Studying the Distribution of Stress in Two-dimensional Compression Piezoelectric Cells under Load-truck Conditions

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Abstract: This research focuses on investigating the impact of stress on piezoelectric cells located on roads with electric voltage. We aim to optimize the design and placement of piezoelectric cells on roads to improve their accuracy and effectiveness in generating electricity from passing vehicles. Our study focuses on three types of loading: one-point loading, uniform distributed loading, and triangle-distributed loading. By analyzing the stress and shear exerted by the pressing truck on the piezoelectric cells, we aim to gain insights into the behavior of these cells under different loading conditions. To conduct this research, we use finite element analysis (FEA) simulations to model the compression cells and simulate the load-truck conditions. The piezoelectric cells are used to measure the electric voltage generated by the stress on the road surface, which is correlated with the stress and shear values obtained from the FEA simulations. The results of this research provide valuable insights into the impact of stress on piezoelectric cells and can be used to optimize the design and placement of these cells on roads, improving their accuracy and effectiveness in generating electricity from passing vehicles. Additionally, this research can inform the development of new materials and technologies for road surfaces that can better withstand the stress and shear exerted by heavy vehicles. Overall, this research has the potential to make significant contributions to the fields of transportation, energy, and materials science.

Keywords: Shear and stress research; Piezoelectric cells; Load-truck conditions; Finite element analysis; Electric voltage

1 Introduction

Shear and stress research has significant applications in various fields, including aerospace, construction, transportation, and materials science. This research is essential for developing new materials and designs that can withstand the stresses and strains of heavy use, as well as for testing the safety and reliability of critical infrastructure. One such application of shear and stress research is in the development of piezoelectric cells for generating electricity from passing vehicles on roads.

1.1 Piezoelectric cells

Piezoelectric materials are considered to be smart materials because of their unique ability to convert mechanical stress or strain into electrical potential and vice versa through the direct and reverse piezoelectric effects, respectively. This conversion process is the basis of piezoelectricity and has numerous practical applications. The piezoelectric material used in a piezoelectric system can operate in different modes, which are defined by the piezoelectric strain constant dij. This constant represents the relationship between the mechanical strain or deformation applied to the material and the resulting electrical voltage output. The subscript "i" indicates the direction of electrical voltage output, while "j" indicates the direction of applied mechanical stress.

There are primarily two constants, d33 and d31, which are commonly used in piezoelectric systems. These constants are characterized by the poling direction being along the 3-axis. The d33 constant represents the piezoelectric strain coefficient in the direction of the electric field, while the d31 constant represents the piezoelectric strain coefficient perpendicular to the direction of the electric field. Understanding these constants is essential for designing effective and efficient piezoelectric systems. In summary, piezoelectric materials are unique and valuable because of their ability to convert mechanical stress or strain into electrical potential, which has many practical applications. The different modes of operation in a piezoelectric system are defined by the piezoelectric strain constant dij, with d33 and d31 being the two most commonly used constants as see in Fig.1.

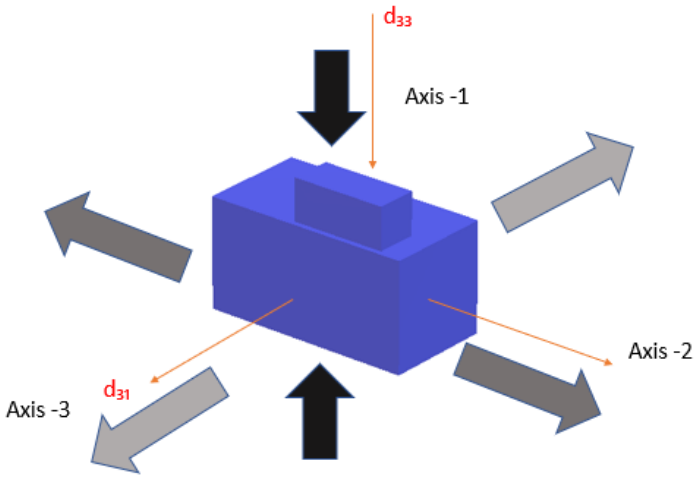

Fig 1. Reference axis generating for piezoelectric material.

1.2 Piezoelectric material

PZT-5J is a type of lead zirconate titanate (PZT) material that is commonly used in piezoelectric systems. It has a high electromechanical coupling coefficient, which makes it an efficient material for converting mechanical stress or strain into electrical energy. It is also more readily available and cost-effective than other PZT materials, making it a popular choice for many applications. The thickness of the PZT module is also an important factor to consider in the design of piezoelectric systems. The thickness of the module affects the sensitivity and responsiveness of the system to mechanical stress and strain. The availability and cost of the PZT-5J is more feasible than the other PZT materials. Therefore, PZT-5J material was chosen here and the module chosen is of thickness 2 mm.

2 Investigating the impact of stress on piezoelectric cells

2.1 Types of impact

In order to understand the impact of stress on piezoelectric cells located on roads with electric voltage, we will be investigating the behavior of these cells under different loading conditions. We will be conducting experiments to analyse the effect of one-point loading, uniform distributed loading, and triangle-distributed loading on the piezoelectric cells. These different loading conditions will be simulated to obtain a better understanding of how the cells react to the stress generated by passing vehicles on roads.

Fig.2 provides an illustration of the different loading trucks used in our research and their corresponding loading conditions on the piezoelectric cells on roads. By studying the behavior of the cells under these different loading conditions, we aim to determine the most effective and efficient design and placement of piezoelectric cells on roads to generate electricity from passing vehicles.

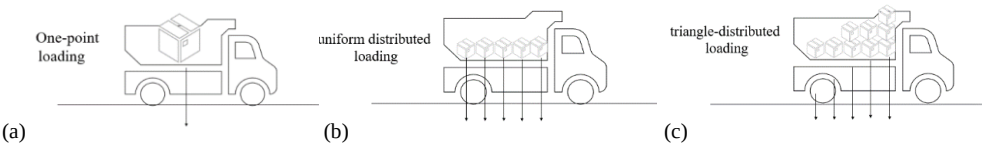

Fig. 2. Different loading truck on piezoelectric cells inside the roads. (a) one point loading, (b) uniform distibuted loading, (c) triangle distibuted loading.

2.2 Analysis for impact of stress on piezoelectric cells

The goal of this analysis is to optimize the design and placement of piezoelectric cells on roads to maximize their energy generation potential. We will use FEA simulations to model the compression cells and simulate different load-truck conditions. The FEA simulations by MATLAB will help us to understand how the cells react to different types and levels of stress generated by passing vehicles on roads so we have finite and infinite elements as shown in Fig. 3.

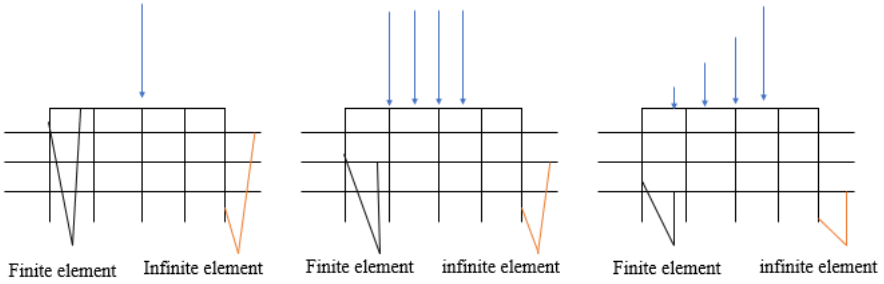

Fig. 3 Finite and infinite drawing under different loading.

Each stress vector (t) in indicial notation tx, ty in the coordinate system (x, y) can be resolved into components along the coordinate lines x, y:

$$\sigma_x i_x + \tau_{xy} i_y = t_x \quad (1)$$

$$\tau_{xy} i_x + \sigma_y i_y = t_y \quad (2)$$

Resolving stress vectors into their normal and shear components can be a valuable approach. This involves breaking down the stress vector (t) into two separate components: one that is parallel to the normal of the surface element (n), which is known as the normal stress (σ), and another component that is perpendicular to the normal (n), which is known as the shear stress (τ). This method is illustrated in Fig. 4, which demonstrates how the normal and shear stresses can be separated and analysed independently. By using this approach, we can gain a better understanding of how the stress is distributed across the surface and how it may impact the behavior of the piezoelectric cells.

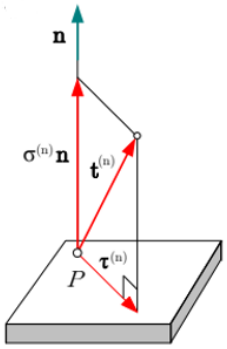

Fig. 4 Graphical representation of the resolution of the stress vector t according to normal element.

The equation of motion in coordinate system of x, y can give as:

$$\frac{\partial t_x}{\partial x} + \frac{\partial t_y}{\partial y} + \rho b = 0 \quad (3)$$

ρb: it referred to forces which act on piezoelectric body in different loading truck.

When we substitute equations (1) and (2) into equation (3), we can derive scalar equations (4), (5) for the stress vectors. This involves using the equations to express the stress vectors in terms of their normal and shear components. By doing so, we can simplify the equations and make them easier to analyse. The resulting scalar equations provide a way to calculate the magnitude of the stress vectors based on their normal and shear components.

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + f_x = 0 \quad (4)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + f_y = 0 \quad (5)$$

The model depicted in Fig. 5 shows an infinite medium that is subjected to various types of loading, shear and stress forces. The purpose of the model is to analyse the behavior of piezoelectric cells under different types and levels of stress. The arrows in the model represent various types and magnitudes of loading, which are applied to the medium to simulate different stress conditions. By analysing how the medium responds to these loadings, we can gain valuable insights into how the piezoelectric cells will behave under

different stress conditions, and how they will deform and generate electrical energy. This analysis is important for optimizing the design and placement of the cells, as it allows us to identify areas of high stress concentration and determine how the cells will perform under different stress conditions. The model may vary depending on the specific application and type of piezoelectric cell being used, but the basic principle is to subject the cell to different types of loading and analyse its behavior under these conditions. By optimizing the design and placement of the cells based on this analysis, we can maximize their energy generation potential and improve their overall performance.

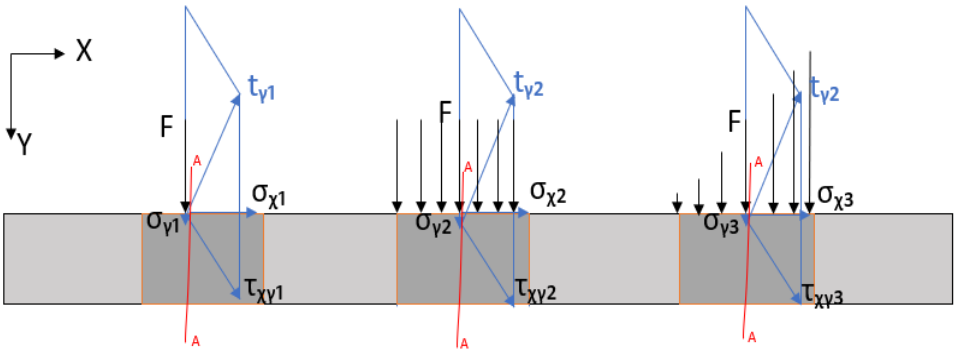

Fig. 5 Infinite medium model that is subjected to various types of loading, shear and stress forces.

Fig. 6 provides a visual representation of the stress distribution in the piezoelectric cell, which is non-uniform and varies across the cell. This stress distribution is observed in equations (4) and (5), as well as in Fig. 5. The figure shows the stress distribution across the cell on the A-A section, with different areas experiencing varying degrees of stress concentration. By analysing this distribution, we can gain a better understanding of how the cell will respond to different types and levels of pressure, and how we can optimize the design and placement of the cells for maximum energy generation potential. The figure models three types of loading on the piezoelectric cell dimension, with the length of the cell along the x-axis and the width of the cell along the y-axis both equal to 20 meters. The loadings include shear forces, compressive forces, and tensile forces, with a magnitude of 1000 kN/m. By modelling these different loadings, we can gain insight into how the cell will respond to different types and levels of stress. This information is important for optimizing the design and placement of the cells to ensure maximum energy generation potential.

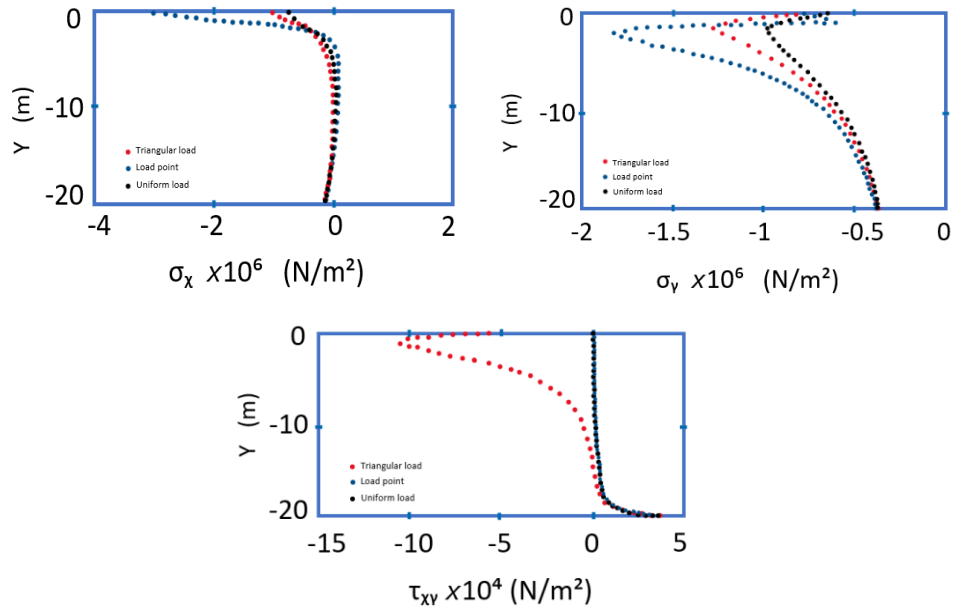

Fig. 6 A visual representation of the stress distribution σ_x, σ_y, and τ_{xy}, in the piezoelectric cell along A-A section under three loads of point, triangular, and uniform.

The Open Circuit Voltage (OCV) is a measure of the voltage generated by the piezoelectric material when it is subjected to mechanical stress or strain. It is an important parameter to consider when designing piezoelectric devices for energy harvesting, as it determines the amount of electrical energy that can be harvested from the mechanical energy.

The OCV can be calculated using the following equation:

$$(\mathrm{OCV}) = g_{33}.\ \sigma\ .\ \mathrm{T} \tag{6}$$

where $g_{3\ 3}$ is the voltage constant and it is a material property that relates the electrical and mechanical properties of the piezoelectric material. In our case of PZE the value of $g_{3\ 3}$ is typically around: $g_{3\ 3} = 21.3\times10^{-\ 3}$ Vm/N.

T: Thickness of piezoelectric cell and here its equal to 2.1 mm.

Similarly, the charge density (CD) is a measure of the amount of electric charge that can be stored in the piezoelectric material. The charge density can be calculated using the following equation:

$$(CD) = \mathrm{d}_{33}\ .\sigma \tag{7}$$

where $d_{3\ 3}$ is the electric charge constant, which is another material property that relates the electrical and mechanical properties of the piezoelectric material. In our cell the value of: $d_{3\ 3} = 485\times10^{-\ 12}$ C/m².

By carefully selecting and designing the piezoelectric material and the device geometry, we can maximize the OCV and charge density, leading to more efficient and effective piezoelectric devices for energy harvesting applications by maximize the amount of stress or strain that it is exposed to, as well as selecting materials with high voltage and charge constants.

3 Results

The results of the stress analysis provide valuable information for the design and analysis of PZE materials, and can help ensure the safety, reliability, and performance of these systems.

According to the stress distribution plots in Fig. 6, it appears that the maximum stress occurs near the cell of the piezoelectric material. This is likely due to the localized deformation and strain that occurs in this region when the material is subjected to mechanical loading.

The maximum stress is observed under point load conditions and is equal to about 1.78×10^{6} N/m² for normal stress σ_{γ}. The minimum stress is observed under uniform distribution load conditions and is equal to 0.96×10^{6} N/m² for normal stress σ_{γ}. For normal stress σ_{χ}, the maximum stress under point load conditions is found to be 0.12×10^{6} N/m², while the stress distribution under uniform and triangular loads appears to be relatively close together.

In terms of shear stress $\tau_{\chi\gamma}$, the maximum stress is observed under triangular load conditions and is equal to 10.3×10^{4} N/m². The stress distribution under point and uniform load conditions for shear stress $\tau_{\chi\gamma}$ appears to be relatively close together. Using the OCV equation with a normal stress of 1.8×10^{6} N/m², the Open Circuit Voltage generated by the piezoelectric material was found to be 76.7 Volts. Using the formula for charge density (CD) with the area of the piezoelectric cell (400 m²), the charge density was calculated to be 0.34 A. Using the current and voltage values, the Power output was calculated to be 26.078 Watt. It's important to note that these calculations assume ideal conditions and may not be representative of the actual performance of the piezoelectric material in practical

applications. Further research and testing may be needed to fully understand and optimize the performance of the material for specific applications.

Conclusion

This research focuses on investigating the impact of stress on piezoelectric cells located on roads with electric voltage and aims to optimize their design and placement to improve their accuracy and effectiveness in generating electricity from passing vehicles. Three types of loading (one-point loading, uniform distributed loading, and triangle-distributed loading) were analysed using finite element analysis (FEA) simulations to model the compression cells and simulate load-truck conditions. The results provide valuable insights into the behavior of piezoelectric cells under different loading conditions and can be used to inform the development of new materials and technologies for road surfaces that can better withstand the stress and shear exerted by heavy vehicles. we found that the normal stress of 1.8×10^6 N/m², the charge density and power output were also calculated to be 0.34 A and 26.078 Watt, respectively, based on the area of the piezoelectric cell (400 m²) and the current and voltage values. This research has the potential to contribute significantly to the fields of transportation, energy, and materials science, as it can inform the development of more efficient and sustainable road systems. By generating electricity from passing vehicles, piezoelectric cells can help reduce the reliance on non-renewable energy sources and promote the use of clean energy. Overall, this study highlights the importance of understanding the impact of stress on piezoelectric cells and provides a foundation for further research and development in this field.

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