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Numerical Analysis of Energy Harvesting on a Wind Turbine Blade by Using Piezoelectric Material

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ABSTRACT

The main concern of this paper is to theoretically prove the absolute possibility of generating electricity from the wind turbine blades' vibration and natural frequency while using piezoelectric material as raw material for turbine blade construction. The reference piezoelectric material used in the design is Lead ZirconateTitanate (PZT-5H).Using design of experiments (DOE), a study was conducted to determine the sensitivity of power with respect to the geometric and material variables. By doing the fluid analysis over the blade, a pressure is obtained which is further used for static analysis and by this pressure mechanical stress is produced and natural vibration is obtained.Due to mechanical stress, electricity formation is 9.497×10^2V and power produced is 1.1527W in whole piezoelectric blade. While in thin piezoelectric blade, electricity formation is 1.138×10^3V and power produced is 2.61W. When stress is taken under consideration, with 4.14Hz natural vibration, electricity will be produced up to 129.4 KW (maximum) for whole piezoelectric blade. For 3.4Hz, at a small section of the blade with a small thickness (about 0.01m) electricity will be produced up to 0.5W.

Keywords: Wind Turbine Blade, Vibration, Piezoelectric Material, DOE, Electricity

1.0Introduction

Wind energy is to be considered as one of the most viable sources of renewable energy when environmental issues such as acid rain, climate change, and imbalance of natural resources have been developed due to use of oil, gas and coal as fuel in power generation[1]. A wind turbine consists of three elements known as Towers, Nacelles and Turbine Blades. A wind turbine tower must be stiff and strong so that it can bear the load of turbine blades and generator. The stiffness is the most important factor to be considered because tower is also subjected to fluctuating wind loads due to rotation of blades. Nacelles are considered as a house of shafts, gearbox, generator and others supporting elements. In case of Nacelles weight is an important factor to be consider not the material. Turbine Blades are required to have an optimum cross section for aerodynamic efficiency to generate the maximum torque to drive the generators.Unused power exists in various forms such as industrial machines, human activity, vehicles, structures and environment sources. Among these, some of the promising sources for recovering energy are periodic vibrations and mechanical stress generated by rotating machinery or engines. Primarily, the selection of the energy harvester as compared to other alternatives such as battery depends on two main factors cost effectiveness and reliability. In recent years, several energy harvesting approaches have been proposed using solar, thermoelectric, electromagnetic, piezoelectric, and capacitive schemes which can be simply classified in two categories such as the power harvesting for sensor networks using MEMS/thin/thick film approach, and power harvesting for electronic devices using bulk approach. As wind turbine blade tolerate various types of loading and vibration extra energy can obtain from this unused energy. Piezoelectric material can produce electricity from mechanical stress and vibration. If we set up this material into the wind turbine blade some electricity can be produced by the mechanical stress develops by the air and natural frequency of its own [3-4].

2.0Mathematical Formulation

Continuity Equation:
According to the law of conservation,

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho V) = 0 \ldots\ldots (1)$$

Navier Strokes Equation:
Transient + Convection = Diffusion + Source

$$\frac{\partial\rho\varphi}{\partial t} + \nabla.(\rho u_\varphi) = \nabla.\lambda\nabla_\varphi + Source_\varphi \ldots\ldots\ldots (2)$$

There are two types of piezoelectric materials PZT and PVDF. When piezo electric materials are deformed or stressed, voltage appears across the materials. The mechanical and electrical behavior can be modeled by

$$\{S\} = S_E\{T\} + d\{E\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\{D\} = d\{T\} + \varepsilon_T\{E\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where, $\{S\}$ = Strain, $\{T\}$ = Stress $\{E\}$ = Electric Field, $\{D\}$ = Electric Displacement S_E = Compliance, d = Piezoelectric Coefficient ε_T = Permittivity

Summary of basic electrical equation

Capacitance parallel, $C_{p(parallel)} = 2K_3^T\varepsilon_0 b\left(\frac{L}{t_p}\right)$…… (5)

Capacitance series, $C_{p(series)} = K_3^T\varepsilon_0 b\left(\frac{L}{2t_p}\right)$…… (6)

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Energy, $W = \frac{1}{2} C_p V^2$ …………….….…..……… (7)

3.0Design and Structural Analysis

Airfoil design:

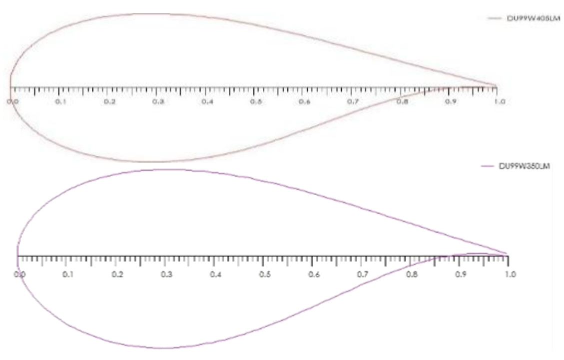

Fig. 3.1: DU99W405LM and DU99W350LM airfoil coordinate.

Model design:

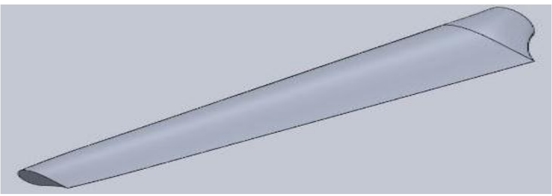

Fig. 3.2: Isometric view of wind turbine blade

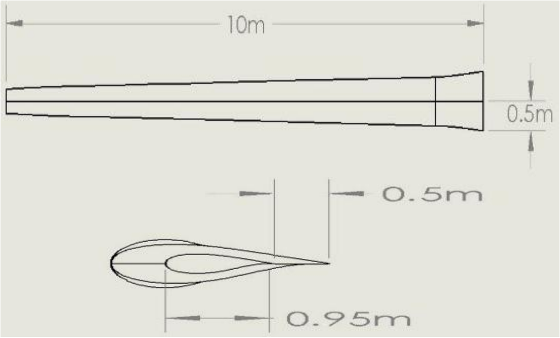

Fig. 3.3: Dimension of wind turbine blade

Material definition:

Properties	Description/ Value
Material	aluminum alloy 1100-H14
Density	2710 kg/m^3
Modulus of elasticity	70GPa
Poison ratio	0.31.

Piezoelectric Materials

Properties	Description/ Value
Material	PZT-5H
Density	7800 kg/m^3,
Modulus of elasticity	62 GPa
Poison ratio	0.31.
Dielectric Properties	3.89E-08 and 3.36E-08
K_3^T	3800
Permittivity	8.85E-12 F/m

Meshing for wind turbine blade:

For CFD analysis ANSYS simulation software is used and for CAE analysis ABAQUS simulation software is used. The meshing is very fine and sizing is much smaller than the default sizing. An inflation layer is created around the surface of the blade body for better contactof fluid.At inlet section fluid velocity is 12m\s and in the outlet the pressure is zero.

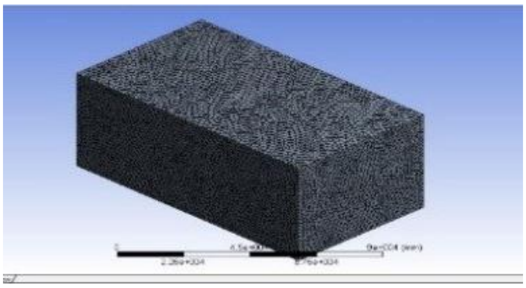

Fig. 3.4: Mesh for fluid analysis

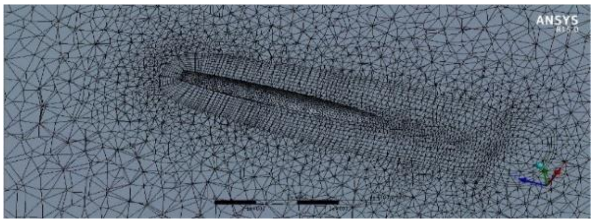

Fig. 3.5: Inflation layer on blade mesh for proper contact of fluid.

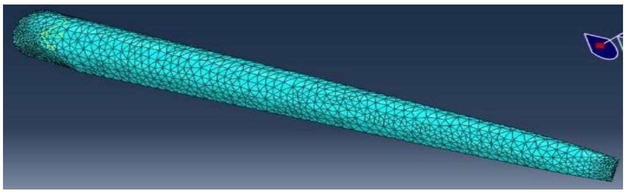

Fig.3.6: Mesh generation in ABAQUS for thin part of the blade for piezoelectric analysis

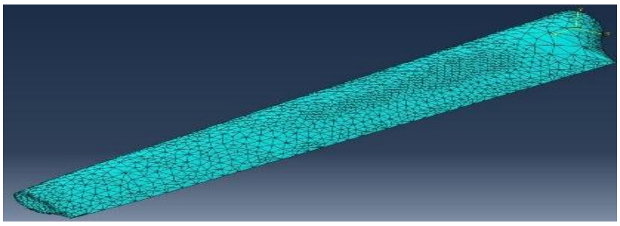

Fig. 3.7: Mesh generation in ABAQUS of the blade

4.0 Boundary condition:

CFD Solution Setup:

Blade body is set as wall. No slip is applied. Inlet is taken as Velocity-inlet. Specification Method is components and the velocity of fluid has only component at X direction of a magnitude of 12 m/sec primarily. Outlet is described as Pressure-outlet with Gauge pressure as zero meaning the atmospheric pressure condition. Top and bottom surface is taken as wall and side surfaces are given symmetry for proper calculation.

CAE Solution Setup:

For static analysis in ABAQUS CAE material properties was given. The blade material is aluminum. Then static general step was selected where a uniformly distributed pressure was given which was obtain from CFD analysis.The value of pressure was 5954 Pa in the bottom surface of the blade. The pressure is given in the bottom surface as maximum positive pressure was given by the air in the bottom surface of the blade.

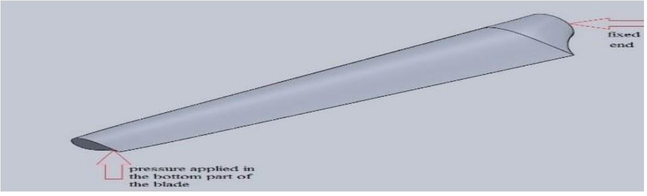

Fig. 4.1: The load and boundary condition

Piezoelectric analysis set up:

Load and Boundary Condition:

A uniform mechanical pressure of 5954 Pa was applied along the y-direction of the system on bottom of the piezoelectric surface. An electrical boundary condition is also imposed.

5.0 Simulation Results and Discussion

CFD Result

First simulation was done for getting pressure by the fluid flow over the blade. This was done by the use of ANSYS FLUENT analysis. The result is given below.

Pressure Contour

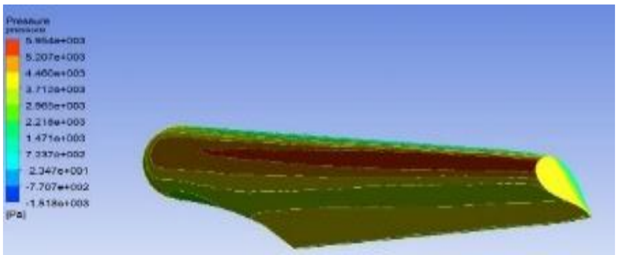

Fig. 5.1: Pressure contour of the wind turbine blade

Pressure Distribution on a Plane perpendicular to the Blade-This shows that the pressure at the upper surface of the airfoil has lower pressure than that of the lower surface of the blade. This generates the lift force that causes the rotation of the blade.

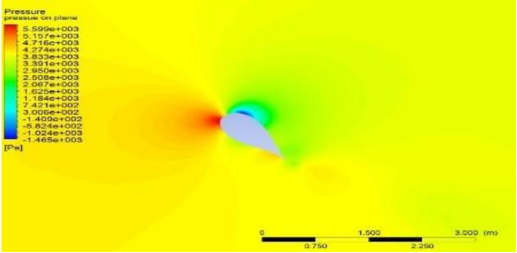

Fig.5.2: Pressure contour on a plane 3m distance from z axis

CAE result on aluminum blade:

From the obtain pressure of ANSYS fluent the next step is static analysis on blade. This was done in ABAQUS CAE. The maximum pressure on blade obtain from ANSYS fluent was 5954Pa and minimum pressure was -1518Pa. now the average pressure is taken as uniformly distributed pressure in case of static analysis.

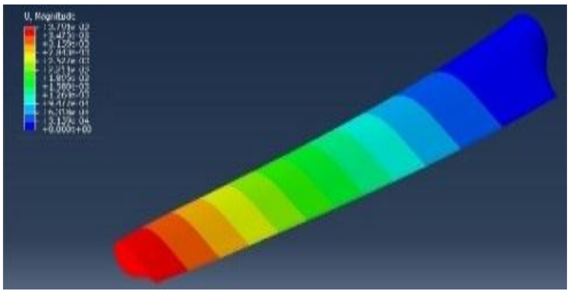

Fig. 5.4: Displacement of blade for applied pressure

As the blade acts as a cantilever beam, somaximum strain will be occurred in the fixed end.

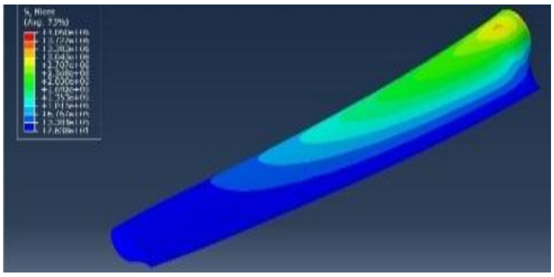

Fig 5.6: Stress on blade due to pressure

CAE result for whole piezoelectric blade:

The average stress magnitude denotes the total stress, we can say the stress is quite low in the free part of the blade but quite high in the fixed end.

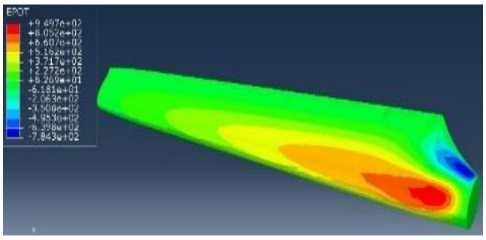

Fig 5.8: Electric potential of whole piezoelectric blade maximum 949.7V for applied pressure

The electric potential at the base state of whole piezo blade is quite low. The maximum electric potential obtains in the fixed end as piezo electric material gives higher response in high mechanical stress

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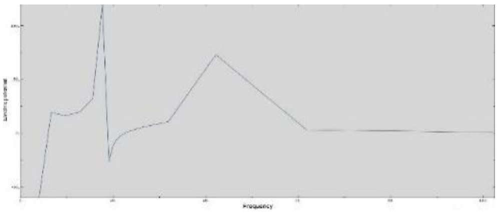

Fig. 5.10: Variation of Electric potential with respect to Frequency graph for whole piezoelectric blade

CAE result for thin piezoelectric blade where air pressure is maximum:For producing lift air will press the wind turbine in the front part of the blade, because of this maximum pressure displacement, stress and strain, efflux and EPOT is shown.

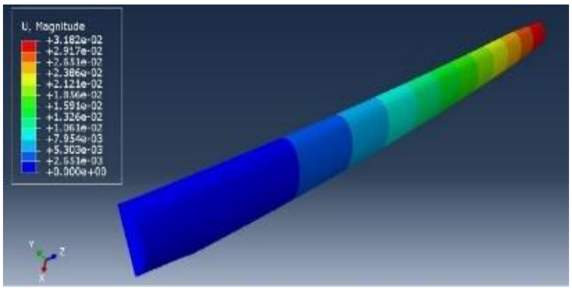

Fig 5.11: Displacement magnitude for thin section

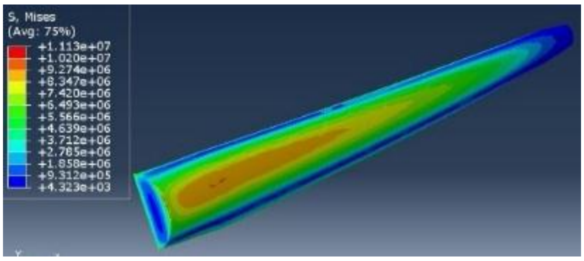

Fig 5.13: Stress magnitude for thin piezoelectric blade

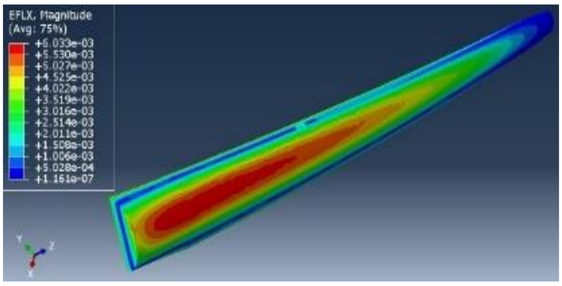

Fig 5.14: EFLUX magnitude for thin piezoelectric blade

The EPOT contour gives the electric potential where no natural frequency is considered and the maximum valueis 1.13KV.

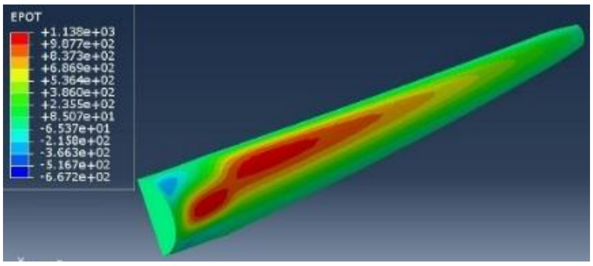

Fig 5.15: Electric potential magnitude

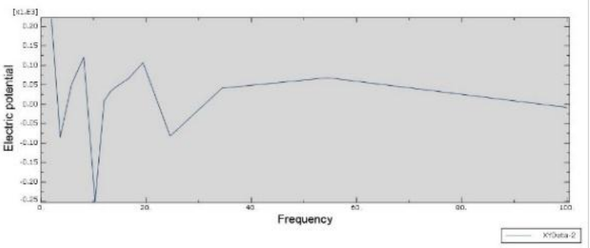

Fig. 5.16: Variation of Electric potential with respect to Frequency graph for thin piezoelectric blade

5.5 Result Calculation:

Power output for whole piezoelectric blade:

From summary of electrical equation in theory section, Due to applied pressure on the piezoelectric blade, in base state the electric potential is,

Capacitance $C_{p(parallel)} = 2K_3^T \varepsilon_0 b\left(\frac{L}{t_p}\right)$ =1.278*10^-6

Length, L=10m, Width b= 1.53m, Thickness, t_p=.81m

Resistance, $R = \frac{1}{\omega C_p}$ =781472.614 Ω

here,$eigen\ frequency\ \omega = 1, at\ base\ state$

Now, from maximum output EPOT at base state, V= 9.497*10^2, Power, $P = \frac{V^2}{R}$ =1.1527 W

From the calculation, we can say the out the output voltage is quite low but we know the typical eigen frequency of wind turbine blade is the range between .83 to 10 Hz. in my model the first eigen frequency is 4.14Hz. Putting this in equation 22 we get, Resistive load, $R = \frac{1}{\omega C_p}$ = 195618.2 Ω.

And, V at first eigen frequency is =1.591*10^5

Now, power is =129.4KW

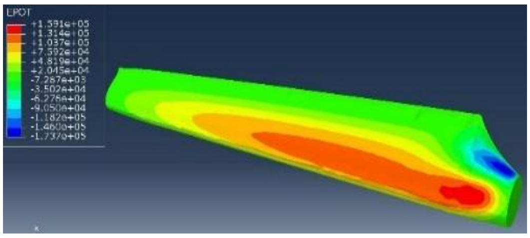

Fig 5.17: The electric potential for 4.147 Hz natural frequency.

Power output for thin piezoelectric blade:
From summary of electrical equation 19,21,22 in theory section, Due to applied pressure on the piezoelectric blade, in base state the electric potential is,

Capacitance $C_{p(parallel)} = 2K_3^T \varepsilon_0 b\left(\frac{L}{t_p}\right)$ =2.0178*10^-6

Length, L=10m, Width, b= 0.6m, Thickness, t_p=.2m

Resistance, $R = \frac{1}{\omega C_p}$ =495589

here, $eigen\ frequency\ \omega = 1, at\ base\ state$
Now, from maximum output EPOT at base state, V= 1.138*10^3,Power, $P = \frac{V^2}{R}$ =2.61 W

When the blade is its first natural frequency the thin blade will be in the same natural frequency. Now for thin blade frequency 3.4 Hz and from the surface shown in the figure the power output will be,

Capacitance $C_{p(parallel)} = 2K_3^T \varepsilon_0 b\left(\frac{L}{t_p}\right)$ =1.022*10^-5

Resistance, $R = \frac{1}{\omega C_p}$ =28778.6

here,$eigen\ frequency\ \omega = 3.4$. Now, from maximum output EPOT at base state, V= -.12*10^3

Power, $P = \frac{V^2}{R}$ =.5w

The surface is shown in the figure

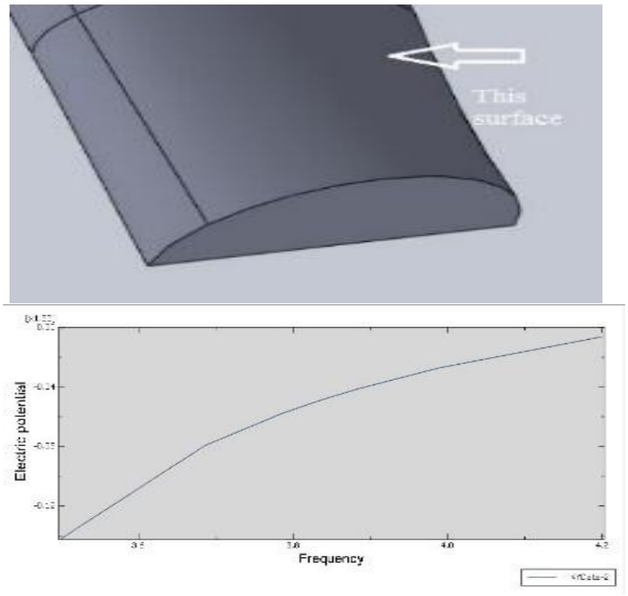

Fig.5.18: The selected surface near the fixed end and the electric potential in that surface

Result Verification:
from theory, the electric potential obtain by piezoelectric material is denoted by this equation 33.

$$V = E * t$$

Here,

V= electric potential [V], E = electric field [V/m]
t= thickness of the material
for datum CSYS and the applied load this equation can be written as

$V_3 = E_3 * t \ = \frac{d_{333} * Y * E_{33} * t}{\epsilon_3}$

Here E_{33} is obtain from strain of thin blade and which is 1.358*10^-4 for the selected node.

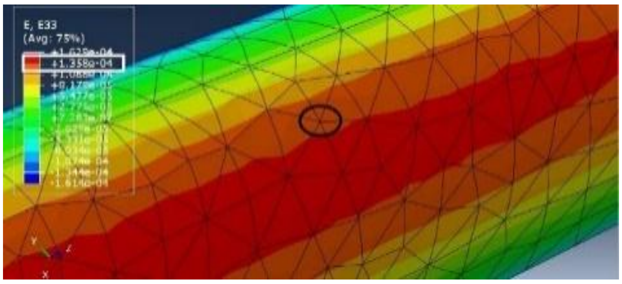

Figure 5.19: The required strain potential for base state

Now for input value and material properties of piezoelectric material the theoretical electric potential is $=\frac{7.2e-10*49e9*(-1.188e-9)*.01}{1.301e-8!}$ =1.2015527*10^3
Now the electric potential obtains from analysis:

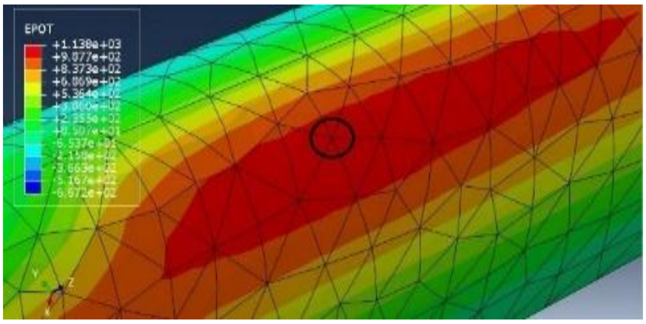

Figure 5.20: The maximum electric potential

Now CAE analysis value is 1.138*10^3

Percentage of error:
theoretical value is =1.201552*10^3, Experimental value is =1.138*10^3, So, percentage of error=5.3%.

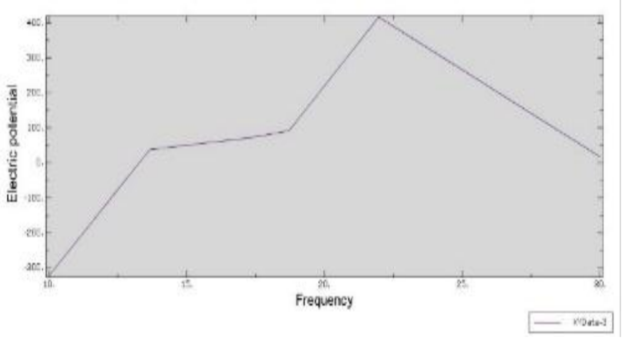

Figure 5.21: Electric potential vs Frequency graph for selected node

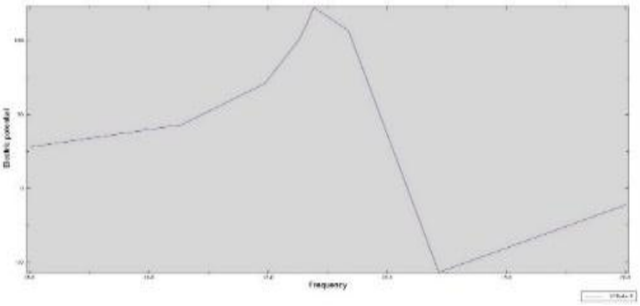

Figure 5.22: Electric potential vs Frequency graph for selected node

This graphs represents the electricity produced in the section in various natural frequency [6].
Ideal graph for electric potential vs frequency [7]:

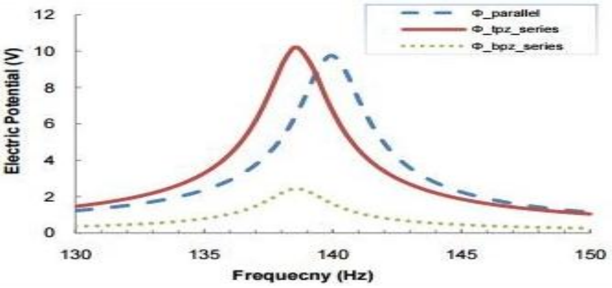

Figure 5.23: Electric potential vs Frequency graph

6.0 Discussion:

From the analysis and calculation, its obtain that electric potential can be obtained from mechanical stress which is developed by the wind pressure and vibration. The piezoelectric material Lead Zirconate Titanate (PZT-5H) was applied firstly to whole wind turbine then it is applied into a thin section of wind turbine where pressure is maximum. From the calculation, due to mechanical stress 1.15 w power can be produced in the whole blade veil with piezoelectric materials. Piezoelectric materials are highly sensitive to natural frequency, so when the blade is its first natural frequency, 129.3KW power can be produced. For mechanical stress 2.61W is produced by the thin section but when it is it's natural frequency a small surface can produce .5W which is very reasonable. By validify the result with the actual mathematical calculation 5.3% error is occurred. This is due to some deviation in taking dimension of curved shape wind turbine blade.

Compare with the ideal graph the main theme of the graph is totally same. If the circuit is closed then the experimental graph will take the shape of the ideal graph.

Last of all, it is quite arduous and costly to fabricate such a huge blade with PZT-5H. But the technology just keeps getting better. An ultra-efficient piezoelectric material that can convert up to 80 percent of mechanical energy into electricity [8]. This paper shows the theoretical possibility of getting voltage from wind turbine blade with PZT.

7.0 Conclusion:

Applying piezoelectric material into the blade and a section of blade electricity is produce. This electricity is produced without applying any external energy source. So, it will be very useful as no input is required. Though the initial cost is very high for the price of piezoelectric material, it can produce electricity for longer period of time. The results are shown as follows,For only mechanical stress electricity produced is 9.497*10^2V and power produced is 1.1527W for whole piezo electric blade.For only mechanical stress electricity produced is 1.138*10^3 V and power produced is 2.61 W for thin piezo electric blade.For stress with 4.14Hz natural vibration will produce maximum 129.4 KW for whole piezoelectric blade.For natural vibration at 3.4Hz of a small section with a small thickness about 0.01 m can produce .5W. with the help of voltage output of 0.12*10^3 V.

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