Effects of Design Parameters of Wind Turbine on Airfoil Coefficients Using Grey-Based Taguchi Method

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Abstract— **Horizontal-Axis Wind Turbine (HAWT) small scaled is widely employed for generating electricity for domestic uses due to higher efficiencies among other turbines. Three-Blade HAWTs power performance can be further improved by optimizing lift (C_L), drag (C_D) coefficients and thus power (C_P) coefficient. In this study, Taguchi design of experiments (DOE) of L_9 orthogonal array (OA) with three parameters and one interaction, namely airfoil, angle of attack, interaction (between the airfoil and the attack angle), and Reynolds number with three value levels are used to determine the single quality (C_L, C_D, C_P) optimization. For multi-qualities optimization, the Grey-based Taguchi is employed which combines the Taguchi DOE orthogonal array with grey relational analysis to determine the grey relational grade, which can convert the multi-response grey relational grade into single grey relational grade, thus the optimal design parameters can be achieved. The Q-Blade software is used to determine lift and drag coefficients and empirical equation used for power coefficient. The obtained results show that the most influence design parameter on airfoil coefficients is Reynolds number with 72.6% contribution followed by attack angle with 16.8%, interaction with 9.1% and airfoil with 1.5%. The F-value indicates that Reynolds number and angle of attack give at least 97.5% and 90% confidence respectively, for this specific set of experiments.**

Keywords— Wind turbine; Taguchi method; Grey relational analysis; Optimization; airfoil coefficients

I. Introduction

The increasing demands for renewable energy resources such as wind energy are the driving force for engineers and researchers to find solutions with cost-effective to improve the wind energy applications in domestic uses with attractive high-performance levels. Horizontal-axis Wind Turbine (HAWT) is among those wind turbine gaining prominence by research and development scientific engineers and researchers to improve aerodynamics performance characteristics, which it would be beneficial for renewable energy sectors. Several research works were reported to predict aerodynamics performance characteristics. Shubham 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. Emre Koc et al. [2] studied 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 Ronit K. Singh et al.[3]. They found that the AF300 airfoil at low Reynolds number showed good aerodynamic performance attaining the highest combinations of optimum C_L and L/D ratios. Srinivas G. et al. [4] studied the analysis of wind turbine blade 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 achieved at 5^0 attack angle for the average velocity.

Recently, Taguchi method [5,6] was applied to several engineering issues to determine optimum process parameters for a single response. However, engineering issues depend on many characteristics, thus Grey method [7,8] were applied for multi-responses. Hatab Ali et al.[9-13] investigated the effects of design process parameters on velocities of hydraulic cylinders, building energy efficiency, tensile properties of 6061 aluminum alloys, properties of 7079 aluminum alloy, friction welding of aluminum alloy.

The aim of this research paper is to investigate the effects of design parameters of a wind turbine on NACA airfoil coefficients and to determine the optimal coefficients using Grey-based Taguchi method. The software Q-Blade under General Public License is used for the analysis of airfoils. The Q-Blade uses the blade element momentum theory (BEM) to predict aerodynamic coefficients, namely lift coefficient (C_L), drag coefficient (C_D). Empirical equation is used to determine the power coefficient for three blade horizontal axis wind turbines (HAWT).

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, angle of attack and Reynolds number and interaction (airfoil x attack angle) are factors considered to affect the power performance of wind turbine. A standard Taguchi experiment of L_9 (3^4) orthogonal arrays with three parameters and one interaction with three levels for each parameter are to be conducted to study the effects of design process parameters combinations and to determine the effects of each parameter on quality characteristics of the wind turbine performance. Tables 1 and 2 show the design process parameters and their levels, and experimental layout of L_9 (3^4) orthogonal arrays Taguchi DOE respectively

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TABLE 1 DESIGN PROCESS PARAMETERS AND THEIR LEVELS

Design Parameters	Level 1	Level 2	Level 3
A – Airfoils	NACA 2412	NACA 2414	NACA 2416
B- Attack angle (deg.)	5	8	10
C- Interaction (Airfoil x attack angle)	-----	-----	-----
D- Reynolds number	50000	75000	100000

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

Experiment Number	A	B	C	D
1	1	1	1	1
	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 parameter affect the quality response. The confirmation test is the final step in Taguchi DOE, which is used to verify the improvement of the performance 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 airfoil coefficient, η, using the optimal levels of airfoil coefficients can be obtained by equation (1):

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

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

B. *Q-Blade*

The software Q-Blade is developed as an open-source for the simulation and design of wind turbines. Q-Blade utilizes the Blade Element Momentum (BEM) method for the simulation of the horizontal axis and Double Multiple Stream tube (DMS) algorithm for the simulation of vertical axis wind turbine performance [14]. In this study, simulation Q-Blade software is employed to calculate the quality responses namely lift coefficients, C_L ($C_L = F_L/0.5\rho v^2 A$) and drag coefficients, C_D ($C_D = F_D/0.5\rho v^2 A$), 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), A is area (m^2). Figure 1 shows the selected NACA airfoils shapes and dimensions for conducting the experiments.

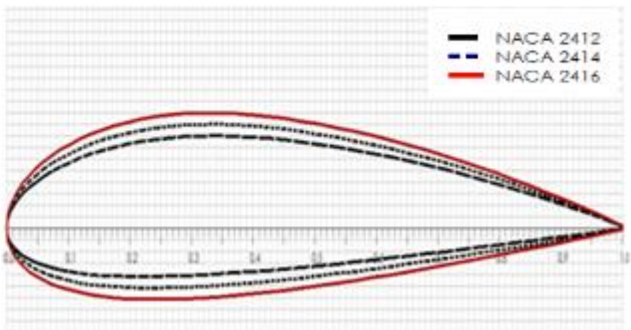

Fig. 1. *Airfoil profile for NACA 2412, NACA 2414 and NACA 2416 [Q-blade]*

III. RESULTS AND DISCUSSION

A. *Single response using Taguchi*

1) *Lift Coefficient*

Taguchi [5, 6] column effects method is a simplified analysis of variance (ANOVA) to indicate columns which have a large influence on the response. Table 3 and Figures 2 and 3 show the experimental results for the lift coefficients. It is obvious from the obtained results that experiment number 6; NACA 2414 airfoil, 10-degrees angle of attack, 75000 Reynolds number or (A2B3C1D2) gives the highest lift coefficient of 1.169. The responses data for effects of parameters on mean lift coefficient and differences are shown in Figure 3 and Table 3 respectively. The differences of values in Table 3 are compared to each other to find the larger effects, indicating that the most influential parameter is attack angle, followed by Reynolds number, airfoil and interaction (airfoil x attack angle) on lift coefficient. The average values of levels (Table 3) specified experiment with design parameters of airfoil NACA2414, 10-degrees attack angle, 100000 Reynolds number or (A2B3C1D3) give the predicted experiment and thus the optimal lift coefficient (equation (1)) is 1.186.

TABLE 3 EXPERIMENTAL RESULTS FOR CALCULATED LIFT COEFFICIENT C_L AND COLUMN EFFECTS OF HAWT

Experiment Number	A	B	C	D	Q-Blade C_L
1	1	1	1	1	0.700
2	1	2	2	2	1.033
3	1	3	3	3	1.154
4	2	1	2	3	0.815
5	2	2	3	1	0.991
6	2	3	1	2	1.169
7	3	1	3	2	0.792
8	3	2	1	3	1.077
9	3	3	2	1	0.963
Average levels 1	0.962	0.769	0.982	0.885	
Average levels 2	0.992	1.034	0.937	0.998	
Average levels 3	0.944	1.095	0.979	1.015	
Differences	0.048	0.326	0.045	0.130	

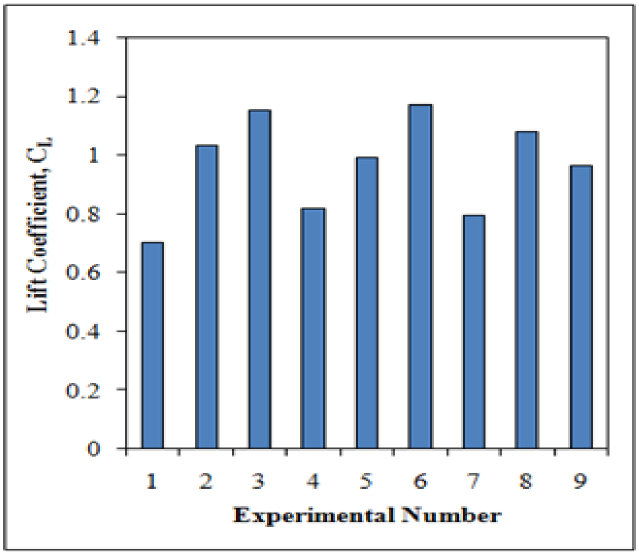

Fig. 2. *Simulated lift coefficient using Q-Blade for HAWT*

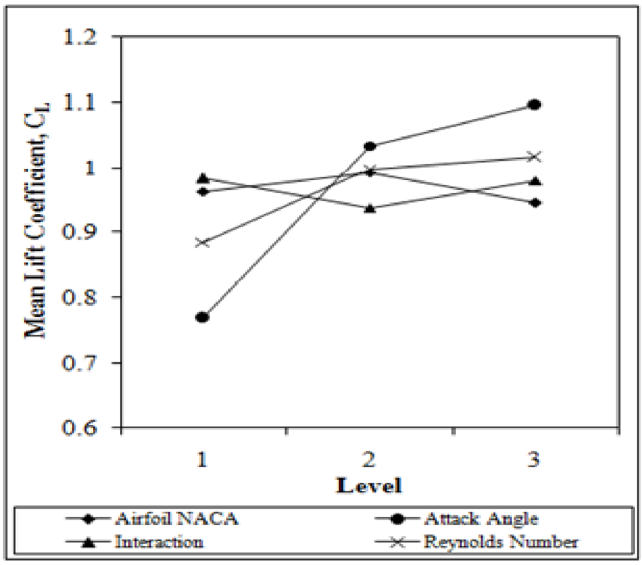

Fig. 3. *Effect of parameters on mean lift coefficient for HAWT*

2) *Drag Coefficient*

The experimental results for the drag coefficient are given in Table 4 and Figures 4 and 5. It is evident, that experiment number 4; airfoil NACA 2414, 5-degrees angle of attack, 100000 Reynolds number or (A2B1C2D3) gives the lowest drag coefficient of 0.019. Figure 5 and Table 4 show the effects of parameters on mean drag coefficient and differences respectively. The value of differences (Table 4) indicated the most affected parameter is Reynolds number, followed by attack angle, airfoil and interaction on the drag coefficient. The average values levels (Table 4) specified the experiment with design parameters of airfoil NACA2414, 5-degrees attack angle, 100000 Reynolds number or A2B1C1D3 give the predicted experiment and thus the optimal drag coefficient (equation (1)) is 0.015.

TABLE 4 EXPERIMENTAL RESULTS FOR CALCULATED DRAG COEFFICIENT C_D AND COLUMN EFFECTS OF HAWT

Experiment Number	A	B	C	D	Q-Blade C_D
1	1	1	1	1	0.036
2	1	2	2	2	0.025
3	1	3	3	3	0.034
4	2	1	2	3	0.019
5	2	2	3	1	0.040
6	2	3	1	2	0.033
7	3	1	3	2	0.027
8	3	2	1	3	0.024
9	3	3	2	1	0.061
Average levels 1	0.032	0.027	0.031	0.046	
Average levels 2	0.031	0.030	0.035	0.028	
Average levels 3	0.037	0.043	0.034	0.026	
Differences	0.006	0.016	0.004	0.020	

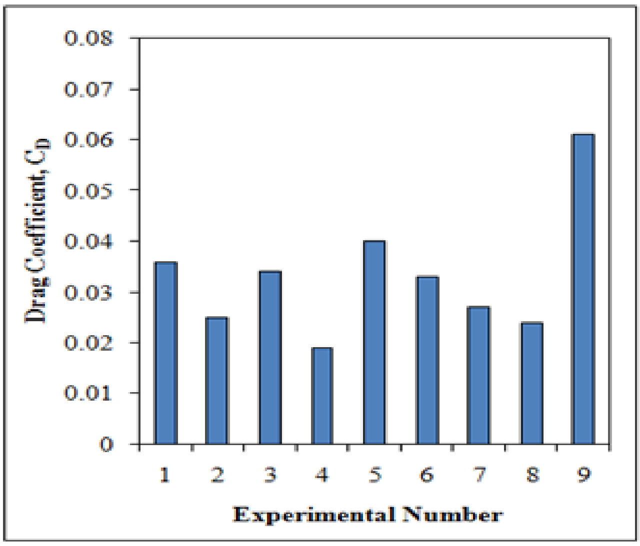

Fig. 4. *Simulated drag coefficient using Q-Blade for HAWT*

3) *Power Coefficient*

The complicated design of a wind turbine rotor due to many configuration variables, it may be beneficial to quickly estimate the maximum power coefficient that can be achieved with a potential rotor configuration. An empirical equation to calculate the maximum power coefficient can be expressed as given in equation (3) [15].

$$C_{pmax} = 0.593\left[\frac{\lambda B^{067}}{1.48 + (B^{0.67} - 0.04)\lambda + 0.0025\lambda^2} - \frac{1.92\lambda^2}{1 + 2\lambda B}\frac{C_D}{C_L}\right] \quad (2)$$

where λ tip speed ratio, B number of blades, C_D/C_L the drag-to-lift ratio at the design angle of attack. The application of equation (2) is used to calculate the power coefficient for three blades and 5 tip speed ratio for HAWT. The power coefficient is treated as a quality response of the higher is better. Table 5 and Figures 6 and 7 show the experimental results for the power coefficient. The experiment number 8; airfoil NACA 2416, 8-degrees angle of attack, 100000 Reynolds number or A3B2C1D3 gives the highest power coefficient of 0.4640.

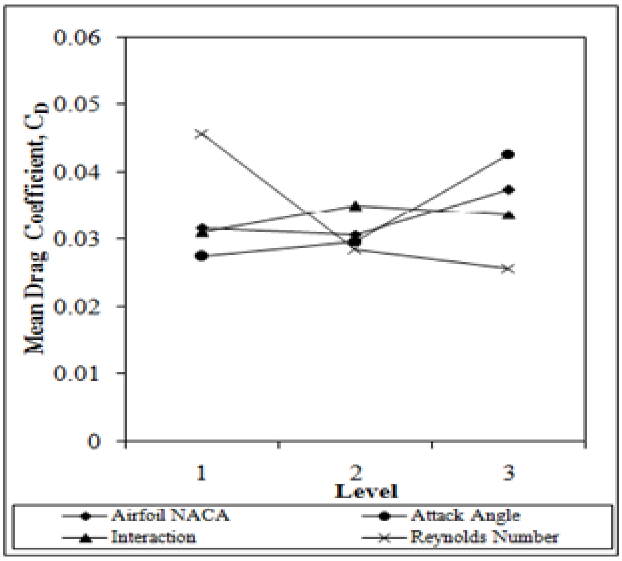

Fig. 5. *Effects of parameters on mean drag coefficient for HAWT*

TABLE 5 EXPERIMENTAL RESULTS FOR CALCULATED POWER COEFFICIENT C_P AND COLUMN EFFECTS OF HAWT

Experiment Number	A	B	C	D	[1]C_P
1	1	1	1	1	0.3838
2	1	2	2	2	0.4588
3	1	3	3	3	0.4443
4	2	1	2	3	0.4612
5	2	2	3	1	0.4142
6	2	3	1	2	0.4477
7	3	1	3	2	0.4315
8	3	2	1	3	0.4640
9	3	3	2	1	0.3509
Average levels 1	0.429	0.425	0.432	0.383	
Average levels 2	0.441	0.446	0.424	0.446	
Average levels 3	0.415	0.414	0.430	0.456	
Differences	0.026	0.032	0.008	0.073	

1- power coefficients are calculated using empirical equation

Figure 7 and Table 5 give the effects of parameters on mean power coefficient and differences respectively. Table 5 determines the most affected parameter is Reynolds number, followed by attack angle, airfoil and interaction on power coefficient. The average levels (Table 5) indicate that experiment with parameters airfoil NACA2414, 5-degrees attack angle, 100000 Reynolds number or A2B2C1D3 gives the predicted experiment and thus the optimal power (equation (1)) is 0.4896.

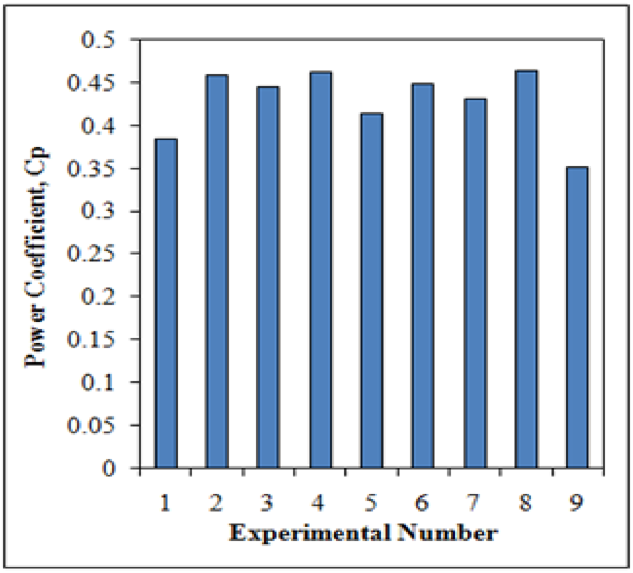

Fig. 6. *Power coefficient calculated using empirical equation for 3-blades, 5 tip seed ratio and Q-Blade simulation of lift and drag coefficients for HAWT*

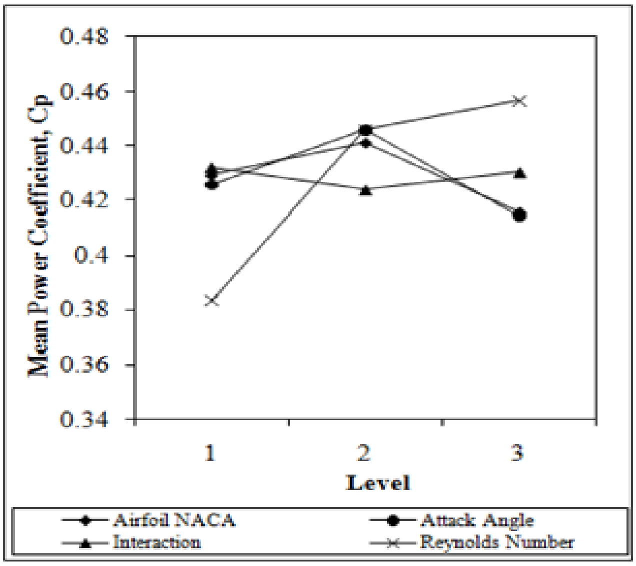

Fig. 7. *Effects of parameters on mean power coefficient for HAWT*

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 C_P; and the calculated response is given by equations (3,4):

$$(X_{ij})_{L.B} = \frac{x_{max}-x_{ij}}{x_{max}-x_{min}} \quad (3)$$

$$(X_{ij})_{H.B} = \frac{x_{ij}-x_{min}}{x_{max}-x_{min}} \quad (4)$$

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 of the response values for the j^{th} performance quality in all the experimental runs. Table 6 shows the X_{ij} response (data preprocessing). The higher value of the X_{ij} is considered the best performance for the C_L, C_D and C_p compared to the ideal value of one. After calculating the X_{ij}, then the grey relational coefficient (ξ_{ij}) is determined using equation (5):

$$\xi_{ij} = \frac{min_i min_j |X_i^o - X_{ij}| + \beta * max_i max_j |X_i^o - X_{ij}|}{|X_i^o - X_{ij}| + \beta * max_i max_j |X_i^o - X_{ij}|} \quad (5)$$

where X_i^0 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 ≤ β ≤ 1. The general 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 (6):

$$\Gamma = \frac{1}{n}\sum_{i}^{n} w_i * \xi_{ij} \quad (6)$$

where w_i is the weighting factor for the j^{th} performance quality, and n is the number of performance. In the present study, the weighting factor for C_L, C_D and C_P are given equal weight value of 1/3. The results are shown in Table 6. Based on the obtained results in Tables 6, the experiment number 2; airfoil NACA 2412, 8-degrees angle of attack, 75000 Reynolds number or A1B2C2D2 has the best combination of design parameters, while Table 7 gives the optimal experiment; airfoil NACA 2414, 8-degrees angle of attack, 100000 Reynolds number or A2B2C2D3. The most significant influential parameter on the performance of is Reynolds number, followed by attack angle, airfoil, and interaction (airfoil x attack angle) as shown in Table 7.

TABLE 6 NORMALIZED VALUES (X_{IJ}) AND CALCULATED GREY RELATIONAL COEFFICIENT AND GREY RELATIONAL GRADE (Γ) OF HAWT

Experiment number	C_L X_{ij}	ξ_{CL}	C_D X_{ij}	ξ_{CD}	C_P X_{ij}	ξ_{Cp}	Γ	Order
1	0.000	0.333	0.595	0.553	0.290	0.413	0.433	9
2	0.710	0.633	0.857	1.000	0.953	0.915	0.849	1
3	0.968	0.940	0.643	0.583	0.825	0.741	0.755	5
4	0.245	0.398	1.000	1.000	0.975	0.952	0.784	4
5	0.620	0.568	0.500	0.500	0.560	0.532	0.533	8
6	1.000	1.000	0.666	0.600	0.855	0.775	0.792	3
7	0.196	0.384	0.810	0.724	0.712	0.635	0.581	6
8	0.804	0.718	0.881	0.808	1.000	1.000	0.842	2
9	0.561	1.000	0.000	0.333	0.000	0.333	0.556	7

TABLE 7 GREY RELATIONAL GRADE (Γ) RESPONSE DATA

Parameters	Level 1	Level 2	Level 3	|Max-Min|	Rank
A- Airfoil	0.6790	0.7029	0.6595	0.0435	4
B- Angle of attack	0.5992	0.7415	0.7007	0.1424	2
C- Interaction	0.6890	0.7294	0.6230	0.1065	3
D- Reynolds Number	0.5073	0.7406	0.7934	0.2861	1
Total mean value of grey relational grade = 0.68046					

C. Analysis of variance for multi response

Analysis of Variance, ANOVA, [5,6] can be accomplished base 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 parameter and interaction. Table 8 specified that the most significant parameter is Reynolds number with 72.6 % contribution, followed by attack angle with 16.8%, interaction with 9.1% and airfoil with 1.5 %. The F-value can be used to determine which design parameters have a statistically significant effect on the airfoil coefficients [5, 6]. The obtained results for F-value indicate that Reynolds number and angle of attack give at least 97.5% and 90% confidence respectively.

A comparison between running experiment confirmation (A1B2C2D2) and predicted experiment (A2B2C2D3) that have the best combination of design

parameters to get the airfoil coefficients of HAWT are shown in Table 9. The optimal (predicted) experiment is compared to the initial (reference) experiment indicate the improvement of 54.28% increase for lift coefficient,
41.66% decrease for drag coefficient, and 25.4% increase for power coefficient.

TABLE 8 ANOVA FOR GREY RELATIONAL GRADE (Γ) RESPONSE DATA OF HAWT

Parameters	Degree of freedom	Sum of Squares	Variance V	F-value	Contribution, %
A- Airfoil	(2)[1]	0.00285[1]	Pooled		
B- Angle of attack	2	0.03224	0.01612	11.312[2]	16.8
C- Interaction	2	0.01732	0.00866	6.077	9.1
D- Reynolds Number	2	0.13904	0.06952	48.786[3]	72.6
Pooled error	2	0.00285	0.001425		1.5
Total	8	0.19144			100

1- Pooled parameter ( ) 2- At least 90% confidence 3- At least 97.5% confidence

TABLE 9 RESULTS OF CONFIRMATION TEST AND COMPARISON OF AIRFOIL COEFFICIENTS AT OPTIMAL LEVELS OF HAWT

Condition	Level	C_L	C_D	C_p	Gray Relation Grade
Initial (Reference)	A1B1C1D1	0.7	0.036	0.3838	0.4331
Prediction (optimal)	A2B2C2D3	1.08	0.021	0.4814	0.7934
Experiment Number 2	A1B2C2D2	1.03	0.025	0.4588	0.8492
Experimental confirmation using Q-Blade	A2B2D3	1.063	0.022	0.4684	------
Improvement		54.28% increase	41.66% decrease	25.4% increase	83.2% Increase

IV. CONCLUSIONS

The present study has demonstrated the application of Grey-based Taguchi method for optimizing aerodynamics performance characteristics of a horizontal axis wind turbine (HAWT), employing the calculation of coefficients to efficiently establish design parameters. The obtained results give that the optimal experiment can be conducted with 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 results specified that the most significant parameter is Reynolds number with 72.6 % contribution, followed by attack angle with 16.8%, interaction with 9.1% and airfoil with 1.5 %. The obtained results for F-value indicate that Reynolds number and angle of attack give at least 97.5% and 90% confidence respectively. The optimal experiment gives an improvement of wind turbine performance of 54.28% increase for lift coefficient, 41.66% decrease for drag coefficient, and 25.4% increase for power coefficient when compared with the initial condition for this set of experiments.

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