Chapter 5

Structural Analysis of VAWT

This chapter presents structural analysis of multi-storey VAWT developed for improving self-starting behavior along with power coefficient. Finite Element Analysis has been done in ANSYS 12.0 software. The performance parameters considered are stress, deflection, Eigen frequency and Eigen vectors.

5.1 Multistorey Vertical Axis Wind Turbine

The Full scale turbine model is developed from mild steel sheet having three storeys as shown in Fig. 5.1, Fig. 5.2 and Fig.5.3 shows storey details of turbine and arrangement of blades and flaps per storey. NACA 68-613 cambered aerofoils is selected for analysis as cambered aerofoil have the benefit of self-starting can be used as compared to symmetrical aerofoils. Two blades of the storey are arranged with opposite leading and trailing edge so that the effect of drag forces at 90° and 180° assist the motion of the wind turbine. Lift force acting on the rotor blades tangentially to the plane of the rotation is producing torque. Flaps used are made
up from rectangular plate 'S' shape so as to have combination of concave and convex shape. Concave shape of the flap gives the major driving force as it has more drag coefficient than convex shape, which further augments the speed of the turbine rotor. Three flaps per storey are used, in which the central flap has bigger radius of curvature as compared to flaps on either side of it. At any position of the turbine at least two flaps viz: central flap and either of the side flaps are exposed to wind so that maximum wind force can be applied on the turbine.

Figure 5.1: CAD figure of turbine
For three storey turbine, three one-storey turbines are attached orthogonal to each other. Fig. 5.4 shows the three storey turbine. The height of each storey of turbine is 0.3 m and total height storey turbine is 0.9m. The shaft diameter is 0.02 m.
Figure 5.4: Three storey turbine
5.2 Estimation of Forces

Various forces coming on the turbine are obtained using the process given in IS-875 [71].

5.2.1 Aerodynamic Force

The aerodynamic force acting on the wind turbine parts is given as follows

\[ F_a = C_f A_e \bar{p}_z G \]  

(5.1)

where, \( \bar{p}_z \) = design pressure at height \( z \) due to hourly mean wind obtained as 0.65 \( V_h \)

1) Estimation of Gust factor

Wind turbine is being checked for wind gust for its safe operation. The gust effect is incorporated while calculation of aerodynamic force. The gust factor depends upon type of terrain.

Terrain category: 1

\[ I_{z,1} = 0.3507 - 0.0535 \log_{10}(\frac{z}{z_{0,1}}) \]  

(5.2)

\[ I_{z,1} = 2.6989 \]

Terrain category: 3

\[ I_{z,3} = I_{z,1} + \frac{3}{7}(I_{z,4} - I_{z,1}) \]  

(5.3)

\[ I_{z,3} = 1.366 \]
Terrain category: 4

\[ I_{z,4} = 0.466 - 0.1358 \log_{10}(\frac{z}{z_{0,4}}) \]  \hspace{1cm} (5.4)

\[ I_{z,4} = 0.371 \]

\( B_s \) = background factor indicating the measure of slowly varying component of fluctuating wind load caused by the lower frequency wind speed variations.

\[ B_s = \frac{1}{1 + \frac{\sqrt{0.26(h-s)^2 + 0.46h^2}}{L_h}} \]  \hspace{1cm} (5.5)

where, \( b_s h \) = average breadth of the structure between heights \( s \) and \( h \)

\( L_h \) = measure of effective turbulence length scale at the height, \( h \) in m

\[ L_h = 85 \left( \frac{h}{10} \right)^{0.25} \]  \hspace{1cm} (5.6)

\[ L_h = 56.84 \]

\( \phi \) = factor to account for the second order turbulence intensity

\[ \Phi = \frac{g_v I_h \sqrt{B_s}}{2} \]  \hspace{1cm} (5.7)

\( \Phi = 0.2745 \)
$H_s = \text{height factor for resonance response}$

\[
H_s = 1 + \left( \frac{s}{h} \right)^2 
\]  

(5.8)

$H_s = 1.562 \text{ m}$

$s = \text{Levels at which action effects are calculated.}$

$S = \text{a size reduction factor given by}$

\[
S = \frac{1}{\left[ 1 + \frac{3.5n_a h}{V_h} \right] \left[ 1 + \frac{4n_a b_0 h}{V_h} \right]} 
\]  

(5.9)

where $b_0 h = \text{average breadth of the structure between 0 and } h$

$N = \text{effective reduced frequency}$

\[
N = \frac{n_a L_h}{V_h} 
\]  

(5.10)

$N = 24.5 \text{ Hz}$

$E = \text{spectrum of turbulence in the approaching wind stream}$

\[
E = \frac{\Pi N}{(1 + 70.8N^2)^{\frac{5}{2}}} 
\]  

(5.11)

$E = 0.0018753$

$\bar{V}_h = \text{design mean value wind speed at height, } h \text{ in m/s basic wind speed}$

map of India, as applicable at 10 m height above mean ground level for
different zones of the country. Basic wind speed is based on peak gust speed averaged over a short time interval of about 3 seconds. \( n_a \) = first mode along wind frequency of the structure in Hz.

\( g_R \) = peak factor for resonant response

\[
g_R = \sqrt{2 \ln (3600n_a)} \tag{5.12}
\]

\( g_R = 5.2214 \)

\( g_v \) = a peak factor for upwind velocity fluctuation = 3.0 for category 1 and 2 terrains and = 4.0 for category 3 and 4 terrains

\[
G = 1 + r \sqrt{\frac{g_v^2 B_s (1 + \phi)^2 + \frac{H_s g^2 SE}{\beta}}{\beta}} \tag{5.13}
\]

\( G = 1.35 \)

\( g \) = peak factor defined as the ratio of the expected peak value to the root mean value of a fluctuating load, and \( r \) = roughness factor which is dependent on the size of the structure in relation to the ground roughness.

Effective Frontal Area (\( A_e \)) The projected area of the structure normal to the direction of the wind.

2. Force Coefficient\((C_f)\) Fig 5.5 shows the chart for force coefficient.
5.2.2 Centrifugal Force

The turbine is subjected to high centrifugal force which depends on the aspect ratio. The values of centrifugal force is calculated for all values of thickness of turbine parts at maximum tip speed of 32.5 m/s.

\[ F_c = \frac{mV^2}{r} \quad (5.14) \]

The total force acting on the turbine parts is sum of aerodynamic force and
centrifugal force.

\[ F_t = F_a + F_c \]  \hspace{1cm} (5.15)

### 5.3 Static Structural Analysis

A three storey vertical axis wind turbine has been designed and developed in a view to increase the performance parameters such as power coefficient and self starting speed. The turbine assembly consists of blades, flaps and plates. Each storey consists set of two blades and three flaps. The upper and lower surface of the blades and flaps are welded to circular plates. The parts of the wind turbine are subjected to aerodynamic force and centrifugal force. To design a turbine structure which is capable of sustaining wind gust to ensure safe operation, each part of the wind turbine having wall thickness of 2mm is analysed individually for the maximum load condition numerically.

The Finite Element Analysis is done in ANSYS 12. Static Structural module is used for performing the analysis. Linear elastic is selected as material mode. The load applied is boundary load which takes into account the uniformly distributed load. The parts of the turbine are fixed at both ends. Free tetrahedral element is used for meshing the turbine components. The mesh size control has been done and convergence has been achieved.

The structural analysis has been done to calculate maximum stress, maximum deflection, Eigenfrequency and Eigenvectors.

**Stress analysis:** The stress analysis is done for blades, flaps and plate of the wind turbine.
i. **Blade**: The blade of wind turbine of thickness 2 mm is subjected to uniformly distributed load of 1444 N. Fig 5.6 shows the maximum stress distribution plot. The maximum stress is induced at the fixed ends and at the center of the blade. The maximum stress of magnitude 1.938 \(N/mm^2\) induced in blade is very less as compared to yield strength of the material which is 495 \(N/mm^2\).

![Figure 5.6: Maximum stress magnitude plot for blade](image)

ii. **Flap**: The flap of thickness 2 mm is subjected to uniformly distributed load of 1444N. Fig. 5.7 shows the maximum stress distribution plot. The maximum stress of magnitude 55 \(N/mm^2\) is induced at the fixed end of the flaps. Stress values from 30-43 \(N/mm^2\) is at middle of the flap.
Fig. 5.7 shows that the maximum stress is seen at the fixed ends.

iii. **Plate**: Fig. 5.8 shows the stress plot for plate. The stress value is maximum at periphery of the plate of magnitude $78\,N/mm^2$ and at center of magnitude $52\,N/mm^2$.

2. **Maximum Deflection**:

   The total deformation of the turbine parts viz: blade, flap and plate is done in the following section.
i. **Blade**: Fig 5.9 shows the maximum deformation plot of blade. Maximum deformation of 0.008 mm is observed at the center of the blade. The deformation goes on reducing from the center towards the supported ends. At the supported end no deflection is observed.

![Figure 5.9: Maximum deflection plot for blade](image)

ii. **Flap**: Fig 5.10 shows the maximum deformation plot of flap. The maximum deformation of 0.006 mm is seen at the center of the flap. Deformation is also noticeable at the extreme edges of the flaps.

![Figure 5.10: Maximum deflection plot for flap](image)

iii. **Plate**: Fig 5.11 shows the maximum deformation plot of plate. The
maximum deflection of 0.4 mm is observed at the center of the plate. The deformation goes on reducing toward the periphery of the plate.

![Maximum deflection plot for plate](image)

Figure 5.11: Maximum deflection plot for plate

### 5.3.1 Eigenfrequency and Mode Shapes

**Eigenfrequency:** For safe operation of Vertical Axis Wind Turbine structure, the natural frequency of the turbine parts must be well above the forcing frequency. The desired 6 number of eigen frequency value is found numerically. Where the forcing frequency is calculated by

\[
\omega_f = \frac{2\pi N_0 p}{60} \text{rad/sec} \tag{5.16}
\]

The maximum tip speed velocity \(r \omega\) is 32.5 m/s. The angular velocity of turbine estimated is 62.5 rad/sec. Fig.5.12-5.14 shows the eigen-frequency values corresponding to turbine parts. The fundamental frequency of each part of turbine is comfortably high as compared to the value of forcing frequency which is calculated as 8 Hz.

From the analysis of stress and deflection it is observed that the stress and deflection magnitude increases from thickness 1-1.5mm considerably as compared
to other incremental steps of thickness. The total mass of the turbine for 1.5 mm thickness is 88 kg, for 2 mm thickness is 118 kg and for 3 mm thickness total mass is 177.8 kg. As the thickness increases the stress and deflection reduces due to increases in mass and stiffness. As the weight of the turbine increases the other performance parameter i.e. self starting speed gets affected. Thus optimum thickness of the turbine parts needs to be assessed from aerodynamic and structural performance. 1-1.5 mm sheet thickness cannot be used for turbine due to problems faced in metal joining process. Using 3 mm thickness sheet the mass increases by 70 kg. This will affect the self starting speed of the turbine. Thus the turbine assembly has been manufactured using 2 mm thickness sheet. This thickness will impart sufficient strength to bear the wind gust and also other performance parameters are satiated.

Figure 5.12 shows the Eigen frequency plot of blade.

Figure 5.12: Eigen frequency plot of blade

Figure 5.13 shows the Eigen frequency plot of flap
Figure 5.13: Eigen frequency plot of flap

Figure 5.14 shows the Eigen frequency plot of flap

Figure 5.14: Eigen frequency plot of blade

Mode shapes: Modal analysis of three storey vertical axis wind turbine is done by using ANSYS 12 software. The vertical axis wind turbine was simulated for six modes. Figure 5.15 shows the Fundamental mode shape of vertical axis wind turbine. The deformation of the turbine is in axial direction. Figure 5.16 shows the second mode shape plot of vertical axis wind turbine. The second mode shape shows bending of the turbine. Figure 5.17 shows the third mode shape plot.
of vertical axis wind turbine. The third mode shape shows that turbine is under torsion. Figure 5.18 shows the fourth mode shape plot of vertical axis wind turbine. The fourth mode shape shows that turbine is under torsion. Figure 5.19 shows the fifth mode shape plot of vertical axis wind turbine. The fifth mode shape shows that turbine is under bending. Figure 5.19 shows the sixth mode shape plot of vertical axis wind turbine. The sixth mode shape shows that turbine is under torsion.

Figure 5.15: Fundamental mode shape of Vertical Axis Wind Turbine

Figure 5.16: Second mode shape of Vertical Axis Wind Turbine
Figure 5.17: Third mode shape of Vertical Axis Wind Turbine

Figure 5.18: Fourth mode shape of Vertical Axis Wind Turbine
In this chapter, structural analysis of the full scale three storey vertical axis wind turbine is carried out using ANSYS 12.0. The vertical axis wind turbine is installed in terrain 2 category and the calculation of aerodynamic forces is done according to the IS 875 part 3 code. The parts of vertical axis wind turbine viz blade, plate and flap are subjected to the loading conditions for thickness 2 mm. A systematic study of stress, deflection, Eigen value and mode shapes are estimated for different
thickness values. This analysis outcome is used to fabricate the full scale turbine model for generation of power explained in next chapter.