Estimating Self-Starting Capabilities of Vertical-Axis Wind Turbines

Marin Ivanković [1,2], Marvin Jentzsch [2], Marinos Manolesos [3], Christian Navid Nayeri [2], Hrvoje Kozmar[1]

[1] *Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10000 Zagreb, Croatia*

[2] *Hermann-Föttinger-Institut, Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany*

[3] *School of Mechanical Engineering, National Technical University of Athens, Heroon Polytechniou 9, 15780 Zografou, Greece*

SUMMARY

This study presents a framework for estimating the aerodynamic characteristics of vertical-axis wind turbines (VAWTs), specifically designed to improve self-starting performance. The study is based on the small-scale wind-tunnel experiments. Blades were equipped with passive flow control devices (PFCDs), i.e., Vortex Generators (VGs) and Gurney Flaps (GFs). All studied cases yielded an improved VAWT performance compared to the baseline airfoil without PFCDs. More specifically, the blades with a GF with a height 2.5% of the chord length yielded a 43.5% decrease in the self-starting time,19.0% increase in the average static torque coefficient, 33.3% increase in the maximum average static torque coefficient, 31.9% increase in the maximal average power coefficient, 27.8% increase in the rated tip-speed-ratio, all considered relative to the blades of the baseline airfoil without PFCDs. These results indicate the suitability of VGs and GFs for the enhancement of the VAWT self-starting performance, while further work, e.g., studying the wake effect on the downstream blade, is still needed to entirely assess this topic.

Keywords: Vertical-axis wind turbine (VAWT), vortex generator (VG), Gurney flap (GF)

1. INTRODUCTION

Before a VAWT reaches its rated tip-speed-ratio (*TSR*), its blades regularly experience angles of attack (*AoA*) significantly greater than the critical one, so flow separation and the dynamic stall may occur, Damiola et al. (2023). The ability of the flow to remain attached can be enhanced by implementing passive flow control devices (PFCDs), e.g., vortex generators (VGs) and Gurney Flaps (GFs), Akhter and Omar (2021). VGs and GFs offer an optimal compromise between simplicity and performance improvements, e.g., Tayebi and Torabi (2024). An efficient procedure to enable a preliminary estimation of the VG and GF benefits, without the need for substantial computational resources, is particularly needed at this moment. For this purpose, a method for the static torque estimation of VAWTs equipped with VGs and GFs was developed by using experimental data obtained on the NACA0021 airfoil. The approach adopted in this study enables a quick assessment of various VGs and GF cases. It provides insights into the underlying physical phenomena.

2. METHODOLOGY

The effect of VGs and GFs on the self-starting characteristics of the NACA0021 airfoil-based VAWT was previously assessed using a simplified aerodynamic model, Worasinchai et al. (2016). In the present work, the following assumptions were assumed: a) inflow velocity is steady and uniform around VAWT blades, b) the effect of velocity is negligible during the entire self-starting since a VAWT rotates at low angular velocity, c) interaction between the blade and the wake of the upstream blade is negligible, d) load on VAWT blades is represented as the load on an airfoil during pitch motion. VAWT angular acceleration α, angular velocity ω and azimuthal position are calculated by the motion equations for circular motion:

$$\alpha(t) = \frac{T(t)}{I}, \tag{1}$$

$$\omega(t + \mathrm{d}t) = \omega(t) + \alpha(t)\mathrm{d}t, \tag{2}$$

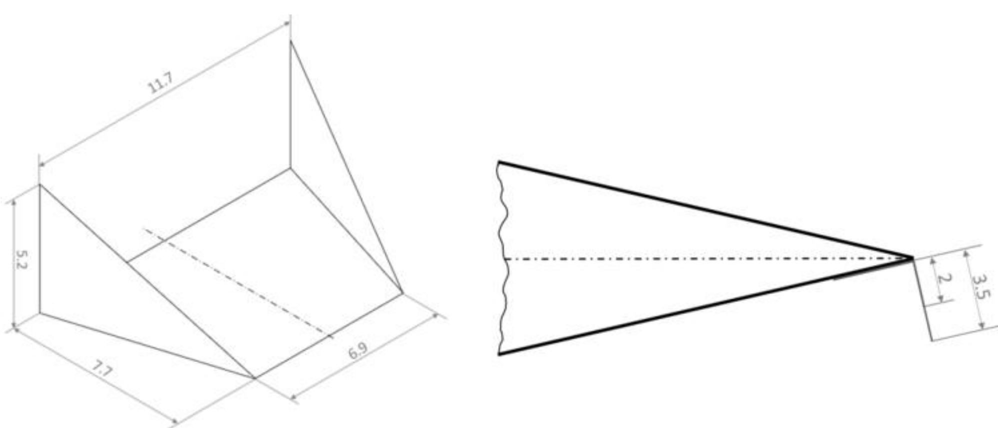
$$\theta(t + \mathrm{d}t) = \theta(t) + \omega(t)\mathrm{d}t + \frac{1}{2}\alpha(t)\mathrm{d}t^2, \tag{3}$$

where t, T and I are the time since the start of VAWT motion, the total aerodynamic torque on VAWT, the VAWT moment of inertia, respectively. The VAWT moment of inertia is determined for the assumption that the blades represent a point mass. The total torque is calculated by summing up the torque created by each VAWT blade,

$$T_{\mathrm{blade}} = -F_N k_N - F_T k_T - M, \tag{4}$$

where F_N, F_T, k_N and k_T are the normal and tangential forces relative to the wind direction, together with their distances from the axis of the VAWT rotation, respectively. All VAWTs considered in this work are H-type, whereas the number of blades is variable.

Four blade configuration cases, by Ivanković et al. (2026), are briefly outlined here. The baseline case is the NACA0021 airfoil-based blade section capable of rotating around 25% of its chord length ($0.25c$) point in a wind tunnel, VG blade is equipped with thirteen $0.037c$ high counter-rotating vane-type VGs placed $0.15c$ downstream of the leading edge, Figure 1a, smaller GF and larger GF blades are equipped with 2 mm ($0.014c$) and 3.5 mm ($0.025c$) high GFs on the trailing edge of the bottom airfoil surface perpendicular to the airfoil surface, Figure 1b.



a) b)

Figure 1. Schematic view of a) VGs, b) small and large GF, all lengths in mm, Ivanković et al. (2026)

The integration of the motion equation was performed in MATLAB, whereas it was observed that the integration time step of $\mathrm{d}t = 1 \cdot 10^{-4}$ s was necessary to achieve the convergence of the results. The second procedure was developed for the effect of the *TSR* on the torque and power coefficients, i.e., c_T and c_P. This approach provides insight in overall VAWT performance, whereas the rotational speed of wind turbine is also considered. This was achieved by forcing the rotation of the wind turbine at the constant TSR for one full circle and averaging the recorded c_T and c_P. This was repeated for all relevant $0 \leq TSR \leq 5$, with a step of 0.1 for various *TSR*.

3. RESULTS

A VAWT generally experiences c_T and c_P at various *TSR*. This encompasses several phases of the self-starting process of VAWTs, Worasinchai et al. (2016). The first phase is the linear angular acceleration, followed by the dead-band region of reduced, yet constant, acceleration, while the self-starting ends by a rapid acceleration until the VAWT settles on the optimal *TSR*. This is due to the changes that blades experience at various *TSR*, which yields different c_T and wind-turbine acceleration.

A comparison of the static torque estimated here and the one in Worasinchai et al. (2016) is shown in Figure 2a. There is a good qualitative agreement between the two methods, while some discrepancies are probably due to the airfoil type and its motion. This indicates that, despite the limitations, the proposed method is suitable for properly assessing the dominant trends of the self-starting phenomenon.

Figure 2b shows c_T for *TSR* in all VAWT cases. It can be observed that all studied cases yield an increased c_T for all *TSR,* whereas the increase is most pronounced for the larger GF case. An increase in c_T is observed for all *TSR*, thus indicating possible improvements in the self-starting time.

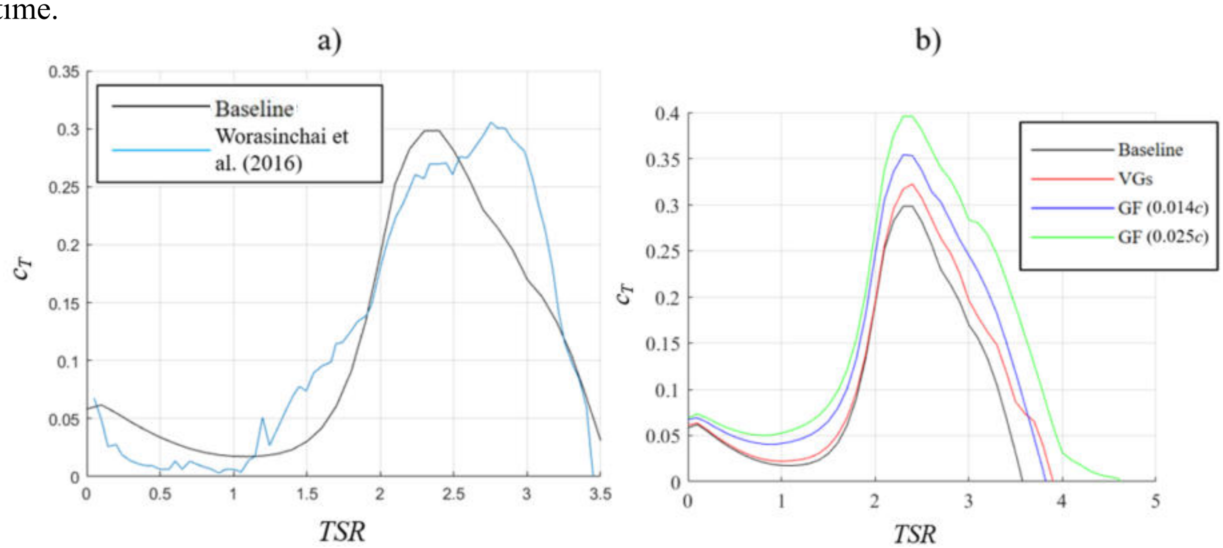


Figure 9. a) Our c_T for various *TSR* in comparison with Worasinchai et al. (2016), b) c_T for various *TSR* in all tested VAWT cases

A summary of the performance of each case, together with the percentage of improvement compared to the baseline case, is outlined in Table 4. These results clearly show that equipping the airfoil with any of the tested PFCDs yields significant improvements in the VAWT performance. In general, VGs improve blade performance only at *AoAs* close to the critical *AoA*, while GFs increase the lift and lift-to-drag ratio for a wider range of *AoAs*, thus yielding a larger VAWT performance increase when compared to VGs, proportional to GF height.

Table 4. Summary of improvements obtained by using VGs and GFs

	Average static c_T	Maximal average c_T	Maximal average c_P	Rated *TSR*	Self-starting time, s
Baseline	0.058	0.30	0.72	3.6	17.0
VG	0.061 (+5.2%)	0.32 (+6.7%)	0.77 (+6.9%)	3.9 (+8.3%)	16.5 (-2.9%)
GF small	0.067 (+15.5%)	0.35 (+16.7%)	0.85 (+18.1%)	3.8 (+5.6%)	12.8 (-24.7%)
GF large	0.069 (+19.0%)	0.40 (+33.3%)	0.95 (+31.9%)	4.6 (+27.8%)	9.6 (-43.5%)

4. CONCLUSIONS

An approach was developed to improve the self-starting characteristics of VAWTs equipped with VGs and GFs. The study is based on wind-tunnel experiments performed on the NACA0021 airfoil. The motion of a VAWT was estimated using motion equations. All studied VGs and GFs cases yield an improved VAWT performance relative to the baseline airfoil (without PFCDs). GF with a height of 0.025 of the airfoil chord length yields the largest enhancement, i.e., 43.5% decrease in the self-starting time, 19.0% increase in the average static torque coefficient, 33.3% increase in the maximum average static torque coefficient, 31.9% increase in the maximum average power coefficient, 27.8% increase in the rated tip-speed-ratio. The results indicate the suitability of VGs and GFs to enhance the self-starting of VAWTs. The obtained enhancements are influenced by modelling assumptions and the selected airfoil aerodynamics data. Further experimental validation is required to confirm the predicted trends and to quantify their practical significance.

ACKNOWLEDGEMENTS

The support of Deutsche Forschungsgemeinschaft (DFG) Project #446073296, Deutscher Akademischer Austauschdienst (DAAD), the Erasmus+ program, and COST Action CA20109 (MODENERLANDS) is gratefully acknowledged. This work was supported by the Croatian Science Foundation under the project number HRZZ-IP-2022-10-9434. Marinos Manolesos acknowledges support from H.F.R.I. in the framework of the "Basic research Financing (Horizontal support of all Sciences)" call, under the National Recovery and Resilience Plan "Greece 2.0" funded by the European Union – NextGenerationEU (H.F.R.I. Project Number: 016749). This paper has been funded by the European Union (NextGenerationEU) under the National Recovery and Resilience Plan 2021–2026 (NRRP), through the UNIZAG FSB institutional project "Structural aerodynamics", approved by the Ministry of Science, Education and Youth of the Republic of Croatia (component C3.2, source 581).

REFERENCES

Akhter, M.Z. and Omar, F.K., 2021. Review of flow-control devices for wind-turbine performance enhancement. *Energies*, *14*(5), 1268.

Damiola, L., Siddiqui, M.F., Runacres, M.C. and De Troyer, T., 2023. Influence of free-stream turbulence intensity on static and dynamic stall of a NACA 0018 aerofoil. *Journal of Wind Engineering and Industrial Aerodynamics*, *232*, 105270, 1-21.

Ivanković, M., Jentzsch, M., Manolesos, M., Nayeri, C.N. and Kozmar, H., 2026. Aerodynamic Characteristics of Airfoils Equipped With Gurney Flaps and Vortex Generators for the Entire Range of Pitch Angles. Wind Energy, 29(5), p.e70106.

Tayebi, A. and Torabi, F., 2024. Flow control techniques to improve the aerodynamic performance of Darrieus vertical axis wind turbines: A critical review. *Journal of Wind Engineering and Industrial Aerodynamics*, *252*, 105820.

Worasinchai, S., Ingram, G.L. and Dominy, R.G., 2016. The physics of H-Darrieus turbine starting behavior. *Journal of Engineering for Gas Turbines and Power*, *138*(6), 062605.