INTRODUCTION

The design of a wind turbine blade plays a vital role in the design of the entire wind turbine. The shape of the blade and its aerodynamics directly affect the efficiency of the wind turbine. Early wind turbine blades were directly improved using airfoils. However, these airfoils are unsuitable for low Reynolds-number flows. To meet the operation requirements of wind turbines under different wind conditions, it is necessary to design wind turbine blades with a high lift-to-drag ratio. With millions of years of evolution, organisms have adapted to complex natural environments by altering their

Bionic coupling design and aerodynamic analysis of horizontal axis wind turbine blades

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Abstract
With millions of years of evolution, owls have developed many excellent characteristics in terms of their flight. The speed of an owl in flight is similar to the relative speed of the blade of a small wind turbine with respect to air. Therefore, the owl wing airfoil is selected as the design airfoil of the wind turbine blade to reduce the flow separation under low Reynolds number. In this study, we analyze an owl wing-section airfoil and the non-smooth leading-edge shape of an owl’s wing, and implement an orthogonal optimum design to optimize the wavelength and amplitude of the non-smooth leading edge. We extract the cross-sectional features of the airfoil and the non-smooth leading-edge shape of the wing. Based on the orthogonal optimum design results, we determine the optimal combination of the wavelength, amplitude, and airfoil, and then design a horizontal-axis wind turbine blade through bionic coupling. The flow field at different tip speed ratios (TSRs) is simulated using the $k - \omega$ SST turbulence model at the rated wind speed. The results show that the power coefficient ($C_p$) of the bionic wind turbine at a high tip speed ratio is 17.7% higher than that of the standard type. Furthermore, we analyze the operation of the turbine at TSRs of 2 and 5. At a high TSR, the leading edge bulge of the bionic wind turbine blade can change the flow direction distribution of the airflow on the blade surface, make the airflow to adhere to the suction surface, and then reduce the stall area on the suction surface of the blade. Thus, the wind turbine produces higher torque, thereby generating higher power.

KEYWORDS
bionic coupling design, horizontal axis wind turbine, non-smooth leading edge, power co-efficient
structure. Graham\textsuperscript{1} studied the characteristics of owl wings and concluded that owls exhibit unique feather structure features, such as the leading-edge feathers in the form of a comb, trailing edge feathers in the form of a fringe, and fluffy down feathers on the wings and legs. In particular, owls can glide and fly silently. Inspired by the swept-back bending of bird wings, Ikeda et al\textsuperscript{2} designed a small wind turbine that imitates the bending of bird wings. The designed bionic wind turbine could output high power at high tip speed ratios (TSRs). Videler et al\textsuperscript{3} conducted a flow field visualization experiment on a swept-wing model and found that the swept wing could produce a stable leading-edge vortex, which could increase the lift generated. Li et al\textsuperscript{4} simulated the flow field around a reverse-reconstructed owl wing blade under two Reynolds numbers (Re = 16 000 and 70 000). The bionic owl wing blade showed a good aerodynamic performance. By analyzing the pressure distribution, the authors concluded that the large camber at the leading edge near the blade root was the main reason for the high lift coefficient of the bionic blade.

The shape of non-smooth leading edges has been widely studied by taking humpback whales as examples. Fish and Battle\textsuperscript{5} studied the fin limb of a humpback whale and found that the wavy bulge at the leading edge of the fin limb helps control the flow separation and blade stall. Ito\textsuperscript{6} designed the serration structure of the main feathers of the owl on the leading edge of the wing. The flow field around the airfoil was visualized in a smoke tunnel. They concluded that the serration structure can effectively improve the aerodynamic characteristics of the wing at low Reynolds number. Through wind tunnel measurements, Miklosovic et al\textsuperscript{7} showed that the ideal model designed on the basis of a certain proportion of the frontal nodule of a humpback whale fin limb can delay the stall angle by approximately 40% and increase the lift and reduce the drag. Serson and Meneghini\textsuperscript{8} found that an airfoil with a wavy leading edge can help delay the stall and maintain a better aerodynamic performance at high angles of attack. Post et al\textsuperscript{9} carried out experiments on two types of airfoils, one with a sinusoidal leading-edge line and another with a smooth leading-edge mode, in a wind tunnel. They showed that the leading-edge sinusoidal-curve airfoil could prevent the sudden decrease in the lift coefficient while still maintaining a large lift coefficient at high angles of attack and delaying the stall. Lin and Chiu\textsuperscript{10} incorporated a raised structure similar to the leading edge of the pectoral fin of a whale at certain intervals on the leading edge of a 25 kW wind turbine blade. This structure helped effectively increase the average output power of the wind turbine. Huang et al\textsuperscript{11} added a convex structure at the leading edge of a horizontal-axis wind turbine blade near the root and compared it with a blade without a convex structure through a wind tunnel test. They found that the convex structure of the leading edge could improve the power coefficient of the wind turbine. However, a performance degradation was observed at high wind speeds. Wang et al\textsuperscript{12} applied a leading-edge sawtooth structure to a vertical-axis wind turbine blade. At low Reynolds numbers, this blade exhibited a higher lift coefficient than the prototype blades. The separation of the boundary layer and the torque fluctuation were suppressed. The torque and power output of the fan were significantly increased, thus increasing the power generation capacity of the wind turbine. Yan et al\textsuperscript{13} added three protrusions with different amplitudes and wavelengths to the leading edge of a vertical axis wind turbine blade. Through large eddy simulation, they found that the leading edge protrusions of the blade can significantly increase the power coefficient of the blade and delay dynamic stall. Hua et al\textsuperscript{14} designed three types of bionic blades based on the wing shape of seagulls. The three bionic blades gave a better torque output than the prototype blades, the active rotation resistance was low, and the boundary layer separation phenomenon did not occur easily.

In summary, compared with the standard airfoil, a bionic airfoil exhibits a significantly better aerodynamic performance; however, studies on the application of bionic airfoils to wind turbine blades are limited. A front convex structure can help delay the separation of the boundary layer and the occurrence of stall; The effect of the coupling between an airfoil and a non-smooth front edge remains unclear. Therefore, by combining the wing configuration characteristics of birds with owl-like feathers and the morphological characteristics of a non-smooth front edge, we studied the bionic coupling design of a wind turbine blade and determined the cross-sectional airfoil and non-smooth front edge characteristics of an owl wing. Based on the combination of the optimal airfoil and the wavelength and amplitude, the bionic-coupled wind turbine blades were designed, with the objectives of increasing the utilization coefficient of wind energy and improving the power generation.

2 | BIONIC COUPLING DESIGN OF WIND TURBINE BLADE

2.1 | Airfoil design

2.1.1 | Airfoil extraction

Many owls show good aerodynamic performance when flying and hunting. This can be mainly attributed to the design of the airfoil. During flight, a sufficient amount of lift should be generated to slide and avoid being discovered by prey. Therefore, the airfoil of the owl is extracted and used in the design of wind turbine blades. Figure 1 shows owl wings (\textit{Otus bakkamoena}). We used a 3D laser scanner (VIVID9i, Konica Minolta) to reverse model the wing of an owl considering the wing shape of the owl while sliding. However,
because the feather near the wingtip is very thin, it was difficult to extract the cross-sectional features. Therefore, the 3D model spanning from the wingtip to the small wing feather was removed. Finally, the scanning results were smoothed to eliminate the facets due to some feather warping. Figure 2 shows the results.

The 3D model of the wing was divided into 10 sections equidistant from the root of the wing to the tip of the winglet, and the section airfoils of each section were obtained. The chord length at the cross section of the airfoil is not uniform, and is not in the horizontal state. We applied the method of scaling and rotation to ensure that the chord length of each section of the airfoil is 100 mm and that it remains in the horizontal state. We extracted the airfoil from each section, as shown in Figure 3 (taking the 50% cross-sectional airfoil as an example). MATLAB was used to perform data fitting on the airfoil points at each section of the owl’s wing. A smooth airfoil curve cannot be obtained using only data fitting. The SEMILOGY function was used to smooth the fitted curve. Polynomial fitting was employed in the data fitting method. The order of the curve-fitting polynomials on the upper and lower surfaces of the airfoil was determined by the degree of dispersion of the airfoil extraction points. Figure 4 shows the fitting curve of the 50% cross-section airfoil of the owl’s wing. The fitting equation can be expressed as follows:

\[
\begin{align*}
y_1 &= -1.1 \times 10^{-9} x^6 + 3.69 \times 10^{-7} x^5 - 4.79 \times 10^{-5} x^4 + 3.04 \times 10^{-3} x^3 - 9.86 \times 10^{-2} x^2 + 1.55 x + 1.58 \\
(R_1^2 &= 0.9817) \\
y_2 &= 3.78 \times 10^{-13} x^8 - 1.56 \times 10^{-10} x^7 + 2.68 \times 10^{-8} x^6 - 2.5 \times 10^{-6} x^5 + 1.39 \times 10^{-4} x^4 - 4.68 \times 10^{-3} x^3 \\
&+ 8.86 \times 10^{-2} x^2 - 0.562 x - 0.809 \\
(R_2^2 &= 0.99082)
\end{align*}
\]

where \(y\) is the ordinate of the upper and lower curves of the airfoil, \(x\) is the abscissa of the airfoil curve, \(x \in \{0, c\}\), and \(c\) is the chord length of the airfoil. Here, \(c = 100\), and \(R^2\) is the fitting accuracy.

2.1.2 | Airfoil selection

Small wind turbines operate at low Reynolds numbers, and because the laminar boundary layer is sensitive to unfavorable pressure gradients, flow separation and stall can easily occur. Although the wings of an owl show excellent aerodynamics while taxiing, the aerodynamics of the airfoil of each wing section is different. The design of wind turbine blades requires the selection of the most aerodynamic airfoil. Based on the airfoil extraction results and combined with the glide and predation speeds of the owl eagle, the wind speed in the simulation was set to 8 m/s, the Reynolds number corresponding to the chord length was \(4.2 \times 10^4\), and the turbulence was modeled on the basis of the flow, which is incompressible, around the blade at low speeds. Because the energy equation does not need to be solved, and the Spalart–Allmaras (SA) model was selected as the solution model. The SA model can more accurately solve gas flows on blade surfaces and meet the requirements of the calculation accuracy. A structural grid was employed as the calculation grid, as shown in Figure 5. The airfoil boundary layer grid satisfies the condition, and the number of grids meets the requirement of grid independence. The NACA4142 airfoil is selected as the standard airfoil. The value of the lift-drag ratio of the standard airfoil and the simulation result is shown in Figure 6. From the figure, the variation trend of the simulation value curve is consistent with the variation trend of the standard value curve. Therefore, using the SA solution model and by varying the angle of attack of the airfoil at the same
wind speed, we obtained the lift-to-drag ratio of 10 airfoils at different angles of attack, as shown in Figure 7.

Figure 7 shows that the lift-drag ratios of the 70%, 80%, 90%, and 100% airfoils are greater than those of the other airfoils at an angle of attack of 5°; however, the four airfoils have a smaller relative thickness and a lower relative camber, making them unsuitable for designing wind turbine blades. At an angle of attack of 5°, although the relative thicknesses of the 10%, 20%, and 30% airfoils are high, their lift-to-drag ratios are lower than those of the other airfoils. Accordingly, the wind turbine blades designed using this airfoil cannot reach the optimal aerodynamic performance, so only the 40%, 50%, and 60% airfoils were considered. Figure 7 shows that with the change in the angle of attack, the lift–drag ratios of the three airfoils show little difference, that is, they exhibit the same change trend. Therefore, the aerodynamic performances of the three airfoils after coupling with the non-smooth leading edge of the owl's wing should be further studied. Figure 8 shows the airfoils at owl wing sections of 40%, 50%, and 60%.

2.2 | Non-smooth leading-edge design

2.2.1 | Extraction of non-smooth leading-edge shape of owl wings

The leading edge of an owl's wing has a non-smooth shape. This non-smooth structure significantly influences the
2.2.2 Orthogonal optimum design

The main factors that determine the structure of the non-smooth front edge are wavelength and amplitude. Through the extraction of the non-smooth leading-edge shape, it is found that the wavelength and amplitude of the protrusion are proportional to the chord length of the airfoil at the position of the protrusion. Combined with the optimal airfoil, determined in Section 2.1.2, in the orthogonal test plan, three factors were considered, namely the wavelength, amplitude, and airfoil shape, with each being assigned four different factor levels regardless of the interaction between each factor, and the highest lift-to-drag ratio exhibited by the airfoil was used as the test index. The lift-to-drag ratio at this time is calculated from the ratio of lift to drag on the airfoil at a wind speed of 8 m/s and an angle of attack of 5°. For the orthogonal scheme, we adopted the \( L_{16} (4^4) \) orthogonal optimum design. Figure 10 shows the schematic of the orthogonal optimum design model. Table 1 lists the factor levels.

We set the chord length (C) of each airfoil to 100 mm. The lift-to-drag ratio of the 2D airfoil was the highest when the angle of attack was 5°; therefore, we performed the orthogonal test on the airfoil at a wind speed of 8 m/s and an angle of attack of 5°. As mentioned previously, the highest lift-to-drag ratio exhibited by the airfoil was used as the test index. The higher the value, the better the aerodynamics of the airfoil. Table 2 presents the analysis of the orthogonal test range. Through the extreme \( R_j \) analysis of the orthogonal test results, the higher the \( R_j \) value, the greater the influence of this factor on the test index, and therefore, the greater its importance. The primary and secondary factors affecting the aerodynamics of the airfoil are the airfoil B, wavelength W, and amplitude A. The magnitude of \( y_{jk} \) determines the optimal level of factor j. From this, the optimal levels of each factor are the airfoil B1, wavelength W3, and amplitude A1, and the optimal level combination is B1W3A1. Table 3 presents the analysis of variance of the orthogonal test results. The \( F \) values of the wavelength and amplitude factors are both less than \( F_{0.25} (3, 6) = 1.76 \), indicating that the wavelength and amplitude have little effect on the aerodynamics of the airfoil at a significance level greater than 0.25, and the \( F \) value of the airfoil factor is \( F_{0.25} (3, 6) = 1.76 < 9.5981 < F_{0.01}(3, 6) = 9.78 \), indicating that the airfoil has a significant influence on the lift-to-drag ratio.

2.3 Bionic coupling design

Biological coupling is the combination of two or more coupling elements into an objective entity or system with one or more biological functions, realized through appropriate methods. Biological coupling design of wind turbine blades involves taking the best airfoil of the owl’s wing as the design airfoil of the bionic wind turbine blade, and the non-smooth leading edge of the wind turbine blade is modeled from the optimal combination of the amplitude and wavelength. The optimal combination selected through the above orthogonal optimum design is that under the condition of the airfoil chord length \( C = 100 \) mm and 50% of the airfoil section of the owl’s wing is selected with an amplitude of 2.5 mm and a wavelength of 37.5 mm as the coupling parameters of the bionic wind turbine blade.

The Wilson algorithm was employed in the design of the bionic wind turbine blade. Considering the influences of the
Angle of attack $\alpha$ and lift coefficient $C_L$ on the blade spanwise distribution, the conventional Wilson algorithm was improved. The NACA4412 airfoil wind turbine was selected as the standard type, for a comparison with the bionic-coupled wind turbine. The designed wind turbine has a rated wind speed of 5 m/s, a rated power of 200 W, and a TSR of 6. Figure 11A shows the standard wind turbine. The torsion angle and chord length of the wind blade vary along the span direction, so the wavelength and amplitude of the bionic non-smooth front edge also vary with the chord length of the blade; the variation range is consistent with that of the non-smooth leading edge extracted from the owl eagle wing. Figure 11B shows the design of the bionic wind turbine blade. According to the leaf blade element theory in wind turbine blade design, the designed bionic wind turbine blade was divided into 10 parts, where the chord length of each part is the average chord length of the front and back chords of the segment. The leading-edge curve of each part, which can be represented by an equation with a sine function, was used along with the optimal combination parameters of the orthogonal optimum design to obtain the design data of the bionic wind turbine blade, as listed in Table 4.

### 3 | COMPUTATION DETAILS

#### 3.1 | Computational fluid dynamics model

The operation of wind turbine blades is associated with an unstable flow field, and the blades typically operate in a turbulent state. A suitable turbulence model plays a vital role in the smooth simulation of such blades. Hamed et al.\(^{18}\) and Moshfeghi et al.\(^{19}\) used the $k-\omega$ SST turbulence model to better simulate the flow field around a horizontal-axis wind turbine, and the simulation results were in good agreement with the experimental data. However, the simulation results in the case of an unstable flow at the root of the wind turbine blade obtained using the S-A and $k-\varepsilon$ turbulence models differ significantly from the experimental values.\(^{20,21}\) An incompressible Reynolds-averaged Navier–Stokes (RANS) solver and the $k-\omega$ shear-stress transport (SST) turbulent model were implemented to solve the problem. For incompressible and unsteady flows, the governing equations, including continuity and momentum equations, are as follows:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$  \hspace{1cm} (2)

$$\frac{\partial}{\partial t} (\rho \bar{u}_j) + \frac{\partial}{\partial x_j} (\rho \bar{u}_i \bar{u}_j) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \bar{u}_i \bar{u}_j \right)$$  \hspace{1cm} (3)

where $\bar{u}$ and $\bar{u}'$ are the mean and fluctuating terms of the velocity, respectively. $p$ is the pressure, $\rho$ is the fluid density, $x_j$ represents the Cartesian coordinates, $t$ is the time, and $\mu$ is the fluid dynamic viscosity.

The transportation equation of the $k-\omega$ SST model is as follows:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k + S_k$$  \hspace{1cm} (4)

$$\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_j} (\rho \omega u_j) = \frac{\partial}{\partial x_j} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega + S_\omega$$  \hspace{1cm} (5)

where $k$ represents the turbulence kinetic energy, $\omega$ is the specific dissipation rate, $G_k$ denotes the generation of the turbulence kinetic energy due to mean velocity gradients, $G_\omega$ is the generation of $\omega$, $\Gamma_k$ and $\Gamma_\omega$ represent the effective diffusivities of $k$ and $\omega$, respectively, $Y_k$ and $Y_\omega$ represent the dissipations of $k$ and $\omega$ due to the turbulence, respectively, $D_\omega$ denotes the cross-diffusion term, and $S_k$ and $S_\omega$ are two user-defined source terms.

### 3.2 | Boundary conditions

To better simulate the operating state of the wind turbine and the flow separation of the blade surface, a combination of rotating and stationary domains was used as the calculation domain. The calculation domain near the entire wind turbine was set as the rotating domain, a dynamic grid was used, the
Mesh Motion was set in FLUENT, and the rest was set as the static domain. The calculation domain was cylindrical, the inlet diameter was 2.5D (D is the rotor diameter), the length was 5.45D, the inlet diameter of the rotating domain was 1.1D, the length was 0.2D, and the distance from the outer domain inlet was 1.5D. The inlet of the calculation domain was the velocity inlet. The corresponding turbulence intensity and turbulence intensity scale were set under different Reynolds number conditions. The outlet was the pressure outlet. The interface between the rotating domain and the stationary region was set as an interface to ensure free passage of the fluid. The wall of the calculation domain was set as a non-slip wall condition, the hub and blade wall were set as moving walls, and the motion mode was the follow-up phase. When adjacent grids rotate simultaneously, the convergence residuals of all the models were set below $10^{-5}$.

### 3.3 | Meshing

The computational grid type is a structural grid. Figure 12 shows the computational domain and grid division. For the grid division, we used the ANSYS 15.0 software, and O-shaped grids were used for the static domain, which does not require very high grids; hence, the number of grids in the entire static domain was low. For the rotating domain grid,
we adopted a combination of a Y-shaped grid and an ordinary hexahedral grid to encrypt the blade and hub grid, and set the boundary layer on the blade and hub to meet the requirements of the surface boundary layer separation for grid accuracy. The $k-\omega$ SST calculation model has high requirements for the grid near the wall of the model. Moshfeghi et al.\(^{19}\) pointed out that for the $k-\omega$ SST calculation model, the dimensionless wall distance $y^+$ should be less than or equal to 1. Therefore, the height of the first layer of the blade and the hub surface satisfies the condition $y^+ \leq 1$.

As shown in Figure 13, to verify the grid independence, the wind speed was set to 5 m/s, the wind turbine speed was 205 rpm, and the blade tip Reynolds number was $1 \times 10^5$. Seven types of grids were simulated: 500 000, 1 million, 2 million, 4 million, 6 million, 8 million, and 10 million. The results of monitoring the torque produced by the blade and hub of the standard and bionic blade designs showed that the number of standard blade meshes is greater than 6 million. When the number of bionic blade meshes was greater than 8 million, the torque change was less than 1%. Therefore, in the simulation calculation, the number of meshes for the prototype and bionic blades was divided into 6 million and 8 million.

4 | RESULTS AND ANALYSIS

4.1 | Basic calculation model of a small wind turbine

The main performance indicators of a wind turbine are the power $P$ and the power coefficient $C_p$. The power coefficient $C_p$ represents the efficiency with which the wind turbine converts wind energy into mechanical energy. It can be expressed as:

$$C_p = \frac{T\omega}{0.5\rho A_1 V^3}$$  \hspace{1cm} (6)
where $A_1$ is the area swept by the wind turbine blade $A_1 = \pi \left( \frac{D}{2} \right)^2$, m²; $V$ is the wind speed, m/s; $\rho$ is the air density, kg/m³; $T$ is the aerodynamic torque around the center of the device, Nm; $\omega$ is the angular velocity, rad/s.

The TSR $\lambda$ is an important parameter in the design of blades. The TSR is the ratio of the linear speed of the blade tip rotation to the wind speed. It can be expressed as:

$$\lambda = \frac{\omega D}{2V}$$  \hspace{1cm} (7)

where $D$ is the diameter of the wind wheel, m.

The Reynolds number $Re$ is a commonly used parameter in fluid mechanics. It is a dimensionless quantity defined as the ratio of the inertial force of a fluid to the frictional force due to its viscosity. For the propeller wind, the Reynolds number can be expressed as:

$$Re = \frac{C_m \sqrt{V^2 + (R \omega)^2}}{\nu}$$  \hspace{1cm} (8)

where $C_m$ is the average chord length, m; $R$ is the wind wheel radius $R = D/2$, m; $\nu$ is the kinematic viscosity coefficient, m²/s (which is $1.51 \times 10^{-5}$ m²/s at standard atmospheric pressure and for air at 20°C).

### 4.2 Result analysis

The higher the power coefficient of a wind turbine, the higher is the utilization factor of the wind energy, and the higher is the power generation. At the rated wind speed (5 m/s), the standard and bionic blades were numerically simulated by varying the TSR, and the power coefficient $C_P$ was compared. In the Wilson algorithm, BEM is used to calculate the power coefficient of the bionic blade and the standard blade. Figure 14 shows the power coefficients of the standard and bionic blades at different TSRs.

As shown, the power coefficient first increases and then decreases with the increase in the TSR. At low TSRs ($\lambda = 1-4$), the power coefficient of the bionic wind turbine does not increase relative to that of the standard type, whereas at high TSRs ($\lambda = 4-7$), it increases by 17.7% compared with that of the standard type. This is because the high power coefficient of the bionic wind turbine at low TSRs is mainly affected by the airfoil (Figure 7 shows that the aerodynamics of the 50% section airfoil is better than that of the NACA4412 airfoil). The non-smooth leading edge cannot change the airflow distribution at low TSRs; the non-smooth leading edge in the bionic wind turbine at high TSRs has the effect of a vortex generator, thus changing the airflow distribution on the blade surface. Therefore, the wind turbine outputs a higher torque and has a higher wind energy utilization factor.
Figure 15 shows the surface pressure cloud diagrams of the wind turbine blade at a wind speed of 5 m/s and TSRs of 2 and 5. When TSR = 2, the pressures on the surfaces of the standard and bionic blades are similar. The pressure on the bionic blade is slightly greater than that on the standard blade only at the front edge of the suction surface, which makes the wind energy coefficient of the bionic blade slightly higher than that of the standard blade at low TSRs. When TSR = 5, the pressure on the top surface of the bionic blade is significantly greater than that on the top surface of the standard blade. However, the pressure on the bionic blade at the leading edge of the blade is lower. This is because the non-smooth leading-edge protrusion provides a shunting effect.

The separation of the boundary layer is the main factor leading to a decrease in the surface pressure of the blade.

Figure 16 shows the streamline diagrams of the blade surface at a wind speed of 5 m/s and blade TSRs of 2 and 5. When TSR = 2, the streamline distributions on the surfaces of the standard and bionic blades are largely the same; under the action of the wind turbine speed, the velocity streamlines flow from the leading edge of the blade to the trailing edge. The leading-edge bulge of the bionic blade does not play a role in diverting the airflow passing through the blade, and the separation of the boundary layer on the blade surface has little effect. When TSR = 5, an evident spanwise flow phenomenon can be observed on the suction surface of the bionic wind turbine blade. A spiral vortex is formed at the leading edge of the bionic blade near the blade root, and the airflow exhibits a reflex phenomenon, which leads to a decrease in the pressure on the blade at this position. Compared with the
standard blade, the airflow is still attached on the surface of the bionic blade in the boundary layer separation zone; this helps avoid stalling.

To compare the pressure distributions at different chord lengths and TSRs of 2 and 5 at the rated wind speed, the 20%, 50%, and 90% sections were selected from the root of the blade for the analysis. Figures 17 and 18 show the distributions of the surface pressure coefficients of the standard and bionic wind turbine blades.

At a low TSR (=2), the pressure coefficients of the bionic and standard blades are largely equal (Figure 17), albeit the surface pressure coefficient of the bionic blade is slightly greater than that of the standard blade on the suction side. The area enclosed by the surface pressure coefficient of the bionic blade is also larger than that enclosed by the surface pressure coefficient of the standard one. Because the area enclosed by the closing pressure coefficient curve represents the lift coefficient of the cross section,22 there is no significant improvement in the lift of the entire spanwise surface of the bionic wind turbine blade at low TSRs.

At a high TSR (=5), Figure 18 shows that the area enclosed by the blade surface coefficient of the bionic wind turbine is larger than that enclosed by the blade surface coefficient of the standard wind turbine at the 20%, 50%, and 90% sections. The pressure coefficient at the leading edge of the bionic blade drops sharply because the leading-edge bulge forms a spiral vortex at the leading edge of the suction force. However, the pressure generated by the bionic blade on the pressure surface is significantly greater than that generated by the standard one. At any position where x/c exceeds 20%, because of the existence of the non-smooth leading edge, the wavy structure and the incoming flow interaction line shift along the blade span direction, resulting in a crossflow on the blade surface. This explains why the bionic blade exhibits a higher pressure coefficient than the prototype blade. However, because of the flow instability, the pressure coefficient curve of the bionic blade fluctuates. At a high TSR, the area enclosed by the surface pressure coefficient of the bionic blade is larger than that enclosed by the surface pressure coefficient of the standard type at the three cross sections. Therefore, the bionic wind turbine exhibits higher lift and better power generation than the standard one under the same working conditions.

5 | CONCLUSION

Through reverse processing of an owl’s wings, a 3D model of the wing was established in this study. The wing was divided into 10 parts, and the airfoils of each section were
The airfoil data of each section were obtained by fitting, and the best-performing airfoil was determined on the basis of a numerical analysis. The non-smooth shape of the wing was extracted and coupled with the optimal airfoil. The optimal combination was determined by conducting an orthogonal optimum design. Finally, the optimal combination was applied to the wind turbine blade to design the bionic-coupled wind turbine blade. At the rated wind speed, we varied the TSR of the standard and bionic wind turbine blades, and the following conclusions can be drawn from the results:

1. The power coefficient graph shows that the power coefficient of the bionic wind turbine could not be improved significantly at low TSRs. Compared with the standard type, the power coefficient of the bionic wind turbine blade was increased by 17.7% at high TSRs.

2. We further analyzed the pressure cloud diagram and streamline diagram on the blade surface under two working conditions: a low TSR of 2 and a high TSR of 5. The pressure cloud chart showed that the bionic blade tip can sustain higher pressure. The streamline diagram of the blade surface showed that the non-smooth leading edge can change the streamline distribution of the flow field at high TSRs, so that the flow can move along the blade spanwise direction, thus avoiding premature separation of the boundary layer on the blade surface. This is also the main reason for the high pressure at the tip of the bionic blade.

3. Based on the pressure coefficient of the blade surface, we found that the bionic-coupled wind turbine blade exhibited higher lift at different cross-sections, higher torque under the same working conditions, and higher power generation than the standard blade.

In this study, the orthogonal optimum design method was used to select the optimal combination of the amplitude and wavelength, the optimum values of which were found to be 2.5 mm and 37.5 mm, respectively. However, the selection of the four levels of the wavelength and amplitude was based on a certain distance, and it is not continuous (as listed in Table 2). In actual situations, the optimal combination may appear at approximately 37.5 mm and 2.5 mm. In the future, we will use a neural network algorithm and the 16 optimum design models presented in this study as the training set for the neural network to obtain a more accurate combination of the wavelength and amplitude.

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CONFLICT OF INTEREST
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author, Kun Chen, upon reasonable request.

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