Implementation of Taguchi Method for Designing a Robust Wind Energy System – A Wind Turbine

Vishal Kaushik[1,*], *R. Naren Shankar*[2], *N. I. Haroon Rashid*[3], *P. B. Khope*[4]

[1]Research Scholar, Department of Aeronautical Engineering, VelTech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India

[2]Associate Professor, Department of Aeronautical Engineering, VelTech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India

[3]Associate Professor, Department of Aeronautical Engineering, B. S. Abdur Rahman Crescent Institute of Science and Technology, Chennai, India

[4]Assistant Professor, Department of Aeronautical Engineering, Priyadarshini College of Engineering, Nagpur, Maharashtra, India

[*]Correspondence: vishalk.kaushik42@gmail.com

Received 1 November, 2022; Revised 8 December, 2022; Accepted 9 December, 2022

Available online 9 December, 2022 at www.atlas-tjes.org, doi: 10.22545/2022/00216

The current paper demonstrates the design parameters and tolerances for a horizontal axis wind turbine which is used to extract the energy from the wind. Here in the present work, one of the DOE (design of experiment) methods namely Taguchi method, a traditional approach for designing a robust wind turbine is adopted. For optimization purpose, the evaluation and estimation of various problems i.e; constrained as well as unconstrained have been done using Taguchi method. For the derivation of design parameters like lift coefficient (C_L), drag coefficient (C_D) and power coefficient (C_P), the L-9 Orthogonal array (OA) comprising of 4 parameters each with three levels (NACA aerofoil type, Mach number, Reynolds number and angle of attack) is considered. Open source Q-Blade designing software is used for determining the power, lift and drag coefficients of the wind turbine. The combination of GRA and orthogonal arrays are used for attaining the optimized parameters. In this paper an investigation has been carried out on the specific NACA aerofoils 4412, 4712, and 4421. Among all the aerofoils NACA 4712 has shown impressive results in terms of a maximum lift coefficient of 0.9491and minimum drag coefficient of 0.02601. Also from signal-to-noise plots it can be inferred that the most influenced parameter for C_L and C_D is Mach number and Aerofoil for C_P.

Keywords: Taguchi method, HAWT, SN ratio, GRA, optimization, Q-blade, optimization.

1 Introduction

Renewable energy is an urgent need in today's world so as to minimize the need for energy from natural resources to some extent. We know that lot of advancements are going on in the field of renewable energy and one of it is wind energy, which is used for sustainable development[1]. For extraction of wind energy, there are two types of wind turbines, horizontal and vertical based on their axis of rotation. The wind turbine industries are emerging day by day in which the share of HAWT is impressive. To enhance the efficiency and performance of these turbines the need of blade optimization has become an important factor. The main interest in this paper is to obtain optimized performance variables which directly or indirectly affect the efficiency of HAWT.

A robust design includes tolerance as well as parameter designing. [2] has presented a methodology by considering various tolerations along with multiple design parameters for a HAWT robust design using Taguchi approach as one of the methods of DOE. For the utilization of wind turbines, both in urban and rural areas lot of research are being carried out in the field of both types of wind turbines[3]. Desired quality values within the acceptance range can be achieved by using a design of experiment Taguchi method [4].

In the year 1956, a method of optimization for improving the quality of manufactured goods was developed by Genichi Taguchi an engineer and statistician from Japan. A statistical method has various kinds of analysis like Factor/Discriminate analysis, Regression Analysis, Pattern Recognition, Cluster Analysis, and Design of Experiments. Taguchi method is one of the methods in DOE which has concluded the experiments with quality characteristics.

Competence of providing the combination of optimized design parameters and having implementation in almost every engineering field, Taguchi method has evolved in past few years. Single and double objective functions for optimization and to operate both the positive and negative objective values of the function Taguchi method has become widened [5]. A module of wind capacity and heat sink of a CPU design was carried out by utilizing Taguchi and ANOVA [6]. A robust HAWT design in view of both parameter and toleration using Taguchi method and its extension has been proposed by [7].

Various types of research have been done for predicting the aerodynamic performance of wind turbines over the years. By using Q-blade and CFD simulations, various analysis has been carried out for obtaining various coefficients of aerodynamics for horizontal axis wind turbines with SG6043 aerofoil [8]. Taguchi method has an implementation in various fields of engineering for determining the optimum process for a single response[9].

Some of the merits related to Taguchi method are as i) handling of parameters required for design is simple when it has discrete values rather than mixed discrete values, ii) it does not need derivatives for the functions unlike genetic algorithm, iii) minimum functions are enough for the optimal and robust designs unlike the approaches having large functions for nonlinear programming, iv) results obtained from this method can be directly implemented as the physical designs[7]. Figure 1 comprises various methods of the statistical approach in OR (Operation Research), which can be classified as cluster analysis, regression analysis, pattern recognition, design of experiments, and factor/discriminate analysis. Taguchi method falls under the category of statistical analysis of operation research.

Various types of research have been carried out in past by different investigators, where they have used Q-blade software for designing and simulation of wind turbines and very few have utilized the Taguchi method for the optimization purpose. In this paper, the authors have tried to fulfill this research gap so as to get the most optimized design based on the combination of variables derived. Many analyses have been carried out on various NACA aerofoils for horizontal and vertical wind turbines using freely available open-source Q-blade designing and simulation software. For the prediction and valuation of various wind turbine parameters like the coefficient of lift, drag, and power, implements the use of blade element theory and empirical equation. For determining and exploration of wind turbine parameters' effect on NACA 4412, 4421, and 4712, a grey-based Taguchi method has been utilized.

2 Taguchi Method of Statistical Analysis

A Statistical method is one of the methods used in operation research for obtaining the relation between the input and output parameters which also affects the whole process. It is very convenient for optimizing the complex characteristics of aerodynamics comprising different variables[10]. One of the statistical methods

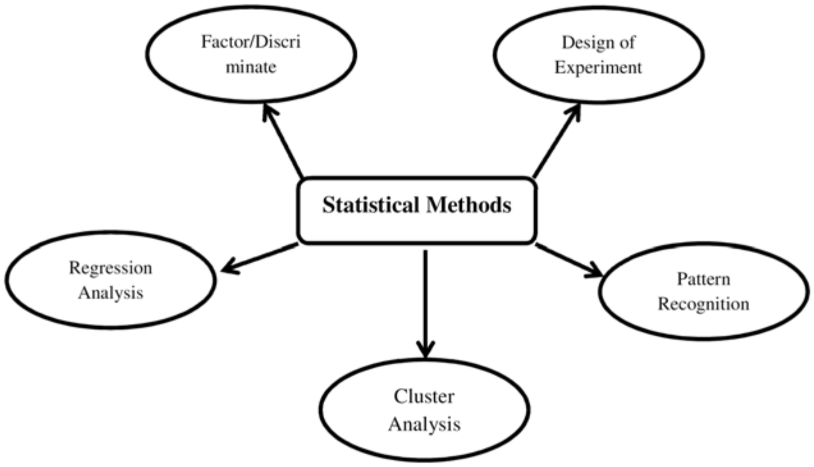


Figure 1: *Classification of statistical method.*

is the Taguchi approach which consists of the various steps which are depicted in Figure 2 below.

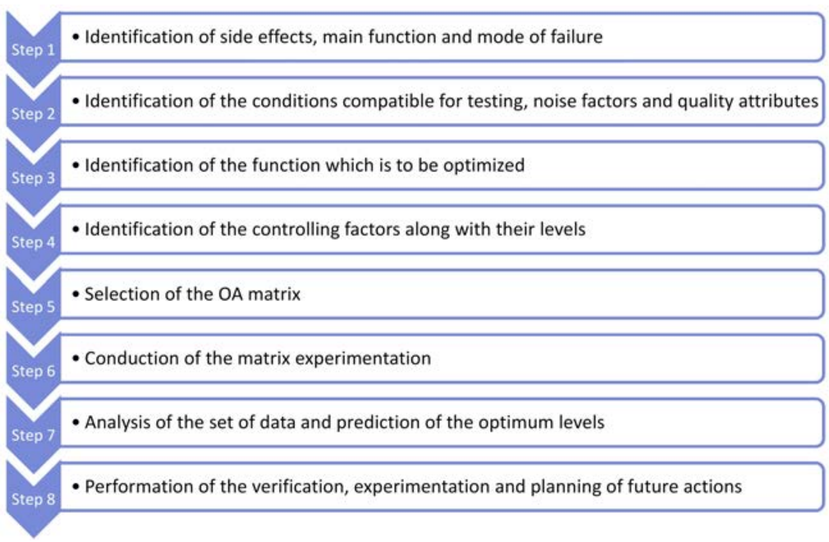


Figure 2: *Various steps in Taguchi method.*

In this paper, the parameters related to wind turbine aerodynamics are aerofoil type, angle of attack, Mach number, and Reynolds number. For obtaining and determining the influence and effect of the considered parameters and their combination on the wind turbine performance, we have considered the Taguchi method with L9 – orthogonal array having three sets of levels having four parameters.

Tables 1 and 2 include information on the number of considered parameters with their level of experimentation ranging from low to high and Taguchi L9 OA representation as ($Level\ design^{No.of factors}$) that is 34. For the analysis, Minitab 19 statistical package is used in which Taguchi method was chosen for obtaining the effect on quality response. [11] had carried out experimentation using Taguchi by considering the orthogonal array of L9, along with one interaction and three parameters to examine the effects which will be of prime importance for the designing process, which ultimately affects the performance of the turbine.

Table 1: Designing parameters levels

Design variables	Levels		
	1 (Low)	**2 (Intermediate)**	**3 (High)**
NACA Aerofoils	4412	4421	4712
Mach Number	0.0087	0.0146	0.0204
Reynolds Number	50000	75000	100000
Angle of attack	2 degree	4 degree	6 degree

Table 2: L-9 OA (orthogonal array) Mapping

Experiment No.	**NACA Aerofoil**	**Mach No.**	**Reynolds No.**	**AOA**
1	4412	0.0087	50000	2 degree
2	4412	0.0146	75000	4 degree
3	4412	0.0204	100000	6 degree
4	4421	0.0087	75000	6 degree
5	4421	0.0146	100000	2 degree
6	4421	0.0204	50000	4 degree
7	4712	0.0087	100000	4 degree
8	4712	0.0146	50000	6 degree
9	4712	0.0204	75000	2 degree

2.1 Robust Design

The Taguchi method can be used to determine the influence of aerodynamic parameters. For the experimental run, the numbers of quality responses considered are lift coefficient, drag coefficient, and power coefficient. Lift and power coefficients are very crucial parameters for deciding the aerodynamic characteristics of a wind turbine and thus these parameters must be kept as high as possible. On the other hand, the drag coefficient must be kept as low as possible to enhance the performance of the turbine, due to this fact drag coefficient is taken as lower is better, and lift and power coefficients are considered as higher is better. For lift coefficient and power coefficient, the following equation 1 is used, which gives the relation for signal-to-noise ratio (SNR). For the maximum SNR, there must be an improvement in the mean value and variance[12].

$$\frac{S}{N} = -\log_{10}\{\frac{1}{n}\left[\sum_{i=1}^{n}\frac{1}{y_i^2}\right]\} \tag{1}$$

Where,
S- Signal
N - Noise
y_i - Response experiment
n - Number of runs

Here in the present paper, the input Mach number (velocity) is taken as a factor of noise, as it affects the HAWT performance.

Researchers utilized one of the DOE methods i.e; Taguchi approach for determining the optimal output responses related to the deflector which is used as an augmenter for their wind turbine setup. An experiment based on a matrix can be designed by defining the controlling factors like noise and control, followed by the performance of experiments based on the matrix. Below is Table 3 represents the factors and levels that were considered by an investigator to determine the effect of 5 factors of deflector on the output power coefficient of the vertical axis wind turbine[13].

Table 3: Number of factors and levels for the deflector[13]

Factors	**Levels**			
	1	**2**	**3**	**4**
Horizontal distance from the axis to top edge of deflector (X)	0	$1/2\,D$	D	$3/2\,D$
Vertical distance between top and bottom edge of a blade (Y)	0	$1/3\,H$	$2/3\,H$	H
Angle of deflection w.r.t turbine rotation (ϕ)	0 degree	30 degree	45 degree	60 degree
Deflector Length (L)	$1/2\,H$	H	$3/2\,H$	2H
Deflector Width (W)	$1/3\,D$	$2/3\,D$	D	$4/3\,D$

2.2 Validation

A similar study has been conducted by Yi Hu et al. [7] and Kriswanto et al. [14] for designing a robust wind turbine using the Taguchi approach. For the present investigation, a detailed procedure is followed by considering the past research, based on Taguchi method for the optimization purpose. For parameters like lift coefficient and power coefficient "higher is better" and for drag coefficient "lower is better," SNR is considered for the present research and accordingly, all the related plots like main effect plot, SN response table and SN plots were generated and analyzed by considering L9 orthogonal array for parameters like aerofoil type, angle of attack, Mach number and Reynolds number, each having three levels as low, intermediate and high.

3 Q-Blade Simulation Software

Q-blade is a simulation tool that is available freely and facilitates the designing and simulation of vertical as well as horizontal axis wind turbines. This software uses the principle of the Blade element momentum method and doubles multiple stream tube algorithm for analyzing horizontal and vertical axis wind turbines[15][16][17].

For calculations, an inbuilt methodology of Q-blade software is utilized, which is based on blade element momentum theory (blade element and momentum) theories, which accounts for the angular momentum of the turbine rotor. These theories are utilized for calculating the local forces acting on a propeller or turbine blade. Angular momentum is included in the model in BEM theory. Here in our calculations, the turbulence consideration was not taken into account.

Figure 3 shows the algorithm associated with Q-blade software which enables the designing and simulation of customized aerofoils, along with their respective polar computations, and polar data extrapolation to 360 degrees. This software consists of various modules namely XFLR5, XFoil Analysis, Polar extrapolation, designing of blade, and analysis of turbine[18].

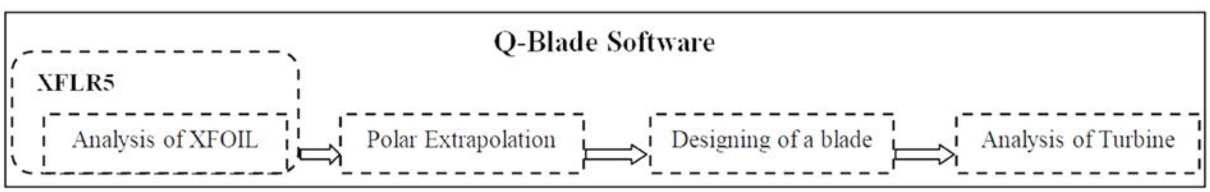


Figure 3: *Different Modules of Q-blade software.*

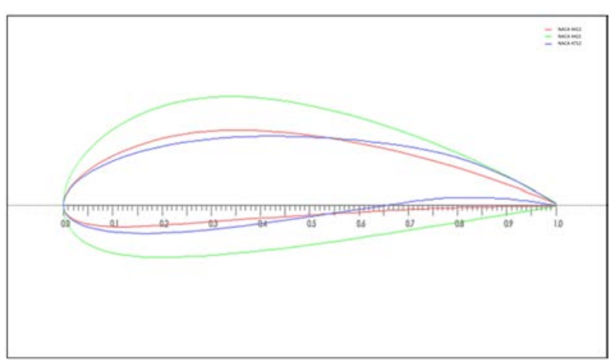


Figure 4: *NACA 4412, 4421 and 4712 aerofoil profiles.*

Figure 4 depicts the profiles of three NACA aerofoils namely NACA4412, 4421, and 4712 which have 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 4421 aerofoil has the maximum thickness among all of them. Also, NACA4421 shows the highest camber among all the aerofoils.

Figure 5, depicts the plot generated using the Q-blade software for all three aerofoils at M = 0.0087 and Re = 50000. For the lift coefficient and Cl/Cd versus angle of attack plots, it can be seen that NACA4712 aerofoil shows impressive results over the wide range of angles in comparison with the other two aerofoils. At AOA 8 degree NACA4712 aerofoil has the maximum value of lift coefficient and Cl/Cd ratio. For the lift coefficient versus Transition point (Xtr) plot, all the aerofoils show a similar down falling trend.[19] has presented the optimization of HAWT by considering different parameters like AOA, aerofoil type, and speed of the wind. The investigators considered various NACA aerofoils namely 4412, 2412, modified 4412, and modified NACA2412 for the analysis using Q-blade software and optimization by using Taguchi method. They concluded that for obtaining the optimal power, the conditions found were aerofoils – Mod NACA 4412 and 2415 placed at 3 degrees AOA for the wind speed of 8 meters per sec. On the basis of ANOVA analysis, the most and least significant factors found were the speed of the wind and AOA respectively.

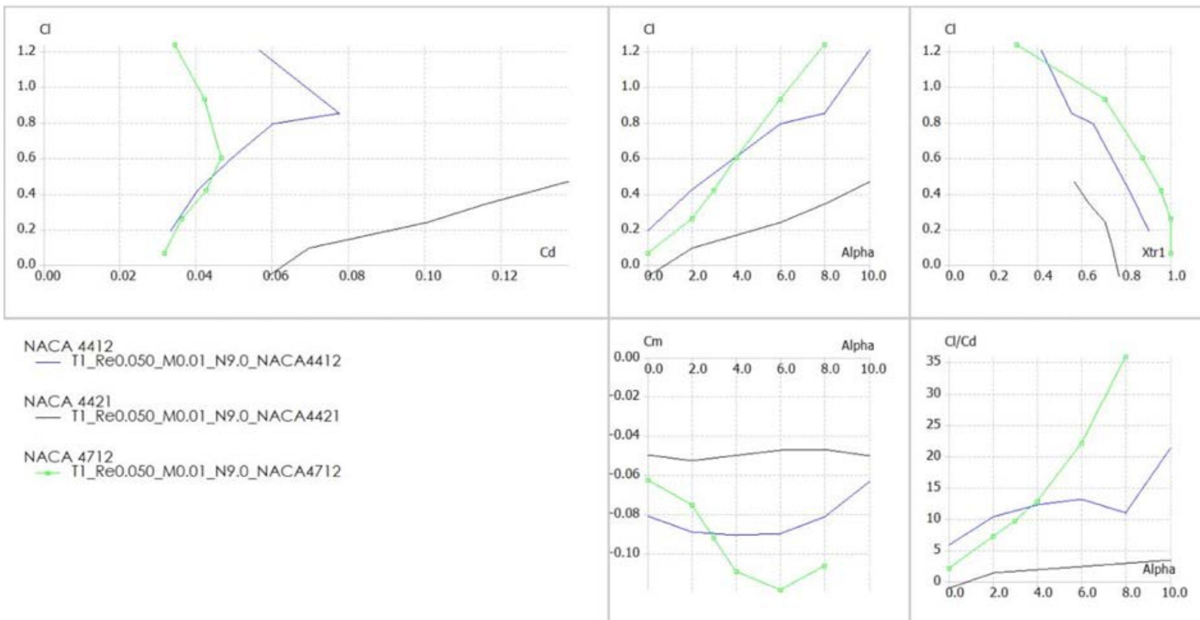


Figure 5: *Plots between various parameters at Mach 0.0087 and Re 50000 for NACA4412, 4421 and 4712 using Q-blade software.*

Table 4 comprises the details of the S/N ratio graph for the rotor power.

Table 4: S/N Ratio response of Roundness of Effect of Factor[19]

Level	Aerofoil	AOA	Wind Speed
1	57.51	57.84	51.27
2	57.56	57.78	56.00
3	57.90	57.70	60.10
4	57.93	57.58	63.53
Delta	0.42	0.26	12.26
Rank	2	3	1

A study has been made on a small capacity HAWT by using Q-blade software which is based on a BEM theory. Also, the effect of chord and angle of twist design was deeply investigated by considering SG6043 aerofoil at 10 varying locations along blade length and the maximum obtained value for the C_L/C_D was at the AOA of 2 degrees. Below is Figure 6 depicting the modified and unmodified blades of the wind turbine with SG6043 aerofoil[20].

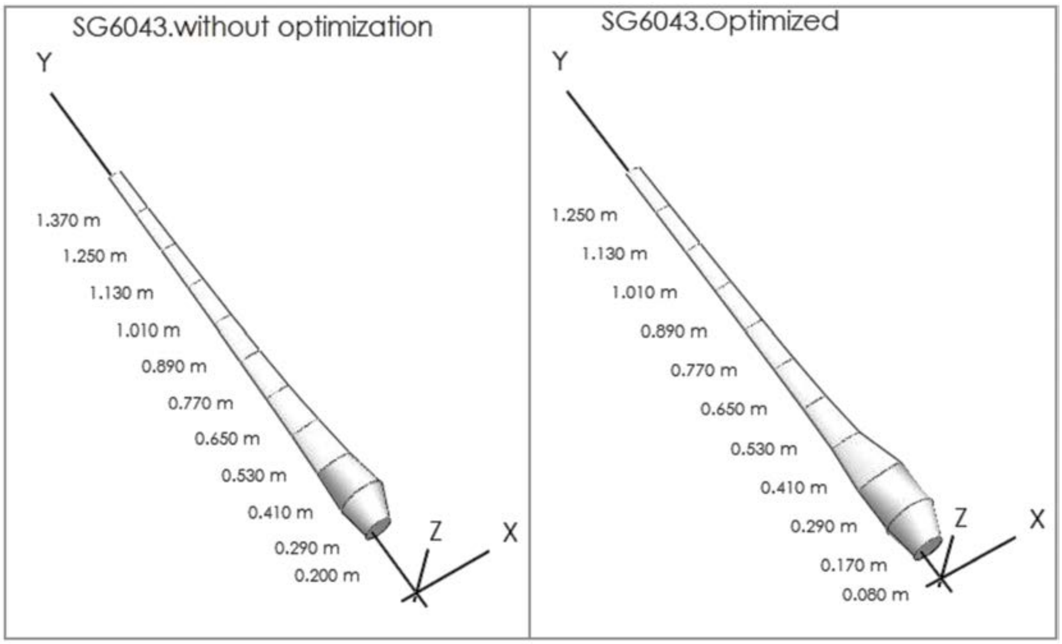


Figure 6: *Wind turbine blades (Source: Q-blade)[20].*

Based on BEM theory research has been carried out on a small-scale HAWT setup. For experimentation and simulation purpose SG6043 aerofoil was selected and its corresponding parameters like the coefficient of lift and drag was taken as a reference. The investigation has been done on the variable chord length and a rotor diameter of 2.5 m by varying the pitch from 5 to 25 degrees. Pressure vector and boundary layer of the selected aerofoil at AOA of – 5 degrees and 15 degrees at Reynolds number of 4 x 10^5 is depicted in Figure 7 [21].

A study has been carried out to investigate the performance of HAWT both with non-yawing and yawing mechanism using Q-blade software. It has been concluded that there was a significance of yaw angles on the turbine performance. It has been observed that there is a decrement in power output by around 15% after 25-degree yawing angle in non-yawed flow and there is almost $\frac{1}{2}$ of the power generation at a yawing angle of more than 45 degrees[22].

In the present study our main focus is to find out the impact of various parameters i.e. Reynolds number, Mach number, angle of attack, and type of aerofoil on the aerodynamic characteristic variables like lift coefficient C_L, drag coefficient C_D, and power coefficient C_P. For that, the value of turbulence considered is the default value in the software tool utilized for the simulation purpose.

3.1 Validation of Q-Blade Simulation Results

An investigation has been carried out by Bili Darnanto Susilo et al.[23] on NACA 4712 and NACA 4412 aerofoils using Q-blade software and CFD simulations at various angles of attack to obtain the results like lift coefficient, drag coefficient, C_L/C_D ratio. It has been concluded that NACA4712 showed higher lift, power coefficients, and C_L/C_D ratios in comparison with NACA4412. Also, the maximum lift coefficients

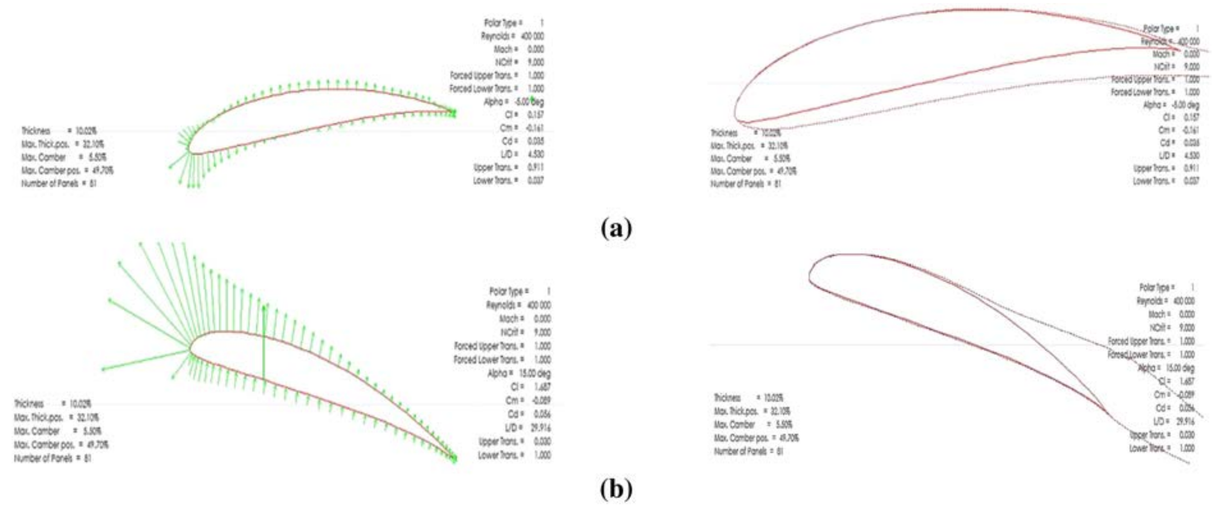


Figure 7: *Pressure distribution and boundary layer of SG6043 aerofoil at (a) AOA of – 5 degree (Re 4 x 104) and (b) AOA of 15 degree (Re 4 x 104) [21].*

obtained for both aerofoils were 1.696 for NACA4712 and 1.628 for NACA4412. And similar trends can be seen in Figure 8, among the present study which demonstrates the close agreement with the past research. In the present research also NACA4712 aerofoil showed impressive results over a wider range of angles in comparison with the other two aerofoils namely NACA4412 and NACA0021.

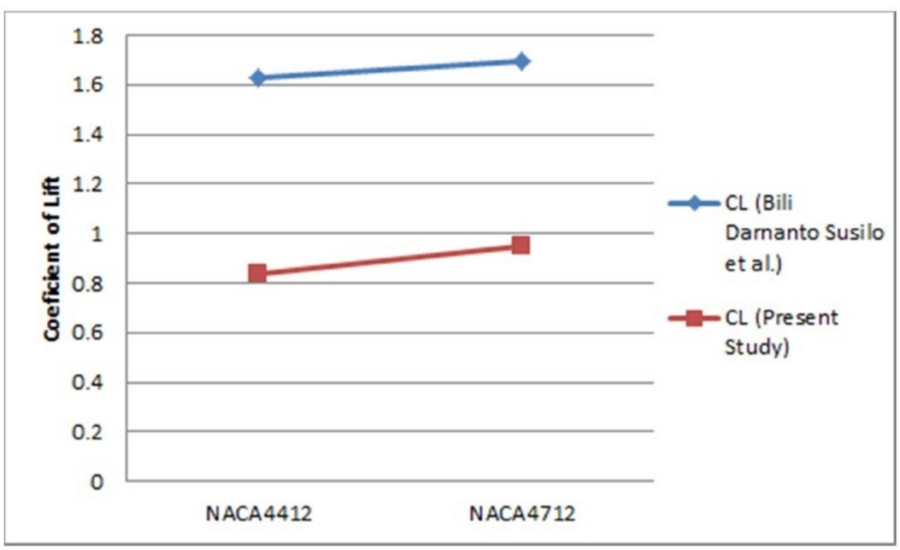


Figure 8: *Comparison of lift coefficients of NACA4412 and NACA4712.*

3.2 Mathematical Formulation Related to Q-Blade

3.2.1 Lift and Drag Coefficients (C_L and C_d)

Lift and drag coefficients are the dimensionless variables of aerodynamic forces and can be formulated by the following mathematical equations (2) and (3)

$$C_L = \frac{L}{0.5\rho A v^2} \tag{2}$$

$$C_L = \frac{D}{0.5\rho A v^2} \tag{3}$$

Where,
L is Lift force in (N)
D is Drag force in (N)
ρ is air density in (kg/m^3)
v is airflow velocity in (m/s)
A is swept area in (m^2)

3.2.2 Lift and Drag Force Extrapolation of an Aerofoil

Each and every section of an aerofoil can be extrapolated by using Montgomerie and Viterna techniques, which are very popular methods among all for extrapolation purposes [24].

Viterna technique: By utilizing the set of aerofoils data obtained from the analysis of XFOIL. The performance of extrapolation for stalling angle of attack to a 90-degree angle of attack is done with the help of the following mathematical equations [24].

$$C_D = B_1 \sin^2 \alpha + B_2 \cos \alpha \tag{4}$$
$$C_L = A_1 \sin 2\alpha + A_2 \cos^2 \alpha / \sin \alpha \tag{5}$$
$$C_{D_{max}} \cong 1.11 + 0.018AR \tag{6}$$

Where
AR is the aspect ratio of wind turbine

$$A_1 = C_{Dmax}/2 \tag{7}$$
$$B_1 = C_{Dmax} \tag{8}$$
$$A_2 = (C_L - C_{Dmax} \sin \alpha_{stall} \cos \alpha_{stall}) \frac{\sin \alpha_{stall}}{\cos^2 \alpha_{stall}} \tag{9}$$
$$B_2 = \frac{C_{D_{stall}} - C_{D_{max}} \sin^2 \alpha_{stall}}{\cos \alpha_{stall}} \tag{10}$$

Montgomerie technique: At a higher angle of attack aerofoil behaves like a thin plate. Here in this technique, the assumption is considered around an aerofoil placed at 00. Below is the equation which defines the curve of potential flow[24]

$$C_L = f \times +(1 + f)s \tag{11}$$

Where,
t – Straight tangent to $C_L(\alpha = 0)$
f – Transformation function

$$f = \frac{1}{(1/f_2 - 1)(\frac{1}{(\alpha_2 - \alpha_m)^4}) \times \Delta\alpha^4} \tag{12}$$

where,
α_m – deviation of C_L from potential flow curve angle

$$\alpha_m = \frac{\alpha_1 - (\sqrt[4]{\frac{1}{f_1} - 1/\frac{1}{f_2} - 1) \times \alpha_2}}{1 - (\sqrt[4]{\frac{1}{f_1} - 1/\frac{1}{f_2} - 1)}} \tag{13}$$

3.2.3 Coefficient of Power of Wind Turbine

The analysis of power coefficient of wind turbines can be done for the wide range of tip speed ratios (TSR)[25]. Mathematically the power coefficient and tip speed ratio are given as follows

$$C_P = \frac{P}{0.5\rho A v^3} \tag{14}$$

$$TSR(\lambda) = \frac{wR}{\nu} \tag{15}$$

where,

w -Angular velocity of a wind turbine

v - Linear velocity

R - Radius of wind turbine

4 Result and Discussion

4.1 Single Response Taguchi Method

4.1.1 Lift Coefficient (C_L)

ANOVA is a simplified effect of the column method of Taguchi which stipulates columns with a large influence on a particular response. The experimental data of the lift coefficient is demonstrated in below Table 5.

Using the Q-Blade simulation tool results have been obtained for NACA 4412, 4421, and 4712 aerofoils for the given parameters like angle of attack, Reynolds number, and Mach number.

Table 5: Table for Mean C_L and SN ratio for L-9 OA

Exp No.	NACA Aerofoil	Mach No.	Re	AOA	MEAN1 C_L	SNRA1
1	4412	0.0087	50000	2 degree	0.4193	-7.5495
2	4412	0.0146	75000	4 degree	0.8337	-1.5798
3	4412	0.0204	100000	6 degree	0.7865	-2.08603
4	4421	0.0087	75000	6 degree	0.4174	-7.58895
5	4421	0.0146	100000	2 degree	0.7152	-2.91145
6	4421	0.0204	50000	4 degree	0.2341	-12.612
7	4712	0.0087	100000	4 degree	0.8117	-1.81209
8	4712	0.0146	50000	6 degree	0.9491	- 0.45376
9	4712	0.0204	75000	2 degree	0.3966	- 8.03295

It can be observed from Table 5 that the C_L max value (Max coefficient lift) is 0.9491 for the experimental run 8 for NACA 4712 aerofoil kept at 6 degrees AOA, 0.0146 Mach number for Reynolds number of 50000. And similarly, the min value of lift coefficient C_L min 0.2341 for the experimental run 6 where the corresponding Mach number is 0.0204, AOA is 4 degrees, and Reynolds number is 50000 for the NACA 4421 aerofoil.

By considering larger is better for C_L, Figure 9 depicts the impact of aerofoil type, Reynolds number, Mach number, and AOA on CL mean along with SNR main effect plots for C_L. Table 6 depicts that the major impact on C_L is due to the Mach number followed by the Reynolds number, and type of aerofoil, and the least influence is due to the angle of attack. Also, the delta value helps us to decide about the variable which has the greater amount of noise (error) associated with it and hence majorly influences the output, here we have a Mach number with a delta value of 5.929, and the least influenced one is AOA with a delta value of 2.788.

Table 6: Signal/Noise response for C_L

Level	**Aerofoil**	**Mach No.**	**Re**	**AOA**
1	-3.738	-5.650	-6.872	-6.165
2	-7.704	-1.648	-5.734	-5.335
3	-3.433	-7.577	-2.270	-3.376
Delta	4.271	5.929	4.602	2.788
Rank	**3**	**1**	**2**	**4**

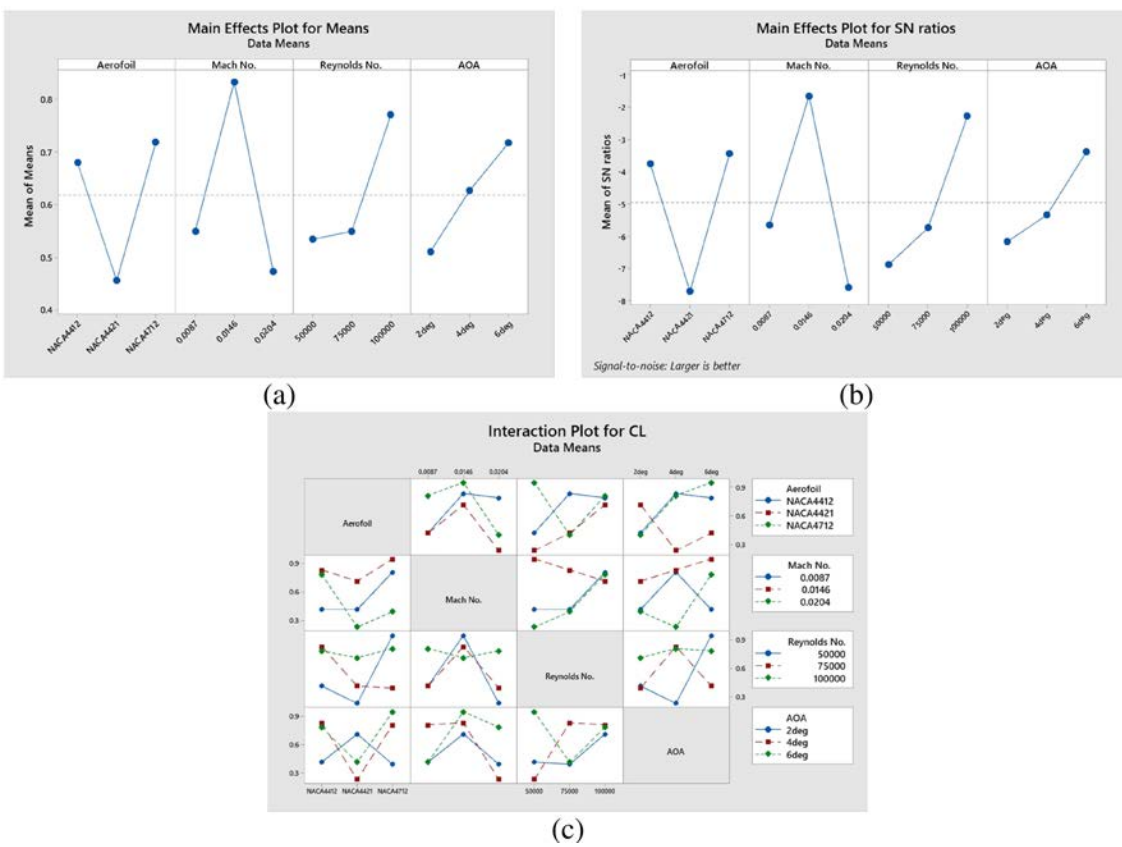


Figure 9: *(a) Effect of Aerofoil, Re, M and AOA on mean C_L, (b) Signal to Noise effect plot for C_L and (c) Plot for interaction of aerofoil, M, Re and AOA.*

4.1.2 Coefficient of Drag (C_D)

The experimental results for the coefficient of drag is presented below in Table 7 which states that the maximum and minimum values of C_D and the corresponding experiment number are $C_{D_{max}} = 0.10066$ for experiment number 6 and $C_{D_{min}} = 0.02601$ for experiment number 7. For experiment 7, the set of parameters influencing the response is NACA 4712 aerofoil (level 3) which is kept at 4 degrees angle of attack (level 2) at an inlet Mach number of 0.0087 (level 1) and corresponding Reynolds number taken as 100000 (level 3).

Table 7: Table for Mean C_D and SN ratio for L-9 OA

Exp No.	NACA Aerofoil	Mach No.	Re	AOA	MEAN1 C_D	SNRA1
1	4412	0.0087	50000	2 degree	0.04056	27.8380
2	4412	0.0146	75000	4 degree	0.02754	31.2007
3	4412	0.0204	100000	6 degree	0.06018	24.4110
4	4421	0.0087	75000	6 degree	0.08034	21.9014
5	4421	0.0146	100000	2 degree	0.02627	31.6108
6	4421	0.0204	50000	4 degree	0.10066	19.9429
7	4712	0.0087	100000	4 degree	0.02601	31.6972
8	4712	0.0146	50000	6 degree	0.04053	27.8445
9	4712	0.0204	75000	2 degree	0.0339	29.3960

By considering smaller is better for C_D, Figure 10 depicts the impact of aerofoil type, Reynolds number, Mach number, and AOA on C_D mean along with SNR main effect plot for C_D. Table 8 depicts that the major impact on C_D is due to the Mach number followed by the type of aerofoil, angle of attack, and least influence by the Reynolds number.

Table 8: Signal/Noise response for C_D

Level	Aerofoil	Mach No.	Re	AOA
1	27.82	27.15	25.21	29.61
2	24.49	30.22	27.50	27.61
3	29.65	24.58	29.24	24.72
Delta	5.16	5.64	4.03	4.90
Rank	**2**	**1**	**4**	**3**

4.1.3 Power Coefficient (C_p)

It is one of the significant aerodynamic parameters for a wind turbine. For the same, it has to be optimized to a greater extent to provide the maximum value of efficiency.

For finding the power coefficient of a wind turbine, the following empirical formula is used, which is expressed as follows [26]:

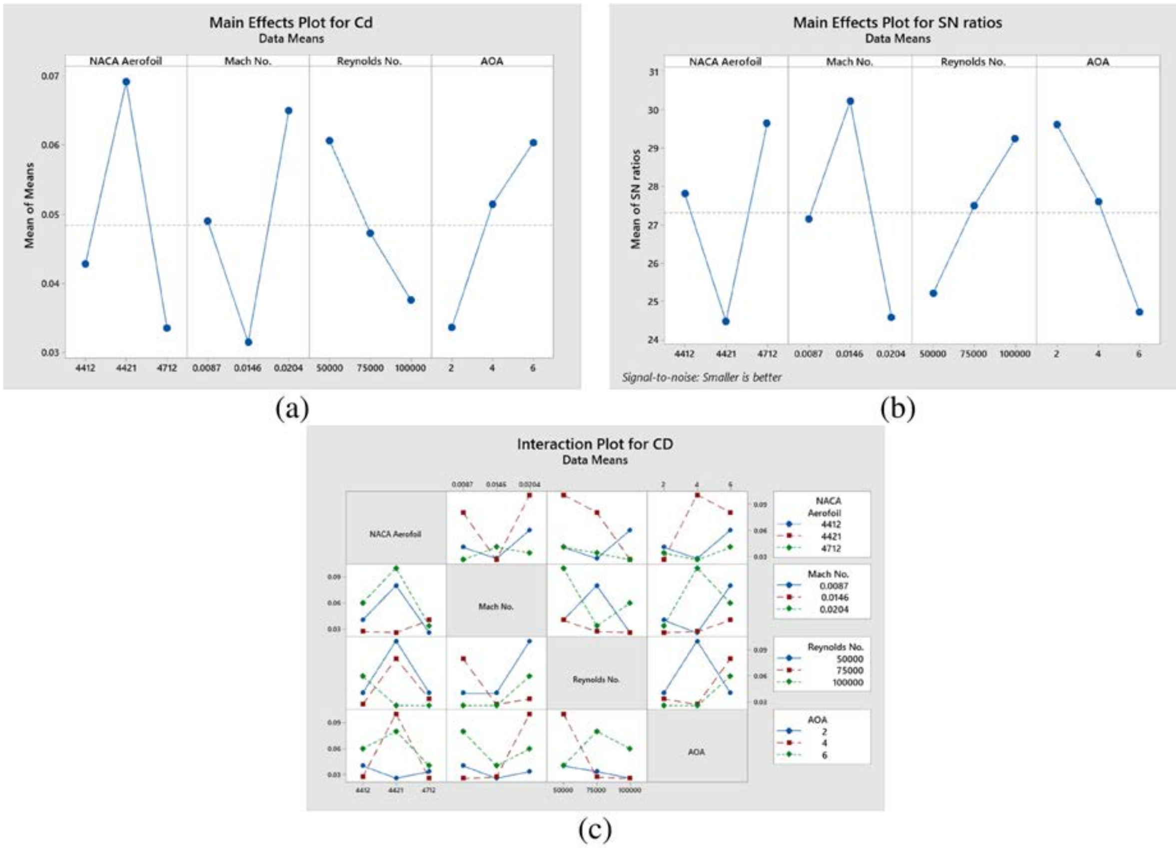


Figure 10: *(a) Effect of Aerofoil, Re, M and AOA on mean C_D, (b) Signal to Noise effect plot for C_D and (c) Plot for interaction of aerofoil, M, Re and AOA.*

$$C_{pmax} = 0.593[\frac{\lambda B^{0.67}}{1.48 + (B^{0.67} - 0.04)\lambda + 0.0025\lambda^2} - \frac{1.92\lambda^2 C_D}{1 + 2\lambda B C_L}] \tag{16}$$

Where,

λ - Tip speed ratio

B - Blade number

C_D and C_L is coefficient of drag and lift respectively.

For analysis purposes, we have considered the value for TSR = 5 and B = 3. For C_P which supposes to be the maximum for a wind turbine, we have considered "larger is better". The results obtained are demonstrated in Table 9. In an experiment run 7, it can be observed that the set of parameters influencing the response is NACA 4712 aerofoil (level 3) which is kept at a 4-degree angle of attack (level 2) at an inlet Mach number of 0.0087 (level 1) and corresponding Reynolds number taken as 100000 (level 3).

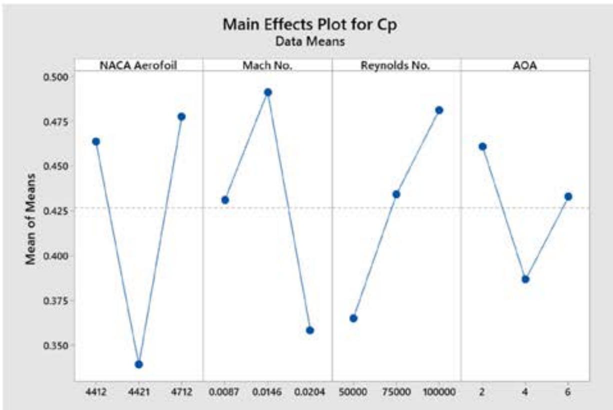
Figure 11 comprises various graphs for CP depicting the signal-to-noise graph, interaction plot and main effects plot and Table 10 depicts the most influencing parameter for CP is the Aerofoil followed by Mach number, Reynolds number, and the least influencing parameter is the angle of attack.

Table 9: Table for Mean C_P and SN ratio for L-9 OA

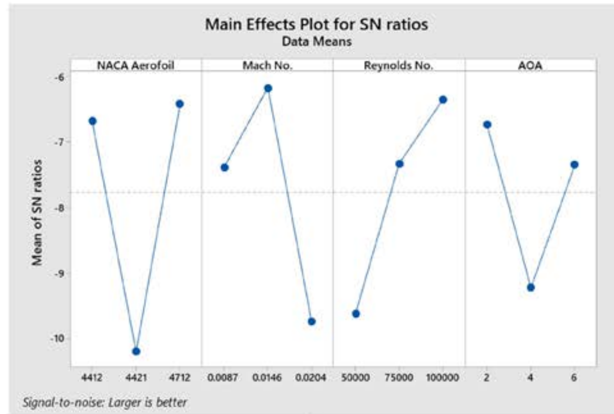
Exp No.	NACA Aerofoil	Mach No.	Re	AOA	C_P	SNRA1
1	4412	0.0087	50000	2 degree	0.440379	-7.1234
2	4412	0.0146	75000	4 degree	0.495263	-6.1032
3	4412	0.0204	100000	6 degree	0.455753	-6.8254
4	4421	0.0087	75000	6 degree	0.356283	-8.9641
5	4421	0.0146	100000	2 degree	0.492102	-6.1589
6	4421	0.0204	50000	4 degree	0.168278	-15.479
7	4712	0.0087	100000	4 degree	0.496196	-6.0869
8	4712	0.0146	50000	6 degree	0.486258	-6.2626
9	4712	0.0204	75000	2 degree	0.450588	-6.9244

Table 10: Signal/Noise response for C_P

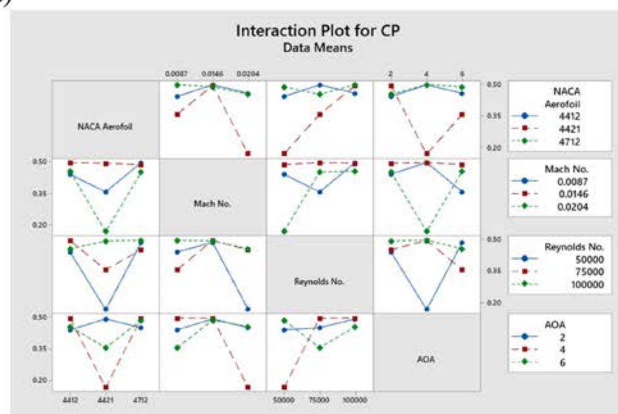
Level	Aerofoil	M	Re	AOA
1	-6.684	-7.392	-9.622	-6.736
2	-10.201	-6.175	-7.331	-9.223
3	-6.425	-9.743	-6.357	-7.351
Delta	3.776	3.568	3.265	2.488
Rank	**1**	**2**	**3**	**4**



(a)



(b)



(c)

Figure 11: *(a) Effect of Aerofoil, Re, M and AOA on mean C_P (b) Signal/Noise ratio effect plot and (c) Plot for aerofoil, M, Re and AOA interaction.*

4.2 Multi response Grey- Based Taguchi Method

[27] had stated that for GRA (grey relational analysis) first step is normalizing the results (output) obtained from the experimentation of simulation and GRA has 0 as a minimum value and 1 as the maximum value.

The response value normalization has concluded by considering the lift coefficient and power coefficient as "higher is better" and the drag coefficient as "lower is better". It can be obtained by considering the following equation. Equation 3 is used for lower is better whereas for higher is better Equation (18) is taken into consideration.

$$X_{ij} = \frac{x_{max} - x_{ij}}{x_{max} - X_{min}} \qquad \text{Lower is better} \tag{17}$$

$$X_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - X_{min}} \qquad \text{Higher is better} \tag{18}$$

Where

X_ij – normalized value for i^{th} experiment for j^{th} performance
x_{max} – value for maximum response
x_{min} – value for minimum response
x_{ij} – response value for i^{th} experiment for j^{th} performance

Table 11 comprises the values of GRA along with normalized values of C_L, C_D and C_P also consisting of GRG (grey relational grade) which can be evaluated by using Equation (20) along the ranking of various parameters.

Table 11: **Normalized Values and Calculated GRC for coefficient of lift, drag and power for L-9 OA and Main effects on mean Grey Relational Grade (GRG)**

Exp No.	NACA Aerofoil	Mach No.	Re	AOA	Normalized Values			Grey Relational Coefficient			GRG	Rank
					C_L	C_D	C_P	C_L	C_D	C_P		
1	4412	0.0087	50000	2 degree	0.25902	0.80509	0.82978	0.40290	0.71951	0.74602	0.6228	7
2	4412	0.0146	75000	4 degree	0.83860	0.979504	0.99715	0.75597	0.96062	0.99434	0.9036	2
3	4412	0.0204	100000	6 degree	0.72587	0.542264	0.87666	0.68738	0.52206	0.80214	0.67052	5
4	4421	0.0087	75000	6 degree	0.25636	0.272204	0.57332	0.40204	0.40723	0.53956	0.4496	8
5	4421	0.0146	100000	2 degree	0.67286	0.99651	0.98751	0.60449	0.99308	0.97563	0.8577	4
6	4421	0.0204	50000	4 degree	0	0	0	0.33333	0.33333	0.33333	0.3333	9
7	**4712**	**0.0087**	**100000**	**4 degree**	**0.80783**	**1**	**1**	**0.7223**	**1**	**1**	**0.9074**	**1**
8	4712	0.0146	50000	6 degree	1	0.80549	0.9696	1	0.7199	0.9428	0.8875	3
9	4712	0.0204	75000	2 degree	0.2272	0.89430	0.8609	0.3928	0.8255	0.7823	0.6669	6

Followed by the normalized values, grey relational coefficient (ξ_{ij}) is evaluated by taking β as 0.5 in Equation 19.

$$\xi_{ij} = \frac{min_i min_j \mid X_i^0 - X_{ij} \mid + \beta max_i max_j \mid X_i^0 - X_{ij} \mid}{\mid X_i^0 - X_{ij} \mid + \beta max_i max_j \mid X_i^0 - X_{ij} \mid} \tag{19}$$

Where,

ξ_{ij} - Grey relational coefficient

X_i^0 - Ideal normalized value

$X_i j$ - Response value for ith experiment for jth performance

$$\Gamma = \frac{1}{n} \sum_{i}^{n} w_i \xi_{ij} \tag{20}$$

Where, w_i is the factor of weighting

In the present work, the multi-response Grey based approach is taken into consideration which is used to solve the practical problems within the limited set of data and gives us the normalized values and GRC i.e; grey relational coefficient. GRC helps us to determine the ranking of all the factor combinations i.e; (Aerofoil, Mach number, Reynolds number and angle of attack). Here we are considering the multiple responses for the optimization process of output by considering input factors/parameters. On the other hand, the single response considers only single output parameter for optimization purposes.

From Table 11, an inference can be drawn that for experimental run 7, the overall rank for all the combined responses is rank 1 with Grey relational grade (GRG) of 0.9074 for the corresponding factors as NACA4712 aerofoil kept at 4 degrees AOA and Mach number 0.0087 for Reynolds number of 100000 and the least ranking i.e; rank 9 was there for the experimental run 6 with GRG of 0.3333.

In comparison with other methods like RSM, regression analysis, ANOVA analysis, etc.. Taguchi approach for experimental designing has supremacy in various aspects like cost reduction, quality improvement, ability to optimize various factors simultaneously along with the extraction of more information through minimum experimental runs, for example, a process having 8 variables each with 3 levels, would require 6561 i.e; 3^8 experimental runs. But by implementing Taguchi approach to this, it would require only 18 experimental runs to get the most optimal result or less than 0.3% of 6561 runs which come to be 19.683. Moreover, this method of DOE is very simple but powerful tool that can be applicable in almost all engineering fields.

5 Conclusions

This research paper presents the implementation of Taguchi method for designing a robust horizontal-axis wind turbine. Designing and simulation were done using Q-blade software. A Design of Experiment method namely Taguchi approach with L-9 orthogonal array mapping was utilized for studying the effect and influence of individual parameters like Reynolds number, aerofoil type, angle of attack, and Mach number on the aerodynamic performance of a wind turbine. Both single and multi-response Taguchi approaches are utilized in the present work.

From the wind turbine designing and simulation software the results obtained are: The maximum lift coefficient obtained is 0.9491 in an experiment run 8 for an input Mach number of 0.0146 when NACA4712 aerofoil was kept at 6 degrees angle of attack at Re of 50000 and on the other hand, the minimum drag coefficient value obtained was 0.02601 for an experiment run 7, for the NACA4712 aerofoil which was placed at 4-degree angle of attack when the input Mach number was 0.0087 with 100000 Re. The inferences are drawn from the obtained signal/noise response for various aerodynamic parameters of wind turbine are:

a) For the coefficient of lift the most and least influenced parameters are Mach number and angle of attack respectively, whereas Reynolds number and aerofoil type are the second and third most influenced variables respectively,
b) Similarly, for drag coefficient, Mach number and Reynolds number are the most and the least influenced parameters, and
c) Aerofoil type followed by Mach number is the prime influenced parameter, whereas the angle of attack is the least one for the power coefficient.

By considering the plot for main effects, the major influencing individual parameters that affect the wind turbine performance are NACA 4712 Aerofoil at (L3), input Mach number of 0.0146 at (L2), and Re of 100000 for all the three coefficients of lift, drag and power, whereas the AOA of 2 degrees is for both drag and power coefficient respectively. And for lift coefficient, the most influenced AOA is 6 degrees.

Funding: The authors did not receive support from any organization for the submitted work.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Authors Contributions: VK and RNS had the idea for this analysis and to optimize the results with Taguchi approach. RNS has supervised the research work. NIHR and PBK supported the research as an expert. All authors critically revised and edited the text and results, and finally approved the manuscript.

References

[1] Aguilar, C. H., López, F. S., & Pacheco, F. A. D. (2022). Sustainable Development Goals index: An analysis (2000-2022). *Transdisciplinary Journal of Engineering and Science*, 13, 111–128. https://doi.org/10.22545/2022/00213.

[2] Rao, S. S. (2015). Robust design of horizontal axis wind turbines using Taguchi method. *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*, 6B-2015, 1–9. https://doi.org/10.1115/IMECE201552093

[3] Kaushik, V., & Shankar, R. N. (2021). Review of Experimental Approaches for the Analysis of Aerodynamic Performance of Vertical Axis Wind Turbines. In N. Gascoin & E. Balasubramanian (Eds.), *Innovative Design, Analysis and Development Practices in Aerospace and Automotive Engineering* (pp. 473–480). Springer Singapore.

[4] Kackar, R. N. (1989). Off-Line Quality Control, Parameter Design, and the Taguchi Method. *Quality Control, Robust Design, and the Taguchi Method,* 51–76. https://doi.org/10.1007/978-1-4684-1472-1_4.

[5] Ku, K. J., Rao, S. S., & Chen, L. (1998). Taguchi-aided search method for design optimization of engineering systems. *Engineering Optimization,* 30(1), 1–23. https://doi.org/10.1080/03052159808941235.

[6] Chiang, K.-T. (2005). Optimization of the design parameters of Parallel-Plain Fin heat sink module cooling phenomenon based on the Taguchi method.*International Communications in Heat and Mass Transfer,* 32(9), 1193–1201. https://doi.org/10.1016/j.icheatmasstransfer.2005.05.015.

[7] Hu, Y., & Rao, S. S. (2011). Robust Design of Horizontal Axis Wind Turbines Using Taguchi Method. *Journal of Mechanical Design,* 133(11). https://doi.org/10.1115/1.4004989.

[8] Emre Koç, Onur Günel, T. Y. (2016). Mini-Scaled Horizontal Axis Wind Turbine Analysis By Qblade and Cfd.*International Journal of Energy Applications and Technologies,* 3(2), 87–92. https://doi.org/https://dergipark.org.tr/en/pub/ijeat/issue/28204/299500.

[9] Roy, R. K. (2010). *A Primer on the Taguchi Method.* Society of Manufacturing Engineers (SME), USA

[10] Khanjanpour, M. H., & Javadi, A. A. (2021). Optimization of a Horizontal Axis Tidal (HAT) turbine for powering a Reverse Osmosis (RO) desalination system using Computational Fluid Dynamics (CFD) and Taguchi method. *Energy Conversion and Management,* 231, 113833. https://doi.org/10.1016/j.enconman.2021.113833.

[11] Hwas, A. M., Lect, P. D., & Hatab, A. M. (2020). *Effects of Design Parameters of Wind Turbine on Airfoil Coefficients Using Grey-Based Taguchi Method.* 7(12), 13103–13109.

[12] Dhamotharan, V., Meena, R., Jadhav, P., Ramu, P., & Prakash, K. A. (2015). Robust Design of Savonius Wind Turbine. In *Renewable Energy in the Service of Mankind,* Vol I (Vol. 1, Issue September, pp. 913–923). Springer International Publishing. https://doi.org/10.1007/978-3-319-17777-9_82.

[13] Qasemi, K., & Azadani, L. N. (2020). Optimization of the power output of a vertical axis wind turbine augmented with a flat plate deflector.*Energy,* 202, 117745. https://doi.org/10.1016/j.energy.2020.117745.

[14] Kriswanto, Romadlon, F., Al-Janan, D. H., Aryadi, W., Naryanto, R. F., Anis, S., Sukoco, I., & Jamari. (2022). 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,* 94(1), 138–151. https://doi.org/10.37934/arfmts.94.1.138151.

[15] Suresh, A., & Rajakumar, S. (2019). Design of small horizontal axis wind turbine for low wind speed rural applications. *Materials Today: Proceedings,* 23(July 2019), 16–22. https://doi.org/10.1016/j.matpr.2019.06.008.

[16] Altmimi, A. I., Alaskari, M., Abdullah, O. I., Alhamadani, A., & Sherza, J. S. (2021). Design and optimization of vertical axis wind turbines using qblade. *Applied System Innovation,* 4(4), 1–11. https://doi.org/10.3390/asi4040074.

[17] D. Marten, J. Wendler, G. Pechlivanoglou, C.N. Nayeri, C. O. P. (2013). QBLADE: an open source tool for design and simulation of horizontal and vertical axis wind turbines. *International Journal of Emerging Technology and Advanced Engineering,* 3(3), 264–269.

[18] D. Marten, J. Wendler, G. Pechlivanoglou, C.N. Nayeri, C. O. P. (2013). QBLADE: an open source tool for design and simulation of horizontal and vertical axis wind turbines.*International Journal of Emerging Technology and Advanced Engineering,* 3(3), 264–269.

[19] Kriswanto, Romadlon, F., Al-Janan, D. H., Aryadi, W., Naryanto, R. F., Anis, S., Sukoco, I., & Jamari. (2022). 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,* 94(1), 138–151. https://doi.org/10.37934/arfmts.94.1.138151.

[20] Alaskari, M., Abdullah, O., & Majeed, M. H. (2019). Analysis of Wind Turbine Using QBlade Software. *IOP Conference Series: Materials Science and Engineering,* 518(3). https://doi.org/10.1088/1757-899X/518/3/032020.

[21] Nabil, T., Dawood, M. K., & ... (2018). Design and Implementation of the Rotor Blades of Small Horizontal Axis Wind Turbine. *Journal of Renewable Energy and Environment,* 5(2), 41–51.

[22] Husaru, D. E., B rsănescu, P. D., & Zahariea, D. (2019). Effect of yaw angle on the global performances of Horizontal Axis Wind Turbine - QBlade simulation.*IOP Conference Series: Materials Science and Engineering,* 595(1). https://doi.org/10.1088/1757-899X/595/1/012047.

[23] Susilo, B. D., Jatisukamto, G., & Kustanto, M. N. (2019). Characteristic Analysis of Horizontal Axis Wind Turbine Using Airfoil NACA 4712. *Journal of Mechanical Engineering Science and Technology,* 3(2), 96–108. https://doi.org/10.17977/um016v3i22019p096.

[24] Mahmuddin, F., Klara, S., Sitepu, H., & Hariyanto, S. (2017). Airfoil Lift and Drag Extrapolation with Viterna and Montgomerie Methods. *Energy Procedia,* 105, 811–816. https://doi.org/10.1016/j.egypro.2017.03.394.

[25] Battisti, L., Benini, E., Brighenti, A., Dell'Anna, S., & Raciti Castelli, M. (2018). Small wind turbine effectiveness in the urban environment. *Renewable Energy,* 129, 102–113. https://doi.org/10.1016/j.renene.2018.05.062.

[26] Spera, D.A. (2009). *Wind Turbine Technology: Fundamental Concepts in Wind Turbine Engineering, Second Edition* (David A. Spera (ed.); second edi). ASME Press. https://doi.org/10.1115/1.802601.

[27] Tarng, Y. S., Juang, S. C., & Chang, C. H. (2002). The use of grey-based Taguchi methods to determine submerged arc welding process parameters in hardfacing.*Journal of Materials Processing Technology,* 128(1–3), 1–6. https://doi.org/10.1016/S0924-0136(01)01261-4.

About the Authors

Mr. Vishal Kaushik is a Ph.D. Scholar in the Department of Aeronautical Engineering at VelTech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India. He is currently working as an Assistant Professor in Department of Aeronautical Engineering, PCE Nagpur with an experience of nearly 7 years. He has received his B.E. degree in Aeronautical Engineering from Nagpur University in 2013 and M.Tech Degree in Aerospace Engineering from JNTU University, Hyderabad, in 2016, respectively. He has published 15 research articles in various International Journals/Conferences and has 6 professional bodies' memberships. ORCID ID: 0000-0001-9007-5636.

Dr. R. Naren Shankar is currently working as an Associate Professor (Research) in Department of Aeronautical Engineering at VelTech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India. He has received Ph.D. in Gas Dynamics from MIT Campus Anna University, Chennai, India. He is having 13.5 years of experience. He has He has completed two funded projects of NSTL-DRDO and Preethi Kitchen Appliances Pvt. Ltd and working on funded projects from SERB-TARE and VEL TECH SEED FUND. He has published 20 research papers in high impact factor Journals indexed in Scopus and SCI. He has also filed 3 patents and is having research collaboration with 5 organizations. Also, he is a book editor of “Aspects and Applications of Incompressible and Compressible Aerodynamics”, IGI Global. He is an Associate member of Aeronautical Society of India (AM7400). Also he is a reviewer of International Journal of Turbojet and Journal of Aerospace (Institute of Mech Engg. Part- G). His main area of interest is in High Speed Jet Flows, Shock waves, Computational analysis of high speed jets, Wind turbine Aerodynamics. ORCID ID: 0000-0002-3363-4478.

Dr. N. I. Haroon Rashid is currently working as an Associate Professor in Department of Aeronautical Engineering at B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai, India. Prior, he has worked as HoD, Department of Aeronautical Engineering, Mohamed Sathak Engineering College, Kilakarai, Tamil Nadu, India. He has received Ph.D. in Aerospace Engineering from Anna University, Chennai, India. He is having nearly 24 years of experience in Academics. He has published several research papers in high indexed International/National Journals. He has also worked as a reviewer for Journal of Mechanical Science and Technology, Seoul. His main areas of interest are Aerodynamics, Aircraft General Engineering & Maintenance Practices, Airframe Maintenance and Repair, Wind Engineering etc. ORCID ID: 0000-0002-0444-2880.

Dr. P. B. Khope is currently working as HoD of Aeronautical Engineering Department, PCE Nagpur. He has received his Ph.D. in Mechanical Engineering from Nagpur University in 2014. He is having nearly 30 years of experience in Academics. He has published over 35 research papers in International/National Journals/Conferences. In addition to this, he has filed 6 patents and is an author of 2 books. He is having 10 professional bodies’ memberships. ORCID ID: 0000-0002-5491-476X.