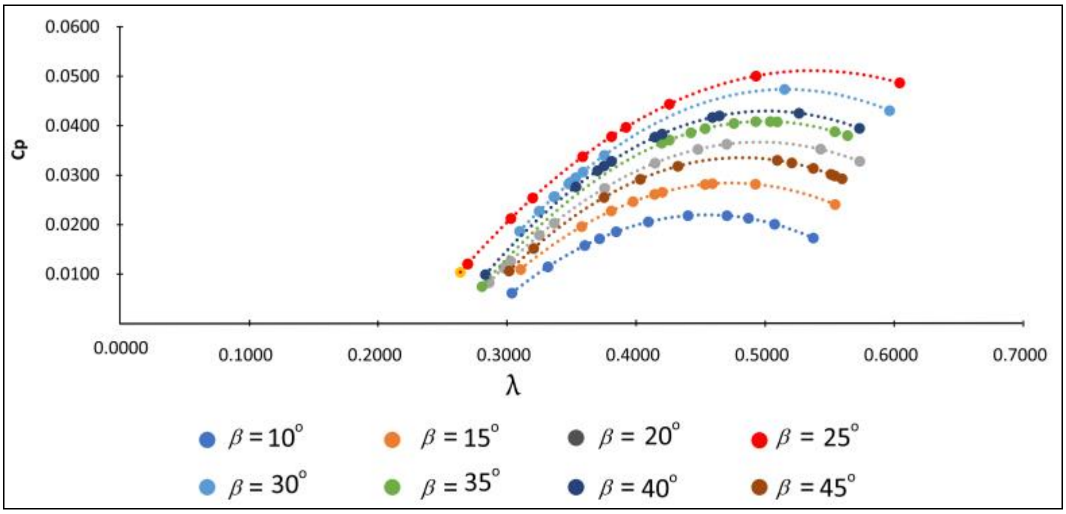

Figure 9. Power coefficient to tip speed ratio at a wind speed of 7.6 m/s and variations in the blade pitch angle

7. Discussion

The results showed that the rotation speed was influenced by wind speed and blade pitch angle while the power coefficient of the model was affected by wind speed, blade pitch angle, and load. The tangential speed of the turbine rotor and wind was compared using the term known as tip speed ratio. It was discovered that wind produced by the tunnel and sent to the vertical or horizontal blade caused lift and drag force, leading to a resultant force with radial and tangential components to the axial line of wind turbine. This resultant force caused torsion in the axis and led to the rotation of wind turbine. An increase in the tangential component, as opposed to the axial torsion in the turbine, enhanced the torsional stress which further elevated the rotation speed and power output of the turbine. The highest percentage of the resultant force tangential component was achieved at specific wind speed and pitch angles. Under these conditions, wind turbine optimally converted wind energy into electrical power, resulting in its peak performance. The highest performance of the model developed was defined based on the shortest time required to attain a constant rotation speed and the maximum power coefficient.

The pitch angle of the vertical blades remained 0° during the test but varied between 10° to 45° for the horizontal blades. At constant wind speed, the resultant force in the vertical blade depended on the position of each blade and the pitch angle over the rotation duration. The performance of the turbine in converting wind energy into electrical energy was observed to be based on wind speed and blade pitch angle. The best turbine performance was based on the highest power coefficient and shortest duration to achieve constant rotation speed.

As shown in **Figure 6** and **Figure 7**, the duration of time required to achieve a constant rotating speed from rest is shorter for higher wind speeds at the same blade pitch angle. The shortest duration of time was achieved at a wind speed of 7.6 m/s with a blade pitch angle of 25°. The power coefficient shown in **Figure 8** and **Figure 9**, the highest wind turbine model power coefficient is achieved at a wind speed of 7.6 m/s with a blade pitch angle of 25°.In every selected constant wind speed, the shortest time to achieve stable rotation speed was approximately 25° pitch angle or 20 seconds in 7.6 m/s. The maximum power coefficient recorded was 5.2 % at 7.6 m/s and 25° pitch angle.

8. Conclusion

In conclusion, based on the test data that has been analyzed and discussed, the results showed that the rotation speed and power coefficient of the cross-axis wind turbine model designed were influenced by wind speed, blade pitch angle, and load. The shortest duration of time required to achieve a constant or stable rotating speed is about 20 seconds and was achieved at a wind speed of 7.6 m/s and a blade pitch angle of 25°. The maximum power coefficient achieved is about 5.2% which occurs at a wind speed of 7.6 m/s and a blade pitch angle of 25° and tip speed ratio of 0.5. The cross-axis wind turbine model that has been developed in this study has a higher performance than the results of previous studies conducted by other researchers who are the main reference. This research recommended further refinement of the testing conditions to ensure they are nearly identical to the actual operational conditions of the cross-axis wind turbine model.

Acknowledgements

The authors are grateful to the Head of Department, Dean of Faculty of Engineering, and the Rector of the University of Pasundan Bandung as well as the Head of Department, Dean of Faculty of Engineering, and Rector of 17 Agustus 1945 University Cirebon, Indonesia, for providing funds and laboratory facility for this research.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

Funding – University of Pasundan Bandung and 17 Agustus 1945 University Cirebon.

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information – No additional information from the authors.

References

[1] W. T. Chong *et al.*, "The development and testing of a novel cross axis wind turbine," in *Proceedings Of The 3rd Aun/Seed-Net Regional Conference On Energy Engineering And The 7th International Conference On Thermofluids (Rcene/Thermofluid 2015)*, 2016, p. 030003. doi: 10.1063/1.4949283.

[2] A. Hemami, *Wind turbine technology*. Cengage Learning, 2012.

[3] T. Burton, N. Jenkins, D. Sharpe, and E. Bossanyi, *Wind energy handbook*. John Wiley & Sons, 2011.

[4] M. Casini, "Small Vertical Axis Wind Turbines for Energy Efficiency of Buildings," *Journal of Clean Energy Technologies*, vol. 4, no. 1, pp. 56–65, 2015, doi: 10.7763/JOCET.2016.V4.254.

[5] W.-T. Chong *et al.*, "Cross axis wind turbine: Pushing the limit of wind turbine technology with complementary design," *Applied Energy*, vol. 207, pp. 78–95, Dec. 2017, doi: 10.1016/j.apenergy.2017.06.099.

[6] S. Basnet, K. Deschinkel, L. Le Moyne, and M. Cécile Péra, "A review on recent standalone and grid integrated hybrid renewable energy systems: System optimization and energy management strategies," *Renewable Energy Focus*, vol. 46, pp. 103–125, Sep. 2023, doi: 10.1016/j.ref.2023.06.001.

[7] M. Ragheb and A. M., "Wind Turbines Theory - The Betz Equation and Optimal Rotor Tip Speed Ratio," in *Fundamental and Advanced Topics in Wind Power*, InTech, 2011. doi: 10.5772/21398.

[8] M. M. M. Saad, "Comparison of Horizontal Axis Wind Turbines and Vertical Axis Wind Turbines," *IOSR Journal of Engineering*, vol. 4, no. 8, pp. 27–30, Aug. 2014, doi: 10.9790/3021-04822730.

[9] A. M. M. Almotairi, F. Mustapha, M. K. A. M. Ariffin, and R. Zahari, "Synergy of Savonius and Darrieus types for vertical axis wind turbine," *International Journal of ADVANCED AND APPLIED SCIENCES*, vol. 3, no. 10, pp. 25–30, Oct. 2016, doi: 10.21833/ijaas.2016.10.005.

[10] W. Chong, M. Gwani, C. Tan, W. Muzammil, S. Poh, and K. Wong, "Design and Testing of a Novel Building Integrated Cross Axis Wind Turbine," *Applied Sciences*, vol. 7, no. 3, p. 251, Mar. 2017, doi: 10.3390/app7030251.

[11] G. Mohammed, A. Ibrahim, U. Mohammed Kangiwa, and J. Benjamin Wisdom, "Design and Testing of Building Integrated Hybrid Vertical Axis Wind Turbine," *Journal of Electrical and Electronic Engineering*, vol. 9, no. 3, p. 69, 2021, doi: 10.11648/j.jeee.20210903.12.

[12] W. T. Chong, A. Fazlizan, S. C. Poh, K. C. Pan, W. P. Hew, and F. B. Hsiao, "The design, simulation and testing of an urban vertical axis wind turbine with the omni-direction-guide-vane," *Applied Energy*, vol. 112, pp. 601–609, Dec. 2013, doi: 10.1016/j.apenergy.2012.12.064.

[13] L. N. Azadani and M. Saleh, "Effect of blade aspect ratio on the performance of a pair of vertical axis wind turbines," *Ocean Engineering*, vol. 265, p. 112627, Dec. 2022, doi: 10.1016/j.oceaneng.2022.112627.

[14] E. Acdhi, B. FAJAR TK, S. H. Winoto, H. Hermawan, and T. Permana, "Distribution of Wind Speed Before and After Through Vane Tube Type Flow Straightener," in *The 9th Asia-Pacific Symposium on Applied Electromagnetics and Mechanics (APSAEM 2018)*, 2018.

[15] W. Tian, J. Bian, G. Yang, X. Ni, and Z. Mao, "Influence of a passive upstream deflector on the performance of the Savonius wind turbine," *Energy Reports*, vol. 8, pp. 7488–7499, Nov. 2022, doi: 10.1016/j.egyr.2022.05.244.

[16] E. Achdi, B. Fajar, S. H. Winoto, and I. Lufti, "Preliminary Test on Cross Axis Type Wind Turbine," *Advanced Science Letters*, vol. 24, no. 12, pp. 9620–9622, 2018.

[17] V. Salgado, C. Troya, G. Moreno, and J. Molina, "Airfoil Selection Methodology for Small Wind Turbines," *International Journal of Renewable Energy Research*, no. v6i4, 2016, doi: 10.20508/ijrer.v6i4.4642.g6930.

[18] F. M. White, *Fluid Mechanics*, 7th Editio. McGraw-Hill, 2011.

[19] M. Ó. Óskarsdóttir, "A General Description and Comparison of Horizontal Axis Wind Turbines and Vertical Axis Wind Turbines," University of Iceland, 2014.

[20] W. Hao, A. Abdi, G. Wang, and F. Wu, "Study on the Pitch Angle Effect on the Power Coefficient and Blade Fatigue Load of a Vertical Axis Wind Turbine," *Energies*, vol. 16, no. 21, p. 7279, Oct. 2023, doi: 10.3390/en16217279.

[21] M. N. Kaya, O. Uzol, D. Ingham, F. Köse, and R. Buyukzeren, "The aerodynamic effects of blade pitch angle on small horizontal axis wind turbines," *International Journal of Numerical Methods for Heat & Fluid Flow*, vol. 33, no. 1, pp. 120–134, Jan. 2023, doi: 10.1108/HFF-02-2022-0128.

[22] M. T. Nguyen, F. Balduzzi, and A. Goude, "Effect of pitch angle on power and hydrodynamics of a vertical axis turbine," *Ocean Engineering*, vol. 238, p. 109335, Oct. 2021, doi: 10.1016/j.oceaneng.2021.109335.

[23] A. Rezaeiha, I. Kalkman, and B. Blocken, "Effect of pitch angle on power performance and aerodynamics of a vertical axis wind turbine," *Applied Energy*, vol. 197, pp. 132–150, Jul. 2017, doi: 10.1016/j.apenergy.2017.03.128.

[24] K. Sathiyamoorthy, G. Naveen Kumar, and R. Allenki, "Effect of pitch angle in the performance of wind turbine using numerical techniques," *Journal of Physics: Conference Series*, vol. 2054, no. 1, p. 012061, Oct. 2021, doi: 10.1088/1742-6596/2054/1/012061.

[25] Y. Yang, Z. Guo, Q. Song, Y. Zhang, and Q. Li, "Effect of Blade Pitch Angle on the Aerodynamic Characteristics of a Straight-bladed Vertical Axis Wind Turbine Based on Experiments and Simulations," *Energies*, vol. 11, no. 6, p. 1514, Jun. 2018, doi: 10.3390/en11061514.

[26] I. Mas'ud and R. Firdaus, "Effect Of Rotor Blade Wing Tip On Wind Turbine Performance Using Naca 0018 Blade," *Procedia of Engineering and Life Science*, vol. 1, no. 2, Jul. 2021, doi: 10.21070/pels.v1i2.979.

[27] F.-B. Hsiao, C.-J. Bai, and W.-T. Chong, "The Performance Test of Three Different Horizontal Axis Wind Turbine (HAWT) Blade Shapes Using Experimental and Numerical Methods," *Energies*, vol. 6, no. 6, pp. 2784–2803, Jun. 2013, doi: 10.3390/en6062784.

[28] R. Roshan, P. Mirshra, and M. Agrawal, "Analysis of Blade Design, Power Output and Efficiency of A Horizontal Axis Wind Turbine on A Working Model," *International Journal of Emerging Technology and Advanced Engineering ISSN*, pp. 2250–2459, 2014.

[29] Y. Sarathi, K. Patel, A. Tirkey, P. K. Sen, and R. Sharma, "Study on Wind Turbine and Its Aerodynamic Performance," *International Journal of Mechanical Engineering and Robotic Research*, vol. 4, no. 1, pp. 249–256, 2015.

[30] P. J. Schubel and R. J. Crossley, "Wind Turbine Blade Design," *Energies*, vol. 5, no. 9, pp. 3425–3449, Sep. 2012, doi: 10.3390/en5093425.

[31] M. P. R. M. S. Sao and M. P. R. Mishra, "Analysis of NACA 4415 Blade profile For Horizontal Axis Wind Turbine Using Various Aerodynamic Characteristics," *International Journal of Engineering and Technical Research (IJETR)*, vol. 7, no. 7, 2017.

[32] P. Ghiasi, G. Najafi, B. Ghobadian, A. Jafari, and M. Mazlan, "Analytical Study of the Impact of Solidity, Chord Length, Number of Blades, Aspect Ratio and Airfoil Type on H-Rotor Darrieus

Wind Turbine Performance at Low Reynolds Number," *Sustainability*, vol. 14, no. 5, p. 2623, Feb. 2022, doi: 10.3390/su14052623.

[33] M. R. Islam, L. Bin Bashar, D. K. Saha, and N. Rafi, "Comparison and Selection of Airfoils for Small Wind Turbine between NACA and NREL's S series Airfoil Familie," *International Journal of Research in Electrical, Electronics and Communication Engineering*, vol. 4, no. 2, 2019, doi: 10.5281/zenodo.3520469.

[34] W. Mangestiyono, B. Setyoko, D. Yoel Tadeus, and Yuniarto, "Mechanical Strength of 10 kW Wind Turbine Blade Utilize Glass Fiber Reinforced Plastic," *Materials Today: Proceedings*, vol. 13, pp. 71–75, 2019, doi: 10.1016/j.matpr.2019.03.190.

[35] S. Widiyanto, Sasongko Pramonohadi, and Mohammad Kholid Ridwan, "Performance Analysis of Small Horizontal Axis Wind Turbine with Airfoil NACA 4412," *International Journal of Science, Technology & Management*, vol. 2, no. 1, pp. 347–357, Jan. 2021, doi: 10.46729/ijstm.v2i1.165.

[36] I. Chikha, Y. Bouzidi, N. Tazi, S. Baklouti, and R. Idir, "Potential recovery of glass and carbon fibers from wind turbine blades through different valorization techniques," *Wind Engineering*, Sep. 2023, doi: 10.1177/0309524X231191056.

[37] A. Muratoglu and M. I. Yuce, "Performance Analysis of Hydrokinetic Turbine Blade Sections," *Advances in Renewable Energy*, vol. 2, pp. 1–10, 2015.