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Effect of Blade Root Dimensions on Physical and Mechanical Characteristics of a Small Wind Turbine Blade

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Abstract- Small wind turbines have the potential to act as a complementary clean energy source to solar PV, especially during nighttime. However, the generally less attractive payback of small scale wind turbines has restrained its widespread application, and one way to improve their cost effectiveness is by improving the efficiency, for which blade design is a crucial factor. The blade design is a complex but interesting process and still demands continuous research at various stages. This research paper presents the effect of flat rectangular root dimensions on blade mass, stresses, strain and deformation for a fixed pitch, horizontal axis small wind turbine blade of 2.5 m length. For the three considered variables root length, width and thickness, four levels of dimensions are selected for each which yields 64 blade models. A total of 16 blade models with different root dimensions are finalized through the Taguchi method and investigated using finite element analysis. The effects of these variables on five characteristics, namely: blade mass, stresses in the blade main body, stresses in the blade root and connecting portion, deformation and strain are studied. Analysis of variance is carried out for all these independent and dependent variables. The results indicate that the thickness, length and width are the most, intermediate and least influencing variables respectively, and cause significant changes in these five characteristics of the blade.

Keywords – ANOVA, finite element analysis, small wind turbine, wind turbine, wind turbine blade.

1. Introduction

Small horizontal axis wind turbines are classified as fixed pitch or variable pitch wind turbines based on the state of the blade during its operation [1, 2]. In fixed pitch wind turbines, as shown in Figure 1, the blade roots having a rectangular cross-section are rigidly connected to the mounting flange and do not rotate about its longitudinal axis to control the rotational speed of the rotor according to wind speed and direction [3-5]. On the other hand, in the variable pitch wind turbine, as shown in Figure 2, the blade having circular cross-sectional root and is also moving about its longitudinal axis to control the rotor speed [2,6]. The construction of the variable pitch wind turbine is complex, and further leads to higher maintenance during operations. The cost of a variable pitched wind turbine is significantly higher than that of the fixed pitch wind turbine. Hence, most of the small wind turbine designers prefer the fixed pitch blades to reduce system complexity, and the need for maintenance and cost, which take greater prominence when targeting small scale applications in the commercial sector as well as the residential sector [2, 7-9].

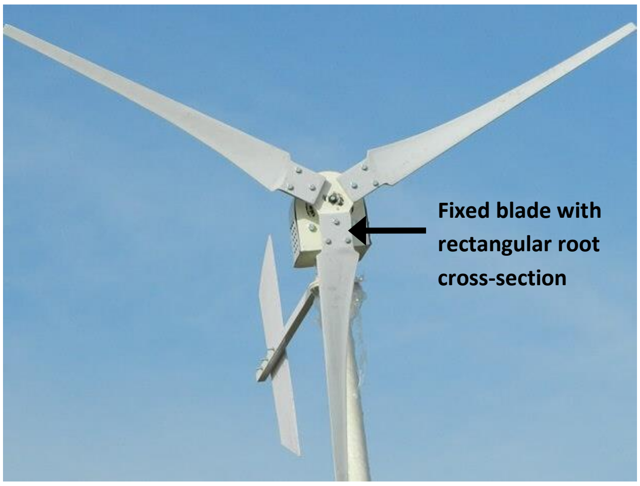

Fig. 1. Fixed pitch wind turbine [Author]

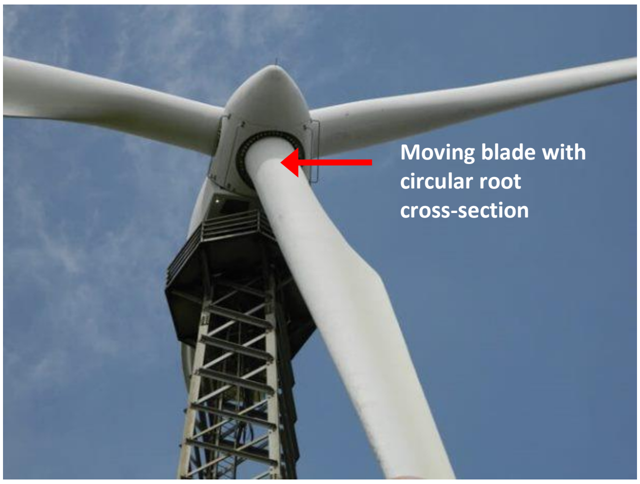

Fig. 2. Variable pitch wind turbine [Author]

Compared to large wind turbines, the research and deployment of small wind turbines are negligible because of many reasons [10-14]. There is significant scope for research and development of various components and overall small wind turbine systems. The research on small wind turbine blades is mainly focused on the development of new airfoils and the determination of the aerodynamic performance of the wind turbine blade and/or rotors [15-18]. Based on a literature search, it was observed that only a few researchers have attempted the task of static and fatigue strength design of small wind turbine blades [19-22]. Specifically, the design of airfoil chord length and thickness based on the aerodynamic and strength performance is studied by a few researchers.

Root is an important portion of the small wind turbine blade. This root connects the blade and transfers all the power to the rotor shaft. The flat root with a rectangular cross-section is the most preferred design for the blade root because of its easy mounting as shown in Figure 1. The root of the blade should have sufficient strength to withstand continuously varying wind conditions and play an important role in the self-starting of the wind turbine. It has been further noted that the appropriate design of blade root dimensions and shape is still an area not researched and documented in the literature with a lack of sufficient research or guidelines. The authors have recognized this limitation and research gap. Authors have predicted that the blade root dimensions may cause a significant effect on the other characteristics of the blade. Hence, this research work is carried out on a small wind turbine blade of 2.5 m length to study the effect of blade root length, width and thickness on the various characteristics such as blade mass, flange mass, blade strength and deformation.

2. Methodology

This section describes the methodology used for the research work presented in this paper. Details of blade profile and base dimensions, of the three independent and five dependent variables are provided.

2.1. Small Wind Turbine Blade Specifications

A non-twisted small wind turbine blade of 2.5 m length is considered for the study. This blade is designed for a fixed pitch wind turbine having a rated power of 2 kW at 8.4 m/s wind speed. A newly developed thin airfoil with a maximum thickness of 8 % at 22 % of the chord length and maximum camber of 4.91 % at 50.8 % of the chord length is used for all cross sections. The maximum chord length was taken as 0.384 m at the first airfoil section and the minimum chord length was taken as 0.084 m at the blade tip. Figure 3. shows the various nomenclature used for blade dimensions. A blade comprises three lengths namely: root length (l), connecting portion length ($L_1 - l$) and main body length (L_2) as illustrated in Figure 3. The root width and root thickness are represented by w and t respectively. The total length of the blade ($L_1 + L_2$) is fixed as 2.5 m to match the swept area of the small wind turbine is investigated.

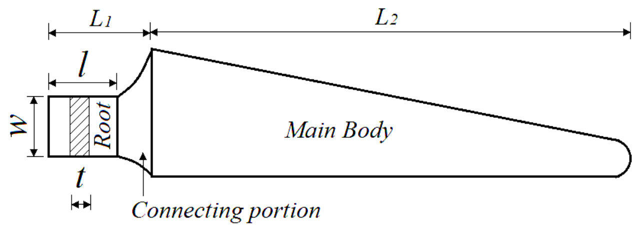

Fig. 3. Nomenclature of the blade dimensions

As stated above, the objective of this research is to study the effect of variations in the dimensional parameters (independent variables - root length, width and thickness) of the blade root on the physical (mass) and the mechanical (stress, strain and deflection) properties of the blade. Hence, for each dimensional variable, four levels are defined and their values are presented in Table 1. Since the length L_1 is kept fixed and the root length (l) is varied, the connecting portion length is also changed accordingly.

Table 1. Blade root dimensional variables

Blade root parameter		Dimensions (mm)
Root length (l)	:	150, 200, 250, 300
Root width (w)	:	150, 175, 200, 225

Root thickness (*t*)	:	15, 20, 25, 30

2.2. Affecting Characteristics of Blade

Change in root dimensions causes the change in the physical and mechanical characteristics of the blade. Five characteristics have been considered as the dependent variables in the study, namely: (1) blade mass, (2) stresses in the blade main body, (3) stresses in the blade root and connecting portion, (4) deformation and (5) strain. The blade and ultimately resulting rotor mass cause the change in rotational speed. Wind turbine blade with lower mass is always desirable. In most cases, it is expected to design parts with low induced stresses, less deformation and minimum weight. Hence, these characteristics are studied and discussed here. Additionally, the change in root dimension also affects other characteristics such as starting behaviour of the rotor, flange mass, rotor mass, cost of the blade, cost of flange and blade life which are not studied yet and hence not in the scope of this research paper.

2.3. Design of Experiments

This problem consists of three factors (variables) and four levels as shown in Table 1. A total of 64 (4^3) experiments are required to test all possible combinations for 3 factors and 4 levels. Hence, a Design of Experiments (DOE) is carried out using the Minitab software by applying the principle of Taguchi Orthogonal Arrays and a total of 16 combinations have been retained among 64 as shown in Table 2. Taguchi Orthogonal Array is one of the most accepted methods and in the selected 16 models using the same, each parameter is tested at least 4 times and provides reasonably acceptable results.

Table 2. Dimensions of the blade root considered for FEA

Blade Model	Root length (mm)	Root width (mm)	Root thickness (mm)
B_1	250	225	20
B_2	300	200	20
B_3	300	225	15
B_4	300	175	25
B_5	250	150	25
B_6	250	200	15
B_7	300	150	30
B_8	150	225	30
B_9	200	225	25
B_{10}	200	200	30
B_{11}	150	200	25
B_{12}	250	175	30
B_{13}	200	175	15
B_{14}	150	175	20
B_{15}	200	150	20
B_{16}	150	150	15

2.4. Determination of Characteristics Using ANSYS

Accordingly, a total of 16 blade models are prepared using Solidworks as per the root dimensions shown in Table 2. The overall length of all blades is kept fixed at 2.5 m and the chord length and thickness of all sections are taken the same in all blade models. The models are exported to ANSYS for further analysis. Glass fiber reinforced plastic [23] is selected as a blade material with a tensile strength of 250 MPa and a density of 1690 kg/m^3 [19]. By maintaining the appropriate and same mesh quality and boundary conditions for all blades, strength analysis is carried at the pressure equivalent to the survival wind speed of 55 m/s. The results extracted from ANSYS Mechanical R18.1 are presented in section 3.

2.5. Calculation of the Influencing Parameters

Analysis of variance (ANOVA) is a well accepted tool to study the effect of an individual independent variable on the output variables and is applied to different studies on wind turbines [24-26]. ANOVA test is used to study the effect of variations in the root dimensions (three independent variables) on the blade mass, stresses in the blade main body, stresses in the blade root, deformation and strain (five dependent variables).

3. Results

The structural finite element analysis (FEA) of all 16 models is carried out using ANSYS Mechanical R18.1. The sample FEA result images for blade model B_1 are shown in Figure 4. The result shows (a) stresses induced on the front surface, (b) stresses induced on back surface, (c) strain values on the front surface, (d) strain values on back surface and (e) blade deformation. The FEA results for the other blade models are summarized in Table 3. From the results, it is observed that the magnitudes of stresses induced in the blade body and blade root portions are differing significantly. Hence, these values are listed separately. The negligible variation in the stress magnitudes is observed on the front and back surfaces of the blades. Hence, only maximum stress in the main body surfaces from these two is considered for each blade.

Blade mass (*m*) is also changing significantly because of the changes in blade root dimensions and determined by considering Glass Fiber Reinforced Plastic as a blade material with a density of 1690 kg/m^3. The blade deformation (δ), maximum stresses in the main body (σ_{body}) and blade root and connecting portion (σ_{root}) obtained through the finite element analysis for all 16 models are added in Table 3.

The minimum and maximum values and the difference between them, obtained from the results of all blades are added to the table. From these values, it is clear that the blade root dimensions have a significant effect on the results and the next section provides a detailed analysis of the correlation between the independent and dependent variables.

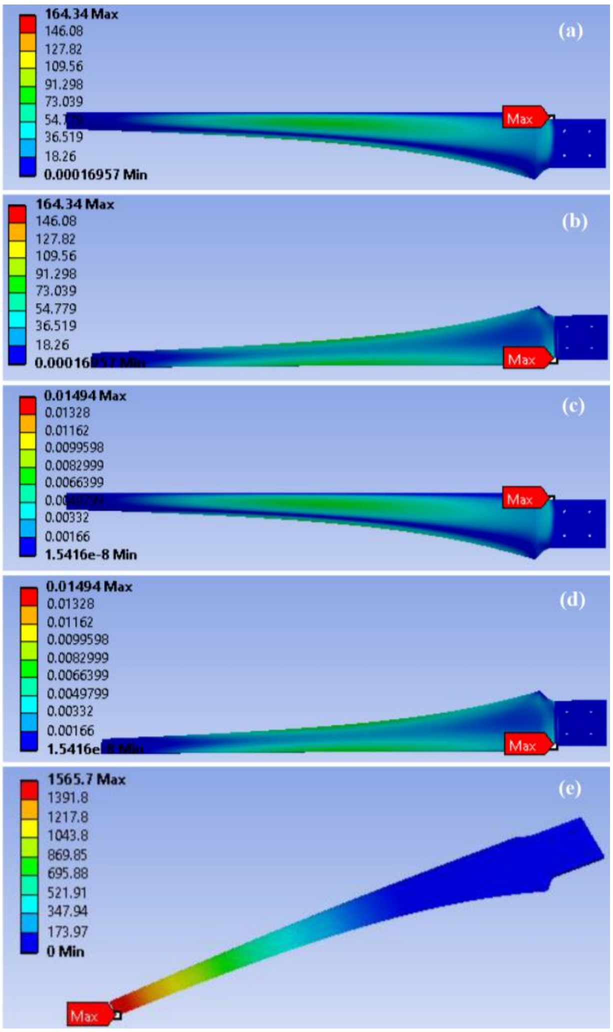

Fig. 4. Sample images of FEA for blade model B1

Table 3. FEA results for the 16 models

Blade Model	*L* (mm)	*w* (mm)	*t* (mm)	*m* (kg)	δ (mm)	σ_{body} (MPa)	σ_{root} (MPa)	ε (mm/mm)
B_1	250	225	20	7.762	1566	78.54	164.34	0.0149
B_2	300	200	20	7.486	1555	79.01	106.22	0.0097
B_3	300	225	15	7.136	1580	78.70	169.72	0.0154
B_4	300	175	25	7.696	1545	78.65	87.52	0.0080
B_5	250	150	25	7.382	1578	78.85	96.21	0.0087
B_6	250	200	15	7.014	1629	78.66	155.56	0.0141
B_7	300	150	30	7.777	1539	78.71	84.56	0.0077
B_8	150	225	30	8.647	1637	96.07	51.77	0.0087
B_9	200	225	25	8.257	1634	96.07	75.13	0.0088
B_{10}	200	200	30	8.433	1620	96.07	61.00	0.0087
B_{11}	150	200	25	8.020	1618	78.78	81.75	0.0077
B_{12}	250	175	30	8.128	1558	79.22	64.80	0.0078
B_{13}	200	175	15	6.934	1749	96.13	167.05	0.0152
B_{14}	150	175	20	7.366	1719	95.91	118.13	0.0108
B_{15}	200	150	20	7.110	1685	96.06	129.79	0.0118
B_{16}	150	150	15	6.858	1801	78.83	204.77	0.0187
Min	150	150	15	6.858	1539	78.54	51.77	0.0077
Max	300	225	30	8.647	1801	96.13	204.77	0.0187
Diff.	150	75	20	1.789	262	17.59	153.00	0.0110

4. Discussion

This section presents the effect of blade root dimensions on the blade mass, stresses in the blade main body, stresses in the blade root, deformation and strain on the basis of the ANOVA tests carried out using Minitab.

4.1 Effect on Blade Mass

The SN ratio obtained from ANOVA for blade mass is presented in Table 4. The results are plotted in Figure 5 which indicates that the root thickness is the most influencing parameter (Rank 1) and the root length is the least influencing parameter (Rank 3) as far as the blade mass is concerned. The blade mass is significantly increased with the increase in the root thickness.

Table 4. SN ratio for blade mass

Level	***l***	***w***	***t***
1	-17.72	-17.24	-16.88
2	-17.68	-17.52	-17.42
3	-17.57	-17.75	-17.88
4	-17.52	-17.99	-18.32
Delta	0.20	0.75	1.44
Rank	3	2	1

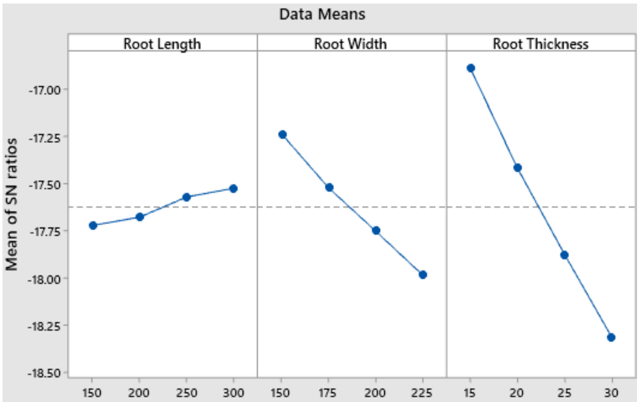

Fig. 5. The effect of root dimensions on the blade mass

4.2 Effect on Main Body Stresses

The root length was found to be the highest impacting parameter to cause stress variation in the main body of the blade as shown in Table 5. From Figure 6, it is observed that the root width and thickness have a considerably low impact on induced stresses in the blade body. The overall variation in magnitudes of stresses in the main body of 16 models are considerably low (17.59 Mpa) for all root lengths. The body stress magnitudes are reaching near to minimum (78 MPa) and maximum (96 MPa) for all varying lengths.

Table 5. SN ratio for main body stresses

Level	*l*	*w*	*t*
1	-38.79	-38.36	-38.36
2	-39.65	-38.80	-38.79
3	-37.93	-38.36	-38.36
4	-37.93	-38.78	-38.80
Delta	1.73	0.44	0.44
Rank	1	3	2

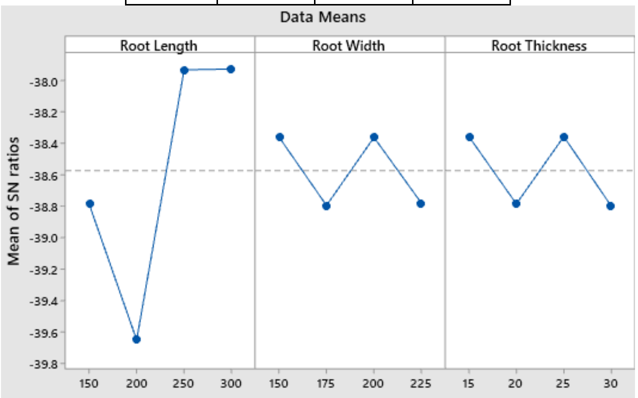

Fig. 6. The effect of root dimensions on main body stresses

4.3 Effect on Root and Connecting Portion Stresses

The ANOVA results obtained for stresses in the root and connecting portion are presented in Table 6 and plotted in Figure 7. From the profiles obtained, it was found that the root thickness has a more predominant effect than that of the length and width. As illustrated, the stresses induced in the root and connecting portion are significantly changed by the variation in root thickness.

Table 6. SN ratio for root and connecting portion stresses

Level	*l*	*w*	*t*
1	-40.05	-41.67	-44.78
2	-39.99	-40.24	-42.14
3	-41.01	-39.58	-38.57
4	-40.63	-40.18	-36.19
Delta	1.03	2.09	8.59
Rank	3	2	1

Fig. 7. The effect of root dimensions on root and connecting portion stresses

4.4 Effect on deformation

The SN ratios of deformation are shown in Table 7. These results are plotted in Figure 8 and here it was found that the change in root length is the most key parameter (Rank 1) with reduced length causing more deformation of the blade. Root thickness (Rank 2) was also found to be a significant parameter for the deformation, where deformation values decreased with increase in root thickness.

Table 7. SN ratio for deformation

Level	*l*	*w*	*t*
1	-64.57	-64.34	-64.54
2	-64.46	-64.30	-64.24
3	-63.99	-64.11	-64.04
4	-63.83	-64.10	-64.02
Delta	0.74	0.23	0.53
Rank	1	3	2

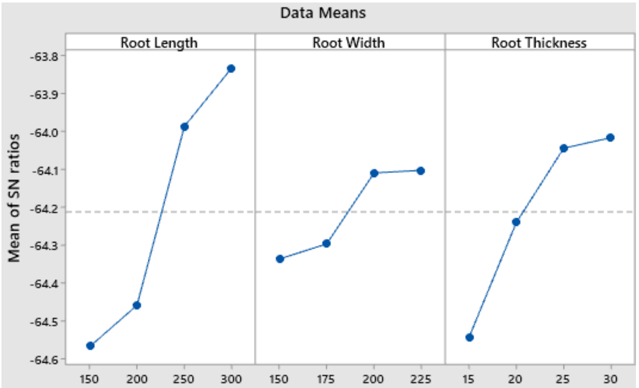

Fig. 8. The effect of root dimensions on deformation

4.5 Effect on Strain

The values of strain on the blade were found to change substantially due to changes in the root dimensions. The results of the effect of root dimensions on the strain values are presented in Table 8. The plot of these values shown in Figure 9 showing clearly the root thickness as the most influencing parameter (Rank 1). Length and width are comparatively less affecting parameters.

Table 8. SN ratio for strain

Level	*l*	*w*	*t*
1	39.34	39.14	36.04
2	39.31	39.96	38.68
3	39.21	40.19	41.63
4	40.20	38.77	41.72
Delta	1.00	1.43	5.68
Rank	3	2	1

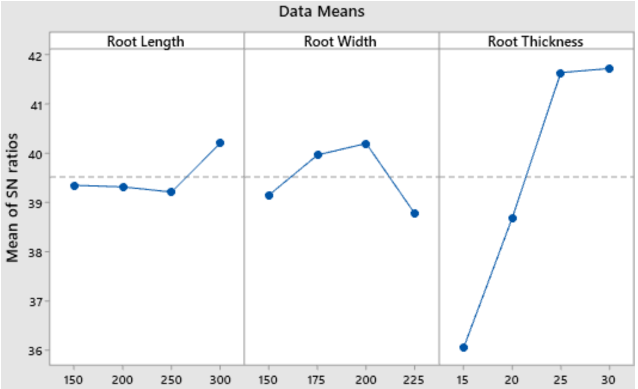

Fig. 9. The effect of root dimensions on strain

Table 9 shows the summary effect of independent variables (root length, width and thickness) on the dependent variables (blade mass, stresses in the blade main body, stresses in the blade root, deformation and strain). These results are also plotted in Figure 10. Thickness is the first ranked influencing parameter and affects the strain, root stresses and mass considerably. Length is the first ranked influencing parameter causing changes in main body stresses and deformation. The main body stresses are reduced with the increase in root length. The root length is not influencing the strain, root stress and mass considerably. The overall effect of thickness is predominant and the effect of width is considerably low compared to others.

Table 9. Summarized ranks showing the effect of *t*, *w* and *l* on blade characteristics

Parameters	***t***	***w***	***l***
Strain	1	2	3
Root stress	1	2	3
Main body stress	2	3	1
Deformation	2	3	1
Mass	1	2	3
Average	**1.4**	**2.4**	**2.2**

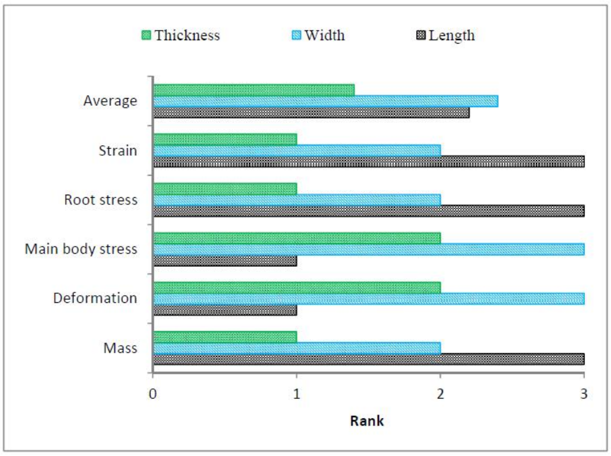

Fig. 10. Combined influence ranks of *t*, *w* and *l* on blade characteristics

The FEA results, tables and plots indicate that the blade root dimensions have considerable effect on various characteristics of the blade, which in turn affect the wind turbine blade life and performance. All these characteristics (blade mass, stresses in the blade main body, stresses in the blade root, deformation and strain) should have low values for improving efficiency of wind energy conversion and achieving structural integrity over the lifetime of the wind turbine. Specifically, reduced blade mass improves the wind turbine performance and reduces the blade cost, while reducing stress, strain and deformation increase the blade life and reliability.

From the result Table 3, it is also analyzed that the changes made in the root dimension predominately caused significant variation in root stress values and strain values than that of the mass, main body stresses and deformation. Also, the values of stresses induced in blade root are more than the main body stresses and also moving towards the permissible stress limit. Table 9, suggests that, these root stress values can be controlled by focusing on the root thickness. More root stresses are induced in the blade models with lower root thicknesses of 15 and 20 mm compared to that of 25 and 30 mm.

The research findings from this study lead to a further research opportunity with respect to the blade root dimensions. The effect of root dimensions on blade cost, flange mass, flange cost and starting behaviour of a wind turbine can be studied. Such a research investigation will allow for the establishment of design guidelines for setting appropriate root dimensions using suitable Multi Criteria Decision Making (MCDM) techniques.

5. Conclusion

The effects of three blade root dimensions *t*, *w* and *l* on five characteristics of a small wind turbine blade were studied. The FEA results obtained for all 16 blade models clearly indicated the changes in root lengths, widths and thicknesses cause considerable variation in blade mass, stresses in the blade main body, stresses in the blade root, deformation and strain. ANOVA results demonstrated the impact of the individual parameter on the physical and mechanical characteristics of the blade. Blade root thickness has been found to be a major factor influencing the target variables with greater thickness leading to the desired reduction of these dependent variables (mass, stress and strain). Root length was also found to have a significant influence on these characteristics. Root width was found to be a low impacting variable compared to thickness and length. Overall, they all have the ability to influence the mass, stresses, strain and deformation of the blade significantly.

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