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Application of Single MEMS-Accelerometer to Measure 3-Axis Vibrations and 2-Axis Tilt-Angle Simultaneously

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Abstract

This paper discusses about a technique to developing an integrated sensor system for measuring mechanical vibrations in 3-axis and tilt angle in the 2-axis simultaneously, using single MEMS-accelerometer, i.e. MMA7361L. The MMA7361L is an analog accelerometer with maximum sensitivity of 800 mV/g. This device has 3-channels output voltage (V_x, V_y, V_z) in response to the acceleration "g" of each axis corresponding work (g_x, g_y, g_z). By using certain techniques in the design of signal conditioning circuits, then the MMA7361L can used to detect 3-axis vibration and 2-axis tilt angle at the same time. To accommodate the 5-signals from output of the sensor system, is constructed a data acquisition system based on PIC16F876 microcontroller, which provides 5-channels internal ADC with 10 bits resolution. Thus, the resulting integrated sensor system becomes very simple and inexpensive. Results of experiment show that the developed sensor system has proven having good performance. For the vibration sensor, voltage gains can be set up to 60 dB (800 V/g) with low-level noise. While the tilt sensor is capable of detecting up to ± 30 angle on the non-linearity of 4.5% (max), with average resolution of about 0.06 degrees.

***Keywords**: Integrated Sensor, Vibration, Tilt-Angle, MEMS-Accelerometer*

1. Introduction

For analyzing the dynamic motion of an object, the measurement of multi-axis vibration and tilt-angle often performed simultaneously. For example, for testing and analysis of the dynamic movement of a ship [1], investigating active volcano [2],[3], determine the health status of industrial machines [4],[5], and so on. In here, to get simultaneous measurement of vibrations and tilt-angle, will require more then one kind of sensor. Then measuring instrument will become complex and may be expensive. The complexity is not only in terms of the sensor design, but also in the data acquisition (DAQ) system.

The measurements of vibration as well as tilt angle can be conducted by using various sensors, of course each of them with their own merits and limitations. In recent year, application of micro electro-mechanical systems (MEMS) accelerometer to detect vibration as well as tilt-angle has been widely used in various fields of application, such as in [4]-[8]. Accelerometer sensors made using MEMS are better than their conventional counterparts because they are smaller in size, low power consumption, sensitive to input variations, easy to integrate into systems or modify, and cheaper.

Nowadays, many kinds of MEMS accelerometer have been available in the commercial market with relatively low-cost. MEMS accelerometers play an important role in the instrumentation of dynamically sensitive systems. MEMS accelerometer has capabilities to detect vibration as well as tilt-angle by precisely and accurately. Therefore, the idea of integrating vibration sensors and tilt sensors into one module by using single chip MEMS accelerometer is very interesting to make the sensor system become simple and low cost.

2. Research Method

2.1. Working principles of the sensor system

Figure 1 shows a block diagram of the integrated sensor system which is developed in this research. The sensor system has capabilities to measure of three components (3-axis) vibrations and two components (2-axis) tilt-angle, simultaneously. The 3-axis vibrations are in

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direction of (x, y, z), i.e. *Vib [X]*, *Vib [Y]*, *Vib [Z]*, while the 2-axis tilt-angle are in direction of (xz) and (yz), i.e. *Tilt [XZ]* and *Tilt [YZ]*.

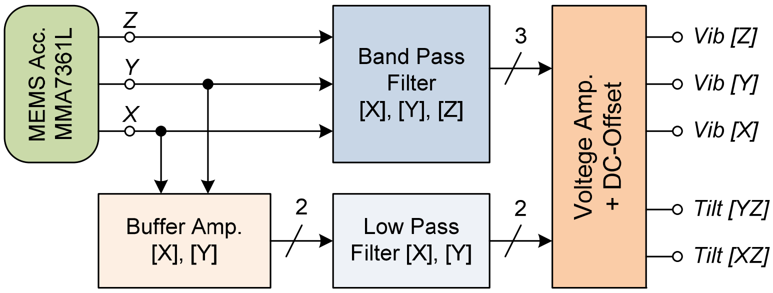
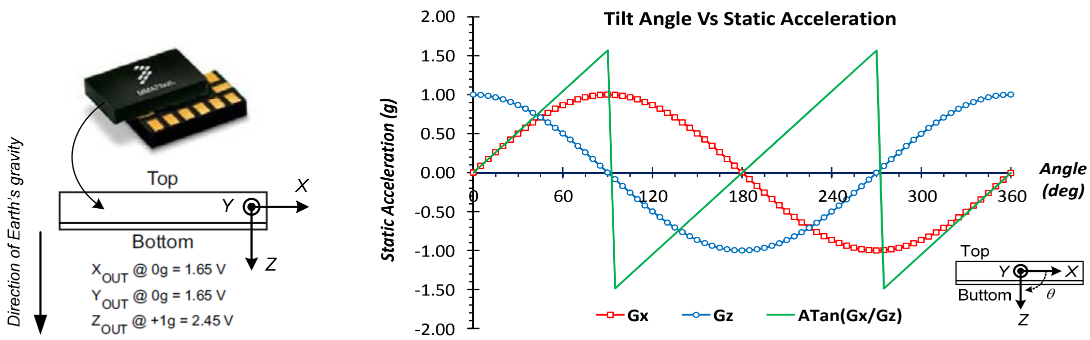


Figure 1. Block diagram of the developed sensor system



(A) (B)

Figure 2. (A) Static acceleration voltages, (B) g-value as function of tilt-angle position

In this research, we use an IC MMA7361L. It is an analog-triaxial capacitive based MEMS accelerometer, fabricated by Freescale Semiconductor. The MMA7361L featuring signal conditioning, temperature compensation, 0 g-detect, and g-select which allows for the selection between two sensitivities (±1.5 g and ±6 g) with sensitivity maximum of 800 mV/g @ 1.5 g. The device can measure both positive and negative mechanical acceleration [9]. Principle of vibration and tilt measurement by using MMA7361L is detection "g" value due to dynamics and static acceleration. With no mechanical acceleration (g=0), the MEMS output voltage is at mid-supply ($V_{DD}/2$). For positive acceleration, the output will increase above $V_{DD}/2$, and for negative acceleration, the output will decrease below $V_{DD}/2$. In horizontal position as shown in Figure 2A, MMA7361L gives a certain voltages on the pin-outs (X_{OUT}, Y_{OUT}, Z_{OUT}) amount depends on the position. By the use of V_{DD} = 3.3 V and g-select = ±1.5g (sensitivity is set to 800 mV/g), the values of the MEMS static voltage are 1.65 V for 0 g, 0.85 V for -1 g, and 2.45 V for +1 g.

Figure 2B shows relationship between the angle position (in degree) and the static acceleration (in 'g') of the MMA7361L in the directions of x-axis and z-axis. As shown in this figure, the relationship between tilt angle and static acceleration is not linear, but as the sine function. Such characteristic is not favorable in terms of a sensor design due to non-linearly. Actually, to get true linearity on the tilt angle measurement by using MEMS accelerometer is required two-axis. Then, g-values calculated by using arc tan (g_x/g_z), as shown on the green line on that figure. However, for small angle, the value of (sin θ) will be almost same with (arc-tan θ), so the use of one axis will not produce too large measurement errors (see Figure 2B).

2.2. Design of 3-axis Vibrations Sensor

According to Figure 1, to build a 3-axis vibration sensor by using MMA7361L, we need all of the output of this device, i.e. X_{OUT}, Y_{OUT}, and Z_{OUT}. These outputs then be connected to the signal conditioning circuit. Procedure to develop the signal conditioning circuit is as follows:

- First, remove static acceleration voltage of the MMA7361L, to make signal swing on the zero-line (0 V),
- Second, filter the signal to reduce high frequency noise,
- Third, amplification the signal, so it is in the range of (-2.5 to 2.5) V,
- Fourth, lift the signal by 2.5 V, to put it on the position in the middle of (0-5) V; it is upon request of the DAQ (which will be described later).

Implementation of the above procedure to build circuit is given in Figure 3. The circuit consists of low pass filter (LPF), high pass filter (HPF), and instrumentation amplifier (IA). Function of LPF is to reduce high frequencies noise, whereas HPF is to remove static voltage (DC) caused by static acceleration of the MMA7361L. Then by applied HPF, the static voltage will removed automatically. In here, both HPF and LPF are designed based on 2^{nd}-order (-20 dB) Sallen-Key filter, and built by using IC LF353. The LF353 is dual Op-amp with low-cost, high-speed, JFET-input with very low input offset voltage. It requires low supply current yet maintains a large gain-bandwidth product and a fast slew rate [10]. The corner frequency of LPF ($f_{C\text{-}LPF}$) as well as HPF ($f_{C\text{-}HPF}$) is given by formula in Eqs.(1) and Eqs.(2) respectively [11]. By determining values of (R_1, R_2, C_1, C_2) and (R_3, R_4, C_3, C_4), then the working frequency (frequency response) of the vibration sensor can be specified.

Furthermore, in view of DAQ system, the internal ADC of the microcontroller needs analog input signals within (0-5) V. To provide this condition, the output signal from the signal conditioning circuit should be in the range of (-2.5 to 2.5) V, and then buffered by 2.5 V. Therefore, the output signals of the MMA7361L (after passing the filter circuits) need to be amplified several times. The value of amplification (voltage gain) is depends on the power of the mechanical vibration which is detected by the MMA7361L. In here, the voltage amplifier circuit performed by an instrumentation amplifier (IA), and constructed by IC AD620. It is low cost device and ideal for use in the precision DAQ systems. The AD620 requires only one external resistor to set voltage gains (Av) of 0 dB to 60 dB, even more. Voltage gains of the AD620 is given by Eqs.(3) [12]. Once the signal is already at the desired level, it then shifted by 2.5 V, through the setting up of a reference voltage (REF) of AD620. Thus, output signal of the vibration sensor will fluctuate (swing) at the value of 2.5 V. Then the signal will has minimum value of at 0 V and maximum value of at 5 V. In addition, Zener Diode (5.1 V) mounted on the IA serves as a safety for the DAQ over voltage excess of the signals. In here, to handle of three-axis vibrations sensor, we need three modules of signal conditioning circuits.

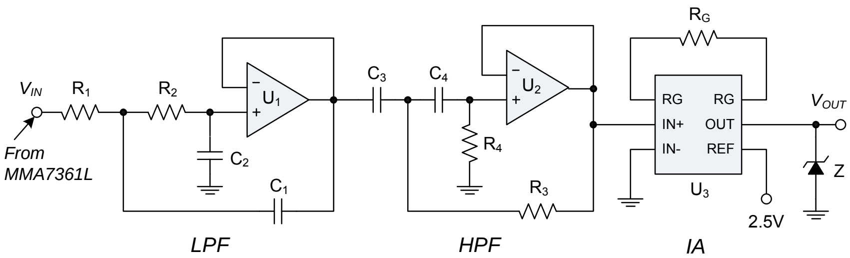


Figure 3. Signal conditioning circuit for vibration sensor

$$f_{C-LPF} = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} Hz \quad (1)$$

$$f_{C-HPF} = \frac{1}{2\pi\sqrt{R_3 R_4 C_3 C_4}} Hz \quad (2)$$

$$A_v = \frac{49.4k\Omega}{R_G} + 1 \quad (3)$$

2.3. Design of 2-axis Tilt-angle Sensor

To build a 2-axis tilt-angle sensor by using MMA7361L, we need two signals of the device, i.e. X_{OUT} and Y_{OUT}. In here, Tilt [XZ] related to the X_{OUT} (Vx), and Tilt [YZ] related to the Y_{OUT} (Vy). The principle of tilt measurement by using MMA7361L is to utilize static acceleration voltage due to the gravitational fields 'g'. Thus, the static acceleration voltage of the MMA7361L is depends on its position against the downward direction (direction of the gravitational field). Relationship between tilt angle and output voltage of the MMA7361L is given in Figure 4. The maximum voltage (2.45 V) correspond to the static acceleration of (+1 g), the minimum voltage (0.85 V) corresponds to the (-1 g), and center voltage (1.65 V) corresponds to the (0 g).

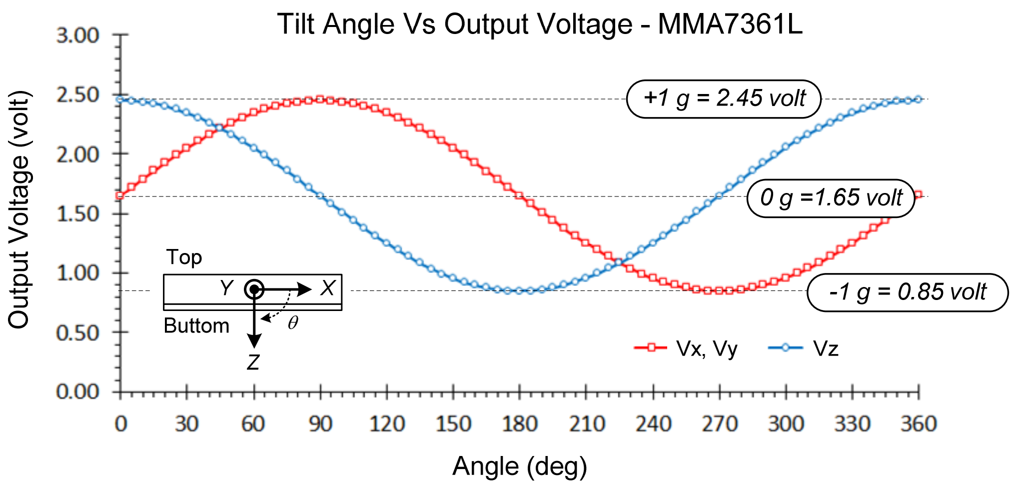


Figure 4. Relationship between angle and output voltage

Figure 5 shows a captured and normalized (zeroing) signals in the range of (-90 to +90) degrees. The additional line (green line) on this figure obtained from arc-tan (Vx/Vz), and it is a linear line. It seems clear that measurement of tilt angle by using MMA7361L will produce linear voltages when performed by two-axis sensing. However, for the reasons of simplification on the sensor design, in this project we use one-axis detection only. As described above, for small angle case, the value of [Vx] is almost equal to the value of arc-tan [Vx/Vz]. For MMA7361L with sensitivity 800 mV/g, and in the position like in Figure 4, then:

$$V_X = V_Y = (0.8 * \sin\theta) \text{ volt; } V_Z = (0.8 * \cos\theta) \text{ volt} \quad (4)$$

Percentage of the maximum non-linearity can be calculated by:

$$\%\ non\,linearity = \left(\frac{V_X - 0.8 * \arctan(V_X / V_Z)}{0.8 * \arctan(V_X / V_Z)} \right) * 100\% \quad (5)$$

By using Eqs.(5), the percentage of maximum non-linearity for some small angle can be calculated. For examples, such as for 30 degrees is 4.5%, 20 degrees is 2.0% and 10 degrees is 0.5%. Smaller angle of measurement will produce smaller non-linearity.

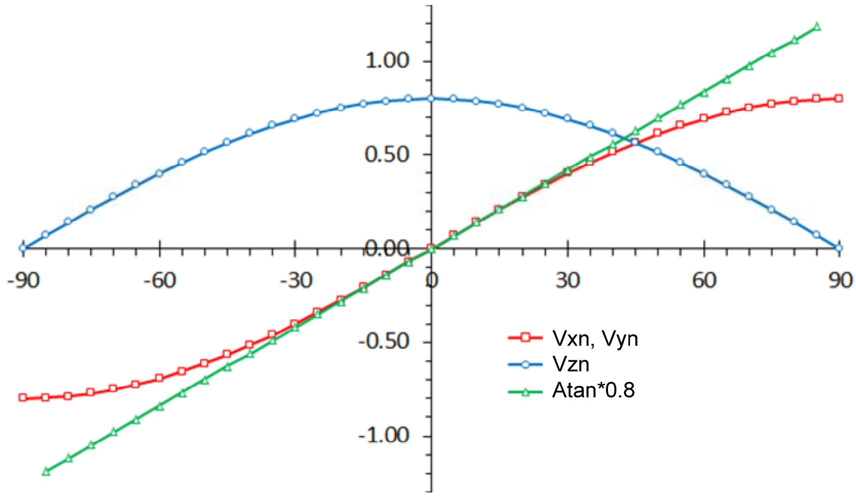


Figure.5. Normalized tilt-angle vs. output voltage

In order to improve resolution of the tilt sensor, measurement data should be in the range of (0 to 5) V. Technically, we need to amplify the signal by several times, and then buffered signal by 2.5 volts. For case where angle of measurement is in the range of (-30 to +30) degrees, the normalized output of the MMA7361L is (-0.4 to 0.4) V. Then, amplification of the signals by 6.25 times, the voltage become (-2.5 to 2.5) V. Graph in Figure 6 shows the calculation result for tilt angle measurement within range of (-30 to +30) degrees after sifted by 2.5 V. The dot-red circle is data from the sensor output (Vx), and black line is arc-tan of the data. It can be seen that the smaller range of angle measurement, the linearity will better.

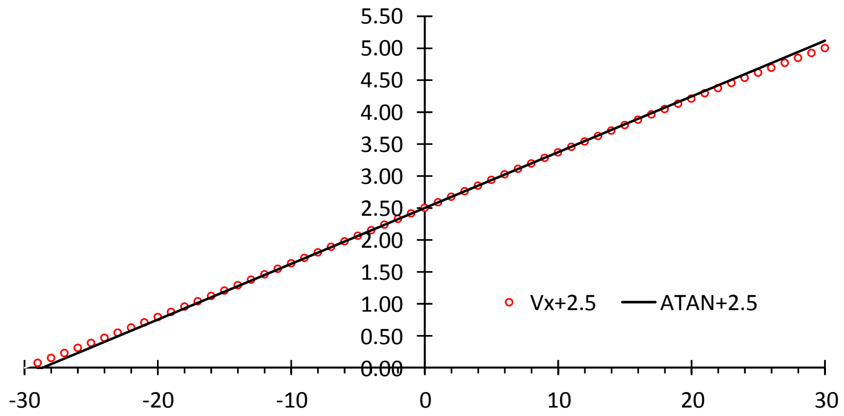


Figure 6. Linearity of tilt angle within -30 to 30 degrees

Based on the working principles of MMA7361L due to static acceleration, the design of signal conditioning for tilt-angle sensor should be follow these steps.

- First, place a high-Z buffer to avoid the loading effect caused by vibration sensor,
- Second, filter the signal to reduce high frequency noise,
- Third, normalize the signal, and amplification to the range of (-2.5 to 2.5) V,
- Fourth, lift the signal by 2.5 V; to put it on the position in the middle of (0-5) V.

Implementation of the above procedures is given in Figure 7. Formulation to calculate corner frequency of the LPF is same with vibration circuit e.g. Eqs (1). Normalized-offset (1.65 V) and sifted-offset (2.5 V) is given by an adjustable voltage regulator, and not expressed on this figure.

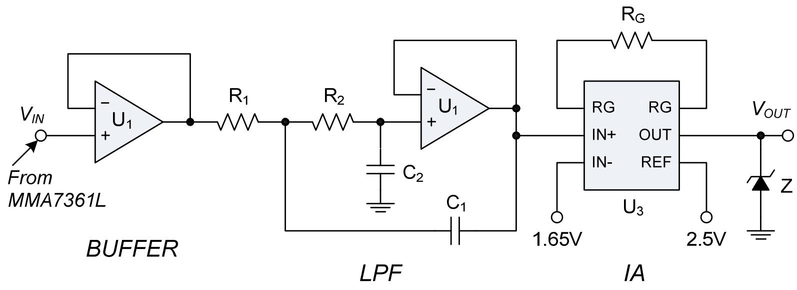


Figure 7. Signal conditioning circuit for tilt-sensor

2.4. Design of Data Acquisition (DAQ)

In the design of DAQ system hardware, the use of a microcontroller as main component is well choice to get a simple form and low budget. The advantages of using a microcontroller to build a DAQ system are small dimensions, programmable, simple, reliable and relatively cheap [13]. Microcontroller also directly connected to the computer (PC) without or with minimum interface. Thus, in this research the DAQ system is built based on PIC16F876 microcontroller, manufactured by Microchip [14]. The device has 5-channels internal ADC with 10 bits resolution. By using a ADC reference voltage (Vref) of 5 V, the analog voltage that can be converted by the ADC is in the range of (0-5) V. Therefore, in the design of signal conditioning circuit, the output voltage of the signal conditioning must be at a value (0-5) V. For the purpose of interfacing to the sensor module, Ch-1 ADC used for Tilt-[XZ], Ch-2 for Tilt-[YZ], Ch-3 to Vib-[X], Ch-4 for Vib-[Y], and Ch-5 for Vib-[Z].

Moreover, communication between DAQ module (microcontroller unit) and PC is arranged by program procedure that has been installed on both microcontroller and PC. This communication can be performed by wire or wireless. Usually, wireless communication is used to long distance measurement via radio telemetry system, and it can be handled easily by using a RF-transceiver such as YS-C20K. It is low cost, and capable to covered around 3 km [15]. Figure 8 shows hardware of DAQ system.

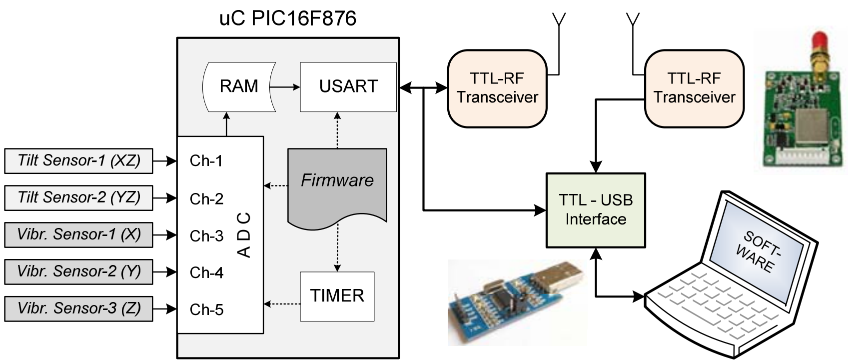


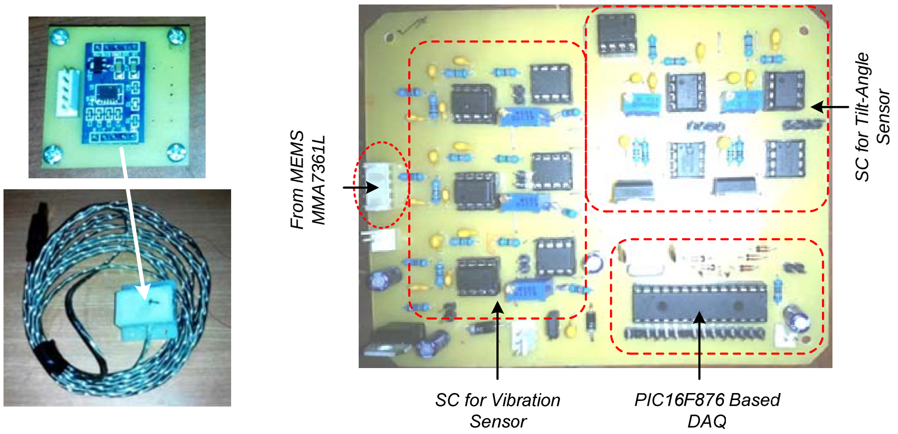
Figure 8. Block diagram of the DAQ module

3. Results and Analysis

Implementation design of the sensor, signal conditioning circuits, and DAQ on a printed circuit board, given in Figure 9. Figure 9A shows photo of the developed sensor module. The sensor module is MMA7361L, and then packed by acrylic material. It is necessary to make not easily shaken and become watertight. In this figure, five pins-out is made up of three pins of the acceleration signals (Vx, Vy, Vz) and two pins for the power supply (GND and Vdd = +5 V). The output of the sensor module is then connected to the signal-conditioning circuits to be formed as vibration signals i.e. Vib-[X], Vib-[Y], and Vib-[Z], and tilt-angle signals, i.e. Tilt-[XZ] and Tilt-[YZ].

According to the explanation above, in true-horizontal position (Fig. 2A) and no dynamics vibration, the outputs of the five signals mentioned above is 2.5 V.

Figure 9B show signal conditioning and DAQ module. This module contains of three signal conditioning circuits for vibration sensors, two signal conditioning circuits for tilt-angle sensors, and a five analog input channels DAQ to acquire signals from all (five) of the sensors. As described above, the signal conditioning for vibration sensor consists of HPF, LPF and voltage amplifier, whereas tilt-angle sensor circuits consists of Buffer, HPF, and voltage amplifier. The DAQ system built based on PIC16F876 microcontroller, it has capabilities to measure up to five channels analog signals simultaneously, with ADC resolution of 10 bits. In addition, the DAQ system module connected to the computer (PC, as hardware controller and data processing) via USB port. We used TTL to USB converter as interface between microcontroller and PC.



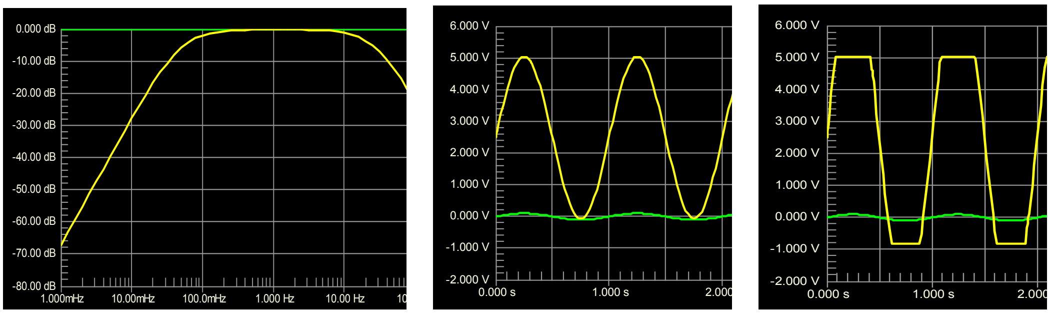
(A) (B)

Figure 9. (A) Sensor module, (B) Signal conditioning and DAQ module

Hereafter, to determine performance of the sensor, we carried out some simulations. By using circuit in Figure 3, and setting value of $R_1 = R_2 = 220$ kΩ; $C_1 = C_2 = 15$ nF; $R_3 = R_4 = 3.3$ MΩ, and $C_3 = C_4 = 1$ μF, then corner frequency of the LPF is around 48.5 Hz, and corner frequency of the HPF is around 0.05 Hz. With this result, frequency response of the vibration sensor is (0.05 to 48.5) Hz (Figure 10A). This frequency range is usually used on the design of seismic sensors, that very important in geophysics field. Further, Figure 10B is simulation of using voltage-offset and gain control to make several gains of the signals. In this figure, amplification of the signal is optimal; signal has value of (0-5) V. It appears that the signal is buffered to 2.5 V, and then vibration signals will fluctuate around this voltage. If amplified signal has more than 5.1 V, it will be truncated by zener diode (Figure 10C). In here, although zener diode will allow negative signal as low as -0.7 V, but it is still in tolerance and will no processed by ADC. By using Eqs.(3), to obtained gain = 20 dB (10x) we use R_G approximately of 5.5 kΩ, for gain = 40 dB (100x) we use $R_G = 500$ Ω, for gain = 60 dB (1000x) we use $R_G = 50$ Ω, and so on. We can choose the appropriate gain, but keep in mind that the larger gain will produce the larger noise. In experiments (Figure 11), the gain of 60 dB still provides noise that can be tolerated.

For the tilt-angle sensor (Figure 7), the mechanism is similar to the vibration sensor, except it no uses the HPF. The tilt-angle sensor will detect static acceleration (DC-signal), and we cannot apply HPF. To normalize the signal to be amplified, is used a reference voltage of 1.65 V that is given at the inverting input IA. Buffer Amplifier in this circuit, has function to make high impedance input. It is needed to overcome loading effect caused by vibration sensor. As described above, to measure the tilt-angle in the range (-30 to 30) degrees, which corresponds to (-0.4 to 0.4) V, for optimal results we set the voltage gain of 6.25x and shifted 2.5 V. With this condition, the signal will fluctuate in value (0-5) volts. By using 10 bits ADC, the smallest angular can still be detected by the tilt sensor is:

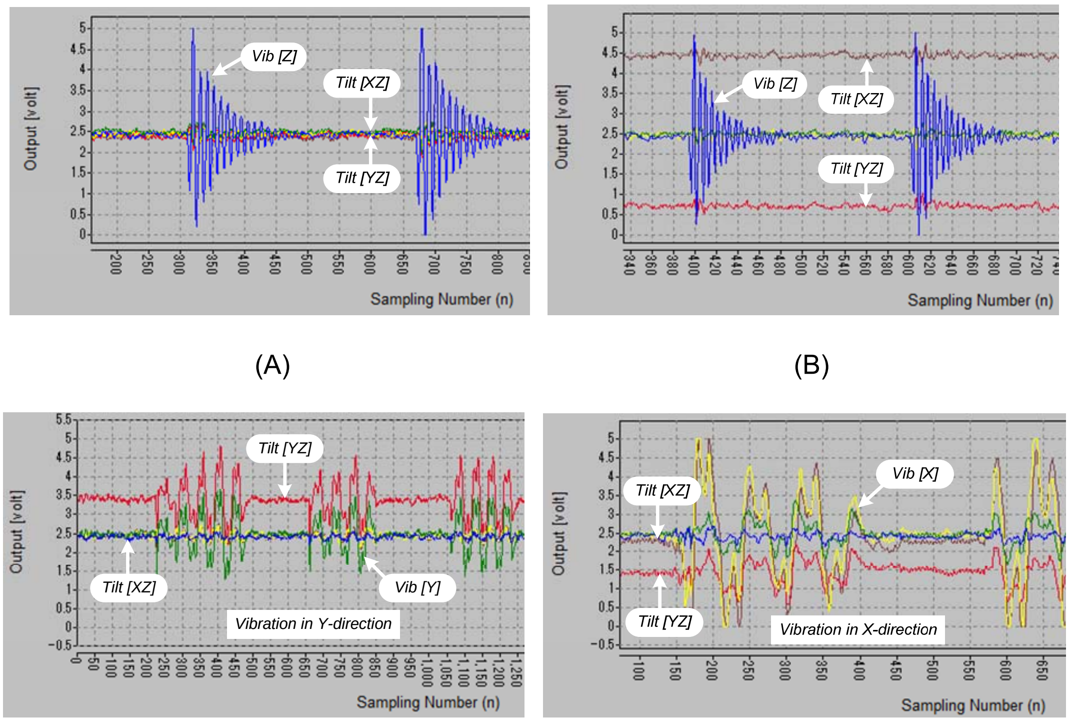
$$LSB_{10} = \left(\frac{5\ volt}{(2^{10}-1)}\right) * \left(\frac{60\deg}{5\,volt}\right) \approx 0.06\deg \qquad (6)$$



(A) (B) (C)

Figure10. (A) Frequency response of the vibration sensor, (B) Amplification and adding DC offset of 2.5 volts, (C) Truncated signal

Finally, Figure 11 shows the captured signal measured by using developed sensor system. In this Figure, the 3-components vibration signal and 2-components tilt-angle signal are measured simultaneously. Here appear, that in Figure 11A tilt angle is in the zero position both for XZ and YZ, and mechanical vibration induced in z-direction. In Figure 11B, tilt angle is exist for both XZ and YZ, and mechanical vibration induced in z-direction. In Figure 11C, tilt angle is exist for YZ but for XZ is zero, and mechanical vibration induced in y-direction. Finally in Figure 11D, tilt angle is still exist for YZ but for XZ is zero, and mechanical vibration induced in x-direction, then vibration signal will swing (vibrate) around its tilt position.



(C) (D)

Figure 11. Measurement of 3-axis vibrations and 2-axis tilt-angle simultaneously

4. Conclusion

In this research, a simple and low-cost sensor and system for integrated measurement of 3-axis vibrations and 2-axis tilt-angles of an object has been developed, using single MEMS-accelerometer. The system is composed of two modules: sensor and data acquisition (DAQ). The sensor module developed based on single chip MEMS accelerometer, i.e. MMA7361L. By using certain techniques in the design of signal conditioning circuits, the MMA7361L can be functioned to measure 3-axis vibrations and 2-axis tilt-angle, at the same time. The data acquisition module is developed based on PIC16F876 microcontroller. The DAQ module has function to collect amount of five signals from sensor module, simultaneously. To validate the developed sensor system, we have conducted several experiments. The results of experiments indicate that the system has capability to measure of 3-axis vibrations and the 2-axis tilt-angle, with good accuracy. For the vibration sensor, voltage gains can be set up to 60 dB (800 V/g) with low level noise. While the tilt sensor is capable of detecting up to ± 30 angle on the non-linearity of 4.5% (max), with average resolution of about 0.06 degrees.

Acknowledgment

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