1. Introduction

Wireless sensor nodes (WSNs) are utilized in today’s electronics field for monitoring and security purposes, etc. These nodes require autonomous power solutions for working throughout their lifetime. Mechanical vibration provides a viable source of energy due to its availability in the environment. Vibration-based energy harvesting is defined as conversion of vibrations to electrical energy. Among the available options for conversion of vibration energy are electrostatic, electromagnetic, and piezoelectric fields. Piezoelectric-based approaches remain the most widely utilized method, as these provide relatively higher energy density. Various designs for vibration-based energy harvesters have been proposed in the literature, but among these designs cantilever-based system are the simplest and most extensively studied. When the vibrating frequency of the source matches the resonant frequency of the device, an optimum condition of maximum displacement is obtained. This displacement creates stress, and a peak power response is generated. A study of ambient vibration sources has shown that the majority of these sources have a frequency range below 150 Hz and a maximum acceleration of 2 g, where \( g \) is acceleration due to gravity (9.8 m/s\(^2\)) [1–4].

Many researchers have investigated different piezoelectric materials and their application in cantilever structures for capturing ambient vibrations [5,6]. These designs provide good power output but are quite bulky in size and hence cannot be used for microscale applications. Most of the designs have a narrow bandwidth of frequencies, which is not suitable for extracting wider random ambient vibrations.

A random behavior of their sources is a problem for harvesters, which generally give maximum performance at resonant frequencies. A 2-DOF energy harvester, which could function at the first two resonant frequencies, could capture the randomness of ambient vibration sources. A 2-DOF design could provide a bandwidth in which randomness in frequencies could be encountered. The output from this harvester can be further amplified by using efficient energy-harvesting circuitry to power microscale WSNs [7]. In the following section, a material and methodology for use in a broadband piezoelectric energy harvester has been described.

2. Material and methodology

2.1. Material

Such material properties as the dielectric constant, piezoelectric strain, and stress coefficients, electro-mechanical coupling coefficient, young’s modulus, density, etc., play significant roles in controlling the performance of piezoelectric energy harvesters. These properties determine the stress on the device and the generated output power [8–10].

Piezoelectric materials can be categorized into two types: lead-based and lead-free materials. Lead is a toxic element and has an adverse impact on the environment; hence, its usage is barred in most countries. In this context, scientists are working toward new materials with comparable or better performance than lead-based materials. Table 1 lists the properties of the piezoelectric materials utilized in this work. The piezoelectric materials used in the present study...
are lead-based piezoelectric materials with two variations of lead zirconate titanate, i.e., PZT-5A and PZT-5H [11–15] and lead-free materials comprising polyvinylidene fluoride (PVDF) [16,17], aluminum nitride (AlN) [18–20] and zinc oxide (ZnO) [21].

PVDF has the lowest Young’s modulus while lead-based PZT materials have the highest density. Aluminum nitride has the lowest relative permittivity but a high Young’s modulus. For piezoelectric constants, lead-based materials have higher values as compared with lead-free materials but zinc oxide shows substantial value for piezoelectric constant and hence can be utilized for energy harvesters.

### 2.2. Methodology

A typical piezoelectric energy harvester consists of a mechanical substrate, piezoelectric material and electrical interface. The mechanical structure is used as an input vibration sensor, which creates stress in the piezoelectric layer due to input vibrations. This stress is converted into voltage and power by the piezoelectric material. The present piezoelectric energy harvester is designed to take advantage of the \( d_{31} \) mode of vibration. In order to increase the average strain and stress levels, proof masses have been added to the structure. The proof masses also help to reduce the resonant frequency of the structure.

A seesaw-based structure consisting of proof masses at both ends has been designed as a 2-DOF energy harvester. The seesaw piezo structure is supported on a fixed pivot located slightly away from the center of the seesaw structure. The silicon base located near the center of the structure acts as the fixed anchor for the seesaw based energy harvester. This energy harvester consists of three layers with a substrate layer sandwiched between two piezoelectric layers acting as a bimorph energy harvester. Proof masses are placed on both arms of the asymmetric seesaw structure. The base is fixed at the bottom of the structure allowing the beam to vibrate at its natural frequency. The first two modes of the beam’s natural frequency are close to each other in order to provide a wider band to harvest power by capturing the randomness of the ambient vibrations. This is a 2-DOF harvester utilizing two vibration modes for its operation. Movement of the beam is possible in six modes. These six vibration modes of the energy harvester are depicted in the Figure 1. Simulations of the design were carried out with a finite-element modeling tool, COMSOL Multiphysics. The design was formed using zinc oxide as a piezoelectric material and silicon as a substrate material. The meshed model consists of 9592 elements, 4502 boundary elements, and 614 edge elements. Resonant frequency analysis was carried out under no load conditions, with the device allowed to vibrate at its own natural frequencies. The first natural frequency was 107.79 Hz and the second was 108.21 Hz.

### Table 1. Piezoelectric materials and their properties.

| Piezoelectric material | Young’s modulus (GPa) | Density (kg/m\(^3\)) | Relative permittivity | Piezoelectric constants |
|------------------------|-----------------------|-----------------------|-----------------------|-------------------------|
| PZT 5H [17]           | 127                   | 7500                  | 1433.6                | \(-6.55\)               | \(-274\)               |
| PZT 5A [18]           | 120                   | 7750                  | 826.6                 | \(-5.4\)                | \(-171\)               |
| PVDF [20]             | 1.31                  | 1780                  | 7.3                   | 0.0098                  | \(-13.6\)              |
| AlN [22]              | 149                   | 3300                  | 9                     | \(-0.58\)               | \(-1.72\)              |
| ZnO [24]              | 105.3                 | 5680                  | 10.204                | \(-0.56\)               | \(-5.43\)              |

![Figure 1. The six resonant frequencies of the seesaw piezoelectric cantilever design.](image)
Piezoelectric material physics needs to be determined [19,23]. A sample of an elastic material is placed under stress, \( T \). This leads to elongation in the direction of the applied load, and the material is under uniaxial strain, \( S \). The slope of this stress–strain curve is called the Young’s modulus:

\[
S = \frac{1}{Y}T = sT
\]

For a piezoelectric material, containing electrical dipoles; hence, the stress, \( T \), causes dielectric displacement, \( D \). \( d \) is the piezoelectric strain coefficient (C/N):

\[
D = dT
\]

Piezoelectric materials also exhibit a converse effect in which an applied electrical field produces a mechanical response. With normal materials, the applied electrical field, \( E \), leads to dielectric displacement, \( D \). The slope of the relationship is dielectric permittivity, \( \varepsilon \).

\[
D = \varepsilon E
\]

With a piezoelectric material, a strain, \( S \), is also produced under an applied electrical field, \( E \):

\[
D = \varepsilon E
\]

Combining Equations (1)–(4) yields

\[
\begin{bmatrix}
S \\
D
\end{bmatrix} = \begin{bmatrix}
s & d \\
d & \varepsilon
\end{bmatrix} \begin{bmatrix}
T \\
E
\end{bmatrix}
\]

Hence, solving Equation (5) for stress, \( T \), and the electrical field, \( E \), can be represented as

\[
\begin{bmatrix}
S \\
D
\end{bmatrix} = \begin{bmatrix}
s & d \\
d & \varepsilon
\end{bmatrix} \begin{bmatrix}
T \\
E
\end{bmatrix}
\]

Coupling of the mechanical and electrical components of the piezoelectric energy harvester generates the electromechanical coupling coefficient \( k \). The piezoelectric constitutive equation can be modified to give the coupling coefficient as follows:

\[
\begin{bmatrix}
T \\
E
\end{bmatrix} = \frac{1}{1 - k^2} \begin{bmatrix}
s^{-1} & -d^{-1}k^2 \\
-d^{-1}k^2 & \varepsilon^{-1}
\end{bmatrix} \begin{bmatrix}
S \\
D
\end{bmatrix}
\]

The coupling coefficient \( k \) is

\[
\begin{bmatrix}
T \\
E
\end{bmatrix} = \frac{1}{1 - k^2} \begin{bmatrix}
s^{-1} & -d^{-1}k^2 \\
-d^{-1}k^2 & \varepsilon^{-1}
\end{bmatrix} \begin{bmatrix}
S \\
D
\end{bmatrix}
\]

An important property of the piezoelectric coupling coefficient is that it is always positive and bounded by 0 and 1. The bounds 0 and 1 represent the fraction of energy converted from the mechanical and electrical domains. The fact that \( 0 < k^2 < 1 \) implies that the term \( 1/(1 - k^2) \) must be greater than 1. A comparison of the electromechanical coefficients of various piezoelectric materials is shown in Figure 2.

A comparison of electromechanical coupling coefficients shows that lead-based materials exhibit better coupling performance as compared to lead-free materials. Among the lead-free materials zinc oxide has shown the best results. For the dielectric displacement \( D = 0 \), the constitutive equation can be reduced to

\[
T = \frac{S}{s(1 - k^2)}
\]

The short-circuit condition refers to shorting of the upper and lower electrodes, while open circuit refers to a no-load condition [20,21]. The constitutive equation under the boundary condition represented by superscripts can be obtained by inverting Equation (9):

\[
S = \begin{cases}
S^{E}T \text{ short circuit} \\
S^{E}(1 - k^2)T \text{ open circuit}
\end{cases}
\]

The piezoelectric constitutive equation can be described in either of two forms, the first of which is the strain–charge form:

\[
S = \begin{cases}
S^{E}T \text{ short circuit} \\
S^{E}(1 - k^2)T \text{ open circuit}
\end{cases}
\]

\[
S_i = \varepsilon_i^{E}T_j + d_{ik}E_k
\]

The stress–charge form, the second form used to describe the constitutive equation, can be deduced from Equations (12) and (13):

\[
T_i = \varepsilon_i^{E}S_j - \varepsilon_{ik}E_k
\]

\[
D_m = \varepsilon_{mj}S_j + \varepsilon_{mk}E_n
\]

where \( D_m = \varepsilon_{mj}S_j + \varepsilon_{mk}E_n \), \( \varepsilon_{mj} = d_{mj}s_{ij}^{-1} \) and \( \varepsilon_{mk} = d_{mk}s_{ij}^{-1} \). Strain and stress tensors are complementary in nature. The strain–charge form of the piezoelectric constitutive equation can be expanded as follows:
The number of variables required to specify the constitutive properties of piezoelectric materials is reduced significantly by considering the symmetry associated with the elastic, electrical, and electromechanical properties.

4. Finite-element model validation

Tip displacement is an important factor for inducing stress in a piezoelectric energy harvester. It depends on the Young’s modulus and the density of both the substrate and the piezoelectric material. It is essential for a harvester to have a large displacement, which would correspond to high stress and increased generated power [24]. Simulations for various piezoelectric materials were conducted under resistive load conditions with $4\Omega$ resistance connected across the electrodes on both sides of the piezoelectric layer. Figure 3 demonstrates that PVDF has the highest displacement, as its Young’s modulus is very low, while AlN has the lowest displacement, as its Young’s modulus is quite high.

The generated output power for energy harvester is a key characteristic of the harvester. The various power levels depend on the electromechanical coupling of the energy harvester substrate and piezoelectric material. A comparison is shown in Figure 4.

An aluminum nitride-based harvester generated the most power, while the poor coupling and low piezoelectric constant of PVDF resulted in the lowest power output for the PVDF system, although the displacement of PVDF is the maximum. Zinc oxide, PZT5A, and PZT5H gave substantial power output, as they had a considerable piezoelectric constant that resulted in good electromechanical coupling. Comparisons of all the characteristics of various harvesters are depicted in Figure 5.

Although aluminum nitride has the highest generated power, the device’s higher resonant frequency eliminates its application for ambient vibration extraction. In order to decrease its resonant frequency, the device’s volume must be increased, which would further limit its range of applications.

On the other hand, lead-based materials are avoided despite showing the best results due to the toxic nature of lead. Among the lead-free materials, zinc oxide demonstrates the best electromechanical coupling and shows substantial results for displacement, stress and power while the device has a resonant frequency of around a 100 Hz. Hence, zinc oxide is the best material, for use in piezoelectric energy harvesting.

4.1. Load resistance value optimization

Output load resistance is an important factor for determining the response of the system. The value of the
output load must be optimized in order to maximize power output. Because zinc oxide has been carefully chosen as the best piezoelectric material, the materials load resistance values have been determined. The values for load resistance vary from 50 $\Omega$ to 6 M$\Omega$. The power response depends on the varying input vibration frequencies for different load resistances. Figure 6 shows that a peak response of around 23 mW is obtained. Hence, a load resistance of 0.14 M$\Omega$ is optimal for maximizing the output power.

The response of the piezoelectric energy harvester is plotted for varying input vibration frequencies at a resistance of 0.14 M$\Omega$. The frequency response has a peak of around 23 mW at 108 Hz of resonant frequency as shown in Figure 7. Hence it has been observed that output power can be enhanced by optimizing the load conditions.

### 5. Conclusion

A novel seesaw-type piezoelectric energy harvester has been analyzed and optimization of its material has been performed. Materials play a vital role in determining the performance of piezoelectric energy
harvesters. Piezoelectric material properties are essential in determining the coupling factor between the harvester’s mechanical and electrical components. Lead-based piezoelectric materials have the best performance, but lead is a toxic that must be avoided for energy harvesting purposes. Among lead-free piezoelectric materials zinc oxide gives comparable results to those of lead-based materials. The output load resistance must be determined, in order to enhance the power response of the system, as maximum power is transferred when input impedance matches the output load. The harvester generates maximum power of around 23 mW of power across a 0.14 MΩ resistance at around 108 Hz.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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**Figure 6.** Generated output power with input vibration frequency for different output load resistances.

**Figure 7.** Optimal generated output power for input vibration frequency.
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