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Comprehensive review of the effect of flap technologies in H-Darrieus vertical axis wind turbines

H-Darrieus dikey eksenli rüzgâr türbinlerinde kanatçık teknolojilerinin etkisinin kapsamlı değerlendirilmesi

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Abstract

This study presents a comprehensive analysis of the application and impact of flap technologies on the performance of Vertical Axis Wind Turbines (VAWTs). As a type of flow control device, flap technologies are proven to enhance aerodynamic performance by delaying flow separation, increasing lift, and reducing drag. Numerous experimental studies and numerical simulations demonstrate how flap technologies significantly improve the efficiency of VAWTs, especially at low wind speeds. Additionally, the role of flap technologies in extending the operational wind speed range and enhancing the self-starting capabilities of VAWTs is highlighted. This enhancement is crucial as it contributes to the viability of VAWTs in urban and suburban settings where wind conditions are highly variable. This study delves into the optimal positioning and arrangement of flap technologies on turbine blades to maximize performance enhancement. Thus, the paper offers a thorough exploration of VGs (Vortex Generators) as a key aerodynamic modification for boosting the performance of VAWTs and encourages continued research and optimization in this area. Further development and refinement of flap technologies could lead to their broader adoption in renewable energy systems, enhancing both the efficiency and sustainability of wind power generation.

Keywords: Wind Energy, Vortex Generator, Vertical Axis Wind Turbine (VAWT), Passive Control, Flap

Öz

Bu çalışma, Dikey Eksenli Rüzgâr Türbinleri (DERT'ler) üzerinde Kanatçık teknolojilerinin uygulanması ve etkileri üzerine kapsamlı bir analiz sunmaktadır. Bir tür akış kontrol cihazı olan Kanatçık teknolojileri, akış ayrılmasını geciktirerek, kaldırma kuvvetini artırarak ve sürtünmeyi azaltarak aerodinamik performansı artırmış olduğu kanıtlanmıştır. Çeşitli deneysel çalışmalar ve sayısal simülasyonlar, Kanatçık teknolojilerinin özellikle düşük rüzgâr hızlarında DERT 'lerin verimliliğini önemli ölçüde nasıl iyileştirdiğini göstermektedir. Ayrıca, Kanatçık teknolojilerinin operasyonel rüzgâr hızı aralığını genişletme ve DERT'lerin kendiliğinden başlama yeteneklerini artırma rolü vurgulanmaktadır. Bu iyileştirme, rüzgâr koşullarının oldukça değişken olduğu kentsel ve banliyö ortamlarında DERT 'lerin uygulanabilirliğine katkı sağlaması açısından hayati öneme sahiptir. Bu çalışma, performans artırımını maksimize etmek için flap teknolojilerinin türbin kanatları üzerindeki optimal konumlandırılması ve düzenlenmesine derinlemesine inmektedir. Böylece, makale DERT 'lerin performansını artırmada anahtar bir aerodinamik modifikasyon olarak VG'leri (Girdap Jeneratörleri) kapsamlı bir şekilde ele almakta ve bu alandaki araştırma ve optimizasyonun devam etmesini teşvik etmektedir. Kanatçık teknolojilerinin daha da geliştirilmesi ve iyileştirilmesi, yenilenebilir enerji sistemlerinde daha geniş bir benimsemeye yol açabilir, rüzgâr gücü üretiminin hem verimliliğini hem de sürdürülebilirliğini artırabilir.

Anahtar kelimeler: Rüzgâr Enerjisi, Girdap Jeneratörü, Dikey Eksenli Rüzgâr Türbini (DERT), Pasif Kontrol, Kanatçık

1 Introduction

Nowadays, the need for energy, which is one of the basic needs of life, is increasing day by day [1]. Renewable energy sources, unlike their fossil fuel counterparts, offer an environmentally sustainable and inexhaustible supply of power with less carbon footprint. Fossil fuels, such as coal, oil, and natural gas, are not only finite but also contribute significantly to global warming due to the emission of greenhouse gases when burned [2]. The combustion of these fuels releases vast quantities of carbon dioxide ($CO2$), a major contributor to the greenhouse effect and climate change [3]. In contrast, renewable energy sources such as wind, solar, and hydroelectric power produce energy with negligible emissions and are thus less harmful to the environment [4]. Additionally, renewables are continuously replenished by natural processes, and their exploitation does not entail resource depletion; they are also relatively inexpensive [5]-[7]. The utilization of renewable energy sources also mitigates the geopolitical risks and price volatility associated with fossil fuel dependence. Furthermore, the advent of advanced technologies has made renewable energy increasingly cost-competitive. By transitioning to a renewable energy-dominated energy mix, we can significantly reduce our carbon footprint, improve energy security, and pave the way towards a sustainable future. Thus, renewable energy sources present a compelling alternative to fossil fuels, promising a blend of environmental stewardship and economic viability [8].

2 Wind energy

Wind energy, harnessed through the conversion of kinetic energy into mechanical or electrical energy by wind turbines, holds several advantages over other renewable energy sources. Unlike solar energy, which is dependent on daylight hours and clear skies, wind energy can be produced both day and night, irrespective of weather conditions, and in more locations globally. Additionally, wind farms, especially offshore

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installations, can scale up to very high capacities, enabling them to generate power on a utility scale. Wind energy also has one of the lowest water consumption footprints among all energy sources, making it a more sustainable choice in areas prone to water scarcity [9]. Moreover, advances in turbine technology have reduced costs and improved efficiencies, making wind energy increasingly cost-competitive. Thus, wind energy offers a potent combination of scalability, efficiency, and environmental sustainability that sets it apart from many other renewable energy sources.

3 Types of wind turbines

As seen in Figure 1 [10],[11], Wind turbines are divided into two types based on the direction of the axis: vertical and horizontal axis turbines [12],[13]. Vertical axis wind turbines (VAWTs) can accept wind from any direction, negating the need for complex yaw mechanisms to orient them towards the incoming wind [14]-[17] which is a requirement for HAWTs [18]. This omnidirectional characteristic makes them particularly suitable for areas where wind direction is highly variable. The generator and gearbox components of VAWTs are located near the ground, simplifying maintenance and reducing the need for robust and tall support structures [19]. In contrast, the heavy components of HAWTs are elevated high off the ground, complicating both their installation and maintenance. VAWTs exhibit better performance in turbulent wind conditions, making them a preferable choice for urban environments where buildings and other structures disrupt wind flow. Furthermore, VAWTs typically have lower cut-in wind speeds than HAWTs, meaning they can start producing electricity at lower wind speeds. VAWTs also tend to produce less noise, which makes them more suitable for residential settings [20].

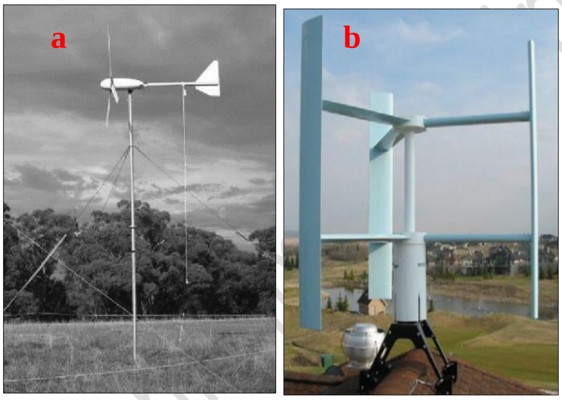


Figure 1. View of (a) HAWT and (b) VAWT [10],[11].

While their efficiency in terms of converting wind to electricity traditionally lags behind HAWTs [21],[22] recent advancements in design and technology are bridging this gap. Vertical turbines can be placed closer together, increasing potential power generation per unit of land area [2]. In HAWTs, the impact on bird populations is quite high [23],[24]; however, VAWTs, due to their shorter stature, are visually less obtrusive and potentially less harmful to bird populations. VAWTs offer a promising and complementary technology to HAWTs, particularly beneficial in settings where wind conditions, space constraints, noise concerns, or visual impact are key consideration.

4 Vertical axis wind turbine (VAWT)

As illustrated in Figure 2 [25],[26], VAWT are generally divided into two as Savonius and H-Darrius [27]-[29]. H-Darrieus turbines, often referred to as "lift-type" turbines , are more efficient than Savonius turbines [30], which operate based on "drag-type" forces [31], enabling H-Darrieus turbines to extract more energy from the wind, H-Darrieus VAWTs can operate at a wider range of wind speeds, providing greater operational flexibility [32],[33]. Furthermore, due to their aerodynamic design, H-Darrieus turbines can achieve higher rotational speeds, which can lead to a higher power output [34]. H-Darrieus VAWT have a more streamlined profile, making them less prone to structural stress and potentially more durable than their Savonius counterparts. Despite the advantages of VAWTs for urban areas, two main factors limit their production process and commercialization [35]. These constraints are low power performance and poor initial excitation issues [36],[37]

Figure 2. (a) Savonious and (b) H- Darrieus VAWT [25],[26].

5 Aerodynamics of the H- Darrieus VAWT

In the context of wind turbines, the tip speed ratio (TSR), represented by λ, is a dimensionless parameter. It is defined as the ratio of the blade tip velocity to the velocity of the free stream wind, expressed as follows [38]-[47]:

$$TSR, \lambda = \frac{R.\omega}{U_\infty} \quad (1)$$

where U_∞ denotes the free stream velocity, R represents the rotor radius, and ω is the angular velocity.

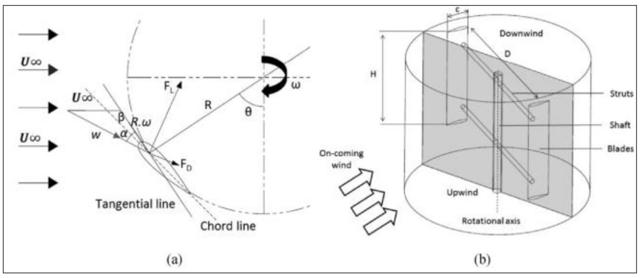


Figure 3. (a) Forces and velocities on H- rotor VAWT (b) Conceptual visualization of a H- Darrieus VAWT [38].

As illustrated in Figure 3, in contrast to horizontal axis wind turbines, the forces exerted on each rotor blade of a VAWT vary continuously with the azimuthal angle (θ). This variation in lift and drag forces across the airfoil results from the constantly changing angle of attack (α) on the blade due to the resultant wind velocity (w). The angle of attack is mathematically defined as the angle between the chord line of the blade and the direction of the resultant wind (w) approaching the airfoil [48].

$$= tan^{-1}\left(\frac{\sin\theta}{\lambda + \cos\theta}\right) - \beta \quad (2)$$

For a Darrieus rotor with a height H and the power (P) and the torque (T) exerted on the axis of the Darrieus turbine can be expressed as follows [49]-[54]:

$$C_T = \frac{T}{0.5.\rho.A.(U_\infty)^2} \quad (3)$$

$$C_P = \frac{P}{0.5.\rho.A.(U_\infty)^3} = \frac{T\omega}{0.5.\rho.A.(U_\infty)^3} = \lambda.C_T \quad (4)$$

$$P = 0.5.C_P.\rho.A.(U_\infty)^3 \quad (5)$$

where C_m and C_p are respectively the torque coefficient and the power coefficient.

6 H-Darrieus WAVT's flap configuration

Flap technology has been extensively studied in the context of HAWTs over the years, examining its impacts on enhancing turbine performance [55]-[58]. However, due to the unique characteristics of VAWTs such as omni-directionality [59], low noise [60], simpler structure, takes up less space and lower center of gravity [61]-[63], the application of flap technology to VAWTs has seen a rapid increase in recent years. The integration of flaps into VAWT design is being recognized as a transformative solution to enhance their efficiency, particularly in urban and low-wind environments where traditional HAWTs face limitations. Given the evolving landscape of wind energy technology and the pressing need for more adaptable and efficient energy solutions, flap technology is anticipated to play a dominant role in the future development of VAWTs.

As shown in Figure 4 [64], Flap technologies, typically associated with aerospace applications, can be integrated into VAWTs to improve their aerodynamic characteristics and overall performance [65]. By dynamically adjusting the angle of the flaps in response to varying wind conditions, the lift produced by the turbine blades can be maximized while the drag is minimized. This circumstance results in an increase in the rotational speed of the turbine, thereby boosting power output. One of the key benefits of this technology is the ability to tailor the turbine's performance to a wider range of wind conditions, including lower wind speeds. Flap technology allows the turbine to operate efficiently in low wind conditions by increasing the angle of attack, which would enhance lift and initiate rotation earlier than fixed-blade designs. At higher wind speeds, the flap angle can be reduced to avoid excessive forces that could damage the turbine, increasing the turbine's operational range and overall durability. Furthermore, flap technologies can also address one of the main issues of VAWTs - the variation in torque as the blades rotate. By adjusting the flaps, the torque produced by the rotor can be more evenly distributed, reducing vibrations and structural stress, thereby extending the lifespan of the turbine. The integration of intelligent control systems with flap technologies can provide real-time adjustment capabilities, further optimizing the performance of VAWTs based on the immediate wind conditions. This feature improves the overall energy capture efficiency and reliability of the turbine, demonstrating the potential of flap technologies as a promising innovation in VAWT design. Since flap technology has a remarkable effect on the performance of VAWT, it has been widely studied in the literature recently.

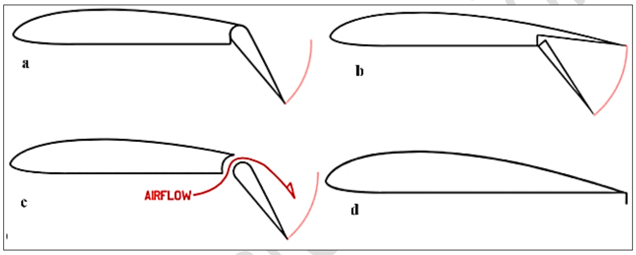


Figure 4. Schematic View of (a) Plain Flap (b) Split Flap (c) Slot Flap, (d) Gurney Flap (GF) [64].

6.1 Flapping flap

A flapping flap is a smaller control surface than the main wing, capable of dynamic movement, typically designed to enhance aerodynamic performance. When used in wind turbines, these small wings can actively manage airflow over the blade, thereby increasing the turbine's self-starting capability and optimizing energy production in low-wind conditions.

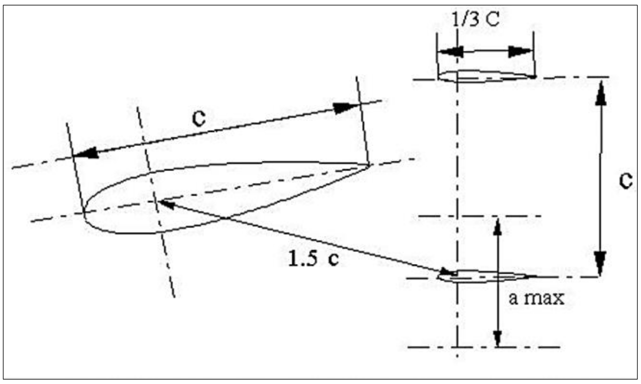


Figure 5. Configuration of the pair of flapping wings attached to the main blade of the turbine [66].

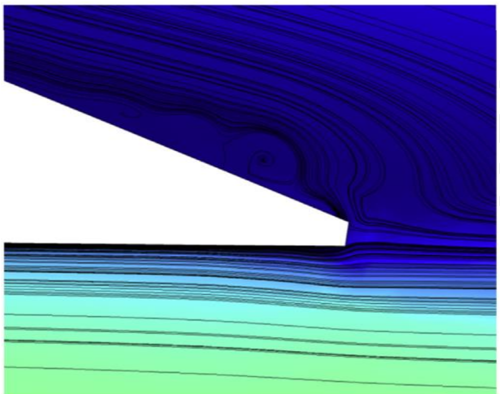
Bouzahera and Hadid's study addresses the prevalent challenges in optimizing the performance of VAWTs, particularly focusing on issues such as dynamic stall and the interference caused by vortices and wakes generated by the turbine blades. The central proposition of this study is the integration of a dynamic control device, which involves attaching a pair of biplane-configured flapping wings to each turbine blade, as depicted in Figure 5. This bio-inspired or biomimetic approach aims to control and modify the airflow around the blades to reduce the adverse effects of vortices and wakes.

Key findings indicate that the proposed model significantly improves the reattachment of the boundary layer and drastically reduces the magnitude of vortices around the blades. At attack angles of 12° and 20°, the implementation of the flapping wings leads to a notable decrease in radiated noise by 0.51 dB and 4.40 dB respectively, while also delaying stall by approximately 3°.

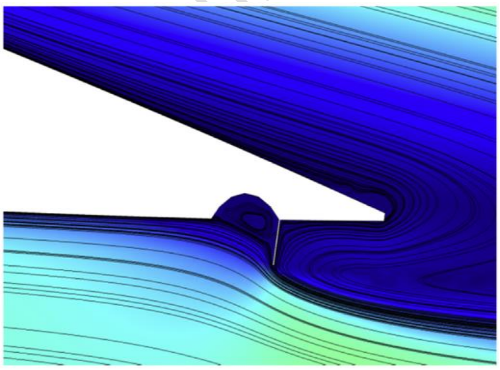
Moreover, the analysis reveals that the positive pressure region around the suction surface of the blades widens significantly, enhancing the ultra-low static pressure areas. This adjustment results in a more uniform pressure distribution across the blade surfaces, thereby increasing the lift coefficient substantially. The overall lift-drag ratio of the VAWT sees a remarkable improvement, confirming the potential of this approach to not only enhance the operational efficiency of VAWTs but also extend their applicability in various wind conditions. In conclusion, the study by Bouzahera and Hadid provides compelling evidence that the integration of biplane-configured flapping wings as a dynamic control mechanism can profoundly improve the performance of VAWTs [66].

6.2 Plain gurney flap (GF)

A Gurney flap is a small, vertical tab or protrusion that is typically mounted perpendicularly to the trailing edge of a wing or airfoil profile. This structure is generally used to direct the aerodynamic interaction on the wing. The primary purpose of the Gurney flap is to influence the airflow over the wing, helping to better manage the flow. Although it is a structurally simple addition, this minor modification can significantly affect the dynamics of the airflow.



(a)



(b)

Figure 6. Flow separation near the trailing edge (TE) for the (a) standard NACA-0015 blade and (b) optimized (both gurney and dimple) aerofoil angle, θ= 60° [67].

Ismail and Vijayaraghavan's study explores optimizing a NACA-0015 airfoil used in VAWTs through profile modifications that include a combination of an inward semi-circular dimple and a Gurney flap on the lower surface, as depicted in Figure 6. The primary objective is not merely to enhance the lift coefficient or the lift-to-drag ratio but to optimize the average (or effective) torque of the VAWT, a more critical indicator of the turbine's power output. The optimization process employs a fully automated Response Surface Approximation (RSA) method, crucial for maximizing the average torque produced by the wind turbine blade. Data necessary for RSA optimization were obtained from CFD simulations conducted at a Reynolds number of approximately 2.55 x 10^5 and a tip speed ratio of 3.5. Figure 6 illustrates the flow recirculation created by the dimple and flap setup at the trailing edge (TE) of the optimized airfoil. This recirculation enhances the lift force, particularly at a positive angle of attack, thereby boosting the value of the tangential force. The results indicate that this optimized combination significantly increases the tangential force by about 35% in steady state and 40% in oscillating conditions (at each revolution). The improvements in tangential force directly contribute to increased torque output, thus enhancing the overall efficiency and effectiveness of the wind turbines [67].

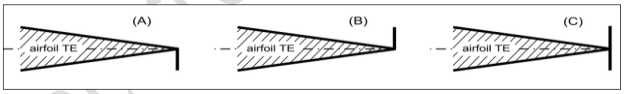


Figure 7. Various compared GF configurations: (a) GF_{in} airfoil (b) GF_{out} airfoil (c) GF_{pair} airfoil [68].

Bianchini et al. comprehensive study focused on optimizing the aerodynamic performance of Darrieus VAWTs using Gurney Flaps (GFs). This work includes an illustration of three different types of Gurney Flaps, as shown in Figure 7. The researchers found that applying a 2%c GF to the inner side of the airfoil increased the peak lift coefficient by 58% compared to the baseline configuration without GFs. This modification notably shifted the entire lift curve upwards while only mildly affecting the static stall angle and not significantly altering the drag coefficient. Dynamic simulations of a single-blade Darrieus turbine equipped with the same GF configuration to isolate and analyze the aerodynamic changes induced by the GFs. The study compared three GF mounting configurations: on the inner side, on the outer side, and on both sides of the rotating airfoil, each analyzed at a TSR of 3.3. The results highlighted a 23.1% increase in C_P at TSR = 3.3 when the GF was mounted on the inner side. In contrast, mounting the flap on the outer or both sides promoted vortex shedding at high-TSR rotating regimes, which could potentially lead to performance losses. To extend the findings, the study evaluated the effects of varying the size of the GF, examining heights of 2%c, 3%c, and 4%c. This analysis revealed that larger GFs could further enhance the power extraction capabilities of the blade, indicating a broader applicability of this approach across different operational regimes of the turbine. Ultimately, the research was scaled up to a three-blade H-Darrieus turbine equipped with NACA0021 airfoils to obtain preliminary results for a more complex system. Applying a 3%c GF on the inner side of the airfoils at TSR = 2.4 resulted in a 21.3% increase in C_P, showcasing the potential of GFs to significantly boost the energy yield capability of VAWTs. Study concluded that GFs represent a promising and effective solution for enhancing the aerodynamic performance of Darrieus turbines, particularly in terms of C_P improvements at lower operational speeds. While the introduction of GFs involves additional material and potential increases in drag, the overall benefits in terms of enhanced power output and more stable operation under varying wind conditions justify further exploration and potential implementation in new turbine designs or as retrofitting solutions in existing setups. [68].

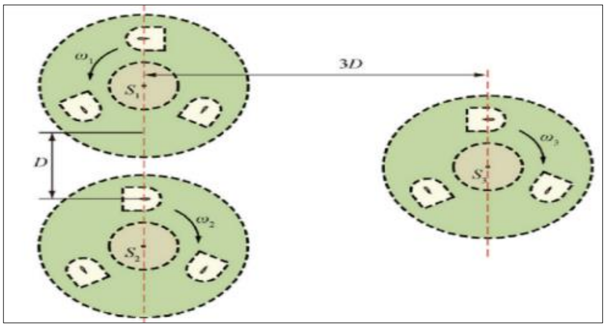


Figure 8. The layout of VAWTs in sequence configurations [69].

As indicated Figures 8 and 9, the influences of the GF and solidity on the performance of VAWTs in three-turbine array configurations were investigated by Ni et al. using CFD simulations. It was found that an increase in the TSR of the upstream pair of VAWTs in these configurations resulted in a higher flow velocity through the gap, increasing power output at high TSRs compared to an isolated turbine. When a GF was added to the upstream VAWTs, an increase in flow velocity through the gap was observed, enhancing the power output of the downstream rotor. Notably, the best performance was noted in the downstream rotor in configurations composed of three GF-VAWTs at TSR < 3.1, showing a maximum average torque increase of up to 36.5% compared to the isolated bare turbine. at all TSRs, it was observed that downstream VAWTs in array configurations outperformed their isolated counterparts in power output, with optimal instance showing a 23.1% increase at TSR = 2.27 when the chord length was 123.5 mm [69].

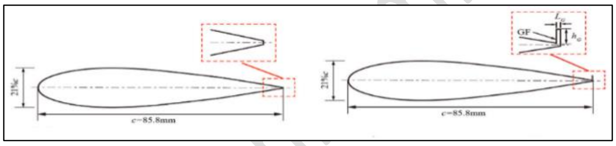


Figure 9. Wind turbine blade model with integrated GF [69].

The impact of the geometric parameters of the GF on the aerodynamic performance of SB-VAWTs was investigated by Zhu et al. through a comprehensive numerical analysis. A novel mathematical model was proposed by the researchers to enhance the reliability of the numerical simulations, taking into account the resistance torque of struts. The findings suggested that the GF significantly improved the aerodynamic performance of SB-VAWTs, with enhancements of up to 21.32% observed at reduced rotational velocities. It was shown that the GF increased the blade tangential force in the upstream area and effectively mitigated aerodynamic losses downstream, especially with a shorter GF. The optimal design parameters for the GF were determined to be a height of 0.75% of the chord length and a width of 0.12% of the chord length, based on an analysis of the C_P curve [70].

As illustrated in Figure 10, the impact of the cavity's vortex trapping capability and the lift improvement mechanism of the GF on the aerodynamic efficiency of the SB-VAWT was investigated by Liu et al.. An active flow control technique was proposed, which involved a pivoting GF that adjusted its position as the airfoil rotated, in an effort to eliminate the flow resistance caused by the GF in the windward zone. CFD simulations were conducted, and the power augmentation potential of a movable cavity-GF (c-GF) was compared to a traditional fixed cavity-GF under various control strategies. The results showed an increase in the CP of the movable c-GF by more than 20% compared to the bare configuration. The movable cavity-GF was discovered to have notable advantages. These include achieving superior power output during the downwind rotation and effectively mitigating the resistance effect in the upwind zone, a problem caused by the fixed c-GF. Particularly at lower TSRs, the benefits of the movable c-GF were distinctly apparent, highlighting its potential utility in the design of new turbines as well as the retrofitting of existing ones [71].

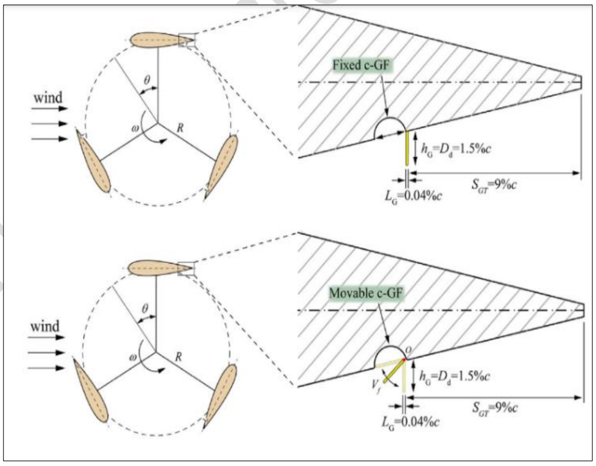


Figure 10. Dimple mounted VAWTs blade with movable and fixed flap [71].

The optimization of GF geometries on a three-SB VAWT was investigated by Syawitri et al. using CFD and the Taguchi method. As indicated Figure 11, the research involved modifying a basic VAWT model by attaching a GF to the TE of a NACA 0021 airfoil. The GF, which was rectangular in shape, had a fixed thickness of 0.33% of the c, while parameters such as its height (H), the mounting angle (θ_{GF}), and the distance from the TE was adjusted in the course of conducting geometry optimization studies. The blade rotating effect was considered at three different TSRs encompassing low, medium, and high ranges. A hybrid RANS-LES model combining stress-blended eddy simulation with the transition SST turbulence model was used in the study. It was found that the optimization of GF geometries should take into account multiple rotating blades rather than a single stationary blade, due to the varying optimal GF geometries and their performances across TSR ranges. The results revealed that the VAWT with GF showed a substantial improvement in C_P at low TSRs (up to 233.19%). The fact that flap structure significantly increases power performance at low TSRs is an indication of the positive effect of flab on self-starting ability. However, this improvement was found to diminish as the TSR range increased, with C_P enhancements of up to 69.94% and 41.36% observed at medium and high TSR ranges, respectively. From a scientific perspective, this study underscored the importance of considering multiple rotating blades in the optimization of GF geometries for VAWTs and provided valuable insights into the performance variations of the VAWT-GF system across different TSR ranges [72].

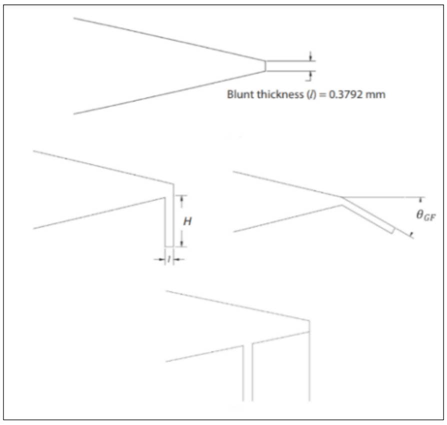


Figure 11. View of bare VAWT and VAWT with GF geometry [72].

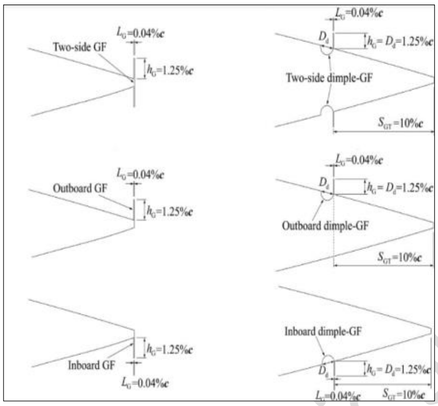


Figure 12. Various dimple and GF configuration [73].

The efficiency of straight-bladed (SB) VAWT was aimed to be boosted by Zhu et al. by incorporating inboard, outboard, two-sided GF, and dimple-GF. An illustration of the geometries of the GF and the dimple-GF at the TE of the NACA0021 airfoil is provided in Figure 12. In the study, the optimal height of the GF was determined to be 1.25% of the chord length (c), hence all GFs in the paper were of this height. The GF width was set at 0.04% of c, while the diameter of the dimple equaled the height of the GF. The TE's distance from the GF was set at 0.1c. The C_P, C_T, vorticity field, and standard deviation of fluctuating aerodynamic loads were assessed using 2D (Computational Fluid Dynamics) CFD simulations. The findings suggested that GFs of all types could enhance the CP within a certain TSR range. Using an outboard dimple-GF, the maximum C_P was found to be increased by 17.92% at a TSR of 3.1, compared to a Bare SB-VAWT with a solidity of 0.25. It was also shown that at all TSRs, the scale and vorticity magnitude of the trailing vortex could be significantly reduced by the two-sided dimple-GF. It was found that when the blade number was five, the aerodynamic performance decreased and load fluctuation was minimized due to intense interactions between the TE vortices of multiple blades [73].

6.3 Adaptive flap

An adaptive flap is a movable aerodynamic component located on the wing surface that can be adjusted according to various flight conditions. These flaps are designed to change their shape or angle when necessary to optimize airflow and aerodynamic efficiency. During flight, adaptive flaps can be adjusted in real-time, enhancing aircraft performance and offering a more efficient and flexible flying experience. In wind turbines, adaptive flaps are used to increase the efficiency and adaptability of turbine blades to wind conditions. These flaps automatically adjust based on wind speed and direction, optimizing energy production and maximizing turbine performance.

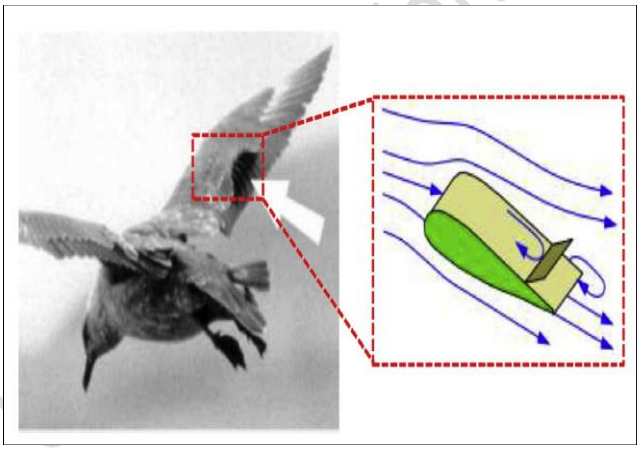


Figure 13. Feathers on bird's wing are raised at the end by flow separation [74].

An adaptive flap model was developed, inspired by the feather arrangement on a bird's wing as depicted in Figure 13. Hao and Li's research focused on the effectiveness of adaptive flaps in reducing flow separation and improving power efficiency in VAWTs through CFD simulations. Their findings revealed that the application of a composite torque to control flap angles resulted in significant enhancements, with the C_P of the VAWT increasing by 54% at a TSR of 0.6 and by 12.8% at a TSR of 1.2. The adaptive flaps demonstrated superior performance compared to leading-edge (LE) serrations, particularly at lower TSRs, significantly aiding the startup phase of VAWTs. Further optimization could involve adjustments in flap length and positioning to better suit the dynamic flow field conditions typical in VAWTs [74].

As indicated Figure 14, the use of an adaptive flap as a novel flow control technique in a high solidity VAWT was explored by Hao et al., with the aim of mitigating the issue of flow separation. The research involving CFD simulations with the shear-stress transport (SST), k-ω model, and the movement of the flap was computed using the fluid-solid interaction methodology. The findings showed that the flap, driven by the backflow resulting from flow separation, effectively blocked this backflow, leading to the mitigation of flow separation and enhancement of the aerodynamic torque of the blades. The negative impact of a long flap due to its untimely retraction at high TSRs was acknowledged in the study. It was noted that a shorter flap, positioned further from the blade LE, circumvented this issue, and a shorter flap closer to the blade LE performed better at low TSRs. The necessity for flow control had been emphasized in order to ensure separation on the outer side of the blade, a requirement that was particularly apparent at a high TSR of 1.5. Under these conditions, an increment in the C_P rate of 29.9% had been achieved, marking a threefold improvement compared to the scenario where the flap was set only on the inner side. These findings offered a theoretical foundation and a practical approach to addressing flow separation in VAWTs [75].

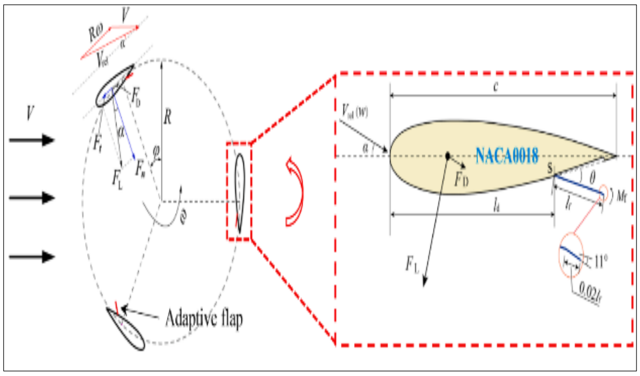


Figure 14. VAWT with the adaptive flaps [75].

Tanürün's study, employing CFD simulations on a VAWT with an adaptive flap, demonstrated notable performance improvements through optimization using the Taguchi method. The optimal flap settings identified were flap position (l_d = 0.65c), flap length (l_f = 0.15c), flap angle (θ= 70°), flap tip length (l_t = 0.06c), and angle of the flap tip length (α_{tip}= 8°), resulting in a C_P 74.01% greater than a conventional VAWT at a TSR of 2.62. Statistical analysis revealed that the flap position contributed most significantly to performance enhancement (39.58%), while the angle of the flap tip length contributed the least (1.34%). These findings underscore the effectiveness of the adaptive flap in enhancing the wake and vertical strength behind the turbine blade, substantiating its potential to significantly elevate VAWT performance [76].

6.4 Serrated gurney flap (SGF)

A serrated gurney flap is a type of aerodynamic control surface with a notched or jagged edge, similar to a serrated knife. The purpose of this design is to manipulate the boundary layer flow over the surface, which can reduce aerodynamic noise and potentially improve the efficiency of airflow around the flap. In applications like wind turbines and aircraft, serrated flaps are used to decrease sound emissions and manage flow separation, which occurs when the airflow breaks away from the surface of the blade or wing. By controlling this separation, serrated flaps can enhance the performance and reduce the noise of the system. This makes them particularly useful in environments where noise reduction is crucial, such as in urban areas or near residential zones.

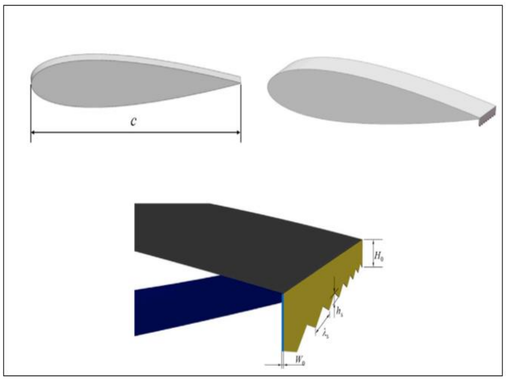


Figure 15. Schematic diagram of SGF airfoil [77].

Based on the research conducted by Hu et al., a comprehensive analysis using the SST k-ω turbulence model, Large Eddy Simulation (LES), and Proper Orthogonal Decomposition (POD) methods has provided insights into the aerodynamic effects and noise reduction capabilities of serrated Gurney flaps (SGFs) on wind turbine airfoils, as shown in Figure 15. The study particularly focuses on the static pressure and vorticity modes at attack angles of 12° and 20°, comparing the airfoil with SGFs against the baseline model. The implementation of SGFs, with a configuration of 6.7%c width and 0.8%c height, significantly enhances the lift coefficient of the airfoil across the investigated attack angles. It is observed that SGFs delay stall by approximately 3°, a critical factor in maintaining aerodynamic efficiency under higher angle conditions. Moreover, the noise radiated by the airfoil sees a substantial reduction, decreasing by 0.51 dB and 4.40 dB at 12° and 20° respectively. This noise reduction is attributed to the alterations in flow behavior induced by the SGF, particularly in modifying the vorticity and distribution of static pressure across the airfoil surfaces. The SGFs notably influence the pressure distribution by widening the positive pressure zone on the pressure surface and significantly improving the ultra-low pressure regime on the suction surface. This adjustment leads to a more uniform pressure distribution across the suction surface, thereby enhancing the lift-drag ratio of the airfoil equipped with SGF. The positive alterations in the static pressure distribution contribute to the overall aerodynamic efficiency by improving lift while reducing drag. POD analysis highlights its effectiveness in extracting the most relevant modes associated with the airfoil surface radiated noise and unsteady flow features. The main vorticity modes identified suggest that vortices predominantly affect the suction surface from the LE to the TE, marking them as a significant unsteady feature of the local flow at an attack angle of 12°. When the angle of attack reaches 20°, the primary unsteady characteristics evolve into shedding vortices at the leading edge, large-scale separation vortices on the suction surface, and wake vortices, indicating a shift in the flow dynamics with increasing angle. Furthermore, the study elucidates the role of SGF serration's span structure in influencing the vorticity mode distribution. The crests and troughs of the serrated flaps differentially affect the evolution of trailing vortices, which in turn impacts the effective curvature of the airfoil and enhances lift. The backward movement of the vortex separation point due to SGF not only delays stall but also contributes to noise reduction by decreasing the vorticity magnitude [77].

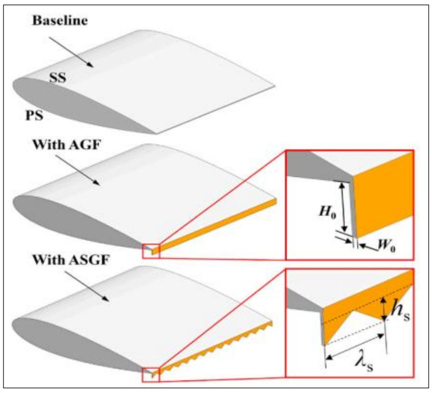
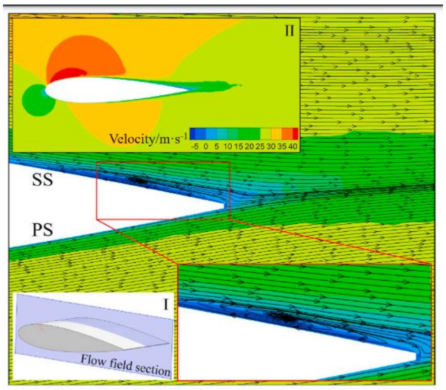
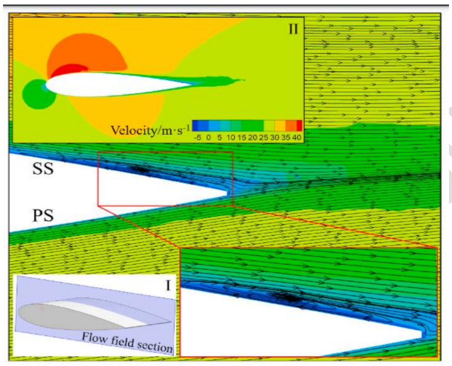


Figure 16. Schematic diagram of baseline, GF and, SGF [78].



(a)



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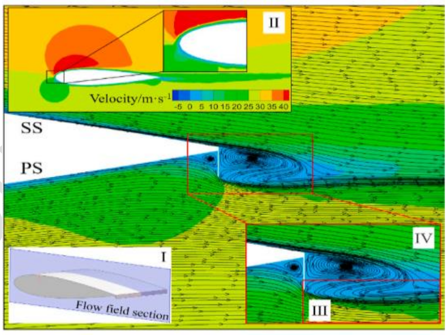


(c)

Figure 17. Velocity distribution and streamlines (a) airfoil (b) gurney (c) gurney and serrated around TE [78].

Ye et al. research investigates the aerodynamic improvements of a novel serrated Gurney flap (SGF) on a NACA0018 airfoil, comparing the baseline Gurney flap with serrated models as illustrated in Figure 16. Utilizing sophisticated aerodynamic models, including the SST k-ω turbulence model and large eddy simulations, the study assesses the impact of the SGF on the airfoil's performance, particularly in terms of lift enhancement, stall delay, and noise reduction.

The research demonstrates that the implementation of SGFs at the TE of the airfoil significantly improves the aerodynamic properties and reduces noise levels. Specifically, the optimized SGF configuration, SGF-0.8-6.7, leads to a notable increase in the lift-to-drag ratio by 8.61%, delays the attack angle of stall by 3 degrees, and achieves a maximum noise reduction of 10.2 dB compared to the baseline airfoil configuration. These improvements are attributed to the SGF's ability to enhance the stability of shedding wakes and lower energy losses, ultimately leading to superior aerodynamic performance and reduced acoustic disturbances.

Further detailed analysis of the airfoil with SGF reveals that the configuration enhances the pressure difference between the pressure side (PS) and the suction side (SS) of the airfoil. This results in a 50% increase in the coefficient of pressure (CP) at the leading edge on the SS, while maintaining a similar CP distribution on the PS. The study also investigates the flow field characteristics, showing that the SGF causes significant changes in flow velocity and direction at the TE, expanding the wake zone and shifting it downwards. This modification increases the effective camber and lift of the airfoil.

The findings from the study also include an examination of the size and distribution of shedding wake vortices. The baseline configuration exhibited the largest wake vortices, while the installation of SGFs effectively altered the vorticity around the airfoil, particularly near the pressure surface. The flow field near the TE for different configurations (baseline, GF, SGF-0.8-6.7) under an angle of attack of 6 degrees was meticulously analyzed Figure 17 provides a comparative analysis of flow separation and the size of wake vortices across different configurations behind the SGF. Figure 17 (a) shows that for the baseline configuration, flow separation occurs at a location of 95%c on the SS, resulting in a clockwise-rotating vortex with minimal impact on the wake generated by the airfoil. Figures 11(b) and 11(c) demonstrate significant changes in the flow near and especially around the pressure surface for the GF and SGF-0.8-6.7 configurations, respectively. These changes enhance the effective camber and lift while reducing the size of wake vortices and promoting a more uniform flow profile.

Additionally, the comparative analysis across configurations revealed that the velocity gradient on the SS around the leading edge is more pronounced for the GF than for the SGF, indicating a more effective management of the vortex zone behind the flap in the SGF configuration [78].

6.5 Split and slot flaps

Split and slot flaps are two different types of flaps used to optimize aerodynamic performance in wind turbines. The split flap is mounted on the underside of the turbine blade and opens to redirect airflow, providing more lift, but typically increases drag due to increased friction. On the other hand, the slot flap is designed with a small gap between the flap and the blade; this gap directs high-energy airflow over the blade to correct the airflow and maintain aerodynamic connectivity even at low speeds. Both types of flaps help wind turbines adapt to varying wind conditions and enhance energy production efficiency.

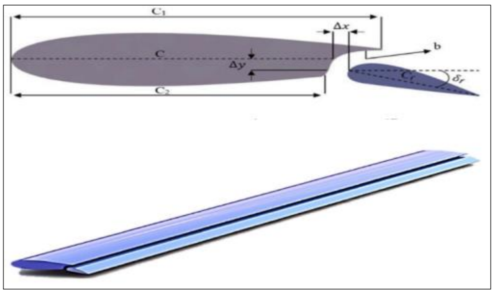


Figure 18. Three-dimensional representation of a turbine blade equipped with a slotted deflective flap [79].

As illustrated in Figure 18, the performance an H-type Darrieus VAWT was aimed to be optimized by Attie et al. through the incorporation of a single-slotted deflective flap at the blade's TE, targeting the issue of dynamic stall and boundary layer separation (BLS) that impeded turbine performance. Optimization was performed using Design of Experiments (DOE) and Computational Fluid Dynamics (CFD) methods, with a focus on the overlap (Δx), deflection angle (δf) and flap's gap (Δy) parameters. The impact of each parameter was determined through the DOE method, revealing the optimal design parameters for the VAWT to be Δx = 2 mm, Δy = 0.5 mm, and δf = 90 at 3 λ. Power output increases of 27% and 19% were demonstrated by two-dimensional (2D) and three-dimensional (3D) CFD simulations, respectively, when using these optimized parameters. A delay in BLS and mitigation in vortex shedding, attributed to high-pressure flow through the slot, were indicated by the simulation results [79].

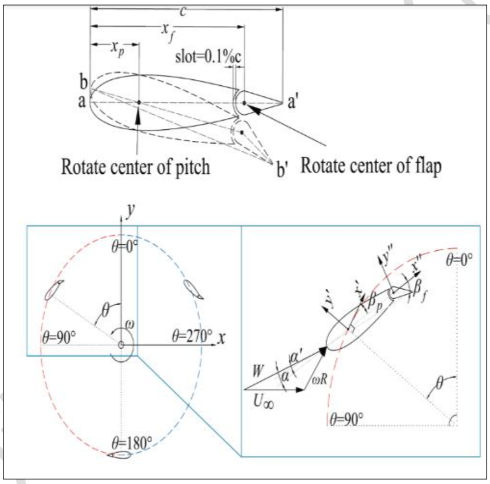


Figure 19. The diagram of the blade and VAWT equipped with a flap along its rotation [80].

As shown in Figure 19, an innovative active control strategy and a new blade structure featuring a slot flap for H-type VAWTs were aimed by Han et al., at enhancing power outputs at various TSRs. The movement of pitch and flap at low to moderate TSRs was optimized using the orthogonal experiment design method. The output characteristics, including the C_P, C_T, tangential force, and thrust of the optimized pitch-flap model, were compared against three other models: the base, pitch-only, and flap-only models. It was observed that flow separation was effectively mitigated and the dynamic stall around the blade was delayed due to the coordinated motion of pitch and flap, resulting in substantial efficiency improvements The optimal aerodynamic performance of the VAWT had been observed at specific flap position, pitch amplitude, and flap amplitude at certain TSRs: at λ =2.05, these were identified as flap position=0.95c, pitch angle=8°, and flap angle =15°, while at λ =2.65, they had been determined as flap angle =0.95c, pitch angle = 6°, and flap angle =10°.The implementation of enhanced sinusoidal pitch and flap movements had substantially improved the power efficiency characteristics of the VAWT at low and medium TSRs, exhibiting an enhancement in C_T of over 130% and 60% for low and medium TSRs respectively when compared to the bare VAWT [80].

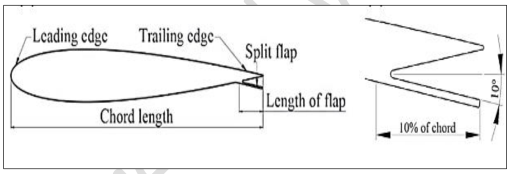


Figure 20. (a) NACA0015 airfoil featuring a split flap (b) Close-up view of the split flap [81].

As shown in Figure 20, A design method for enhancing the performance of a 3.5 kW H-type VAWT with NACA0015 airfoil by installing split flaps at the blade's TE was proposed by Zhang et al.. The effects of flap length (10%-30% c), position (70%-90% c), and deflection angles (10°-30°) on VAWT performance were examined using 2D URANS equations, with a Reynolds number of 2x10^5 and a TSR between 1 and 3. By maximizing the wind energy utilization ratio (C_{Pmax}) and the efficient operating range ($\Delta\lambda_{max}$), optimal parameters were determined to be a flap length of 22% c, a deflection angle of 10°, and an arrangement position of 92% c. After the installation of the split flaps, an increase of 5.8% in C_{Pmax} and 25.9% in $\Delta\lambda_{max}$ was observed. The Kutta-Joukowsky TE boundary condition was found to be altered by split flaps, which increased the flow circulation around the blade and improved the aerodynamic performance of VAWTs by increasing the positive pressure difference in the upwind area and reducing the negative pressure difference in the downwind area [81].

6.6 Several other types

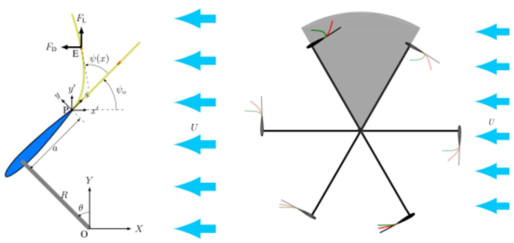


Figure 21. a) Aerodynamic forces acting on a segment of the flexible blade when it is at the azimuthal static position θ. b) The starting torque generated by flexible blades across various dimensionless wind speeds, accompanied by overlaid images illustrating the vertical axis wind turbine with flexible blades affixed to the TEs of the airfoil-shaped blades [82].

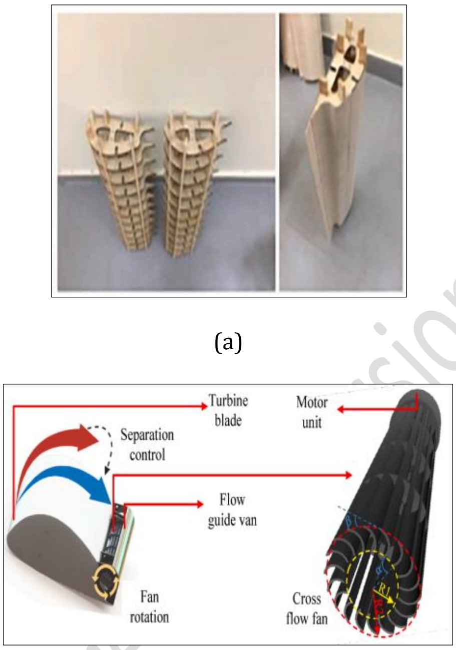
Tavallaeinejad et al. explored innovative self-starting mechanisms for Darrieus SB VAWTs, focusing on the use of pliable plates to overcome the inherent self-starting difficulties of these turbines, as shown in Figure 21, particularly in urban environments where consistent self-starting is crucial. The proposed designs involve two distinct configurations: flexible blades directly attached to the TE of rigid airfoil-shaped blades, and blades attached to separate arms positioned at specific orientation angles.

The results from numerical simulations demonstrated that the innovative configurations allowed the turbines to self-start effectively. The flexible blades were shown to generate sufficient torque to overcome the dead band in the turbine's rotation, particularly at low wind speeds. This was quantified as a notable increase in the starting torque, with improvements in static torque coefficients observed, leading to a self-starting capability that was absent in the traditional designs.

In the specific scenarios tested, the turbines equipped with the new self-starting mechanism were capable of initiating motion from a stationary position, which is a significant advantage over conventional H-type VAWTs that lack such capability. The optimized configuration, where flexible blades were placed on the inner side of the airfoils, consistently outperformed a Savonius-based mechanism across a range of azimuthal angles, offering better self-starting characteristics.

The study concluded that flexible blades attached in either of the proposed configurations could significantly enhance the self-starting performance of VAWTs. These configurations not only simplify the design and reduce manufacturing and maintenance costs but also improve reliability compared to more complex mechanical or electrical starting mechanisms.

Despite these promising results, Tavallaeinejad and team suggested that further research is needed to fully understand and optimize the interactions between the flexible and rigid components of the turbines. This includes studying the dynamic behavior of the blades once the turbine is in motion and their impact on overall turbine performance at higher speeds. Additionally, the interaction of these flexible blades with blade-vortex interactions (BVI), crucial for power generation in conventional VAWTs at high rotational speeds, remains to be explored. The findings justify more extensive research into this novel approach or its derivatives to refine and potentially implement these solutions in future VAWT designs [82].



(a)

(b)

Figure 22. Blade of cross-flow fan integration (a) Schematic representation of the flow control strategy that involves a cross-flow fan generating suction pressure at the airfoil's TE, which helps in mitigating flow separation and enhancing aerodynamic performance, (b) Schematic representation of the flow control employing a cross-flow fan generating suction pressure at the airfoil TE, also aimed at mitigating flow separation and improving aerodynamic performance [83].

Aboelezz et al. introduce a novel approach for enhancing the performance of VAWTs through the integration of a cross-flow fan (CFF) for active flow control, as demonstrated in Figure 22. This innovative method utilizes a CFF at the TE of the airfoil to regulate flow separation by leveraging suction. The study involved designing and fabricating a thick airfoil VAWT with a 35% thickness-to-chord ratio, measuring 1 m in diameter and 0.5 m in height, alongside a standard NACA 0018 wind turbine for comparative analysis. Both turbines underwent experimental testing in a wind tunnel using a custom-designed test rig that measures output power, incorporating a fixation mechanism, a torque measurement system, and a mechanical brake for load variation.

Power assessments were conducted to estimate the real turbine power increase, taking into account the power consumed by the fans. A fan map was created to determine the optimal conditions and rotational speeds for fan operation, highlighting the operational parameters for maximizing efficiency. Results from the study revealed significant performance enhancements when the CFF was employed. Specifically, the VAWT with the CFF off demonstrated an impressive 200% increase in output power at low wind speeds and approximately 33% at high wind speeds compared to the conventional NACA 0018 turbine. These improvements were attributed to the innovative straight-blade design of the turbine, which notably enhances efficiency and performance over conventional airfoil blade designs. The VAWT with CFF also showed improved startup performance, achieving quicker steady-state rotational speed attainment and higher rotational speeds.

The CFF's speed could effectively augment the output power. When the power consumed by the fan was factored into the performance assessments, the results indicated a 9% increase in pure output power due to active flow control by the CFF, significantly boosting the turbine's overall output power. The study suggests that CFF should be avoided for wind speeds below 8 m/s, and fan rotational speeds above 3030 should not be utilized for active flow control, although they are beneficial during startup phases. The research concluded that while the proposed wind turbine with CFF active flow control exhibited promising results, it necessitates a control system to optimize when and at what rotational speed the fan should be activated. Future research directions could include enhancing the control system, reducing costs related to CFF implementation, and further optimizing the turbine's performance under various wind conditions. Overall, this study by Aboelezz et al. the potential of incorporating innovative flow control strategies like CFF in wind turbines, especially beneficial in low wind speed environments. It provides a significant contribution to wind turbine design and development literature, offering valuable insights for future designs that integrate active flow control strategies to enhance efficiency and performance [83].

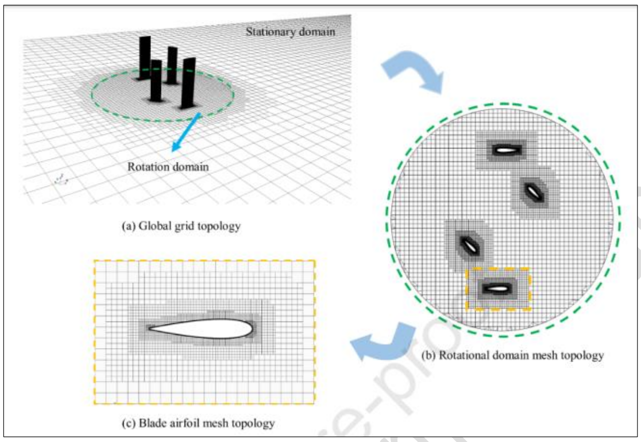


Figure 23. Double Darrieus VAWT mesh domain [61].

Shen et al. delve into optimizing the Double Darrieus (DD) VAWT for enhanced performance at low tip speed ratios, focusing on improving the C_P and reducing the maximum instantaneous torque coefficient, as demonstrated in Figure 23. The study employs a multi-objective optimization approach using various design variables, including the inner ring wind turbine diameter (d), height (h), blade airfoil chord length (c), and the phase angle (θ) between the inner and outer wind turbine rings.

Utilizing response surface analysis, a regression model is developed to link critical structural parameters with performance metrics like C_Ps and maximum instantaneous torque coefficients. The model incorporates quadratic and two-factor interaction (2FI) models to assess the impact of each design variable on turbine performance.

Further exploration through response surface analysis demonstrates that the C_P increases as the d decreases and as the h increases. Conversely, the maximum instantaneous torque coefficient shows an increase with a decreasing diameter and a decrease with an increasing phase angle, under certain conditions for d and h.

The optimization process utilizes the multi-objective particle swarm optimization (MOPSO) method to find the Pareto optimal solutions. The optimal design parameters achieved are a diameter of 1.01 m, height of 1.19 m, chord length of 0.249 m, and a phase angle of 90°. These parameters lead to optimal objective functions with values of 0.1883 for the C_P and 0.3556 for the maximum instantaneous torque coefficient, indicating a substantial enhancement in aerodynamic performance and fatigue characteristics at low tip speed ratios [61].

7 Conclusions

This study investigates the impact of various flap configurations on the power performance and self-starting capabilities of Vertical Axis Wind Turbines (VAWTs).

VAWTs are notably advancing with impressive developments. Specifically, flap technology enhances efficiency significantly, achieving over 100% at low Tip Speed Ratios (TSRs), and respectively, over 60% and 40% at medium and high TSRs. Additionally, the integration of flap technology considerably improves the self-starting abilities of VAWTs. Flap technology enables wind turbines to produce more power, maximizing energy production. Furthermore, in urban areas with low wind potential, flap technology addresses the fundamental issue of self-starting for VAWTs. It is anticipated that soon, factories and urban rooftop applications will harness the potential to generate their own electricity locally, thanks to flap-integrated VAWTs. This advancement offers significant benefits in terms of sustainability and energy independence. Flaps also enhance the aerodynamic performance of turbines, allowing them to operate effectively regardless of wind speed and direction. These features enable VAWTs to achieve energy production efficiencies nearly comparable to those of Horizontal Axis Wind Turbines (HAWTs).

Despite their beneficial effects, flap technologies also impose additional structural and aerodynamic loads on the VAWT blades. Therefore, their design and integration require careful consideration to ensure a net positive effect on the turbine performance. Furthermore, the durability of these devices under various operational conditions, including high wind speeds and turbulent flows, is an area of ongoing research. Also, the optimal design and positioning of vortex generators depend on the specific characteristics of the VAWT, such as the blade shape and size, rotational speed, and the expected wind conditions. Thus, a one-size-fits-all approach cannot be adopted, and customization based on the specific requirements of the VAWT is often necessary.

In conclusion, flap technologies hold significant promise in enhancing the self- starting, C_P and wider TSR range performance of VAWTs. By modulating the flow around the turbine blades, these devices can help harness more wind power and make VAWTs more efficient and versatile. Despite the challenges associated with their design and implementation, ongoing research and technological advancements are likely to make flaps an integral part of future VAWT designs. Furthermore, the implementation of serrated Gurney flaps on vertical axis wind turbines has demonstrated significant noise reduction, a critical improvement for urban environments where noise pollution is a pressing concern. This reduction enhances the viability of deploying these turbines in densely populated areas, offering a sustainable energy solution with minimal auditory impact. Thus, serrated Gurney flaps provide a distinct advantage in urban settings, aligning with the increasing demand for environmentally friendly and community-compatible renewable energy sources.

8 Author contribution statements

In the scope of this study, Autor1 contributed by forming the idea, reviewing the literature, evaluating the results, writing, proofreading, and supervising the manuscript.

9 Statement of ethical committee approval and conflict of interest

There is no need to obtain permission from the ethics committee for the article prepared. There are no conflicts of interest with any individual/entity in the prepared article.

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