5.1 Introduction

The development of modern airfoil, for their use in wind turbines was initiated in the year 1980. The requirements for such airfoils differ from standard aviation airfoils, due to the structural reasons and extensive aerodynamic off-design operation conditions. The wind turbine airfoils operate frequently under fully separated flow, whenever stall is used for power regulation at high wind speeds. Even in the case where traditional aviation airfoils are used on wind turbines, their performance needs to be verified in the entire operational range and at suitable Reynolds numbers.

Eventually these traditional aviation airfoils are modified for achieving improved performance by aerodynamic devices, such as vortex generators and gurney flaps. Apart from these two techniques the surface roughness plays a vital role in the flow separation or transition of laminar flow to turbulent flow. Thus there is a need for continuous testing of new airfoil configurations. Modern airfoils are to a large extent developed, based on the numerical calculations and optimization studies. The flow conditions such as separation at high angles of attack, laminar separation bubbles and transition from laminar to turbulent flow are difficult to predict accurately using conventional methods. Hence, testing of airfoils using the present numerical method becomes an
important issue in airfoil design. The present research addresses the effect of surface roughness of HAWT blade and optimizing the roughness value.

5.2 Studies on Roughness

Turbulence has an important influence on the average output power of a wind turbine. The wind dynamics coupled to the turbine dynamic characteristics results in a fairly complicated behavior. Thus the common "static" model of calculating the average power based on the turbine power curve and the average wind speed, may result in increasing errors as pointed out by Rosen and Sheinman (1994).

Sohn (2005) designed a rotor blade for the variable speed operation on the pitch controlled direct drive wind turbine 750 kW KBP-750D. The blade geometry was based on the modified NACA 63 and AE02 series profiles. The cylindrical profile was adopted near the blade root for easy connection with rotor hub and to assure the structural strength on the inner part of the blade. The designed blade showed good aerodynamic performances. The characteristics of aerodynamic design of the rotor blade for the KBP-750D were studied.

A prototype of 750 kW direct-drive wind turbine generator systems, KBP-750D was under development in Korea. For the gearless, direct-drive prototype a synchronous generator with permanent magnets was developed. This upwind 3-blade type machine employed variable speed and pitch control. A general performance requirement of the new airfoil families was to exhibit a maximum lift coefficient. The airfoil families address the needs of stall-regulated, variable-pitch, and variable-rpm wind turbines. The airfoils having greater thickness result in greater blade stiffness and low tower clearance. Airfoils of low thickness result in less drag and were better suited for downwind machines and these were analyzed by Tangler (1995).
The energy generating costs of wind turbines directly depend on the wind turbine output. The output of wind turbine depends upon the characteristics of the turbine blades and their surface roughness. An important operating requirement that relates to wind turbine airfoils was its ability to perform when the smoothness of its surface was degraded by dust. The effect of surface roughness of rotor blades due to accumulated dust on the blade surface of stall-regulated, horizontal axis 300 kW wind turbine was investigated. The effect of operation period of wind turbines on the blade surface roughness intensity was investigated by Khalfullaha and Koliubb (2007) experimentally. Also, the quantity of dust accumulated on the blade leading edge and the effect of changing dust area on blade surface were studied.

Wang et al. (2008) used the CFD tool in the scoop model for validating the wind turbine experimental results with and numerically predicted power. The test results were used to validate the CFD modeling. In the wind tunnel test, the pressure and velocity distribution were measured and compared against the CFD predicted results.

Ren and Ou (2009) work on full two-dimensional Navier-Stokes algorithm and the SST k-ω turbulence model were investigated on incompressible viscous flow past the wind turbine two-dimensional airfoils of the wind turbine under clean and roughness surface conditions. The lift coefficients and the drag coefficients of NACA 63-430 airfoils was computed under different roughness heights, different roughness areas and different roughness locations.

Jun et al. (2009) carried out an experimental study on the aerodynamic characteristics of a low-drag high-speed natural laminar flow (NLF) airfoil. The comparison of the measured results with the calculated proved the acceptability
of the airfoil and its aerodynamic characteristics had satisfied the design requirements.

This research by Hussian (2010) had used Navier Stokes Solver, analyzing on the effect of Reynolds number on the surface roughness parameters. The effect of different parameters on surface roughness was analyzed and presented in this study.

Amirulaei et al. (2010) studied the design and selection procedure of airfoil sections for small wind turbine blades. It is found that for blades up to 5 m long, two different airfoils mixed at the outer third of the span will be sufficient and have demonstrated good strength and aerodynamic characteristics. The effects of unsteady parameters, such as, amplitude of oscillation, reduced frequency, and Reynolds number on the aerodynamic performance of the model was investigated. Computational Fluid Dynamics (CFD) was utilized to solve Navier–Stokes (N–S) equations based on the finite volume method (FVM). The resulting instantaneous lift coefficients were compared with analytical data. The simulation results revealed the importance in the aerodynamic performance of the system. Thus, achieving the optimum lift coefficients demands a careful selection of these parameters.

The surface-flow field of finite wings having an aspect of ratio ten were visualized using the smoke wire and surface oil-flow schemes. According to the smoke-streak flow patterns for the low Reynolds number (Re <1.5×10^4), five characteristic flow modes were defined. They were surface flow, separation, separation vortex, separation near the leading-edge and bluff-body wake. Based on the surface oil-flow patterns for the high Reynolds numbers (Re>3×10^4), six characteristic flow modes were defined. They were laminar separation, separation bubble, leading-edge bubble, bubble extension, bubble burst and turbulent boundary layer. The velocity field around the wing was quantified.
using the particle image velocimetry (PIV) in this study by Yen and Huang (2010).

5.3 Methodology

The methodology used for the present work is followed similar to that used in Chapter 4. Further the pressure and suction sides of all the three blades are divided into various parts as shown in Table 5.1 and Figures 5.1-5.6. The surface roughness of uniform grain size of 0.001 m, 0.002 m, 0.003 m and 0.004 m are given as boundary conditions for the surface roughness height.

Figure 5.1 Blade A’s pressure side middle part surface.

Figure 5.2 Blade A’s pressure side root part surface

The power generated with each roughness height was predicted by the numerical methods.
Figure 5.3 Blade A’s pressure side part surface.

Figure 5.4 Blade A’s pressure side tip part surface

Figure 5.5 Blade B in the HAWT assembly
Effect of Surface Roughness on Performance of Wind Turbine

Figure 5.6 Blade C in the HAWT assembly

Table 5.1 Various surface parts of the three blades

<table>
<thead>
<tr>
<th>Blade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade-A-psm</td>
<td>Blade A’s pressure side middle part surface as shown in fig 5.1</td>
</tr>
<tr>
<td>Blade-A-psr</td>
<td>Blade A’s pressure side root part surface as shown in fig 5.2</td>
</tr>
<tr>
<td>Blade-A-psr</td>
<td>Blade A’s pressure side tip part surface as shown in fig 5.3</td>
</tr>
<tr>
<td>Blade-A-ssm</td>
<td>Blade A’s suction side middle part surface.</td>
</tr>
<tr>
<td>Blade-A-ssr</td>
<td>Blade A’s suction side tip part surface.</td>
</tr>
<tr>
<td>Blade-B-psm</td>
<td>Blade B’s pressure side middle part surface.</td>
</tr>
<tr>
<td>Blade-B-psr</td>
<td>Blade B’s pressure side root part surface.</td>
</tr>
<tr>
<td>Blade-B-psr</td>
<td>Blade B’s pressure side tip part surface.</td>
</tr>
<tr>
<td>Blade-B-ssm</td>
<td>Blade B’s suction side middle part surface.</td>
</tr>
<tr>
<td>Blade-B-ssr</td>
<td>Blade B’s suction side root part surface.</td>
</tr>
<tr>
<td>Blade-B-ssr</td>
<td>Blade B’s suction side tip part surface.</td>
</tr>
<tr>
<td>Blade-B-tip</td>
<td>Blade B’s tip part surface.</td>
</tr>
<tr>
<td>Blade-C-psm</td>
<td>Blade C’s pressure side middle part surface.</td>
</tr>
<tr>
<td>Blade-C-psr</td>
<td>Blade C’s pressure side root part surface.</td>
</tr>
<tr>
<td>Blade-C-psr</td>
<td>Blade C’s pressure side tip part surface.</td>
</tr>
<tr>
<td>Blade-C-ssm</td>
<td>Blade C’s suction side middle part surface.</td>
</tr>
<tr>
<td>Blade-C-ssr</td>
<td>Blade C’s suction side root part surface.</td>
</tr>
<tr>
<td>Blade-C-ssr</td>
<td>Blade C’s suction side tip part surface.</td>
</tr>
<tr>
<td>Blade-C-tip</td>
<td>Blade C’s tip part surface.</td>
</tr>
</tbody>
</table>
### Table 5.2 Area of separated surface zones

<table>
<thead>
<tr>
<th>Zone Name</th>
<th>Normal Blade Area-1 in m²</th>
<th>Roughness changed blade Area-2 in m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>blade-A-psr</td>
<td>20.994221</td>
<td>20.994221</td>
</tr>
<tr>
<td>Blade-A-sst</td>
<td>20.994221</td>
<td>20.994221</td>
</tr>
<tr>
<td>Blade-A-tip</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Blade-B-psm</td>
<td>30.589773</td>
<td>30.589773</td>
</tr>
<tr>
<td>Blade-B-psr</td>
<td>23.5753</td>
<td>23.5753</td>
</tr>
<tr>
<td>Blade-B-psr</td>
<td>28.969892</td>
<td>28.969892</td>
</tr>
<tr>
<td>Blade-B-ssm</td>
<td>30.589773</td>
<td>30.589773</td>
</tr>
<tr>
<td>Blade-B-ssr</td>
<td>23.536695</td>
<td>23.536695</td>
</tr>
<tr>
<td>Blade-B-sst</td>
<td>28.969892</td>
<td>28.969892</td>
</tr>
<tr>
<td>Blade-B-tip</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Blade-C-psm</td>
<td>33.293415</td>
<td>33.293415</td>
</tr>
<tr>
<td>Blade-C-psr</td>
<td>22.908458</td>
<td>22.908458</td>
</tr>
<tr>
<td>Blade-C-psr</td>
<td>29.101543</td>
<td>29.101543</td>
</tr>
<tr>
<td>Blade-C-ssm</td>
<td>33.293415</td>
<td>33.293415</td>
</tr>
<tr>
<td>Blade-C-ssr</td>
<td>22.909929</td>
<td>22.909929</td>
</tr>
<tr>
<td>Blade-C-sst</td>
<td>29.101543</td>
<td>29.101543</td>
</tr>
<tr>
<td>blade-c-tip</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
5.4 Results & Discussion

Moments generated by both pressure force and viscous force on the various surface zones of the three blade surfaces at varying roughness height values are compared in the Figure 5.7.

It is evident from the results plotted that the pressure moments predominate the moment generation followed by viscous moments.

The area of each surface zone and its moment generation are also given in the Figure 5.7 and it is evident the tip surfaces of blades generate more moments.

The moments generated by surface roughness height value 0.001 m are lower than the others and further increase in roughness value above 0.004 m does not give much appreciable enhancement of moment generation.
The pressure moments generated by the various parts of the blades of the HAWT are given in Table 5.3. The roughness increment of 1mm and the relative pressure moment generated by the various parts are compared in the table.

<table>
<thead>
<tr>
<th>Zone</th>
<th>0.001 m</th>
<th>0.002 m</th>
<th>0.003 m</th>
<th>0.004 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade-a-psm</td>
<td>20099.47</td>
<td>20078.707</td>
<td>20063.384</td>
<td>20022.392</td>
</tr>
<tr>
<td>Blade-a-psr</td>
<td>3192.6153</td>
<td>3186.2918</td>
<td>3181.8229</td>
<td>3172.9391</td>
</tr>
<tr>
<td>Blade-a-pst</td>
<td>35498.533</td>
<td>35508.893</td>
<td>35518.472</td>
<td>35504.611</td>
</tr>
<tr>
<td>Blade-a-ssm</td>
<td>-378.29363</td>
<td>-384.21517</td>
<td>-391.05572</td>
<td>-401.52652</td>
</tr>
<tr>
<td>Blade-a-ssr</td>
<td>-837.6766</td>
<td>-835.95132</td>
<td>-834.65209</td>
<td>-833.39552</td>
</tr>
<tr>
<td>Blade-a-sst</td>
<td>1554.5337</td>
<td>1629.9518</td>
<td>1663.9275</td>
<td>1730.4054</td>
</tr>
<tr>
<td>Blade-b-psm</td>
<td>23309.76</td>
<td>23310.701</td>
<td>23311.812</td>
<td>23294.596</td>
</tr>
<tr>
<td>Blade-b-psr</td>
<td>3126.5573</td>
<td>3124.2341</td>
<td>3122.7661</td>
<td>3118.8928</td>
</tr>
<tr>
<td>Blade-b-pst</td>
<td>51668.637</td>
<td>51698.32</td>
<td>51700.3122</td>
<td>51714.99</td>
</tr>
<tr>
<td>Blade-b-ssm</td>
<td>5175.2098</td>
<td>5172.1092</td>
<td>5168.7102</td>
<td>5163.1549</td>
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<td>Blade-b-ssr</td>
<td>244.22124</td>
<td>243.79272</td>
<td>244.15512</td>
<td>243.70222</td>
</tr>
<tr>
<td>Blade-b-sst</td>
<td>23383.309</td>
<td>23397.954</td>
<td>23397.727</td>
<td>23388.934</td>
</tr>
<tr>
<td>Blade-c-psm</td>
<td>26663.567</td>
<td>26665.299</td>
<td>26666.317</td>
<td>26648.59</td>
</tr>
<tr>
<td>Blade-c-psr</td>
<td>4002.5256</td>
<td>3998.8416</td>
<td>3996.073</td>
<td>3989.9098</td>
</tr>
<tr>
<td>Blade-c-pst</td>
<td>59089.534</td>
<td>59125.334</td>
<td>59195.6878</td>
<td>59145.067</td>
</tr>
<tr>
<td>Blade-c-ssm</td>
<td>7916.2345</td>
<td>7907.897</td>
<td>7899.6684</td>
<td>7888.3606</td>
</tr>
<tr>
<td>Blade-c-ssr</td>
<td>63.63058</td>
<td>66.172009</td>
<td>67.802109</td>
<td>69.890381</td>
</tr>
<tr>
<td>Blade-c-sst</td>
<td>29558.814</td>
<td>29536.986</td>
<td>29506.71</td>
<td>29464.314</td>
</tr>
</tbody>
</table>
Figure 5.8 Pressure moments generated by Blade-A-psm, Blade-A-ssm and Blade-B-psm, Blade-B-ssm for different surface roughness heights.

Figure 5.9 Pressure moments generated by Blade-A-pst, Blade-A-sst and Blade-B-pst, Blade-B-sst for different surface roughness heights.

Figure 5.10 Pressure moments generated by Blade-A-psr, Blade-A-ssr and Blade-B-psr, Blade-B-ssr for different surface roughness heights.
From Figures 5.8, 5.9, 5.10 it is evident that there is no variation in the pressure moment generated by the various parts of blade A and B. From this we can conclude that there is no effect of surface roughness in pressure momentum generation.

![Figure 5.11](image1.png)

**Figure 5.11** Pressure moments generated by Blade-C-psm, Blade-C-ssm and Blade-C-ps, Blade-C-ss for different surface roughness heights.

![Figure 5.12](image2.png)

**Figure 5.12** Pressure moments generated by Blade-C-psr, and Blade-C-ssr for different surface roughness heights.

From Figures 5.11 and 5.12 it can be conformed that the blade C also makes no significant difference in pressure moment generation because of
Effect of Surface Roughness on Performance of Wind Turbine

surface roughness variation. From Figures 5.8 to 5.12 it can also be conformed that the relative position of the blade doesn’t make any difference in pressure moment generation because of varied surface roughness values,

**Table 5.4** Comparison of viscous moment

<table>
<thead>
<tr>
<th>Zone</th>
<th>0.001 m</th>
<th>0.002 m</th>
<th>0.003 m</th>
<th>0.004 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade-a-psm</td>
<td>1523.0074</td>
<td>1832.0317</td>
<td>2083.9606</td>
<td>2289.5838</td>
</tr>
<tr>
<td>Blade-a-psr</td>
<td>103.67431</td>
<td>121.1845</td>
<td>134.62532</td>
<td>145.63139</td>
</tr>
<tr>
<td>Blade-a-pst</td>
<td>5650.7557</td>
<td>6636.2116</td>
<td>7391.3514</td>
<td>8021.5268</td>
</tr>
<tr>
<td>Blade-a-ssm</td>
<td>7.9970473</td>
<td>7.4886484</td>
<td>7.0368462</td>
<td>5.5343632</td>
</tr>
<tr>
<td>Blade-a-sst</td>
<td>2630.7362</td>
<td>3026.4079</td>
<td>3317.6546</td>
<td>3544.9307</td>
</tr>
<tr>
<td>Blade-a-tip</td>
<td>32.907783</td>
<td>39.239557</td>
<td>39.06198</td>
<td>38.20733</td>
</tr>
<tr>
<td>Blade-b-psm</td>
<td>1320.8853</td>
<td>1587.277</td>
<td>1803.9189</td>
<td>1980.0849</td>
</tr>
<tr>
<td>Blade-b-psr</td>
<td>81.048615</td>
<td>94.50524</td>
<td>104.78046</td>
<td>113.2336</td>
</tr>
<tr>
<td>Blade-b-pst</td>
<td>5566.3291</td>
<td>6731.4081</td>
<td>7852.0212</td>
<td>8454.9456</td>
</tr>
<tr>
<td>Blade-b-ssr</td>
<td>-4.877601</td>
<td>-5.8109229</td>
<td>-6.5450504</td>
<td>-7.3260489</td>
</tr>
<tr>
<td>Blade-b-sst</td>
<td>1776.3985</td>
<td>2068.1337</td>
<td>2287.9415</td>
<td>2466.3245</td>
</tr>
<tr>
<td>Blade-c-psm</td>
<td>1418.0369</td>
<td>1704.1043</td>
<td>1936.4345</td>
<td>2126.6908</td>
</tr>
<tr>
<td>Blade-c-psr</td>
<td>109.17285</td>
<td>127.57422</td>
<td>141.67565</td>
<td>153.27725</td>
</tr>
<tr>
<td>Blade-c-pst</td>
<td>5699.096</td>
<td>6875.776</td>
<td>7644.9788</td>
<td>8612.5438</td>
</tr>
<tr>
<td>Blade-c-ssm</td>
<td>-88.420174</td>
<td>-106.87867</td>
<td>-121.52038</td>
<td>-134.71192</td>
</tr>
<tr>
<td>Blade-c-sst</td>
<td>1060.1656</td>
<td>1226.6574</td>
<td>1349.4566</td>
<td>1441.4187</td>
</tr>
<tr>
<td>Blade-c-tip</td>
<td>33.104398</td>
<td>38.950361</td>
<td>38.726441</td>
<td>37.955443</td>
</tr>
</tbody>
</table>
The viscous moment generated by the various parts of the three blades of the HAWT are tabulated in Table 5.4 for roughness values ranging from 0.001 m to 0.004 m at the intervals of 0.001 m.

Figure 5.13 Viscous moments generated by Blade-A-psm, Blade-A-ssm and Blade-B-psm, Blade-B-ssm for different surface roughness heights

Figure 5.13 shows the viscous moments generated by the middle part of blade A and B at both suction and pressure side. There is a heavy increase in viscous moment generation with increase in the roughness values on the pressure side middle part of both the blades A and B. Negligible and a very small variation in viscous moment generation in the middle parts of the suction sides of blades A and B.
Viscous moments generated by the pressure side and the suction side tips of blade A and B are graphically shown with respect to roughness values increase in the Figure 5.14. The surface parts of blade B pressure side tip region and blade A pressure side tip region both show considerable increase in viscous moment generation increment with increase in roughness values. Among these two blades B pressure side tip has more increment in viscous moment generation when compared to the others. The suction side tip region surface of the blade A and B both show reasonable increase in viscous moment generation with the increase in surface roughness value.

Again from Figure 5.15 it can be understood that the pressure side tip region surface of the blades A and B show an increase in viscous moment generation as the roughness value increases. In contrary the suction side tip surface region of blade A and B which are already having negative values of viscous moment generation further decreases. The same concepts applicable to blade C surface as shown in Figure 5.16.
Figure 5.15 Viscous moments generated by Blade-A-psr, Blade-A-ssr and Blade-B-psr, Blade-B-ssr for different surface roughness heights.

Figure 5.16 Viscous moments generated by Blade-C-sst, Blade-C-pst and Blade-C-ssm, Blade-C-psm for different surface roughness heights.

Figure 5.17 Viscous moments generated by Blade-C-psr, and Blade-C-ssr for different surface roughness height
Table 5.5 Comparisons of total moment generated by different rough surfaces.

<table>
<thead>
<tr>
<th>Zone</th>
<th>0.001 m</th>
<th>0.002 m</th>
<th>0.003 m</th>
<th>0.004 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade-a-psm</td>
<td>21622.478</td>
<td>21910.738</td>
<td>22147.344</td>
<td>22311.976</td>
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<tr>
<td>Blade-a-psr</td>
<td>3296.2896</td>
<td>3307.4763</td>
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<td>3318.5705</td>
</tr>
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<td>41149.288</td>
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<td>43526.138</td>
</tr>
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<td>-395.99216</td>
</tr>
<tr>
<td>Blade-a-ssr</td>
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<td>-847.24739</td>
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<td>4656.3597</td>
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<td>5275.3361</td>
</tr>
<tr>
<td>Blade-a-tip</td>
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<td>27.721011</td>
<td>27.56267</td>
<td>26.739734</td>
</tr>
<tr>
<td>Blade-b-psm</td>
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<td>24897.978</td>
<td>25115.731</td>
<td>25274.681</td>
</tr>
<tr>
<td>Blade-b-psr</td>
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<td>3218.7393</td>
<td>3227.5466</td>
<td>3232.1262</td>
</tr>
<tr>
<td>Blade-b-pst</td>
<td>57234.966</td>
<td>58429.728</td>
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Table 5.5 shows the total moment generated by the various surface parts of the three blades of the HAWT, when they have different roughness values.

![Table 5.5](image)

**Figure 5.18** Comparison of total moments generated by various surfaces of blades in Y axis.

Figure 5.17 shows that there is no variation in the areas of the blades because of varying the surface roughness values.

**Figure 5.18** shows the Comparisons of total moments generated by various surfaces of blades in Y axis

### 5.5 Conclusions

The following conclusions can be arrived from the Chapter 5.

- The surface roughness values over the blade surface of the HAWT can be effectively modeled.

- The effect of surface roughness over the aerodynamic performance of the blades of the HAWT can be numerically simulated and results can be predicted.

  - The capability of numerical methods to solve the NS equation with the bound flow of air over the blades of HAWT with various surface roughness values is established.
Effect of Surface Roughness on Performance of Wind Turbine

- The analyses show that the viscous moments generated by the blades increases with increase in surface roughness values. The velocity of air is not much changed by increase in surface roughness value and thus the pressure moment generated is not appreciably changing.

- Because of the change in surface roughness value, the friction between the blade surface and flowing air increases, thus leading to an increase in the viscous moment.

- The study shows that there is a sharp increase in viscous moment generation with increase in surface roughness value on the pressure sides of turbine blades.

- By optimizing the surface roughness value power generation from an HAWT can be increased by approximately 1.5%.