Design and Analysis of Airfoil Structure for Vertical Axis Wind Turbine

Zhihao Si*, Cheng Qian, Jie Shi, Haiyang Zhai, Yuhang Chen, Weijie Zhang

College of Information Science and Engineering, Jiaxing University,118# Jiahang road, Jiaxing, China
* Corresponding author: Zhihao Si

Abstract: With the vigorous development of the world's industry, the environmental pollution of the earth and the shortage of non-renewable energy such as oil are increasingly serious, all countries in the world are vigorously developing and researching the acquisition and utilization of clean energy. With the rapid development of expressways and the gradual establishment and improvement of urban expressways, the flow field formed by the fast running of cars on these roads provides new erection sites for the wind power generation system, and provides corresponding electric energy for the surrounding lighting and signage, which is a development path. It is proposed to rotate the blades of the vertical-axis wind power generation system by using the airflow driven by the high-speed car, and then convert the energy through the connected generator, and make full use of the airflow kinetic energy to generate electricity. In order to obtain high power generation efficiency and improve energy utilization coefficient, it is necessary to design and study the generator blade carefully. Determine the overall scheme of the vertical axis wind power generation system, complete the design of the blade airfoil and rotating shaft of the vertical axis wind power generation system. Through the theoretical analysis and force analysis, the wind turbine blade structure suitable for expressway is obtained. Conclusions for a small vertical axis generator driven by the perturbed wind speed generated by the driving of the car.

Keywords: Wind power generation; Vertical axis wind power generation; Airfoil structure

1. Research Status

FX168 Financial News Agency (North America) According to Euronews on Wednesday (August 25, 2021), Istanbul, Turkey's latest clean energy breakthrough: harvesting wind energy from vehicles on the road to generate electricity. A new device has appeared next to the road in Istanbul, it is called ENLIL, this device can use the airflow generated by moving vehicles to generate energy, vertical axis wind turbines are installed in the green belt of the highway to collect the high-speed traffic on the road when the vehicles pass by airflow to generate energy. Convert the kinetic energy of the wind into electrical energy. Simple structure, low maintenance cost later; easy to assemble and fix. The breeze generated from passing vehicles may not seem like much, but the vertical blades can collect the breeze and convert the wind energy, eventually enough to generate one kilowatt per hour [1].

The British company Apha311 has proposed a simple and ingenious method: installing cylindrical wind turbines on lamp posts beside the highway, and using the wind power generated by passing cars to power street lamps. In this way, the existing highway infrastructure can be fully utilized. Turbines in the middle of the road, in particular, can "extract" a lot of energy from road traffic using the wind generated by moving vehicles. Test data shows that a single turbine can generate as much electricity as a 21-square-meter solar panel a day, enough to power 10 households. Apha311 estimates that it would cost about $2,646 to build a turbine on the highway. The electricity generated by the turbines can be fed into the grid via street light cables to power more homes or factories. Currently, the company is preparing to install the first turbines for wind power generation in the UK and the US [2].

2. Design Scheme

2.1. Design Ideas

As my country resolutely implements the strategies of "rejuvenating friendship through science and education", "rejuvenating friendship with talents" and "strengthening friendship with science and technology", the economy is changing with each passing day, and it once became the second largest economy in the world. People's living materials are greatly enriched, and private cars have become more and more commonly, the number of private cars is increasing rapidly. According to the survey of the number of private cars in my country, the statistics are shown in Table 1 [3].

Table 1. Private car ownership

years	Private car ownership (10,000 units)	years	Private car ownership (10,000 units)
2002	968.98	2012	8838.6
2003	1219.2	2013	10501.7
2004	1481.7	2014	12339.4
2005	1848.1	2015	14099.1

2006	2333.3	2016	16330.2
2007	2876.2	2017	18515.1
2008	3501.4	2018	20574.9
2009	4574.9	2019	22509
2010	5938.7	2020	24285.2
2011	7326.8	2021	26246

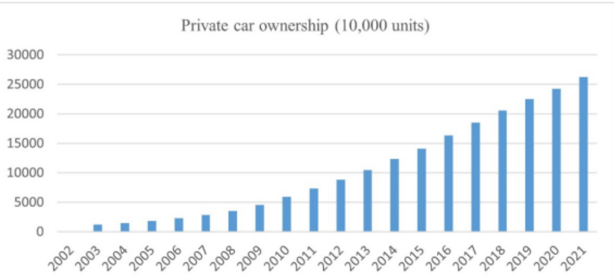


Figure 1. Private car ownership

Figure 1 clearly expresses the rapid increase in the number of private cars in my country in recent years. With the increase in the number of vehicles, the total mileage of expressways in my country is also increasing at an unprecedented rate. By the end of 2019, the total mileage of expressways in my country has reached 142,600 kilometers, ranking first in the world.

When we ride in a car, we can often feel a gust of wind generated by the driving of the car, especially at high speeds. The faster the speed of the car, the greater the wind force generated. When two cars pass by each other, the fan is quite large. Therefore, a small wind turbine that can make full use of the wind generated by the car is designed to be installed in the center of the road.

2.2. Design Size

Combined with the requirements for saving space in road traffic, lighting, and municipal pipeline layout in the implementation code of municipal engineering, traffic signs, road lighting facilities, communication cables, etc. must be erected on poles and columns. The belt width is at least 1.5m [4].

The maximum outer dimension of the car is the main factor that produces the disturbance speed. My country's national standard GBl589--89 clearly stipulates the outline size limits of automobiles, and the maximum outline dimensions of automobiles should not exceed the following restrictions:

1. Total height: 4.0m;
2. Overall width (excluding rear-view mirror): 2.5m, take = 1.25m in polar coordinates;
3. Overall length:
(1) 12.0m for trucks (including off-road trucks);
(2) 12.0m for passenger cars: 18.0m for articulated passenger cars;
(3) The tractor to the semi-trailer 16.5m;
(4) 20.0m for all-car trailer trains.
4. The disturbance effect of automobiles on wind turbines

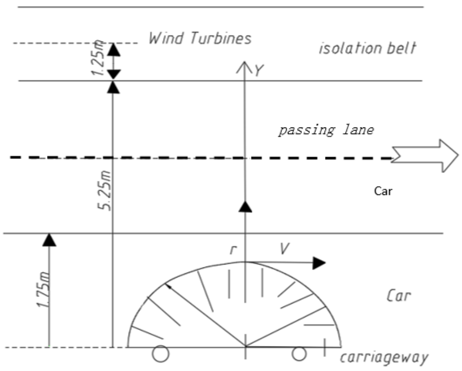


Figure 2. Schematic diagram between the car and the wind turbine when driving on the highway

In Figure 2, taking the half r0=1.25m of polar coordinates, the expression of the bit function yao obtained according to the theory of bit flow is:

$$\Phi=u_0 r \cos\theta(1+r_0^2/r^2) \quad (1)$$

or

$$\Phi=u_0 r \sin\theta(1-r_0^2/r^2) \quad (2)$$

The component velocities in polar coordinates are decomposed as:

Speed along the radius:

$$U_r=u_0 \cos\theta(1-r_0^2/r^2) \quad (3)$$

Velocity along the tangent direction:

$$U_\theta=-u_0 \sin\theta(1+r_0^2/r^2) \quad (4)$$

Now we consider the velocity U_θ along the tangent direction, when $r=r_0$, $U_\theta=-2\cdot u_0\cdot\sin\theta$. The negative sign in the formula indicates that the speed U_θ points to the S_θ axis, and the direction of the positive axis is determined according to the reading direction of the coordinate angle θ, as shown in Figure 1 for details. At that time, $\theta=\frac{\pi}{2}$, $r=r_0$, $U_\theta=2\cdot U_0=v_0$ is exactly the direction of the speed of the car. There are two terms in the parentheses of formula (4), the disturbance speed term generated by the car driving is $U_{\theta 2}=-v_0\cdot\sin\theta\cdot\frac{r_0^2}{r^2}$, and $\theta=\frac{\pi}{2}$, is taken as: $U_{\theta 2}=-v_0\cdot\frac{r_0^2}{r^2}$.

The theoretical calculation value of the disturbance speed V of the car on the road (r=5.25m at the blade of the wind turbine) is shown in Table 2

Table 2. The relationship between vehicle speed and disturbance wind speed r=5.25m

V_0(km/h)	V_0(m/s)	$V_{r=5.25}$(m/s)
80	22	1.3
90	25	1.4
100	28	1.6
110	30	1.7
120	33	1.9

130	35	2.0

When the car is driving in the passing lane, r0=1.25m, the diameter of the wind turbine blade is 2m, the radius R=1m, and r=2.75m at the wind turbine blade. At this time, the theoretical calculation value of the disturbance speed *V* of the car driving on the passing lane (*r*=1.75m at the blade of the wind turbine) is shown in Table 3.

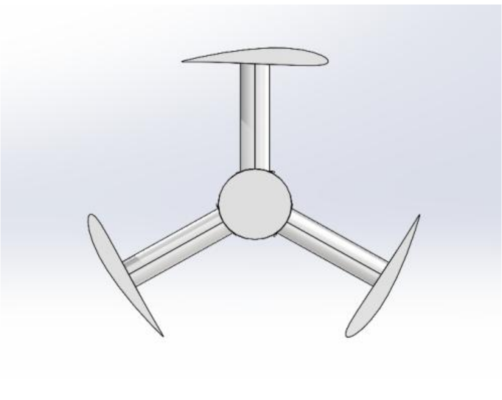
Table 3. Relationship between vehicle speed and disturbance wind speed r=1.75m

V_0(km/h)	V_0(m/s)	$V_{r=1.75}$(m/s)
80	22	3.0
90	25	5.0
100	28	5.8
110	30	6.2
120	33	6.8
130	35	7.4

It can be clearly seen from the calculation that the vehicle driving in the first lane (overtaking lane) has the best disturbance speed to the wind power generation, ignoring the natural wind speed. According to the specification and calculation, the design wind speed of the wind turbine can be selected as V design=5m/s [5].

According to my country's national conditions, the adaptive traffic volume of the expressway is Class II (equivalent to Class C in the United States), that is, the calculated driving speed is 120km/h. Because the performance of small passenger cars in my country is worse than that of developed countries, and the mixing rate of large vehicles such as trucks is high, if the wind turbine is placed in the isolation belt, for the sake of conservative, it is reasonable to consider the driving speed of 100km/h in the design of wind power generation.

Through the above reference, a small wind turbine blade, as shown in Figure 3, suitable for placement in the isolation belt, is designed to be rotated by the wind generated by the car to achieve the purpose of generating electricity. So as to achieve better utilization of wind energy. The rotation radius of the fan is 0.66m, and the blade length is 2.1m, so that the wind speed generated by cars and large trucks can achieve the effect of generating electricity. The blade can achieve the purpose of wind power generation by connecting the generator.



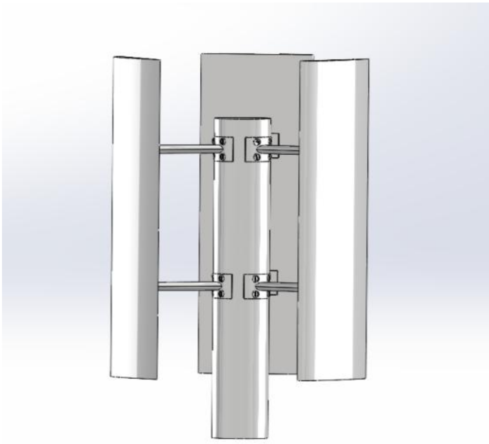


Figure 3. Small vertical axis wind turbine blade model

3. Analysis of Leaves

The principle of physics shows that in the air flow field, the pressure in the area with fast airflow is small, and the pressure in the area with slow airflow is high. When there is relative motion between the blade element and the atmosphere, the airflow produces lift d*L* and drag d*D* in the blade element. The drag force is parallel to the direction of the relative velocity, and the lift force is perpendicular to the direction of the relative velocity. The angle between the relative airflow direction and the geometric chord of the blade element airfoil is called the angle of attack, which is represented by *a*.

The lift force on the leaf element is:

$$dD = \frac{1}{2}\rho \cdot w^2 \cdot c \cdot C_l \cdot dr \tag{5}$$

The resistance on the leaf element is:

$$dD = \frac{1}{2}\rho \cdot w^2 \cdot c \cdot C_d \cdot dr \tag{6}$$

where: ρ is the density of air, in kg/m3; w is the relative velocity, in m/s; c is the geometric chord length, in m; C_l is the characteristic coefficient of lift; d*r* is the length of the blade element, in units is m; C_d is the resistance characteristic coefficient. The lift characteristic coefficient C_l and the drag characteristic coefficient C_d are dimensionless parameters that describe the force on the airfoil, and the lift-drag ratio C_l / C_d is an important parameter to measure the ability of the blade airfoil to generate lift and drag in different environments. The larger the value of lift-drag ratio, the greater the lift the airfoil receives, the better the aerodynamic performance of the blade airfoil, and the better the blade can utilize the wind energy to improve the power generation efficiency [6].

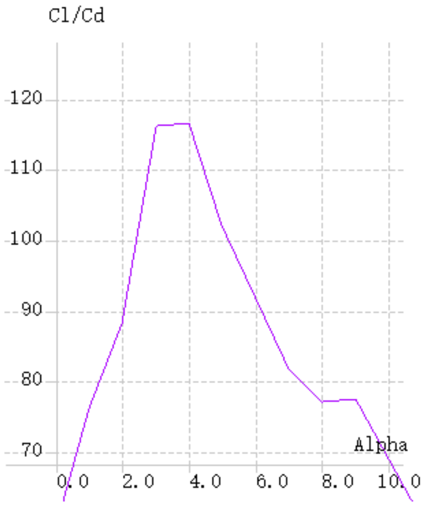


Figure 4. NACA4412 lift-to-drag ratio

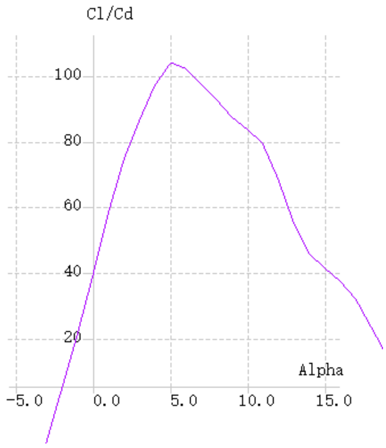
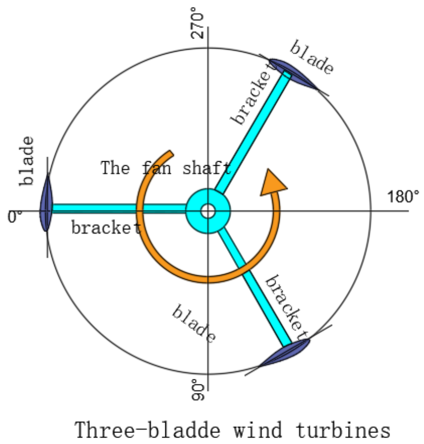


Figure 5. NACA2214 lift-to-drag ratio

Through the separate analysis of the two blades, it can be clearly seen that the lift-drag ratio of Figure 4 NACA4412 is larger than that of Figure 5 NACA2214, which shows that the greater the lift the NACA4412 airfoil receives, the better the aerodynamic performance of the blade airfoil and the better utilization of the blade. Wind energy to improve power generation efficiency. The power regulation of the wind turbine is the key technical means of the wind power generation system, and its main methods include fixed pitch stall regulation, variable pitch stall regulation and active stall regulation. The fixed pitch stall adjustment fixes the fan blades and the hub, and the blade top angle cannot be adjusted with the wind speed. Its structure is relatively simple and the reliability is strong. The output power of the fan changes with the wind speed, so its utilization rate is low at low wind speeds. Pitch adjustment is to adjust the conversion efficiency of wind energy by changing the pitch angle, improve the conversion efficiency of wind energy as much as possible, and keep the output power of the fan stable. Active stall regulation adjusts the output power by actively stalling the blades. When the wind speed is lower than the rated wind speed, it is regulated by the control system; when the wind speed exceeds the rated wind speed, the pitch system makes the blades stall by increasing the angle of attack of the blades, thereby limiting the absorbed power of the wind rotor [7].



(a)Top view of the rotation of the three-blade fan

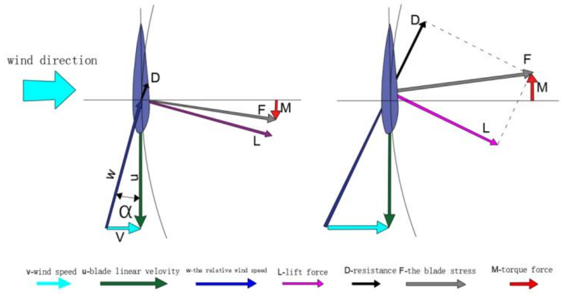


Figure 6. Force analysis of blade

There are many explanations for the lift principle of the airfoil. In summary, the main basis is that the airflow deflection based on Newton's law produces a reaction force, and the airflow velocity based on Bernoulli's principle produces a pressure difference as shown in (a) and Figure 6. We combine these two principles. The type of lift is explained in a popular way [8]. Since the angle of attack of the flat blade is slightly larger, it is easy to cause airflow separation and increase the resistance; the strength of the flat plate is also very low, so the official blade section is streamlined, even if there is a certain thickness, the resistance is very small.

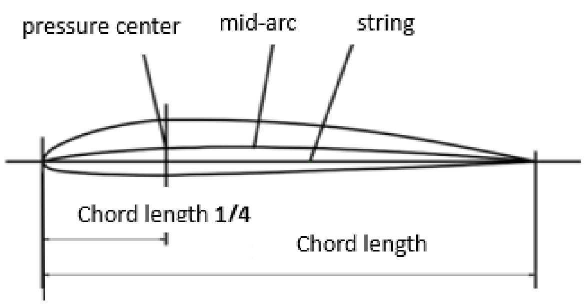


Figure 7. Airfoil geometry parameter dD

Figure 7 is a geometric parameter diagram of a common airfoil. The mid-arc of the airfoil is an upwardly curved arc. This airfoil is called an asymmetric airfoil or a cambered airfoil, which is a typical cambered airfoil. Figure 8 and

Figure 9 show the pressure diagram at the angle of attack is 0 ° of Type 8NACA4412 and 9NACA2414 for US respectively

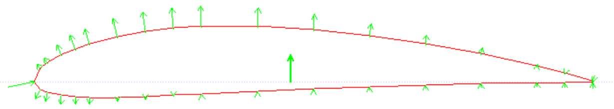


Figure 8. NACA4412 angle of attack is 0 °pressure diagram

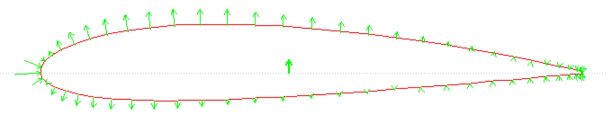


Figure 9. NACA2414 angle of attack is 0 °pressure diagram

4. Conclusion

1. Make full use of wind energy resources and reduce the consumption of conventional energy, which is in line with the direction of national energy reform. And wind energy is an inexhaustible renewable energy source.

2. Compared with coal-fired power plants of the same scale, wind power plants emit zero pollutants into the atmosphere, and achieve zero emissions of solids and gases. It has a positive effect on protecting the atmospheric environment.

Compared with coal-fired power plants, wind power plants can save a lot of fresh water resources and reduce water pollution. It is especially important for coastal and arid regions lacking freshwater resources.

3. Solve the problem that the traditional wind turbine cannot be started due to the small wind power, improve the power generation efficiency of the wind turbine, and maximize the benefits.

With the introduction of the policy of carbon neutrality and carbon peaking, wind energy is an inexhaustible new energy source. It will further enter people's field of vision, and wind turbines on highways will also be popularized step by step. It is believed that wind turbines on highways will also be widely used in the near future.

Acknowledgements

This work was supported in part by the College Student Research Training Program of Jiaxing University (SRT) (Grant number: CD8517211432), the National Innovation and Entrepreneurship Training Program for College Students (Grant number: 202110354055).

References

[1] Euronews. Turkey's latest clean energy breakthrough the wind power generated by the speed of the vehicle is used to power the wind energy up to 1000 watts/hour. FX168 Financial News (North America) News. August 25, 2021.

[2] "Singularity Science". 2021.05 issue p8.

[3] Wang Pengcheng. Research on the development trend of private car ownership in my country—taking the past twenty years after the reform and opening up as an example. Basic Science; Engineering Science and Technology II; Economics and Management Science, 2018(03).

[4] Wen Chunyan. The application of the location and width of urban road green belts. Engineering Science and Technology II. Transportation World. 2018(15).

[5] Zhang Weizhi, Song Guoping, Highway Planning, Survey and Design Institute of Sichuan Provincial Department of Communications. A new field of wind energy utilization - wind power generation on expressways. 38-43.

[6] Yu Xinqing, He Yongling, Huang Fangwu, Wu Fei, Hu Kai. Comparison and analysis of aerodynamic performance of wind turbine blade airfoils suitable for wind conditions in the Beibu Gulf of Guangxi. Engineering Science and Technology Series II. Journal of Wuhan University of Technology (Transportation Science and Engineering Edition).

[7] Cheng Yazhou. Discussion on wind power generation and its application. Shandong: Shandong University. 2019294.

[8] Zhang Chenchen. On the Conservation of Fluid Energy and the Application of Pressure Potential Energy and Bernoulli's Principle Engineering Science and Technology II. Basic Science China Equipment Engineering. 2022(03).