Enhancement of Lift and Drag Coefficients of Wind Turbine Using Q-Blade and Grey-Taguchi

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Abstract—The determination of lift (C_L) and drag (C_D) coefficients for Three-Blade Horizontal-Axis Wind Turbine (HAWT) power performance can be computed using the Q-Blade software, and optimization by employing Taguchi design of experiments (DOE). In the present investigation, the orthogonal array (OA) L_9 with 3-factors namely airfoil type, angle of attack, and Reynolds number with 3-levels are applied to determine single response optimization of C_L and C_D. For multiple response optimization, the Grey-based Taguchi is applied which combines the Taguchi orthogonal array with grey relational analysis to determine the grey relational grade, which can convert the multiple response grey relational grade into a single grey relational grade, thus the optimal design factors can be achieved. The obtained results show that the airfoil type S1210, attack angle 10 and Reynolds number 125000 are given the optimal value of 1.936 and 0.023 for lift and drag coefficients respectively. The most affected design factors for lift and drag coefficients are airfoil type with 43.64% contribution followed by attack angle with 35.69%, and least affected factor is Reynolds number with 12.5% contribution for this specific set of HAWT experiments.

Keywords—HAWT; Airfoil coefficients; Taguchi method; Grey relational analysis; Optimization; Q-Blade

I. INTRODUCTION

The growing interest at present in renewable energy resources, especially wind energy, prompting researchers to intensify efforts to improve the production of energy extracted from wind turbines to contribute to filling the energy needs. Horizontal axis wind turbines (HAWT) are among the predominant wind turbines compared to other types, and for this reason, they have gained the most attention from engineers and researchers in the field of research and development to improve their aerodynamic performance characteristics, which will be beneficial to the renewable energy sectors. A lot of research studies have been done to evaluate and predict aerodynamic performance characteristics. S. Raut et al. [1] studied the design and optimization of micro wind turbine blades (wind speed 8.4 m/s, SG6043 airfoil) using Q-Blade. They reported a maximum value of power coefficient (C_p) of 0.45 at a wind speed of 8.4 m/s determined by Q-Blade simulation. E. Koc et al. [2] studied a mini-scaled horizontal axis wind turbine (SG6043 airfoil) using Q-blade and Computational Fluid Dynamics (CFD) to predict aerodynamic coefficients. They found a good agreement between Q-Blade and CFD analyses. A low Reynolds number airfoil was designed for applications in small horizontal axis wind turbines to achieve better startup and low wind speed performances were reported by R. K Singh et al [3]. They found that the AF300 airfoil at a low Reynolds number showed good aerodynamics performance attaining to the highest combinations optimal C_L and L/D ratios. Srinivas G. et al. [4] studied the analysis of wind turbine blades using Computational Fluid Dynamics (CFD). They reported that the coefficient of lift increases with an increase in the angle of attack up to 14^0, and the maximum L/D ratio is achieved at 5^0 attack angle for the average velocity.

Taguchi's method [5, 6] has been applied in recent years to solve many engineering problems, and to determine the optimal process parameters for a single response. However, engineering problems depend on many characteristics, and for this reason, the gray method [7, 8] had to be used on multiple responses. A. Hwas and A. Hatab [9] found that the optimal experiment can be conducted with the design parameter of airfoil NACA 2414, 8-degree attack angle, 100000 Reynolds number, which gives optimal coefficients of 1.08 for lift, 0.021 for drag and 0.4814 for power coefficients. The objective of this research paper is to further improve responses namely; lift and drag coefficients for horizontal axis wind turbines. The lift coefficient (C_L), and drag coefficient (C_D) can be determined using Q-Blade. The gray-based Taguchi method is employed to optimize airfoil coefficients. The Q-Blade program is used under a general public license for Airfoils analysis. Q-Blade uses the blade element momentum theory (BEM) to predict the aerodynamic lift and drag coefficients.

II. EXPERIMENTAL PROCEDURE

A. *Design of Experiment*

Taguchi [5, 6] design of experiments (DOE) can be used to optimize a complicated aerodynamic performance characteristic that has several variables. Hence, the airfoil types, angle of attack, and Reynolds number are factors considered to affect the power performance of wind turbines. A standard Taguchi experiment of L_9 (3^4) orthogonal arrays with three factors with three levels for each factor are to be performed to investigate the effects of design factor combinations and to determine the effects of each factor on response characteristics of the wind turbine performance. Tables 1 and 2 show the design factors and their levels, and the experimental layout of L_9 (3^4) orthogonal arrays Taguchi DOE respectively.

TABLE 1. DESIGN FACTORS AND THEIR LEVELS

Design Parameters	Level 1	Level 2	Level 3
A – Airfoil type	NACA2414	SG6043	S1210
B- Attack angle (deg.)	10	11	12
C- Reynolds number	75000	100000	125000

TABLE 2. EXPERIMENTAL LAYOUT L_9 (3^4) ORTHOGONAL ARRAYS[5]

Experiment Number	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

After selecting the appropriate OA, the next steps in Taguchi DOE are to run the experiments and then to evaluate the results of experiments by applying statistical analysis in order to determine which factor affects the quality response. The confirmation test is the final step in Taguchi DOE, which is used to verify the performance improvement measured. If the results of the confirmation test do not agree with the result runs, then a new Taguchi DOE method is required. The predicted lift and/or drag coefficients, η, using the optimal levels of lift and/or drag coefficients can be given by equation (1):

$$\eta_{pred.} = \eta_{mean} + \sum_{i=1}^{n} \{\eta_{optimal} - \eta_{mean}\} \qquad (1)$$

In this study, the lift (C_L) and drag (C_D) coefficients are treated as quality responses, and hence the higher is better (HB) is used for maximizing the lift coefficient and the lower is better (LB) used for minimizing the drag coefficient.

B. Q-Blade

The Q-Blade software is an open source for the simulation and design Three-Blade Horizontal-Axis Wind Turbines and also vertical-axis wind turbines [10]. It utilizes the Blade Element Momentum (BEM) method for the simulation of HAWT. Based on blade element theory, the blade can be divided into several cross-sectional elements along its length. A blade element j is obtained by sectioning the blade with two parallel planes located at distances r and (r + dr) from the hub and perpendicular to the blade. Figure 1 shows the blade element profile and the undertaken aerodynamic loads [11, 12],

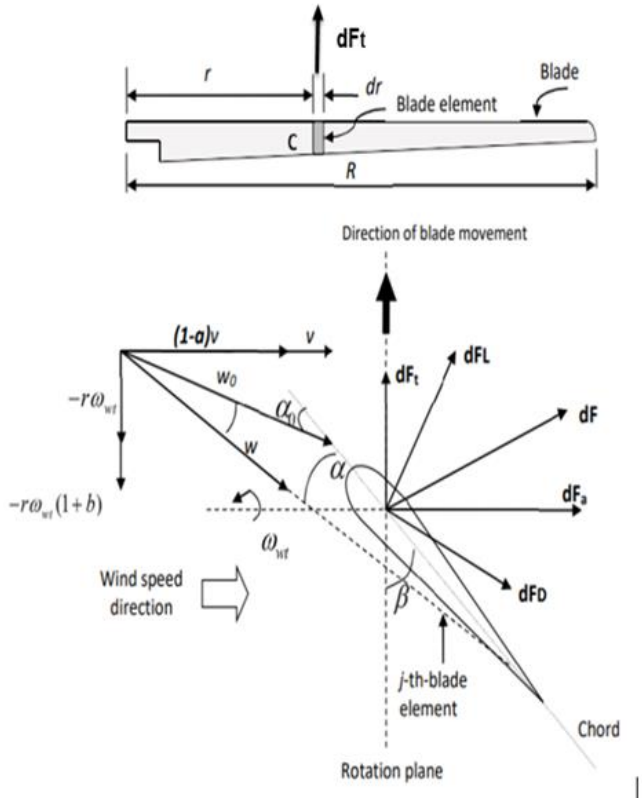

Fig. 1. Aerodynamic loads along the blade profile [12].

Where;

v : wind speed (m/s)

ω_{wt} : rotational speed of the rotor (rad/s)

β : blade-pitch angle (degrees)

w : relative wind speed to the blades when the vortex motion is considered (m/s)

w_0 : relative wind speed to the blades when the vortex motion is not considered (m/s)

a : axial flow interference factor

b : tangential flow interference factor

dF : total force acting on the blade element (N)

dF_D : elementary drag force (N)

dF_L : elementary lift force (N)

dF_t : elementary tangential force in the direction of rotation (N)

dF_a : elementary axial thrust force (N)

The elementary tangential force is given in equation (2), and θ = α + β as shown in Figure 1. Thus, the simulation of Q-Blade software is applied determine single response (C_L, C_D). The responses C_L and C_D are calculated using equations (3) and (4), where F_L and F_D are the lift and drag forces (N), ρ is air density (kg/m^3), v is the velocity (m/s), and A is the area which is given by $A = \int cdr$, where c is the chord.

$$\begin{cases} dF_t = 0.5\rho w^2 c(r)[C_l \sin(\theta) - C_D \cos(\theta)]\, dr \\ dF_a = 0.5\rho w^2 c(r)[C_l \cos(\theta) + C_D \sin(\theta)]\, dr \end{cases} \qquad (2)$$

$$C_{L.} = \frac{F_L}{0.5\rho V^2 A} \qquad (3)$$

$$C_{D.} = \frac{F_D}{0.5\rho V^2 A} \qquad (4)$$

III. RESULTS AND DISCUSSION

A. *Single response using Taguchi*

1) *Lift Coefficient*

Figure 2 gives the experimental results for the lift coefficients. It is obvious from the obtained results that experiment number 7; S1210 airfoil, 10-degrees angle of attack, 125000 Reynolds number or (A3B1C3) gives the highest lift coefficient of 1.907. The response data for effects factor levels on the mean lift coefficient is shown in Table 3. The difference values (Max. – Min., Table 3) indicates that the most influential factor is airfoil type, followed by attack angle and the least influential factor is Reynolds number.

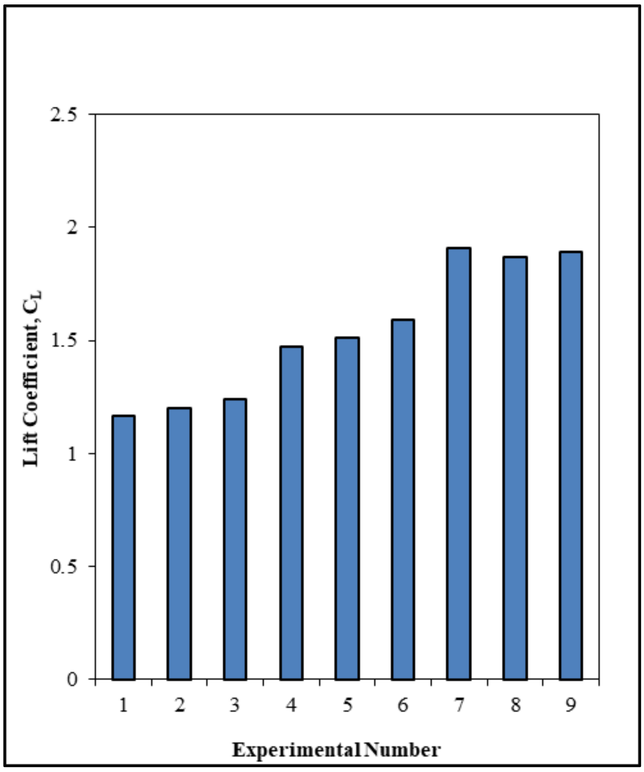

Fig. 2. Experimental Results for lift coefficient, simulated by Q-Blade for HAWT.

TABLE 3. EFFECTS OF FACTOR LEVELS ON MEAN RESPONSE FOR LIFT COEFFICIENT OF HAWT.

Factors	Level 1	Level 2	Level 3	Max.- Min.	Rank
A-Airfoil type	1.202	1.524	1.889	0.687	1
B-Attack angle	1.516	1.527	1.572	0.56	2
C-Reynolds Number	1.543	1.552	1.552	0.031	3

2) *Drag Coefficient*

The experimental results for the drag coefficient are given in Table 4 and Figure 3. It is evident, that experiment number 7; airfoil S1210, 10-degrees angle of attack, 125000 Reynolds number or (A3B1C3) gives the lowest drag coefficient of 0.032. Table 4 shows the effects of factors on the mean drag coefficient and the most affected factor is attack angle, followed by airfoil type and Reynolds number.

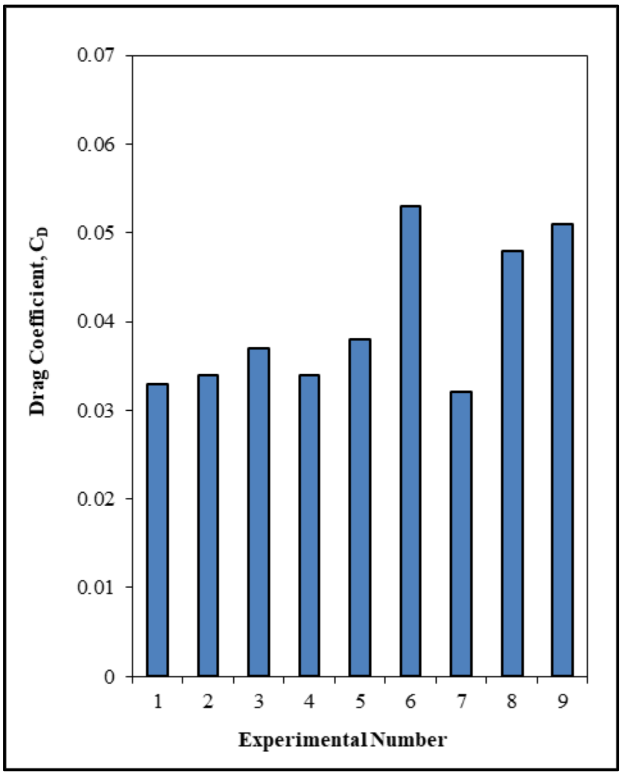

Fig. 3. Experimental Results for drag coefficient, simulated by Q-Blade for HAWT.

TABLE 4. EFFECTS OF FACTOR LEVELS ON MEAN RESPONSE FOR DRAG COEFFICIENT OF HAWT.

Factors	Level 1	Level 2	Level 3	Max.- Min.	Rank
A-Airfoil type	0.0347	0.0417	0.0437	0.009	2
B-Attack angle	0.0330	0.0400	0.0470	0.0140	1
C-Reynolds Number	0.0447	0.0397	0.0357	0.009	3

B. *Multi-response using Grey- Based Taguchi*

In the grey relational analysis [7,8], the data preprocessing must be performed first (generation of grey relation) to normalize the experimental results in the range of zero to one. In this investigation, the values of responses are normalized for the lower-is-better (LB) for C_D, and higher-is-better (HB) quality response for C_L; and the calculated response is given by equations (5,6):

$$(X_{ij})_{L.B} \frac{x_{max} - x_{ij}}{x_{max} - x_{min}} \tag{5}$$

$$(X_{ij})_{H.B} \frac{x_{ij} - x_{min}}{x_{max} - x_{min}} \tag{6}$$

where X_{ij} is the normalized value for the j^{th} performance quality in the i^{th} experimental run. The X_{ij} is the response value for the j^{th} performance quality in the i^{th} experimental run. x_{min} and x_{max} are the minimum and the maximum response values for the j^{th} performance quality in all the experimental runs.

Table 5 shows the X_{ij} response (data preprocessing). The higher value of the X_{ij} is considered the best performance for the C_L and C_D compared to the ideal value of one. After calculating the X_{ij}, then the grey relational coefficient (ξ_{ij}) is determined using equation (7):

$$\xi_{ij} = \frac{min_i min_j |X_i^o - X_{ij}| + \beta * max_i max_j |X_i^o - X_{ij}|}{|X_i^o - X_{ij}| + \beta * max_i max_j |X_i^o - X_{ij}|} \quad (7)$$

where X_{i0} is the ideal normalized value for the j^{th} performance quality in the i^{th} experimental run, and β is the distinguish coefficient which is defined in the range $0 \leq \beta \leq 1$. The generally used value for β is 0.5. Note that the (ξ_{ij}) is to express the relationship between the ideal and the actual X_{ij} of the experimental results. After determining the (ξ_{ij}) the weighting method is used to determine the grey relational grade (Γ), and is given by equation (8):

$$\Gamma = \frac{1}{n}\sum_{i}^{n} w_i * \xi_{ij} \quad (8)$$

where w_i is the weighting factor for the j^{th} performance quality, and n is the number of performances. In the present study, the weighting factor for C_L and C_D are given an equal weight value of 1/2. The results are shown in Table 5. Based on the obtained results in Table 5, the experiment number 7; airfoil S1210, 10-degrees angle of attack, 125000 Reynolds number or A3B1C3 has the best combination of design factors, while Table 6 gives the optimal experiment; airfoil S1210, 10-degrees angle of attack, 125000 Reynolds number or A3B1C3. The most significant influential factor on the performance is airfoil type, followed by attack angle and Reynolds number as shown in Table 6.

TABLE 5. NORMALIZED (X_{ij}) ANDCALCULATED GREY RELATIONAL COEFFICIENT AND GREY RELATIONAL GRADE (Γ) OF HAWT.

Experimental Number	C_L X_{ij}	ξ_{CL}	C_D X_{ij}	ξ_{CD}	Γ	Order
1	0.0000	0.3333	0.9524	0.9130	0.6232	6
2	0.0420	0.3429	0.9047	1.0000	0.6715	3
3	0.0935	0.3555	0.7619	0.6774	0.5164	8
4	0.4133	0.4601	0.9047	0.8400	0.6501	5
5	0.4634	0.4824	0.7143	0.6363	0.5593	7
6	0.5691	0.5371	0.0000	0.3333	0.4352	9
7	1.0000	1.0000	1.0000	1.0000	1.0000	1
8	0.9512	0.9111	0.2381	0.3962	0.6537	4
9	0.9770	1.0000	0.0952	0.3559	0.6780	2

TABLE 6. FACTOR LEVELS EFFECT ON MEAN GREY RELATIONAL GRADE (Γ) FOR LIFT AND DRAG COEFFICIENTS OF HAWT.

Factors	Level 1	Level 2	Level 3	Max. – Min.	Rank
A-Airfoil type	0.6037	0.5482	0.7772	0.2290	1
B-Attack angle	0.7577	0.6282	0.5432	0.2145	2
C-Reynolds Number	0.5707	0.6665	0.6919	0.1212	3

TABLE 7. RESULTS OF ANOVA OF MULTIPLE RESPONSES (LIFT AND DRAG COEFFICIENTS) OF HAWT

Factors	Degree of freedom	Sum of Squares	Variance V	Contribution %
A-Airfoil Type	2	0.085625	0.0428125	43.64
B-Attack angle	2	0.070031	0.0350155	35.69
C-Reynolds Number	2	0.024525	0.0122625	12.50
Error	2	0.016036	0.008018	8.17
Total	8	0.196217		100

TABLE 8. RESULTS OF CONFIRMATION TEST AND IMPROVEMENT ON AIRFOIL COEFFICIENTS OF HAWT

Condition	Levels	C_L	C_D	Gray Relation Grade
Initial (Reference)	A1B1C1	1.169	0.033	0.6232
Prediction (optimal)	A3B1C3	1.936	0.023	1.0000
Experiment Number 7	A3B1C3	1.907	0.032	1.0000
Experimental confirmation by Q-Blade for optimal	A3B1C3	1.907	0.032	0.940811
Improvement		65.61% increase	30.30% decrease	60.46% Increase

C. *Analysis of variance for multi-response*

Analysis of Variance, ANOVA, [5,6] can be accomplished based on the total sum of squares deviations from the total mean of grey relational grade (Γ). The total sum of squares is decomposed into the sum of squares due to each factor and interaction. Table 7 specified that the most significant factor is airfoil type with 43.64 % contribution, followed by attack angle with 35.69% and Reynolds number with 12.5%, and error with 8.17 %.

D. *Confirmation test for multi-response*

A comparison between running experiment confirmation (A3B1C3) and predicted experiment (A3B1C3) that have the best combination of design factors to get the airfoil coefficients of HAWT are shown in Table 8. The obtained results indicate that the improvement of grey relation grade is 60.46% increase when compared to initial condition.

IV. CONCLUSIONS

In this paper, the gray-based Taguchi method is applied to improve the aerodynamic performance characteristics of horizontal axis wind turbines (HAWT), employing the calculation of coefficients to efficiently establish design factors. The obtained results give that the optimal experiment can be conducted with the design factors of airfoil S1210, 10-degree attack angle, 125000 Reynolds number (A3B1C3), which gives optimal coefficients of 1.936 for lift and 0.023 for drag coefficients. The results specified that the most significant factor is airfoil type with 43.64 % contribution, followed by attack angle with 35.69% and Reynolds number with 12.5%, and error with 8.17 %. The optimal experiment gives an improvement of wind turbine performance of 65.61% increase in the lift coefficient and 30.30% decrease in the drag coefficient when compared with the initial condition (A1B1C1) for this set of experiments.

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