

FLOW RAPIDS

Design and experiment of a novel vertical axis wind turbine with adaptive Darrieus–Savonius hybrid blades

Chaojie Gu, Michael MacDonald  and Lihua Tang

Department of Mechanical and Mechatronics Engineering, The University of Auckland, 5–7 Grafton Road, Auckland, New Zealand

Corresponding authors: Michael MacDonald; Email: michael.macdonald@auckland.ac.nz, Lihua Tang; Email: l.tang@auckland.ac.nz

Received: 1 October 2025; **Revised:** 22 December 2025; **Accepted:** 19 January 2026

Keywords: adaptive blades; Darrieus–Savonius hybrid blades; self-starting; VAWTs; wind tunnel experiment

Abstract

Wind energy is a sustainable and plentiful form of clean energy. The vertical axis wind turbine (VAWT) is one type of cost-effective, acoustically quieter and lightweight turbines. The two mainstream types of VAWTs – Darrieus (lift type) and Savonius (drag type) – have contradictory strengths and weaknesses. Darrieus turbines possesses high efficiency but suffer from poor self-starting, while Savonius turbines start easily with poor aerodynamic performance. In this study, a novel VAWT with adaptive Darrieus–Savonius hybrid blades has been designed. Wind-tunnel experiments assessed the effectiveness of the proposed design and compared it against a conventional Darrieus-type rotor with similar dimensions. The results showed that the static torque coefficient was improved by over 65% and the self-starting wind speed was reduced from 8 to 6 ms^{−1}. The adaptive blades can remain in the Savonius configuration at low rotation speed, facilitating self-starting, and automatically transition to the Darrieus configuration at higher rotation speed, integrating and leveraging the strengths of the two types of VAWTs.

Impact statement

Vertical axis wind turbines are promising for urban and low-wind environments but suffer from poor self-starting and efficiency trade-offs. This study introduces a novel adaptive blade that passively switches between Savonius and Darrieus modes. A key innovation of this research is achieving automatic mode switching based on rotation speed without any additional active control mechanisms, thereby eliminating the aerodynamic drawbacks of the Savonius configuration at high tip speed ratios. It is expected that the proposed blade can facilitate self-starting and improve the wind energy utilisation rate, making it suitable for internet of things applications.

1. Introduction

Small-scale wind turbines can effectively utilise ubiquitous wind energy and allow installation in varied environments such as rooftops, between buildings and along roadsides (Kumar *et al.* 2018; Wang *et al.* 2023). Compared with large-scale systems, they also offer more manageable costs and simpler maintenance. They can work at low wind speeds and be installed in various locations in limited urban spaces, which makes them ideal for powering internet of things devices (Kumar *et al.* 2018; Li *et al.* 2021). Compared with traditional battery-based solutions, it has the advantages of autonomous energy supply, longer lifespan, eco-friendliness and lower maintenance cost (Lethien *et al.* 2019). Among various

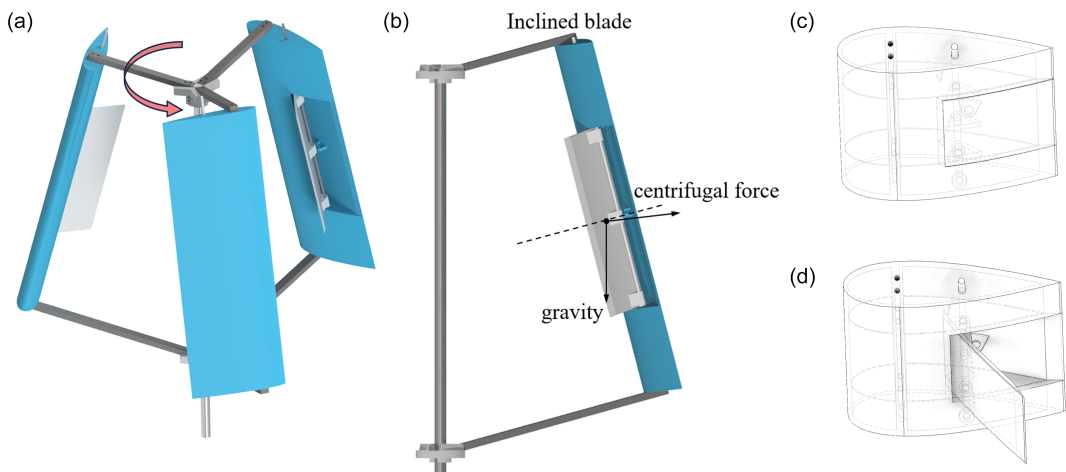


Figure 1. Schematics of (a) the proposed VAWT rotor and (b) single adaptive blade in (c) closed state and (d) open state.

wind turbine types, vertical axis wind turbines (VAWTs) are acoustically quieter, omni-directional and lightweight (Kumar *et al.* 2019). Vertical axis wind turbines can be grouped into two categories: lift-driven Darrieus turbines and drag-driven Savonius turbines (Asr *et al.* 2016; Bianchini *et al.* 2015; Islam *et al.* 2008). Darrieus VAWTs exhibit superior efficiency at high tip speed ratios (TSRs), but suffer from the poor self-starting ability (Celik 2021), usually requiring an external power source to assist in starting up. Savonius VAWTs harness wind energy based on the difference in drag force between the upstream- and downstream-rotating blade faces, but the large surface area of these blades also restricts their speed and leads to poor aerodynamic performance (Pietrykowski *et al.* 2023). Many studies have been conducted to improve the performance of VAWTs. Apart from using deflectors (Wong *et al.* 2018) and variable pitch control (Elkhoury *et al.* 2015), much attention has been focused on modifications to the blade design, such as J-shaped airfoils (Celik *et al.* 2022; Celik 2021), bio-inspired blades (Du 2016), inclined pitch axis (Guo *et al.* 2019), dual-blade configuration with auxiliary blades (Jiang *et al.* 2024; Scungio *et al.* 2016; Su *et al.* 2020) and drag-type blades with variable swept area (Pietrykowski *et al.* 2023). Although these blades are designed to adapt their shapes across varying TSRs, current studies lack the implementation of adaptive mechanisms that enable real-time shape transformation. This paper presents a design of a VAWT that can passively switch blade modes to achieve both high performance and self-starting ability. A novel adaptive blade is proposed, which can enable the turbine to remain in the Savonius configuration at low TSRs and automatically switch to the Darrieus configuration at high TSRs.

2. Design

Figures 1(a) and 1(b) present the schematic of the proposed VAWT rotor and a single adaptive blade, respectively.

To realise the hybrid blade design, the blade cross-section is configured as an openable airfoil profile, allowing adaptive geometry modifications. This adaptive blade is installed with an inclination angle relative to the vertical axis, and its state is affected by competing gravitational and inertial forces. The flap is constantly affected by gravity, keeping stably open when the rotor is stationary or rotating at a low speed, as shown in figure 1(d). In this state, the blade has a larger contact area with the wind, like the conventional Savonius VAWT, allowing the generation of a larger torque. Since the inertial force is proportional to the rotation speed squared, it can easily overcome the gravitational force and help it transition to the closed state at a high rotation speed, as illustrated in figure 1(c). In this state, the blade

operates similar to a conventional Darrieus VAWT. Thus, it is envisioned to stay in the Savonius configuration at low wind speeds and rotation speeds, and automatically switch to the Darrieus configuration at high wind speeds and rotation speeds. This combines the advantages of both the Darrieus turbine (high efficiency) and the Savonius turbine (good self-starting capability). The role of aerodynamic forces in the adaptive blade's transformation requires confirmation through wind-tunnel experiments.

A preliminary design involved a 'clamshell' blade, wherein the suction and pressure surfaces of the blade were made as two separate segments. However, manufacturing issues meant there were leading-edge gaps in the closed state, resulting in air leakage and pressure loss across the hollow clamshell blade. As such, the present configuration uses a smaller flap attached to an enclosed blade, making the blade more closely approximate a fully sealed conventional rotor blade. In addition, the inclination angle should be determined according to the actual manufactured dimensions and materials. Smaller inclination angles can result in a reduced gravitational force for opening. Since frictional forces are inevitably present during the flap opening and closing process, a smaller gravitational force may be insufficient to overcome friction and open the blade, potentially causing the flaps to become stuck and fail to move.

The experiments in this paper were conducted in a boundary-layer wind tunnel, which is a closed loop circuit wind tunnel. The dimensions of the test section are 20 m (length) $\times$ 3.6 m (width) $\times$ 2.5 m (height), and the blockage ratio of the VAWT and associated equipment is 0.97%, <1%. Thus, velocity corrections were not applied in the experiments. Tests were performed at free-stream wind speeds ranging from 5 to 8 ms⁻¹, with a baseline turbulence intensity of 1.3 %. The VAWT was positioned outside the 500 mm-thick boundary layers (Kay & Richards 2025) adjacent to the four tunnel walls. The performance of the rotor with adaptive hybrid blades is evaluated and compared using a dynamic torque sensor (model: TERED SKI-A-1N m) and a servo motor (model: YZ-42AIM30, maximum speed: 1500 RPM). To validate the feasibility and effectiveness of the proposed blades, a conventional Darrieus VAWT (conventional rotor) with the same size but straight blades was built for comparison. With reference to the common VAWT configuration (Edwards *et al.* 2012; Howell *et al.* 2010), the airfoil NACA 0022 is selected as the conventional blade profile in this study. The detailed parameters are as follows: blade chord is 100 mm, blade length is 290 mm and rotor radius is 150 mm. Both adaptive and conventional VAWTs had three blades. The blades and associated components were 3D printed with polylactic acid, and the entire rotor was supported by two ceramic bearings.

3. Experiment set-up

Figures 2(a) and 2(b) show the actual appearance of the two blade types in the wind tunnel. To ensure a valid comparison, the proposed rotor has the same swept area and blade dimensions as the conventional rotor. In the adaptive blade design, a small flap is set at the mid-chord location of the airfoil. The flap has a length of 150 mm, a width of 52 mm and a thickness of 2 mm. The beam of the adaptive blade is inclined at an angle of 15° to the horizontal plane, realising the natural opening of the flap due to gravity. In addition, a torsional spring is installed between the flap and the main blade to assist in reopening the flap when the rotation speed is reduced.

Three experiments were conducted: a static torque test, a dynamic torque test and a self-starting test. In the static (non-rotating) torque test, the adaptive blade opens like the drag-type VAWTs. The entire shaft is fixed by the motor, and the static torques of two types of rotors were measured by the torque sensor at different wind speeds. As illustrated in figure 2(c), the azimuthal angle between the blade and the incoming flow is defined accordingly. At the initial position (azimuthal angle = 0°), the most upstream blade is oriented perpendicularly toward the incoming flow. Measurements were taken from 0° to 120° with an increment of 10°, and the rotation angle is controlled by the turntable positioned at the bottom of the wind tunnel. Next, in the dynamic torque test, the rotation speed of the rotor is controlled at a constant value by the motor. The torque sensor measures the instantaneous torque acting on the shaft: a positive torque indicates that the rotor is driving the motor (i.e. generating power), while a negative torque indicates that the motor is driving the rotor. At a given wind speed, multiple operating

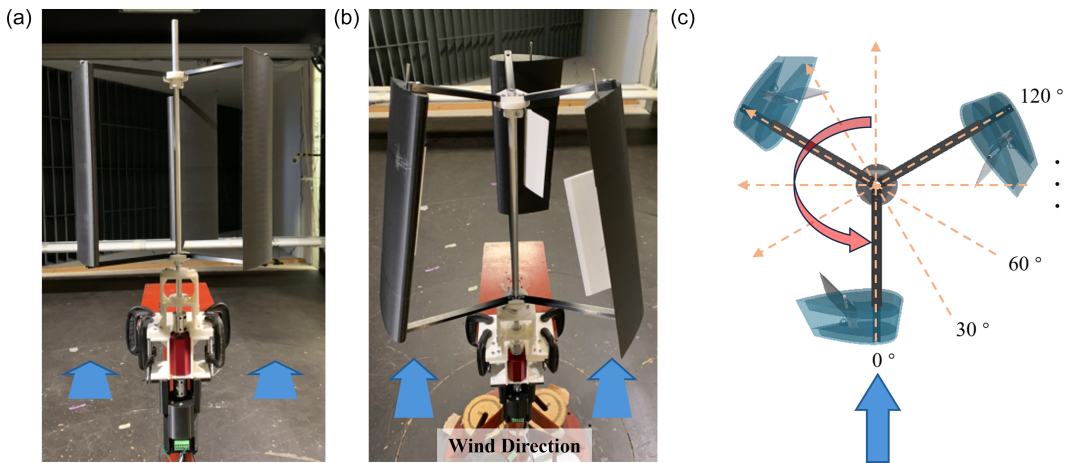


Figure 2. Schematics of (a) the conventional rotor and (b) the adaptive rotor, and top view (c) of the rotor with azimuthal angle definition. Wind direction shown by the blue arrows.

conditions corresponding to different TSRs are tested. For each TSR, torque data are recorded for over 30 s and then averaged. These averaged torque values, together with the TSRs, are used to calculate the power coefficients, which are then plotted as the power curve of the rotor. The negative torque region in the power curve corresponds to the dead band, where the turbine cannot self-sustain rotation without external input. Finally, in the self-starting test, the rotor operated in a free-spinning mode without the motor. Upon the application of a specified wind speed, the time history of the rotor's rotation speed from the static state was recorded.

To assess the VAWTs' performance, the following dimensionless parameters of TSR, power coefficient (C_p) and torque coefficient (C_t) are used in this study:

$$\text{TSR} = \frac{\text{RPM} \cdot 2\pi r}{60 \cdot u}, \quad C_p = \frac{P}{\frac{1}{2} \rho A u^3}, \quad C_t = \frac{T}{\frac{1}{2} \rho A r u^2}, \quad (3.1)$$

where RPM is the rotation speed in revolutions per minute, r is the rotor radius (m), u is the wind velocity (ms^{-1}), $P = T \times (\text{RPM}/60) \times 2\pi$ is the power (W), ρ is the air density (kg m^{-3}), A is the swept area of the rotor (m^2) and T is the torque (Nm). In the following tests, the rotor radius r is 0.15 m, and the swept area A is 0.87 m^2 . In addition, the laboratory's thermal regulation system maintained a stable ambient temperature of 18°C , corresponding to an approximate air density of 1.212 kg m^{-3} .

4. Results

4.1. Static torque test

Figure 3(a) shows the static torque coefficients of two VAWTs at an incident wind speed of 6 ms^{-1} . The proposed adaptive rotor exhibits a higher overall starting torque as compared with its conventional counterpart. In addition, the conventional rotor exhibits a wider range of azimuthal angles with near-zero torque, indicating a lower likelihood of initiating rotation. The torque curves of the two blade types display different trends: the conventional rotor reaches its maximum negative torque at an azimuthal angle of 90° , where the adaptive rotor achieves its maximum starting torque. This is because the flap of one of the adaptive blades is fully opened at 90° by the wind, allowing it to capture the maximum torque from the wind. The adaptive rotor reaches its minimum positive torque at azimuthal angles of 30° and 40° , for a similar reason as mentioned above. At an azimuthal angle of 30° , the adaptive blades located on the windward side (at 270° azimuth) are opened, as shown in figure 3(b), thereby increasing aerodynamic drag and reducing torque compared with the conventional rotor.

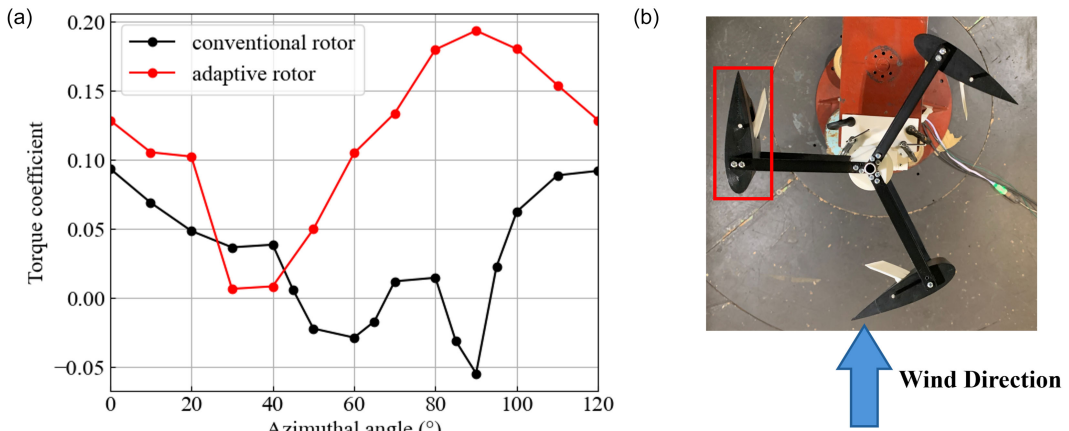


Figure 3. (a) Static torque coefficient at different azimuthal angles and (b) blade status photograph at 30° azimuthal angle at the incident wind speed of 6 ms^{-1} .

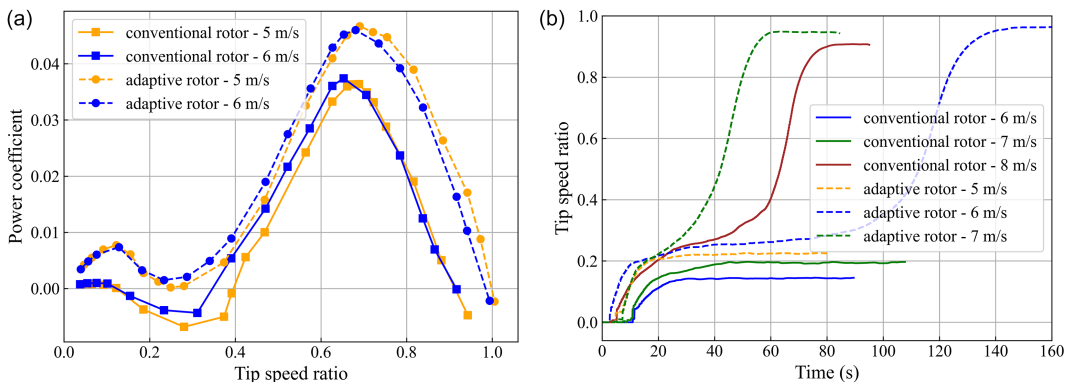


Figure 4. (a) Performance and (b) self-starting behaviour comparison of conventional and adaptive rotors at different wind speeds.

Based on the average values of these static torque coefficients ($C_{t,ave}$) within the 120° range, the adaptive rotor ($C_{t,ave} = 0.114$) achieves an increase of 0.088 compared with the conventional rotor ($C_{t,ave} = 0.026$) at 6 ms^{-1} . A larger starting torque can help the static rotor overcome frictional resistance and begin to rotate. However, the starting torque is only one aspect of the VAWT's self-starting ability and it cannot guarantee that the rotor will accelerate to a high TSR. A comprehensive assessment of self-starting performance requires the consideration of its overall aerodynamic behaviour.

4.2. Dynamic torque test

The comparison of the two rotors' aerodynamic performance is presented in figure 4(a), wherein the rotor spins at a fixed rotation speed. It can be seen that, at the same wind speed, the adaptive rotor has a wider effective TSR range for generating useful power compared with the conventional rotor, which surpasses the normal TSR range of conventional Savonius rotors. At high rotation speeds, the power curve trends of both rotors are closely aligned, indicating that the adaptive blade, when in its closed state, follows a similar operation pattern as the conventional blade – characterised by lift-driven performance. It is worth noting that, due to the addition of a torsion spring, when the flap remains in a sustained closed state, a small gap persists between the trailing edge of the flap and the main blade body until the inertial

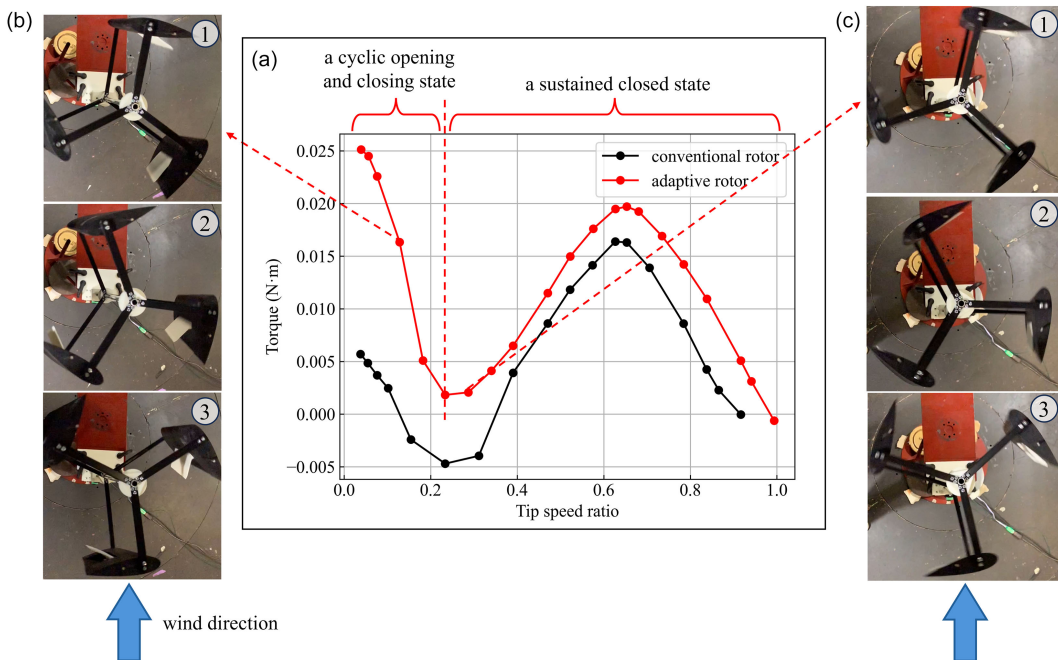


Figure 5. (a) Torque curve of the adaptive blade at various rotation speeds under a wind speed of 6 ms^{-1} and corresponding operational states at TSR of: (b) 0.131 and (c) 0.288.

force generated by rotation becomes sufficiently large. This small gap and the inclination of the blade may contribute to the observed deviation in the power curve. The detailed adaptive blade's behaviour at rotation speeds of 30, 60, 90, 150 and 250 RPM under a wind speed of 6 ms^{-1} is demonstrated in the supplementary videos. The video shows that, at high rotation speeds, the flaps close, and the blade maintains an airfoil shape throughout the rotation cycle. Therefore, the adaptive blade is indeed capable of operating like a conventional Darrieus blade at high rotation speeds.

4.3. Self-starting test

Figure 4(b) presents the time-varying TSR results of the two rotors at different wind speeds, wherein the rotors are able to freely spin with no motor. It can be clearly observed that the conventional rotor at 8 ms^{-1} escaped the plateau stage (Celik 2021) and reached its steady-state operating condition, which provides the evidence of successful self-starting. Compared with the conventional blade, the adaptive rotor exhibits a stronger self-starting ability. The conventional rotor can only achieve self-starting at a wind speed of 8 ms^{-1} , while the adaptive rotor can self-start at just 6 ms^{-1} . Moreover, the adaptive rotor experienced a significantly shorter plateau stage at 7 ms^{-1} than that of the conventional rotor at 8 ms^{-1} .

During the wind-tunnel testing, we observed that the adaptive blades exhibited two distinct operational states: (i) at low TSRs, the flap of blade alternates between opening (when travelling downwind) and closing (when travelling upwind); (ii) at high TSRs, the blade remains closed over a full rotation, achieving performance comparable to that of a conventional straight-bladed Darrieus rotor. Using the case of a 6 ms^{-1} wind speed as an example, figure 5 illustrates the adaptive behaviour of the blade during rotation. At the low rotation speed, the blade operates in a cyclic opening and closing state. With increasing rotation speed, the opening amplitude progressively diminishes until the flap does not reopen. As shown in figure 5(b), the flaps remain in a cyclic opening and closing state at 50 RPM (TSR = 0.131), where the adaptive rotor can generate a much higher torque compared with a conventional rotor, which facilitates self-starting. It can be inferred that the flap opening on the leeward side increases aerodynamic drag, and this drag drives the rotor to rotate in the positive direction. At 110 RPM (TSR = 0.288),

the flaps are almost closed (figure 5c), resembling the configuration of a conventional Darrieus blade where the torque obtained by the adaptive rotor is very close to that of the conventional rotor.

Both the self-starting and shutdown videos of the adaptive rotor have been demonstrated in the supporting materials. As the rotation speed increases, the blade transitions automatically between states. Moreover, in windless conditions, the flap can return to its initial open state due to the inclined orientation of the blades. This further validates that the envisioned passive control mechanism is feasible and effective.

5. Conclusion

In summary, this paper designs and manufactures an adaptive Darrieus–Savonius hybrid blade. The adaptive blade exploits gravity to passively open a flap at low rotation speeds and automatically closes the flap by centrifugal force as rotation speed increases. A series of wind-tunnel experiments were conducted in three stages to verify the blade's functionality. The results revealed that, compared with the conventional Darrieus blade, the proposed adaptive blade can obtain a higher starting torque, exhibit stronger self-starting ability and achieve similarly high efficiency even at high TSRs. It achieves passive control, rather than relying on active control mechanisms.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/flo.2026.10043>.

Acknowledgements. We would like to thank A. Zaki for his technical support with the wind-tunnel experiments.

Data availability statement. The data that support the findings of this study are openly available by contacting the authors directly via email.

Author contributions. Conceptualisation: C.G; L.T. methodology: C.G; M.M; L.T. data curation: C.G. data visualisation: C.G. writing – original draft: C.G. writing – review and editing: C.G; M.M; L.T. supervision: M.M; L.T. All authors approved the final submitted draft.

Funding statement. This work is supported by a PhD scholarship from the China Scholarship Council (No. 202408320107).

Competing interests. The authors declare that they have no conflict of interest.

Ethical statement. The research meets all ethical guidelines, including adherence to the legal requirements of the study country.

References

- Asr, M. T., Nezhad, E. Z., Mustapha, F., & Wiriadidjaja, S. (2016). Study on start-up characteristics of H-Darrieus vertical axis wind turbines comprising NACA. 4-digit series blade airfoils. *Energy*, 112, 528–537. <https://doi.org/10.1016/j.energy.2016.06.059>
- Bianchini, A., Ferrara, G., & Ferrari, L. (2015). Design guidelines for H-Darrieus wind turbines: Optimization of the annual energy yield. *Energy Conversion and Management*, 89, 690–707. <https://doi.org/10.1016/j.enconman.2014.10.038>
- Celik, Y. (2021). *Aerodynamics and self-starting of vertical axis wind turbines with J-shaped aerofoils* (Doctoral dissertation). University of Sheffield. <https://etheses.whiterose.ac.uk/id/eprint/29030/>
- Celik, Y., Ingham, D., Ma, L., & Pourkashanian, M. (2022). Design and aerodynamic performance analyses of the self-starting H-type VAWT having J-shaped aerofoils considering various design parameters using CFD. *Energy*, 251, 123881. <https://doi.org/10.1016/j.energy.2022.123881>
- Du, L. (2016). *Numerical and experimental investigations of Darrieus wind turbine start-up and operation* (Doctoral dissertation). Durham University. <https://etheses.dur.ac.uk/11384/>
- Edwards, J. M., Angelo Danao, L., & Howell, R. J. (2012). Novel experimental power curve determination and computational methods for the performance analysis of vertical axis wind turbines. *Journal of Solar Energy Engineering*, 134(3), 031008. <https://doi.org/10.1115/1.4006196>
- Elkhoury, M., Kiwata, T., & Aoun, E. (2015). Experimental and numerical investigation of a three-dimensional vertical-axis wind turbine with variable-pitch. *Journal of Wind Engineering and Industrial Aerodynamics*, 139, 111–123. <https://doi.org/10.1016/j.jweia.2015.01.004>

- Guo, J., Zeng, P., & Lei, L. (2019). Performance of a straight-bladed vertical axis wind turbine with inclined pitch axes by wind tunnel experiments. *Energy*, 174, 553–561. <https://doi.org/10.1016/j.energy.2019.02.177>
- Howell, R., Qin, N., Edwards, J., & Durrani, N. (2010). Wind tunnel and numerical study of a small vertical axis wind turbine. *Renewable Energy*, 35(2), 412–422. <https://doi.org/10.1016/j.renene.2009.07.025>
- Islam, M., Ting, D. S. K., & Fartaj, A. (2008). Aerodynamic models for Darrieus-type straight-bladed vertical axis wind turbines. *Renewable and Sustainable Energy Reviews*, 12(4), 1087–1109. <https://doi.org/10.1016/j.rser.2006.10.023>
- Jiang, T., Zhao, Y., Wang, S., Zhang, L., & Li, G. (2024). Aerodynamic characterization of a H-Darrieus wind turbine with a Drag-Disturbed Flow device installation. *Energy*, 292, 130522. <https://doi.org/10.1016/j.energy.2024.130522>
- Kay, N., & Richards, P. (2025). Comparing the upper- and lower-surfaces of a NACA0012 in turbulence at low Reynolds numbers. *Aerospace Science and Technology*, 166, 110578. <https://doi.org/10.1016/j.ast.2025.110578>
- Kumar, P. M., Sivalingam, K., Narasimalu, S., Lim, T.-C., Ramakrishna, S., & Wei, H. (2019). A review on the evolution of darrieus vertical axis wind turbine: Small wind turbines. *Journal of Power and Energy Engineering*, 7(4), 27–44.
- Kumar, R., Raahemifar, K., & Fung, A. S. (2018). A critical review of vertical axis wind turbines for urban applications. *Renewable and Sustainable Energy Reviews*, 89, 281–291. <https://doi.org/10.1016/j.rser.2018.03.033>
- Lethien, C., Le Bideau, J., & Brousse, T. (2019). Challenges and prospects of 3D micro-supercapacitors for powering the internet of things. *Energy & Environmental Science*, 12(1), 96–115. <https://doi.org/10.1039/C8EE02029A>
- Li, S., Li, Y., Yang, C., Wang, Q., Zhao, B., Li, D., & Xu, W. (2021). Experimental investigation of solidity and other characteristics on dual vertical axis wind turbines in an urban environment. *Energy Conversion and Management*, 229, 113689. <https://doi.org/10.1016/j.enconman.2020.113689>
- Pietrykowski, K., Kasianantham, N., Ravi, D., Jan Gęca, M., Ramakrishnan, P., & Wendeker, M. (2023). Sustainable energy development technique of vertical axis wind turbine with variable swept area – An experimental investigation. *Applied Energy*, 329, 120262. <https://doi.org/10.1016/j.apenergy.2022.120262>
- Scungio, M., Arpino, F., Focanti, V., Profili, M., & Rotondi, M. (2016). Wind tunnel testing of scaled models of a newly developed Darrieus-style vertical axis wind turbine with auxiliary straight blades. *Energy Conversion and Management*, 130, 60–70. <https://doi.org/10.1016/j.enconman.2016.10.033>
- Su, H., Dou, B., Qu, T., Zeng, P., & Lei, L. (2020). Experimental investigation of a novel vertical axis wind turbine with pitching and self-starting function. *Energy Conversion and Management*, 217, 113012. <https://doi.org/10.1016/j.enconman.2020.113012>
- Wang, H., Xiong, B., Zhang, Z., Zhang, H., & Azam, A. (2023). Small wind turbines and their potential for internet of things applications. *iScience*, 26(9). <https://doi.org/10.1016/j.isci.2023.107674>
- Wong, K. H., Chong, W. T., Sukiman, N. L., Shiah, Y.-C., Poh, S. C., Sopian, K., & Wang, W.-C. (2018). Experimental and simulation investigation into the effects of a flat plate deflector on vertical axis wind turbine. *Energy Conversion and Management*, 160, 109–125. <https://doi.org/10.1016/j.enconman.2018.01.029>