Earthquake versus Electric Field
(A Resistant Design with Piezo Ceramic Materials)

Ankur Tayal

Department Of Civil Engineering, Inderprastha Engineering College, Ghaziabad, U.P., India
E-mail:ankurtayal3@gmail.com

I. ABSTRACT

This paper relates to vibration control using piezo electric materials. The vibration controlefficiencyrelies on the optimization of thevibration energytransfer between a structure and Lead-Zirconate-Titanate (PZT) piezoelectric ceramic material. In this paper, an analytical study of electric field producedby applied stresses of earthquake vibrations to control and damp them is presented.The influence of electric field formed around ceramic material forms a shield to further counter effect the upcoming vibrations is discussed.

Keywords:
Electric field , Shield, Voltage, Strain, Piezo Lead-Zirconate-titanate (PZT)

II. INTRODUCTION

Earthquake resistant design structureshas been a subject of engineering research for the past few decades till now. Many Researches in this field haveundergone to control the vibratory effect of earthquakes.Earthquakes occur due to sudden release of stored energy . Mostearthquakes take place along faults in the upper 25 miles of the earth's surface when one side rapidly moves relative to the otherside of the fault. This sudden motion causes shock waves (seismic waves) to radiate from their point of origincalled the **focus** and travel through the earth. The stresses developed due to these vibrations are firstly affect the foundation of a structure. Hagood and von Flotow (1991) have demonstrated vibrations of a structure can be controlled with piezo materials . The piezoelectric materials convert vibration energy to electrical energy by polarizing themselves. Due to polarization voltage is induced which can be used to create a 3d network or cover of electrical fields around . The cover of fieldformed act as a shield between the foundation and earthquake vibrations.

III. WORKING OF PIEZO MATERIALS

- *Direct Piezoelectric effect*

Deformation of the piezomaterial causes an electrical charge on certain opposite faces of the piezo electric material. The separation between negative and positive charge sites (the electric dipole) leads to a netpolarization. The polarization generates a voltage. Theproduced voltage can be used to create electric field lines. These field lines generated are in form of concentric circles around the crystal. Figure 1 shows a schematic diagram of piezo material with applied force . The force leads to polarization of the crystal with positive side on upper side and negative down side.

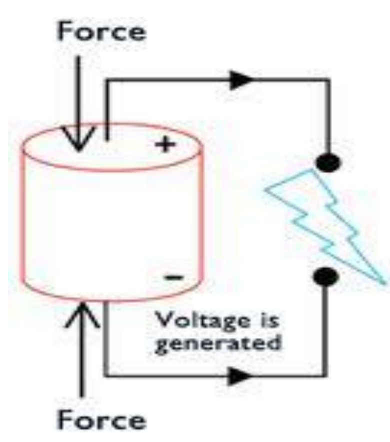

Figure 1 Generation of Voltage

This generates a high power voltage. Due to high power voltage current is set up as shown. This set up current has tendency to create Shield of electric field around them

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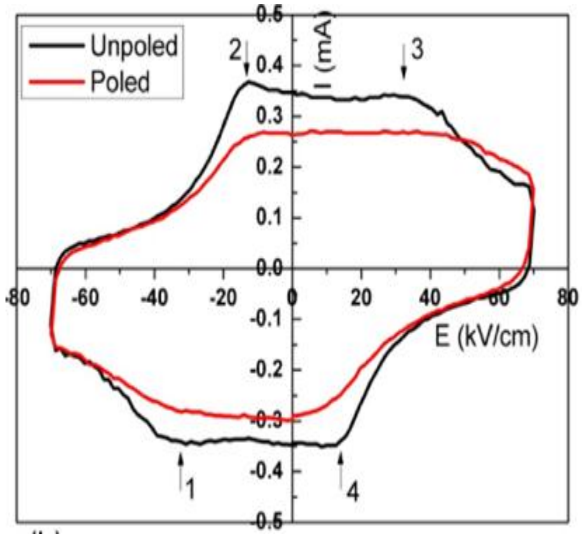


Figure 2. A plot for voltage produced current and electric field in Piezo material

A. Electric Field As Shield

The key concept of this paper lies in the fact that laying of such materials within the foundations of structures such that in conditions of earthquakes these material experiences the net effective stress resulting in effective strain which Creates electric field pattern This pattern acts as protecting shield or umbrella for the upcoming vibrations. The shield will continue until the effect of vibrations last longs and keep on acting against the vibrations of earthquakes by strong opposite head on collisions against them.

B. Actuation of Structural Components by Piezoelectric Crystals

a) When a poled ceramic material is maintained below its curietemperature and issubjected to a macroscopicexpansion along the polingaxis and contraction perpendicular to it dipoles respond collectively to produce an effective electric field.

b) Electric field due to geometry and deformation of PZT poled in the 3 direction of a simple cube.

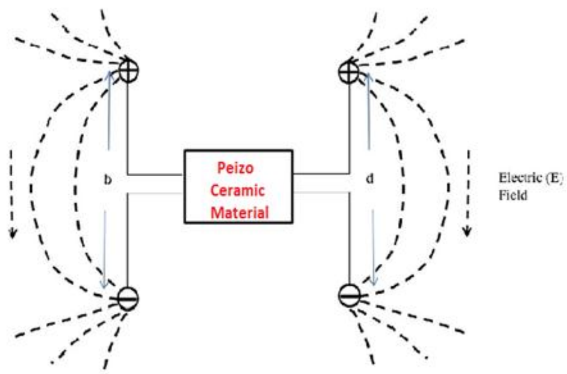


Figure 3. Electric field lines around cubic Crystal

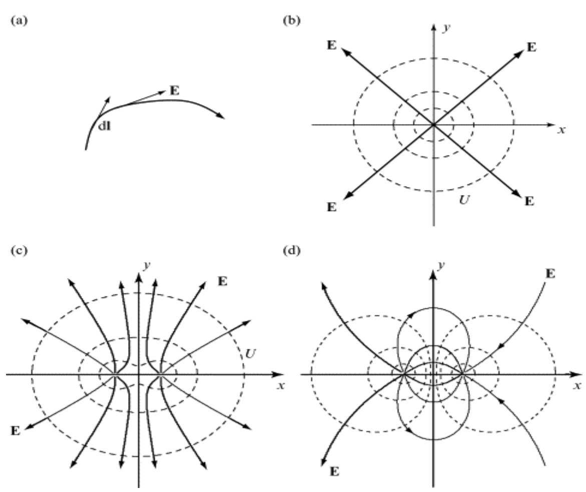


Figure 4. Electric Field Patterns forming Field line Shield

C. Basic Key Concept Model

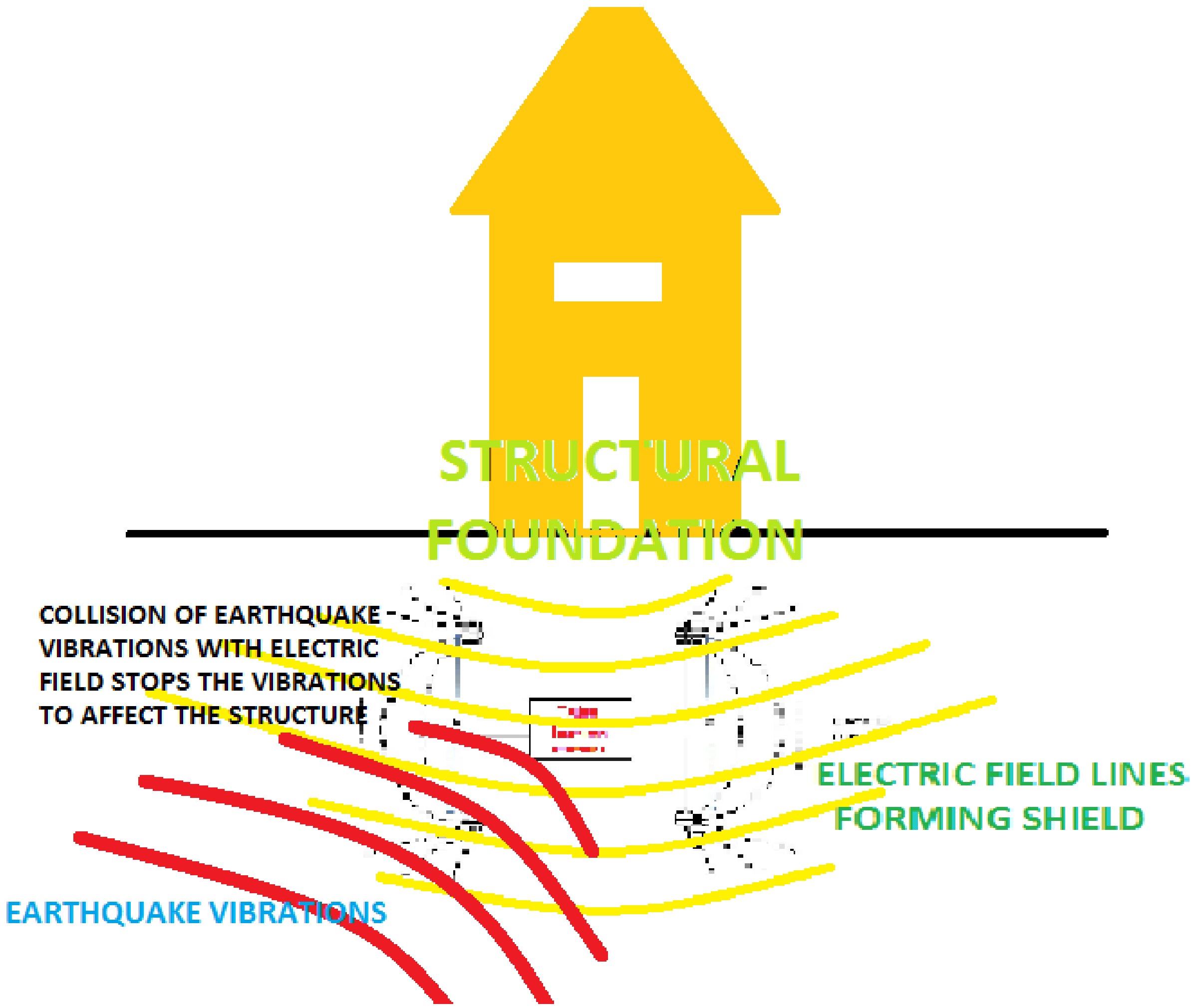


Figure 5.Research Concept Model

Figure 5illustrates the basic concept of the research work. The model represents the structure installed with a piezo ceramic material . This material when acted upon by earthquake vibrations generates strong yellow colour electric field around the foundation of structure. Collision between electric field and earthquake vibrations occurs which results in resisting and damping of destructive vibrations and safeguarding the structure from hazardous earthquake.

IV. ELECTRIC FIELD AND STRAIN RELATIONSHIP

A. *g" CONSTANT:*

The piezoelectric constants relating the electric field produced by a mechanical stress are termed the voltage constants, or the "g" coefficients. The units may then be expressed as **volts/meter per newtons/square meter**.

$$g = \frac{\text{open circuit electric field}}{\text{applied mechanical stress}}$$

Output electric field is obtained by dividing the calculated voltage by the thickness of ceramic between electrodes . A "33" subscript indicates that the electric field and the mechanical stress are both along the polarization axis . A "31" subscript signifies that the pressure is applied at right angles to the polarization axis, but the voltage appears on the same electrodes as in the "33" case. A "15" subscript implies that the applied stress is shear and that the resulting electric field is perpendicular to the polarization axis. High g_{ij} constants favor large voltage output. Although the g coefficient are called voltage coefficients, it is also correct to say the g_{ij} is the ratio of strain developed over the applied charge density with units of meters per meter over coulombs per square meter.

Strain refers to effective deformation produced due to application of stresses. Relationship between field strength and strain is quantified by the piezoelectric moduli $\boldsymbol{d_{ij}}$.

Where
i : direction of the electric field
j : direction of the resulting normal strain
For example:

$$\varepsilon_{33} = d_{33} \cdot \frac{V}{t},$$

$$\varepsilon_{11} = d_{31} \cdot \frac{V}{t},$$

Where
V : voltage applied in the 3-direction
t : thickness of the specimen

Typical values of the piezoelectric of piezoelectric moduli are given in following table:

Table. Typical Piezoelectric Moduli of PZT materials (V/m)

	d_{33}	d_{31}
Hard PZT	225×10^{-12}	-100×10^{-12}
Soft PZT	600×10^{-12}	-275×10^{-12}

For the same produced strain due toequal applied stresses, soft
PZT will generate strong electric shield.

B. *Mathematical Solution With Model References for Generated Voltage And Field*

i. Electrical equivalent circuit

The study of the transient dynamic characteristics of a PZT bender utilizing electrical equivalent models has been performed in previous studies and the model has shown fair accuracy in various conditions of mechanical stress The electrical equivalent model has been studied and implemented in this research compare the accuracy and validity of the and the analytical results from models based on beam theory and energy conservation for PZT beam.

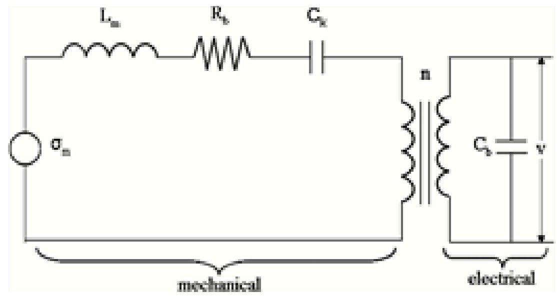


Figure 6. An electric equivalent circuit model for a PZT beam

where a voltage source is connected in series with an inductor, a resistor and a capacitorthat build a resonant circuit. The transformer represents the voltage adaptation while the capacitor indicates the inherent capacitance of the device.

The circuit can be described by using Kirchhoff's voltage law:

$$\sigma_{\text{in}} = L_m \varepsilon + R_b \dot{\varepsilon} + \frac{\ddot{\varepsilon}}{C_k} + nV \qquad (1)$$

$$i = C_k \dot{V}. \qquad (2)$$

The equivalent circuits leads to the correlation between the strain *e* and voltage *V* .

$$\ddot{\varepsilon} = \frac{-Y}{k_1 k_2 m}\varepsilon - \frac{b_m}{k_1 m}\dot{\varepsilon} + \frac{Y}{k_1 k_2 m}\frac{d_{31}}{2t_c}V + \frac{\ddot{y}}{k_2},$$

and

$$V = \frac{n_p t_c d_{31} Y}{\varepsilon}\dot{\varepsilon}$$

where

$\ddot{\varepsilon}, \dot{\varepsilon} \rightarrow$ second and first time derivative of strain.

ii. Beam theory (Timoshenko and Euler–

Bernoulli)

The static analysis of a piezoelectric cantilever sensor is typically performed by the use of calculations employed for de ection of a thermal bimorph proposed by Timoshenko The principle is based on the strain compatibility between three heterogeneous bimorph where two piezoelectric layers are bonded on cantilever beams joined along the along the bending axis . Due to forces applied by one or all of the layers, the de- ection of the three layer structure is derived from a static equilibrium state. The structure considered is a piezoelectric is assumed to be approximately the same to those of the structure, simply because of the assumption both sides of a purely elastic layer, i.e. brass with a pure elasticity is sandwiched between the upper and lower layers of the PZT material. The beam thickness is much less than the piezoelectric – induced curvature. The radius of curvature for all the layers that the thickness is much less than the overall beam curvature. The total strain at the surface of each layer is the sum of the strains caused by the piezoelectric effect the axial force, and the bending.

$$\varepsilon_i = \varepsilon_{\text{piezo}} + \varepsilon_{\text{axial}} + \varepsilon_{\text{bend}} = d_{31} E_i + \frac{F_i}{A_i Y_i} \pm \frac{t_i}{2r} \qquad (5)$$

where εpiezo in the linear constitutive equation above considers the transverse piezoelectric coupling coefficient d31 and the electric field across the thickness of the layer Ei· for a piezoelectric material, t1 and t3 are the thickness of the PZT layer and t2 is the thickness of the center shim, Ai is the area of the corresponding layer and Yi is the young's modulus of elasticity.

Hence the radius of curvature is given by the term:

$$\frac{1}{r} = \frac{2d_{31} DA^{-1}C}{2 - DA^{-1}B}$$

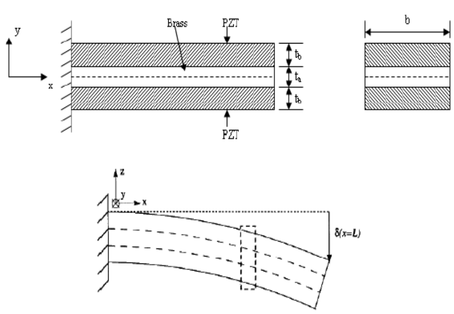


Figure7.Geometry of strain beam due to Stresses

where

$$A = \begin{bmatrix} \frac{1}{A_1 Y_1} & -\frac{1}{A_2 Y_2} & 0 \\ 0 & \frac{1}{A_2 Y_2} & -\frac{1}{A_3 Y_3} \\ 1 & 1 & 1 \end{bmatrix}, \qquad B = \begin{bmatrix} t_1 + t_2 \\ t_2 + t_3 \\ 0 \end{bmatrix},$$

$$C = \begin{bmatrix} -E \\ E \\ 0 \end{bmatrix}.$$

Euler–Bernoulli beam theory describes the relationship between the radius of curvature and the force applied, by the following equation:

$$\rho A \frac{\partial^4 w(x,t)}{\partial t^4} + YI \frac{\partial^4 w(x,t)}{\partial x^4} = F(t) \qquad (7)$$

where ρ is the density, I is the moment of inertia and *F(t)* is the applied force. A general solution for this equation is given by

$$w(x,t) = \sum q_i(t) X_i(x)$$

Equations For Vibrations Produced Due to Displacement :

$$X_i(x) = \cosh(\beta_i x) - \cos(\beta_i x) - \frac{\sinh(\beta_i L) - \sin(\beta_i L)}{\cosh(\beta_i L) + \cos(\beta_i L)} \times (\sinh(\beta_i x) - \sin(\beta_i x)) \qquad (9)$$

$$q_i(t) = \frac{1}{\omega_{di}} e^{-\zeta \omega_{ni} t} \int_0^t F_i(\tau) e^{-\zeta \omega_{ni} t} \sin(\omega_{di}(t-\tau))\, d\tau \qquad (10)$$

and

$$\beta_i^4 = \frac{\omega_{ni}^2}{C^2} \qquad (11)$$

ωn, is the natural frequency obtained by solving the transcendental equation:

$$\mathrm{Cosh}(\beta_i L)\mathrm{Cos}(\beta_i L) + 1 = 0. \qquad (12)$$

The radius of curvature is given by the following equations:

$$r = \frac{1}{2w(L)} L^2, \qquad \text{where } \frac{1}{r} = \dot{w}(x) \text{ and } w(x) = \frac{1}{2r} x^2.$$

Hence by substituting the radius of curvature term in equation (6), **the voltage produced for the PZT** is given by:

$$V = \frac{2w(L)t_p}{L^2}\frac{2-DA^{-1}B}{2d_{31}DA^{-1}}\begin{bmatrix}-1\\1\\0\end{bmatrix}^{-1}. \qquad (13)$$

iii. Conservation of energy

The principle is based on the fact that the total energy of the PZT bender stored isequal to the sum of the mechanical energy applied to the beam. When a mechanical stress is applied, the energy stored in a PZT layer is the sum of themechanical energy and the electric-field-induced energy. Thus, the energy stored in a PZT layer is expressed as follows:

$$U_u = \tfrac{1}{2}(s_{11}^E\sigma_1 - d_{31}E_3)\sigma_1 = \tfrac{1}{2}s_{11}^E\sigma_1^2 \qquad (14)$$

where σ is the stress and s is the stiffness matrix. The energy in the metal layer can be expressed by a simple equation

$$U_m = \tfrac{1}{2}s_m\sigma_1^2. \qquad (15)$$

The total energy of the beam is given as [15]:

$$U_{\text{total}} = \int_0^L\int_0^W\left(\int_{\frac{t_1}{2}}^{\frac{t_2}{2}+t_1} \mathrm{d}U_u\,\mathrm{d}z + \int_{-\frac{t_2}{2}}^{\frac{t_2}{2}} \mathrm{d}U_m\,\mathrm{d}z + \int_{-\frac{t_2}{2}-t_3}^{-\frac{t_2}{2}} \mathrm{d}U_l\,\mathrm{d}z\right)\mathrm{d}y\,\mathrm{d}x. \qquad (16)$$

the electric field is given by ***E = V/(2t3).***

The total electrical energy is equal to a product of the charge and the voltage. Thus, the charge generated in the beam is obtained by a partial derivative of the total energy with respect to the voltage:

$$Q = \frac{\partial U_{\text{total}}}{\partial V} = -3\frac{d_{31}s_m(t_2+t_3)L^2}{X}F_o.$$

The capacitance of the piezoelectric material is described as the relation between the voltage and charge on the piezoelectric material.

$$C_{\text{free}} = \frac{\nu_{33}^{\mathrm{T}}WL}{2t_3}\left(1+\frac{(6s_m t_3(t_2+t_3)^2 - X)}{X}K_{31}^2\right) \qquad (18)$$

where $K31$ is the coupling coefficient

Thus, the voltage generated is found as a function of the applied force:

$$V = \frac{Q}{C_{\text{free}}} = -\frac{6d_{31}s_m t_3(t_2+t_2)L}{\nu_{33}^{\mathrm{T}}WX(1+(\frac{6s_m t_3(t_2+t_3)^2}{X}-1)K_{31}^2)}F_o. \qquad (19)$$

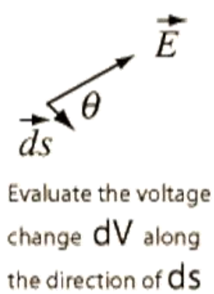
All of the modelsdescribed above are solved by using Matlab/Simulink. Simulation results are compared with the experimental results in the following sections:

$$V = -\frac{6d_{31}s_m t_3(t_2+t_3)L}{\nu_{33}^{\mathrm{T}}WX(1+(\frac{6s_m t_3(t_2+t_3)^2}{X}-1)K_{31}^2)}M_{\text{end}}\times\ddot{Z}(t).$$

C. *V and E relationship*

The scalar electric potential (voltage) is that the electric field can be calculated from it. The component of electric field in any direction is the negative of rate of change of the potential in that direction. If the differential voltage change is calculated along a direction ds, then it is seen to beequal to the electric field component in that direction times the distance ds.

$$dV = -\vec{E}\cdot\vec{ds} = -E_s ds$$



The electric field can then be expressed as

$$E_s = -\frac{dV}{ds} \text{ along ds, or } E_s = -\frac{\partial V}{\partial s}$$

For rectangular coordinates, the components of the electric field are

$$E_x = -\frac{\partial V}{\partial x} \quad E_y = -\frac{\partial V}{\partial y} \quad E_z = -\frac{\partial V}{\partial z}$$

Thus taking the partial derivative of above all Voltage equations Eq. [3] , [13] and [19] with x, y and z gives the electric field in that direction.

V. RESULTS

The above Electric field lines obtained when encounters with the vibrations originating from focus of the earth , the collision between the two results in the slowly reducing and then simultaneously damping of the earthquake radiations. As they approaches close to crystal their effect reduces rapidly due to the continuous increase in intensity of electric field. Characteristic functions of earthquake vibrationsrepresented as functions in the form of their **mobility (1) or slowness (2):**

$$V(s) = H\frac{c_k s^k + c_{k-1}s^{k-2} + \ldots + c_1 s}{d_l s^l + d_{l-1}s^{l-2} + \ldots + d_0}$$

$$U(s) = H\frac{d_l s^l + d_{l-1}s^{l-2} + \ldots + d_0}{c_k s^k + c_{k-1}s^{k-2} + \ldots + c_1 s}$$

where:
k, l - natural numbers,
c, d - real numbers,
H - any positive real number.

$$V(s) = \frac{c_1}{s} + m_1 s + \cfrac{1}{\cfrac{s}{c_2} + \cfrac{1}{m_2 s + \ldots + \cfrac{1}{\cfrac{s}{c_n} + \cfrac{1}{m_n s}}}}$$

$$U(s)\frac{1}{H} = \frac{c_1}{s} + m_1 s + \frac{1}{\frac{s}{c_2} + \frac{1}{m_2 s}} + \ldots + \frac{1}{\frac{s}{c_n} + \frac{1}{m_n s}}$$

where:
c - elastic elements,
m - inertial elements.

Thus V(s) and U(s) are the slowness functions which represents the slowing and damping down the effect of consecutive vibrations of earthquake. These factors results in losing of velocity of earthquake vibrations and gradually damping of them.

VI. CONCLUSIONS

This paper presents a theoretical approach in the field of civil engineering. The concept discussed above with mathematical solutions shows that using the ability of peizo ceramic materials to gets polarized under effective stresses resulting strain creates a potential difference within the crystal. This potential can be harnessed to produce high voltages. The partial derivative of this voltage developed in three dimensions creates a network of electric field around the structure under which it is laid. This network acts a shield or cover to safeguard the structure from the consecutive effect of vibrations originating from focus of the earthquake. The voltage equations Provided in section [B.1],[B.2]and [B.3] shows voltage can be effectively produced in piezo materials whereas article [C] presents the solution to generate electric field from that voltage produced.

The slowness factor discussed under results section V. indicates the slowing and damping effect of vibrations under the influence of developed electric shield.

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REFERENCES

[1] N. W. Hagood and A. von Flotow, "Damping of Structural Vibrations with Piezoelectric Materials and Passive Electrical Networks", Journal of Sound and Vibration, 146(2), pp. 243 – 268, 1991

[2] ME 493 Introduction to Smart Structures and Materials, SPRING 2011, METU, Ankara Dr. Gökhan O. ÖZGEN

[3] Application of mechanical andelectrical elements in reduction of vibration K. Białas* Institute of Engineering Processes Automation and Integrated ManufacturingSystems, Silesian University of Technology, .ul. Konarskiego 18a, 44-100 Gliwice, Poland

[4] A Survey of Recent Innovations in Vibration Damping and Control Using Shunted Piezoelectric Transducers S. O. RezaMoheimani, *Senior Member, IEEE*

[5] Modeling and analysis of a bimorphpiezoelectric cantilever beam for voltage generation J Ajitsaria1, S Y Choe1, D Shen2 and D J Kim2 , AL 36849 USA

AUTHOR

First Author : Ankur Tayal
B.tech (3rd year)

Department of Civil Engineering
Inderprastha Engineering Colleg
63 Site IV Surya Nagar Flyover
Road Sahibabd Ghaziabad U.P.
ankurtayal3@gmail.com

Correspondence Author: Ankur Tayal
4647/15 Jai Mata Market
Tri Nagar New Delhi New
Delhi – 110035
9582974527 (m)
011 – 27392941 ®
ankurtayal3@gmail.com