Journal of Mechanical Research and Application (JMRA), Vol. 13 No.3, 1402(2023),44-55

Expediency in Designing a Small Scale Horizontal Axis Wind Turbines Based on Blade Element Momentom and Finit Element Method Analysis

Ali Abjadi[1*], Mohammadamin Karimkhani[2], Seyed Reza Mirmotahary[3], Farzad Ghafoorian[3]

[1]Department of Mechanical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran.

[2] Department of Chemical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

[3]School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran.

****

Abstract

With the increasing use of renewable energy sources, the adoption of horizontal axis wind turbines (HAWTs) has become more common. However, the optimal design of the turbine blades to improve efficiency is still being discussed. An ideal blade should have strength and an acceptable mass, both at the same time. To address this issue, a study was conducted to evaluate and determine the most efficient HAWT blade design using three types of NACA airfoil profiles: 2412, 4412, and 0024. The blade profil NACA 4412 turbine was found to have the highest efficiency at TSR equal to 10. The blade structure employed in the study comprised three designs, namely, spanwise hollow, hollow with spar, and solid. The results revealed that the solid blade weighed a total of 11 kg, which could lead to numerous operational challenges. Moreover, the blades exhibited a maximum stress range of 0.2 to 0.3 MPa. These findings underscore the importance of selecting the appropriate blade type to ensure optimal performance and safety.

Keywords: *horizental axis wind turbine; BEM method; FEM theory ; Qblae open source package*

---

[*] Corresponding author. Department of Mechanical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran. E-mail address: a_abjadi@azad.ac.ir (Ali Abjadi).

1. Introduction

The global shift toward green energy due to environmental concerns makes wind energy the most reliable source[1]. Enhancing the technological capabilities of wind turbines is of paramount importance for optimizing their performance. Advancements in wind turbine technology are essential for reducing the cost of energy production and increasing the overall efficiency of wind energy systems. Therefore, it is imperative to invest in research and development of wind turbine technologies to ensure their continuous improvement[2]. By doing so, we can contribute to the growth of the renewable energy sector and promote sustainable development practices. The classification of wind turbines can vary, but the most important and widely recognized classification is based on their rotating axis. Wind turbines are generally classified into two groups: Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs). The most commonly used type of wind turbine is the HAWT[3]. Three diffrenet HAWTs was been investigated experimentaly and numerically. Optimum blade shape (OPT), untampered and optimum twist (UOT), untaptered and untwisted (UUT) are the configurations. Results shows opt and uot has the maximum power coefficient but the tip speed ratio is different. And obviously uut blade has the lower power coefficient[4]. An analysis was performed to evaluate the impact of varying wind profiles and frequencies. The findings indicated an 8% discrepancy in the verification stage. Furthermore, a decrease of 25% in stiffness was detected at the blade's base when examining the turbine's inherent frequencies. Additional inaccuracies were identified in both the span-wise and edge-wise directional natural frequencies[5]. An optimizion on aerodynamic blade shape of was conducted numerically. Optimum pitch angles and twist was found. The important poin here is that this optimizion was case study realistic wind profile in Deniliquin[6]. A case study on airfoil and blade optimization was conducted at multiple points in Iran. As a result, 43 suitable airfoils were extracted and the optimum blade was found. Based on two parameters, an efficiency improvement ranging from 7.7% to 22.7% was achieved[7]. It is possible to vary the airfoil profile from the hub to the tip of a blade. According to a numerical study, a blade made up of two types of airfoils, namely NACA2412 and NACA4412, is more efficient than a blade with a single airfoil type[8]. Parametric studies on horizontal-axis wind turbines (HAWTs) using the blade element momentum (BEM) method are common. The number of blades, solidity, rotor diameter, and blade airfoil profile can have a significant impact on HAWT performance[9]. The impact of using different airfoils on the total strength of horizontal-axis wind turbines (HAWT) was investigated through experimental and numerical analysis using the QBlade software. The results showed that among the airfoils tested, the NACA 4412 had the highest strength. However, based on power generation and acceptable stress values, the Eppler 417 was considered the most optimal cross-section for the HAWT[10].

In this study, a turbine is investigated utilizing the two complementary perspectives of blade element momentum (BEM) and finite element method (FEM). We assess the power factor as a function of tip speed ratio (TSR) to evaluate the output power of the turbine. Moreover, we analyze the vane structure to determine its mass and natural frequency. The study aims to provide insights into the performance of the turbine. The BEM approach provides a simplified yet accurate representation of the aerodynamics of the turbine, whereas the FEM approach allows for a detailed analysis of the structural dynamics. By combining these two perspectives, we can gain a comprehensive understanding of the turbine's behavior under various operating conditions. With respect to the vane structure, the analysis aims to identify the mass and natural frequency of the vanes. The results of this analysis are critical in ensuring the safe and reliable operation of the turbine. Furthermore, the study offers valuable insights into the design of the vane structure, which can lead to improvements in the turbine's performance. Overall, this study utilizes advanced methods to investigate the performance and design of turbines, with the ultimate goal of improving their efficiency and reliability.

2. Governing equations

Lift and drag coefficients are calculated from the following relationships.

$$C_L = \frac{2L}{\rho A V^2} \tag{1}$$

$$C_D = \frac{2D}{\rho A V^2} \tag{2}$$

L and D are lift and drag, respectively. Also, $A(m^2)$ is the blade airfoil profile area, V(m/s) is considered as wind velocity, and ρ is air density, which is equal to 1.225 (kg/m^2).

Also, to evaluate the obtainable power of the turbine, a dimensionless parameter called the power coefficient is defined, as well as a dimensionless parameter called the tip speed ratio, which depends on the incoming wind velocity, rotational speed, and rotor radius. Cp and TSR is defined as:

$$C_p = \frac{P}{1/2\rho A V^3} \tag{3}$$

$$TSR = \frac{R\omega}{V} \tag{4}$$

where d is the displacement vector, M_S is the mass matrix of structure, C_S is the damping matrix of structure, K_S is the stiffness matrix of structure, f_p is the node vector of fluid force on the fluid-structure interface, and f_0 is the external excitation vector except f_p.

$$M_S\ddot{d} + C_S\dot{d} + K_S d + f_p + f_0 = 0 \tag{5}$$

By writing down the equations of shape function of structure element and using virtual work, the equation of motion of the structure under the fluid can be expressed as:

$$M_S\ddot{d} + C_S\dot{d} + K_S d - B^T p + f_0 = 0 \tag{6}$$

where p is a fluid dynamic pressure. This equation forms a fluid-structure coupling system between blades and flow field.

3. Problem description and solution strategy

In this study, a small-scale HAWT is modeled by the Qblade open-source package is nominated for numerical modeling. The Qblade commercial code couples the BEM method with the actuator disc theory to conduct a systematic mathematical model that encapsulates the intricate phenomenon in the actual blade. The turbine blade is discretized into a finite number of blade elements. Each piece of the blade's cross-section is characterized by radial position, airfoil profile, chord length, and twist angle. The relative wind velocity for every section is calculated using the actuator disk or blade element momentum theory. HAWT prototype dimensions and geometrical specifications are given in Table 1. Also, the rotor blades are divided into eleven sections, and the characteristics of the rotor blade in each radial position are presented in Table 2. It should be noted that the blade profiles of this rotor are not the same from the hub to the tip, so that the first two sections of the blades have a circular section and the other sections are made of NACA series profiles. The third to fifth, sixth to eighth, and ninth to eleventh radial sections have NACA 0024, NACA2412, and NACA4412 airfoil profiles, respectively.

Table 1 Dimensions and main geometric specifications of the simulated HAWT

	Quantity	Value
1	Number of blades (B)	3
2	Rotor diameter (D)	4.2(m)
3	Hub diameter (d)	0.1 (m)
4	Blade airfoil profiles	NACA4412 NACA2412 NACA0024

Table 2 Blade design parameters

Section number	Radial position(m)	Chord length(m)	Twist angle(degree)
1	0.1	0.076	0
2	0.302	0.126	0
3	0.504	0.119	18.312
4	0.706	0.076	12.191
5	0.908	0.063	8.660
6	1.11	0.055	6.379
7	1.312	0.050	4.789
8	1.514	0.045	3.619
9	1.716	0.042	2.722
10	1.918	0.039	2.014
11	2.12	0.036	1.440

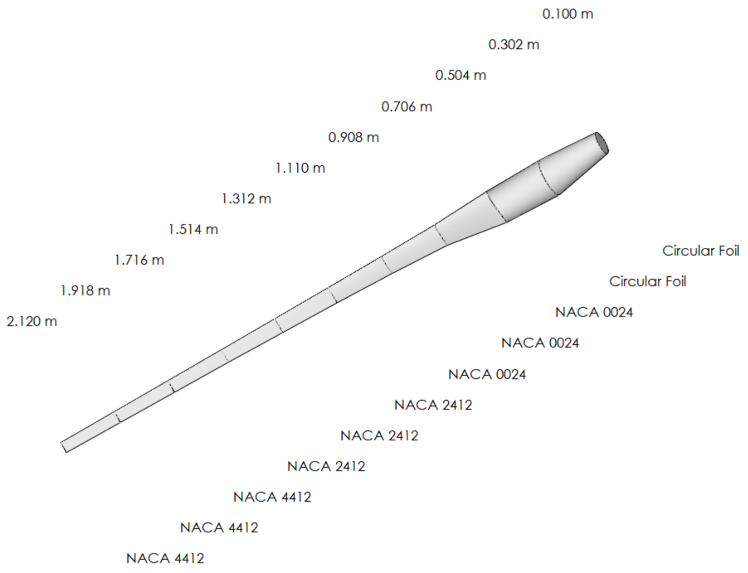

Figure 1 Blade configuration

All three employed airfoil profiles are classified as low Reynolds airfoils. Reynolds number 5×105 and Ncrit number 9 are considered. Also, the considered AoAs are from -5° to 25°. These values for Reynolds and Ncrit numbers signify turbulent flow within a low Reynolds number range. The nominated values reflect the conditions of an average wind tunnel regime, neither exceptionally clean nor heavily laden with dust. Knowing the aerodynamic characteristics across various AoA is essential to determine the airfoil's efficiency. To understand the aerodynamic characteristics of airfoils, the diagram of lift and drag coefficients according to the angle of attack is given in figures 2 and 3.

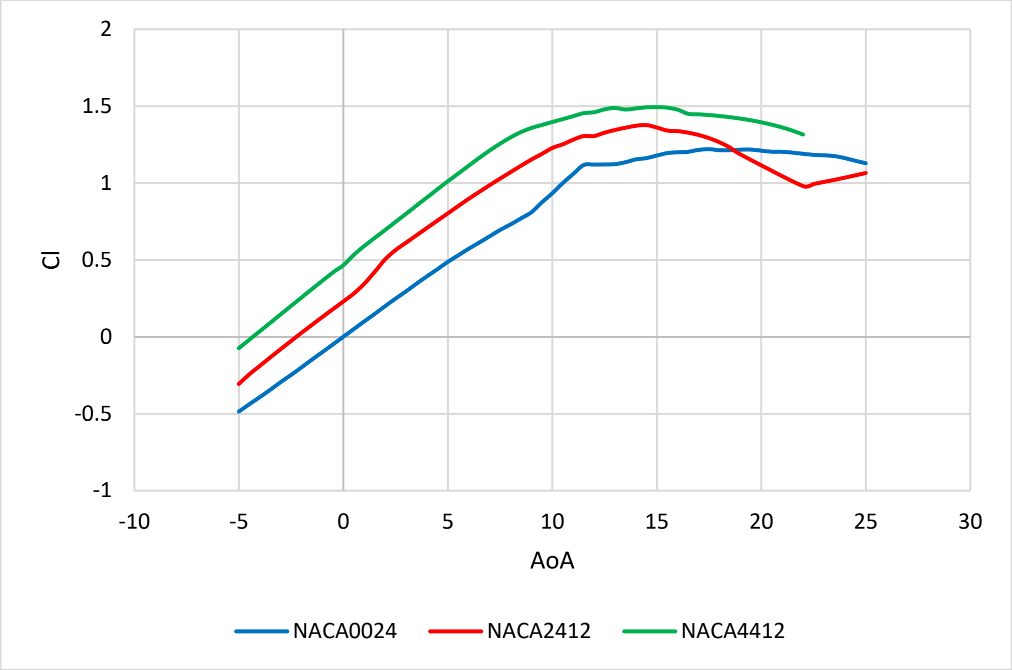

Figure 2 Cl as a function of angle of attack

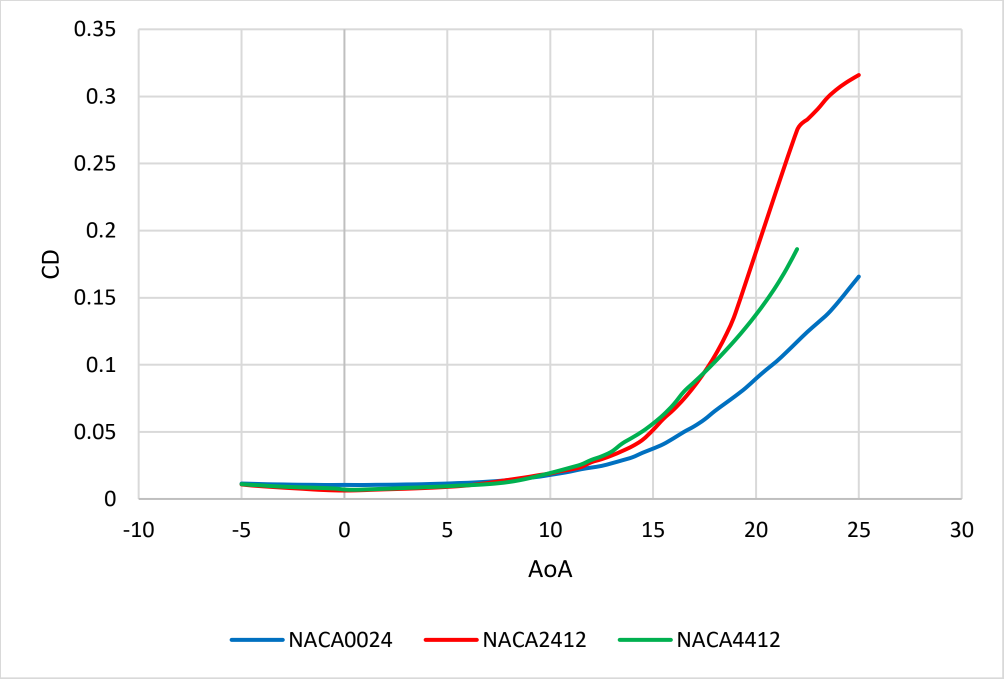

Figure 3 Cd as a function of angle of attack

4. Results and discussion

In this section, the results obtained from the analysis of the flow around the turbine based on the BEM and actuator disc theory methods are given, then the stress and vibration analysis of the blade based on the load applied along the length of the blade is discussed with the FEM method.

4.1. BEM results

This section investigates the effect of using different airfoils for blade design. Different airfoils, due to their aerodynamic characteristics and different lift and drag coefficients, as well as the difference in thickness and chord length, cause differences in the angle of attack, which changes the efficiency and performance of the rotor.

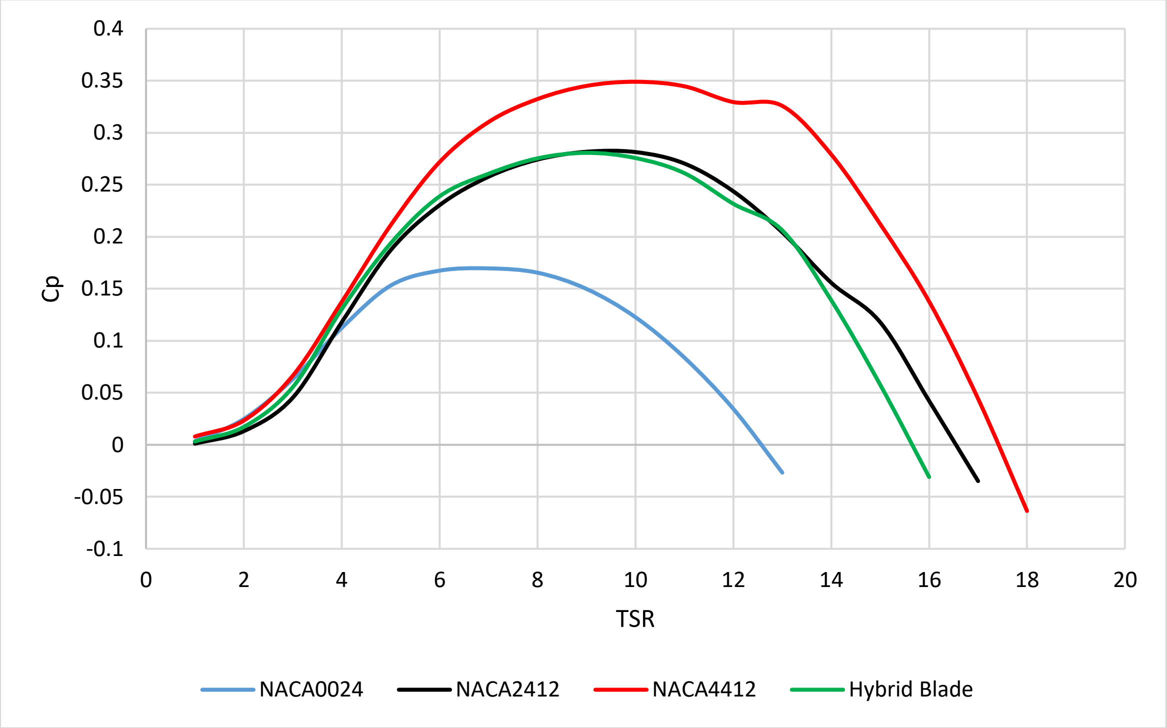

Figure 4 Cp as function of TSR

According to the shape of the turbine with a blade consisting of NACA4412 airfoil, it showed the highest Cp equal to 0.35 in TSR=10, while the turbine with NACA 0024 airfoil profile had the lowest Cp among all cases, and the highest Cp value of this turbine was equal to 0.16 in TSR =6 has been. Also, the turbine with blades made of NACA0024 has shown the lowest operating range.

4.2. FEM simulation

Three different modes are considered for airfoils: simple hollow blades, hollow blades with spar, and solid blades. Shell thickness and spar thickness are assumed to be 0.02% and 0.08%, respectively. It should be noted that the spars are vertical and have no angles.

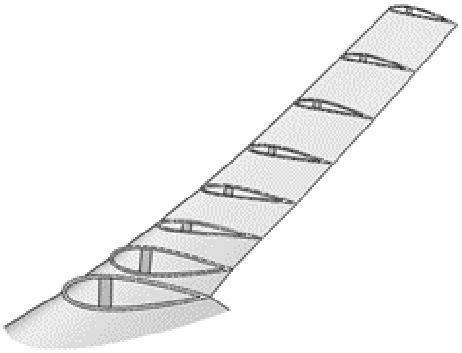

Figure 5 Hollow blade with spar

Table 3 FEM results

Blade type	Mass(kg)	Natural frequency in mode 1(Hz)	Natural frequency in mode 2(Hz)	Natural frequency in mode 3(Hz)	Natural frequency in mode 4(Hz)

Hollow	1.5	6	26	60	100
Hollow with spar	2.5	6	24	55	95
Solid	11.5	5	21	48	79

As it is clear, the turbine with solid blades is very heavy and has serious challenges in operation and installation. Also, in different modes, the natural frequency of the hollow turbine is higher than all modes based on the Flawise model. Also, hollow turbine with and without spar has the highest stress equal to 0.3MPa and the highest stress of solid blade equals 0.2MPa. The stress distribution coutour plot on the blade is given below.

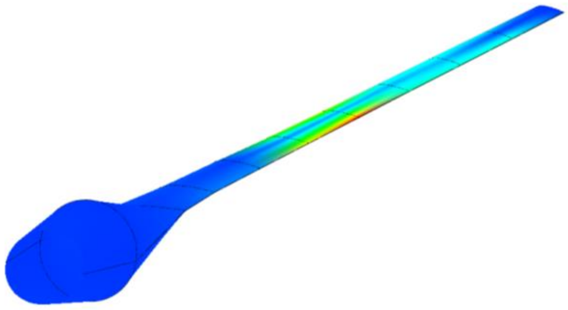

Figure 6 Stress distribution

5. Conlusion

In this study, we conducted an analysis using Qblade open source software, based on both BEM and FEM theory. The findings revealed that the turbine equipped with airfoil blade profile NACA 4412 exhibited the highest efficiency. Furthermore, the FEM analysis demonstrated that the turbine with a hollow blade had the highest natural frequency.

References

[1] *Aircraft Propulsion and Gas Turbine Engines, Second Edition*. CRC Press, 2017. doi: 10.1201/9781315156743.

[2] S. L. Dixon and C. A. Hall, *Fluid mechanics and thermodynamics of turbomachinery*, Seventh edition. Amsterdam ; Boston: Butterworth-Heinemann is an imprint of Elsevier, 2014.

[3] W. Tong, "Fundamentals of wind energy," in *WIT Transactions on State of the Art in Science and Engineering*, 1st ed., vol. 1, WIT Press, 2010, pp. 3–48. doi: 10.2495/978-1-84564-205-1/01.

[4] F.-B. Hsiao, C.-J. Bai, and W.-T. Chong, "The Performance Test of Three Different Horizontal Axis Wind Turbine (HAWT) Blade Shapes Using Experimental and Numerical Methods," *Energies*, vol. 6, no. 6, pp. 2784–2803, 2013, doi: 10.3390/en6062784.

[5] D. Adams, J. White, M. Rumsey, and C. Farrar, "Structural health monitoring of wind turbines: method and application to a HAWT," *Wind Energ.*, vol. 14, no. 4, pp. 603–623, May 2011, doi: 10.1002/we.437.

[6] N. Khlaifat, A. Altaee, J. Zhou, Y. Huang, and A. Braytee, "Optimization of a Small Wind Turbine for a Rural Area: A Case Study of Deniliquin, New South Wales, Australia," *Energies*, vol. 13, no. 9, 2020, doi: 10.3390/en13092292.

[7] M. Mohammadi, A. Mohammadi, and S. Farahat, "A New Method for Horizontal Axis Wind Turbine (HAWT) Blade Optimization," *IJRED*, vol. 5, no. 1, pp. 1–8, Feb. 2016, doi: 10.14710/ijred.5.1.1-8.

[8] K. Kriswanto *et al.*, "Rotor Power Optimization of Horizontal Axis Wind Turbine from Variations in Airfoil Shape, Angle of Attack, and Wind Speed," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 94, pp. 138–151, Apr. 2022, doi: 10.37934/arfmts.94.1.138151.

[9] H. Sedighi, P. Akbarzadeh, and A. Salavatipour, "Aerodynamic performance enhancement of horizontal axis wind turbines by dimples on blades: Numerical investigation," *Energy*, vol. 195, p. 117056, Mar. 2020, doi: 10.1016/j.energy.2020.117056.

[10] B. Somaiday, I. Czajka, and M. A. R. Yass, "STRENGTH ANALYSIS OF A BLADE WITH DIFFERENT CROSS-SECTIONS".