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Recent advances in VAWT aerodynamic performance research: Optimal design

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Abstract. Vertical axis wind turbine is a popular research direction in recent years, and its aerodynamic performance directly affects its power generation efficiency. Using CFD method simulation, the aerodynamic characteristics of wind turbine blades can be deeply analyzed. In this paper, the numerical simulation progress of the aerodynamic performance of vertical axis wind turbines with airfoil as the main object in recent years is studied, the influence of different design parameters on the performance of wind turbines is discussed, the characteristics of current research are summarized, and the future research trends are prospected.

Keywords: VAWT CFD the numerical simulation aerodynamic.

1. Introduction

As a clean, renewable and widely distributed energy, wind energy resources are of great significance in promoting the diversification of energy structure, coping with global climate change, and promoting technological innovation and industrial development, and are gradually becoming a key force in the transformation of global energy structure; At present, the main use of wind energy is wind power generation. Compared with solar power, hydropower, geothermal power and other non-traditional energy generation methods, wind power has relatively low operating costs and good long-term economic benefits. And its main use of vertical space, small footprint and other advantages, wind power is not only an important way to achieve sustainable development, but also a key part of the future energy transformation and environmental protection.

Wind turbines are divided into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT), wherein horizontal axis wind turbines have been developed for a long time, in contrast, VAWT has developed slowly in the past decades because the wind energy utilization rate is slightly lower than horizontal axis wind turbines. However, in recent years, VAWT has attracted the attention of many scholars and society again due to its multiple advantages such as simple structure, easy maintenance, low noise pollution, no yaw, safe operation, and can be combined with buildings and suitable for application in cities [1].

Wind turbine technology involves mechanics, mechanical engineering, material science, electricity and gas, control, production and technology, and is a highly multidisciplinary technology. Among them, wind turbine aerodynamics determines the performance, efficiency, stability and safety of wind turbine, which is the first key issue in wind turbine technology and a major field of theoretical research of wind turbine [2]. At the same time, the optimal arrangement of wind turbines is an important part of wind

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farm design and planning, and the array of wind turbines directly affects the power generation of wind farms, and then the overall economic benefits of wind farms [3].

There are three methods to study flow phenomenon and understand its essence: analytical solution, numerical simulation and wind tunnel test [4]. With the rapid development of computational fluid dynamics, CFD numerical simulation technology has been widely used in the study of wind turbine aerodynamic performance. CFD method is to first through the structure modeling, and then import it into the relevant calculation software for calculation, and can display the real-time process on the computer.

Based on the research literature of CFD numerical simulation technology in the field of VAWT aerodynamic characteristics in the past three years, this paper will focus on the latest progress of using CFD method in this field and review. At the same time, the future research trend is forecasted.

2. Basic Principles and Parameters

This section will introduce the basic principles of CFD limited to the simulation of the aerodynamic characteristics of vertical wind turbines and the key aerodynamic parameters limited to VAWT.

2.1. Fundamentals of CFD

Using CFD you can view the flow around the blade as a vector plot and scalar features can be represented as a contour plot. In the process of CFD analysis, there are three main steps: pre-processing, solving and post-processing.

2.2. Key aerodynamic parameters of VAWT

The main aerodynamic performance parameters of airfoil mainly include lift coefficient C_l, drag coefficient C_d, tangential force coefficient C_t and normal force coefficient C_n.

$$\begin{cases} C_l = \frac{2F_l}{\rho W^2 \cdot c} \\ C_d = \frac{2F_d}{\rho W^2 \cdot c} \end{cases} \tag{1}$$

$$\begin{cases} C_t = C_l \sin\alpha - C_d \cos\alpha \\ C_n = C_l \cos\alpha - C_d \sin\alpha \end{cases} \tag{2}$$

Where: F_l : lift force perpendicular to the direction of incoming flow, N; F_d : the drag force parallel to the direction of incoming flow, N; ρ: air density, kg /m3; W: relative wind speed, m /s; c: airfoil chord length, m; α: Angle of attack, (°).

Solid σ is one of the important parameters that affect the aerodynamic performance of VAWT [5], which is calculated as follows:

$$\sigma = \frac{Nc}{2R} \tag{3}$$

Where: N: number of leaves, each; R: radius of rotation, m.

The tip ratio λ reflects the ratio of the blade to the incoming flow velocity:

$$\lambda = \frac{R\omega}{V_\infty} \tag{4}$$

Where: ω: angular velocity, rad /s; V_∞: incoming flow velocity, m /s.

Torque coefficient C_P and wind energy utilization ratio C are both important indicators to measure the aerodynamic performance of VAWTs:

$$C_m(\theta) = \frac{2T(\theta)}{\rho A R V_\infty^2} \tag{5}$$

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$$C_p = \frac{2P}{(\rho A V_{\infty}^{3})} \tag{6}$$

Where: T(θ): the torque at the phase Angle θ, N/m; P: output power, W; A: sweep area, m^2.

3. Progress in research

Vawts can be divided into lift and drag types. After classifying the literature, the author classifies the current ways to improve the aerodynamic performance of a single VAWT into two types: improving and optimizing airfoil and blade from the aspects of structure and parameters and external auxiliary pneumatic devices. This section will elaborate the latest progress of wind airfoil and external aerodynamic structures from the aspects of lift type and drag type.

3.1. Lift type VAWT

At present, the most widely used type of lift VAWT is Darrieus, which includes wind turbines with curved blade structure and straight blade structure [6]. In recent years, linear wing vertical axis fan (SB-VAWT) has been greatly developed in recent years [7]. It is shown in Figure 3 [8]. Therefore, this section mainly discusses the latest progress of aerodynamic performance research of linear wing vertical axis fan.

3.1.1. Straight Blade VAWT Because the structure of SB-VAWT is relatively fixed, the optimization of SB-VAWT mainly focuses on the optimization design of airfoil. Airfoil refers to the profile shape perpendicular to the rotating shaft on the blade of VAWT. As the most important working part, it can directly affect the aerodynamic performance of VAWT. Therefore, it is of great significance to find out the optimal aerodynamic characteristics and geometric parameters of the airfoil for the development of VAWT.

(1)Airfoil parameter optimization: M. Rasoul Tirandaz[9] et al. focused on the influence of symmetrical airfoil shape on dynamic stalling performance of VAWT. Based on 252 high-fidelity transient CFD simulations of 126 identical airfoil shapes, they conducted a comprehensive analysis of three shape defining parameters of airfoil, namely maximum thickness, position and leading edge radius. The results showed that, When λ is reduced from 3.0 to 2.5, the optimal airfoil changes from NACA0018-4.5/2.75 to NACA0024-4.5/3.5, that is, the maximum thickness increases from 18%c to 24%c, its position increases from 27.5%c to 35%c, and the leading edge radius index I is maintained at 4.5. The results provide a basis for the design of VAWT variant airfoil.

the symmetrical NACA 0018 airfoil is commonly used in small and medium-sized vertical axis wind turbines. Krzysztof Rogowski et al. [10] based on the two-equation k-ω SST model, the Transition SST four-equation turbulence model was adopted to analyze the aerodynamic characteristics of the NACA 0018 airfoil. The numerical study is carried out under the condition of string Reynolds number of 160,000, Angle of attack of 0 ~ 11 degrees and free flow turbulence intensity of 0.05%. The results show that the calculated lift and drag coefficients, aerodynamic derivatives and the position and length of laminar bubbles are in good agreement with the experimental measurements verified in the literature. Zhang Zhaohuang et al. [11] proposed a parabolic PWX0007MX-xx series symmetric airfoil for H-type VAWT. When the constant C≥7.74, all the obtained parabolic symmetric airfoil bars are superior to NACA four-figure series symmetric airfoil after equal ratio. When C=10.21, the aerodynamic performance of this series of airfoils is the highest, and the maximum lift-drag ratio and maximum lift coefficient are significantly improved compared with the commonly used NACA and four-digit series symmetrical airfoils. The research results can provide an effective reference for the application of VAWT trailing edge flaps. Saif Al Hamad et al. [12] used numerical simulation to study the effect of internal opening ratio on aerodynamic performance of symmetrical J-shaped airfoil with different thickness, and found that compared with the corresponding solid airfoil without any opening, J-shaped airfoil formed by introducing an opening reduces the lift-drag ratio of all study cases. The NACA 0008 equipped with 33.33% opening achieves the best aerodynamic performance among all studied J-airfoils and has a higher lift-drag ratio in all angles of attack. Teeab Tahzib et al. [13] compared the performance of NACA0018 and S1046 airfoils in the range of TSR and pitch Angle by using CFD method and k-ω SST turbulence model. The results showed that under a certain TSR, the higher the TSR of the two airfoils, the higher the output power. The S1046 airfoil performs better than NACA 0018 in almost all blade pitch angles and TSR. Finally, it is pointed out that the self-starting capability of VAWT is another avenue worth exploring in the future. Yunus Celik [14] proposed a new hybrid blade design by combining the traditional airfoil (i.e. NACA 0018) with its J-type. Studies have shown that when the opening ratio is 40%, the blade can show better overall performance and self-starting performance, while providing a wider turbine operating range and improving turbine peak efficiency. It is worth mentioning that this study proposed a new design method based on two-dimensional CFD calculation, and verified its accuracy, which can accurately predict the torque and power generation of hybrid blade turbines under different working conditions.

Bionic airfoils are also a major development direction of VAWT airfoils. Xu Xianshen et al. [15] used numerical simulation method to study a fish swing-tail airfoil. According to the study, when the bend of the wind wing of the fish swing-tail airfoil is 41%, the thickness of the airfoil is 4%, and the installation Angle is 12°, the power coefficient reaches the maximum, and the optimization of the airfoil effectively weakens the tip vortex falling off.

(2)Airfoil structure optimization design: After literature reading, the author divides the structural optimization of airfoil into Gurney flap, changing leading edge line and trailing edge line and other structural optimization.

Change the leading edge line and trailing edge line:Guo Xin et al. [16] used CFD method to study the influence of different groove structures at different positions on the aerodynamic performance of VAWT for NACA0012 airfoil. In addition, wind tunnel experiments at four installation angles of 0^o, 2^o, 4^o and 6^o show that the corrugated groove structure at the leading edge of 0.1c-0.4c can effectively improve the aerodynamic performance, and the aerodynamic performance of the wind turbine with curved groove at the rear of the inner surface of 0.9c can be significantly improved at high tip speed ratio.

Li Gen et al. [17] took NACA0021 airfoil as the research object and carried out numerical simulation by CFD method to study the influence of active fluve-flap on the aerodynamic performance of VAWT. The results show that the active flut-flap structure with dynamic control of Gurney flap through active control can further improve the wind energy utilization coefficient, which can be improved by up to 26.85% compared with the static flut-flap structure. However, when the tip ratio λ exceeds the optimal tip ratio, its effect on the aerodynamic performance of the wind turbine will gradually weaken. Later, Li Gen et al. [18] continued to combine parameters such as Gurney flap height, Gurney flap position and groove diameter through orthogonal experimental design, and studied the aerodynamic performance and flow field structure of VAWT through numerical calculation, analyzing the flut-flap flow control mechanism and its effect on VAWT. It is pointed out that Gurney flap height is the main influence factor on VAWT's aerodynamic performance. Groove-flap can effectively inhibit the flow separation on the surface of VAWT blade airfoil, and has a significant effect on improving the aerodynamic performance of VAWT.

Abolfazl Abdolahifar et al. [19] adopted the 3D numerical simulation method to accurately analyze the aerodynamic performance and corresponding flow structure of different slotted Darrieus VAWT blade designs with straight blades. The study points out that turbines with slotted blades are easier to start at lower wind speeds, and the effective TSR range of the slotted designs is given.

At low tip ratio, VAWTs blades are often in a state of high Angle of attack during operation, which is easy to stall due to flow separation and reduce the utilization rate of wind energy. The flow separation caused by the stall mainly starts at the leading edge of the airfoil, so the leading edge flow state is particularly important for the aerodynamic performance of the airfoil [20]. Airfoil slotting is a passive control method to change the leading edge flow characteristics.

Zhang Qiang et al. [21] proposed an elliptical slot structure for H-VAWTs. According to the research results, they point out that the elliptical and gradually shrinking wing slot can improve the aerodynamic performance of the blade at different tip ratios.

Ni Lulu et al. [22] proposed three new types of wing slits for NACA0021 airfoil, namely double-side guide, internal guide and external guide, and studied their aerodynamic performance by CFD method. The results show that the aerodynamic performance of the internal guide is better than that of other wing slits, the bilateral guide is not suitable for SB-VAWT, and the aerodynamic performance of the external guide is poor.

Gurney flaps: Xiang Bin et al. [23] modified the dynamic structure of the Gurney flap model and proposed four ways in which the extension height varies with the phase Angle. Using the numerical simulation method based on the SST k-ω turbulence model, the influence of Gurney flap's different motion modes and extension height on the aerodynamic performance of VAWT was studied. It is found that dynamic Gurney flaps can effectively improve the utilization of wind energy. The starting torque of wind turbine at low wind speed can be effectively improved by using Gurney flaps at low tip ratio. When the extension height of the Gurney flaps at the trailing edge of the blade is greater than 0.02c, the effect of improving the wind energy utilization will gradually weaken.

Wang Peilin et al. [24] arranged jet flaps on the pressure surface of the trailing edge of the airfoil, proposed five jet control strategies, and used CFD method to find the optimal strategy. The research showed that when the phase Angle was between 210° and 360°, the trailing edge jet flaps greatly improved the pressure difference of the airfoil in the lee zone of the VAWT, and significantly improved the aerodynamic performance of the wind turbine. The closer the trailing edge jet flaps are to the trailing edge, the better the effect of improving the aerodynamic performance of VAWT.

Based on the CFD method and H-type VAWT, Dai Mengyi et al. [25] conducted numerical research on the aerodynamic performance of three separate trailing edge flaps, NACA 0018, NACA 0021 and NACA 0024. The results show that compared with the model in which the trailing edge flaps do not deflector, the average power coefficient of wind turbine decreases with the increase of the absolute flap deflection Angle. In the upwind region ($45° \leq \theta < 135°$), the positive flap deflection Angle can effectively improve the bending moment coefficient of the blade. When the flap deflection Angle is negative, the degree of wind energy utilization affected by the deflection Angle is positively correlated with the airfoil thickness.

Other Structural optimization: Luo Shuai et al. [26] placed the suction holes on the upper and lower surfaces of the wind airfoil and proposed three different suction control strategies. Based on the CFD method, the improvement effect of different control strategies on its aerodynamic performance was studied, and the research showed that the three strategies can greatly improve the aerodynamic efficiency of the whole machine at low tip velocity ratio. In consideration of energy consumption, alternating inhalation in the facing and leeward zones is the best control mode, and this strategy should be adopted for flow control of wind turbines. This study can provide reference for the reasonable application of inspiratory control technology in VAWTs and energy saving strategies.

Ahmed Aboelezz et al. [27] explored a passive flow control method by adding a guide vane outside the wing, as shown in figure 1. Taking NACA 0018 as the research object, the influence of guide vane on its aerodynamic performance was studied by using ANSYS fluent SW tool. The research indicates that the maximum lift coefficient of guide vane is greatly improved when the guide vane is in the middle and above the airfoil, the Angle of guide vane relative to the airfoil has a great influence on VAWT performance, and guide vane can effectively reduce turbine vibration.

Salem A. Bakhumbsh et al. [28] took NACA 0018 as the research object, conducted aerodynamic analysis based on the finite volume method and URANS equation of shear stress transport k-ω SST turbulence model, and studied the influence of installing micro-cylinders at different positions of airfoil on the performance of Darrieus VAWT. The results show that the micro cylinder can effectively delay air separation, and the average power coefficient can be improved when the diameter is small and the micro cylinder is installed in front of the leading edge of the blade. Conversely, if the diameter of the micro cylinder is larger or located below the suction side or pressure side of the leading edge of the blade, the turbine performance deteriorates.

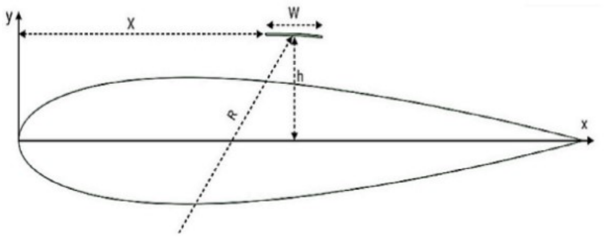

Figure 1. Schematic diagram of guide vane airfoil

Ao Huahao et al. [29] proposed an inclined column structure airfoil (TIC) that can automatically retract with the change of wind turbine azimuth Angle. Taking the NACA0021 airfoil as the research object, numerical simulation method was used to show that the arrangement of a telescopic inclined column at the trailing edge of the airfoil and the adoption of an active control strategy could significantly improve the VAWT wind energy utilization coefficient, and the TIC airfoil made the wind turbine move to a low tip speed ratio in the best working condition, thus reducing the rotational speed of the wind turbine at the same wind speed and improving the operation safety of the wind turbine.

3.2. Resistance type VAWT

Since the invention of resistance type VAWT, in order to maximize its power, scholars have carried out a lot of optimization design for its blade profile, and many blade profiles have appeared. This section will mainly discuss Savonius VAWT in resistance VAWT.

There are two basic types of Savonius VAWT, the ordinary type and the cyclotron type. [30]

Ganti et al. [31] took the cycloidal Savonius VAWT as the research object, proposed the expression method of VAWT airfoil profile based on sine trigonometry function, and designed a new blade profile, SIN2, which had the maximum power coefficient and the value of the maximum power coefficient was 0.283 when the tip speed ratio was 1.3 in an environment with an incoming wind speed of 14m/s. An increase of 0.039, or about 16%.

3.3. Composite VAWT

The combination of composite VAWT is also a development direction to improve the utilization of wind energy. The common ones are lift resistance compound and double Darrieus type compound.

3.3.1. Lift-drag Composite VAWT Mohammad Asadi et al. [32] studied the effects of parameters such as free wind speed (U_∞), TSR and attachment Angle (φ) inside the rotor on the performance of Darrieus and Savonius hybrid wind turbines by using CFD method. In addition, compared with the existing experimental data of Darrieus and Savonius, this paper fills the gap in the research on the performance of hybrid wind turbines, especially under low TSR.

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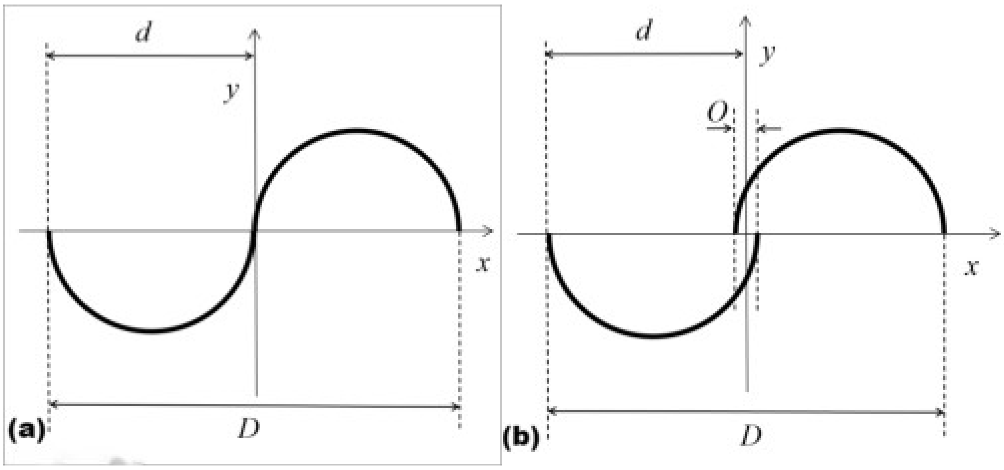

Figure 2. Two basic types of Savonius VAWT

Zhou Yang et al. [33] designed a lift-resistance composite VAWT on the basis of the traditional H-type wind turbine, as shown in figure 3. The opening and closing of the components under the support arm can be adjusted according to different wind speeds, so as to form a working state that conforms to the working principle of the resistance or lift type wind turbine, so as to cope with different working conditions.

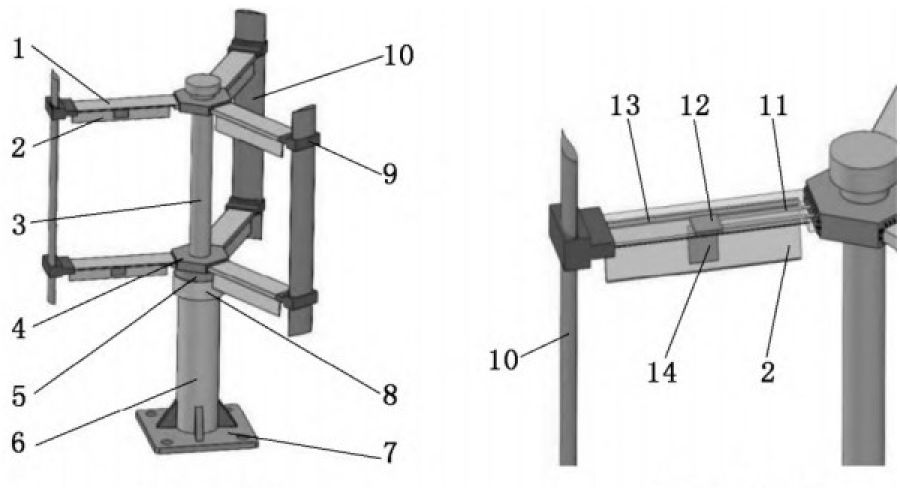

Figure 3. axonometric map and local view
1- Support arm; 2- support arm lower component; 3- rotating shaft; 4- mounting plate; 5- brake ; 6-uprights; 7- square plate; 8- generator; 9- connecting plate; 10- blade;
11- wire; 12- electromagnet; 13- rotating shaft; 14- sheet metal

3.3.2. Double-Darrieus hybrid VAWT Muhammad Ahmad et al. [34] Design a straight-blade Double-Darrieus hybrid VAWT with high power coefficient and self-starting capability, And through a series of CFD research methods, it is found that compared with Darrieus and Savonius hybrid wind turbines and standard Darrieus wind turbines, the higher static torque of hybrid VAWT helps to achieve the best operating state in a short time.

3.4. Auxiliary pneumatic device
The additional pneumatic structure mainly includes air collecting device (WGD) and diversion device.

(1)Air collecting device: The installation of air collecting device (WGD) on the rotor is a very popular research result in recent years, the main principle is to improve the rotor self-starting performance. CAI

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Hongtao et al. [35] designed a ring wind collecting device for H-type wind turbine, which can transform the natural horizontal wind in any direction into the wind flowing clockwise along the ring,. The experiment shows that the H-type VAWT can have better starting performance. When the symmetrical airfoil NACA0012 is used, the power coefficient can reach 41.5%. Zhang Wei et al. [36] conducted a study on the wind collecting device of the wind lens and pointed out that after the configuration of the wind lens acts on VAWT, the half-open Angle of the diffuser has a greater impact on the aerodynamic performance of VAWT, followed by the flange. Zhang also proposed to optimize the configuration of the wind lens by Bezier curve, and verified that this method can effectively improve the operating efficiency of VAWT.

(2)Diversion device: The diversion device can significantly improve the VAWT output power. Su Zhenluan et al. [6] designed a linear baffle installed around the wind turbine of the linear wing VAWT, and adopted the method of combining numerical simulation and wind tunnel test. The research results showed that the average starting torque coefficient of the wind turbine with the baffle was increased by 35.6% compared with that of the wind turbine without the baffle in 1/4 cycle at a wind speed of 10m/s. At the same time, the experiment shows that the wind turbine with the baffle installed can start by itself and the time to reach the maximum speed is greatly shortened.

4. Summary and suggestions

For a long time, researchers always optimize parameters for specific working conditions on the basis of existing research. However, in recent years, the practical value of this kind of optimization only for specific conditions and specific parameters to improve the aerodynamic performance of VAWT has gradually declined. Through the review of the literature, the author makes a summary and outlook here:

- The key to improving airfoil aerodynamic performance is to delay flow separation, reduce trailing edge vortex and blade tip loss, and improve wind energy utilization coefficient. However, the research lacks the analysis of the coupling mechanism of airfoil geometric parameters on airfoil wind energy utilization capability, so it is difficult to design an airfoil from scratch.
- The methods for improving the aerodynamic performance of VAWT can be classified into three directions: parameter optimization, structure optimization and combination optimization.
- The value of airfoil parameter optimization for a single working condition or a specific working condition is gradually decreasing, and deformable airfoil that can adapt to different working conditions is an important direction for future development. In most cases, the research is still based on NACA four-digit series airfoil, and the research object is relatively single.
- CFD, with its advantages of low cost and visualization, has become an indispensable part of VAWT aerodynamic performance research, which is complementary to the progress of VAWT aerodynamic performance research. The combination of CFD with the rapid development of artificial intelligence, data science and other achievements in recent years can effectively promote the development of CFD and reduce the manpower cost in the optimization of airfoil parameters.

References

[1] Zhu Hai-Tian, Hao Wen-Xing, Li Chun, Ding Qen-Wei & Yu Wan.(2019). Numerical study on aerodynamic characteristics of building enhanced vertical axis wind turbine. Journal of Harbin Institute of Technology (01), 87-93.

[2] Li Zuowu & He Dexin.(2013). Research status and progress of hydrodynamics in wind energy engineering. Advances in Mechanics (05),472-525.

[3] Frandsen, S., Barthelmie, R., Pryor, S., Rathmann, O., Larsen, S., Højstrup, J., & Thøgersen, M. (2006). Analytical modelling of wind speed deficit in large offshore wind farms. Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology, 9(1-2), 39-53.https://doi.org/10.1002/we.189

[4] Fan Hongyu. Wind Power Equipment Industry Report [R]. Changjiang Securities. 2005, 11.

[5] Khan, M. J., Iqbal, M. T., & Quaicoe, J. E. (2006, July). Design considerations of a straight bladed Darrieus rotor for river current turbines. In 2006 IEEE international symposium on industrial electronics (Vol. 3, pp. 1750-55). IEEE.
[6] Su Zhenluan. (2021). A guide plate vertical axis wind turbine aerodynamic characteristics study master's (dissertation, northeast agricultural university). https://link.cnki.net/doi/10.27010/d.cnki.gdbnu.2021.000589.
[7] Sun, X., Y. Chen, Y. Cao, G. Wu, Z. Zheng, and D. Huang. 2016. Research on the aerodynamic characteristics of a lift drag hybrid vertical axis wind turbine. Advances in Mechanical Engineering 8 (1):1687814016629349. doi:10.1177/1687814016629349.
[8] Möllerström, E., P. Gipe, J. Beurskens, and F. Ottermo. 2019. A historical review of vertical axis wind turbines rated 100 kW and above. Renewable and Sustainable Energy Reviews 105:1–13. doi:10.1016/j. rser.2018.12.022.
[9] Tirandaz, M. R., & Rezaeiha, A. (2021). Effect of airfoil shape on power performance of vertical axis wind turbines in dynamic stall: Symmetric Airfoils. Renewable Energy, 173, 422-441.https://doi.org/10.1016/j.renene.2021.03.142
[10] Rogowski, K., Królak, G., & Bangga, G. (2021). Numerical study on the aerodynamic characteristics of the NACA 0018 airfoil at low Reynolds number for Darrieus wind turbines using the transition SST model. Processes, 9(3), 477.https://doi.org/10.3390/pr9030477
[11] Zhang Zhao-Huang, Hu De-Peng & Gao Di.(2022). Research on parabolic airfoil theory and aerodynamic characteristics of H-VAWT airfoil. Renewable Energies (10), 1358-1364. doi:10.13941/j.cnki.21-1469/tk.2022.10.009.
[12] Al Hamad, S., Habash, O., Hasan, A., & Amano, R. S. (2022). Effect of the J-Shaped Wind Turbine Airfoil Opening Ratio and Thickness on the Performance of Symmetrical Airfoils. Journal of Energy Resources Technology, 144(5), 051303.https://doi.org/10.1115/1.4053743
[13] Tahzib, T., Hannan, M. A., Ahmed, Y. A., & Kamal, I. Z. M. (2022). Performance analysis of H-Darrieus wind turbine with NACA0018 and S1046 aerofoils: impact of blade angle and TSR. CFD Letters, 14(2), 10-23.https://doi.org/10.37934/cfdl.14.2.1023
[14] Celik, Y., Ingham, D., Ma, L., & Pourkashanian, M. (2023). Novel hybrid blade design and its impact on the overall and self-starting performance of a three-dimensional H-type Darrieus wind turbine.Journal of Fluids and Structures,119, 103876.https://doi.org/10.1016/j.jfluidstructs.2023.103876
[15] Xu Xian-Shen. (2022). Master's Degree in Structural Optimization of vertical axis Wind Turbine with fish swing-tail type (Dissertation, Henan University of Science and Technology). Master's https://link.cnki.net/doi/10.27115/d.cnki.glygc.2022.000655 doi: 10.27115 /, dc nki. Glygc. 2022.000655.
[16] Guo Xin, Chen Yong-Yan, Tian Rui, Han Cheng-Rong, He He & Yu Lei-Lei.(2022). Research on aerodynamic characteristics of a three-blade H-vertical axis wind turbine with changing airfoil profile. Renewable Energy (01), 2012, 33 (3) : 107-108. 73-78 doi: 10.13941 / j.carol carroll nki. 21-1469 / tk. 2022.01.007.
[17] Li Gen, Miao Wei-Run, Li Chun & Liu Qing-Song.(2021). Influence of active flut-flap on aerodynamic performance of vertical axis wind turbine. Thermal power engineering (01), 136-144. The doi: 10.16146 / j.carol carroll nki RNDLGC. 2021.01.019.
[18] Li Gen, Liu Qing-Song, Li Chun, Miao Wei-Run & Yue Min-Nan.(2023). Numerical study of wind turbine based on orthogonal test fluve-flap vertical axis. Journal of Solar Energy (05), 294-301. (in Chinese) doi:10.19912/j.0254-0096.tynxb.2021-0918.
[19] Celik, Y., Ingham, D., Ma, L., & Pourkashanian, M. (2023). Novel hybrid blade design and its impact on the overall and self-starting performance of a three-dimensional H-type Darrieus wind turbine. Journal of Fluids and Structures, 119, 103876.https://doi.org/10.1016/j.jfluidstructs.2023.103876

[20] Man star, fang hj, qing-song liu & Deng Yunhe. (2019). The wind turbine blade aerodynamic load on flow separation control technology were reviewed. The heat power engineering (09), 1 to 13. Doi: 10.16146 / j.carol carroll nki RNDLGC. 2019.09.001

[21] Zhang Qiang, Miao Wei-Run, Li Chun & Zhang Wan-Fu. (2021). Influence of nozzle slot on aerodynamic performance of vertical axis wind turbine. Chinese Journal of Mechanical Engineering (22), 335-343

[22] Ni Lulu, Zhu Haitian, Li Chun & Miao Weifang. (2021). Diversion type slot on the straight blade vertical axis wind turbine aerodynamic performance. The influence of thermal power engineering (7), 129-136. The doi: 10.16146 / j.carol carroll nki RNDLGC. 2021.07.021.

[23] Xiang Bin, Miao Wei-Run, Li Chun & Ni Lulu. (2021). Influence of dynamic Gurney flaps on vertical axis wind turbine performance. China Mechanical Engineering (02), 163-170.

[24] Wang Peilin, Liu Qingsong, Miao Weifang, Li Chun, Luo Shuai & Li Gen. (2022). Effects of unsteady trailing edge jet flaps on aerodynamic characteristics of vertical axis wind turbines. Chinese Journal of Solar Energy (09), 242-250. doi:10.19912/j.0254-0096.tynxb.2021-0137.

[25] Dai Mengyi, Zhang Zhihao, Tu Jia-Huang, Han Zhao-Long, Zhou Dai & Zhu Hong-Bo. (2022). Of different airfoil trailing edge flap deflection Angle of vertical axis wind turbine aerodynamic influence research. Journal of Shanghai jiaotong university (12), 1619-1629. The doi: 10.16183 / j.carol carroll nki jsjtu. 2022.110.

[26] Luo Shuai, Miao Weifang, Liu Qingsong, Li Chun & Zhang Wanfu. (2022). Influence of suction control strategy on aerodynamic performance of vertical axis wind turbine. Acta Solar Energy Sinica (05), 287-295. doi:10.19912/j.0254-0096.tynxb.2020-0946.

[27] Aboelezz, A., Ghali, H., Elbayomi, G., & Madboli, M. (2022). A novel VAWT passive flow control numerical and experimental investigations: Guided Vane Airfoil Wind Turbine. Ocean Engineering, 257, 111704.https://doi.org/10.1016/j.oceaneng.2022.111704

[28] Bakhumbsh, S. A., & Mohamed, M. H. (2022). Effect of micro-cylinder as a passive controller on the Darrieus wind turbine performance. Ocean Engineering, 266, 113118.https://doi.org/10.1016/j.oceaneng.2022.113118

[29] Ou Huahao, Ye Zhou, Liu Qingsong, Li Gen, Luo Shuai & Li Chun. (2023). Effect of telescopic inclined column on aerodynamic performance of vertical axis wind turbine. Acta Solar Energy Sinica (05), 376-383. doi:10.19912/j.0254-0096.tynxb.2021-1616.

[30] Ni ShouYuan.(2000)."Wind Power Lecture 2: Working Principle and aerodynamic characteristics of wind turbines." Solar Energy 03:12-16.

[31] Gan D. (2021). Research on Blade Optimization Design and Performance Analysis of Savonius Vertical axis Wind Turbine Master's Degree (Dissertation, Hubei University of Technology). Master's https://link.cnki.net/doi/10.27131/d.cnki.ghugc.2021.000446 doi: 10.27131 /, dc nki. Ghugc. 2021.000446.

[32] Asadi, M., & Hassanzadeh, R. (2021). Effects of internal rotor parameters on the performance of a two bladed Darrieus-two bladed Savonius hybrid wind turbine. Energy Conversion and Management, 238, 114109.https://doi.org/10.1016/j.enconman.2021.114109

[33] Zhou Yang, Li Chao, Ni Guolin & Li Zhuo-Lin. (2023). Structural design of a new type of lift-resistance vertical axis wind turbine. Mechanical Engineering and Automation (02), 92-93+96

[34] Ahmad, M., Shahzad, A., Akram, F., Ahmad, F., & Shah, S. I. A. (2022). Design optimization of Double-Darrieus hybrid vertical axis wind turbine. Ocean Engineering, 254, 111171.https://doi.org/10.1016/j.oceaneng.2022.111171

[35] Cai Hongtao & Xiao Boqi. (2021). A new type of vertical axis wind turbine gathering device. Journal of Wuhan Institute of Technology (01), 110-113+118. doi:10.19843/j.cnki.CN42-1779/TQ.202007010.

[36] Zhang Wei, Ye Zhou, Li Chun, Li Xiandong & Ou Huahao. (2023). Research on aerodynamic performance of vertical axis wind turbine with optimal configuration of wind lens. Acta Solar Energy Sinica (03), 39-45. doi:10.19912/j.0254-0096.tynxb.2021-0866.