Electricity Generation Due to Vibration of Moving Vehicles Using Piezoelectric Effect

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Abstract

Vibration energy (mechanical energy) that is generated by vehicle movement on the road converted into electric energy by piezoelectric effect. Piezoelectricity is the electric charge that accumulates in certain solid material (notably crystal, certain ceramic and biological matter such as bone, DNA and various proteins) in response to applied mechanical stress. The aim of this research work is to make power generation more sustainable, economical and ecological by utilizing the advancement in the technology.

Keywords: Vibration energy, piezoelectric effect, sustainable power.

1. Introduction

As piezo energy harvesting has been investigated only since the late 1990s [1], it remains an emerging technology. When vehicles move on the road, the piezoelectric materials under the road are vibrated due to vehicle suspension in the tires that force the road and produces electricity in large amount [2]. Piezoelectricity is the electric charge that accumulates in certain solid materials (such as crystals, certain ceramics, and biological matter such as bone, DNA and various proteins) [3] in response to applied mechanical stress. Piezoelectricity was discovered in 1880 by French physicists Jacques and Pierre Curie [4]. The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry [5]. The piezoelectric effect is a reversible process in that materials exhibiting the direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force)
also exhibit the reverse piezoelectric effect (the internal generation of a mechanical strain resulting from an applied electrical field) [6-9]. For example, lead zirconate titanate crystals will generate measurable piezoelectricity when their static structure is deformed by about 0.1% of the original dimension. Conversely, those same crystals will change about 0.1% of their static dimension when an external electric field is applied to the material. The inverse piezoelectric effect is used in production of ultrasonic sound waves [6, 8, 10]. Piezoelectricity is found in useful applications such as the production and detection of sound, generation of high voltages, electronic frequency generation, microbalances, and ultrafine focusing of optical assemblies. It is also the basis of a number of scientific instrumental techniques with atomic resolution, the scanning probe microscopies. Most piezoelectric electricity sources produce power [11-12] on the order of milliwatts, too small for system application, but enough for hand-held devices such as some commercially available self-winding wristwatches. One proposal is that they are used for micro-scale devices, such as in a device harvesting micro-hydraulic energy.

2. Mechanism for Piezoelectricity
Many materials, both natural and synthetic, exhibit piezoelectricity. Crystals which acquire a charge when compressed, twisted or distorted are said to be piezoelectric. This provides a convenient transducer effect between electrical and mechanical oscillations. The generation of an electric charge in certain nonconducting materials, such as quartz crystals and ceramics, when they are subjected to mechanical stress (such as pressure or vibration), or the generation of vibrations in such materials when they are subjected to an electric field. Piezoelectric materials exposed to a fairly constant electric field tend to vibrate at a precise frequency with very little variation. The nature of the piezoelectric effect is closely related to the occurrence of electric dipole moments in solids. Of decisive importance for the piezoelectric effect is the change of polarization $P$ when applying a mechanical stress. This might either be caused by a re-configuration of the dipole-inducing surrounding or by re-orientation of molecular dipole moments under the influence of the external stress. Piezoelectricity may then manifest in a variation of the polarization strength, its direction or both, with the details depending on (i) the orientation of $P$ within the crystal, (ii) crystal symmetry and (iii) the applied mechanical stress. The change in $P$ appears as a variation of surface charge density upon the crystal faces, i.e. as a variation of the electrical field extending between the faces caused by a change in dipole density in the bulk. For example, a 1 cm$^3$ cube of quartz with 2 kN (500 lbf) of correctly applied force can produce a voltage of 12500 V [13]. There is a magnetic analog where ferromagnetic material respond mechanically to magnetic fields. This effect, called magnetostriction, is responsible for the familiar hum of transformers and other AC devices containing iron cores. Piezoelectric materials also show the opposite effect, called converse piezoelectric effect, where the application of an electrical field creates mechanical deformation in the crystal. Piezoelectric materials exhibit both a direct and a reverse piezoelectric effect. Fig. 1 indicates conversion of vibration/ mechanical energy into
Electricity Generation Due to Vibration of Moving Vehicles Using Piezoelectric

Electrical energy and vice versa. The direct effect produces an electrical charge when a mechanical vibration or shock is applied to the material, while the reverse effect creates a mechanical vibration or shock when electricity is applied. Any spatially separated charge will result in an electric field, and therefore an electric potential. In a piezoelectric device, mechanical stress, instead of an externally applied voltage, causes the charge separation in the individual atoms of the material. Fig. 2 indicates generation of piezoelectricity. For polar crystals, for which $P \neq 0$ holds without applying a mechanical load, the piezoelectric effect manifests itself by changing the magnitude or the direction of $P$ or both. For the non-polar, but piezoelectric crystals, on the other hand, a polarization $P$ different from zero is only elicited by applying a mechanical load. For them the stress can be imagined to transform the material from a non-polar crystal class ($P = 0$) to a polar one [14], having $P \neq 0$. Fig. 3 shows mechanism of piezoelectric effect in quartz.

**Fig. 1:** Conversion of vibration/mechanical energy into electrical energy and vice versa.

**Fig. 2:** Generation of piezoelectricity.

**Fig. 3:** Mechanism of piezoelectric effect in quartz.
3. Mathematical Descriptions

Piezoelectricity is the combined effect of the electrical behavior of the material: \( \mathbf{D} = \varepsilon \mathbf{E} \), where \( \mathbf{D} \) is the electric charge density displacement (electric displacement), \( \varepsilon \) is permittivity and \( \mathbf{E} \) is electric field strength, and Hooke's Law: \( \mathbf{S} = s \mathbf{T} \), where \( \mathbf{S} \) is strain, \( s \) is compliance and \( \mathbf{T} \) is stress. These may be combined into so-called coupled equations, of which the strain-charge form is:

\[
\{ \mathbf{S} \} = [\mathbf{s}^{E}] \{ \mathbf{T} \} - [\mathbf{d}]\{ \mathbf{E} \} \quad \& \quad \{ \mathbf{D} \} = [\mathbf{s}^{I}]\{ \mathbf{T} \} - [\mathbf{d}^{T}]\{ \mathbf{E} \}
\]

where \( [\mathbf{d}] \) is the matrix for the direct piezoelectric effect and \( [\mathbf{d}^{T}] \) is the matrix for the converse piezoelectric effect. The superscript \( E \) indicates a zero, or constant, electric field; the superscript \( T \) indicates a zero, or constant, stress field; and the superscript \( t \) stands for transposition of a matrix. The strain-charge for a material of the 4mm (C\(_{4v}\)) crystal class (such as a poled piezoelectric ceramic such as tetragonal PZT or BaTiO\(_3\)) as well as the 6mm crystal class may also be written as:

\[
\begin{bmatrix}
S_1 \\
S_2 \\
S_3 \\
S_4 \\
S_5 \\
S_6
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 2(\varepsilon_{11} - \varepsilon_{12}) \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
T_1 \\
T_2 \\
T_3 \\
T_4 \\
T_5 \\
T_6
\end{bmatrix} + \begin{bmatrix}
\varepsilon_{11} & 0 & 0 & 0 & 0 & 0 \\
0 & \varepsilon_{12} & 0 & 0 & 0 & 0 \\
0 & 0 & \varepsilon_{13} & 0 & 0 & 0 \\
0 & 0 & 0 & \varepsilon_{22} & 0 & 0 \\
0 & 0 & 0 & 0 & \varepsilon_{33} & 0 \\
0 & 0 & 0 & 0 & 0 & \varepsilon_{33}
\end{bmatrix} \begin{bmatrix}
E_1 \\
E_2 \\
E_3
\end{bmatrix}
\]

where the first equation represents the relationship for the converse piezoelectric effect and the latter for the direct piezoelectric effect [15]. Although the above equations are the most used form in literature, some comments about the notation are necessary. Generally \( \mathbf{D} \) and \( \mathbf{E} \) are vectors, that is, Cartesian tensor of rank-1; and permittivity \( \varepsilon \) is Cartesian tensor of rank 2. Strain and stress are, in principle, also rank-2 tensors. But conventionally, because strain and stress are all symmetric tensors, the subscript of strain and stress can be re-labeled in the following fashion: \( 11 \to 1; \ 22 \to 2; \ 33 \to 3; \ 23 \to 4; \ 13 \to 5; \ 12 \to 6. \) (Different convention may be used by different authors in literature. Say, some use \( 12 \to 4; \ 23 \to 5; \ 31 \to 6 \) instead.) That is why \( \mathbf{S} \) and \( \mathbf{T} \) appear to have the "vector form" of 6 components. Consequently, \( s \) appears to be a 6 by 6 matrix instead of rank-4 tensor. Such a re-labeled notation is often called Voigt notation. In total, there are 4 piezoelectric coefficients, \( d_{ij}, \varepsilon_{ij}, g_{ij}, \) and \( h_{ij} \) defined as follows:
Electricity Generation Due to Vibration of Moving Vehicles Using Piezoelectric

\[
d_{ij} = \left( \frac{\partial D_i}{\partial E_j} \right)^T = \left( \frac{\partial S_i}{\partial E_j} \right)^T
\]

\[
e_{ij} = \left( \frac{\partial D_i}{\partial S_j} \right)^T = -\left( \frac{\partial E_i}{\partial S_j} \right)^T
\]

\[
g_{ij} = -\left( \frac{\partial E_i}{\partial T_j} \right)^T = \left( \frac{\partial S_i}{\partial T_j} \right)^T
\]

\[
h_{ij} = -\left( \frac{\partial T_i}{\partial S_j} \right)^T = -\left( \frac{\partial T_i}{\partial D_j} \right)^T
\]

where the first set of 4 terms correspond to the direct piezoelectric effect and the second set of 4 terms correspond to the converse piezoelectric effect [16]. Formalism has been worked out for those piezoelectric crystals, for which the polarization is of the crystal-field induced type that allows for the calculation of piezoelectrical coefficients \(d_{ij}\) from electrostatic lattice constants or higher-order Madelung constants.

4. Application & Scope

Industrial and manufacturing units are the largest application market, for piezoelectric devices, followed by the automotive industry. There is also high demand from medical instruments as well as information in telecommunication. The global demand for piezoelectric devices was valued at approximately US$14.8 billion in 2010. The largest material group for piezoelectric device is piezocrystal and piezopolymer due to its low weight and small size. Piezoelectric crystals are now used in buzzer, solar system also. This technique can solve the problem of electricity to road lighting system, and without the need of kilometers of electrical wire which runs along the side of the road. It is more efficient operation techniques with cost effective device. Piezoelectric materials are capable of carrying high load and operating very high frequencies. It requires no maintenance as there are no moving parts. It acts as a capacitor and therefore requires very little power. However, protection of sensitive piezoelectric devices is required against harsh weather condition, and strong electric fields (200-500V/mm) can break down dipoles and depolarize a piezoelectric material.

5. Conclusion

Piezoelectric materials have the ability to transform mechanical strain energy into electrical charge. The amount of energy generated depends on the number of passing vehicles and the number of piezoelectric elements on the road. Vehicles that are moving slowly appears to generate slightly more energy than faster – moving vehicles, but further research is needed to confirm this piezoelectric power generation system works successfully. It has tremendous scope for future energy/ power solution towards sustainability.
References


