Wireless sensor module for 3-axis vibration and tilt monitoring on the structural building

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Abstract. In this paper, a simple and low-cost wireless sensor module has been developed for structural health monitoring (SHM) purposes. The module can be divided into three main parts: sensing unit, data acquisition (DAQ) unit, and data communication (DC) unit. The sensing unit is three-axis vibration and tilt sensor. It is composed using single MEMS accelerometer e.g. MMA7361L, and signal conditioning circuit for both tilt and vibration parameters. The DAQ unit function for A/D converter and data formatting, built based on a microcontroller PIC16F873. Whereas DC unit is radio (RF) transceiver, it is used to communicate with the control module (monitoring room) wirelessly. In here, we use RF-transceiver YS-C20K. In the control room, vibrations and tilts data are analysed using the developed software to get information about dynamics condition of structural building being monitored. Results of experiment and evaluation show the tilt sensor is capable to detect up to ± 30 degrees dynamic range with resolution of about 0.05 degrees, while the vibration sensor can achieved up to sensitivity of (80 V/g) with noise compensation. To get portability and easiness in field installation, the sensor system was packaged into one module.

1. Introduction

SHM system (structural health monitoring) in recent years has become an active research because of the need for civil infrastructure analysis that continue to observation performance of degradation construction due to material aging, inexpedient use, and other types of harmful events [1]. Structure of building can be monitoring and get the information using the structural health monitoring system, it collects and analyzes information so the indications of structural damage can be identified early [2]. Instrumentation systems for structural health monitoring (SHM) that combines various sensor connected with DAQ (data acquisition) and capabilities to process data [3], will provide sustainable conditions assessment of civil engineering assets, improve the quality and levels of safety and reduce the costs of maintenance [4]. Degradation phenomena with long-term monitoring of the structure aging will enable the optimization of preventive maintenance so as to reduce the cost of repair and improve security [5].

Nowadays, MEMS accelerometer as micro electro-mechanical systems is use to detect the vibration and tilt angle, it has been widely used in various fields including for SHM [1] [6]. In view of instrumentation and data communication systems, SHM process can be done more practically when we use the wireless system, it can be economics and more advanced way [7]. In previous research, application of wireless sensor system has been developed to monitor traffic based on number of vehicle [8]. In this paper, we propose wireless sensor module dedicated for SHM in simple system design and low-cost in budget. The sensor system is developed using single MEMS accelerometer, it
is used for collecting the information about condition parameters of structural building being monitored. The measured data from sensor then transmitted to the Master Terminal Unit (MTU), which is placed in the control room. In the MTU, data will be analyzed using developed software to get information about structural condition based on vibration and tilt data.

2. Experimental Methods

2.1 Description of the System
A distributed wireless sensor is deployed in specific places the building. The use of wireless sensor network can make advantages, the network setup can be carried out without fixed infrastructure. It can be accessed online on central base station and reduce the wiring complexity. Accelerometer sensor attached to the wireless sensor node. Tilting angle and vibration of building detected use the accelerometer sensors. A 433 MHz radio transceiver is use for transmit data of the sensor to the base station. The same frequency band needed to make the base station and sensor nodes can be work. Sensor nodes are same in wireless sensor system structure. The main important parts in the wireless sensor nodes is unit of sensing, RF 433 MHZ, signal conditioning, signal processing module, microcontroller. In the wireless sensor node the sensing unit make a big parts. Accelerometer sensors (MMA7361L) are used to detect the tilting angle and vibration of the building. The MMA7361L is an analog-triaxial capacitive based MEMS accelerometer featuring signal conditioning (1 pole Low Pass Filter), two sensitivities (±1.5 g and ±6 g) with sensitivity maximum of 800 mV/g at 1.5 g [9]. Signal conditioning is consists of range matching, amplification, filtering, and converting etc. The sensor needed the conditioning to make output of the sensor suitable for further processing. Data of the sensor is in the form of analog signal (voltage). We use the A/D converter to convert data form analog into digital form or digital signal and ready to transmitted into MTU.

2.2 Design and Implementation
A. Vibration and Tilt Angel Module
The vibration sensor by using MMA7361L use to detect the mechanical vibrations and converted into proportionally of electrical voltage. For tilt measurement is static acceleration voltage due to the gravitational fields ‘g’ [9]. When the sensor detects no acceleration which is g=0, output of the voltage from sensor is at mid supply (VDD/2). When we get the positive acceleration, the output will increase above VDD/2 and otherwise, for negative acceleration the value of output will decrease below to the VDD/2. This MMA7361L has 3 output pins related to (XOUT, YOUT, ZOUT). To get high sensitivity (800mV/g) the g select can be set to ±1.5g whereas the MEMS static voltage are 1.65 V for 0g, 0.84 V for ±1.5g, and 2.45 V for 1g.

A 3-axis vibration and tilt angel sensor can build by using MMA7361L, three output of this device needed, i.e. XOUT, YOUT, and ZOUT. To remove static acceleration voltage of the MMA7361L three outputs then be connected to the signal conditioning that designed, then signal will swing on the zero-line (0 Volt) whereas differential amplifier used to remove static voltage (DC) the caused by static acceleration of the MMA7361L. Then LPF is applied to reduce high frequencies noise. LPF is designed based on 2nd-order (-20 dB) Sallen-Key filter, and built by using IC LM324. The LM324 is quad OP-AMP, can operated in single supply, and low input offset voltage[10]. The internal ADC from DAQ system based on microcontroller needs analog input signals within (0-5) V. Then the signal conditioning circuit have to make in the range of (-2.5 to 2.5) V, and then buffered by 2.5 V. The MMA7361L need to be amplified several times after passing the filter circuits. We use IC AD623 to perform the voltage amplifier circuit by an instrumentation amplifier (IA). It can be use as an ideal system for precision DAQ, also it low cost device and can operated for single supply application [11]. The offset can be divided into two parts, normalized-offset (1.65 V) and sifed-offset (2.5 V) and it given by an adjustable voltage regulator, and not expressed on this figure. Implementation of the above procedures is shown on figure 1.
Figure 1. Signal Conditioning of 3 Axis Vibration and Tilt

Based on figure 1, VREF used a voltage level adjustment to make the conditions for the output signal. It will make the signal from the sensor module in the range of 0-5 volts, it was required by the data acquisition system. The signal conditioning circuit is made of 3 pieces based on output of each axis accelerometer X, Y, and Z. In the case of small angle case, the value of output potential $V_x$ is almost equal to the value of $\text{arc-tan} \left(\frac{V_x}{V_z}\right)$.

MMA7361L with sensitivity 800 mV/g and with the position based on Figure 3, then:

$$V_x = V_y = (0.8 \times \sin \theta) \text{volt} \quad (1)$$

$$V_z = (0.8 \times \cos \theta) \text{volt} \quad (2)$$

The corner frequency of LPF (FC-LPF) is given by formula:

$$f_c - \text{LPF} = \frac{1}{2\pi \sqrt{R_1 R_2 C_1 C_2}} \quad (3)$$

Voltage gains of the AD623 is given by [11]:

$$A_v = \frac{100k\text{ohm}}{R_G} \quad (4)$$

B. Design of Data Acquisition (DAQ)

A microcontroller use as main component to build a DAQ system, it used to get a simple form and low cost [12]. It built based on PIC16F873 microcontroller, which is featuring 5-channels internal ADC with 10bit resolution and serial communication. DAQ module (microcontroller unit) and PC use communication arranged by program procedure that has been installed on microcontroller and development software on PC and performed by wireless communication handled easily by using a RF-transceiver YS-C20K that can used for long distance communication up to 3km [13]. Figure 5 shows hardware of DAQ system.
In figure 3 it shows the diagram of Wireless Sensor Network (WSN). This diagram shows when used for multi node, each sensor node can be easily handled and controlled by single gateway. With this WSN system, we have an advantages in easy installation, flexible for increase or decrease the number of node, and well choice for long distance monitoring.

When the system is start, base station sends the data collecting command via PC through wireless communication. Because of each node uses same wireless communication device (same band frequency), to avoid error command in each node, so each node will be set to have special command different from each node installed on their firmware system. After finishing the data collecting procedure, PC will receive data from the node. By using developed software, the data can be analyzed to find information. In addition, for online monitoring through internet, the data can be uploaded to the database server.
3. Results and Discussion
The implementation of design sensor, signal conditioning circuits, and DAQ on a printed circuit board, given in Figure 4(A). This module contains of MEMS accelerometer MMA7361L sensor, three signal conditioning circuits for vibration sensors and tilt-angle sensors, signal processing, and power source. The signal conditioning for vibration and tilt angle sensor consists of LPF, differential amplifier, offset adjustment, and voltage amplifier. Microcontroller PIC16F873 is used to build a DAQ system, the system has capabilities to measure up to 3 channels analog signals simultaneously, with 10 bits ADC resolution.

![Figure 4. (A). Implementation of Sensor Design, (B). Modular System Sensor](image)

Figure 5. Experimental Results
In circuit on figure 1, by setting of $R1 = R2 = 33 \, k\Omega$; $C1 = C2 = 100 \, nF$ so corner frequency of the LPF is around 50 Hz. To adjust the voltage gain, it can be done by setting the value of $RG$. For optimal results it set the voltage gain of $3.125x$ and shifted $2.5 \, V$. For optimal results we set the voltage gain of $3.125x$ and shifted $2.5 \, V$. With this condition, fluctuate of the signal in value (0-5) volts for vibration and for tilt angel it can measure the tilt-angle in the range (-30 to 30) degrees, which...
corresponds to (-0.4 to 0.4) V the signal will fluctuated in value around (1.2-3.75) volts. To get portability and easy installation, the system was packaged into a one module expressed in figure 4 (B). Experimental results are shown in figure 5 (A-D). In figure 5 (A), shows that the system capable to measure tilt angle up to 30 degrees with non-linearity around 4.5%. Next, in figure 5 (B), shows the measured signal of tilt angel from 3 axis of the sensor. Finally, figure 5 (C) and (D) shows that the system can used to measure vibration and tilt angel at same time continuously. When used for SHM system, based on this sensor module and experimental results, it can be used to determine the condition of structural building based on damping factor, and slope of the building.

4. Conclusion
In this research, we successfully developed wireless sensor module that dedicated for SHM system, with simple design and low budget. The sensor system is proficient to measure three-components of vibration and tilt parameters simultaneously. The tilt sensor is capable to detect up to ±30 degrees dynamic range with resolution of about 0.05 degrees, while the vibration sensor can achieved up to sensitivity of (80 V/g) with noise compensation. Experiment results show that the developed sensor and system can be used to determine condition of structural building based on damping factor, and slope of the building. For long distance monitoring, the communication module (RF-transceiver) can handle up to 2 km, and can be easily improved by replacing high power (wattage) RF-transceiver.

5. Acknowledgment
This research is funded by the Directorate of Research and Community Service, Directorate General of Research Affirmation and Development, Ministry of Research, Technology, and Higher Education based on research contract no: 054/SP2H/LT/DRPM/2018.

6. References

[1] S. Kavitha, R. Joseph Daniel, and K. Sumangala, “High performance MEMS accelerometers for concrete SHM applications and comparison with COTS accelerometers,” Mech. Syst. Signal Process., vol. 66, pp. 410–424, 2016.
[2] A. Girolami, D. Brunelli, and L. Benini, “Low-cost and distributed health monitoring system for critical buildings,” 2017 IEEE Work. Environ. Energy, Struct. Monit. Syst. EESMS 2017 - Proc., 2017.
[3] D. R. Santoso, “A Simple Instrumentation System for Large Structure Vibration Monitoring,” Indones. J. Elektr. Eng., vol. 8, no. 3, pp. 265–274, 2010.
[4] F. Tondolo, A. Cesetti, E. Matta, A. Quattrone, and D. Sabia, “Smart reinforcement steel bars with low-cost MEMS sensors for the structural health monitoring of RC structures,” Constr. Build. Mater., vol. 173, pp. 740–753, 2018.
[5] A. B. Noel, A. Abdaoui, T. Elfouly, M. H. Ahmed, A. Badawy, and M. S. Shehata, “Structural Health Monitoring Using Wireless Sensor Networks: A Comprehensive Survey,” IEEE Commun. Surv. Tutorials, vol. 19, no. 3, pp. 1403–1423, 2017.
[6] W. Weiţjens, T. Verbelen, E. Capello, and C. Devriendt, “Vibration based structural health monitoring of the substructures of five offshore wind turbines,” Procedia Eng., vol. 199, pp. 2294–2299, 2017.
[7] O. Avci, O. Abdeljaber, S. Kiranyaz, M. Hussein, and D. J. Inman, “Wireless and real-time structural damage detection: A novel decentralized method for wireless sensor networks,” J. Sound Vib., vol. 424, pp. 158–172, 2018.
[8] D. R. Santoso, Abdurrouf, and L. Nuriyah, “Development of a Simple Traffic Sensor and System with Vehicle Classification Based on PVDF Film Element,” Sensors and Transducers, vol. 126, no. 3, pp. 74–84, 2011.
[9] Freescale Semiconductor, “Micromachined Accelerometer MMA7361L,” Sensors (Peterborough, NH). Retrieved from http://www.freescale.com/files/sensors/doc/data_sheet/MMA7361L.pdf, pp.
1–11, 2008.

[10] S. Circuit et al., “Single Supply Dual Operational Amplifiers,” *Order A J. Theory Ordered Sets Its Appl.*, pp. 1–14, 2003.

[11] A. Devices, “Single-Supply, Low Cost Instrumentation Amplifier,” 2008.

[12] Y. J. Chan and J. W. Huang, “Multiple-point vibration testing with micro-electromechanical accelerometers and micro-controller unit,” *Mechatronics*, vol. 44, pp. 84–93, 2017.

[13] R. Switch, P. Name, B. Introduction, and P. Description, “7/5/2018 RF module, wireless data module, data radio, data transceiver, Remote control, Tx-rx module, transmitter & receivers - ShenZhen YiShi El…,” pp. 7–8, 2018.