

# Aerodynamic Performance of an H-Darrieus Vertical-Axis Wind Turbine with a Curved Gurney Flap Under Low-Wind Conditions

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**Abstract.** This study experimentally evaluates a curved Gurney flap (GF) as a passive trailing-edge modification to improve the low-wind aerodynamic performance of an H-Darrieus vertical-axis wind turbine (VAWT). A small-scale three-bladed rotor based on a NACA 0018 profile (chord = 100 mm, diameter = 320 mm, height = 300 mm) was fabricated via fused-deposition modeling (PLA) in two configurations: a clean baseline and a curved-GF design with flap height  $h_{GF} = 0.05c$ . Wind-tunnel tests were attempted at  $V = 3\text{--}8$  m/s; however, steady-state rotation was achieved only at  $V = 5\text{--}8$  m/s and performance metrics are reported for this range. Rotational speed was measured using a tachometer, and shaft torque was obtained using a rope brake dynamometer to compute tip-speed ratio (TSR), mechanical power, and power coefficient ( $C_p$ ). Compared with the clean baseline, the curved-GF configuration increased peak efficiency, achieving  $C_{p_{max}} = 0.2276$  at  $\text{TSR} = 1.10$ , representing a 23.43% improvement over the baseline ( $C_{p_{max}} = 0.1845$  at  $\text{TSR} = 0.92$ ). Across the steady-state test conditions, the curved-GF rotor maintained higher  $C_p$  values than the clean configuration, indicating that a curved GF can serve as a practical, low-cost passive enhancement for small VAWTs operating in low-wind regimes.

## 1 Introduction

Wind energy is a key technology in the transition toward low-carbon and decentralized power generation; however, many prospective deployment sites are characterized by low to moderate wind speeds, where conventional horizontal-axis wind turbines may operate away from their optimal regime. Under these conditions, turbine concepts and blade-level design modifications that improve energy conversion at low wind speeds are of practical interest. Vertical-axis wind turbines (VAWTs), particularly the H-Darrieus configuration, are attractive for such environments because their omnidirectional operation eliminates the need for yaw mechanisms and can better accommodate variable wind direction. Despite these advantages, H-Darrieus turbines commonly exhibit reduced aerodynamic efficiency at low

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tip-speed ratio (TSR), limiting power coefficient ( $C_p$ ) and overall energy capture in low-wind operation [1], [2]. Accordingly, prior work has examined both the aerodynamic drivers of low-TSR losses and passive approaches for improving torque production and power conversion in lift-type VAWTs. Hand et al. [1] synthesized key performance parameters and highlighted low-TSR operation as a persistent limitation, while Sengupta et al. [2] and Reddy et al. [3] reported that starting behavior and performance trends are strongly influenced by rotor configuration under low-wind conditions. Rogowski et al. [4] further showed that blade profile selection can significantly affect the performance of H-Darrieus turbines across operating regimes. More broadly, Tayebi and Torabi [5] reviewed flow-control techniques for Darrieus turbines and identified passive devices as practical options for performance enhancement without added control complexity. Within this class, trailing-edge Gurney flaps (GFs) have been investigated as lift-enhancement modifications for Darrieus and straight-bladed VAWTs, with reported performance gains that depend strongly on flap geometry, placement, and operating TSR [6]–[9].

Motivated by the demonstrated sensitivity of GF performance to geometric design and the need for additional experimental validation under low-wind conditions, this study experimentally evaluates an H-Darrieus VAWT equipped with a curved Gurney flap relative to a clean baseline rotor using wind-tunnel testing. Performance is quantified using  $C_p$ –TSR characteristics and  $C_p$  trends with wind speed derived from measured rotational speed and rope-brake torque. The results provide experimental evidence on the extent to which a curved GF can serve as a low-cost, passive modification to improve the aerodynamic efficiency of small H-Darrieus turbines under steady-state low-wind operation.

## 2 Materials and Methods

This section describes the turbine configurations, experimental setup, measurement instrumentation, and procedures used to evaluate performance.

### 2.1 Turbine design and configurations

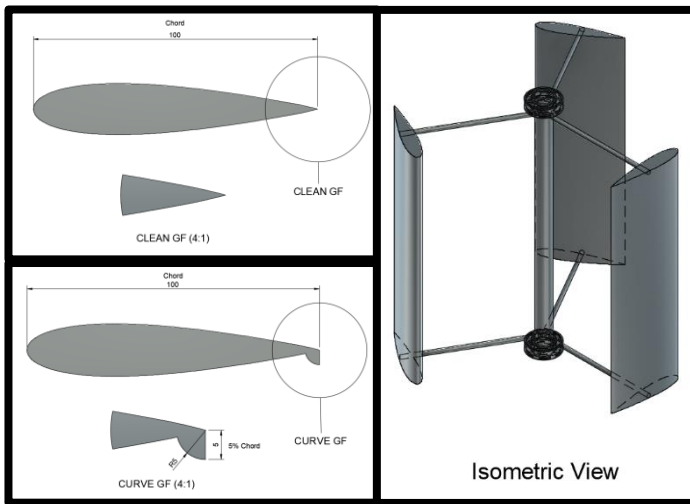
The turbine blades were based on a NACA 0018 symmetric airfoil profile. Two configurations were developed for comparison: (1) a clean baseline rotor without trailing-edge modification and (2) a rotor equipped with a curved Gurney flap (GF). The curved GF was installed at the blade trailing edge with a height equal to 5% of the chord length ( $h_{GF} = 0.05c$ ). Each blade had a chord length of 100 mm, and the rotor consisted of three blades arranged in an H-Darrieus configuration. The rotor geometry was modeled in Autodesk Fusion 360 and maintained identical principal dimensions for both configurations: rotor diameter  $D = 320\text{ mm}$  and rotor height  $H = 300\text{ mm}$  as shown in Table 1.

**Table 1.** H-Darrieus VAWT Specifications.

Specification		
Blade Profile	NACA 0018	
Number of Blades	3	
Blade Chord Length, $C$	100 mm	[0.100 m]
Height of the Rotor, $H$	300 mm	[0.300 m]
Diameter of the Rotor, $D$	320 mm	[0.320 m]
Radius of the Rotor, $R$	160 mm	[0.160 m]
Area, $A$	96,000 mm <sup>2</sup>	[0.096 m <sup>2</sup> ]
Blade Material	PLA	

## 2.2 Fabrication and assembly

Turbine components were fabricated using fused-deposition modeling (FDM) with polylactic acid (PLA) filament at the Department of Trade and Industry Fabrication Laboratory. Dimensional accuracy was verified using digital calipers. The blades were mounted on a stainless-steel hub and assembled with careful alignment to reduce imbalance and vibration during operation. The same hub, shaft, and support structure were used for both configurations to ensure that performance differences were attributable to the blade modification as shown in Figure 1.



**Fig. 1.** Blade and rotor geometry of the tested H-Darrieus VAWT: NACA 0018 blade profiles for the clean baseline and the curved Gurney-flap configuration ( $c = 100\text{ mm}$ ,  $h_{GF} = 0.05c$ ), and isometric view of the three-bladed rotor assembly.

## 2.3 Wind tunnel facility and test conditions

Wind tunnel experiments were conducted at the Central Philippine University Wind Energy Research and Development Facility. The test section measured  $1.5\text{ m} \times 1.5\text{ m}$ , providing a uniform flow field suitable for small-scale turbine testing. Tests were attempted at free-stream wind velocities of 3–8 m/s to represent low-wind operating conditions; however, steady-state rotation could not be sustained at 3–4 m/s and  $C_p$ -based performance results are therefore reported for 5–8 m/s. Wind speed was measured using a handheld anemometer (manufacturer/model not recorded; display resolution 0.1 m/s). Because the manufacturer specification was unavailable, a conservative uncertainty of  $\pm 0.5\text{ m/s}$  was assumed. Rotor rotational speed was measured using a handheld tachometer (manufacturer/model not recorded; display resolution 1 rpm), and a conservative uncertainty of  $\pm 1\%$  of reading was assumed. All instruments were checked for functionality and repeatability prior to testing. For each wind-speed level, each configuration was tested in three repeated runs, with each run lasting 60 s.

## 2.4 Torque measurement

Shaft torque was measured using a rope brake dynamometer coupled to the turbine shaft. A rope was wrapped around a brake drum attached to the turbine shaft, and braking load was applied by adjusting the rope tension until the rotor reached a steady rotational speed at each wind-speed setting. The tensions on the tight side and slack side of the rope were quantified using two digital scales. Each scale reading was recorded as mass ( $m_1$  and  $m_2$ , in  $kg$ ) and converted to force using  $F = mg$ , where  $g = 9.81 \frac{m}{s^2}$ . The net braking force was computed as:

$$\Delta F = (m_1 - m_2)g \quad (1)$$

The shaft torque was then obtained from:

$$T = \Delta F * r_{eff} \quad (2)$$

where  $T$  is torque ( $Nm$ ) and  $r_{eff}$  is the effective brake radius ( $m$ ) defined as the drum radius plus half the rope diameter ( $r_{eff} = r_{drum} + 0.5 d_{rope}$ ), and was measured using calipers. During each 60 s run, scale readings and rotational speed were monitored and recorded after steady operation was achieved, and three repeated runs were performed per wind-speed level for each configuration.

## 2.5 Data reduction and performance parameters

Data were processed in MATLAB R2025b. Angular velocity ( $\omega$ ) was computed from rotational speed  $N$  (rpm) as:

$$\omega = \frac{2\pi N}{60} \quad (3)$$

Mechanical power ( $P$ ) was computed as:

$$P = T\omega \quad (4)$$

The tip-speed ratio ( $\lambda$ ) was computed as:

$$\lambda = \frac{\omega R}{V} \quad (5)$$

where  $R$  is rotor radius ( $m$ ) and  $V$  is wind speed ( $m/s$ ). The power coefficient ( $C_p$ ) was computed as:

$$C_p = \frac{P}{0.5\rho AV^3} \quad (6)$$

where  $\rho$  is air density ( $\frac{kg}{m^3}$ ) and  $A$  is the rotor swept area ( $m^2$ ). For an H-Darrieus rotor, the swept area was taken as:

$$A = DH \quad (7)$$

where  $D$  is rotor diameter ( $m$ ) and  $H$  is rotor height ( $m$ ). For each wind-speed setting,  $C_p$ -TSR performance curves were generated and compared between the clean and curved-GF configurations using the mean values from three repeated runs.

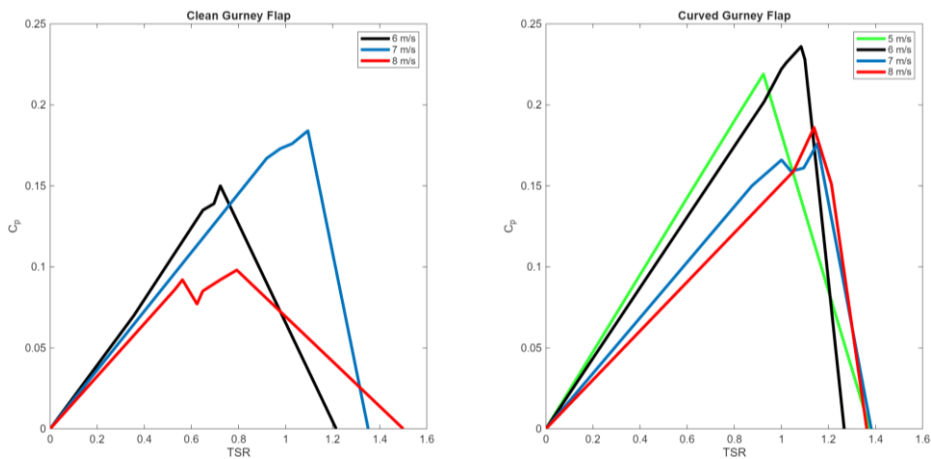
All reported  $C_p$  and TSR values were computed consistently for both configurations under the same wind-tunnel and measurement conditions. Performance curves ( $C_p$  versus TSR) were generated to compare the clean and curved GF configurations across the tested wind speeds.

### 3 Results

This section presents the measured steady-state performance of the clean baseline rotor and the curved GF rotor under wind-tunnel conditions. Results are reported in terms of tip-speed ratio (TSR) and power coefficient ( $C_p$ ), computed from tachometer rotational speed and rope-brake torque measurements as described in Section 2. Wind speeds from 3 to 8 m/s were investigated; however, steady-state rotation could not be sustained at 3–4 m/s under the present measurement procedure. Therefore,  $C_p$ -based performance results are reported for  $V = 5$ –8 m/s.

#### 3.1 Aerodynamic Efficiency ( $C_p$ -TSR characteristics)

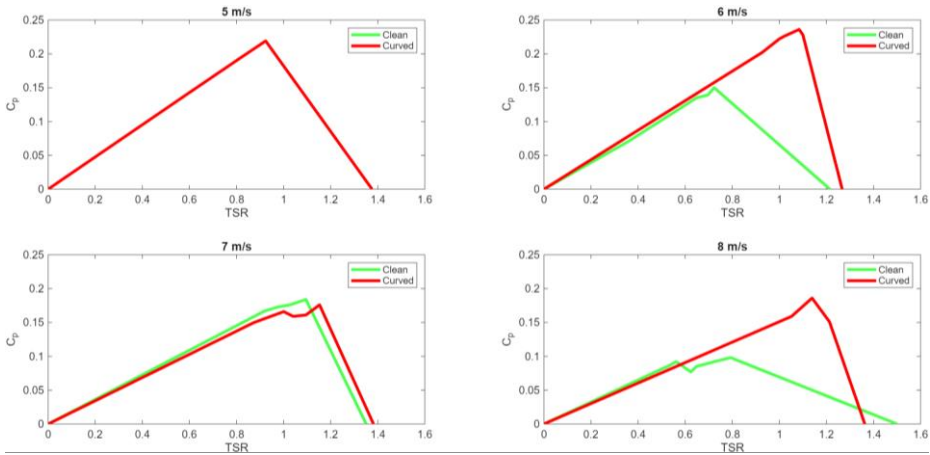
The aerodynamic efficiency of the turbine was assessed using  $C_p$ -TSR characteristics. Figure 2 compares the  $C_p$ -TSR performance of the two configurations for steady-state test points ( $V = 5$ –8 m/s). The clean configuration achieved a maximum  $C_p$  of 0.1845 at TSR = 0.92. In contrast, the curved-GF configuration achieved a maximum  $C_p$  of 0.2276 at TSR = 1.10, corresponding to a 23.43% increase in peak  $C_p$  relative to the baseline. Across the measured TSR range, the curved-GF rotor produced higher  $C_p$  values than the clean rotor, indicating improved aerodynamic efficiency, particularly in the low-TSR operating region.



**Fig. 2.** Power coefficient ( $C_p$ ) versus tip-speed ratio (TSR) for the clean and curved-GF configurations (wind-tunnel tests; steady-state data at  $V = 5$ –8 m/s). No steady-state data were obtained at 3–4 m/s due to unsustainable rotation.

### 3.2 Performance Across Wind Velocities (Cp trends)

Figure 3 summarizes Cp variation with wind speed for the steady-state test points ( $V = 5\text{--}8$  m/s), where each point represents the mean of three runs. The curved-GF configuration achieved  $C_p = 0.2193$  at  $V = 5$  m/s and increased to  $C_p = 0.2362$  at  $V = 6$  m/s. At  $V = 8$  m/s, the curved-GF configuration maintained  $C_p = 0.2276$ . The clean configuration exhibited lower Cp values at all measured wind speeds. Overall, the curved-GF rotor maintained a Cp advantage over the baseline across 5–8 m/s, indicating improved energy conversion under low-wind operation within the steady-state regime.



**Fig. 3.** Power coefficient ( $C_p$ ) versus wind speed for the clean and curved-GF configurations (mean of three runs per wind speed; steady-state data at  $V = 5\text{--}8$  m/s). No steady-state data were obtained at 3–4 m/s due to unsustainable rotation.

### 3.3 Summary of key results

The curved-GF configuration increased the peak power coefficient from  $C_p = 0.1845$  (TSR = 0.92) for the clean baseline to  $C_p = 0.2276$  (TSR = 1.10), representing a 23.43% improvement in maximum  $C_p$ . In addition, the curved-GF rotor maintained higher  $C_p$  values than the clean baseline across the steady-state wind-speed range of 5–8 m/s, demonstrating improved aerodynamic performance under the tested low-wind operating conditions.

## 4 Discussion

### 4.1 Interpretation of results

The results indicate that the curved Gurney flap (GF) improved the aerodynamic efficiency of the tested H-Darrieus VAWT under low-wind conditions. The curved-GF configuration increased peak  $C_p$  from 0.1845 to 0.2276 and maintained higher  $C_p$  values across the steady-state wind-speed range (5–8 m/s), indicating improved energy conversion under conditions where small VAWTs typically experience reduced lift-to-drag performance and intermittent separation.

The observed trends are consistent with the established aerodynamic role of Gurney flaps as passive lift-enhancement devices. By acting as a small trailing-edge tab, the GF increases the effective camber of the blade section and strengthens circulation, which increases sectional lift and improves the tangential force component responsible for torque production.

In addition, a GF promotes the formation of a stable near-wake vortex system at the trailing edge, effectively modifying the pressure distribution between the suction and pressure sides and increasing lift at moderate angles of attack. This mechanism is particularly beneficial for H-Darrieus turbines operating at low TSR, where blades experience large azimuthal variations in effective angle of attack and are prone to intermittent separation and dynamic stall. The curved GF geometry may further reduce abrupt separation by providing smoother flow turning at the trailing edge compared with a sharp-edged flap, helping maintain lift over a larger portion of the azimuthal cycle while avoiding a proportional drag increase under the tested conditions.

## 4.2 Comparison with related studies

The measured improvements in start-up threshold and  $C_p$ -TSR performance for the curved-GF configuration are consistent with previous investigations indicating that Gurney flaps can augment Darrieus-type turbine aerodynamics when the flap design is matched to the operating regime. Bianchini et al. [6] discussed the applicability of Gurney flaps for Darrieus turbine performance augmentation, supporting trailing-edge devices as a passive enhancement strategy. Zhu et al. [7] showed that GF geometric parameters can yield measurable performance gains in straight-bladed VAWTs, indicating that flap configuration is a key determinant of net benefit. Syawitri et al. [9] likewise demonstrated, through geometry optimization, that GFs can improve VAWT performance across TSR ranges, underscoring sensitivity to flap design and operating conditions. Liu et al. [8] further assessed an innovative GF concept for straight-bladed VAWTs and reported enhanced performance, reinforcing that trailing-edge modifications can provide practical gains when properly implemented. While a substantial portion of the prior literature emphasizes CFD-based evaluation and optimization, as exemplified by Syawitri et al. [9], the present study contributes complementary wind-tunnel evidence in the low-wind range (3–8 m/s).

## 4.3 Limitations and Future Work

This study is limited to wind-tunnel testing of a single rotor scale and a single curved Gurney flap geometry ( $h_{GF} = 0.05c$ ); therefore, the reported gains may not directly generalize to other rotor sizes or Reynolds number regimes, and the configuration should not be interpreted as optimized. The rope brake dynamometer may introduce uncertainty due to frictional effects, possible slip, and sensitivity to steady-state conditions; future work should include formal uncertainty quantification and, where feasible, independent torque/power validation. Further studies should also evaluate performance and durability under field-relevant inflow conditions (turbulence, gusts, and yawed flow) and conduct systematic geometry optimization (height, curvature, and placement) using combined CFD and experimental testing.

## 5 Conclusion

This study experimentally evaluated the steady-state aerodynamic performance of a small H-Darrieus vertical-axis wind turbine (VAWT) in two configurations: a clean baseline rotor and a rotor equipped with a curved trailing-edge Gurney flap ( $h_{GF} = 0.05c$ ). Wind-tunnel measurements at sustained operating conditions ( $V = 5$ –8 m/s) showed that the curved-GF configuration achieved higher  $C_p$ -TSR performance than the baseline. The maximum power coefficient increased from  $C_p = 0.1845$  at  $TSR = 0.92$  (clean) to  $C_p = 0.2276$  at  $TSR = 1.10$  (curved GF), corresponding to a 23.43% improvement in peak  $C_p$ . Across the measured

operating range, the curved-GF rotor maintained a consistent  $C_p$  advantage, indicating improved energy conversion under low-TSR operation. These results support curved Gurney flaps as a practical passive modification for enhancing the low-wind steady-state efficiency of small H-Darrieus turbines without introducing active control complexity. Future work should (i) optimize flap geometry and placement across Reynolds-number and scale effects, (ii) quantify measurement uncertainty and validate torque/power using an independent method, and (iii) assess robustness under field-relevant inflow conditions (turbulence, gusts, and yawed flow) and longer-duration operation.

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