Aerodynamic Performance Sensitivity Analysis of Blade Design for a 100 kW HAWT

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Abstract

Wind energy is gaining ever increasing popularity among renewable energy sources. In some European countries installed wind turbine capacity has reached over 20 % of the total power generation capacity. This paper examines aerodynamic performance sensitivity of wind turbine blades for main design variables. The sensitivity analysis has been conducted on a sample 100 kW three-bladed horizontal axis wind turbine (HAWT). Taguchi robust design techniques and orthogonal arrays have been used to perform experimental optimization using five main parameters: airfoil NACA profile, root chord length, tip chord length, root radius and chord profile distribution along the blade's length. The airfoil profiles and their aerodynamic data are taken from the NACA airfoil database for which experimental lift and drag coefficient data are available. The airfoils for the studied blades have the same profile from root to tip. Three sets of analyses have been performed according to three different base load wind speeds. The sensitivity results have been presented for the optimal tip speed ratio values

Keywords: Blade design, Wind turbine, Aerodynamic performance, Sensitivity analysis

1. Introduction

Worldwide, total wind energy installed capacity has exceeded 200 GW by the end of 2010. Moreover, its fast growth ensures that the wind power will be an important part of electricity generation in the close future. The inevitable increase in fossil fuel prices will also make wind energy more competitive. The competitiveness of wind energy conversion systems (WECS) depends on price and efficiency trade off. To able to capture this renewable and clean energy efficiently the entire WECS have to be optimized taking the wind conditions into consideration. In this context, turbine blade design needs to be optimized in order to maximize the aerodynamic performance. In 1920's, Betz formulated the basic analysis for the limiting case for HAWT efficiency valued at 16/27 (around 59.3 %) of maximum power factor. Blades should be designed so that lifting forces are maximized while drag and tip losses are minimized. Airfoil selection is one of the most difficult topics in wind blade design process. Performance characteristics and chord specifications used for airplane profiles are not necessarily applicable for wind turbine blades. However, both the aviation and wind turbine profiles benefit from long laminar flow and relative low drag coefficients. Experiments with commercial wind turbines during 1980s explored most of the useful operational characteristics of NACA 44XX, 63XXX, 230XX and NASA LS series profiles. Some researchers attempted to optimize blade thickness with innovative profiles for large wind turbines [1]. Many have done aerodynamic performance tests for specific commercial wind turbines. Some tried to perform optimization of specific airfoil series using genetic algorithms [2]. Today, wind turbine blade design has not been yet a subject where information is abundant in the literature. It appears that no sensitivity analysis has been performed using a DOE approach.

In this work, a performance sensitivity analysis of main blade design parameters has been applied to a 100 kW HAWT. Calculations of the aerodynamic performance have been performed by a commercially available code based on BEM (Blade Element Momentum) theory. The methodology of the analysis is driven by a DOE (Design of Experiments) approach where three different analysis matrices have been studied and compared for different base load wind speeds. The preliminary findings do not point to a global optimum to achieve the highest aerodynamic performance. However, the obtained performance trends for main parameters may guide blade designers. The results are particularly relevant for small wind turbines as analyses have been conducted for a 100 kW turbine. For smaller or larger turbines, some parameters like airfoils may change.

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This paper is structured as follows; first the context of the work and the assumptions have been given. Then main design variables have been identified and assigned to orthogonal Taguchi arrays. The analyses have been conducted for each design combination as simulated experiments. Then, performance results for each case have been evaluated. The effect of changing each parameter on aerodynamic performance have been extracted to identify sensitive factors. Finally, a discussion of future work have been presented.

2. Blade Performance Analysis

2.1. Blade Geometry

In this work a three-bladed horizontal axis wind turbine has been studied. It has been assumed that the blades are rigidly mounted on the turbine's hub. The study considers main geometric parameters for blade to include hub radius, root chord length, tip chord length, chord profile distribution along the blade and base NACA profile for the airfoils. As 100 kW output power is considered, blade radius or length is fixed depending on the wind speed. The optimum angle of attack is calculated and used for maximum aerodynamic efficiency.

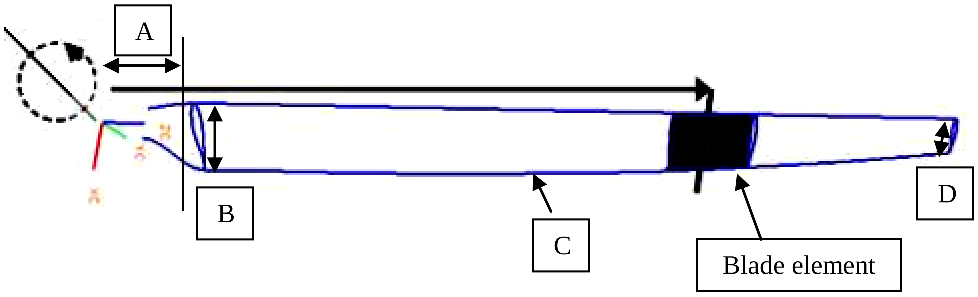
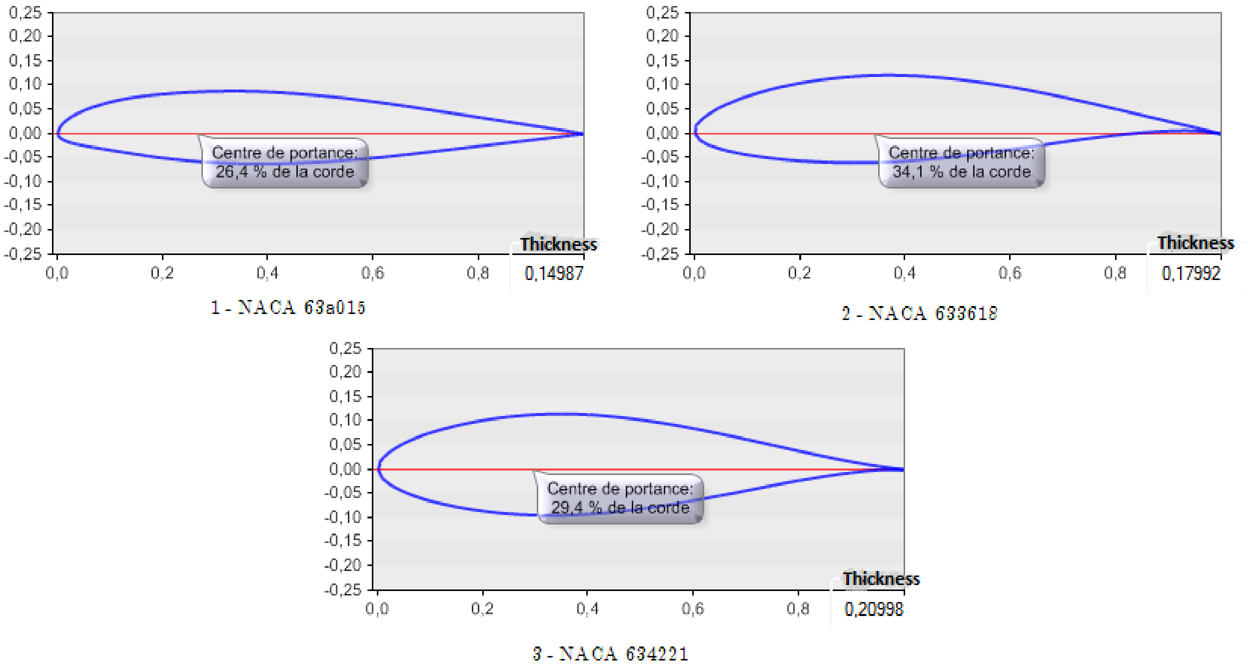


Figure 1. Blade parameter: hub radius (A), root chord (B), chord profile (C) and tip chord (D)



1 - NACA 63a015

2 - NACA 633618

3 - NACA 634221

Figure 2. The three different NACA profiles selected for simulations (NACA 63xxx: a015, 3618 and 4221)

2.2. Design of Experiments (DOE)

In order to study effects of various blade design parameters on aerodynamic efficiency, a systematic design of experiments approach has been implemented. Five main parameters have been considered for study; hub radius, chord length at blade root section, chord length at blade tip section, chord profile distribution along the blade, and type of NACA 63xxx airfoil profile. For an unbiased search through the design space, an orthogonal array has been used. In order to capture any nonlinear relationships that may exist between the selected parameters and blade aero-performance, each parameter has been analyzed at 3 different levels. Table 1 presents the studied design variables and selected test levels.

Table 1. Design parameters and their test level values for DOE. R denotes turbine blade radius

Parameter	A	B	C	D	E
Level	Root chord % of R	Tip chord % of R	Chord Profile Distribution	NACA Profile 63xxx Series	Hub radius % of R
1	10	4	concave	63a015	6
2	13	6	Linear	633618	8
3	16	8	Convex	634221	10

The parameter level values are expressed in percent of the turbine blade radius for chord length at blade root, chord length at blade tip and hub radius. Chord profile distribution from root to tip is defined to follow either linear or convex or concave variations. The degree of convexity or concavity is set constant for all of the simulations.

The three different NACA 63xxx profiles that have been selected for study are represented in Figure 2. Each profile has different thickness. The thickness is equal to 15% of the chord for the NACA 63a015, 18% for the NACA 633618, and 21% of the chord for the NACA 634221 profile. NACA 63xxx series has been chosen, because it has proven its performance for light and medium wind conditions in the past. This NACA profile series is also commonly been used for wind turbines in the power range below 500 kW [3]. The main disadvantage of this series is that it is fairly sensitive to surface dirt. More recent studies on wind turbine airfoil performance have focused on another series like S series [4]. Once a NACA airfoil profile is selected, the same profile is used along the blade's length. As Reynold numbers greatly vary from blade root to tip, it may be beneficial to change airfoil profile along the blade's length as well. However, this constitutes a separate study, and considered beyond the scope of this work.

Table 2. The L18 Taguchi array adopted in this blade performance study

Design Combination	A Root chord	B Tip chord	C Chord Distribution	D NACA 63xxx	E Hub radius
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	2	1	1	2	2
5	2	2	2	3	3
6	2	3	3	1	1
7	3	1	2	1	3
8	3	2	3	2	1
9	3	3	1	3	2
10	1	1	3	3	2
11	1	2	1	1	3
12	1	3	2	2	1
13	2	1	2	3	1
14	2	2	3	1	2
15	2	3	1	2	3
16	3	1	3	2	3
17	3	2	1	3	1
18	3	3	2	1	2

When 5 design parameters need to be studied at 3 different levels each, a typical full resolution DOE requires $3^5 = 243$ design combinations to be analyzed for a complete scan through entire design space. In order to limit the number of analyses Taguchi orthogonal arrays have been utilized. Taguchi techniques allow same or similar DOE resolution with much less number of runs via trading high level interaction effects with actual first order parameter effects that are the subject of real interest. However, there is a risk of interaction effects blending with the main parameter effects while the number of combinations is reduced. Therefore, a special 3 level Taguchi L18 array [5] has been used. L18 array is a special design that distributes interaction effects to each parameter column. This eliminates any risk of unexpected interaction effects to distort/bias judgment on parameter effects, and allows for study of individual parameter effects. Table 2 presents the main L18 test array with suggested design combinations.

2.3. Analysis Conditions

Typically, wind turbines limited to ideal power coefficient of slightly below 0.6 which is called the Betz limit. However, operating turbines fall below this performance, some operating as low as 0.45 power coefficient. In fact, approximately 20-25% of the energy is lost due to aerodynamic, gearbox, generator and control losses etc. Taking these possible losses into account, the turbine diameter is selected so that power produced at blades gives around 130 kW at the Betz limit. Considering approximately 30 kW total losses this design results in 100-110 kW range wind turbine. In this work, three different wind turbine optimization studies have been conducted for three different wind velocities; 8 m/s, 10 m/s and 12 m/s. In order to keep overall turbine power in 100 kW range, turbine blade radius values are calculated as 15, 10.7 and 8.2 m which correspond respectively to 8, 10 and 12 m/s of selected wind speeds.

Once the geometric configuration is defined, the code calculates the efficiency for various rotational speed values. As rotor speed changes with blade diameter and operating wind speed. The optimal rotor speed is identified to maximize efficiency for each wind speed. The performance results are shown only for the optimal rotational speed values.

As BEM theory is used for calculations, there are discrete number of elements along the blade length. The preliminary analyses indicated that 10 elements across the blades yields sufficient resolution to compare different design combinations' effectiveness providing a compromise with the run time cost with increasing element numbers.

The following assumptions have been employed in the analyses:

- Constant wind speed without turbulence
- Wind is in the direction of the horizontal axis of the turbine
- Blades are rigid, and any losses implied by blade bending are not taken into account.

3. Results

The analyses have been conducted according to the experimental design per L18 orthogonal array. The results are presented in Table 3 for each design combination and for three different wind speeds. The results show that for some design combinations the calculated efficiency is slightly above 59 % indicating some level of performance over estimate. This limited over estimation is attributed to the discrete nature of the analysis, and can be further improved at the expense of increased run time.

The presented results in Table 3 indicate that average blade efficiency for V=8 m/s is 56.88, for V=10 m/s is 56.98, V=12 m/s is 56.9. The grand average of the data (for an average turbine efficiency) is 56.92 for various wind speeds.

3.1. Calculation of Main Effects

Once DOE is completed with simulated experiments (i.e. BEM analyses in our case) for each design combination, the data can be analyzed. Effect of each design parameter on overall blade performance is extracted from the data. Blade performance for different parameter levels are determined. For example, when parameter A (Root Chord Length) is at level 1, following from Table 3 blade performance values are determined as follow. First, checking from Table 1 parameter A is at level 1 (A1) in design combinations 1, 2, 3 and 10, 11, 12. Following from Table 3 the corresponding blade performance values for 8 m/s wind speed are 56.43, 57.3, 54.7 and 57.58, 54.57, 55.9.

Table 3. Calculated efficiency values for each design combination for three different wind speeds.

Design Combination	Efficiency for V= 8 m/s (R=15 m)	Efficiency for V= 10 m/s (R=10.2 m)	Efficiency for V= 12 m/s (R=8.2 m)
1	56.43	56.73	56.4
2	57.3	57.45	57.1
3	54.7	54.65	55.02
4	58.82	**59.19**	**59.44**
5	57.3	57.18	57.26
6	55.6	55.5	55.6
7	57.12	57.25	57.29
8	58.35	58.33	58.47
9	56.5	56.61	56.96
10	57.58	57.77	57.52
11	54.57	55.12	55.21
12	55.9	55.7	55.83
13	57.7	58.5	58.42
14	56.2	56.39	55.7
15	56.4	56.73	55.17
16	**58.9**	58.68	58.8
17	58.1	57.95	58.16
18	56.3	55.94	56.03

The effect of Root Chord Length (parameter A) when it is at level 1 is calculated as

$$\text{Blade efficiency when A is at level 1} = \frac{\sum \text{Performance values when A is at level 1}}{\text{Number of design combinations when A is at level 1}}$$

that is,

$$A1 = \frac{56.43 + 57.3 + 54.7 + 57.58 + 54.57 + 55.9}{6} = 56.16$$

Similarly, blade performance when Root Chord Length (parameter A) is at level 2 and 3 are calculated as

$$A2 = \frac{58.82 + 57.3 + 55.6 + 57.7 + 56.2 + 56.4}{6} = 57.0$$

$$A3 = \frac{57.12 + 58.35 + 56.54 + 58.9 + 58.1 + 56.3}{6} = 57.54$$

The effects or other parameters at different levels are also calculated in similar manner. The entire process is repeated for each wind speed case. It should be noted that each design parameter is analyzed/tested at each level exactly 6 times. The equal number of data points for each parameter and each level is ensured by the orthogonal array. This provides unbiased evaluation and comparison of parameter effects. Once individual parameter effects are calculated, impact of each parameter on overall efficiency can be plotted. These main effect plots have been presented for each parameter for three different wind speeds in Figure 3.

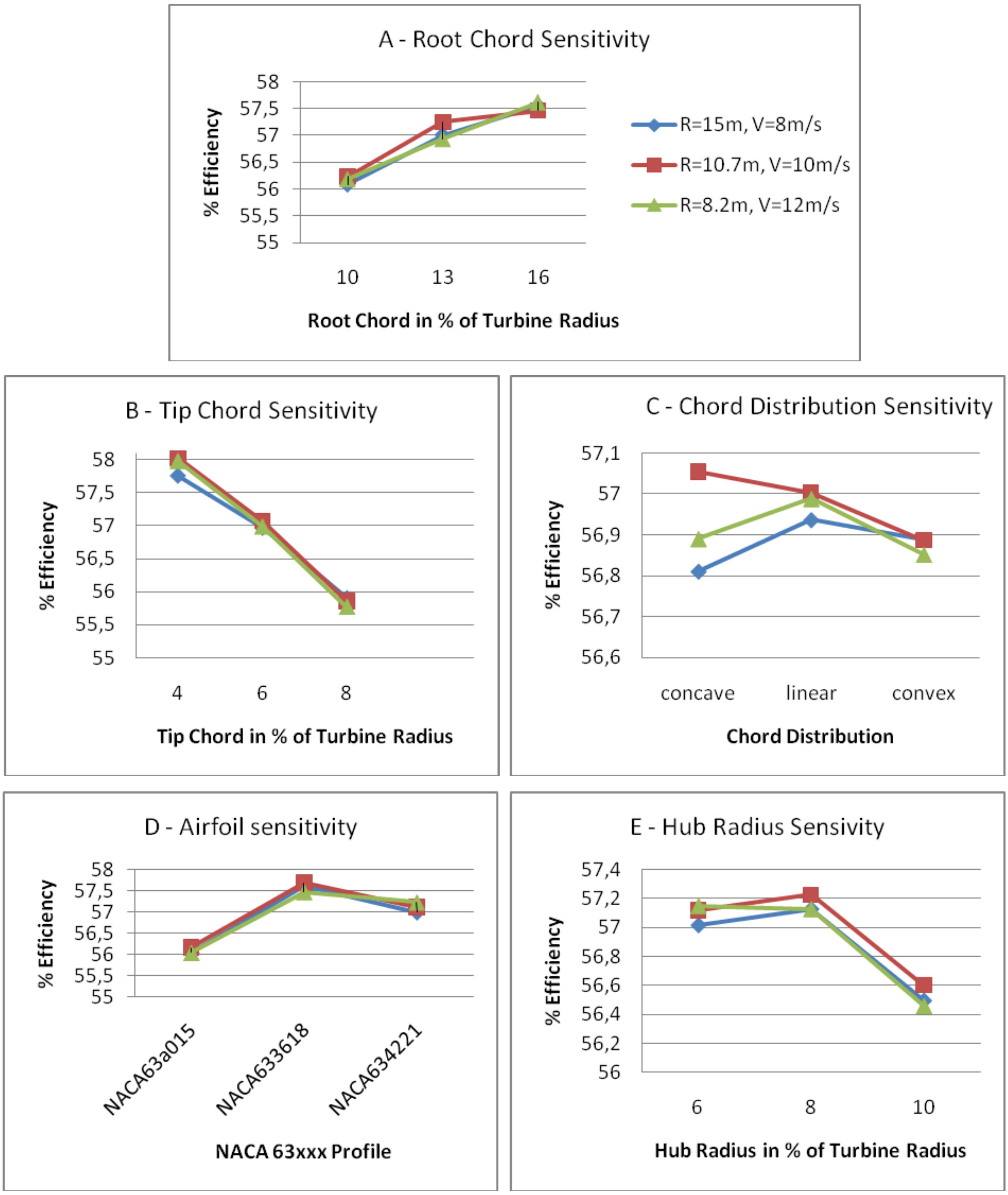


Figure 3. Main effect charts for variation of efficiency with changing design parameter values

3.2. Sensitivity

The main affect plots that are presented in Figure 3 also indicate the sensitivity of blade efficiency for the design parameters. In order to better illustrate performance sensitivity of the parameters DOE results are processed one step further to generate response tables. Response table values are generated by taking the difference between the best and the worst performance for each factor. This provides magnitude of the differential effect that each parameter has on the output, i.e. efficiency. Table 4 presents the response table for all 5 design parameters studied. The sensitivity results have been ranked, and further plotted in Figure 4.

Table 4. Response table illustrating overall main effect sensitivity for each variable (V=8 m/s)

	A Root Chord	B Tip Chord	C Chord Distribution	D NACA 63xxx	E Hub Radius
Highest Value	57,54	57,92	56,99	57,59	57,17
Lowest Value	56,16	55,84	56,85	56,08	56,52
Main effect = Δ	**1,38**	**2,08**	**0,14**	**1,51**	**0,65**

Figure 4 indicates that blade efficiency is most sensitive to Parameter B which is the chord length at blade tip. Blade performance is inversely proportional to the chord length at the tip as efficiency increases sharply with decreasing tip chord length. Blade efficiency is also very sensitive to the selection of airfoil NACA profile. The third most sensitive parameter is the chord length at blade root section. The hub radius has somewhat lesser effect than previously mentioned three parameters. Although a previous study [7] indicated that an elliptic distribution reduces tip losses and so gives better performance, the results of the DOE have indicated that changing chord profile distribution has minimal impact on aerodynamic efficiency. Therefore, careful selection of airfoil NACA profile and chord lengths would yield much better efficiency. It should be also noted that the conducted DOE results are valid within the design space considered.

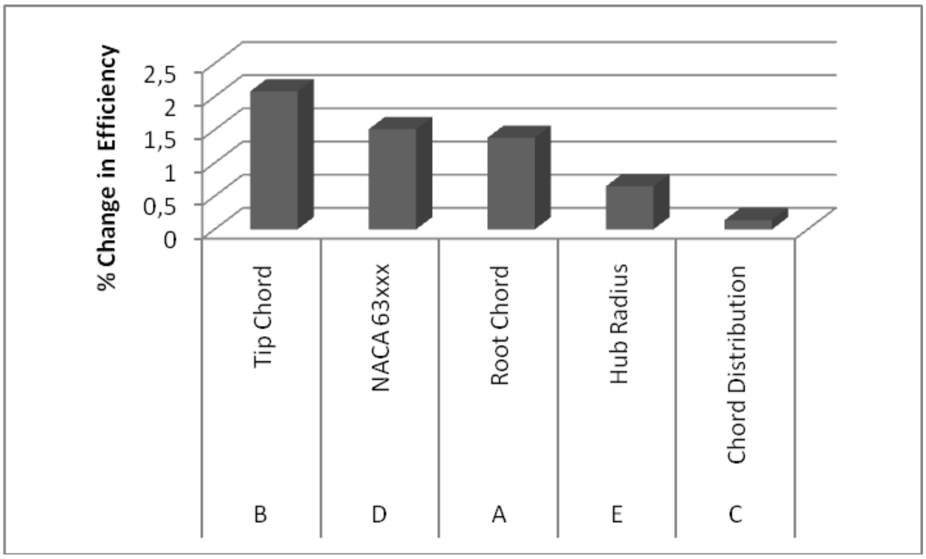


Figure 4. Performance Sensitivity Chart

3.3. Design Optimization

The response table (Table 4) and performance sensitivity chart (Figure 4) are used to determine the factors that dominate the blade performance. The dominating factors are called as the “strong factors” and the rest are labeled as the “weak factors”. According to the results illustrated in Table 4 and Figure 4, strong factors have been determined as the root and tip chords and the airfoil NACA profile. The strongest factor is the tip chord.

For a design optimization with an objective to maximize blade efficiency, individual parameter sensitivity charts in Figure 4 have been studied. The chart for parameter A indicates that blade performance is maximized when Root Chord parameter is at level 3, i.e. A3. Similarly, the chart for parameter B indicates maximum efficiency is achieved when Tip Chord is at level 1, i.e. B1. When optimum level for each parameter is studied, the following parameter combinations are indicated as the best designs to maximize efficiency:

A3 B1 C2 D2 E2 for V=8 m/s
A3 B1 C1 D2 E2 for V=10 m/s
A3 B1 C2 D2 E1 for V=12 m/s.

As in most DOE studies none of these combinations exists in the main L18 array that has been studied. Since the experimental optimization indicates that these are the best designs, these combinations has been run to confirm optimum performance. The results of the confirmation runs have been presented in Table 5.

Table 5. Confirmation analysis results for optimal design conditions

	Average Efficiency from L18 Array	**Efficiency of the Best Combination in L18 Array**	**Confirmation Combination Efficiency**	**Δ Efficiency Improvement over Average**
V=8 m/s	56,88	58,9	**59,41**	**+ 2,53**
V=10 m/s	56,98	59,19	**59,62**	**+2,64**
V=12 m/s	56,91	59,44	**59,25**	**+2,34**

The results show that the indicated optimum design combinations in fact give the maximum efficiency for both V=8 m/s and V=10 m/s cases. For the highest wind speed, the confirmation run resulted in slightly lower performance than L18 run #4. This is an indication for the presence of strong interactions between some of the design parameters.

As data in Figure 3 (first chart) clearly indicates, blade efficiency is maximum when factor A is at level 3. However, design combination #4 in L18 array yields better performance due to possible strong interactions. It should be noted that parameter interactions have not been taken into account in this paper as L18 Taguchi array distributes interaction effects equally in every data column. There may be interactions between some parameters especially between the root and tip chord. Although there is not much performance difference between Taguchi indicated optimum and combination #4, a different array should be used to include interactions in the optimization process. However, at a minimum an L27 array needs to be used in order to include interactions in a 3 level experiment. This would increase the required run time by 33 %.

Based on the confirmation run results the final set of optimum design combinations have been determined as follows.

for V=8 m/s	A3 B1 C2 D2 E2	as indicated by confirmation run
for V=10 m/s	A3 B1 C1 D2 E2	as indicated by confirmation run
for V=12 m/s	A2 B1 C1 D2 E2	combination #4 of L18 Array

Details of optimum design parameters are given in Table 6. As indicated earlier, its is expected that calculated efficiency values would approach to Betz limit as BEM resolution is further increased. Overall, DOE based Taguchi robust design optimization process has been successfull applied to yield 2.5 % efficiency increase over average design.

Table 6. Confirmation analysis results for optimal design conditions

	Root Chord	Tip Chord	Chord Distribution	NACA 63xxx	Hub Radius	**Max Efficiency**
V=8 m/s	16	4	linear	3618	8	**59,41**
V=10 m/s	16	4	concave	3618	8	**59,62**
V=12 m/s	13	4	concave	3618	8	**59,44**

4. Conclusion

A comprehensive DOE, sensitivity analysis and optimization study have been conducted on a 100 kW horizontal axis 3-blade wind turbine using Taguchi Robust Design process. Chord lengths at blade tip and blade root sections, airfoil NACA airfoil type, hub radius and chord profile distribution along the blade are selected as 5 main parameters for study. In order to capture any nonlinear parameter effects a 3 level L18 orthogonal array has been used. Three set of analyses have been conducted to capture blade performance at three different wind velocities (8, 10 and 12 m/s). Based on the DOE analysis results a set of optimum design configurations has been selected. A separate group of confirmation runs have been conducted to validate maximum performance of the indicated best design configurations. Taguchi robust design DOE techniques have been successfully applied to wind turbine blade optimization to achieve more than 2.5% efficiency increase over average data. The results also indicate the following:

- Aerodynamic performance of a fixed 3-blade horizontal axis wind turbine is dominated by the choice of airfoil NACA profile, tip and root chord length of the blades.
- For a 100 kW turbine NACA 633618 series provide the best efficiency.
- Decreasing tip chord length increases performance
- Increasing root chord length increases performance
- Efficiency is also affected by hub diameter to some degree. Effect of hub diameter becomes more visible when hub diameter exceeds 8% of the overall blades diameter. Efficiency starts decreasing, if hub diameter is further increased.
- Performance effects are nonlinear for hub radius variation and chord profile distribution. Therefore, a 3-level DOE is required for these parameters.
- Analysis slightly overestimates performance indicating number of BEM elements per blade should be further increased.
- There are some strong interactions between main design parameters. If an orthogonal array larger than L18 is utilized, effect of interactions can be studied and used for optimization.

Further work to include lower and higher power wind turbines will be useful in order to determine if the indicated trends are common for all sizes, or vary by size. There are some studies considering variation of airfoil profile along the blade's length where the thickness to chord ratio decreases [8]. Similarly, extending this work with variable airfoil NACA profiles along the blade length would also reveal if further improvements are possible. Finally, eventual introduction of blade flexibility and twisting into the analysis will be the next study, and provide better insight to blade performance trends.

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