Development of small domestic wind turbine tower and blades systems: An optimization approach

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Abstract

Building up a clean energy future has been recognized as one of the great challenges of our time. To deal with this challenge, a comprehensive new energy plan was developed, which demands some percent of our electricity to be utilized from renewable resources. An assured use of electricity from renewable resources, such as wind, along with the latest deployment of large turbines that grow to great heights, makes achieving the most efficient and safe designs of the structures that support them incredibly. In attaining this goal, the present work inquires to understand how optimization concepts and suitable optimization capabilities can be involved in wind turbine blades and tower design. Furthermore, this work spread out on the work of previous researchers to study how considering the tower as an integral system, where imperfect rigid tower support conditions are in place, which impacts the optimal design. Exclusively, the originated optimization problems are solved with and without consideration of effect of wind velocity, wind direction, deflections, ensuing from the foundation's rotational and horizontal stiffness, on natural frequency calculations. The general methodology used to transliterate the design of domestic wind turbine blades and towers into an optimization problem embrace information on design requirements and parameter values. The objective function is to consider the sum of the tower and blades material and fabrication cost. Reducing the frequency drastically reduces material usage. Prominent conclusion from this work comprises of optimization concepts, optimization capabilities and analysis that may be evolved from reasonable conceptual level designs.

Keywords: *Renewable resources optimization problem, Domestic wind turbine towers and blade*

1. Introduction

Drastic demand of electricity in current generation is of key importance due to the sort of mankind lead. Power production by conventional strategies has taken its toll on environment and the earth has been polluted to degrees beyond imagination. The need of the hour is an alternative and green energy from natural recourses. Technology serves human need and luxuries but still it does not show any impact to our planet. With growing awareness on our needs and priorities one alternative source to draw power would be the wind.

The first use of a large windmill to generate electricity was a system built in Cleveland, Ohio, in 1888 by Charles F. Brush [1-3]. The Brush machine was a post mill with a multiple-bladed "picket-fence" rotor 17 meters in diameter, incorporating a large tail hinged to turn the rotor out of the wind. It was the first windmill to featuring a step-up gearbox (with a ratio of 50:1) in order to turn a direct current generator at its required operational speed. Despite its virtual successful operation for 20 years, the Brush windmill exploded the limitations of the low-speed, high-solidity rotor for electricity production applications.

The 17-meter rotor pales produces 12kilowatts whereas a comparably- sized, modern, lift-type rotor produces 70-100kilowatts. European Tower mills utilised the first electrical output wind machine incorporating the aerodynamic design principles (low-solidity, four-bladed rotors incorporating primitive airfoil shapes).By the end of World War I, usage of 25kilowatt electrical output machines had stretched throughout Denmark, but cheaper and larger fossil-fuel steam plants soon vanishes the mill operators off the business.

Modified propellers utilized by the first small electrical-output wind turbines drive direct current generators. Initially lighting farms and charging batteries used to power crystal radio sets were installed.

Two types of structural systems: lattice and tubular, are frequently employed for wind turbines. Pros and cons vary for each system. Rolling steel plates forms tubular systems and flanged bolted connections join them. Owing to their aesthetically pleasing look and predictable dynamic and fatigue properties, industries prefer them. By increased tower height, the thickness of the tubular sections enlarges resulting in increased manufacturing cost. Further, transport was challengeable and step up these heavy steel sections in the field. In contrast, L-shaped steel profiles through bolding form lattice systems. Effective resistance of the system is obtained by the truss action and larger base dimensions thriving to a lighter structural design. Additionally, lattice topology reduces the wind loads. Manufacturing cost diminishes on standard profiles and bolted connections usage, rather than tubular sections. Eventually, construction costs are saved in much by the lattice tower transportation to the field in multiple small pieces. Material usage gets reduced by using lattice towers.

1.1. Objective of this research

- Power generation at reduced cost in remote areas
- At 1KW DC power gets generated
- Ongoing research involvement possible by upgradeable parts.
- Space to install both a commercial and hand-made generator.
- Easy installing with Hinged 30 foot tower.
- Reduced power loss from generation to transmission.
- Based on the optimization in wind turbine blades and tower.

2. Design requirements

The various design parameters considered for both blade and tower for proper designing are:

2.1 Blade design requirements

Significant design parameters in blade design are the chord length, radius of blade and angle of twist of blade. The optimal chord length based upon the number of turbine blades B, their radius R, and the tip speed ratio λ, which is the linear speed of the blade tips divided by the wind speed. The expressions for chord length and tip-speed ratio are given below,

$$C = 16\frac{\pi R\left(R/r\right)\big)}{9\lambda^2 B} \quad (1)$$

$$\lambda = \frac{R\omega}{V_o} \quad (2)$$

Power developed in the wind turbine blade is calculated by using the following general equations,

Lift Force $F_L = 0.5\rho V_r^2 C_L$ (3)

Drag Force $F_D = 0.5\rho V_r^2 C_D$ (4)

Resultant Wind Velocity $V_r = \left(V_0^2 + V^2\right)^{\frac{1}{2}}$ (5)

Resultant Force $F_R = \left(F_L^2 + F_D^2\right)^{\frac{1}{2}}$ (6)

Wind Power = $0.5\rho A V_0^3$ (7)

Actual Power Generated = $0.5\rho A V_0^3 C_p$ (8)

Where C_P is the coefficient of performance which will not exceed 0.59 which is the betz limit, C_L, C_D are the coefficient of lift and drag respectively. Varying the blade radius or the wind velocity the wind power can be increased. Increasing the blade radius increases the power by square and increasing the wind velocity increases the power by cubic.

2.2 Tower design requirements

The various design requirements in lattice tower design are:

i. Cross sectional area of truss bars

Influenced by transportation limitations the outer diameter of tubular towers cannot exceed 4.5m but the cross section area can be varied to reduce the frequency and deflection is reduced in lattice design.

ii. Tower top deflection

The maximum deflection at the tower top is limited to 1 and ¼ percent of the tower height to avoid excessive motion. The maximum rotation at the tower top is limited to5º in order to avoid interference between the turbine blade and the tower.

iii. Design for minimum vibration

The most cost-effective solutions for a successfully wind turbine design is acquired by minimization of the overall vibration level. It fosters other important design goals, such as long fatigue life, high stability and low noise level. Vibration decreases with reduced tower frequency. Material usage gets reduced by reducing the frequency of the wind turbine system.

3. Analysis

3.1 Wind turbine blade analysis

The problem focused is the aerodynamic design of a small horizontal-axis domestic wind turbine blade. To understand the comparison, a turbine with established geometry and performance data was found. Table.1 gives the geometry, operational data and the material properties of the existing blade.

Table 1: Existing blade information

Diameter [m]	1.3
No. of Blades	3
Tip Chord [m]	0.045
Root Chord [m]	0.15
Angle of Twist (degree)	10
Wind Speed, V_0 [m/s]	12
Tip Speed Ratio	3
Power Output [W]	680

Table 2: Kevlar fiber reinforced epoxy resin properties

Properties	Kevlar
Density g/cc	1.38
Tensile strength, MPa	3620
Tensile modulus, GPa	127

The Existing blade is made of Kevlar fiber reinforced epoxy resin and the blade is shown in Fig.1.

Figure 1. Existing blade

CATIA was used in modeling turbine's geometry and then improved performance is obtained after further modification. For similar comparisons the rotational rate, wind speed, and number of blades were kept constant. Due to the requirement of analysis at constant rotational rate, the constant-speed turbines were only preferred. Recently constant-speed turbines were only used much so that this was not an unreasonable assumption.

An intentional design improvement was preferred for an increased output power through wind turbine. A simple equation represents the output power of the turbine,

Power = (Torque). (Rotational Rate)

The rotational rate was kept constant the coefficient of lift and drag was calculated by the 3D analysis tool ANSYS. On the account of ideas originated on how to improve wind turbine geometry, research was performed.

Taking six control points located from the root to the tip, the optimal chord distribution as defined in Equation (1) was calculated; this distribution is given in Table 3.

Table 3: Chord and twist distribution across the blade

Blade Radius (m)	Chord (1) (m)	Chord (2) (m)	Twist (1) (degree)	Twist (2) (degree)
0	0.07	0.05	0	0
0.04	0.98	0.90	0	0
0.2	0.108	0.10	0	0
0.44	0.133	0.12	3	2
0.56	0.155	0.14	12	7
0.68	0.190	0.17	21	12

The final wind turbine blade designed using CATIA is shown below in Fig. 2.

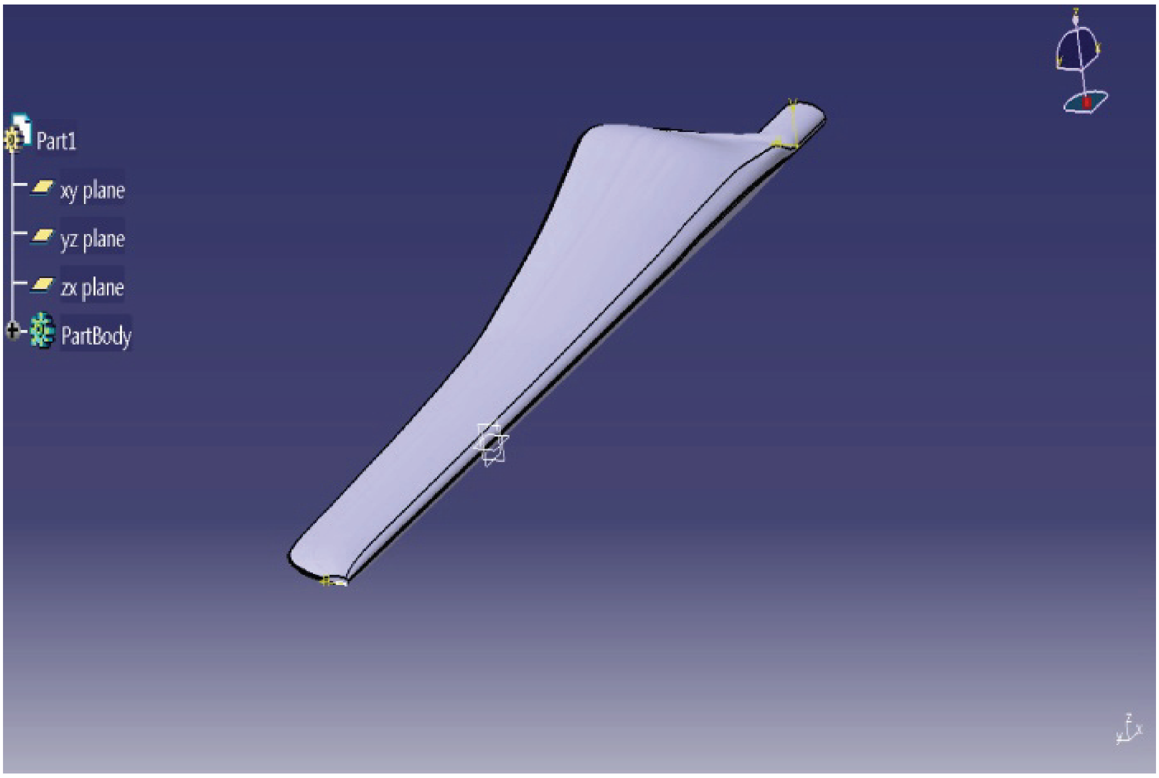

Figure 2. Final blade design

Wind velocity, specified as the load in analysis is assumed to be 12m/s and the new blade length is 0.82m. The coefficient of not only lift and drag but also the power is calculated for various angles of attack. Meshing is done during analysis and defined the boundary conditions as Inlet, outlet and wind velocity is given in wind wall inlet given and in outlet atmospheric pressure is given provided with a stationary wall. Tip speed ratio of the blade is kept constant.

CATIA is utilized for creating various blade designs by varying the radius, chord length and ANSYS is used to analyze twist for various angles of attack and on varying the angle of attack the blade produces a power of 1KW. Depending on the relative wind, twisting the blade along the length favors the angle of attack to be optimized. In addition, on changing the angle of attack, the lift was maximized; increasing the rotational moment and ultimately the power output the maximum power generated by various blades is shown in Table 4.

Table 4: Design results

Blade	Power (watts)	Angle of attack
Existing blade	650	7
Chord1 (21°)	860	14
Chord1 (12°)	1030	10
Chord2 (12°)	855	10
Chord2 (21°)	730	13

From my analysis performed, the blade with a chord length of 0.19m and radius of 0.82m is competent to produce 1KW power when 10° angle of attack of the blade is provided. The tip speed ratio of the turbine is 3. The C_p value of the optimum blade to produce 1KW power is 0.45 .The power generated by the optimum blade at various angles of attack is shown in Fig.4.

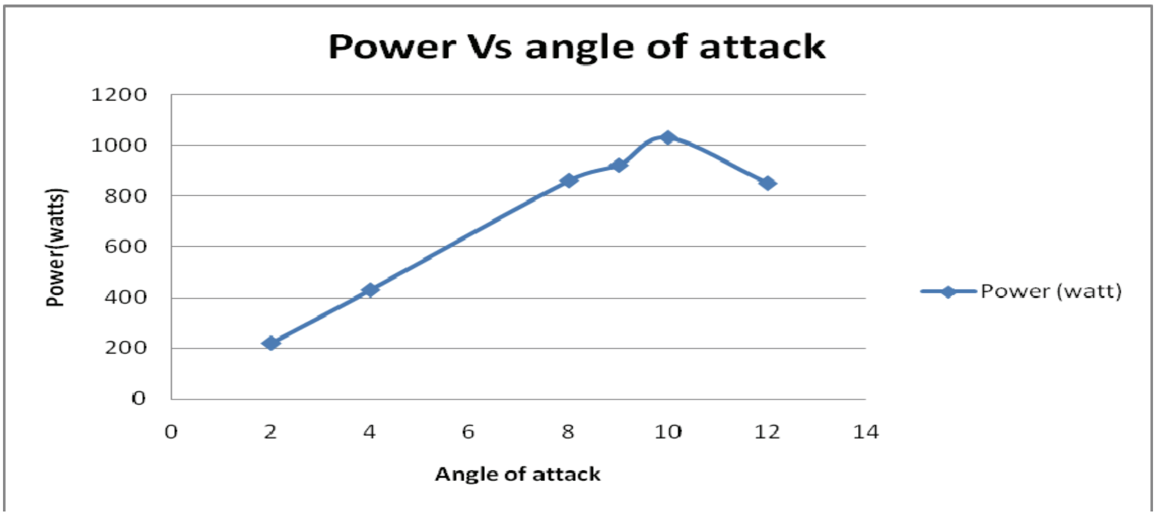

Figure 3. Comparison of power and angle of attack for the finalized blade

From the above graph it is understood that till a particular angle of attack, the lift value of the blade increases and then dwindle resulting in drag increase and at any particular angle of attack stall will occur that is no lift will be generated.

3.2 Tower analysis

Assumed loading on tower is described under this section. The tower loading comprises of loads from the turbine, wind, self-weight and internal fixtures. Turbine load at the tower top, acquired from a structural load document is shared by the turbine manufacturer. In tower analysis, the moment and the drag force are provided as the load. On varying the tower height, tower base diameter, tower top diameter, arrangement of truss bars, cross sectional area of truss bars, the deflection and the frequency is calculated.

In tower design the L bars made of steel are used as the trusses. The properties of steel are given in Table 5.

Table 5: Steel properties

Density	7800 kg/m
Young modulus of elasticity	200 GPa
Shear modulus	77000 MPa
Poisson ratio	0.3

Exclusive designs are obtained by varying the bottom and top diameter, height of the tower and the number of links. Top surface of the tower is applied with 295N of turbine load. Effective analysis of the created design is performed and their relative frequency is calculated. The various design parameters are shown in Table 6.

Table 6: Lattice tower design parameters and their levels

Design parameter	Unit	Symbol	Level 1	Level 2	Level 3
Base length	m	A	1.1	1	0.9
Top length	m	B	0.4	0.3	0.2
Tower height	m	C	7.5	7	6.5
Number of sections		D	12	11	10

ANSYS has been used to design tower and Top deflection, frequency are calculated through static and model analysis. Fig. 4 shows the tower design with deflection.

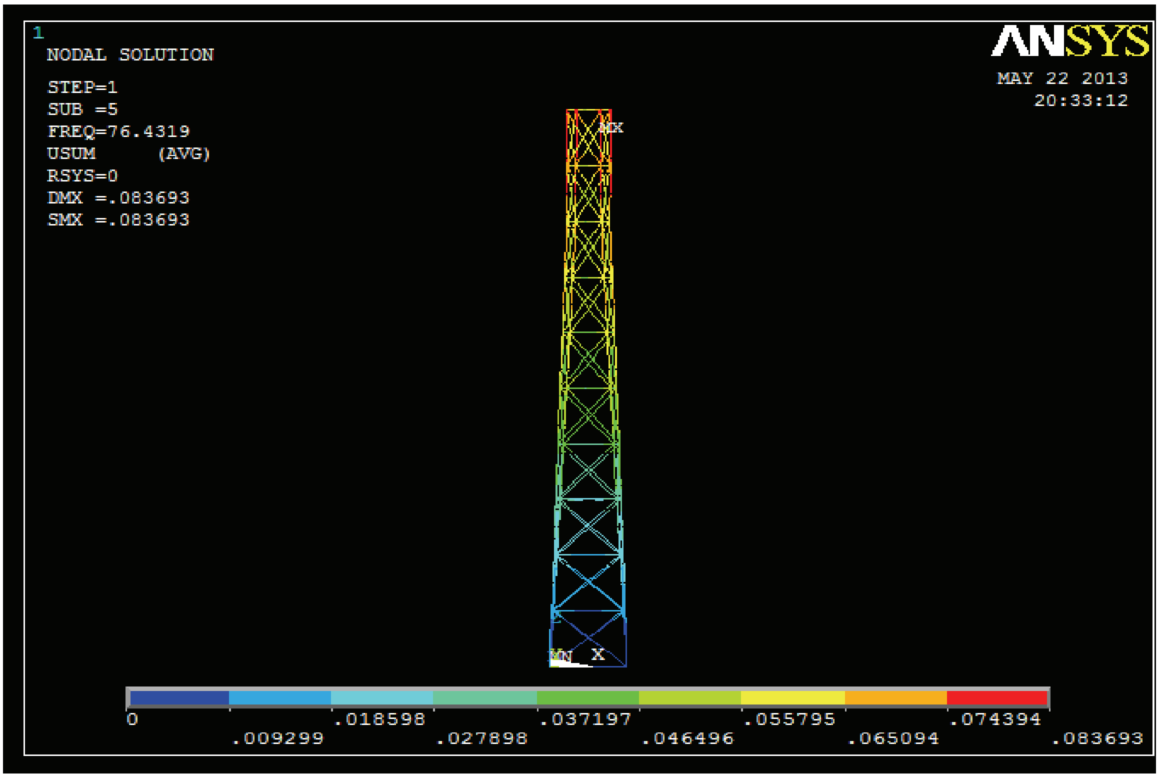

Figure 4. Tower design (displacement)

The main objective of our work is to lessen the vibrations and annoying sound from the tower. For better result the frequency has to be optimized since with wide range of designs and dimensions, the frequency varies and it would also satisfies to be the developed finalized design.

4. Taguchi method for the optimization of lattice towers

On the account of manipulation of large number of variables with a small number of experiments, Taguchi approach, a statistical technique is used which handles a set of orthogonal arrays from design of experiments theory. The number of experimental runs to be performed is reduced predominantly by the orthogonal arrays. Furthermore, over the entire Experimental region evolved by the control factors and their settings, valid conclusions pinched off from small scale experimental runs. [18]. Earlier discovered noticeable Orthogonal arrays are not unique to Taguchi.

In this study the Taguchi approach of experimental design methodology was engaged, with the orthogonal array design involved to analyze the effects of the design parameters, such as base length, top length, tower height and number of sections. The main operational parameters and levels depend upon the experiments conducted and from previously reported studies .The four selected design parameters at three levels for this experiment is shown in Table3. A four level three factor, L_9 (3^3) nine experiments were preferred to conduct the experimental runs is shown in Table 7.

Table 7: Orthogonal array L_9 (3^3) of the experimental runs

Experimental runs	Process parameters and their levels				Frequency
	A	B	C	D	
1	1	1	1	1	83.377
2	2	1	2	3	86.6014
3	3	3	2	1	101.243
4	1	2	2	2	96.0474
5	3	1	3	2	90.2574
6	2	3	1	2	93.3245
7	2	2	3	1	100.311
8	1	3	3	3	103.319
9	3	2	1	3	82.0808

Under nine sets of experimental conditions, the analysis on frequency of lattice towers is shown in Table 7. The experimental results depict that experiment run 8 obtain a maximum frequency of 103.319, among the nine set of experimental runs with optimal parameters. Experimental run 9 expresses the lowest frequency of lattice tower, at 82.0808. However, it is likely that selecting the optimal conditions using the Taguchi method for the design of an experiment would not be an ideal way. Taguchi method uses the signal-to-noise (S/N) ratio, exhibiting log functions of desired output, and serve to optimization as objective functions, helping in data analysis and prediction of optimum results. Variations in characteristics are observed for different S/N ratios, of which there are generally three types, i.e. smaller-the-better, larger-the-better and nominal-the-better. In this carried out work, frequency is to be reduced hence smaller the better is chosen for S/N ratio calculations The loss function of the smaller-the-better, the Mean Squared Deviations (MSD) of each experiment can be articulated by the following equation:

$$MSD = \frac{1}{n}\sum_{i=1}^{n} fi^2 \qquad (9)$$

Where n is the number of replications of each experimental run and f_i the frequency of the lattice towers. Then, the S/N ratio was evaluated using the following equation:

$$\frac{S}{N} ratio = -10\log(MSD) \qquad (10)$$

The S/N ratios for the nine sets of experiments are also shown in Table 8. Experiment run no. 9 signifies the lowest frequency of lattice towers added with highest S/N ratio. Likewise the relationship between frequency and the S/N ratio was also observed in other experiments.

Table 8: Frequency and S/N Ratio

Experimental Run	%Yield of FAME	S/N Ratio
1.	83.377	-38.42
2.	86.6014	-38.75
3.	101.243	-40.11
4.	96.0474	-39.65
5.	90.2574	-39.11
6.	93.3245	-39.39
7.	100.311	-40.03
8.	103.319	-40.28
9.	82.0808	-38.28

Table 9: Mean S/N ratiofor the design parameters

Level	Parameter A	Parameter B	Parameter C	Parameter D
1	-39.45	-38.76	-38.70	-39.52
2	-39.39	-39.32	-39.50	-39.39
3	-39.17	-39.93	-39.81	-39.11

A. Analysis of variance (ANOVA)

The intention of the ANOVA is to examine which Design parameter has appreciably affected the frequency of the lattice tower. The results of the ANOVA are shown in Table 10.

Table 10: Results of ANOVA

Symbol	Degrees Freedom	Sum of Squares	Mean Square	% Contribution
A	2	14.947	7.474	3.004
B	2	236.348	118.174	47.50
C	2	218.085	109.043	43.83
D	2	28.164	14.082	5.66
Error	16	0.001	0.00006	0.006
Total	24	497.545		

From the ANOVA results, tower top length percentage contribution is likely to be weighed against with other parameters are shown if Figure 5. Tower frequency is influenced by the major parameters namely tower top length and height of the tower. The parameters in which the frequency will be minimum is obtained from the S/N ratio graph which is shown in Figure 6.

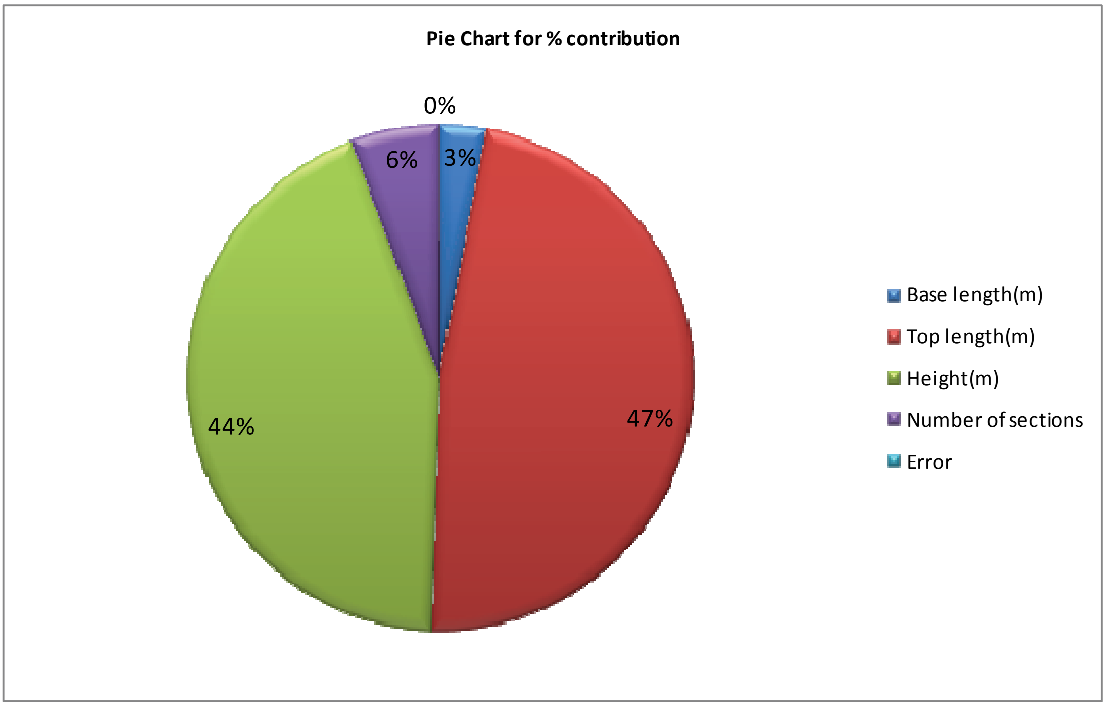

Figure 5. Percentage contribution of design parameters

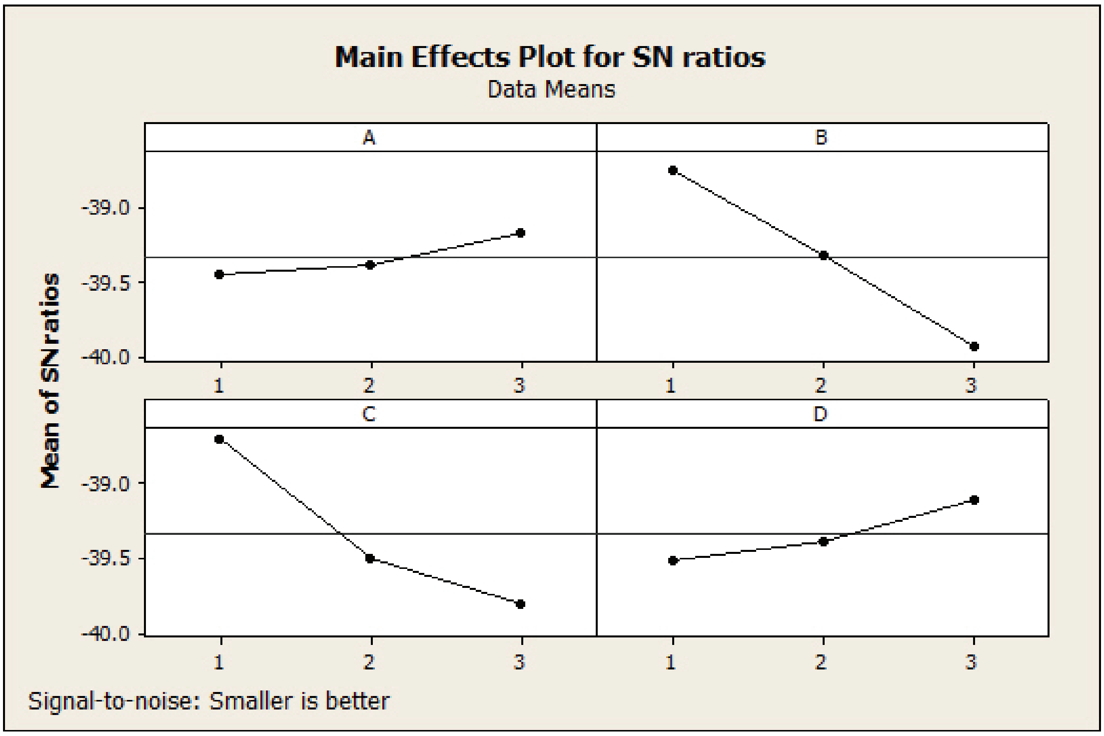

Figure 6. S/N Ratio graph for design parameters

Analysis was performed for reducing tower frequency, in line to validate the optimal conditions derived from this study. The analysis is accomplished with optimum Design parameters, i.e. Tower Base length at level 3, tower top length at level 1, tower height at level 1and number of sections at level 3 to find out the tower optimum frequency as 76.4313Hz. Minimum result is achieved from the optimum design parameters comparatively to the result acquired from the experimental run 9 (82.0808Hz). This result illustrates the noteworthy enhancement of the process performance with the optimized parameters for the design of lattice towers.

5. Conclusion

In this carried out work, the small domestic wind turbine blades are designed which is competent of producing 1KW power is preferred as the optimal blade design. The blade with chord length of 0.19m and length of 0.82m and twist angle of 12 degrees is chosen to be the optimum blade design. The tower is analyzed for various dimensions and its relative frequency was calculated. This paper presents a first stage of a complete analysis of the full-height lattice tower concept. Supplementary work will spotlight the enhancement of the tower by optimization approach, the extension of several parameter studies and the evaluation of suitability of the concept in future domestic installations. The Taguchi method was employed to design experimental trials, with an ANOVA implemented to analyze the relative importance of each experimental parameter on the frequency of the tower. The frequency of the tower has much impact by high range of contribution of tower top length. The frequency obtained with the optimal experimental parameters was smaller than that obtained from experimental run no. 9, which results lowest frequency from the experimental runs. The experiment conducted under the optimized conditions illustrates a meaningful superior process performance. The Taguchi method provides a logical and efficient mathematical approach to calculate and optimize the design parameters for the fabrication of lattice towers. Finally, the current accurate optimization analysis saves much of the computer time essential by the finite element method.

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