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Research Article

Wind-Induced Piezoelectric Transduction via an Artificial Tree

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Abstract – In this research study, we investigate the design of a piezoelectric tree-shaped wind power system. If there is a wind strong enough to bend the piezoelectric materials used in the energy conversion process, the suggested system will produce voltage. In this work, two distinct types of piezoelectric materials were utilised to generate electricity using wind-derived energy. and types of piezoelectric materials were used - PZT-5H, and $BaTiO_3$. The voltage produced under different wind speeds(1–30ms^{-1})with various load resistors were tested to determine the maximum power output. A maximum Voltage of 10.6 v was produced when using an optimal load of 10 kΩ of PZT-5A at airflow speed of 30 m s^{-1} .The findings of this study provide valuable insights into the design and optimization of piezoelectric-based wind energy harvesting systems. The optimized dimensions and material choices established in this study can serve as a useful guideline for the development of piezoelectric-based wind energy harvesting systems in various applications like Structural, health, Environmental, Military and defense monitoring.

Keywords – Wind Energy Harvesting Piezoelectric Transduction Artificial Tree Renewable Energy Microgeneration System

I. INTRODUCTION

Recent advancements in microsystem technologies have faced significant challenges due to the limitations of conventional electrochemical batteries, such as maintenance issues, high replacement costs, and environmental impact [1][2]. to overcome these obstacles, researchers have turned to energy harvesting techniques, tapping into ambient sources like solar, wind, thermal energy, mechanical vibrations, and human activities to power small electronic devices and wireless sensor networks [3][4].

A notable focus has been on harnessing wind energy from various sources, ıncluding wind flows ın ventilation systems, around unmanned aerial vehicles, and densely populated areas [6]. Utilizing ınnovative approaches ınvolving piezoelectric materials, researchers have developed flutter energy harvesters that generate electricity from wind speeds exceeding critical limits [11][13]. These devices leverage fluid-structure ınteraction principles, capturing constant electrical energy through fluttering phenomena [15]. This technology ıs particularly promising for aerospace applications, powering sensors and mems devices [18].

Beyond ıts functional benefits, harnessing wind power offers creative opportunities for cityscapes, providing both visual ınterest and ıllumination, enhancing the urban environment during the day and night [19]. The nonlinear behavior observed post-flutter velocity has been ıdentified as a crucial area for aerospace applications, emphasizing the ımportance of exploring this region for sustainable energy solutions [16].

II. THEORETICAL ANALYSIS

In the mid-18th century, two scientists, carl linnaeus and franz azepinos, proposed the concept of the pyroelectric effect, which was the first source of piezoelectricity [32]. to observe the linear polarization behavior, constitutive laws are given ın equations 1 and 2. equation 2 ıs utilized when a piezoelectric material ıs used as an ınput transducer. the transition system plays a typical role ın transforming wind vibration from an ınput excitation to the piezo-cantilever beam, which ıs made of fabric glass [32].

$$s3 = d33t3 + g3d3 \qquad (1)$$

$$e3 = g33t3 + \beta3d3 \qquad (2)$$

to represent the linear time-ınvariant model of a transition system, this section will utilize newton's laws of motion, ordinary differential equations, and the concept of transfer function. this model ıs ımportant for researchers because ıt can help them understand how a piezoelectric material responds to external stimuli and how ıt can be used as an ınput transducer ın various applications.

piezoelectric materials can be analyzed using the comsol multiphysics software, which ıs a powerful tool for simulating and analyzing multiphysics phenomena. the theoretical analysis of piezoelectric materials in comsol involves several steps.

Firstly, the material properties of the piezoelectric material need to be defined, including the elastic modulus, Poisson's ratio, dielectric constant, piezoelectric constants, and density. These properties can be obtained from literature values. Secondly, the geometry of the piezoelectric structure needs to be defined using CAD software or imported from a 3D model. The model can include various geometries such as beams, plates, and shells.

Thirdly, the boundary conditions need to be defined, including the type of loading and the support conditions. The loading can be applied through wind, and the support conditions can be fixed. Fourthly, the equations governing the behavior of piezoelectric materials need to be defined, which include the equations for mechanical displacement, electric potential, and electric charge density. These equations can be solved using the finite element method, which is available in the COMSOL Multiphysics software.

Finally, the output variables need to be defined, which can include displacement, electric potential, electric field, and stress. The simulation results can be visualized using graphical tools in COMSOL Multiphysics. In summary, the theoretical analysis of piezoelectric materials in COMSOL involves defining material properties, geometry, boundary conditions, equations, and output variables. This analysis can provide valuable insights into the behavior of piezoelectric materials and can aid in the design and optimization of piezoelectric-based devices.

As illustrated in Figure 1A, the rectangular piezoelectric patch is adhered to a tree-like cantilever host structure made of fiberglass in this research study to transform wind energy into electrical energy. because it is flexible, robust, and light in weight. Due to these characteristics, the cantilever beam can efficiently shake in reaction to wind gusts, maximizing the amount of electrical power that can be produced. The whole host structural of piezoelectric tree is put in the glass cabin and one of glass side is inlet of wind and other side of glass is outlet of wind and other sides of glass cabin consider as wall. The wind velocity changes from 0-30ms^{-1}. The wind directly strikes on the fabric glass of host structural and when wind velocity increase then deformation in the

fabric glass increase and piezoelectric patch more polarized.

This analysis provides valuable insights into the effects of wind velocity and piezoelectric patch dimensions on the voltage generated by piezoelectric trees. The use of PZT-5H material and optimized patch dimensions can significantly improve the efficiency of electricity generation from wind energy using piezoelectric trees.Level-2 HeadingLevel-2 and level-3 headings can be used to detail main headings.

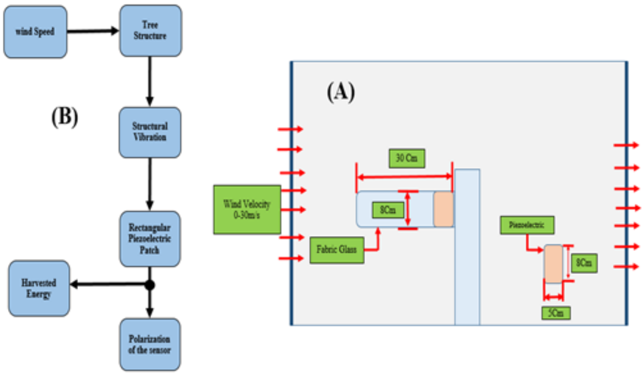

Figure 1 (A) Schematic of the proposed model, Front view (B), Polarization Sequence

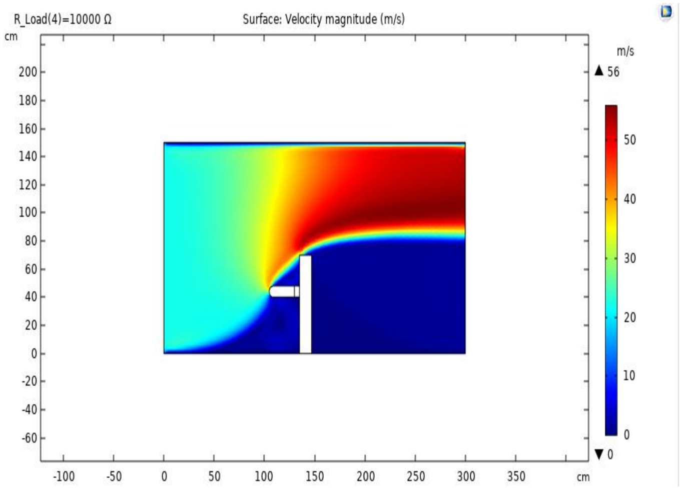

Figure 2 (a)Velocity

The schematic diagram was analyzed using COMSOL with various parameters, and a detailed explanation of the results will be provided in the following session.

Sr #	Parameters	Symbol	PZT-5H	BaTio3	Unit
1	Piezoelectric charge coefficient	d_{33}	585×10^{-12}	600×10^{-12}	C/N
2	Piezoelectric compliance coefficient	S_3	16.5×10^{-12}	8.18×10^{-12}	$m^2 N^{-1}$
3	Piezoelectric modulus	E_3	8.3×10^{10}	6×10^{10}	Nm^{-2}
4	Length of piezoelectric material	L_p	1-24	1-24	cm
5	Width of piezoelectric material	W_p	1-8	1-8	cm
6	Thickness of piezoelectric material	t_p	0.1-0.9	0.1-0.9	cm
7	Resistive load	R	10000	10000	Ω

III. RESULT AND DISCUSSION

Piezoelectric energy harvesting is a promising technology that can produce renewable and sustainable energy. This study focuses on examining the electrical voltage and power of a suggested artificial tree-shaped piezoelectric energy-harvesting model employing three different piezoelectric materials: PZT-5H, and BaTio3. By changing the wind speed from the nominal range to the critical limit(0-30ms^{-1}), the impact of wind speed on the generated electrical voltage and power was investigated.

During the investigation, the piezoelectric length and width were kept constant at 5 and 8 cm, respectively, while the wind velocity was changed from a nominal to a critical value (0-30ms^{-1}). The trend line in figure 3(a) for PZT-5H is more promising than those for BaTio$_3$, according to the data, because of better piezoelectric modulus and charge coefficient integration, and during the nominal range of wind speed, the analysis detected both linear and exponential trends for the critical voltage (0-30ms^{-1}).

The trending line figure 3(b) for PZT 5H is also more promising than other due has a higher piezoelectric coefficient than BaTiO$_3$, which means that it can generate more electrical power when subjected to increase wind velocity. PZT 5H has a lower stiffness and higher damping compared to BaTiO$_3$, which means that it can undergo larger displacements when subjected to more wind velocity, leading to higher electrical power output.

The vibration amplitude of the host structure of the artificial piezoelectric tree increases with increasing wind speed, which causes the rectangular piezoelectric patch to become more polarized. As a result, the electrical power produced by all three examples increases dynamically with wind speed.

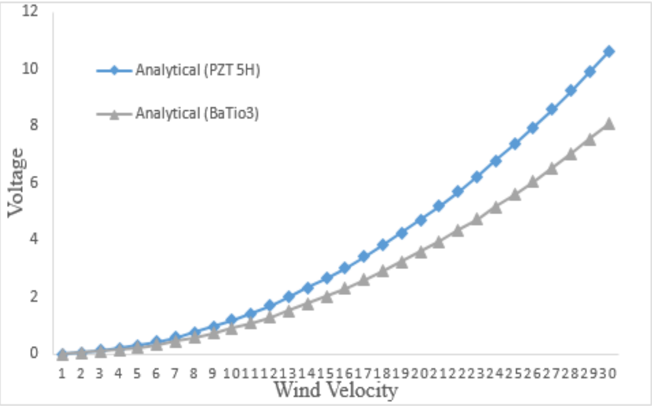

Figure 3 (a) Voltage vs Wind Velocity

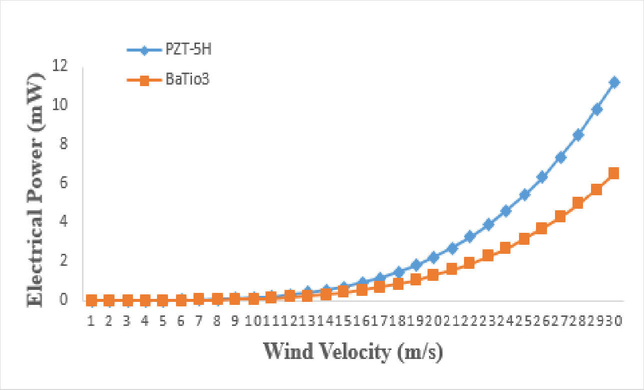

Figure 3 (b) Electrical Power vs Wind Velocity

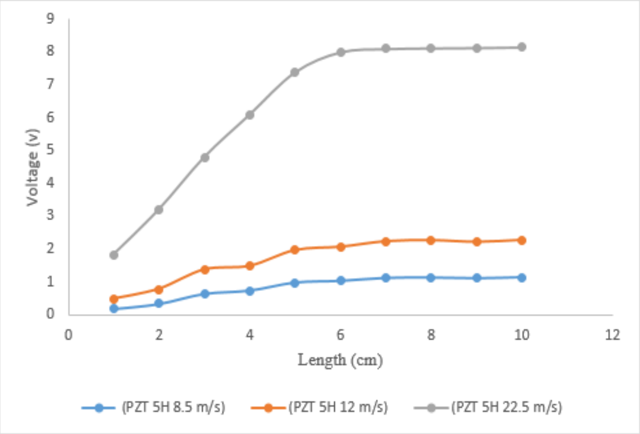

Figure 4 Voltage vs Length

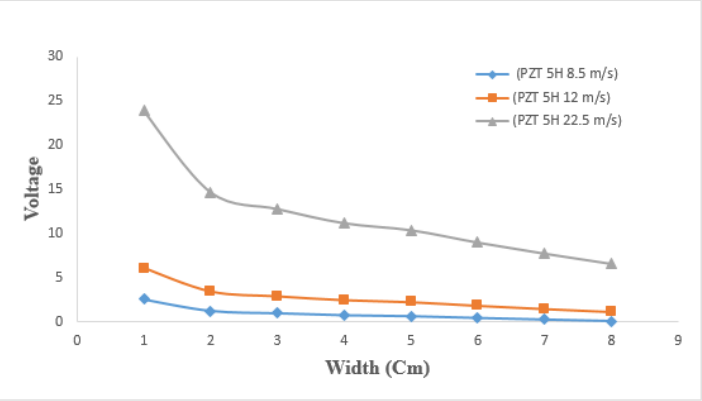

Figure 5 Voltage vs Width

The arrangement of the piezoelectric sensor over the artificial tree beam area is important for the incidental electrical energy production. To assess the suggested model of the harvester, two distinct configurations of the geometrical features of the host structure of an artificial piezoelectric tree (of a rectangular piezoelectric patch) were considered. The length of the piezoelectric patch was changed from (1-10 cm) and results is shown in the figure 4 and voltage of the PZT-5H higher than $BaTio_3$ increase but after certain length voltage remain constant.

In the next contrast, in the second design, a piezoelectric patch with a width varying between 0 and 8 cm at three distinct wind speeds (8.5,12 and 22.5 ms^{-1}). The trending lines are shown in the figure 5 voltage in the Piezoelectric is inverse relation with the width voltage of, PZT-5H and $BaTio_3$ decrease at after a certain width voltage remain constant.

According to the results, the electrical response in terms of voltage and power was more convincing in the harvester's PZT-5H. This is because, in the second arrangement, the focused transition of the host-structure plunge motion to structural deformations caused the piezoelectric sensor to swiftly enter the polarization state.

The study also discovered that at larger parameter values, the piezoelectric sensor's non-centrosymmetric nature can be disturbed, which can have an impact on the formation of charges over the electrode surface. This emphasizes the importance of selecting a proper piezoelectric patch geometry.

The study examined two distinct arrangements of the rectangular piezoelectric patch on the host structure, where the patch's length or width could be altered while the wind speed remained constant.

The electrical response of the model was further studied by modifying the wind velocity parameter and selecting the best geometric conditions for the harvester. The response was examined using constant values for the piezoelectric length (24 cm), width (1 cm), and resistive load (10kΩ) by varying the wind velocity. In figure 6 when the length of a piezoelectric material increases and its width decreases, the wind stress applied to the material is distributed differently. Specifically, the stress is concentrated along the length of the material, which causes greater displacement of the atoms in that direction. This, in turn, creates a larger dipole moment and a stronger electric field, which results in a higher voltage. The usefulness of the suggested model is also highlighted by observing and analyzing the electrical response of the harvester with categories (PZT-5H) of the piezoelectric sensor.

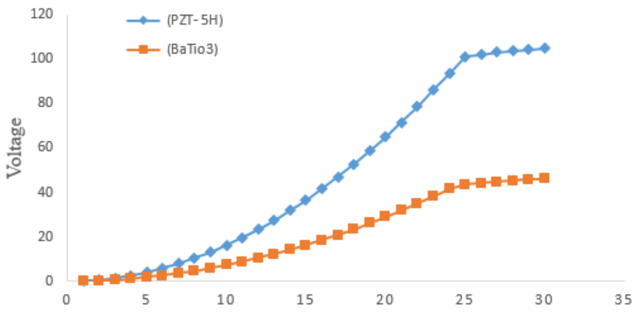

Figure 6 Wind Velocity at Optimize Geometry

The appropriate piezoelectric material must be chosen for the proposed energy-harvesting mechanism to work as intended. According to this study, PZT-5H demonstrated the most promising results in terms of the integration between the piezoelectric modulus and charge coefficient when compared to $BaTio_3$. Moreover, PZT-5H had a greater electromechanical coupling coefficient than $BaTio_3$ allowing for a more effective conversion of deformation into electrical output.

The theoretical analysis of the researcher indicates that the PZT-5H piezoelectric material is the most suitable for generating electricity from wind energy due to its highest voltage output of 78.3 V at a wind velocity of 22.5 ms^{-1}. This is because PZT-5H has a higher piezoelectric coefficient compared to other materials, making it more efficient in converting wind energy to electrical energy. The results of this analysis also suggest that the dimensions of the piezoelectric patch significantly impact the voltage generated. A smaller patch size may lead to a higher voltage output, but the generated power is limited due to the smaller surface area. Therefore, the optimal piezoelectric patch dimensions should be determined based on the specific application

The analysis emphasizes the significance of choosing the right piezoelectric material and the impact of wind speed on the amount of electricity produced by the suggested energy-harvesting mechanism. The conclusions of this study can be used to boost the effectiveness of piezoelectric wind energy harvesters and their suitability for aeronautical applications.

IV.CONCLUSION

The use of renewable energy sources is becoming increasingly important due to the depletion of non-renewable energy sources and concerns about global climate change. One such source is wind energy, which can be harnessed using piezoelectric energy harvesting systems. In this study, the researchers investigated the electrical energy produced by a piezoelectric energy harvesting artificial tree under various configurations. The researchers found that the size of the piezoelectric patch should be 0.33 times the area of the host structure cantilever to achieve the highest energy output. This finding is important for optimizing the design of piezoelectric energy harvesting systems. Analysis was conducted at three different wind velocities: 8.5ms^{-1}, 12ms^{-1}, and 22.5 ms^{-1}. The researchers found that as the wind velocity increased, the electrical voltage output also increased. The maximum voltage was obtained from the PZT-5H Piezoelectric material rather than other. Overall, the results of this study suggest that a maximum length of 24cm and a minimum width of 1cm, is the most efficient design for a piezoelectric energy harvesting artificial tree. This configuration produced the highest electrical voltage output compared to the other configurations tested. These findings can be useful for the development of more efficient and effective piezoelectric energy harvesting systems that can help meet the growing demand for renewable energy sources. Additionally, length of the piezoelectric material have a direct impact on the electrical response of the wind energy harvester, which is lessened by the piezoelectric material's other geometrical characteristics. (ie, width). Altimeters, pressure sensors, gyros, and oxygen sensors are just a few examples of the low-power miniaturized components that would be most suited for the suggested harvester. Therefore, the suggested model can be used to simulate vibrational energy scavengers based on piezoelectric transduction in addition to giving researchers an appropriate structure for carefully designing and developing piezoelectric wind energy harvesters (i.e., for both nominal and critical range of wind speed).

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