Scientific Bulletin of the „Petru Maior” University of Târgu Mureş
Vol. 8 (XXV) no. 2, 2011, ISSN 1841-9267
inter-eng 2011

STUDYING ACCELEROMETERS WITH CAPACITIVE SENSING ELEMENTS

Ágoston Katalin
”Petru Maior”University of Târgu Mureş, Romania
kagoston@engineering.upm.ro

ABSTRACT

This paper presents types and operating mode of vibration sensors. Differential capacitor sensing elements are often used in integrated accelerometers. It will be investigate the structure and transfer function of the seismic mass type sensing element. The article presents how the piezoelectric sensing element works and compares with capacitor sensing element and how can be modeled with an electronic circuit and Simulink models. The transfer functions of the capacitor sensing element models are studied in Matlab and the results are presented.

Keywords: capacitive sensing element, vibration transducers, Matlab, Simulink model

1. Introduction

Vibration and shock are present in all areas of our lives. They may be generated and transmitted by motors, turbines, machine-tools, bridges, towers, and even by the human body. Some vibrations are desirable; others may be disturbing or even destructive. Consequently, there is often a need to understand the causes of vibrations and to develop methods to measure and prevent them.

Accelerometers can be used in a wide variety of low g applications such as tilt and orientation, vibration analysis, motion detection, etc. There are many types of sensors that measure acceleration, vibration, shock, or tilt. These sensors include piezo-film, electromechanical servo, piezoelectric, liquid tilt, bulk micromachined piezo-resistive and capacitive sensors, as well as surface micromachined capacitive sensors. Each of these sensors has distinct characteristics in the output signal of the sensor. Measurement of acceleration can also provide velocity by single integration and position by double integration. Vibration and shock can be used for machine health determination as well as motion and shock detection for car alarms, airbags, and sports training products. Static acceleration due to gravity can be used to determine tilt and inclination.

The piezoelectric accelerometers are widely accepted as the best choice for measuring absolute vibration. Compared to the other types of sensors, piezoelectric accelerometers have important advantages: extremely wide dynamic range, almost free of noise - suitable for shock measurement as well as for almost imperceptible vibration, linearity over their dynamic range, wide frequency range, compact and highly sensitive, no moving parts - long service life, self-generating - no external power required, great variety of models available for nearly any purpose, integration of the output signal provides velocity and displacement determination. The disadvantage of piezoelectric sensors, only alternating acceleration can be measured. This type of accelerometer is not capable of true dc response, e.g. gravitation acceleration. The sensor has a high impedance output what needs to be converted first into a low impedance signal. For sensors with charge output, an external charge amplifier is required. For processing the sensor signal, a variety of equipment can be used, such as: RMS and peak value meters, frequency analyzers, recorders, PC instrumentation. However, the capability of such equipment would be wasted without an accurate sensor signal. In many cases the accelerometer is the most critical link in the measurement chain. To obtain precise vibration signals some basic knowledge about piezoelectric accelerometers is required. [1], [6]

2. The vibration sensor

The displacement, the velocity and the acceleration are bond. If we know the equation which describes the motion of a piece (of a body) due to a force, we can provide through single derivation the velocity and acceleration by double derivation. In practice we measure the acceleration with a proper sensor and we get velocity and displacement through integration, because integration circuits are most simple.

The acceleration transducers have two parts: sensing element and conversion circuit. The sensing element is a seismic mass type and it’s fixed on the moving body and takes over the movement precisely (fig.1). The movement of the seismic mass can be described with the equation:

$$m\frac{d^2y}{dt^2}+c\frac{dy}{dt}+ky=F\cdot a=-m\frac{d^2x}{dt^2} \qquad (1)$$

Where m is the seismic mass, k is springiness coefficient, c is the damping coefficient, a is the acceleration and F is the force. [8]

The transfer function of the sensor's system is:

$$H(s)=\frac{Y(s)}{X(s)}=\frac{-s^2}{s^2+2\xi\omega_0 s+\omega_0^2} \tag{2}$$

Where $\omega_0=\sqrt{k/m}$ has the meaning of resonance pulse and $\xi=\frac{c}{2\sqrt{km}}$ damping factor.

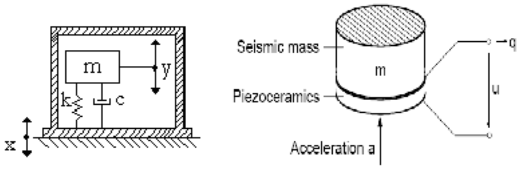

Fig.1. Sensing element's general structure and piezoelectric sensing element.

Depending on the relation between m, k and c the movement of the seismic mass is proportional with displacement, or velocity, or acceleration of the body. For acceleration measurement m and c are small, negligible against k.

$$ky\approx -m\frac{d^2x}{dt^2}\Rightarrow y\approx -\frac{m}{k}\frac{d^2x}{dt^2} \tag{3}$$

The sensing element of a piezoelectric accelerometer, the piezoceramic material, is sandwiched between two electrodes. A force applied perpendicular to the disk causes a charge production and a voltage at the electrodes. Since the seismic mass is constant the charge output signal is proportional to the acceleration of the mass. [2] [6]

The charge sensitivity of the piezoceramic material is $S_q=q/a$, and the voltage sensitivity $S_u=u/a$.

Over a wide frequency range both sensor base and seismic mass have the same acceleration magnitude. Hence the sensor measures the acceleration of the test object.

A piezoelectric accelerometer can be regarded as a mechanical low-pass filter with resonance peak. The seismic mass and the piezoceramics form a spring mass system. The resonance frequency of the system defines the upper frequency limit of an accelerometer. To achieve a wider operating frequency range the resonance frequency should be increased. This is usually done by reducing the seismic mass. However, the lower the seismic mass, the lower the sensitivity. Figure 2 shows a typical frequency response curve of an accelerometer when it is excited by a constant acceleration. [7]

At approximately 1/5 of the resonance frequency the response of the sensor is 1.05. This means that the measured error compared to the lower frequency is 5%.

At approximately 1/3 of the resonance frequency the error is 10%. For this reason the "linear" frequency range should be considered limited to 1/3 of the resonance frequency. The 3dB limit with approximately 30% error is obtained at approximately one half times of the resonance frequency.

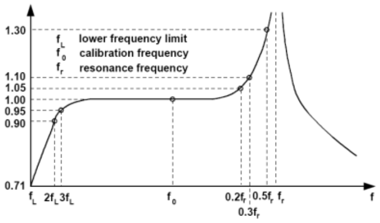

Fig.2. Frequency response of an accelerometer.

The output of the sensor can be a charge or a voltage. Accelerometers with charge output generate an output signal in the range of some pC with very high impedance. To process this signal by standard ac measuring equipment it needs to be transformed into a low impedance voltage signal with a charge amplifier. The input stage of a charge amplifier (fig.3) features a capacitive feedback circuit which balances the effect of the applied charge input signal. The feedback signal is then a measure of input charge.

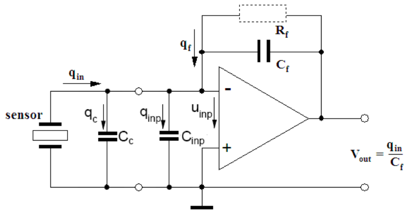

Fig.3. Charge amplifier.

The C_c is the cable capacitance, C_{inp} is the amplifier input capacitance and C_f the feedback capacitor. We can assume that the input voltage of the charge amplifier u_{inp} is equal to zero and we get an output voltage proportional to the input charge. The feedback resistor R_f has the function to provide dc stability to the circuit and to define the lower frequency limit of the amplifier (the RC time constant). The voltage signal can be transmitted over longer distances.

The charge amplifier and other added circuits can form a built-in circuit powered by a constant current source (fig.4). The vibration signal is transmitted back to the supply as a modulated bias voltage. Both supply current and voltage output are transmitted via the same coaxial cable (IEPE transducer). The capacitor C_C is a coupling capacitor and removes the sensor bias voltage from the instrument input providing a zero-based ac signal. Cc and R_{inp} acts as a high pass filter, its time constant should be sufficiently high to let all relevant low frequency components of the sensor signal pass. The output impedance is typically 100 - 300Ω. The dc output voltage of the sensor without excitation is between 8 and 12 V and it varies with supply current and temperature. In most applications voltage output accelerometers are used. [3], [7]

Charge sensitivity or voltage sensitivity describe the relationship between acceleration and output. The voltage sensitivity is expressed in mV/g or mV/ ms^{-2}. [3] [8]

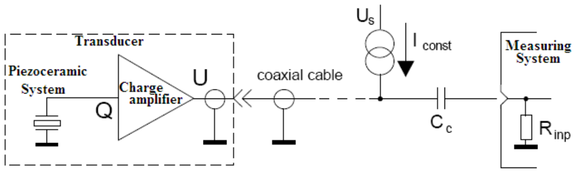

Fig.4. IEPE accelerometers.

3. Modeling the capacitive sensor element

The ADXL202 is a low cost, low power, complete dual axis accelerometer with a measurement range of ±2 g from Analog Device. The ADXL202 outputs analog and digital signals proportional to acceleration in each of the sensitive axes. The ADXL202 can serve as a low cost, multifunction sensor for vehicle security systems, capable of acting simultaneously as a shock/vibration detector as well as a tilt sensor. The ADXL202 is a silicon micromachined type sensor with additional BiMOS circuit on-chip to provide signal conditioning too [5].

Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces. Deflection of the structure is measured using a differential capacitor that consists of independent fixed plates and central plates attached to the moving mass. 180° out of phase square waves drive the fixed plates. Acceleration will deflect the beam and unbalance the differential capacitor, resulting in an output square wave whose amplitude is proportional to acceleration. Then the analogue signal is converted to a duty cycle output. Through an external resistor can be set the period of the duty cycle output. At 0g acceleration we have 50%duty cycle output. The acceleration can be determined by measuring the length of the pulses with a counter/timer. An analog voltage output can be also obtained by passing the duty cycle signal through an RC filter.

Designing an acceleration measurement system means to determinate a few external components for the sensor, which set the period of the duty cycle, the bandwidth, the noise of the acceleration measurement, the measurement resolution due to the counter on the microcontroller. Analog Devices has simplified the design procedure by providing an excel spreadsheet “The XL202 Interactive Designer” that can be downloaded from their website. Through this we can obtain the values for the external components, all we need is to feed the supply voltage, the bandwidth, the time required to calculate the acceleration for two channels, needed to calculate the period of the duty cycle output, and finally the counter rate of the measurements system is used to calculate the measurement resolution due to the counter in g’s and degrees of tilt [4] [5].

Figure 5 presents the ADXL202 sensor with calculated external components.

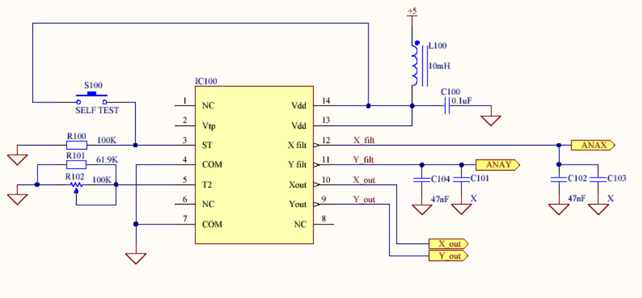

Fig.5. The ADXL accelerometer with external components.

The ADXL202 outputs a pulse width modulated signal at both outputs proportional to the tilt in X and Y direction of the sensor’s plane. The period of the output signal is:

$$T(s) = R_{SET}(\Omega)/125M\Omega \tag{4}$$

For T=0.2ms R_{SET}=25kΩ.

The sensing element of the ADXL202 is a differential capacitive type, where the central mobile plate is moving with the seismic mass. Figure 6 shows the differential capacitor structure and the voltage distribution between the plates.

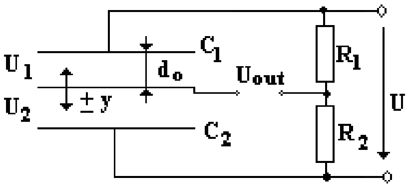

Fig.6. Differential capacitor structure connected to the Sauty bridge.

The capacitive variation is converted in voltage through a Sauty bridge and the output voltage varies linear with the central plate movement.

$$\begin{aligned} U_1 &= U\frac{d_0 + y}{2d_0} \\ U_2 &= U\frac{d_0 - y}{2d_0} \\ U_{out} &= \frac{U}{d_0}\cdot y \approx \frac{U}{d_0}\left(-\frac{m}{k}\frac{d^2x}{dt^2}\right) \end{aligned} \tag{5}$$

At acceleration measurement we use relation 3 which means the output voltage is proportional to acceleration.

The output voltage of the bridge can be written as a function of the bridge elements also and the displacement of the central plates appears in this relation:

$$U_{out} = U\frac{d_0(R_1 - R_2) - y(R_1 + R_2)}{2d_0(R_1 + R_2)} \tag{6}$$

The differential capacitor is supplied through a constant voltage which means the variation of the capacitor leads to a modification of the electric charge. This case reflects a similarity between the piezoelectric sensor model (fig.7a) and the capacitive element sensor model (fig.7b).

The model of the capacitive sensor includes the sensor's capacitance C_S, the mechanical elasticity represented by C_e, seismic mass and inertia of the sensor represented by *L*, the total resistance of the bridge R_i. If the sensor is connected to a load resistance (input resistance of the measurement circuit), this also acts in parallel with the bridge resistance, both increasing the high-pass cutoff frequency of the sensor (fig.7b).

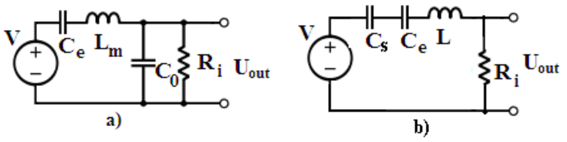

Fig.7. Piezoelectric and capacitive sensor element models.

The transfer function of the piezoelectric sensor model is [9]:

$$H(s)=\frac{Y(s)}{X(s)}=\frac{\frac{R_i\cdot C_e}{L_m\cdot C_e+1}s}{\left(\frac{R_i\cdot C_e}{L_m\cdot C_e+1}+C_0\right)s+1}=\frac{a\cdot s}{(a+C_0)s+1} \tag{7}$$

The transfer function of the capacitive sensor element model is:

$$H(s)=\frac{Y(s)}{X(s)}=\frac{R_i s}{Ls^2+R_i s+C} \tag{8}$$

Where C is the equivalent capacitor for C_S and C_e.

The capacitive sensor element can be studied through the equation which described the electronic circuit. The equations suitable for the circuit from figure 7b are:

$$\begin{aligned} u_{out} &= u_{Ri} = R_i\cdot i \\ u_{Ri} &= V-u_{Cs}-u_{Ce}-u_L=u_{in}-\frac{1}{C_S}\int idt-\frac{1}{C_e}\int idt-L\frac{di}{dt} \end{aligned} \tag{9}$$

The proper Simulink model is presented on fig. 8.The output signal is the voltage on the R_i resistance.

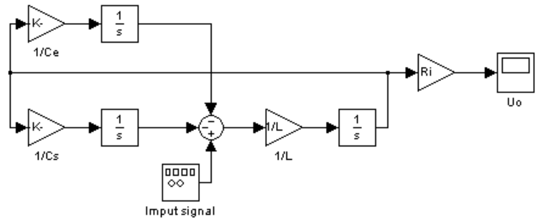

Fig.8. Simulink model of the circuit.

The frequency response of the system and the influence of the R_i resistance, is presented on the figure 9.

4. Conclusions

The ADXL type accelerometers for two or three axes are widely used for measuring absolute vibration, acceleration or tilt. To obtain precise output signals proportional to the input some basic knowledge about capacitive sensing elements accelerometers is required. In many cases the accelerometer is the most critical part in the measurement equipment.

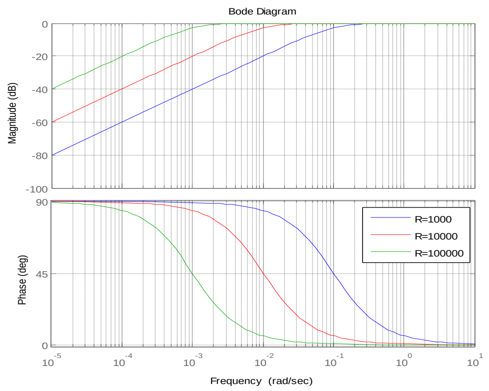

Fig.9. The frequency response.

It is presented the general structure of the sensing element which is a seismic type related to a differential capacitor. The output voltage equation and the equivalent electronic circuit model are presented. Simulink models are developed for the proper equations. Differential capacitive sensing element related to the seismic mass is simpler as the piezoelectric sensing element. Transfer functions can be used to simulate the frequency response of the electronic models with different *L* (seismic mass) values.

References

[1].*** - *Application note AN1E. Piezoelectric accelerometers. Introduction.* Metra Mess- und Frequenztechnik Radebeul, Germany, 2003.

[2].*** - *Application note AN2E. Piezoelectric accelerometers. Piezoelectric principle.* Metra Mess- und Frequenztechnik Radebeul, Germany, 2003.

[3].*** - *Application note AN4E. Piezoelectric accelerometesr. IEPE Accelerometrs.* Metra Mess- und Frequenztechnik Radebeul, Germany, 2008.

[4].H.Weinberg, C.Lemaire, *Using the ADXL202 Accelerometer as a Multifunction Sensor (Tilt, Vibration and Shock) in Car Alarms,* Analog Device Inc. www.analog.com.

[5].*** - ADXL202 *Accelerometer*. Datasheet, www.analog.com

[6].*** - *Introduction to Shock & Vibration,* Brüel & Kjaer, www.bk.com

[7].*** - *Vibration Transducers and Signal Conditioning*, Brüel & Kjaer, www.bk.com

[8].Agoston K. - *Senzori in automatizari industriale,* Editura Universitatii "Petru Maior", Tg.Mures, 2004.

[9]. Agoston K. – *Studying and Modeling Vibration Transducers and Accelerometers*, Scientific Bulletin of the "Petru Maior" University of Tg.Mures, 2010. vol.7. nr.2. pag.14-17.