Experimental Study to Design and Manufacturing of NACA 0012 Horizontal Axis Wind Turbine Blade

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Abstract

In this research, the design, analysis, improvement, and manufacturing of a horizontal axis wind turbine with symmetrical blade section type (NACA 0012) airfoil have been achieved. For better performance and behavior, it is necessary to install some parameters and controlled the others to achieve the best wind turbine performance.

Fortran 90 computer programs are used to analyze and calculate the design data as well as compare these data with the results of CFD code. Then the optimization methods Scmitz, betz and lift/drag optimization were used to improve chord and pitch angle for a wind turbine. Turbine blades were drawn by solidwork program, and then this data was transferred to the 3D printer to manufacture the blades. Note that the blades were made of fiberglass material. The results were as follows, where the Cp =0.481 at TSR=7 before optimization and after optimization, the best results were as follows Cp = 0.556 at Schmitz chord optimization and lift/drag twist optimization, Also Cp = 0.53 at Betz chord optimization and lift/drag twist optimization at same TSR.

Keywords: Wind turbine design, NACA 0012 airfoil, Symmetrical airfoil, CFD program, Blade manufacturing, Optimal design, Betz, Schmitz and lift/drag optimization

List of symbols

Symbol	Definition	Units
P	Power	w
W	Relative Wind speed	m/sec
V_1	Stream velocity	m/sec
α_D	Angle of attack	deg
$C_{(r)}$	Chord length	m
$\beta_{(r)}$	Pitch angle	deg
R	Blade radius	m
M	Torque	N.m
v	Axial speed	m/sec
u	Normal speed	m/sec
T	Thrust	N
X	Tip speed ratio	___
n	Rotational speed	1/sec
r	Rotor local radius	m
F_L	Lift force	N
F_D	Drag force	N
C_x	Coefficient of axial force	____
C_y	Coefficient of normal force	____
C_l	Lift coefficient	____
C_d	Drag coefficient	____

Introduction

Wind energy is the cleanest form of available renewable energy **[1]**. Wind energy is an abundant source in comparison with other renewable sources **[2]**. Many countries will ensure that wind power was increasingly used in the near future to supply power **[3]**. Growing awareness of rising levels of greenhouse gases, global warming and increasing prices of fossil fuels have led to shift towards investing into low-cost small wind turbines. Simple structured, compact in design, portable and low noise **[4][5]**, the small wind turbines are now vital wind power extracting devices in the rural Small wind turbines have been integrated on domestic house roof, farms, remote communities and boats **[6]**. In contrast to larger horizontal axis wind turbines (HAWTs) that were located in areas dictated by optimum wind conditions, small wind turbines were required to produce power without necessarily the best of wind conditions **[7][8]**.

The most of generated power from wind turbines were produced in wind farms, or large fields that have many large commercial wind turbines. From an environmental outlook, a wind farm was much more preferred than a coal burning plant because of carbon emissions and other factors, but both methods of power generation require the consumer buy this power from a utility corporation. About 80 percent of global energy requirements were accomplished using fossil fuels. The main problems related to fossil fuels are exhausted in time and cause environmental damage **[9]**. Wind energy is a relatively clean and sustainable energy source. Old history stated that wind power was used independently in different locations around the world **[10]**.

The wind speed in a certain area was not constant but varied at the right time. Fortunately, the difference in wind speed in a particular area was expected. The different control mechanisms were accompanied by changing the wind speed and changing the wind direction. The revolution of the turbine changes in one minute as the next wind changes so that its production power also changes **[11]**. One of the problems with wind power is coming from wind speed is unpredictable. In order to obtain high quality outputs, different controls were introduced in the wind turbine rotor. One of these controls is pitch control. When winds flow over wind turbines, they exert dynamic air forces on wind turbine blades. There are two types of aerodynamic forces, powerful lifting and pulling. By rotating the blades of the wind turbine around its axis, it changes these aerodynamic forces **[12]**. So in order to get a certain kind of quality, wind turbine blades spin in response to change the wind speed coming.

1. Betz optimization

The velocities and the angles in a given distance (r), from the rotor axis as shown in Figure (1). As shown below, the blade number is B = 2. For rotor, designing must design the pitch angle β and the length of blade chord c.

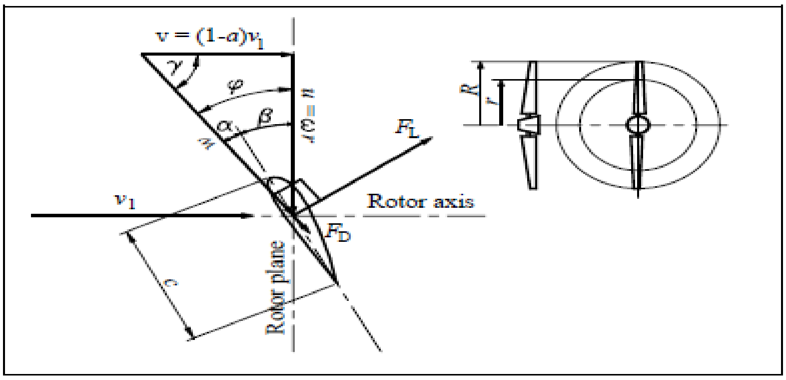

Figure (1) Velocities and angles [13].

We have

$$W^2 = V^2 + u^2 \quad (1)$$

Wind rotation is not supported in betz, i.e. $a' = 0$

Therefore $u = \omega r \quad (2)$

We need to define the following parameters as follows: **[13]**

$$X = \frac{V_{tip}}{V_1} = \frac{\omega R}{V_1} \quad (3)$$

$$\gamma(r) = \arctan\frac{3r X}{2 R} \quad (4)$$

$$\phi(r) = \arctan\frac{2 R}{3r X} \quad (5)$$

$$\beta(r)\text{Betz} = \arctan\frac{2 R}{3r X} - \alpha_D \quad (6)$$

Chord length c(r)

The lift force at the turbine blade in distance (r) from the hub axis with blade thickness *dr* presented below: **[14]**

$$dF_L = \frac{1}{2}\rho\, w^2\, c\, dr\, C_L \quad (7)$$

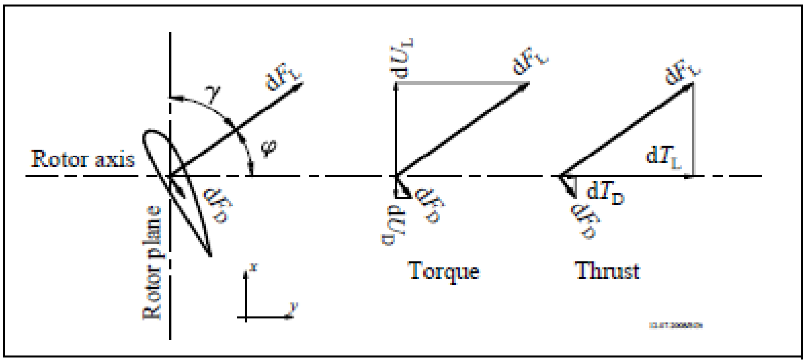

Figure (2) the forces applied on the blade section [14].

$$dU = \frac{1}{2}\rho\, w2\, c\, dr\, Cx \quad (8)$$

$$Cx = CL \sin(\phi) - CD \cos(\phi) \quad (9)$$

For the rotor axis (thrust) we have: **[14]**

$$dT = \frac{1}{2}\rho\, w2\, c\, dr\, Cy \quad (10)$$

$$Cy = CL \sin(\phi) + CD \cos(\phi) \quad (11)$$

$$dU = \frac{1}{2}\rho\, w2\, c\, dr\, CL \cos(\gamma) \quad (12)$$

$$dP = B\,\frac{1}{2}\rho\, w2\, c\, d\, r\, CL \cos(\gamma)\, r\, \omega \quad (13)$$

According to Betz

$$dP = \frac{16}{27}\frac{1}{2}\rho V_1^2 (2\pi\, r\, dr) \quad (14)$$

Using $v_1 = 3/2\, w \cos(\gamma)$ and $u = w \sin(\gamma)$ gives:

$$c(r)\text{Betz} = \frac{16\pi R}{9B\, CL{,}D}\,\frac{1}{X\sqrt{X^2\left(\frac{r}{R}\right)^2+\frac{4}{9}}} \quad (15)$$

2. Schmitz optimization

Schmitz developed a more detailed flow model on the rotor plane. The blade torque M on the rotor shaft can only be established due to the wake rotation.

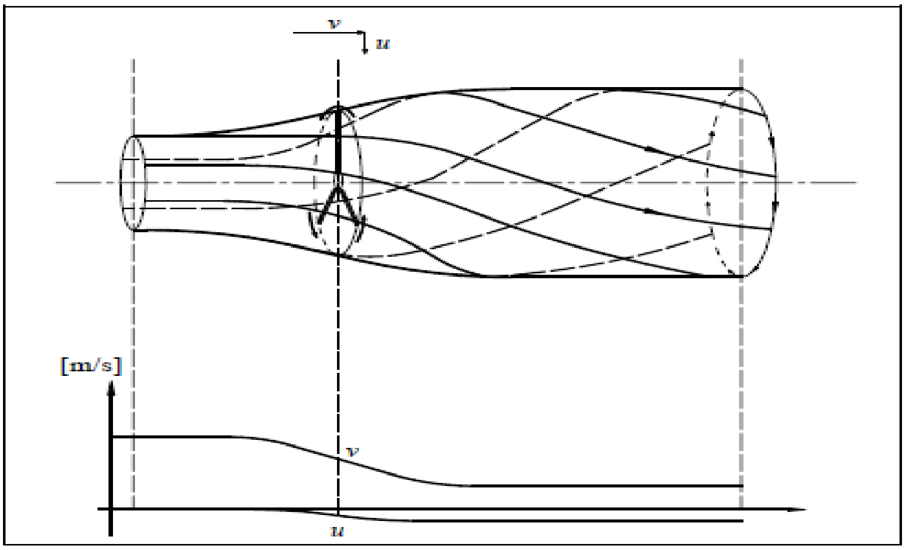

Figure (3) wake downstream rotation [13].

The power extracted from wind is **[13]**

$$P = M\,\omega \quad (16)$$

$$u = r\,\omega + \tfrac{1}{2}\Delta u \quad (17)$$

$$u = r\,\omega(1 + a') \tag{18}$$

$$w = w1\cos(\phi 1 - \phi) \tag{19}$$

$$v = w\sin(\phi) \tag{20}$$

$$v = w1\cos(\phi 1 - \phi)\sin(\phi) \tag{21}$$

$$\Delta w = 2w1\sin(\phi 1 - \phi) \tag{22}$$

$$\mathrm{d}FL = \Delta w \mathrm{d}q \tag{23}$$

$$\mathrm{d}q = 2\rho\,\pi\,r\,\mathrm{dr}\,v \tag{24}$$

$$\mathrm{d}P = \mathrm{d}M\,\omega = r\,2\omega\,\rho\,2\pi\,\mathrm{dr}\,w_1^2\sin[2(\phi 1 - \phi)]\sin 2(\phi 1)$$

$\phi\max = \frac{2}{3}\phi_1$ **[13]** Or (25)

$$\phi\max = \frac{2}{3}\arctan\frac{v1}{\omega\,r} \tag{26}$$

$$\beta(r)\text{Schmitz} = \frac{2}{3}\arctan\frac{R}{r\,X} - \alpha_D$$
(27)

$$\begin{aligned}\mathrm{d}F_L &= \Delta w\,\mathrm{d}q\\ &= w1\sin(\phi 1 - \phi)\,2\rho\pi\,r\,\mathrm{dr}(w1\cos(\phi 1 - \phi)\sin(\phi))\\ &= 2\,w_1^2\,2\rho\pi\,r\,\mathrm{dr}\sin\left(\frac{\phi 1}{3}\right)cos\left(\frac{\phi 1}{3}\right)\sin\left(\frac{2\phi 1}{3}\right)\\ &= 2\,w_1^2\,2\rho\pi\,r\,\mathrm{dr}\sin^2\left(\frac{\phi 1}{3}\right)cos^2\left(\frac{\phi 1}{3}\right)\end{aligned} \tag{28}$$

$$\begin{aligned}\mathrm{d}F_L &= ½\rho\,w^2\,B\,c\,\mathrm{dr}\,C_L\\ &= ½\rho\,w^2\,B\,c\,\mathrm{dr}\,C_L cos\left(\frac{\phi 1}{3}\right)\end{aligned} \tag{29}$$

$$c(r)\text{Schmitz} = \frac{1}{B}\frac{16\pi\,r}{C_L}\sin^2\left(\frac{\phi 1}{3}\right) \tag{30}$$

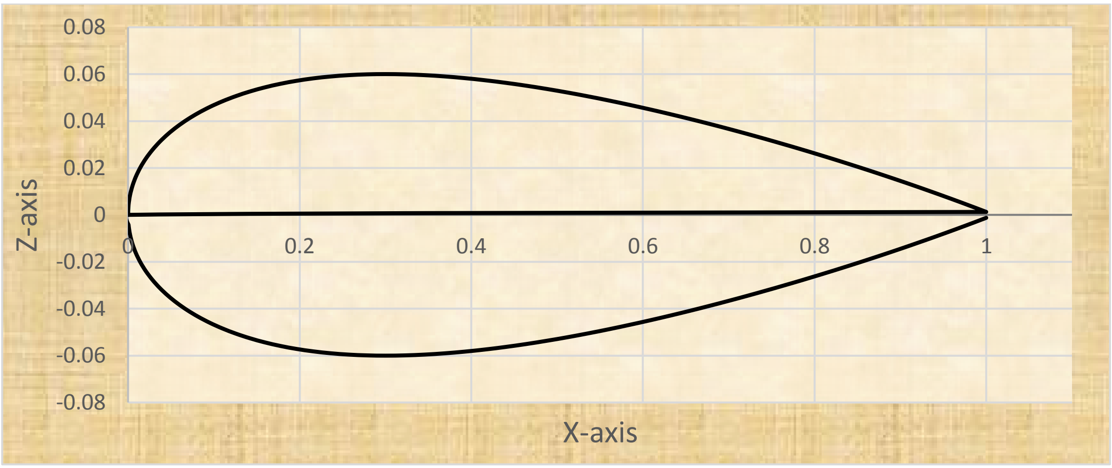

Figure (4) NACA 0012 airfoil.

The solidwork program used to design the blade section. Where the blade is designed in the form of many sections for each specific length section, chord and the angle of twisting; Weight is also calculated and distributed in the section. When designing a section, a gap is designed inside the section and its purpose is to connect sections together, add strength and durability to the blade when designing the section, a bump and a joint are added in each section in order to connect with the other section.

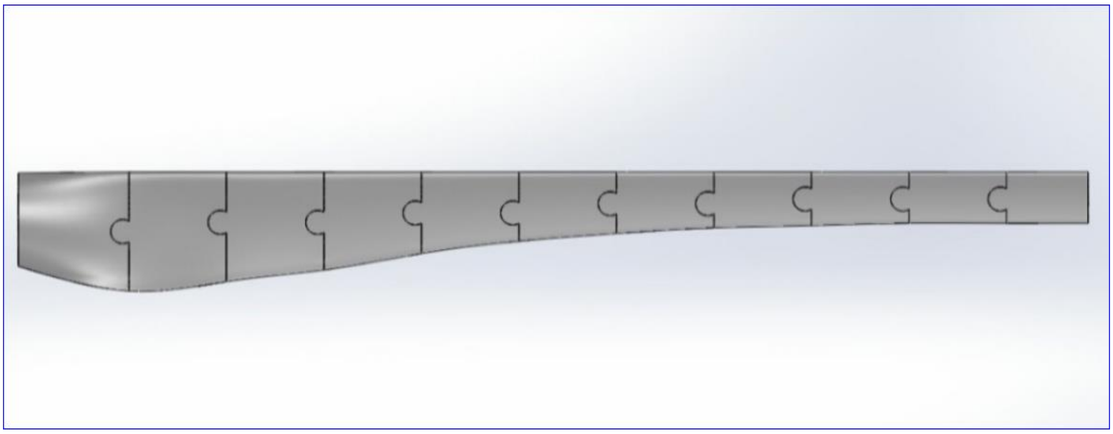

Figure (5) Solidwork design for NACA 0012 blade.

Figure (6) shows the three blades manufactured during the 3D printer machine, the sections are connected with each other through the protrusions and through a shaft of iron pass through the feather from tip to root, and this iron shaft is connected to the hub and is well fixed by screws for the most efficient, cohesive and strong blade resisting air force.

Figure (6) NACA 0012 blades manufactured with 3D printer.

In the previous, figure can notice the existence of spaces between the sections and cracks in them, as well as that the surfaces are not smooth and this causes problems when the airflow over the turbine which will generate unwanted vibrations. Figure (7) shows the filling of spaces between the sections and removal of the resulting excrescences during manufacturing, in addition, the surfaces become and resulting from smooth blade, soft surfaces and ready to be attached to the turbine.

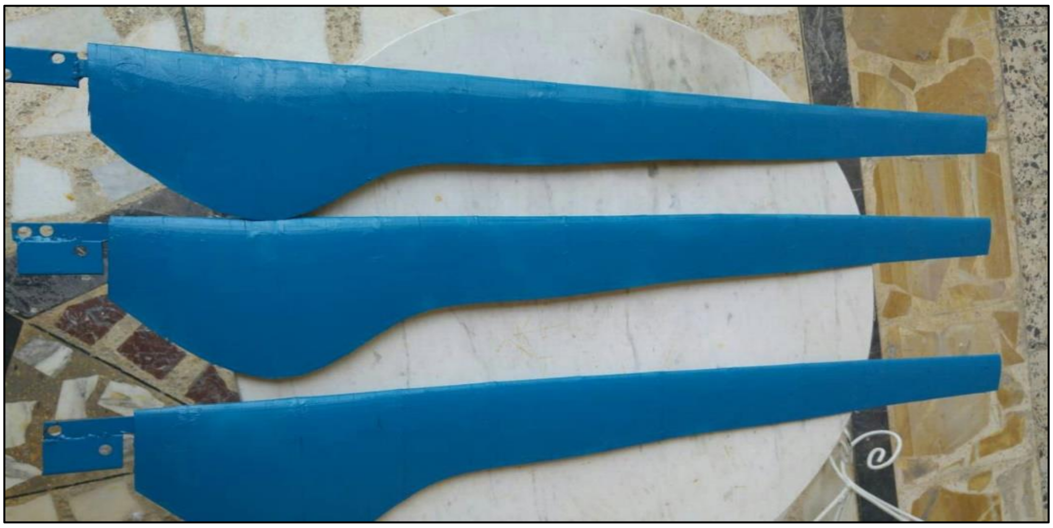

Figure (7) Blades painting.

Results and Discussion

The aerodynamic design point of view for all wind turbine blade is the airfoil section which is the further sophisticate aerodynamic principles to capture the wind energy more effectively .L/D ratio is the technical point of selecting the airfoil and doesn't matter what type of airfoil select except some side view point which also important, and its related to L/D ratio like amount of angle at each section of wind mill blade for giving high L/D ratio, so the significant point to select the maximum L/D ratio range from the working area of the airfoil section and the amount of angle at that range that gives quieter and capable of generating more power from less wind speed, so it gives higher TSR many factors to e consider for chord optimization one of these factors tangential interference because the rotation of the wind does exist, number of blades which present the frontal area facing the wind, as well the blade length which is a manger parameter to be considered for chord optimization.

Twist angle which based on L/D ratio is the significant parameter to calculate for chord optimization.

All these parameter, optimization method Betz, Schmitz lift/drag twist optimization and genetic algorithm have been built to gather to get the best result for the highest coefficient of power.

The optimization methods have been applied on the airfoil NACA 0012 with the following cases:

1- Non twist optimization, Schmitz's chord optimization (NS).
2- Non twist optimization, Betz chord optimization method (NB).
3- Lift/drag twist optimization method, Non-chord optimization (ON).
4- Lift/drag twist optimization method, Schmitz's chord optimization (OS).
5- Lift/drag twist optimization method, Betz chord optimization (OB).

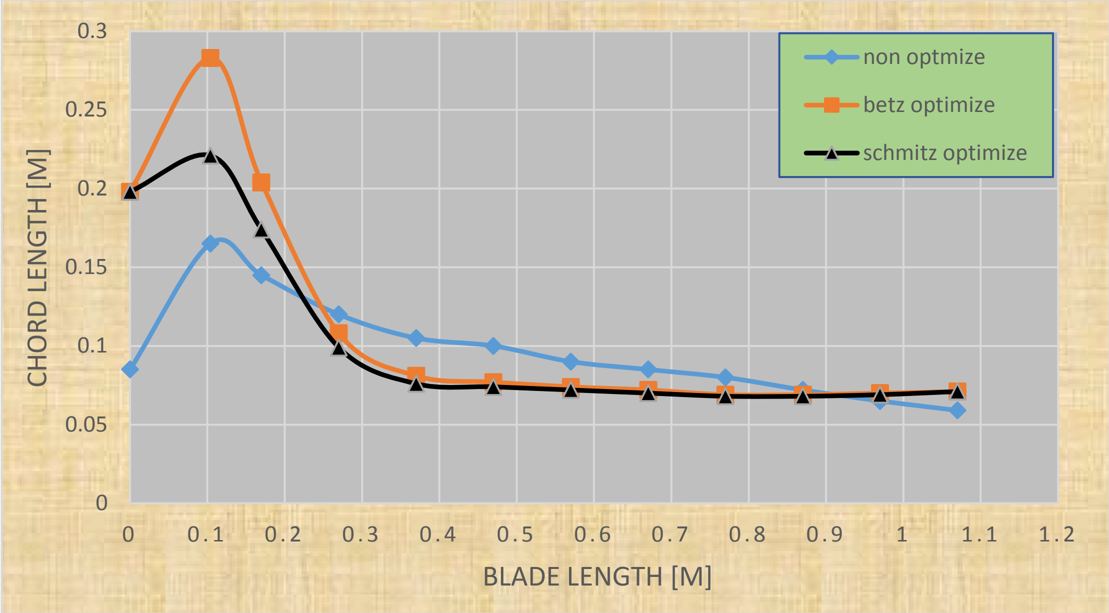

Figure (9) Comparison of chord length calculated with many optimization methods for NACA 0012 airfoil at no twist case.

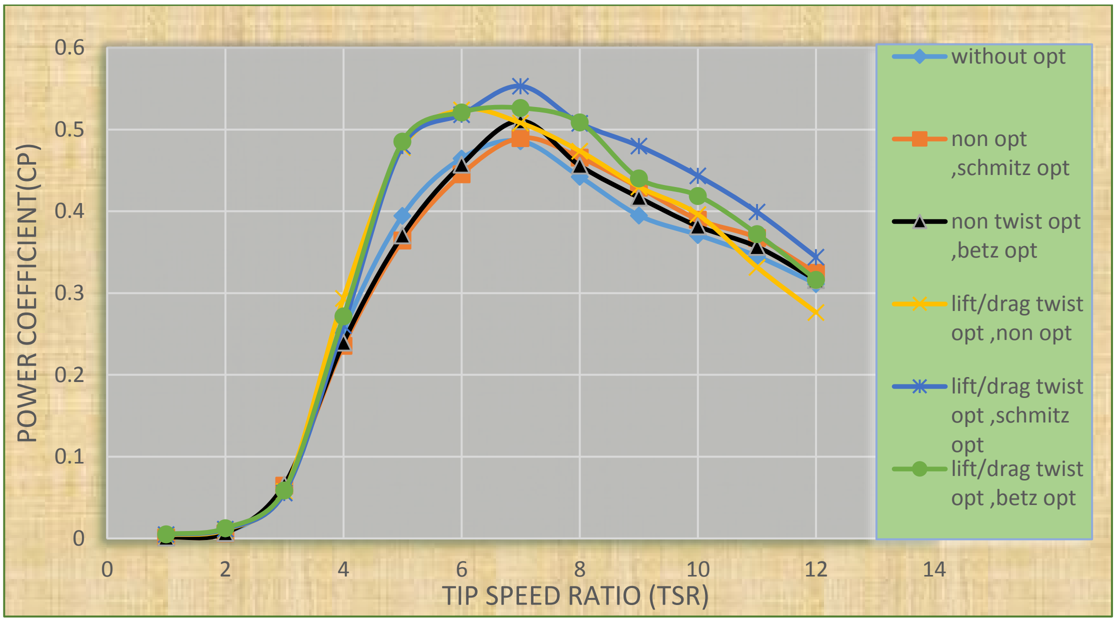

Figure (10) Comparison of Power Coefficient Calculated with Many Optimization Methods for NACA 0012 Airfoil.

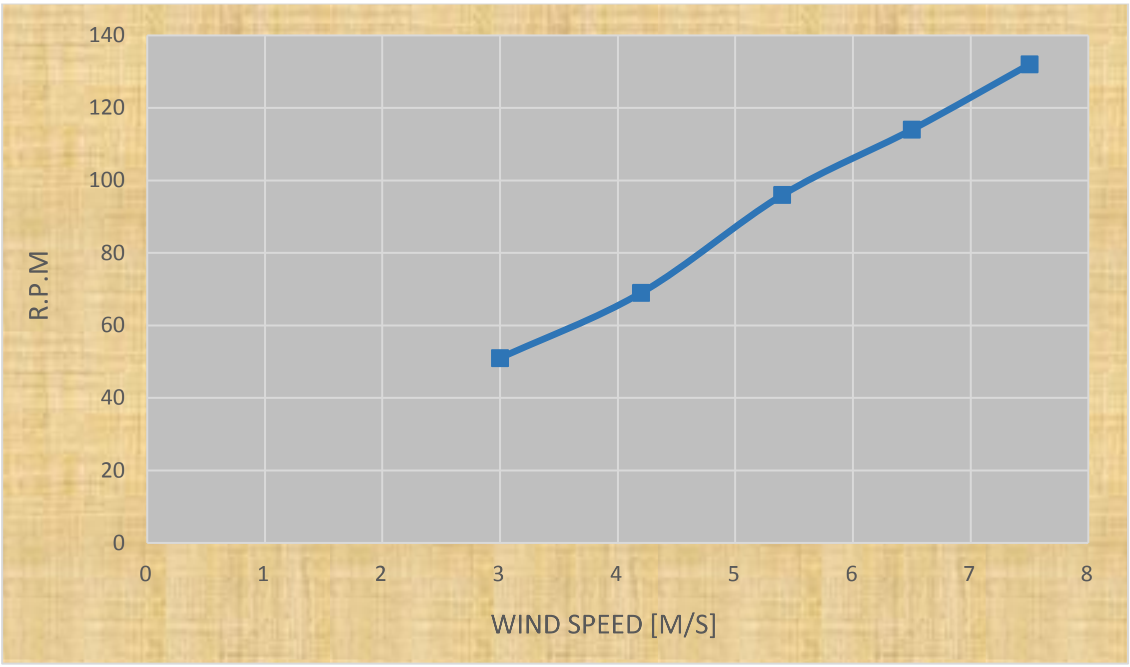

Figure (11) R.P.M versus wind speed for NACA 0012 experimental results.

Figure (12) used digital Anemometer. **Figure (13): used digital tachometer.**

Table (1) chord optimization methods.

Position (m)	Non Optimized Chord (m)	Betz Chord Optimization (m)	Schmitz Chord Optimization (m)
0	0.085	0.198	0.195
0.104	0.165	0.283	0.221
0.17	0.145	0.204	0.174
0.27	0.12	0.108	0.099
0.37	0.105	0.081	0.076
0.47	0.1	0.077	0.074
0.57	0.09	0.074	0.072
0.67	0.085	0.072	0.07
0.77	0.08	0.069	0.068
0.87	0.072	0.069	0.068
0.97	0.065	0.07	0.069
1.07	0.059	0.071	0.071

Table (2) power coefficient (Cp) calculated with many optimization methods.

TSR	NN Optimization	NS Optimization	NB Optimization	ON Optimization	OS Optimization	OB Optimization
1	0.00155	0.0014	0.0014	0.0041	0.0047	0.00522
2	0.00648	0.0066	0.0067	0.0107	0.0115	0.0127
3	0.0621	0.0644	0.0656	0.058	0.056	0.059
4	0.254	0.236	0.24	0.293	0.26	0.272
5	0.4	0.366	0.373	0.48	0.482	0.488
6	0.47	0.45	0.459	0.527	0.522	0.525
7	0.481	0.497	0.521	0.51	0.556	0.53
8	0.456	0.485	0.48	0.479	0.51	0.507
9	0.432	0.452	0.445	0.447	0.475	0.474
10	0.397	0.416	0.409	0.41	0.442	0.441

Table (3) Experimental results for the used airfoils.

Wind speed (m/s)	NACA 0012 r.p.m
3	51
4.2	69
5.4	96
6.5	114
7.5	132

Conclusion

1. Best windmill blade airfoil selection should be at high L/D and low angle of attack.
2. Highest CP can be attained if optimization is done for twist angle and for chord length to gather.
3. Highest CP optimization value always occurs at mid-length of the blade (approximately 55% of blade length).
4. Optimization increases the CP value about 10-16%.
5. Optimum methods increase the root chord approximately 100% at the root and 30% at the tip

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دراسة عملية لتصميم وتصنيع ريشة توربين ريحي افقي المحور نوع (NACA 0012)

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الخلاصة

في هذا البحث تم تصميم وتحليل وتحسين وتصنيع ريشة توربين رياح افقي المحور ذات مقطع متناظر نوع NACA) (0012. للحصول على اداء وسلوك أفضل من الضروري تثبيت بعض العوامل والتحكم في عوامل اخرى للوصول الى أفضل أداء لريشة توربين الرياح.

تم استخدام برنامج فولرتران 90 لتحليل وحساب بيانات التصميم وكذلك مقارنة هذه البيانات مع نتائج CFD Code. كذلك تم استخدام طرق التحسين (Scmitz, betz and lift/drag optimization) لتحسين وتر وزاوية الملعب لريشة توربين الرياح. من ثم رسم ريش التوربين بواسطة برنامج solidwork بعد ذلك ارسال هذه البيانات الى 3D printer ليتم تصنيع الريش. علما ان الريش صنعت من مادة الالياف الزجاجية.

النتائج كانت كالتالي، حيث كانت قبل التحسين Cp =0.481 عند TSR=7، وبعد التحسين اصبحت

Cp = 0.556 .عند استخدام نظرية Schmitz لتحسين الوتر وطريقة lift/drag optimization لتحسين زاوية الملعب، وكانت

الـ Cp = 0.53 عند استخدام نظرية Betz لتحسين الوتر وطريقة lift/drag optimization لتحسين زاوية الملعب.

كلمات مفتاحية: تصميم توربين رياح، مقطع ريشة متناظر، تصنيع ريشة توربين رياح، التصميم الامثل، betz, Schmitz and lift/drag optimizationبرنامج السوائل الحسابية الديناميكية.