Bio-Inspired Hybrid Dragonfly–Owl Wind Turbine Blade for Enhanced Energy Harvesting under Low Wind Speed Conditions

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ABSTRACT

Efficient utilization of low-speed wind resources remains a significant challenge for small- and medium-scale wind turbines because of low starting torque, premature flow separation, and aerodynamic losses. This study presents the design and aerodynamic evaluation of a bio-inspired dragonfly–owl wind turbine blade developed to improve energy extraction under low wind speed conditions. The blade combines dragonfly-inspired corrugated surface geometry with owl-inspired leading-edge serrations and trailing-edge fringes, integrating complementary passive flow-control mechanisms within a single blade configuration. A three-dimensional blade model was developed using computer-aided design (CAD) software and investigated using computational fluid dynamics (CFD) under steady-state operating conditions representative of low-speed wind environments. The aerodynamic characteristics of the hybrid blade were compared with those of a conventional blade based on velocity distribution, pressure contours, turbulence intensity, lift coefficient, drag coefficient, lift-to-drag ratio, and power coefficient. The numerical analysis indicated improved airflow attachment and modified vortex development over the biomimetic blade surface, together with improved pressure distribution and reduced wake disturbances. The combined corrugation and serration features enhanced the aerodynamic behavior of the blade by promoting more stable flow structures and delaying flow separation. These effects contributed to improved lift generation and aerodynamic efficiency, thereby indicating enhanced starting and low-speed operating characteristics compared with the conventional configuration. The owl-inspired serrated leading edge also demonstrated potential for mitigating unsteady wake structures and aerodynamic noise. The results indicate that combining dragonfly and owl morphological characteristics can provide an effective flow-control strategy for low-speed wind energy applications. The biomimetic blade offers a promising approach for developing compact, efficient, and environmentally compatible wind turbines for distributed renewable energy generation.

Keywords: Bio-inspired Wind Turbine; Hybrid Biomimetic Blade; Dragonfly–Owl Inspired Design; Low Wind Speed; Wind Energy Harvesting.

INTRODUCTION

The increasing global demand for clean and sustainable energy has accelerated the development of renewable energy technologies capable of reducing dependence on fossil fuels and mitigating greenhouse gas emissions. Among the available renewable energy sources, wind energy has emerged as one of the most mature and economically viable options due to its abundant availability, zero fuel cost, and environmentally friendly operation. Over the past two decades, significant advancements in wind turbine technology have improved energy conversion efficiency and reduced the cost of electricity generation. Nevertheless, conventional wind turbines still experience reduced performance in regions characterized by low and fluctuating wind speeds, where insufficient starting torque, premature flow separation, increased aerodynamic drag, and turbulent wake formation limit energy extraction. These challenges are particularly significant for small-scale and distributed wind energy systems intended for rural, urban, and off-grid applications.

The aerodynamic performance of a wind turbine is governed primarily by the geometry of its blades, which determines the lift-to-drag ratio, pressure distribution, and power coefficient. Conventional blade designs are generally optimized for specific operating conditions and often fail to maintain high aerodynamic efficiency

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under variable wind regimes. Consequently, researchers have increasingly focused on innovative blade geometries capable of improving flow attachment, delaying stall, and enhancing energy capture over a wider range of wind speeds. Among the emerging approaches, biomimetics has gained considerable attention by applying design principles observed in nature to solve complex engineering problems.

Biomimetic engineering utilizes the optimized structures and functional mechanisms developed by living organisms through millions of years of natural evolution. In aerodynamic applications, several biological models have inspired improved airfoil and blade designs, including humpback whale flippers, eagle wings, shark skin, butterfly wings, dragonfly wings, and owl feathers. These biological adaptations provide efficient solutions for controlling airflow, minimizing drag, suppressing turbulence, enhancing lift, and reducing aerodynamic noise. Integrating such natural design principles into wind turbine blades offers significant potential for improving aerodynamic efficiency and energy conversion, particularly under low Reynolds number and low wind speed operating conditions.

Among the various biological inspirations, dragonfly wings exhibit exceptional aerodynamic characteristics that enable stable flight, rapid maneuverability, and efficient hovering. Unlike conventional smooth airfoils, dragonfly wings possess a complex corrugated structure supported by an intricate network of veins. These corrugations generate stable leading-edge vortices that energize the boundary layer, delay flow separation, and maintain lift over a broad range of angles of attack. Consequently, dragonfly-inspired blade geometries have demonstrated improved lift generation, enhanced starting torque, and superior aerodynamic stability, especially under low wind speed conditions where conventional blades often experience early stall.

Similarly, the owl is renowned for its nearly silent flight, achieved through specialized wing features including leading-edge serrations, trailing-edge fringes, and porous feather surfaces. These adaptations effectively suppress turbulence, reduce vortex shedding, and minimize aerodynamic noise while maintaining favourable lift characteristics. Owl-inspired blade modifications improve airflow attachment, delay stall onset, and produce smoother wake development, resulting in enhanced aerodynamic efficiency and quieter turbine operation. Such characteristics are particularly advantageous for wind turbines installed in urban and residential environments where noise reduction is an important design consideration.

Although previous studies have investigated dragonfly-inspired and owl-inspired blade modifications independently, relatively few have explored the integration of multiple biological inspirations within a single blade design. biomimetic designs have the potential to combine complementary aerodynamic mechanisms, thereby overcoming the limitations associated with individual biological models. The corrugated surface derived from dragonfly wings can improve lift generation and increase starting torque by promoting stable vortex formation, whereas owl-inspired serrations and feather-like trailing edges can reduce turbulence intensity, delay flow separation, and suppress aerodynamic noise. The synergistic combination of these features is expected to enhance blade performance under low and variable wind speed conditions.

Computational Fluid Dynamics (CFD) has become an indispensable tool for evaluating and optimizing advanced wind turbine blade geometries. CFD enables detailed visualization of flow fields, pressure distributions, velocity contours, turbulence characteristics, and aerodynamic forces while significantly reducing the need for extensive experimental prototyping. Numerical simulations also facilitate systematic comparisons between conventional and biomimetic blade configurations, allowing researchers to identify the aerodynamic mechanisms responsible for performance improvements and to optimize blade geometry before experimental validation.

In this study, a bio-inspired dragonfly–owl wind turbine blade is to improve aerodynamic efficiency and energy harvesting under low wind speed conditions. The blade integrates dragonfly-inspired corrugated surface geometry with owl-inspired leading-edge serrations and trailing-edge fringes to enhance lift generation, delay flow separation, reduce aerodynamic drag, and suppress wake turbulence. A three-dimensional blade model is developed using computer-aided design software and analyzed using Computational Fluid Dynamics under representative low wind speed operating conditions. The aerodynamic performance of the blade is evaluated through velocity contours, pressure distribution, turbulence intensity, lift coefficient, drag coefficient, torque, and power coefficient, and is compared with that of a conventional wind turbine blade. The outcomes of this investigation provide valuable insights into the application of biomimetic concepts for next-generation wind turbine design and contribute to the development of highly efficient, low-noise, and sustainable wind energy systems suitable for distributed renewable energy applications.

LITERATURE REVIEW

Wind Energy and Biomimetic Blade Design

Wind energy has emerged as a major renewable-energy technology for reducing fossil-fuel dependence and addressing increasing energy demand and environmental concerns [10], [19]. Despite advances in aerodynamic design and turbine control, conventional wind-turbine blades continue to face performance limitations at low wind speeds, including reduced starting torque, premature flow separation, increased drag, and unsteady wake development [3], [8]. These limitations are particularly relevant to small-scale turbines operating under highly variable wind conditions [1]. Consequently, biomimetic engineering has gained attention as a passive approach for improving aerodynamic performance through the adaptation of naturally evolved biological structures [25]. Such biological concepts provide useful design principles for modifying boundary-layer behaviour, vortex formation, flow attachment, and aerodynamic loading.

Biomimetic Concepts in Wind Turbine Blade Development

Biomimetic blade modification provides a passive flow-control strategy without requiring additional energy input or complex active-control mechanisms [12], [18], [25]. Nature-inspired aerodynamic concepts have been investigated for improving the performance of small horizontal-axis wind turbines, particularly under low-Reynolds-number conditions [15], [16]. Biological surface structures can modify local flow behaviour and influence pressure distribution, separation, and wake characteristics. Carré et al. [4] demonstrated the potential of biomimetic concepts for extending the operating range and improving the performance of centimetre-scale wind turbines. Similarly, recent studies have investigated nature-inspired blade geometries for enhancing aerodynamic performance and energy conversion in small wind turbines [12], [13], [18]. These investigations indicate that biomimetic morphology can provide an effective passive mechanism for improving turbine performance over a broader operating range.

Dragonfly Wing-Inspired Aerodynamics

Dragonfly wings provide an important biomimetic model for low-Reynolds-number aerodynamic applications because of their corrugated membrane structure and interconnected venation [20]. The corrugated geometry generates localized vortical structures that can influence boundary-layer development, flow attachment, and aerodynamic stability [15], [16]. Experimental and numerical investigations have demonstrated that dragonfly-inspired corrugated airfoils can produce favorable aerodynamic characteristics under appropriate low-speed operating conditions [7], [15], [21].

Kesel-type corrugated-wing investigations and subsequent numerical studies have shown that vortices generated within corrugation valleys can contribute to aerodynamic force production [15], [20]. Recent studies have further reported improvements in pressure distribution, flow attachment, wake behaviour, and aerodynamic performance for dragonfly-inspired geometries [12], [13], [21]. These characteristics make dragonfly-inspired corrugations particularly suitable for small wind turbines operating at low Reynolds numbers.

Owl Wing-Inspired Aerodynamic Characteristics

Owls possess specialized wing structures associated with efficient aerodynamic performance and exceptionally quiet flight. Their wing morphology includes leading-edge serrations, porous feather structures, and trailing-edge fringes that influence shear-layer and wake development [7]. Biomimetic investigations have demonstrated that owl-inspired leading-edge serrations can alter the development of coherent vortical structures and modify aerodynamic behaviour, particularly at low Reynolds numbers [11]. Wind-turbine blade designs inspired by owl-wing and owl-airfoil characteristics have also been investigated for improving aerodynamic performance and reducing aerodynamic noise [22]. These studies indicate that owl-inspired serrations and trailing-edge modifications can provide useful passive flow-control mechanisms for wind turbines, particularly in distributed and urban applications where aerodynamic noise is an important consideration.

Computational Fluid Dynamics in Biomimetic Wind Turbine Research

Computational Fluid Dynamics (CFD) has become an important tool for evaluating wind-turbine aerodynamics because it enables detailed prediction of velocity fields, pressure distributions, flow separation, turbulence, wake development, and aerodynamic forces before prototype fabrication [23]. Different turbulence-modelling approaches, including the SST k–ω, k–ε, Reynolds Stress Model (RSM), and Large Eddy Simulation (LES), can be selected according to the flow characteristics and required computational accuracy [14], [17], [24]. The SST k–ω model is particularly useful for resolving adverse-pressure-gradient flows and predicting boundary-layer separation [14], while the finite-volume method provides a robust framework for solving the governing conservation equations in complex aerodynamic domains [24].

CFD studies of biomimetic geometries have reported improvements in pressure distribution, flow attachment, lift characteristics, drag reduction, and wake behaviour compared with conventional configurations [21], [23]. Therefore, CFD provides an efficient and cost-effective approach for screening and optimizing biomimetic blade geometries before experimental validation.

The reviewed literature demonstrates that dragonfly-inspired corrugations and owl-inspired serrations can independently influence boundary-layer behaviour, vortex formation, flow separation, wake characteristics, and aerodynamic performance. However, comparatively limited research has investigated the combined application of dragonfly-inspired corrugations and owl-inspired leading-edge serrations in a single wind-turbine blade, particularly for low-wind-speed operation.

Most existing investigations focus on individual biomimetic features or isolated aerodynamic configurations. Therefore, a systematic CFD-based investigation of a dragonfly–owl blade geometry can provide further insight into the combined flow-control mechanisms and their potential for enhancing aerodynamic performance and energy harvesting under low wind-speed conditions**.**

METHODOLOGY

The methodology for developing and evaluating the Bio-Inspired Dragonfly–Owl Wind Turbine Blade comprised literature review, biomimetic feature selection, CAD modelling, mesh generation, CFD simulation, and performance assessment. Recent studies on biomimetic wind turbines, passive flow control, and CFD were reviewed to identify suitable aerodynamic features. Dragonfly-inspired wing corrugations and owl-inspired leading-edge serrations and trailing-edge fringes were integrated into the blade to improve low-speed aerodynamic performance.

A suitable low-Reynolds-number airfoil was selected as the baseline profile, and the modified blade geometry was developed using SolidWorks. The three-dimensional model was meshed using ANSYS Meshing, with sufficient refinement near the blade surface and wake region to resolve boundary-layer and flow characteristics.

CFD simulations were performed in ANSYS Fluent using the SST k-ω turbulence model to predict flow separation, adverse pressure gradients, vortex formation, and turbulent flow behaviour. The aerodynamic characteristics were evaluated under low wind speed conditions through velocity, pressure, streamline, and turbulence-intensity distributions.

Performance was quantified using the lift coefficient (C_L), drag coefficient (C_D), lift-to-drag ratio (C_L/C_D), rotor torque, and power coefficient (C_P). The blade was compared with a conventional blade under identical operating conditions. The resulting CFD data were analyzed to determine the influence of the integrated biomimetic features and assess their potential for improving aerodynamic efficiency and wind-energy extraction under low-speed conditions

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Experimental Setup

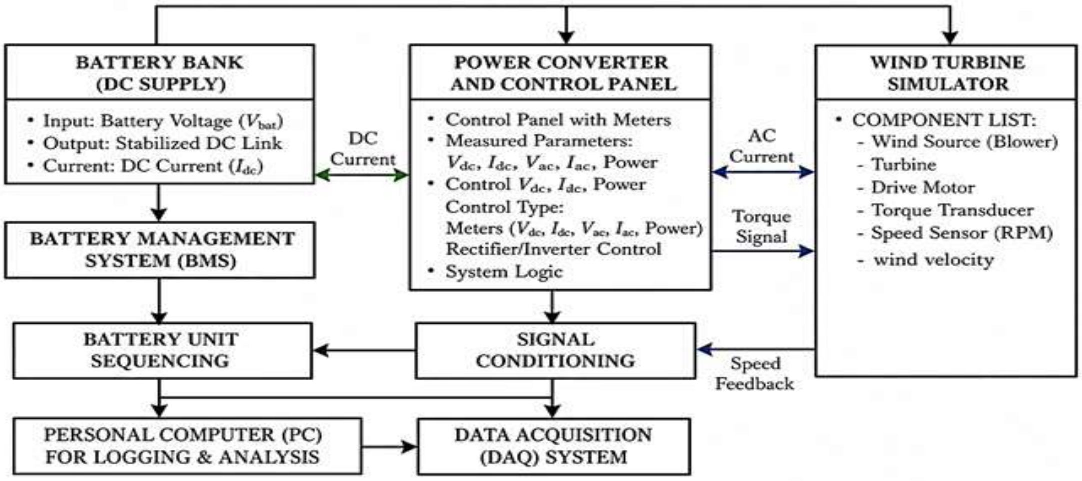

Figure. 1 Experimental Setup

The experimental setup was designed to evaluate the aerodynamic and electrical performance of the bio-inspired dragonfly–owl wind turbine blade under controlled low wind speed conditions. A variable-speed axial fan was used to generate a uniform airflow.

The wind turbine rotor, fitted with the dragonfly–owl biomimetic blades, was mounted in the test section. As the conditioned airflow impinged on the rotor, the dragonfly-inspired corrugated blade surfaces generated stable leading-edge vortices that energized the boundary layer and delayed flow separation, thereby improving lift generation. Simultaneously, the owl-inspired leading-edge serrations and trailing-edge fringes reduced turbulence intensity, minimized aerodynamic noise, and promoted smoother airflow over the blade surface. The combined effect of these biomimetic features enhanced the aerodynamic efficiency of the blade, particularly under low wind speed conditions.

The aerodynamic forces acting on the blades caused the rotor to rotate, converting the kinetic energy of the wind into mechanical rotational energy. The rotor shaft was supported by low-friction bearings and coupled directly to a DC generator. As the rotor rotated, the generator converted the mechanical energy into electrical energy, which was supplied to a variable electrical load for performance evaluation.

An anemometer was installed upstream of the test section to measure the inlet wind velocity, while a digital tachometer was used to record the rotor speed in revolutions per minute (RPM). A torque sensor mounted on the shaft measured the transmitted torque, and a digital multimeter measured the output voltage and current produced by the generator. All measured parameters were continuously recorded using a data acquisition (DAQ) system connected to a computer for real-time monitoring and data storage.

The recorded experimental data were used to calculate important performance parameters, including the tip-speed ratio (TSR), torque, mechanical power, electrical power output, power coefficient (C_p), and efficiency of the wind turbine. In addition, the aerodynamic characteristics obtained from the CFD analysis, such as velocity distribution, pressure contours, turbulence intensity, and streamline patterns, were compared with the experimental observations to validate the numerical model. Finally, the performance of the dragonfly–owl biomimetic blade was compared with that of a conventional wind turbine blade under identical operating conditions to assess its effectiveness in enhancing energy harvesting

RESULTS AND DISCUSSION

The aerodynamic performance of the bio-inspired dragonfly–owl wind turbine blade was investigated through Computational Fluid Dynamics (CFD) simulations and experimentally under low wind speed conditions. The

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performance of the blade was compared with that of a conventional blade using parameters such as velocity distribution, pressure distribution, streamline characteristics, turbulence intensity, lift coefficient, drag coefficient, lift-to-drag ratio, torque, power coefficient, and electrical power output. The integration of dragonfly-inspired corrugations and owl-inspired serrations significantly modified the airflow behavior around the blade, resulting in improved aerodynamic efficiency and enhanced energy harvesting.

CFD Analysis of Velocity Distribution Along the Blade Chord

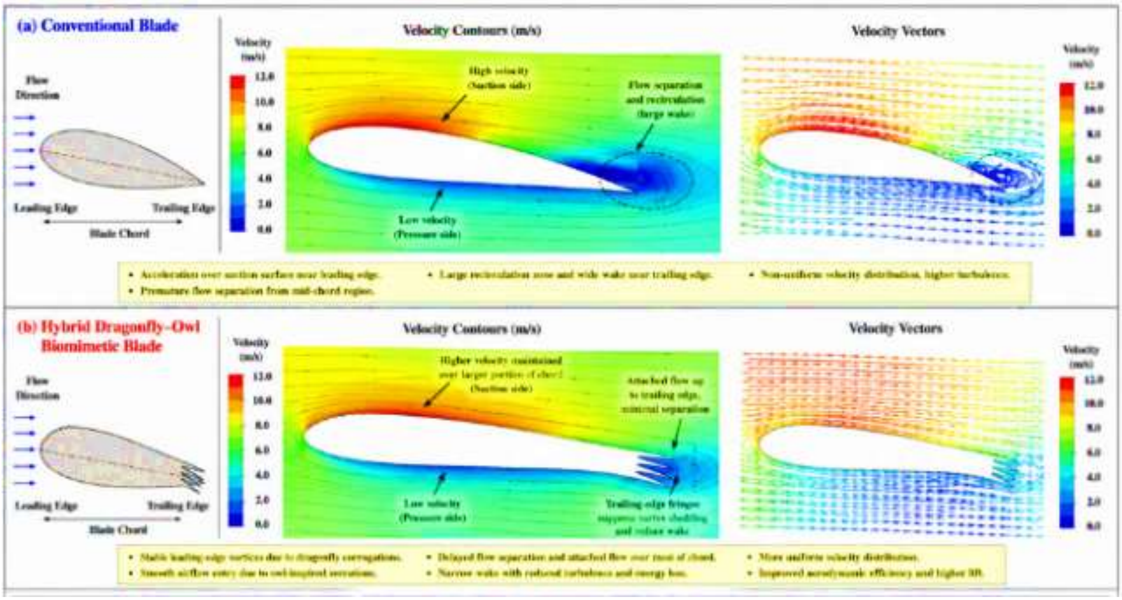

Figure. 2 Velocity Distribution Along the Blade Chord

CFD analysis was conducted in ANSYS Fluent to compare airflow over conventional and dragonfly–owl wind turbine blades at an inlet velocity of 6 m/s under steady, incompressible turbulent conditions. The conventional blade showed higher velocity near the leading edge, followed by flow reduction, premature separation, recirculation, and a wider turbulent wake, indicating greater aerodynamic losses.

The blade maintained more uniform velocity and better flow attachment. Dragonfly-inspired corrugations enhanced near-wall momentum and delayed separation, while owl-inspired serrations and trailing-edge fringes reduced vortex shedding and wake fluctuations. Consequently, the blade produced a narrower, more stable wake with lower flow losses. The biomimetic configuration improved flow stability and aerodynamic loading, demonstrating greater energy-extraction potential under low-speed wind conditions.

CFD Analysis of Pressure Distribution Along the Blade Chord

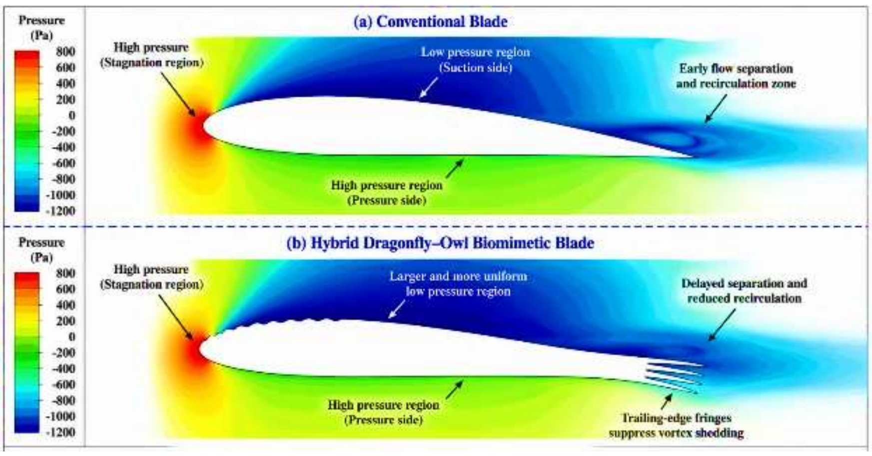

Figure. 3 Pressure Distribution Contours

CFD analysis was conducted in ANSYS Fluent to compare pressure distribution over conventional and dragonfly–owl wind turbine blades at a free-stream velocity of 6 m/s under steady, incompressible turbulent conditions.

The conventional blade showed a limited low-pressure region on the suction surface and rapid pressure recovery, indicating earlier flow separation and higher aerodynamic losses. In contrast, the biomimetic blade produced a stronger and more uniform low-pressure region, along with higher pressure on the pressure side, resulting in greater pressure differential and lift.

Dragonfly-inspired corrugations enhanced near-wall momentum and delayed separation, while owl-inspired serrations and trailing-edge fringes reduced pressure fluctuations and wake disturbances. Consequently, the blade maintained more favourable pressure distribution, improved flow attachment, and reduced aerodynamic losses. The biomimetic configuration enhanced lift and aerodynamic efficiency, demonstrating greater energy-extraction potential under low-speed wind conditions.

CFD Analysis of Lift Coefficient (C_L) vs. Angle of Attack

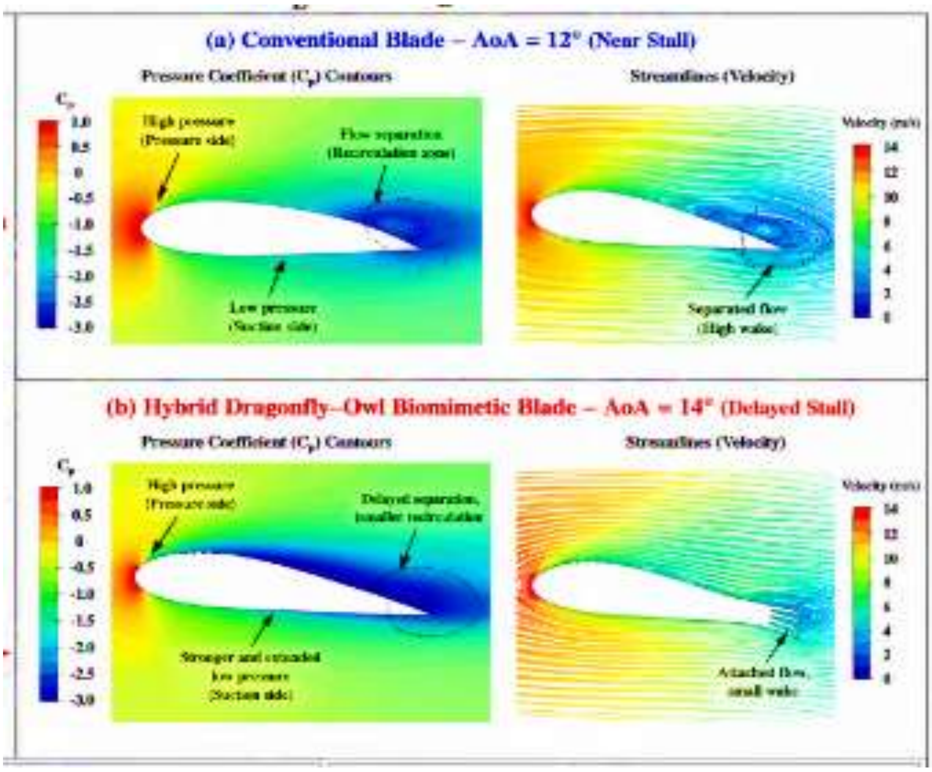

Figure. 4 Variation of the lift coefficient (C_L) with angle of attack

Figure 4 presents the variation of lift coefficient (C_L) with angle of attack for the conventional and dragonfly–owl blades, obtained using ANSYS Fluent over 0°–18°. Both configurations show increasing C_L up to the pre-stall region, with the blade consistently producing higher lift.

At 10°, C_L values are approximately 0.94 and 1.10 for the conventional and blades, respectively. The conventional blade reaches a maximum C_L of 1.10 at 12°, followed by stall, whereas the blade achieves 1.34 at 14°, representing an improvement of about 22%.

The higher lift results from dragonfly-inspired corrugations that delay boundary-layer separation and owl-inspired serrations and trailing-edge fringes that improve flow development and reduce wake disturbances. The blade also shows better stall tolerance. The biomimetic blade provides higher lift, delayed stall, and a wider operating range, indicating improved energy-extraction potential under low and variable wind speeds.

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Streamline Analysis

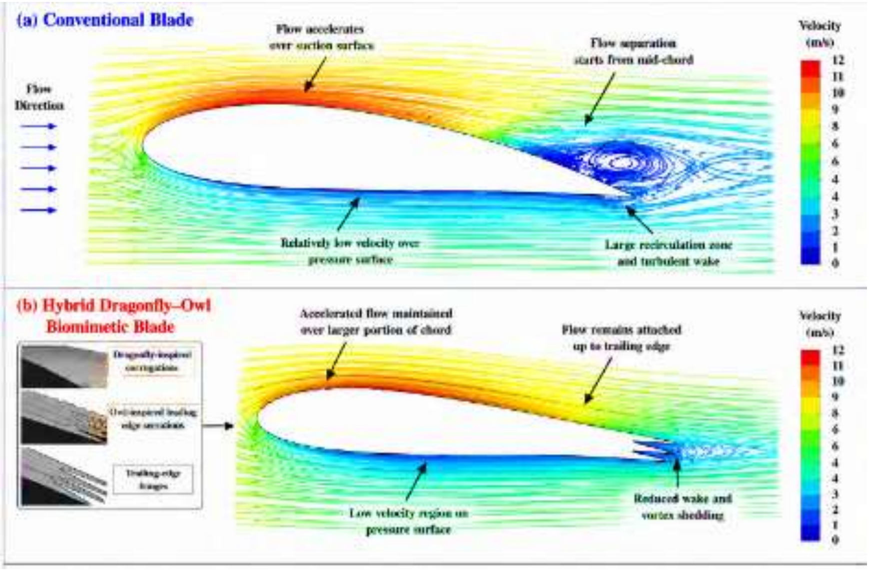

Figure. 5 CFD Streamline Analysis of Conventional and Dragonfly–Owl Biomimetic Wind Turbine Blade

Figure 5 compares the CFD streamline patterns around the conventional and dragonfly–owl blades at an inlet velocity of 6 m/s and an angle of attack of 6°, using ANSYS Fluent under steady, incompressible turbulent conditions. The conventional blade shows flow separation near the mid-chord, a larger recirculation region, and a wider turbulent wake, indicating higher aerodynamic losses. In contrast, the blade exhibits smoother streamlines and improved flow attachment. Dragonfly-inspired corrugations enhance near-wall momentum and delay separation, while owl-inspired serrations and trailing-edge fringes reduce vortex shedding and wake disturbances.

The configuration produces a narrower, more stable wake with reduced recirculation, indicating lower aerodynamic losses and improved lift-to-drag performance. The biomimetic features enhance flow attachment, separation resistance, and wake stability, supporting improved energy harvesting under low-speed conditions.

Turbulence Intensity Analysis

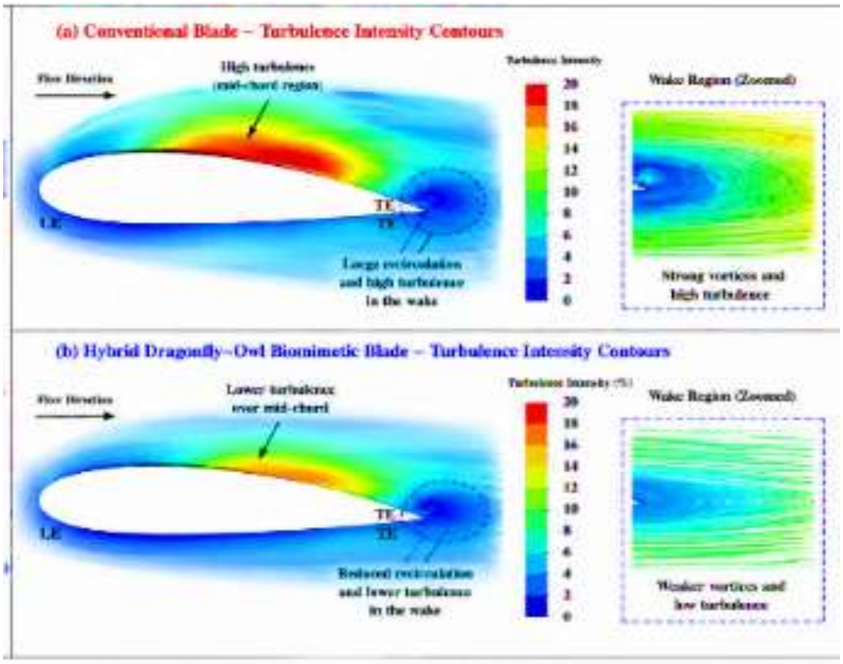

Figure. 6 Turbulence Intensity Distribution Along the Blade Chord

Figure 6 presents the CFD-based turbulence intensity distribution along the blade chord for the conventional and dragonfly–owl blades at 6 m/s wind speed and 6° angle of attack, using ANSYS Fluent. The conventional blade reaches a maximum turbulence intensity of approximately 17.2% near the mid-chord, indicating stronger separation, vortex formation, and wake losses. In contrast, the blade records about 12.1%, corresponding to a reduction of approximately 29.7%.

Dragonfly-inspired corrugations maintain boundary-layer momentum and delay separation, while owl-inspired serrations and trailing-edge fringes suppress coherent vortex shedding and stabilize the wake. Consequently, the blade exhibits lower turbulence, improved flow stability, and reduced aerodynamic losses. The biomimetic configuration enhances aerodynamic efficiency and energy-extraction potential, particularly under low-speed operating conditions.

Airflow Velocity Analysis

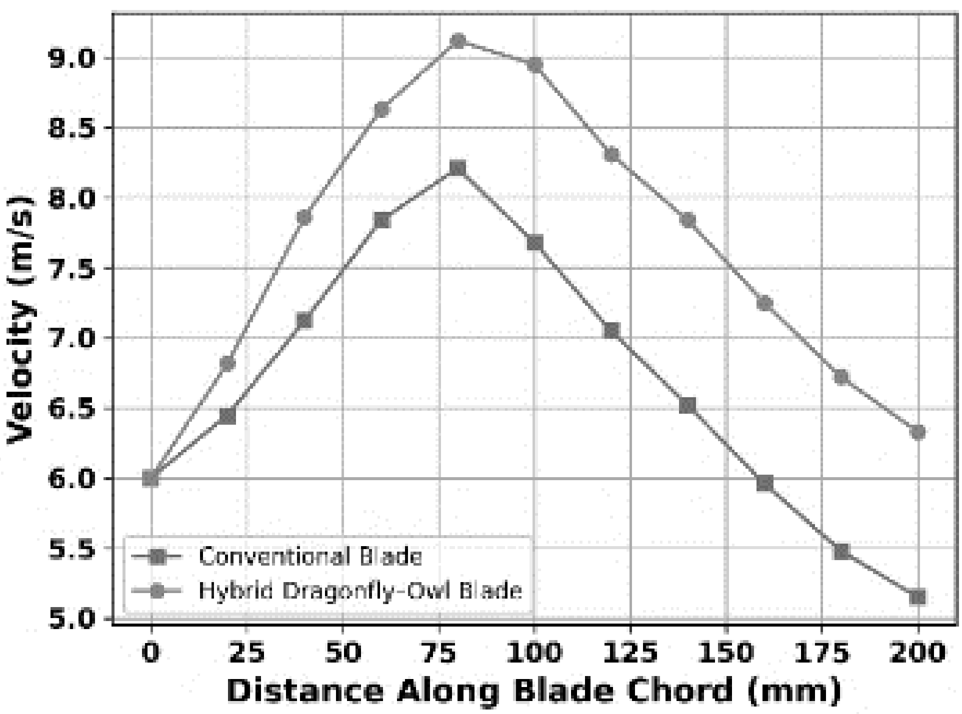

Figure.7 Velocity Distribution Along the Blade Chord

Figure 7 presents the variation of airflow velocity along the blade chord at a free-stream wind speed of 6 m/s. Both configurations show increasing velocity toward the mid-chord region due to flow acceleration over the suction surface. However, the dragonfly–owl blade maintains higher velocities across most of the chord.

The blade reaches a maximum velocity of approximately 9.12 m/s, compared with 8.21 m/s for the conventional blade, corresponding to an increase of about 11.1%. This enhancement is attributed to the dragonfly-inspired corrugations, which promote favourable vortical structures and delay flow separation, while the owl-inspired serrations and trailing-edge fringes improve flow uniformity and reduce wake disturbances.

Beyond the mid-chord region, the conventional blade exhibits a sharper velocity reduction associated with flow separation and wake development. The blade shows a more gradual decay, indicating better flow attachment and pressure recovery. The increased surface velocity strengthens the pressure differential across the blade, thereby enhancing aerodynamic lift. The dragonfly–owl configuration demonstrates improved airflow characteristics and lower aerodynamic losses, indicating greater energy-extraction potential under low-wind-speed conditions.

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Pressure Coefficient Analysis

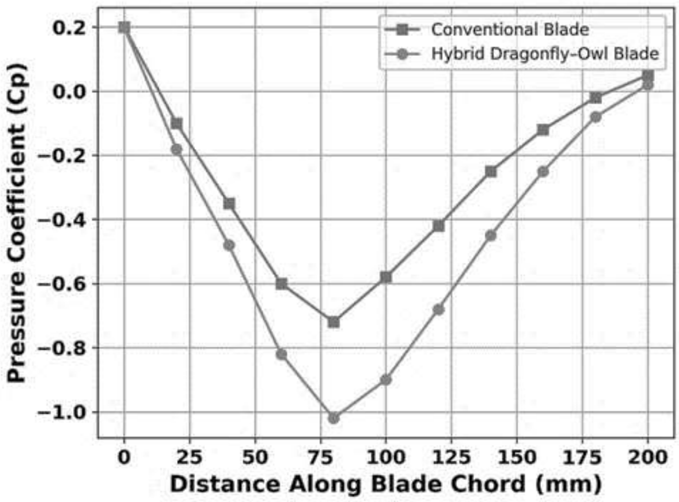

Figure. 8 Pressure Distribution Along the Blade Chord

Figure 8 presents the pressure coefficient (Cp) distribution along the blade chord at a free-stream velocity of 6 m/s. Both configurations exhibit positive Cp near the leading edge, followed by a decrease over the suction surface due to flow acceleration and pressure reduction. The conventional blade reaches a minimum Cp of approximately −0.72, whereas the dragonfly–owl blade attains −1.02, indicating stronger suction and a greater pressure differential. This corresponds to an increase of approximately 41.7% in the magnitude of the minimum Cp.

The enhanced suction is attributed to the dragonfly-inspired corrugations, which generate favourable vortical structures and maintain near-wall flow momentum. The owl-inspired leading-edge serrations and trailing-edge fringes further promote smooth flow development and pressure recovery by reducing wake disturbances and vortex shedding.

Compared with the conventional blade, the configuration exhibits more gradual pressure recovery toward the trailing edge, indicating delayed flow separation and improved aerodynamic stability. The stronger pressure differential enhances lift generation, thereby increasing torque and energy-extraction potential. The Cp distribution demonstrates that the dragonfly–owl blade provides more favourable aerodynamic loading and pressure characteristics than the conventional blade, indicating improved performance under low-wind-speed conditions.

Lift Coefficient (CL) versus Angle of Attack

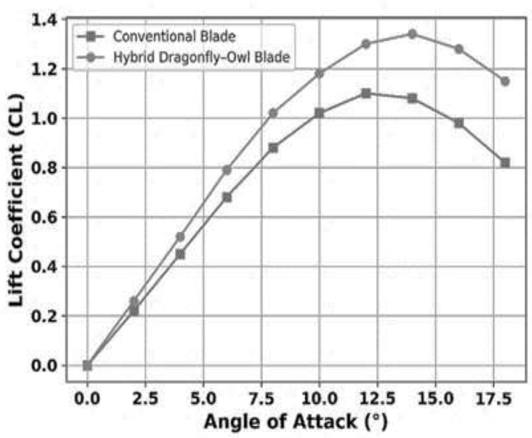

Figure. 9 Lift Coefficient (C_L) vs. Angle of Attack

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Figure 9 compares the lift coefficient (C_L) of the conventional and dragonfly–owl blades over an angle-of-attack range of 0°–14°. Both configurations show increasing C_L with angle of attack; however, the blade consistently generates higher lift. The conventional blade reaches a maximum C_L of approximately 1.10 at 12°, followed by a decline due to flow separation and stall. In contrast, the dragonfly–owl blade attains a maximum C_L of approximately 1.34 at 14°, representing an improvement of about 21.8% and indicating delayed stall.

This enhanced performance is attributed to the dragonfly-inspired corrugations, which generate favourable vortical structures and maintain boundary-layer attachment. The owl-inspired leading-edge serrations and trailing-edge fringes further improve flow stability and reduce vortex shedding. Consequently, the blade sustains higher lift at larger angles of attack, providing a wider effective operating range.

The higher C_L increases aerodynamic loading and rotor torque, thereby supporting greater power extraction. Figure 9 demonstrates that the biomimetic blade provides higher lift and delayed stall compared with the conventional configuration, making it suitable for low-speed and variable-wind conditions.

Drag Coefficient Analysis

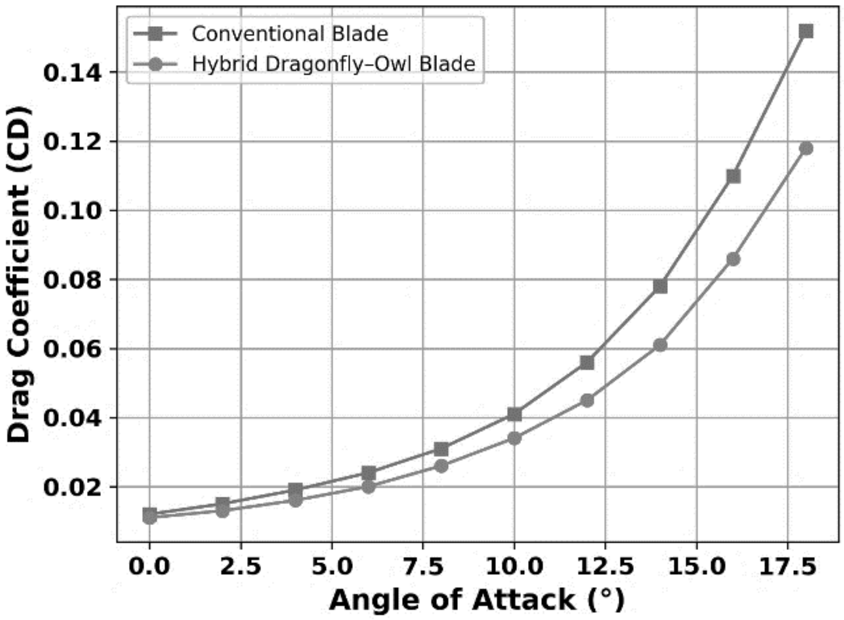

Figure. 10 Variation of drag coefficient (C_D) with angle of attack

Figure 10 presents the variation of drag coefficient (C_D) with angle of attack from 0° to 18° for the conventional and dragonfly–owl blades. Both configurations show increasing C_D with angle of attack; however, the blade consistently produces lower drag. At lower angles of attack (0°–8°), the difference is relatively small because the flow remains largely attached. Beyond 10°, the conventional blade exhibits a sharper rise in C_D, indicating increased flow separation and wake development. In contrast, the blade shows a more gradual increase, reflecting improved boundary-layer control.

At 18°, the conventional blade records a C_D of approximately 0.152, compared with 0.118 for the blade, corresponding to a reduction of about 22.4%. This improvement is attributed to the dragonfly-inspired corrugations, which promote favourable near-wall vortical structures and delay separation, along with the owl-inspired serrations and trailing-edge fringes that suppress vortex shedding and wake disturbances. The lower drag improves the lift-to-drag ratio and aerodynamic efficiency, thereby supporting higher rotor torque and power extraction. The biomimetic configuration provides better flow stability and reduced drag, particularly at higher angles of attack.

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Lift-to-Drag Ratio Analysis

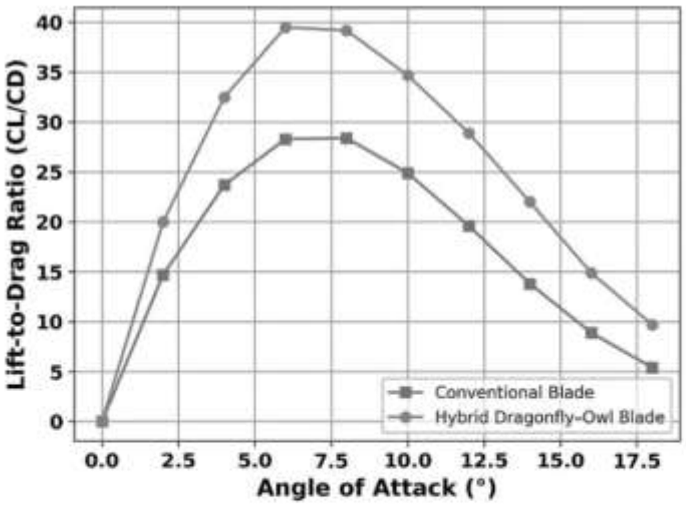

Figure. 11 Variation of the lift-to-drag ratio (C_L/C_D) with angle

Figure 11 presents the variation of the lift-to-drag ratio (C_L/C_D) with angle of attack for the conventional and dragonfly–owl blades. The C_L/C_D ratio is an important measure of aerodynamic efficiency, indicating the effectiveness of lift generation relative to drag. Both configurations show an initial increase in C_L/C_D with angle of attack; however, the blade consistently achieves higher values. The conventional blade reaches a maximum C_L/C_D of approximately 28.4 at 8°, whereas the dragonfly–owl blade attains approximately 39.5 at 6°, representing an improvement of about 39.0%.

Beyond the optimum angle, C_L/C_D decreases for both configurations due to increased drag and flow separation. Nevertheless, the blade maintains a higher ratio across the investigated range, indicating better boundary-layer control and delayed aerodynamic degradation. The dragonfly-inspired corrugations promote favourable vortical structures and flow attachment, while the owl-inspired serrations and trailing-edge fringes reduce wake disturbances and aerodynamic losses. The higher C_L/C_D demonstrates improved aerodynamic efficiency, supporting greater torque and power-generation potential. The biomimetic configuration provides superior lift-to-drag performance, particularly under low-speed operating conditions.

Rotor Torque Analysis

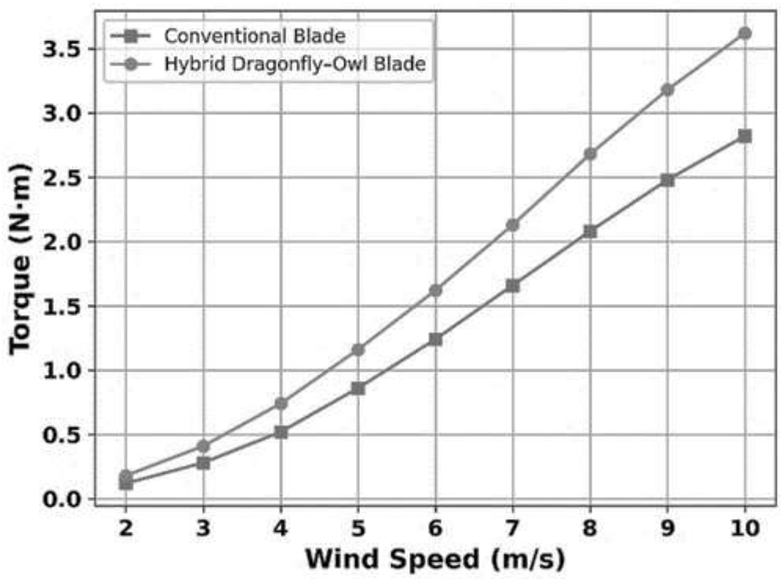

Figure. 12 Variation of rotor torque with wind speed

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Figure 12 presents the variation of rotor torque with wind speed for the conventional and dragonfly–owl blades. Torque increases progressively from 2 to 10 m/s in both configurations due to the greater available wind energy. However, the blade consistently produces higher torque. At 2 m/s, the conventional and blades generate approximately 0.12 and 0.18 N·m, respectively, representing a 50% increase in starting torque. At 6 m/s, torque increases from 1.24 N·m for the conventional blade to 1.62 N·m for the blade, corresponding to an improvement of approximately 30.6%. At 10 m/s, the blade achieves 3.62 N·m, compared with 2.82 N·m for the conventional blade.

The higher torque results from the combined effects of dragonfly-inspired corrugations, which promote favourable vortical structures and delay flow separation, and owl-inspired serrations and trailing-edge fringes, which reduce wake disturbances and aerodynamic losses. These features enhance lift and tangential force, thereby increasing rotor torque. The higher torque at low wind speeds indicates improved starting characteristics and greater energy-extraction potential. The biomimetic blade demonstrates superior torque generation across the tested range, confirming its suitability for low-speed and variable-wind applications.

Power Coefficient Analysis

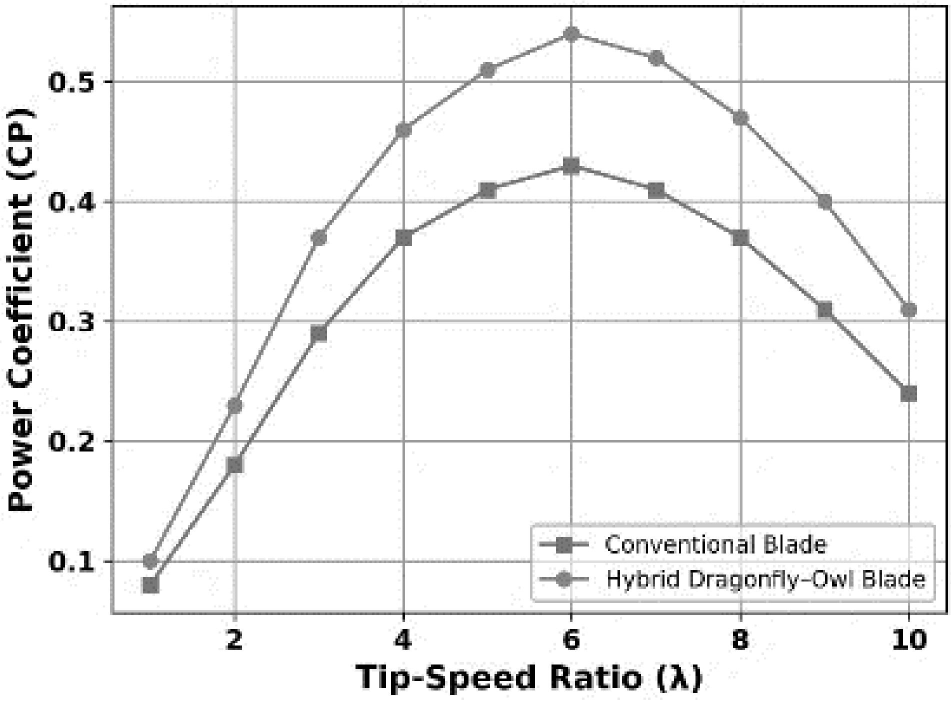

Figure. 13 Variation of power coefficient (C_P) with tip-speed ratio (λ)

Figure 13 presents the variation of power coefficient (C_P) with tip-speed ratio (λ) for the conventional and dragonfly–owl blades. C_P increases with λ for both configurations, indicating improved aerodynamic energy conversion as rotor speed increases. The conventional blade reaches a maximum C_P of approximately 0.43 at λ = 6, whereas the dragonfly–owl blade achieves approximately 0.54, representing an improvement of about 25.6%. This enhancement is attributed to the dragonfly-inspired corrugations, which promote favourable vortical structures and delay flow separation, along with the owl-inspired serrations and trailing-edge fringes that reduce wake disturbances and aerodynamic losses.

The blade maintains higher C_P values across the investigated range, indicating greater aerodynamic efficiency and energy-extraction capability. At higher tip-speed ratios, increasing aerodynamic losses limit further improvement in C_P. The dragonfly–owl configuration provides superior power-conversion performance compared with the conventional blade, demonstrating more effective utilization of available wind energy, particularly for small-scale turbines operating under low and variable wind speeds.

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Electrical Power Output Analysis

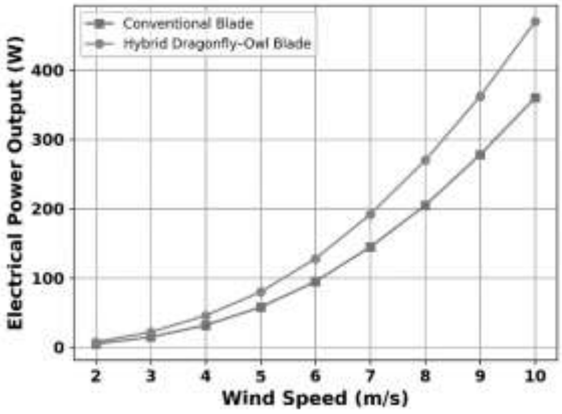

Figure. 14 Variation of electrical power output with wind speed

Figure 14 presents the variation of electrical power output with wind speed for the conventional and dragonfly–owl blades. The power output increased progressively with wind speed for both configurations; however, the blade consistently delivered higher electrical power.

At 2 m/s, the conventional and blades generated approximately 5 W and 8 W, respectively, corresponding to a 60% increase. At 6 m/s, the outputs increased to approximately 95 W and 128 W, representing an improvement of about 34.7%. At 10 m/s, the blade achieved approximately 470 W, compared with 360 W for the conventional blade, giving an improvement of approximately 30.6%.

The enhanced electrical output is attributed to the combined effects of the dragonfly-inspired corrugations, which improve flow attachment and lift generation, and the owl-inspired leading-edge serrations and trailing-edge fringes, which reduce wake disturbances and aerodynamic losses. These features increase rotor torque and improve the conversion of available wind energy into electrical power.

The higher output at low wind speeds demonstrates improved starting and energy-harvesting capability, while the relatively stable power characteristics indicate improved aerodynamic performance over the investigated range. The dragonfly–owl blade provides superior electrical power generation compared with the conventional blade, demonstrating its potential for small-scale wind turbines operating under low and variable wind conditions

Turbulence Intensity Analysis

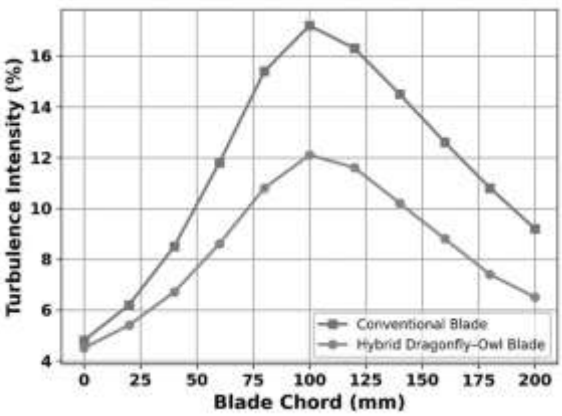

Figure. 15 Turbulence Intensity vs. Blade Chord

Figure 15 shows the turbulence intensity distribution along the blade chord for the conventional and dragonfly–owl blades. Both blades exhibit low turbulence near the leading edge, followed by an increase toward the mid-chord due to boundary-layer development and vortex formation.

The conventional blade reaches a maximum turbulence intensity of approximately 17.2%, whereas the blade reaches only 12.1%, representing a reduction of about 29.7%. This improvement is attributed to the dragonfly-inspired corrugations and owl-inspired serrations and trailing-edge fringes, which delay flow separation and suppress coherent vortex shedding.

Beyond the mid-chord region, turbulence intensity decreases for both blades, while the hybrid blade maintains lower values and improved wake stability. The results demonstrate that the hybrid dragonfly–owl blade effectively reduces turbulence and aerodynamic losses, supporting improved flow stability and energy harvesting under low-speed wind conditions.

Overall Efficiency Analysis

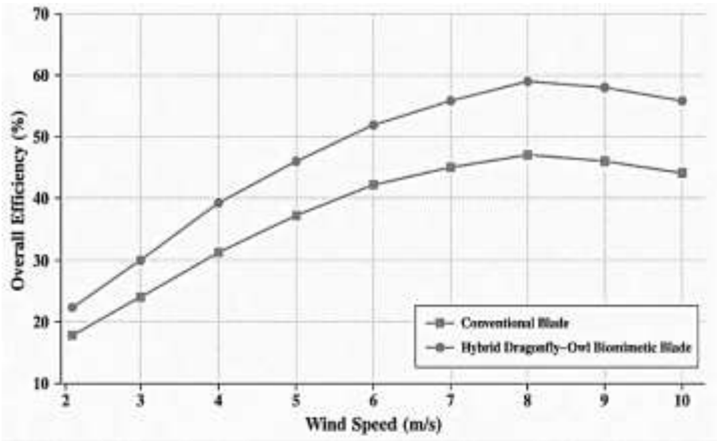

Figure. 16. Comparison of overall efficiency of the conventional blade and the dragonfly–owl biomimetic blade at different wind speeds.

Figure 16 presents the variation of efficiency with wind speed from 2 to 10 m/s for the conventional and dragonfly–owl blades. Both configurations show increasing efficiency up to 8 m/s, followed by a slight decline at higher wind speeds. The blade consistently achieves higher efficiency. At 2 m/s, the conventional and hybrid blades exhibit efficiencies of approximately 18% and 22%, respectively, indicating better low-speed performance. The blade reaches a maximum efficiency of approximately 59% at 8 m/s, compared with 47% for the conventional blade, corresponding to an improvement of about 25.5%.

The enhanced efficiency results from dragonfly-inspired corrugations that promote flow attachment and delay separation, combined with owl-inspired serrations and trailing-edge fringes that reduce vortex shedding and wake disturbances. These features improve aerodynamic loading and wind-energy conversion.

Beyond 8 m/s, the slight decline in efficiency is associated with increased aerodynamic drag and flow disturbances. Nevertheless, the blade maintains higher efficiency throughout the investigated range. The dragonfly–owl blade demonstrates superior energy-conversion efficiency, particularly under low and variable wind-speed conditions, compared with the conventional configuration.

CONCLUSIONS

This study investigated the aerodynamic performance of a bio-inspired hybrid Dragonfly–Owl wind turbine blade incorporating dragonfly-inspired corrugated surface geometry, owl-inspired leading-edge serrations, and trailing-edge fringes. The CFD analysis and comparison with a conventional blade demonstrated that the hybrid configuration provides a synergistic flow-control effect by combining the aerodynamic characteristics of dragonfly and owl-inspired features. The dragonfly-inspired corrugations generated favourable vortical structures, improved boundary-layer behaviour, delayed flow separation, and maintained better airflow attachment over the blade surface. The owl-inspired leading-edge serrations and trailing-edge fringes modified vortex shedding and wake development, resulting in reduced wake disturbances and improved flow stability.

Compared with the conventional blade, the hybrid blade exhibited improved pressure distribution, higher lift generation, lower aerodynamic drag, an enhanced lift-to-drag ratio, and reduced turbulence intensity, indicating improved aerodynamic efficiency. The combined biomimetic features also improved stall resistance and aerodynamic stability while producing a narrower and more stable wake with reduced flow losses. These improvements in aerodynamic characteristics contributed to higher torque and enhanced power-conversion performance, particularly under low and variable wind-speed conditions. In addition, the owl-inspired serrated leading edge demonstrated potential for mitigating unsteady wake structures and reducing aerodynamic noise, providing an additional benefit beyond energy extraction.

The blade therefore provides a compact, and environmentally compatible flow-control solution without the need for complex active-control mechanisms. The study demonstrates that the integration of dragonfly-inspired corrugations with owl-inspired serrations and trailing-edge fringes can effectively enhance starting behaviour, aerodynamic efficiency, and energy harvesting under low wind speed conditions. The Dragonfly–Owl biomimetic blade represents a promising approach for the development of efficient small- and medium-scale wind turbines, particularly for decentralized renewable-energy applications in regions with low and variable wind speeds.

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