Development of a Low Cost Vibration Sensor based on Flat Coil Element

Mitra Djamal, Ramli, Suparno Satira and Suprijadi

***Abstract*—** A new type of vibration sensor based on flat coil element has been made. This paper describes the development of vibration sensor based on flat coil element that has low manufacturing cost and high sensitivity. In this research, the flat coil element is used to measure the position of a vibrating object as a function of time. Its working principle is based on position change of a seismic mass that put in front of a flat coil element. The flat coil is a part of a LC oscillator; therefore the change of seismic mass position will change its resonance frequency. A sensor model based on mathematical approach for determining frequency and amplitude of the sensor has been developed. The model shows a good result with relative error under 3%.

***Keywords*—** flat coil element, LC Oscillator, sensor model, vibration sensor.

I. INTRODUCTION

HIGH quality measuring systems could be realized at low cost level by using microprocessor system in combination with simple sensor element and specific sensor algorithm[1,2]. By using intelligent microcomputers it is possible to design physically simple and cost-effective sensors that have very high resolution and do not need any mechanical calibration.

Vibrations like earthquake, vibration of a bridge, vibration of machinery, and many others, are physical phenomena that could be found everywhere. Vibration characteristic of these phenomena can be used as a utility for an early warning system that could reduce loss or damage. For measuring of vibration, one needs a vibration sensor. Vibration sensor has been applied in various fields [3,4,5,6].

There are some kinds of vibration sensor, such as proximeter, seismic-velocity pick-up and accelerometer. These kinds of sensor are differentiated by its measurement principle. Proximeter measures position shift, seismic-velocity pick-up measures velocity and accelerometer measures acceleration of vibration [7]. Some of them which recently used in industry or laboratory has expensive price.

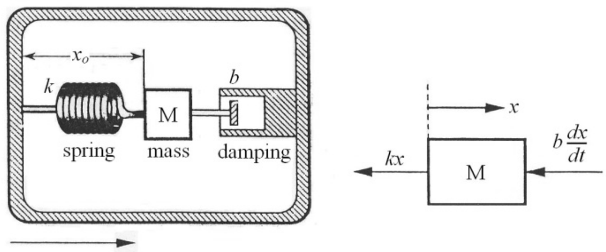
There are many methods which could be used to measure vibration, for example by measuring the capacitance, change of electrical charge of a piezoelectric material [8,9,10], change of position in a Linear Variable Differential Transformer (LVDT) [11], using optical-fiber cantilever [12], using magnetic sensor [13] or using elastomagnetic composite [14]. In this paper, we would like to show vibration sensor using flat coil element that we have developed for some applications in last years [15,16,17,18,19].

Vibration is a dynamic mechanical phenomenon, which involves oscillatory motion around an equilibrium position. In some cases like shock analysis, linear acceleration, etc., the oscillating aspect might be missing but the measurement and design of the sensor remains similar. There are two quantities, which should be measured by a vibration sensor namely amplitude or acceleration and frequency. These quantities can be determined by using a good sensor model that can be processed by a microcomputer.

II. MATHEMATICAL MODEL

Mathematical model of a sensor is a powerful tool in asserting its performance. The model may address two issues namely static and dynamic. Static models usually deal with the sensor's transfer function. However, here, we briefly outline how sensors can be evaluated dynamically.

Dynamic mechanical elements are made of masses or inertias, which have been attached onto springs and dampers. Often the damping is viscous and for the rectilinear motion, the retaining force is proportional to velocity. Similarly, for the rotational motion, the retaining force is proportional to angular velocity. Also the force or torque exerted by a spring or shaft is usually proportional to displacement. Let us consider a monoaxial vibration sensor, which consists of an inertia element where its movement could be transformed into an electrical signal. Fig. 1 shows a general mechanical structure of such vibration sensor [11].



(A) (B)

Fig. 1. Mechanical model of a vibration sensor (A) and a free-body diagram of mass M (B).

Mass M is supported by a spring, which have stiffness k and the mass movement is damped by a damping element with a coefficient b. Mass might be displaced with respect to vibration sensor housing only in the horizontal direction. During operation, the housing is subject to be accelerated by $\frac{d^2y}{dt^2}$, and the output signal is proportional to the deflection x_0 of the mass *M*.

Since the vibration mass is constrained as a linear motion, the system has one degree of freedom. Fig. 1(B) shows a free-body diagram of mass *M* and displacement *x*. By applying Newton's second law of motion, it gives

$$Ma = -kx - b\frac{dx}{dt}, \tag{1}$$

where *a* is the acceleration of the mass *M* and is given by

$$a = \frac{d^2x}{dt^2} - \frac{d^2y}{dt^2} \tag{2}$$

Substituting for *a* gives the required equation of motion

$$M\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = M\frac{d^2y}{dt^2}. \tag{3}$$

To solve the equation (3), it is convenient to use Laplace transformation, which yields

$$Ms^2X(s) + bsX(s) + kx(s) = -MA(s) \tag{4}$$

where *X(s)* and *A(s)* are the Laplace transform of *x(t)* and $\frac{d^2y}{dt}$ respectively. Solving the above for *X(s)* we receive

$$X(s) = \left(\frac{-MA(s)}{Ms^2 + bs + k}\right). \tag{5}$$

We introduce a conventional variable $\omega_0 = \sqrt{k/M}$ and $2\zeta\omega_0 = b/M$, then Eq. (5) can be expressed as:

$$X(s) = \frac{-A(s)}{s^2 + 2\zeta\omega_0 s + \omega_0^2}. \tag{6}$$

The value of ω_0 represents the sensor's angular natural frequency of the system and ζ is the normalized damping coefficient. Let us set

$$G(s) = \frac{-1}{s^2 + 2\zeta\omega_0 s + \omega_0^2}, \tag{7}$$

therefore Eq. (6) becomes $X(s) = G(s)A(s)$, and the solution can be expressed in terms of the inverse Laplace transform operator as

$$x(t) = L^{-1}\{G(s)A(s)\}. \tag{8}$$

From the convolution theorem, the Laplace transform can be expressed as

$$x(t) = \int_0^1 g(t-\tau)a(\tau)d\tau \tag{9}$$

where *a* is the time dependent impulse of the sensor body and $g(t)$ is the inverse transform $L^{-1}\{G(s)\}$. If we set $\omega = \omega_0\sqrt{1-\zeta^2}$ then Eq. (9) has two solutions. One is for the under-damped mode $(\zeta < 1)$

$$x(t) = \int_0^t -\frac{1}{\omega}e^{-\zeta\omega_0(t-\tau)} \sin\omega(t-\tau)a(t)d\tau. \tag{10}$$

While for the over-damped mode $(\zeta > 1)$

$$x(t) = \int_0^t -\frac{1}{\omega}e^{-\zeta\omega_0(t-\tau)} \sinh\omega(t-\tau)a(t)d\tau \tag{11}$$

where $\omega = \omega_0\sqrt{\zeta^2 - 1}$. The above solutions can be evaluated for different acceleration inputs applied to the sensor base. This can be found elsewhere [20]. Fig. 2 shows amplitude as function of frequency for different ζ.

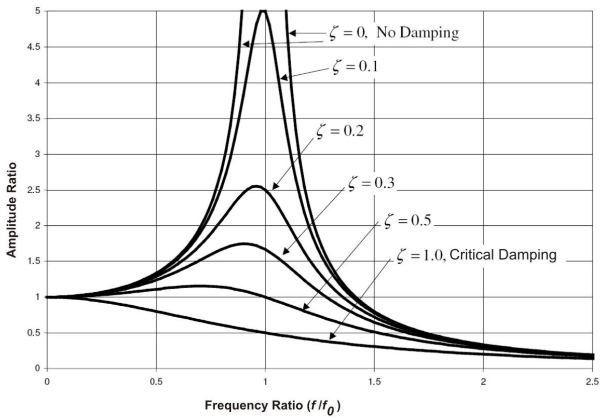


Fig. 2. Graph of amplitude versus frequency of a vibration for different ζ [21].

III. The Flat Coil Element

Fig. 3. The developed flat coil element.

Fig. 3 shows the developed flat coil element. The physical principle of a flat coil sensor is based on eddy current [22]. Flat coil inductance changes due to the disruption of conductive material in the magnetic field so that generates eddy currents. A coaxial ring replaces each turn of the coil with radius being approximately the mean radius of the corresponding turn.

Magnetic field around a flat coil will arise when an electric current flowing through it. When the conductor material is placed in front of a flat coil, the conductor free electrons will experience a magnetic force. This magnetic force causes the electrons to move against this force and produce induction currents. This induction current produces induction magnetic field around the conductor material and influenced by the source magnetic field, so that the total magnetic field is influenced by the source magnetic field (self-inductance) and the induction magnetic field (mutual inductance).

The total inductance L can be calculated by summing up the self-inductance L_j and the mutual inductance M_{jk} [23,24] (see Fig. 3).

$$L = \sum_{j=1}^{N} L_j + \sum_{j,k=1}^{N} M_{jk} \tag{12}$$

with

$$L_j = 2\pi\left(D_j - \frac{d}{2}\right)\left[\left(1 + \frac{\left(\frac{d}{2D_j}\right)^2}{\left(1 - \frac{d}{2D_j}\right)^2}\right)K(k_j) - 2E(k_j)\right], \tag{13}$$

$$M_{jk} = \frac{2\pi\sqrt{D_{ij}D_{2k}}}{k_{jk}}\left[\left(2 - k_{jk}^2\right)K(k_{jk}) - 2E(k_{jk})\right] \tag{14}$$

with

$$K(k) = \int_0^{\frac{\pi}{2}} \frac{d\varphi}{\sqrt{1 - k^2 \sin^2\varphi}}, \tag{15}$$

$$E(k) = \int_0^{\frac{\pi}{2}} \sqrt{1 - k^2 \sin^2\varphi}\, d\varphi \tag{16}$$

$$k_{jk} = \frac{\sqrt{D_{1j} + D_{2k}}}{\sqrt{\left(\frac{D_{1j} + D_{2k}}{2}\right)^2 + l^2}} \tag{17}$$

where $K(k)$ is elliptic integral I, $E(k)$ is elliptic integral II, D is diameter of the ring, d is diameter of the wire, and l is distance between two rings.

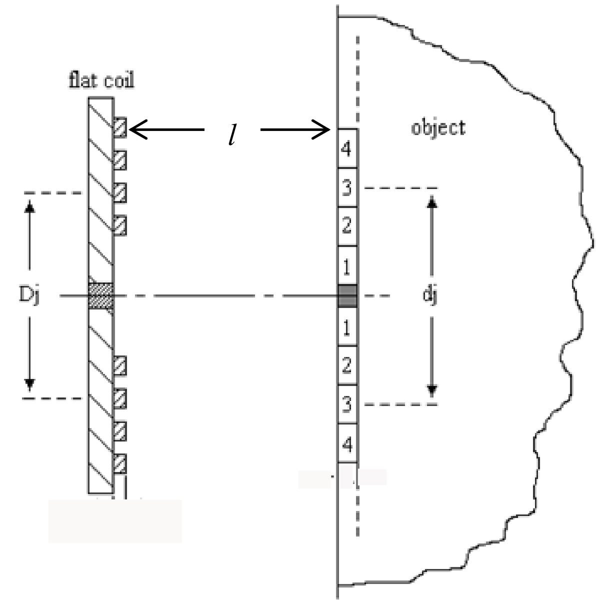


Fig. 4. Dividing the printed circuit coil in coaxial rings.

IV. Sensor Characteristic

For measuring static characteristic of the sensor element an instrument calibration that can work semi automatically has been developed. Fig. 5 shows its calibration system of flat coil as proximity sensor. Position of an object is determined by a micrometer, which works using a stepper motor. The stepper motor is controlled by a microprocessor.

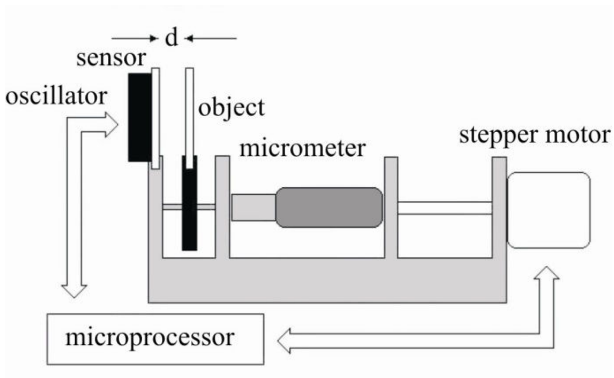


Fig. 5. Calibration system of flat coil as proximity sensor.

The sensor element is used as a part of LC Oscillator. The resonance frequency of the oscillator is a function of distance. By using a phase locked loop (PLL) the change of the resonance frequency is converted into voltage. Fig. 6 shows the output voltage of the developed sensor as a function of distance. From Fig. 6 we can see that the sensor has a good sensitivity (~3mV/µm).

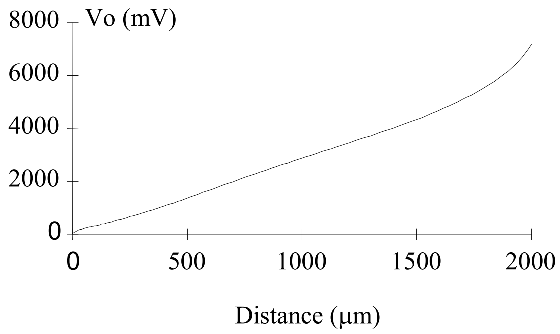


Fig. 6. Output voltage of the sensor as function of distance.

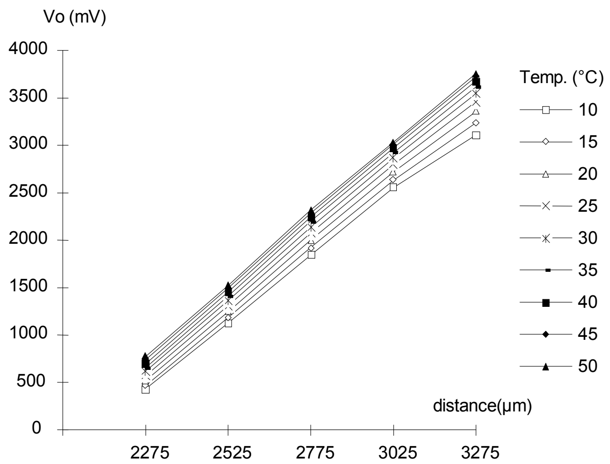
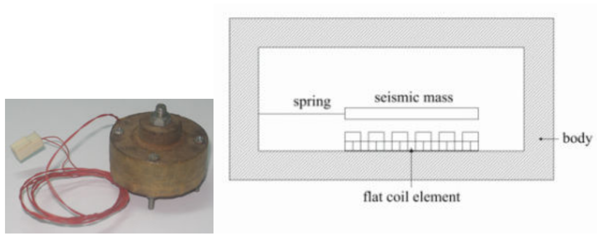


Fig. 7. Influence of temperature on the flat coil element.

The influence of temperature on the flat coil element has also been measured. Fig. 7 shows that temperature increase cause raise of the output voltage slightly. These can be corrected mathematically using a basic function [25].

V. Vibration Sensor

Based on the developed flat coil element, a vibration sensor has been developed. The systems consist of a flat coil element, seismic mass, spring and body (Fig. 8) [26]. Complete scheme of a vibration measurement system consists of flat coil element, analog signal processing, digital signal processing and display. Block diagram of the measurement system is shown in Fig. 9. Microcontroller controls the whole process included process in ADC and sends the data to a PC. The PC can be used for further data processing such as calculation of amplitude and frequency of vibration.



(A) (B)

Fig. 8. The developed vibration sensor (A) and its block diagram (B).

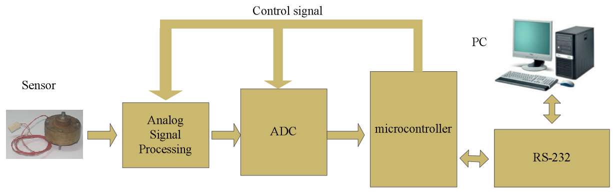


Fig.9. Block diagram of the measurement system

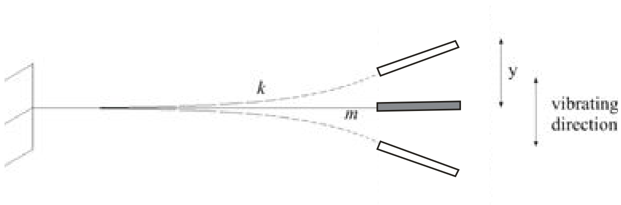


Fig. 10. Simple harmonic vibration system.

Fig. 10 shows a simple harmonic vibration system. Based on Fig. 10 we can derive equation of motion system. From Hooke's law it is found that

$$ma = -ky \tag{18}$$

where m, a, k, y are respectively seismic mass, acceleration of the seismic mass, spring constant and displacement. The resonance frequency of the seismic mass is

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}\,. \tag{19}$$

At the resonance frequency f_0 the displacement and sensitivity have their maximum values (Fig. 11). By choosing the right k and m of the sensor material, we can determine the desired f_0. Fig. 11 shows that the developed sensor following the pattern of vibration in Fig. 2.

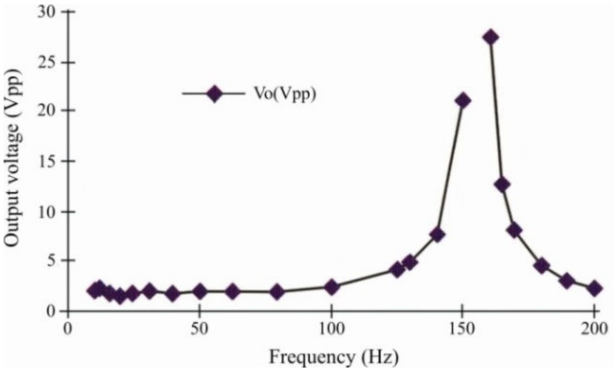


Fig. 11. Characteristic of the seismic mass of the developed sensor by acceleration 0.2g. Output voltage is a function of frequency with resonance frequency 155Hz.

VI. Fourier Transform

If the sensor is placed on a vibrating system, the seismic mass will vibrate with the same frequency as the frequency of the vibrating system. According to Hooke's law [27], if the amplitude of vibration is small enough, then there is a linear relationship between acceleration and the amplitude of the vibrating system. The flat coil element will measure position of the seismic mass dynamically. According to Nyquist's law, the minimum sampling of frequency shall be twice of the frequency of the vibrating system [28]. In our case, we use sampling frequency 10 times or more of it. By using Fourier Transform, position data is converted into frequency. The peak of Fourier Transform spectrum shows the frequency-component and the amplitude shows the magnitude of the vibrating system [29].

For example the function of seismic mass position is *x(t)* and its Fourier Transform *X(ω)*. Both of the functions are connected in the form of

$$x(t) = \int_{-\infty}^{+\infty} X(\omega) e^{j\omega t} d\omega \text{ and} \quad (20)$$

$$X(\omega) = \int_{-\infty}^{+\infty} x(t) e^{-j\omega t} dt \cdot \quad (21)$$

We will also refer to x(t) and X(ω) as a Fourier Transform pair with the notation

$$x(t) \overset{F}{\leftrightarrow} X(\omega).$$

According to Parseval's relation, there is a linear correlation between amplitude of the position and amplitude of the Fourier Transform.

In fact the position data of the seismic mass are taken discretely, so that we need the discrete-time Fourier transform (DFT) in the form of

$$x[n] = \tfrac{1}{2\pi} \int_{2\pi} X(\Omega) e^{j\Omega n} d\Omega \text{ and} \quad (22)$$

$$X(\Omega) = \sum_{n=-\infty}^{+\infty} x[n] e^{-j\Omega n} d\Omega \cdot \quad (23)$$

Often these signals are of quite long duration and in such cases it is very important to use computationally efficient procedures. One of a very efficient technique for calculation of the DFT of finite-duration sequences is the Fast Fourier Transform (FFT) algorithm. This algorithm is used to calculate the results of our measurements.

Fig. 12 shows position data of the developed sensor as function of time with source frequency 130 Hz and sampling frequency 28 kHz.

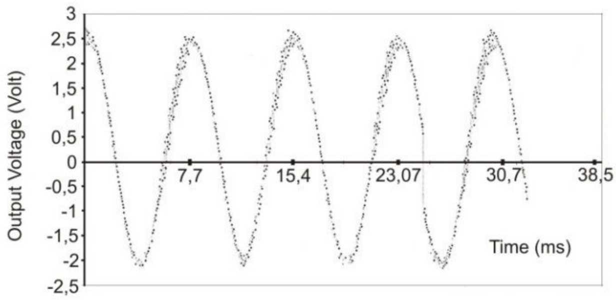


Fig. 12. Position data of the developed sensor as function of time with f_{source}= 130Hz and $f_{sampling}$= 28kHz

The Fast Fourier Transform of position data of Fig. 12 is shown in Fig. 13.

Fig. 13 shows a good correlation between the frequency of peak spectrum of the FFT with the applied source frequency (130Hz). Fig. 14 shows a measuring result with output FFT as function of frequency and acceleration at fix frequency of the vibrating system (62 Hz) and different acceleration (0.1-0.9 g).

From Fig. 14 it is shown that peak of the FFT amplitude is located on the vibrating frequency of the system and the amplitude of FFT is linear to acceleration as shown in Fig. 15.

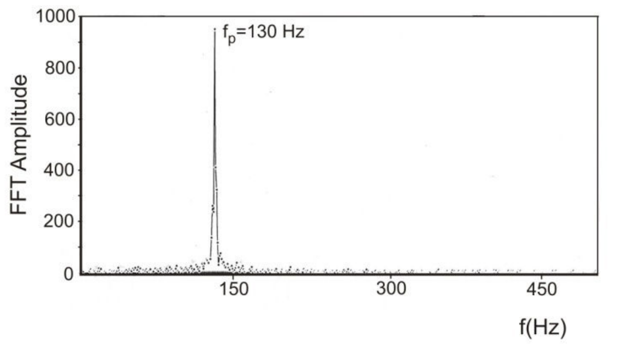


Fig. 13. Spectrum of the Fourier Transform of the position data on Fig. 12

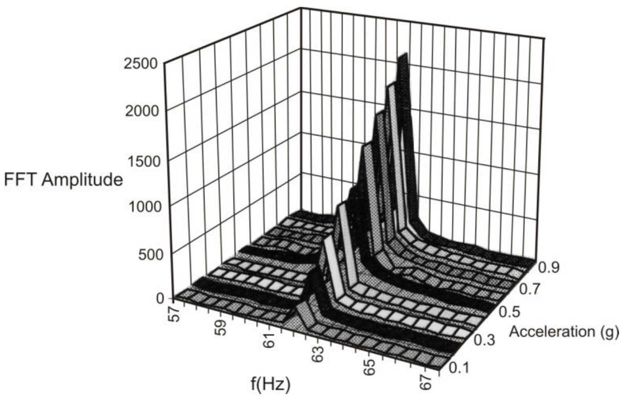


Fig. 14. Measuring result of sensor calibration at fix frequency (62 Hz) and different acceleration.

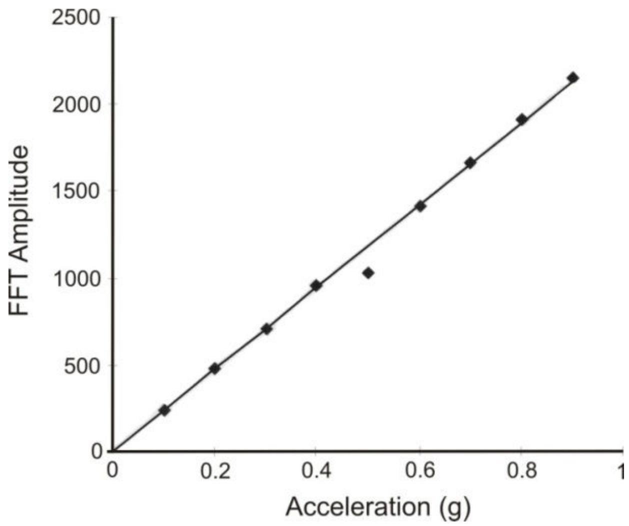


Fig. 15. Relationship between FFT amplitude and acceleration.

From Fig. 12-15 we can see that the Fourier Transform can be used to calculate amplitude and frequency of a vibration directly. Details information of using Fourier Transform for calculating amplitude and frequency of a vibration can be found in [29].

VII. Calibration

Calibration is carried out to know the sensor characteristic. As calibrator, a calibrator-system from Bruel & Kjaer Type 4345 was used. Fig. 16 shows the sensor output voltage as function of acceleration for difference frequencies.

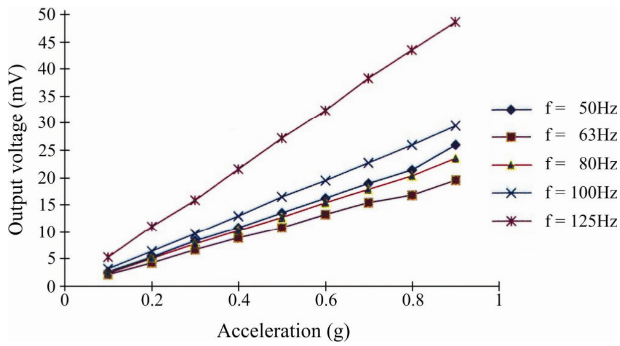


Fig. 16. Sensor output voltage as function of acceleration for difference frequencies.

VIII. Sensor Model

Fig. 16 shows that there is a linear dependency between acceleration and the sensor output voltage on each frequency. By using linear approximation (least square) we can determine a mathematical model of the sensor in the form of

$$V_o(a, f) = m(f) \cdot a \tag{24}$$

where a, f, and m are respectively acceleration, frequency of the vibration, and slope (Fig. 17).

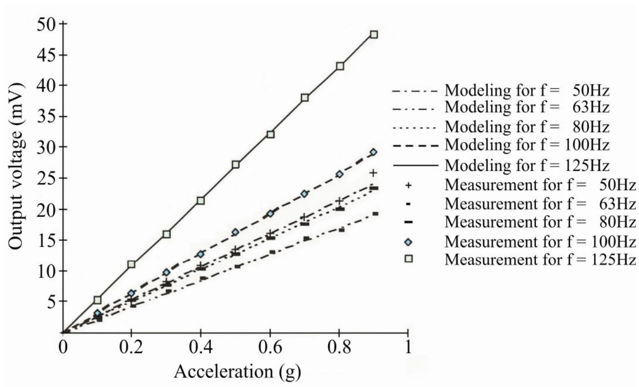


Fig. 17. Mathematical model of the developed vibration sensor.

The correlation between slope m and frequency f of the vibration is shown in Fig. 18. The curve on Fig. 18 can be approximated using a mathematical equation in the form of

$$m(f) = \frac{15.03 - 0.33 f}{1 - 0.006 f}\,. \tag{25}$$

By inserting equation (25) into equation (24), we obtain the output voltage as a function of frequency and amplitude of vibration

$$V_o(a, f) = \frac{(15.03 - 0.33 f) \cdot a}{(1 - 0.006 f)}\,. \tag{26}$$

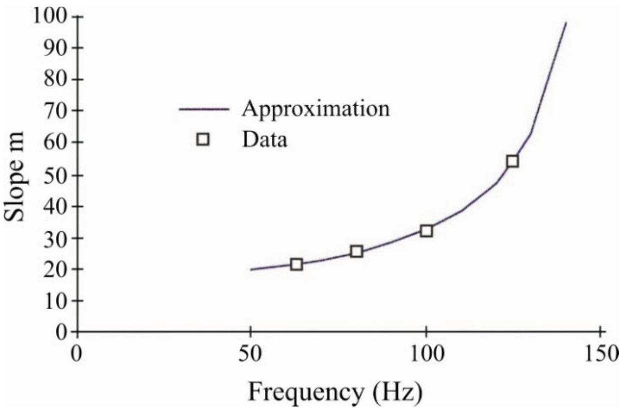


Fig. 18. Parameter slope *m* as a function of frequencies.

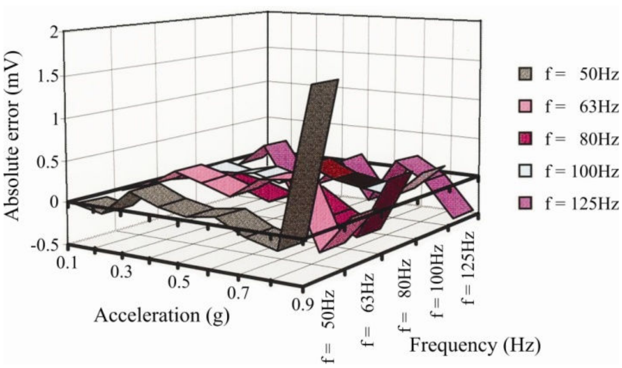


Fig. 19. Absolute error of the developed sensor using mathematical approach of equation (26).

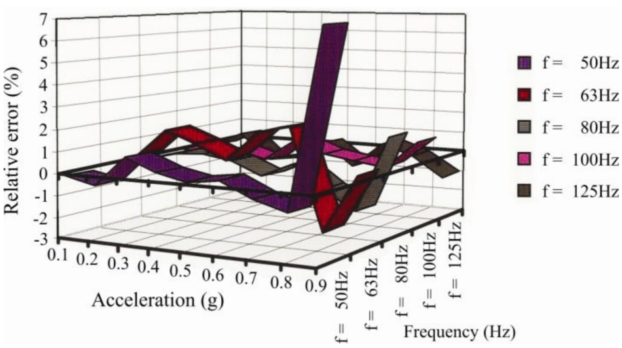


Fig. 20. Relative error of the developed sensor using mathematical approach of equation (26).

Fig. 19 and 20 show respectively the absolute and relative error of the developed sensor. Fig. 20 shows that the relative error of the developed sensor using mathematical model of equation (26) is smaller than 3%. At the frequency of 50 Hz there is enough big error emerge. This error comes from the electrical net.

IX. Conclusions

It is shown that the flat coil element can be used well as vibration sensor. There is a linear dependency between amplitude of vibration system and the sensor output signal. The sensitivity of the sensor is varied against frequencies. It depends on the characteristic of the sensor material and the form of seismic mass and the spring.

There is a linear dependency between acceleration and amplitude of Fourier Transform. By using Fourier Transform amplitude and frequency of a vibration can be calculated directly.

Using mathematical model and numerical approach, a good sensor model as function of acceleration and frequency of the vibration can be well determined. By mean this model, a vibration sensor with relative error under 3% has been developed.

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