



ELECTRICITY GENERATION BY VIBRATING PIEZOELECTRIC CRYSTAL IN ROADWAY USING SIMULINK

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Abstract: Over the past few years, considerable information has surfaced on these uses of piezoelectric-based energy-harvesting technology. There is a need to obtain a third party independent assessment of the available information and to determine if a specific future evaluation or demonstration will facilitate the commercial success of the technology. One area of interest is to determine if the technology has the potential to generate electricity with performance, reliability, and cost projections that are comparable to existing or emerging renewable energy sources. The objective of this project is to provide a vibration and displacement in the light motor vehicles and heavy motor vehicles. And the same vibration is passed to piezoelectric material which is present under the road. Piezoelectric-based energy-harvesting technology as applied to the generation of electricity from roadways.

Keyword: Road mapping, suspension system, piezoelectricity, simulation.

I. Introduction

A. Piezoelectric Materials

Piezoelectric materials fall within a class of multiple solid state materials that can generate electricity with the application of some stimulus such as heat, stress, or light. Photovoltaic materials generate electricity with the application of light (the basis of solar panels), and thermoelectric materials generate electricity with the application of heat. Piezoelectric materials generate electricity with the application of stress. These materials are all semiconductors, meaning they are much like conventional electronics, generally constructed of Silicon (Si) or Germanium (Ge) with additional elements.

Using piezoelectrics to harvest vibration energy from humans walking, machinery vibrating, or cars moving on a roadway is an area of great interest, because this vibration energy is otherwise untapped. Since movement is everywhere, the ability to capture this energy cheaply would be a significant advancement toward greater efficiency and cleaner energy production.

B. Physics of Piezoelectricity

There is one characteristic equation which governs all piezoelectric devices. It is called the piezoelectric equation, and it is given in equation 1. This equation relates the compressive force per unit area (pressure) to the Electric Displacement. This is the basic equation used in analysis of piezoelectric devices.

$$D_i = d_{ij} \cdot \sigma_j = d_{ij} \frac{F}{A} \quad (1)$$

where: D_i = Electric Displacement; d_{ij} = Piezoelectric Constant;

σ_j = Mechanical Stress; F = Force; A = Area

The equivalent circuit element equations for a piezoelectric material at electromechanical resonance are shown in equations 2, 3 and 4 for the resistance, inductance and capacitance, respectively. Equation 6 shows the natural capacitance of the material, formed by a dielectric material sandwiched between two metal plates.

$$R_m = \frac{\eta}{A\epsilon^2} = K_R \eta \quad (2)$$

$$L_m = \frac{\rho_s l^2}{2A\epsilon^2} = k_L \rho_s \quad (3)$$

$$C_m = \frac{A\epsilon^2}{cl} = k_c \frac{1}{c} = k_c S \quad (4)$$

where: c = elastic constant; s = compliance coefficient;
 e = piezoelectric stress constant; A = area;
 l = height of the material; ρ_s = surface mass density; η = viscosity

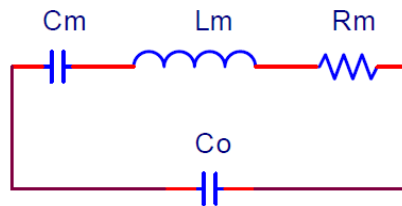


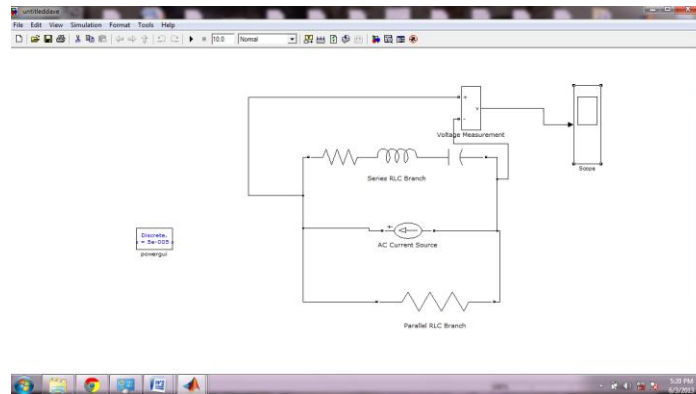
Figure 1: Piezoelectric Material Equivalent Circuit Model

$$C_0 = \frac{\epsilon A}{l} \quad (5)$$

where: c = elastic constant; s = compliance coefficient;
 e = piezoelectric stress constant; A = area;
 l = height of the material; ρ_s = surface mass density; η = viscosity

$$T_1 = \frac{F}{\pi r_k^2} \quad (6)$$

Explanation (1):



Changing the value of C_0 into current source taking 1V energy generation by one block of piezo electric crystal all values are standard for 1V Generation by taking

Second order RLC equation $i(t) = V(t)/R + 1/L \int V(t)dt + CdV(t)/dt$
 $C_0 = 1.44F, R_m = 1.66M\Omega, L_m = 2.96mH, C_m = 88pF$ and by converting

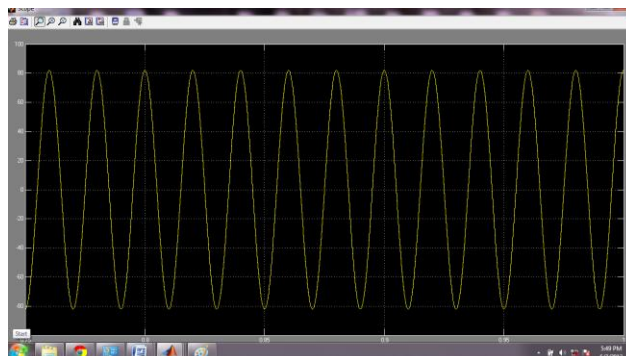
$V = 1 = 1/C_0 \int i(t) \sin \omega t dt$

Taking laplace Transform

$i(s) = \omega C_0 S / (S^2 + \omega^2)$

taking inverse laplace Transform

$i(t) = 144 \cos(90^\circ + \omega t)$



This means if $2n$ units are there in 0.34 m span and n units are hit by automobile then $80V$ of Electricity will produce where $n=100$.

II. Resonator Model

A. Introduction

Basic control theory was used to develop a model for the mechanical mass-spring resonator. This allowed the research of the transfer functions representing mechanical systems and their time-domain counterparts. Using this information, the mass-spring resonator (MSR) was modeled as a single axis of motion mechanical system, consisting of a spring, with a mass attached to its free end. When a force is applied to the mass, the mass spring system starts to oscillate. The piezoelectric material is placed between the spring and the rigid attachment. It was assumed that there was no deviation in the physical dimensions of the piezoelectric material, such as thickness, radius, and Young's Modulus. This is not perfectly the case, but since the actual deviations are minute, on the order of nanometers, this is an appropriate approximation. The force that is transmitted through the piezoelectric material is then found by calculating the force exerted through the spring. This is done by taking the deflection of the spring and multiplying it by the spring constant.

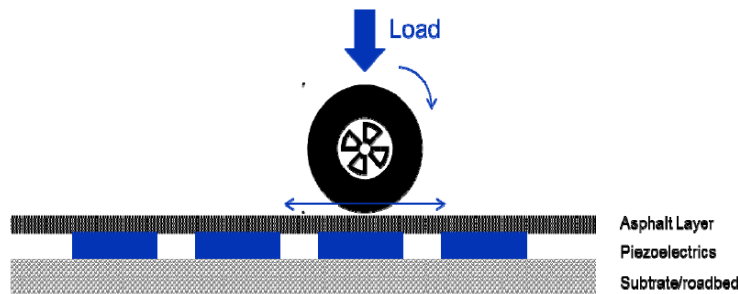


Figure 1: Schematic of an Accelerated Ageing Platform for a Piezoelectric Energy Harvester Application

B. Derivation of Mechanical Model

The first steps taken were to analyze the mechanical system itself. The system consists of a housing, in which a ring shaped piece of PZT material is mounted. This material is sandwiched between the housing and the mass spring unit. The mass spring unit consists of a machined piece of metal which has been cut in such a way that it works as a spring with a high spring constant, on the order of N/m. This spring has a mass associated with it, on the order of several grams. The combined mass-spring system will oscillate when it is subjected to an input force. This oscillation will compress the piezoelectric material and thus the piezoelectric material will generate a voltage.

Some assumptions were made about the system to make analysis easier. It was assumed that the system was one dimensional, meaning that it would not be responsive to any excitations that are exerted upon it outside of its primary axis. Secondly, the deflection of the piezoelectric material was ignored. Lastly, the internal damping of the materials was also ignored. It was assumed that the contribution of this effect is very small, and of little consequence to the overall performance of the system.

1. First Generation Model - Development

To approach developing a real-time model for the resonator concentrated in the area of mechanical system representations. Using the fact that force is conservative, equations 7 and 8 were written.

$$M \frac{d^2 x(t)}{dt^2} + Kx(t) = f(t) \quad (7)$$

$$Ms^2 X(s) + KX(s) = F(s) \quad (8)$$

where: M – Mass;

K - Spring Constant of the resonator;

$x(t)$ - Position of the oscillating spring relative to its static position;

$X(s)$ - Denotes the frequency-domain representation of the spring position. From these equations a relationship may be established which relates the position of the spring to the external force applied to the mass-spring system. This relationship is called the mass-spring system transfer function, and is critical because with it, the exact position of the spring can be known in real-time.

Equation 9 shows the transfer function for this mass-spring system.

$$G(s) = \frac{X(s)}{F(s)} = \frac{1}{Ms^2 + K} \quad (9)$$

2. Second Generation Model - Derivation

Once these problems were identified, it was decided that the internal damping of the spring was not inconsequential, and therefore needed to be accounted for. To accomplish this, the derivation procedure used previously for the undamped mass spring resonator was again used. The new equations are shown in equations 10 and 11. The difference between these two equations, and the equations derived previously is the presence of the f_v term, which is the damping constant.

$$M \frac{d^2 x(t)}{dt^2} + f_v \frac{dx(t)}{dt} + Kx(t) = F(t) \quad (10)$$

$$Ms^2 X(s) + f_v X(s) + KX(s) = F(s) \quad (11)$$

Again the system transfer function needed to be calculated. The only difference between the undamped and damped transfer function is the presence of the f_v term in the damped function. Shown in equation 12 is the damped transfer function.

$$G(s) = \frac{X(s)}{F(s)} = \frac{1}{Ms^2 + f_v s + K} \quad (12)$$

Another difference is that the input force to the system was changed. It was realized that since the system is not attached to a fixed object, but rather is moving itself, that change must be accounted for. Shown in equation 18 is the input force to the system. “ y ” is the position of the system in space, and is calculated by taking the double integral of the acceleration of the system. “ x ” is the position of the spring in relation to the system. Therefore, the spring extension is the difference between “ y ” and “ x ”.

$$F(s) = Ky + f_v y \quad (13)$$

C. Determination of the Damping Constant

The next task was to determine the damping constant of the internal damping of the material. There is one type of sensor which closely resembles the resonator being examined. This sensor is also a mass-spring mechanical system like the resonator, in which the mechanical damping of the resonator is calculated. In research material discussing this sensor, a series of formulas which allow the internal damping to be calculated from the observed resonance frequency are provided. This data was implemented into the model and the resonator system.

$$\omega_o = \sqrt{\frac{K}{m_s}} \quad (14)$$

$$\omega_d = \sqrt{\frac{K}{m_s} (1 - \theta^2)} \quad (15)$$

$$\theta = \frac{\alpha}{2m_s} \quad (16)$$

where: α = fading constant

$$m_s \left(\frac{d^2 x}{dt^2} \right) + \alpha \frac{dx}{dt} + Kx = F(t) \quad (17)$$

where: m_s - mass; α - damping constant; K - spring constant

III. Mechanical Modelling

Figure 2 shows the two DOF system schematic that was used to determine the equations of motion of the vehicle.

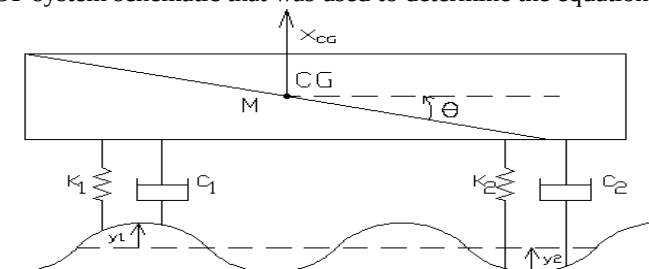


Figure 2: Spring-mass-damper model of the vehicle

To determine the equations of motion, Lagrange's equations, also known as the energy method, were utilized. Equation (18) shows the general form of Lagrange's equations

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = Q_i \quad (18)$$

where L is the sum of the kinetic and potential energies, or

$$L = T - U \quad (19)$$

where T is the kinetic energy, U is the potential energy of the system. The terms q_i and Q_i from Eq. (19) represents a degree of freedom and the non-conservative work for each DOF (subscript i denoting the first and second degrees of freedom); represents the derivative of q_i .

To derive the equations of motion using Lagrange, the degrees of freedom i needs to be defined. This is shown in Eqns. (20) and (21)

$$q_1 = x \quad (20)$$

$$q_2 = \theta \quad (21)$$

Next, the kinetic energy of the system is shown in Eq. (22)

$$T = \frac{1}{2} M \dot{x}_{CG}^2 + \frac{1}{2} J \dot{\theta}^2 \quad (22)$$

where M is the mass of the body, $\dot{x}_{CG}$ is the bounce velocity of the body about its center of gravity, J is the polar moment of inertia, and $\dot{\theta}$ is the angular acceleration of the body. The potential energy of the system is shown in Eq. (23)

$$U = \frac{1}{2} k_1 (x_{CG} - l_1 \theta - y_1)^2 + \frac{1}{2} k_2 (x_{CG} + l_2 \theta - y_2)^2 \quad (23)$$

where k_1 and k_2 are the equivalent spring rates of the front and rear suspension, x_{CG} is the displacement of the body's center of gravity, l_1 and l_2 are the distances from the center of gravity to the front suspension and rear suspensions, and y_1 and y_2 are the input functions of the road for the front and rear of the system.

Combining Eqs. (22) & (23) produces the energy equation, Eq. (24)

$$L = T - U = \frac{1}{2} M \dot{x}_{CG}^2 + \frac{1}{2} J \dot{\theta}^2 - \left[\frac{1}{2} k_1 (x_{CG} - l_1 \theta - y_1)^2 + \frac{1}{2} k_2 (x_{CG} + l_2 \theta - y_2)^2 \right] \quad (24)$$

The equations for non-conservative work for both degrees of freedom are shown in Eqs. (25) & (26)

$$Q_1 = -c_1 (\dot{x}_{CG} - l_1 \dot{\theta} - \dot{y}_1) - c_2 (\dot{x}_{CG} + l_2 \dot{\theta} - \dot{y}_2) \quad (25)$$

$$Q_2 = -l_1 c_1 (\dot{x}_{CG} - l_1 \dot{\theta} - \dot{y}_1) - l_2 c_2 (\dot{x}_{CG} + l_2 \dot{\theta} - \dot{y}_2) \quad (26)$$

where Q_1 and Q_2 are non-conservative work for q_1 and q_2 , c_1 and c_2 are the damping coefficients of the system and are the time derivatives of the road input function.

The parameters of the system are as follows: $k_1 = k_2 = 30000$ N/m, $c_1 = c_2 = 3000$ N*s/m, $M = 2000$ kg, $J = 2500$ kg*m², $l_1 = 1$ m, and $l_2 = 1.5$ m. Substituting these values and expanding Eqs. (19) & (20) yields Eqs. (21) & (22)

The car is traveling at 13.88 m/s over road that is assumed to be sinusoidal in cross-section with an amplitude of 10 millimeters (0.01 meters) and having a wavelength of 5 meters.

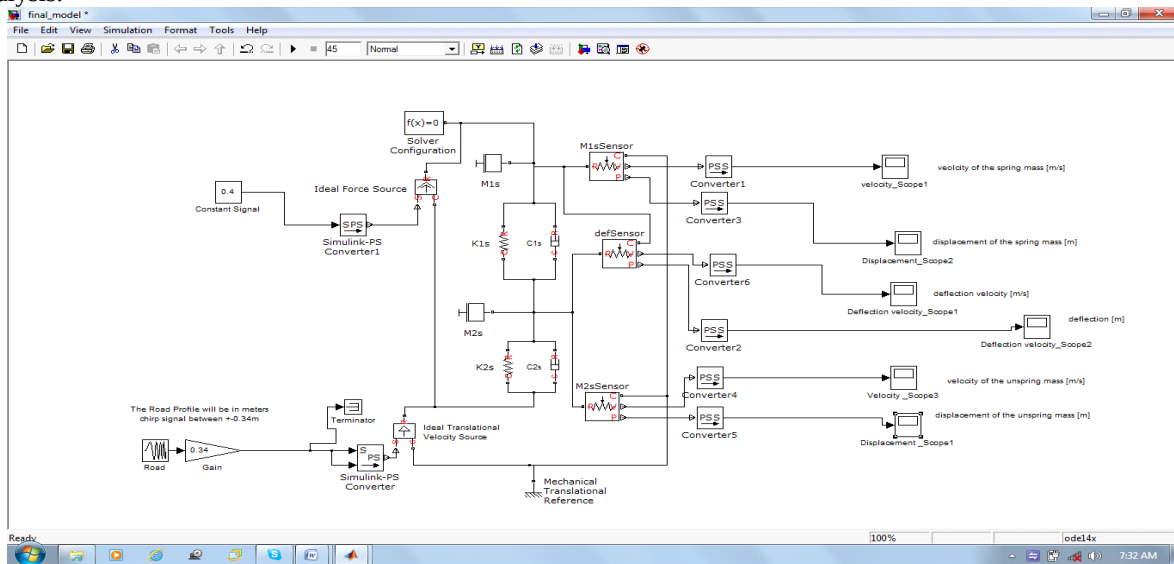
Where, t is the time traveled and π is the time shift that accounts for the time that it takes for the rear suspension to negotiate the "bump" that the front suspension had negotiated.

IV. RESULTS

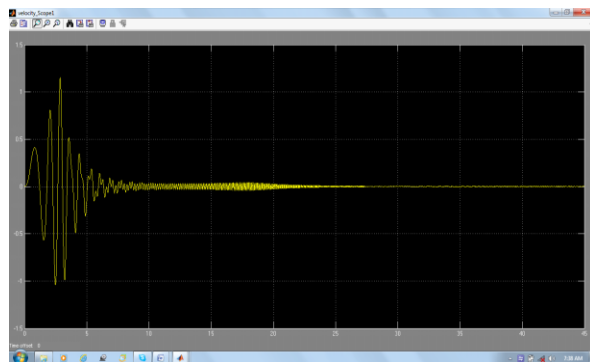
A. Simulink

The system was simulated using MATLAB's SIMULINK program. Figure 3 shows the schematic that was used for

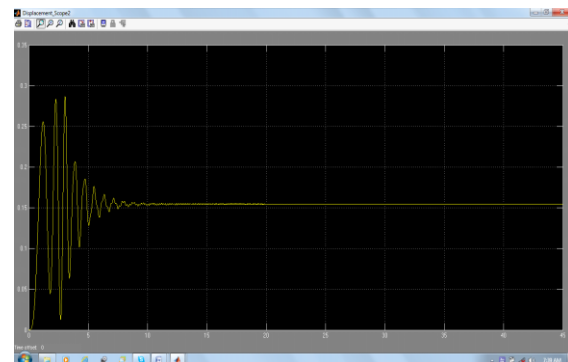
analysis.



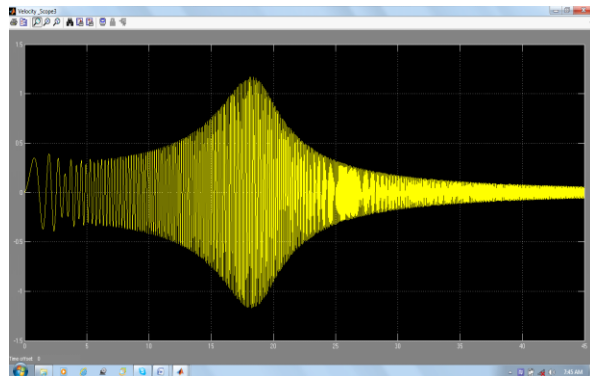
The schematic shown in Figure 3 was used to determine the natural frequencies ω_1 and ω_2 of the system. Using MATLAB, the modes of vibration, which are due to the system possessing two different natural frequencies, were calculated to determine ω_1 and ω_2 in SIMULINK. From MATLAB, the first and second modes of vibration were 0.477 and -0.596 (see MATLAB results). Rest figures show the plots produced by SIMULINK, which contains the natural frequencies, and verify the MATLAB results. From Figures, the natural frequencies were determined from the "Power Spectral Density" plots (middle graphs) and were $\omega_1 = 5.1$ rad/s and $\omega_2 = 6.5$ rad/s.



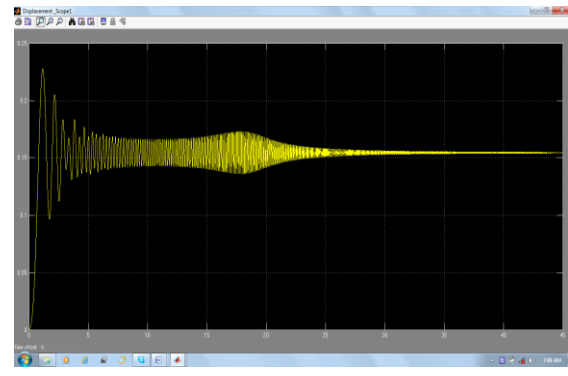
Vibrations generated by the front of the model

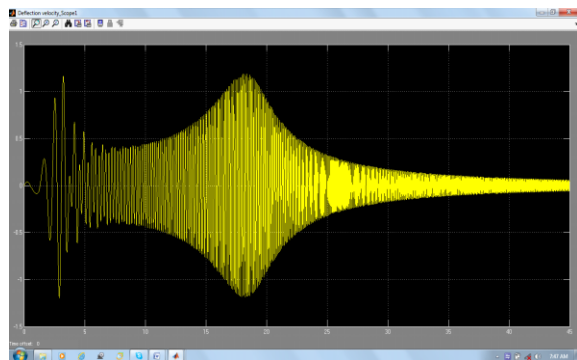


Displacement during vibration

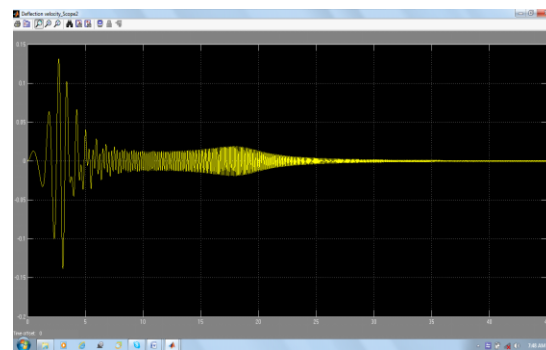


By second





Resultant frequency



Resultant displacement

V. Conclusion

The following simulink results shows that at a road highway where frequency of ongoing vehicles are high generates a huge amount of electricity as the accumulation of a unit of crystal is at few meter say 0.34m as results are generated the range of production of electricity varies in watts and association of such units can generate ample amount of electricity fulfill the requirement of homes nearby highway, this is a basic a prototype model of electricity generation and can be applicable.

Explanation (2):

Second order RLC equation $i(t) = V(t)/R + 1/L \int V(t)dt + CdV(t)/dt$

$$M \frac{d^2 x(t)}{dt^2} + f_v \frac{dx(t)}{dt} + Kx(t) = F(t) \quad \text{for Mechanical system}$$

Both systems are Analogues and represent as a part of Electro-mechanical energy conversion process, as mentioned above in Explanation (1) how 1V capacitance value can produce 80V Electricity is a example of electrical energy Harvesting.

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