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Modelling and Simulation of Vibration Sensor for Vehicle Accident

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ABSTRACT

Many sensors have been applied as accident detectors. This paper proposes the application of the vibration sensor, model SPM8667VC for accident detecting in accident reporting systems. The sensor parameters were put into consideration alongside with its operational voltage of 500mV. Various mathematical models were developed to cater for the mechanical and electrical properties of the sensor. This led to the development of a Simulink which was simulated on MATLAB 2014a environment for the various states of accident. The simulation result led to the formulation of a mathematical model that caters for the various levels of accident based on threshold voltages. These levels are categorized as mild accident with a voltage of 150mV, medium accident with a voltage of 280mV and severe accident with a voltage of 580mV. The various levels determine accident severity and when apply in accident reporting system, guide rescuers decision to embark on rescue mission or not.

Keywords:
Accident levels, Accident models, Transducer, Vibration Sensor, Vibration Simulink

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1. INTRODUCTION

Vibration is widely found in nature and human social life and it is a physical phenomenon (Song *et al.,* 2013 & Hou *et al.,* 2000). It is visually described that vibration is a dynamic phenomenon and reciprocating that can be observed in a balance position. It is also the transfer and storage of energy cause by one or more force effect in structure (Li *et al.,* 2013 & Wang *et al.,* 2009). The rapid development of sensors and their digital multi-functional and intelligent is an important feature of modern sensor development (Liu *et al.,* 2012 & Wang *et al.,* 2004). The vibration sensor found wide application in many areas. It is applied as illegal intruder trigger that transmits alarm signal to host computer which in turn monitors camera, video and lighting operations during intrusion (Wu,ng, 2019). It is also applied in micro-energy harvester that employed two-stage mutual ferromagnetic interaction frequency up-convert sub-g weak vibration energy into electricity (He *et al.,* 2018). The application of the vibration sensor in accident detecting and reporting systems can reduce mortality. Most deaths resulting from road accidents are due to the lack of quick medical assistance to accident victims (Nicky *et al.,* 2017). Vibration sensor for vehicle accident is a device that automatically sense vibration when an accident occurs. Depending on the amount of impact resulting from a vehicle accident, the vibration sensor produces signals that correspond to the different impact levels.

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1.1 Transducer

A transducer is defined as a device that converts energy from one form to another. The energy forms could be mechanical, electrical, chemical, solar, thermal etc. Two classifications exist, namely passive and active transducers. Passive transducer requires power source for its workability while active transducer requires no external source to operate. When a transducer converts a measurable quantity (vibration, sound pressure level, optical intensity, magnetic field, etc.) to an electrical voltage or an electrical current, it is called a sensor**.** In the reverse, when a transducer converts an electrical signal into another form of energy, such as sound, light, mechanical movement, it is called an actuator**.** Vibration transducers could be Microelectromechanical systems (MEMS) or Piezoelectric in nature (Sunil, 2013)**.**

1.2 Microelectromechanical systems (MEMS) transducer.

Vibration is a physical phenomenon found in nature and human social life (Song, 2013 & Hou *et al.,* 2009). Microelectromechanical systems (MEMS) transducers are described as vibration sensors that utilizes compliant micro flexures attached to a proof mass that displaces in response to an environmental acceleration as shown in Figure 1. They found wide applications in vibration and shock monitoring on industrial systems and robotics, guidance and navigation in global positioning systems, seismometry in earthquake prediction, image stabilization in digital cameras, and automobile safety and stability. The vibrating sensor is approximated as a lumped mass system undergoing damped harmonic oscillation. When attached to a vibrating structure, the system undergoes base excitation (Rebello, 2009).

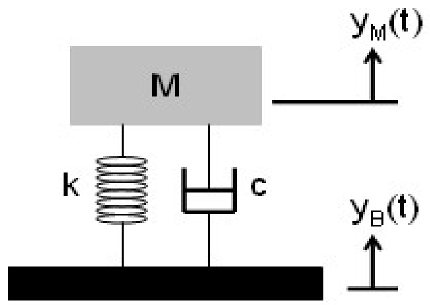

Figure 1. Lumped mass approximation with base excitation, $y_B(t)$ (Rebello, 2009).

1.3 Piezoelectric transducer

Mukti *et al.* (2014) described the piezoelectric transducer as a shock sensor capable of measuring shock or vibration. Depending upon the severity of intensity of shock, the sensor can be used for security purposes warning beep or sound or to monitor accidents. More advanced sensors send different information depending on how severe the shock is. A sensor detecting vibration must have a mechanical displacement to generate electrical signal. This a called a piezoelectricity mechanism. Many materials, both natural and synthetic exhibit piezoelectricity. Figure 2 is a piezoelectric transducer that operate as shock sensor that generate electric polarization, which is linearly related to the applied force (stress) as shown in.

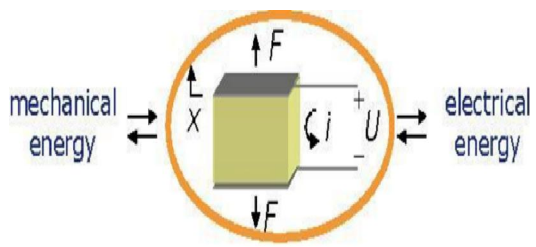

Figure 2. Conversion of energies in a piezoelectric crystal (Sunil, 2013).

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. Piezoelectric materials when exposed to a fairly constant electric field tend to vibrate at a precise frequency (Fraden, 2004)**.**

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1.4 Sensors Selection

The development of modern sensors is based on the fast growth in intelligent, multi-functional and digital technologies. Three parameters representing motion detected by vibration sensors are displacement (m), velocity (m/s), and acceleration (m/s^2). These parameters are mathematically related and can be derived from multiple types of motion sensors. Selection of a sensor is proportional to displacement, velocity or acceleration depends on the frequencies of interest and the signal levels involved. Piezoelectric sensor ranges between 10 and 100 mV/g; while its frequency ranges from 2Hz to 5kHz depending on level of vibration (Frederick, 2013).

2. MATERIALS AND METHODS

2.1 Model for Vibration Sensor

The vibration sensor is a device that operate on the principle of energy transformation. It transforms mechanical energy into electrical energy. Therefore, the sensor models are presented and analyzed in the two operational models.

2.2 Mode 1: Mechanical Operation model

Liu *et al.* (2012) and Wang *et al.* (2009) described vibration as a dynamic phenomenon with a reciprocating balanced position. Shown in Figure 3 is a micro-acceleration sensor that includes an elastic beam, inertial mass (m), a damper with constant coefficient (λ) and a spring with constant coefficient (k). F(t) is an inertial force that acts on a sensitive mass (m) of the system.

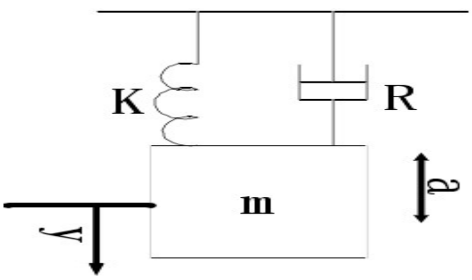

Figure 3 The mechanical operational model (Aiyin, 2014).

From D' Alembert's principle of linear elastic spring, equation 1 present the second order differential equation with constant coefficients and single degree of freedom that governs the spring system (Kovac, 2013).

$$m\ddot{x} + R\dot{x} + kx = f(t) \quad (1)$$

where,
m = mass of vibrating object
R = dynamic damping coefficient
k = spring constant.
x = displacement of the mass.

$m\ddot{x} = \frac{d^2x}{d^2t}$ is the inertial force.

$\dot{x} = R\frac{dx}{dt}$ is the dynamic resistance.

Equation 2 is obtained by dividing equation 1 by m.

$$\ddot{x} + 2\zeta\dot{x} + \omega_n^2 x = g(t) \quad (2)$$

where,

$2\zeta = \frac{R}{m}$ or

$\zeta = \frac{R}{2m}$,

$\omega_n^2 = \frac{k}{m}$ or

$\omega_n = \sqrt{\frac{k}{m}}$ (Natural frequency)

and

$g(t) = \frac{f(t)}{m}$.

Equation 3 is obtained by taking the Laplace transform of equation 2.

$$s^2X(s) - sx(0) - \dot{x}(0) + 2\zeta sX(s) - 2\zeta x(0) + \omega^2X(s) = G(s) \quad (3)$$

Therefore,

$$X(s) = \frac{(s+2\zeta)x(0)+\dot{x}(0)+G(s)}{s^2+2\zeta s+\omega_n^2} \quad (4)$$

Equation 5 is the general solution of equation 4.

x(t) = x(t)transient state + x(t)steady state (5)

Equation 6 is the inverse Laplace transform of equation 4.

$$x(t) = \mathcal{L}^{-1}\left\{\frac{(s+2\zeta)x(0)+\dot{x}(0)}{s^2+2\zeta s+\omega_n^2} + \frac{G(s)}{s^2+2\zeta s+\omega_n^2}\right\} \quad (6)$$

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where,

$$x(t)_{transient\ state} = \mathcal{L}^{-1}\left\{\frac{(s+2\zeta)x(0)+\dot{x}(0)}{s^2+2\zeta s+\omega_n^2}\right\} \quad (7)$$

and,

$$x(t)_{steady\ state} = \mathcal{L}^{-1}\left\{\frac{G(s)}{s^2+2\zeta s+\omega_n^2}\right\} \quad (8)$$

Equations 9, 10 and 11 are further computations for the transient state solution.

$$x(t)_{transient\ state} = \mathcal{L}^{-1}\left\{\frac{(s+\zeta)x(0)+\zeta x(0)+\dot{x}(0)}{(s+\zeta)^2+\omega_n^2-\zeta^2}\right\} \quad (9)$$

$$x(t)_{transient\ state} = \mathcal{L}^{-1}\left\{\frac{(s+\zeta)x(0)}{(s+\zeta)^2+\omega_n^2-\zeta^2} + \frac{\zeta x(0)+\dot{x}(0)}{(s+\zeta)^2+\omega_n^2-\zeta^2}\right\} \quad (10)$$

$$x(t)_{transient\ state} = x(0)e^{-\zeta t}\cos\omega t + \frac{\zeta x(0)+\dot{x}(0)}{\omega}e^{-\zeta t}\sin\omega t \quad (11)$$

where,

$$\omega \equiv \sqrt{(\omega_n^2-\zeta^2)}$$

Note that as t → ∞, x(t) → 0 while as t = 0, x(t) = x (0) and $\dot{x}(0)$,

Equation 12 is the further computation for the steady state solution.

$$x(t)_{steady\ state} = \mathcal{L}^{-1}\left\{\frac{G(s)}{(s+\zeta)^2+\omega_n^2-\zeta^2}\right\} \quad (12)$$

Applying convolution property of Laplace transformation,

$$\mathcal{L}^{-1}\{X(s)\,G(s)\} = \int_0^t X(t-u)\,G(u)\,du \quad (13)$$

Therefore,

$$x(t)_{steady\ state} = \frac{1}{\sqrt{(\omega_n^2-\zeta^2)}}\int_0^t e^{-\zeta(t-u)}\sin\left\{(\omega_n^2-\zeta^2)^{\frac{1}{2}}(t-u)\right\}G(u)\,du \quad (14)$$

Note that,

$$g(t) = \frac{f(t)}{m} = \frac{F_o}{m}\cos\omega t \quad (15)$$

where,

Fo is maximum initial force of vibration.

For simplicity, assume very minimal or no damping, that is $\zeta \approx 0$ and the force f(t) is sinusoidal as shown in equation 15.

$$x(t)_{steady\ state} = \frac{F_o}{m\omega_n}\int_0^t \sin\{\omega_n(t-u)\}\cos\omega u\,du \quad (16)$$

but,

$$\sin(\omega_n t-\omega_n u) = \sin\omega_n t\cos\omega_n u - \cos\omega_n t\sin\omega_n u \quad 17)$$

Equation 18 is the substitution of equation 17 into equation 16.

$$x(t)_{steady\ state} = \frac{F_o}{m\omega_n}\int_0^t \sin\omega_n t\cos\omega_n u\,du - \int_0^t \cos\omega_n t\sin\omega_n u\,du \quad (18)$$

Equations 19 and 20 are further computations for the steady state solution.

$$x(t)_{steady\ state} = \frac{F_o}{m\omega_n}\left[\sin\omega_n t\int_0^t \cos\omega_n u\cos\omega u\,du - \cos\omega_n t\int_0^t \sin\omega_n u\cos\omega u\,du\right] \quad (19)$$

$$x(t)_{steady\ state} = \frac{F_o}{m\omega_n}\left[\sin\omega_n t\left(\frac{\sin(\omega_n-\omega)t}{2(\omega_n-\omega)}+\frac{\sin(\omega_n+\omega)t}{2(\omega_n+\omega)}\right)+\cos\omega_n t\left(\frac{\cos(\omega_n-\omega)t}{2(\omega_n-\omega)}+\frac{\cos(\omega_n+\omega)t}{2(\omega_n+\omega)}-2\right)\right] \quad (20)$$

Equation 21 is therefore the general equation guiding the sensor mass displacement, x(t) as obtained from equation 11 and equation 20.

$$x(t) = x(0)e^{-\zeta t}\cos\omega t + \frac{\zeta x(0)+\dot{x}(0)}{\omega}e^{-\zeta t}\sin\omega t + \frac{F_o}{m\omega_n}\left[\sin\omega_n t\left(\frac{\sin(\omega_n-\omega)t}{2(\omega_n-\omega)}+\frac{\sin(\omega_n+\omega)t}{2(\omega_n+\omega)}\right)+\cos\omega_n t\left(\frac{\cos(\omega_n-\omega)t}{2(\omega_n-\omega)}+\frac{\cos(\omega_n+\omega)t}{2(\omega_n+\omega)}-2\right)\right] \quad (21)$$

Equation 22 is obtained by assuming $\zeta << \omega_n$ and $\omega << \omega_n$

$$x(t) = x(0)e^{-\zeta t}\cos\omega_n t + \frac{\zeta x(0)+\dot{x}(0)}{\omega_n}e^{-\zeta t}\sin\omega_n t + \frac{F_o}{m\omega_n^{\ 3}}\left[\sin^2\omega_n t + \cos^2\omega_n t - 2\omega_n^{\ 2}\right] \quad (22)$$

Since,

$$\sin^2\omega_n t + \cos^2\omega_n t = 1 \quad (23)$$

Equation 22 is now Equation 24.

$$x(t) = x(0)e^{-\zeta t}\cos\omega_n t + \frac{\zeta x(0)+\dot{x}(0)}{\omega_n}e^{-\zeta t}\sin\omega_n t + \frac{2a}{\omega_n^{\ 3}}(1-2\omega_n^{\ 2}) \quad (24)$$

Equation 25 shows the consideration of only mass displacement, that is when its maximum.

velocity, $\dot{x}(0) = 0$ and hence its acceleration, a=0.

$$x(t) = x(0)e^{-\zeta t}\cos\omega_n t + \frac{\zeta x(0)}{\omega_n}e^{-\zeta t}\sin\omega_n t) \quad (25)$$

Equation 26 is the factorization of equation 25.

$$x(t) = x(0)e^{-\zeta t}(\cos\omega_n t + \frac{\zeta}{\omega_n}\sin\omega_n t) \quad (26)$$

2.3 Mode 2: Electrical Operation model

Shown in equation 27 is electrical equivalent RLC resonant second-order differential equation of equation 1 (Aiyin, 2014 & Lou *et al.,* 2006).

$$C\ddot{v_o} + \frac{1}{R}\dot{v_o} + \frac{1}{L}v_o = \frac{1}{L}v_i \quad (27)$$

The corresponding equivalent circuit of equation 27 is shown in Figure 4.

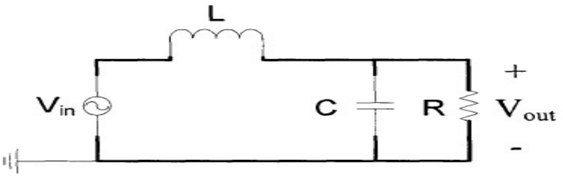

Figure 4 RLC equivalent circuit (Aiyin, 2014)

Equation 28 is therefore the electrical equivalent model of the sensor that can be compared with that of its mechanical model of equation 2.

$$\ddot{v_o} + \frac{1}{RC}\dot{v_o} + \frac{1}{LC}v_o = \frac{1}{LC}vi \quad (28)$$

The following equivalent parameters can be obtained from comparison as presented in equations 29-32.

$$\zeta = \frac{1}{2RC} \quad (29)$$

$$\omega_n = \sqrt{\frac{1}{LC}} \quad (30)$$

$$m = LC \quad (31)$$

$$x = Vo \quad (32)$$

Therefore, equation 26 can be represented as equation 33

$$v(t) = Voe^{-\zeta t}(\cos\omega_n t + \frac{\zeta}{\omega_n}\sin\omega_n t) \quad (33)$$

Table 1 shows the is accident detection actual maximum g-force range using the accelerometer sensor as obtained from test.

Table 1. Thresholds g-forces for accident detection (IEEE, 2009)

Accident Severity (m)	Actual Maximum g-force Range
No Accident	0-4g (0<m≤4g)
Mild Accident	4-20g (4g<m≤20g)
Medium Accident	20-40g (20g<m≤40g)
Severe Accident	40g + (m>40g)

3. RESULTS AND DISCUSSION

Figures 5, 6, and 7 are equivalent electrical signal responses that conformed to the various levels of vibration of the sensor to determine the nature of accident that occur using a developed Simulink model on MATLAB 2014a Environment.

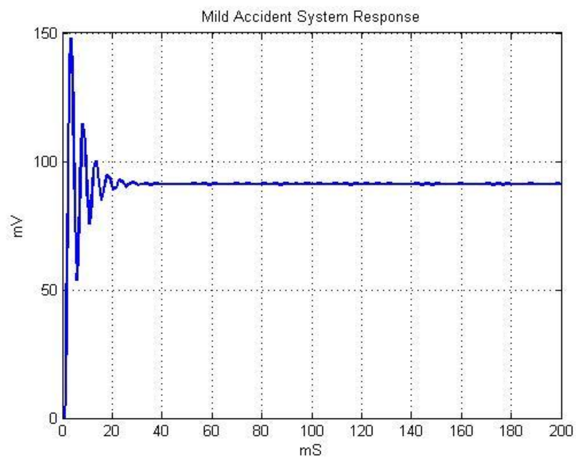

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Figure 5. Mild accident response curve

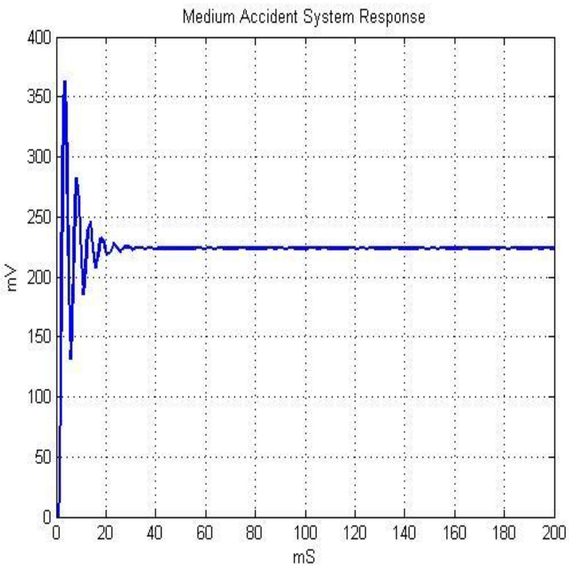

Figure 6. Medium accident response

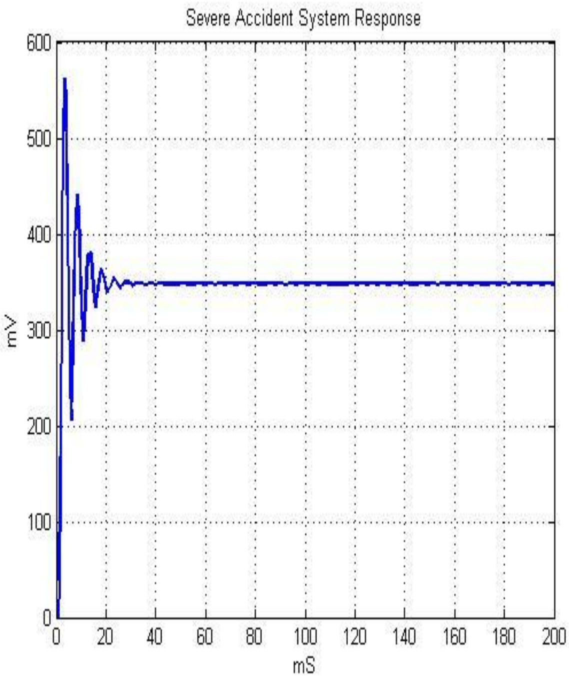

Figure 7. Severe accident response

Analysis of Figure 5, 6 and 7 show that the sensor threshold voltages are recorded at the same time response of 20ms with different critical damping values. Figure 5 presented simulated threshold voltage of 150mV at a critical damping of about 80mV at 20ms time response. This voltage in comparison with the sensor output voltage of 500mV is classified as mild accident. Figure 6 presented simulated threshold voltage of 360mV at a critical damping of about 280mV at 20ms time response. This voltage in comparison with the sensor output voltage of 500mV is classified as medium accident. Figure 7 presented simulated threshold voltage of 580mV at a critical damping of about 440mV at 20ms time response. This voltage in comparison with the sensor output voltage of 500mV is classified as severe accident. The mechanical parameters employed in the simulation for the above accident signals as obtained from the developed Simulink are:

$m = 15.0g$, $R = 6.0Nsm^{-1}$, $k = 37.0Ns^{-1}$,
at $\zeta = 0.200$ and $\omega_n = 1.570Hz$.

Equation 34 is therefore, the vibration sensor mechanical mode model for accident vibration levels.

$$15\ddot{x} + 6\dot{x} + 37x = f(x) \qquad (34)$$

4. CONCLUSION

The vibration sensor SPM8667VC was simulated for accident impact in MATLAB 2014a environment. This was realized with the aid of the sensor parameters. For every displacement, there is a corresponding electrical response. The sensor signal responses to accident impact are shown in Figures 5, 6, and 7 while the corresponding accident levels was successfully simulated using the developed models of equations 26 and 31. The analysis of the simulation results led to the formulation of a mathematical model shown in equation 34 to cater for the various states of vibrations in conformity to the various levels of accident impact. These states are identified as mild, medium and severe accidents. The sensor is therefore recommended for use as impact sensor for vehicle accident reporting systems based on its accessibility, cost, reliability and non-complex circuit design.

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