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Statistical Analysis using Taguchi Method for Designing a Robust Wind Turbine

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ABSTRACT

The current paper presents the tolerance and parameter design for robust wind turbine. By utilizing the traditional Taguchi method along with its extensions, there is a way of designing a robust wind turbine by considering multiple objectives, constraints and design variables. The concept of design of experiment (DOE) i.e.; Taguchi Method is used to evaluate the constrained and unconstrained problems for the optimization. The current work produces an inexpensive and simpler approach for robust vertical axis wind turbine. DOE (Taguchi Method) of L-9 Orthogonal Array having four parameters along with their three levels i.e; type of NACA aerofoil, Reynolds number, Mach number and Angle of attack are utilized for the optimization and to derive the corresponding optimal values of CL, CD and CP. The parameters like coefficient of lift, drag and power for the wind turbine was determined by Q-Blade software, which is use for designing of wind turbine blades. From the obtained results the inferences drawn were: for CL the major impact was due to Reynolds number and least was due to angle of attack, for CD the major and minor impacting factors were angle of attack and Mach number respectively and for CP the most and least influenced parameters were Reynolds number and Mach number respectively. Also, for obtaining the optimized parameters, the Grey based Taguchi method was utilized which has the combination of orthogonal arrays and grey relational analysis. The analysis showed that the NACA0021 has the maximum lift coefficient of 1.0361 and the minimum drag coefficient of 0.02190 in the case of NACA0021 aerofoil.

1. Introduction

In today's era lot of researches and investigations are being carried out in the field of renewable energies like wind, solar, tidal and many more so as to avoid and minimize our dependency on the natural resources to some extent. Many issues and problems are arising across the globe like drastic rise in the cost of petroleum products, global warming and exploitation of natural resources [1]. There is an alarming situation for the world to seek its attention on the alternative sources of energy like wind.

The wind power capacity worldwide has increased over the past decades and many more to be achieved in near future [2]. Horizontal axis wind turbines have their major share in wind industries

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whereas new opportunities can be seen in the field of vertical axis wind turbines. In last few years it has been observed that the demands for the renewable energies has been raised impressively and is seeking the attention of young researchers and investigators for optimization and to come up with innovative designs along with cost effectiveness of wind turbines for their usage in domestic and urban areas [3,4]. Countries like India and China which is growing tremendously and has very large percentage of population, need to take more effort in this direction so as to make use of these alternative clean resources to greater extent [5]. To extract maximum amount of energy from wind through setups like VAWT and HAWT, optimization in their blade design and configuration is being carried out across the globe [6].

In the year 1956, a Japanese statistician and engineer named Genichi Taguchi has developed a design of experiment methodology for improvising the manufactured good's quality and this method is use to known as Taguchi method for optimization. In Design of Experiment we have Taguchi orthogonal array method which has concluded the quality characteristics in experimentations by variation minimization.

It has applications in almost every field of engineering due to its capability of giving the optimized combination of various parameters for design. To determine the effects and the variation, there can be a co-occurrence of ANOVA along with the Taguchi method [7]. Taguchi method has been broaden to operate the positive along with the negative objective function values in optimization of the objective functions both single and double [8]. For designing the computer CPU's module of heat sink and wind capacity ANOVA technique and Taguchi method was used by Chiang [9]. For enhancing the output by minimizing the vibrations in the turbine blades a modification in the genetic algorithm was executed by Jureczko *et al.*, [10]. By utilizing the Taguchi and its extended penalty based method to maximize the output at the designing stage of the HAWT was proposed. By considering both the tolerance and parameter design a robust design was presented by Hu *et al.*, [11].

The prediction of the characteristics of aerodynamic performance of wind turbines has been revealed by various researches [12]. The prediction of aerodynamic coefficients of HAWT having (SG6043 airfoil) has been done by utilizing CFD and Q-blade software and was having prominent accord within the two approaches [13]. For a single response determining the optimum process, the Taguchi method was used and has its application in many engineering problems [14]. There are various merits of Taguchi method due to which its application is there in almost every engineering fields for the optimization purpose. Some of the merits are discussed here. (a) in comparison to the usage of mixed discrete nonlinear programming the handling of design parameters as discrete values are much simpler, (b) for the robust and optimal designs the usage of minimum functions is sufficient apart from the nonlinear programming approaches having large functions, (c) no need for the derivatives for the functions is there like in genetic algorithm (GA) it doesn't requires the derivatives for the functions, The ease of handling of mean values and tolerances of design parameters following the same approach in different stages of Taguchi method and (e) there can be direct implementation as physical designs of the results of this method [11]. In Table 1 list if various techniques and methods of operation research are listed. Mainly the OR can be classified in mainly three categories as Statistical Methods, Stochastic Techniques and Mathematical Techniques. The Taguchi method falls in the sub category of DOE which is a statistical method in operation research.

Table 1
Listing of various operation research (or) methods

Statistical Methods	Stochastic Techniques	Mathematical Techniques
Factor/Discriminate analysis	Simulation methods	Geometric programming
Design of Experiments	Renewal theories	Calculus of variations
Regression Analysis	Markov process	Quadratic programming
Pattern Recognition	Statistical decision theory	Dynamic programming
Cluster Analysis	Queuing theory	Linear programming
	Renewal theories	Multi-objective programming
		Simulated annealing
		Neural Network
		Game theory
		Genetic Algorithm
		Network methods
		Calculus methods
		Nonlinear programming
		Stochastic programming
		Separable programming

In past many investigators had utilized Q-blade software for designing and simulating both the vertical axis as well as horizontal axis wind turbines, but very few of them has implemented the Taguchi approach for the optimization purpose. In current paper the authors have tried to bridge this research gap so as to derive the most optimized wind turbine.

Q-Blade is the open source software utilized by various investigators for investigating different NACA aerofoils. It make a use of empirical equation and theory of BEM for predicting the various parameters of the wind turbines such as power coefficient, lift and drag coefficients. By utilizing Grey based Taguchi method this paper aims to explore and determine the effects of wind turbine design parameters on NACA 0015, 0018 and 0021 aerofoils.

2. Design of Experiment Using Taguchi Method

One of the important statistical methods of operation research for the optimization is DOE. It is an organized method for determining the correlation amongst the input parameters that affects the process and the output parameters. This is very useful for the optimization of the output by managing of the input process. The optimization of complex aerodynamic characteristic having various variables associated with it is done by utilizing the Taguchi method [15].

Therefore the aerodynamic parameters considered for the performance of wind turbines are Reynolds number, angle of attack, input velocity (Mach number) and type of aerofoil. To determine the effect and influence of the considered individual parameter and their combination on the performance characteristics of the wind turbine, a Taguchi method of L9 OA (orthogonal array) with 4 parameters along with 3 set of levels i.e.; low, intermediate and high level has been conducted. Below Table 2 and 3 comprise the details of parameters along with their levels (low, intermediate and high) and the experimental representation of Taguchi L9 OA ($\textit{Level design}^{\textit{No.of factors}}$) that is 3^4.

Hassanpour *et al.*, [16] had considered Taguchi method for optimization of the VAWT pair by designing the numerical experiments by taking three factors and three levels for L9 OA.

Using statistical package Minitab 19 software which is use for analyzing of statistical data, Taguchi method was selected as a DOE for determining the effect on the quality response of selected parameters that are the type of aerofoil, Reynolds number (Re), angle of attack (AOA) and Mach number (M). By selecting the Taguchi Design in DOE using Minitab software followed by 3 level designs and 4 numbers of factors for L9 runs is depicted below.

Table 2
Levels of variables require for designing

Design parameters	LEVELS		
	1 (Low)	2 (Intermediate)	3 (High)
NACA Aerofoils	0015	0018	0021
Mach No.	0.0087	0.0146	0.0204
Reynolds No.	50000	75000	100000
AOA	5 degree	8 degree	10 degree

Table 3
Mapping of L9 OA (orthogonal array) with 4 parameters along with 3 set of levels

No. of Exp	Aerofoil	Mach No.	Reynolds No.	AOA
1	NACA0015	0.0087	50000	5deg
2	NACA0015	0.0146	75000	8deg
3	NACA0015	0.0204	100000	10deg
4	NACA0018	0.0087	75000	10deg
5	NACA0018	0.0146	100000	5deg
6	NACA0018	0.0204	50000	8deg
7	NACA0021	0.0087	100000	8deg
8	NACA0021	0.0146	50000	10deg
9	NACA0021	0.0204	75000	5deg

2.1 Robust Design

The wind turbine performance has the effect and influence of various aerodynamic parameters which can be evaluated by utilizing the Taguchi method (DOE) [17]. Number of quality responses for the run are taken as coefficient lift, drag and power, for the C_L and C_P which are the prime important aerodynamic performance parameters are taken as higher is better and for C_D to be minimized, lower is better is taken into consideration. Therefore the following equation for the signal to noise ratio (SNR) is used for the C_L and C_P. The improvement in the mean value along with variance minimization leads to maximizing SNR [18].

$$\frac{S}{N} = -10\log_{10}\{\frac{1}{n}[\sum_{i=1}^{n}\frac{1}{y_i^2}]\} \quad (1)$$

where y_i is response experiment and n are the number of runs.

In this paper we have considered the input velocity (Mach number) as a noise factor as it affects the performance of the VAWT. Below is Figure 1 that depicts about the controllable and uncontrollable input parameters during the process and its responses or output. Here the controllable input parameters fed into a certain process which leads to an output. During the process there are few uncontrollable factors also which affects the process.

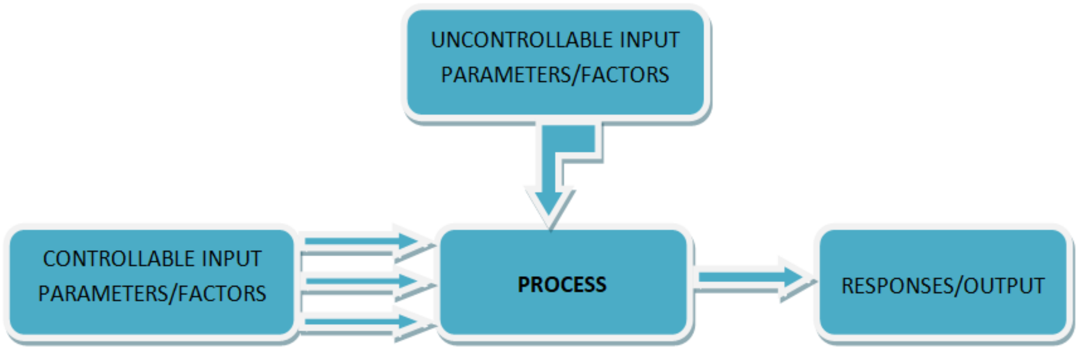


Fig. 1. Factors and Responses associated with process

3. Q-Blade simulation tool

It is an open source software apply for the designing and simulation of wind turbines [19]. It makes use of DMS (Double Multiple Stream tube) algorithm and BEM (Blade element momentum) method for VAWT and HAWT respectively and also to determine various quality responses like C_L and C_D for the aerofoils shown in the figure below [20], [21]. Figure 2 depicts the profiles of three NACA aerofoils namely 0015, 0018 and 0021 which has been generated using the Q-blade software by taking chord length as 1 m. Also it can be concluded that for all the aerofoils the maximum thickness is there at the location of 0.3 m from the leading edge of an aerofoil and NACA 0021 aerofoil has maximum thickness amongst all of them. Also NACA0021 shows the highest camber amongst all the aerofoils.

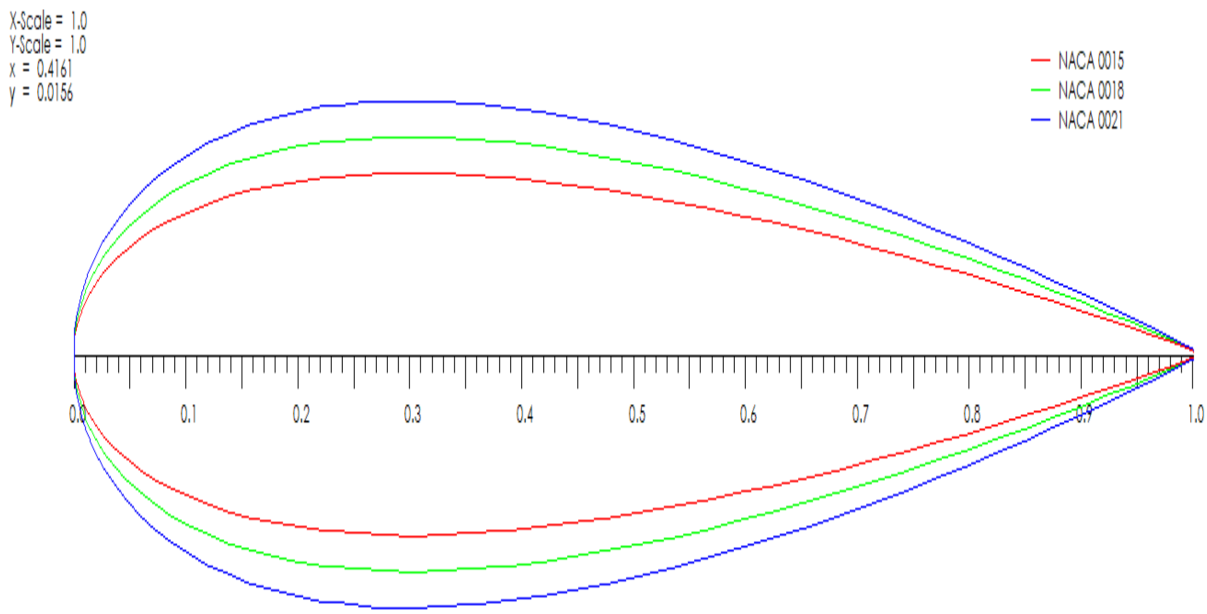


Fig. 2. Q-blade various NACA aerofoil profiles

4. Result and Discussion

4.1 Taguchi Method (Single Response)

4.1.1 Coefficient of lift (C_L)

ANOVA is a simplified effect of column method of Taguchi which stipulates columns with the large influence on a particular response. The experimental data of lift coefficient is demonstrated in below Table 4 and Figure 3. The results have been obtained using the Q-blade simulation software for the three aerofoils namely (NACA0015, NACA0018 and NACA0021) in the given set of parameters like input Mach number, Reynolds number and angle of attacks. As indicated in the below table the obtained optimum value of C_L is 1.0361 in experiment 7 for NACA0021 aerofoil having 0.0087 Mach number placed at 8 degree angle of attack and 100000 Reynolds number.

The corresponding parameters which yield the minimum lift coefficient is 0.2993 from experiment number 8 for NACA0021 at 0.0146 Mach number kept at 10 degree AOA with 50k Reynolds number.

Table 4
Tabulation of Mean C_L and SN ratio value as per Taguchi's OA

Exp No.	NACA Aerofoil	Mach No.	Re	AOA	MEAN1 C_L	SNRA1
1	0015	0.0087	50×10^3	5deg	0.6729	-3.441
2	0015	0.0146	75×10^3	8deg	0.8833	-1.077
3	0015	0.0204	100×10^3	10deg	1.0100	0.086
4	0018	0.0087	75×10^3	10deg	1.0352	0.300
5	0018	0.0146	100×10^3	5deg	0.7757	-2.206
6	0018	0.0204	50×10^3	8deg	0.8621	-1.288
7	0021	0.0087	100×10^3	8deg	1.0361	0.308
8	0021	0.0146	50×10^3	10deg	0.2993	-10.477
9	0021	0.0204	75×10^3	5deg	0.8353	-1.563

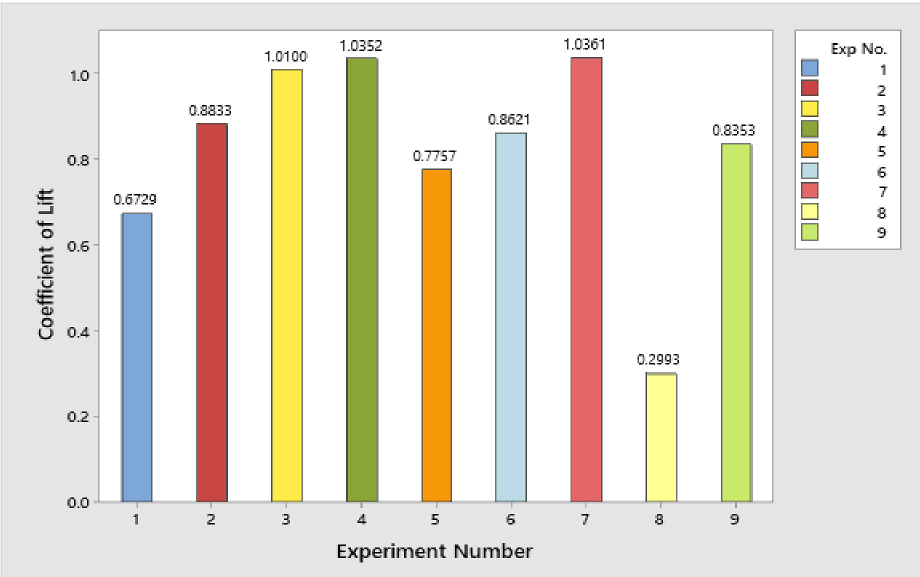


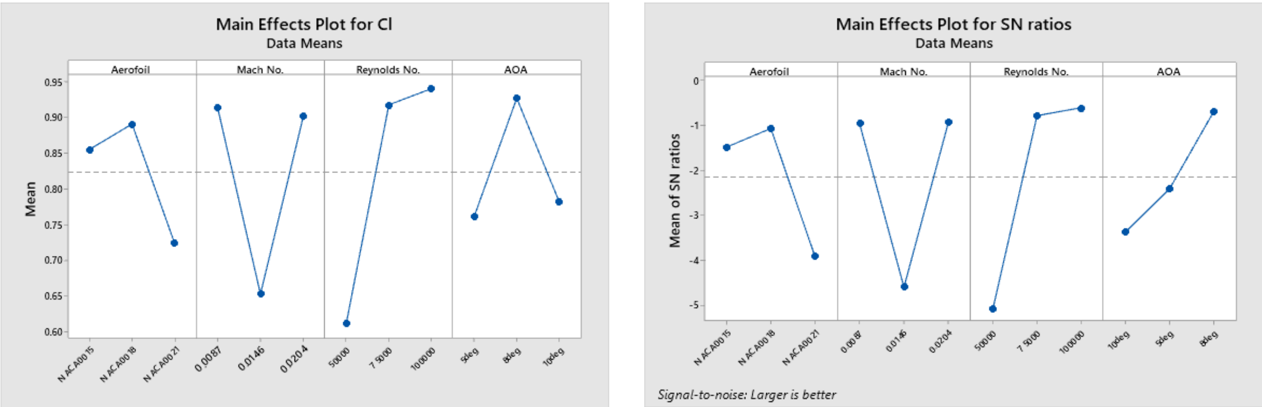
Fig. 3. Bar graph of coefficient of lift for number of experimentations

Influence of various parameters on mean lift coefficient, signal to noise ratio, main effects plot and interaction plot for aerofoil, Mach number, Reynolds number and AOA for the lift coefficient by considering *larger is better* is shown in Figure 4.

Below is the response as shown in Table 5 for Signal to Noise Ratios (SNR) for drag coefficient by taken larger the better, demonstrating that the major influence is due to Re followed by Mach number, type of aerofoil and least influence by angle of attack.

Table 5
SNR response table for C_L

Level	Aerofoil	Mach No.	Re	AOA
1	-1.4775	-0.9442	-5.0692	-3.3637
2	-1.0648	-4.5873	-0.7802	-2.4034
3	-3.9110	-0.9219	-0.6039	-0.6862
Delta	2.8462	3.6654	4.4653	2.6774
Rank	3	2	1	4



(a) (b)

Fig. 4. (a) Effect of various parameters on mean C_L and (b) SN ratio effect plot for C_L

4.1.2 Coefficient of drag (C_D)

The results gathered from the experimentation for C_D are tabulated in the below Table 6 and Figure 5. By referring the experimental table below, it is apparent that experiment number 5 shows the minimum value for C_D of 0.02190, whereas experiment number 8 depicts the maxima of 0.12180. In experiment 5 the set of parameters influencing the response are NACA0018 aerofoil (level 2) which is kept at 5 degree angle of attack (level 1) at inlet Mach number of 0.0146 (level 2) at corresponding Reynolds number of 100000 (level 3).

Table 6
Tabulation of Mean C_D and SN ratio value as per Taguchi's OA

Exp No.	NACA Aerofoil	Mach No.	Re	AOA	MEAN1 C_D	SNRA1
1	0015	0.0087	50×10^3	5deg	0.02848	30.909
2	0015	0.0146	75×10^3	8deg	0.02963	30.565
3	0015	0.0204	100×10^3	10deg	0.03405	29.357
4	0018	0.0087	75×10^3	10deg	0.03832	28.331
5	0018	0.0146	100×10^3	5deg	0.02190	33.191
6	0018	0.0204	50×10^3	8deg	0.04392	27.146
7	0021	0.0087	100×10^3	8deg	0.02893	30.773
8	0021	0.0146	50×10^3	10deg	0.12180	18.287
9	0021	0.0204	75×10^3	5deg	0.03083	30.220

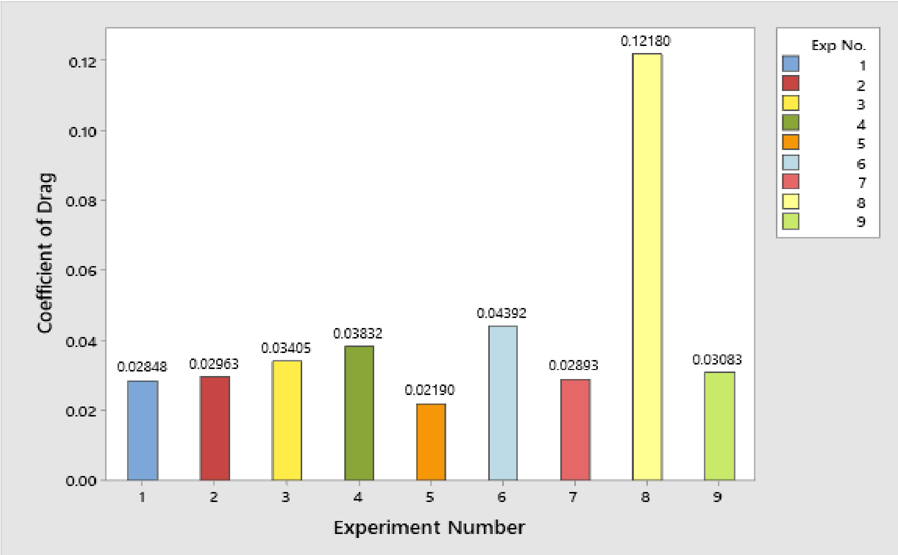
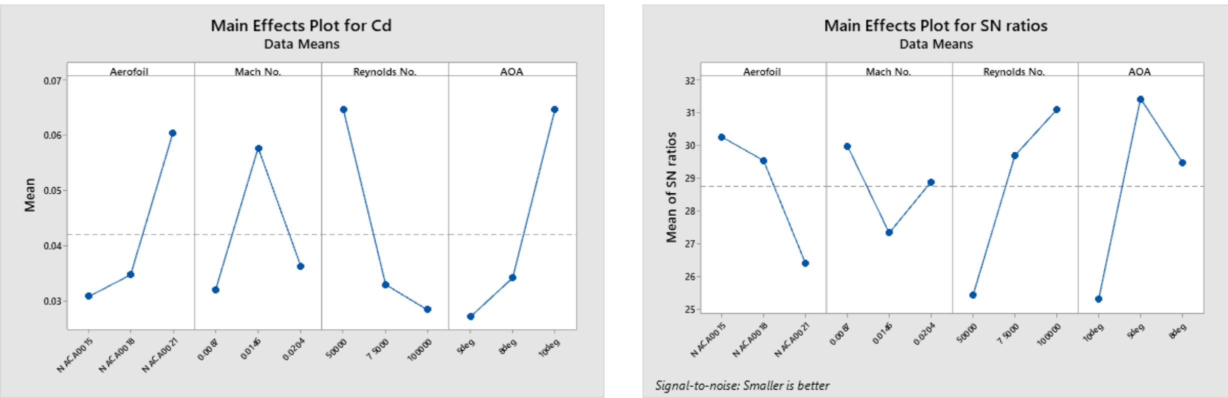


Fig. 5. Bar graph of coefficient of drag for number of experimentations

Figure 6 shows the main effect plot, SN graph plot and interaction plot amongst the various parameters stating the various effects of parameters on the response C_D. Table 7 represents Signal to Noise Ratio for drag coefficient by taken into consideration *smaller is better*, demonstrating that the major influence is due to AOA, followed by Reynolds number, type of aerofoil and least influence by Mach number.

Table 7
SNR response table for C_D

Level	Aerofoil	Mach No.	Re	AOA
1	30.28	30.00	25.45	25.33
2	29.56	27.35	29.71	31.44
3	26.43	28.91	31.11	29.50
Delta	3.85	2.66	5.66	6.11
Rank	3	4	2	1



(a) (b)

Fig. 6. (a) Effect of various parameters on mean C_D, (b) SN ratio effect plot for C_D and (c) Plot for interaction of aerofoil, M, Re and AOA

4.1.3 Coefficient of power (C_p)

One of the prime important aerodynamic parameter for the wind turbine is power coefficient. To enhance the efficiency of the turbine we need to optimize the power coefficient for the same. Also the configuration of a wind turbine plays a key role in achieving the optimal C_p. For calculating the maximum coefficient of power an empirical equation is expressed as [22].

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

where λ is tip speed ratio, B is blade number, C_D and C_L is coefficient of drag and lift respectively. For determining the value of C_p for the wind turbine, Eq. (1) is utilized by considering the value of TSR as 5 and number of blades as 3.

As one of the prime important responses the coefficient of power has been taken as *larger is better* and the experimental results for the given set of input parameters are demonstrated in the Table 8 and Figure 7. In experiment 7 It can be clearly perceive the set of parameters influencing the response are NACA0021 aerofoil (level 3) which is kept at 8 degree angle of attack (level 2) at inlet Mach number of 0.0087 (level 1) and corresponding Reynolds number taken as 100000 (level 3).

Table 8
Tabulation of Mean C_P and SN ratio value as per Taguchi's OA

Exp No.	NACA Aerofoil	Mach No.	Re	AOA	C_P	SNRA1
1	0015	0.0087	50 x 10^3	5deg	0.462642	-6.6951
2	0015	0.0146	75 x 10^3	8deg	0.470703	-6.5451
3	0015	0.0204	100 x 10^3	10deg	0.470548	-6.5479
4	0018	0.0087	75 x 10^3	10deg	0.467515	-6.6041
5	0018	0.0146	100 x 10^3	5deg	0.475580	-6.4555
6	0018	0.0204	50 x 10^3	8deg	0.454727	-6.8450
7	0021	0.0087	100 x 10^3	8deg	0.475865	-6.4503
8	0021	0.0146	50 x 10^3	10deg	0.127880	-17.863
9	0021	0.0204	75 x 10^3	5deg	0.467614	-6.6022

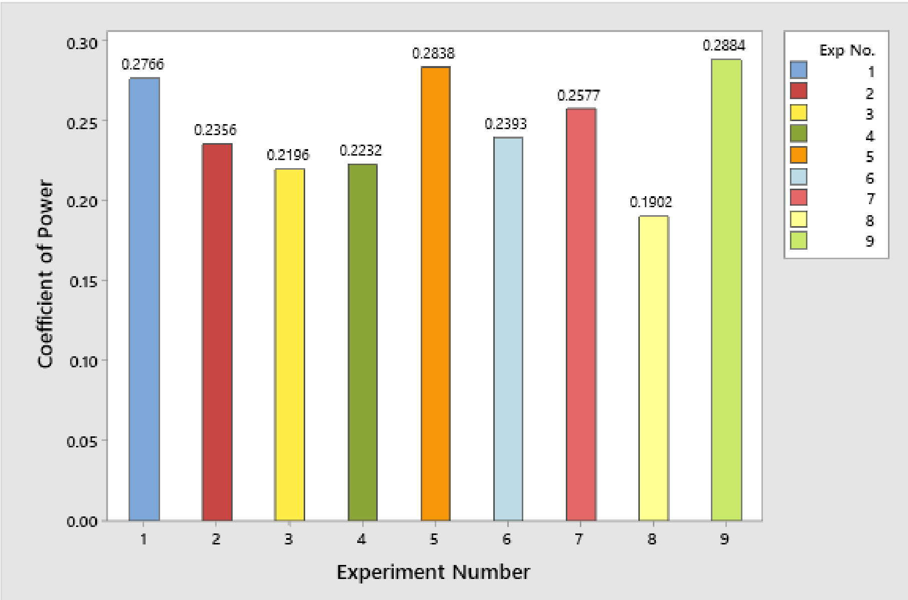


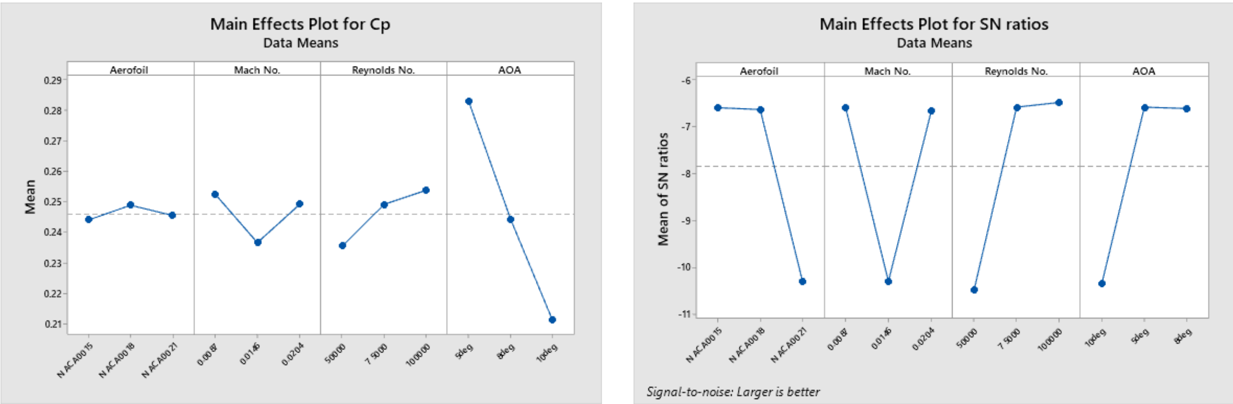
Fig. 7. Bar graph of coefficient of power for number of experimentations

Below is Figure 8 showing the main effects plot, SN graph plot and interaction plot amongst the various parameters stating the various effects of parameters on the response i.e; C_p. Response table 9 presents SNR for power coefficient by considering *larger is better*.

Table 9 also shows that the most influencing parameter is Reynolds number, angle of attack on the second rank followed by type of aerofoil and Mach number with the least effect on the response.

Table 9
SNR response table for C_P

Level	Aerofoil	Mach No.	Re	AOA
1	-6.596	-6.583	-10.468	-10.339
2	-6.635	-10.288	-6.584	-6.584
3	-10.306	-6.665	-6.485	-6.613
Delta	3.709	3.705	3.983	3.754
Rank	3	4	1	2



(a) (b)

Fig. 8. (a) Effect of various parameters on mean C_P, (b) SN ratio effect plot for C_P and (c) Plot for interaction of aerofoil, M, Re and AOA.

4.2 Grey - Based Taguchi (Multi Response)

The initial step is to normalize the experimental output results in GR analysis (grey relational) for which is having the minimum and maximum value as 0 and 1 respectively [23]. The normalization of response value was done by taking higher is better for C_L and C_P whereas for C_D it was lower-is better and the value was determined by the following equations.

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

(Lower is better)

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

(Higher is better)

where,
X_{ij} – normalized value for i^{th} experiment for j^{th} performance
x_{max} – maximum response value
x_{min} –minimum response value
x_{ij} – response value for i^{th} experiment for j^{th} performance [23]

Table 10 depicts the normalized values of various coefficients based on higher or lower is better along with the corresponding Grey Relational Coefficient.

After finding out the normalized values, grey relational coefficient (ξ_{ij}) can be calculated by using Eq. (5) where β is considered as 0.5.

$$\xi_{ij} = \frac{min_i min_j |X_i^0 - X_{ij}| + \beta max_i max_j |X_i^0 - X_{ij}|}{|X_i^0 - X_{ij}| + \beta max_i max_j |X_i^0 - X_{ij}|} \tag{5}$$

where,
ξ_{ij} - grey relational coefficient
X_i^0 - ideal normalized value
X_{ij} - response value for i^th^ experiment for j^th^ performance [23]

Table 10
Normalized values, calculated GRC for coefficient of lift, drag and power

Exp No.	NACA Aerofoil	Mach No.	Re	AOA (Deg)	Normalized Values			Grey Relational Coefficient		
					C_L	C_D	C_P	C_L	C_D	C_P
1	0015	0.0087	50000	5	0.637993	0.04395	0.95383	0.58004	0.34339	0.915471
2	0015	0.0146	75000	8	0.847702	0.05163	0.79342	0.76652	0.34521	0.707637
3	0015	0.0204	100000	10	0.973986	0.08115	0.73082	0.95054	0.3524	0.650046
4	0018	0.0087	75000	10	0.999103	0.10968	0.74490	0.99820	0.35963	0.662172
5	0018	0.0146	100000	5	0.740455	0	0.98200	0.65828	0.33333	0.965256
6	0018	0.0204	50000	8	0.826571	0.14708	0.80789	0.74246	0.36957	0.722438
7	0021	0.0087	100000	8	1	0.04695	0.87988	1	0.34410	0.806306
8	0021	0.0146	50000	10	0.26562	0.66730	0.61579	0.40506	0.60046	0.565482
9	0021	0.0204	75000	5	0.799859	0.05965	1	0.71414	0.34713	1

After estimating the grey relational coefficient we can find the grey relational grade by following equation and the main effects on mean grey relational coefficient along with the ranking of parameters is shown in Table 11.

$$\Gamma = \frac{1}{n} \sum_i^n w_i \, \xi_{ij} \tag{6}$$

where
w_i is the factor of weighting [23]

Table 11
Main effects on mean GRG

Factors	Mean Gray relational Grade			Max - Min	Rank
	Level 1	Level 2	Level 3		
NACA Aerofoil	0.766	0.701	0.6554	0.1105	1
Mach No.	0.7474	0.6813	0.6936	0.066	2
Reynolds No.	0.6965	0.7175	0.7083	0.021	3
AOA (Deg)	0.7034	0.6991	0.7198	0.0207	4

4.3 Analysis of Variance (ANOVA) Method

Signal to noise ratio (SNR) graphs helps in interpretation of the behaviour of a particular model, but for the comprehensive understanding of the particular effect of varieties of factors can be achieved using Analysis of Variance. Consequently the L-9 OA of Taguchi Method is put through the above method for the simulation whose results are depicted in table below. The significance of the variables necessary for the designing purpose can be identified by statistic F and P values. If the value of P is less than 0.05 then that variable is a key significant variable and vice versa. The null hypothesis can be rejected or support on the basis of statistic F value which is used to determine the P value and give us an idea whether the results have happened by chance or not. Like if the value of F is greater than its critical value then there is probability of rejecting the null hypothesis [24].

5. Conclusion

The current paper demonstrates the utilization of Taguchi method for designing of a robust vertical axis wind turbine which includes both tolerance as well as parameter design. Open source Q-blade software that works on BEM theory is considered for designing and evaluating the aerodynamic characteristics of a turbine. For determining the effect and influence of angle of attack (AOA), Reynolds number, Mach number and type of aerofoil along with their combination on wind turbine's performance, a Taguchi approach of L-9 OA is applied. From Q-blade software the maximum value of C_L obtained is 1.0361 in experiment 7 for conventional NACA0021 aerofoil having 0.0087 as input Mach number that is placed at 8 degree angle of attack at 100000 Reynolds number and experiment number 5 shows the minimum value for C_D of 0.02190.

Also by referring the SN ratio graphs for all the three responses C_L, C_D and C_P the following inferences can be drawn

i. For Lift coefficient - The major influence is due to Reynolds number (Re) followed by Mach number (M), type of aerofoil and least influence due to angle of attack (AOA).
ii. For Drag coefficient - The major influence is due to AOA followed by Reynolds number, type of aerofoil and least influence by Mach number.
iii. For Power coefficient - The most influencing parameter is Reynolds number, angle of attack on the second rank followed by type of aerofoil and Mach number with the least effect on the response.

Also by considering the plot for main effects, the most influencing individual parameters that affect the output aerodynamic parameters of a wind turbine are: for lift coefficient: NACA 0018 aerofoil at level 2, Mach number of 0.0087 at level 1, Reynolds No. of 100000 at level 3 and AOA of 8 Degree at level 2. Similarly for drag coefficient the most influenced individual parameters are NACA 0015 aerofoil at level 1, Mach number of 0.0087 at level 1, Reynolds number of 100000 at Level 3 and AOA of 8 Degree at level 2 and for power coefficient the highly influenced parameters are NACA 0015 aerofoil at level 1, Mach no. of 0.0087 at level 1, Reynolds No. of 100000 at level 3 and AOA of 8 Degree at level 2.

There are further many scopes related with the optimization of wind turbines like ANOVA, RSM, SPSS and many more. Further comparative study can be done using different kind of methods for the optimization of wind turbines.

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