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Real Time Prototype to Measure Structural Acceleration and Tilt of High-Rise Building

***Abstract**. Smart sensor is the new invention applying to detect the damage of the high-rise civil building structural health. Sensor technology offers new opportunities to advance monitoring for civil large building infrastructure health and maintenance by providing relevant information regarding the condition of high-rise building structural strength at a light price and greater bulk than traditional monitoring tactics. The aim of this article is to validate the MEMS accelerometer sensor to measure vibration and tilt of the high-rise civil building infrastructures. The experimental result shows that the propose prototype has been successfully measured high-rise building vibration and tilt sensing information.*

***Streszczenie.** W artykule opisano możliwości zastosowania czujników przyśpieszenia typu MEMS do pomiaru wibracji i odchylenia konstrukcji budynków. Przedstawione wyniki badań eksperymentalnych potwierdzają przydatność tych czujników szczególnie w sytuacjach dużych zagrożeń.* ***Prototyp systemu pomiarowego do badania wibracji i odchylenia konstrukcji budynków**.*

Keywords: Structural health monitoring, acceleration, tilt, MEMS sensor.
Słowa kluczowe: czujniki przyśpieszenia, czujniki MEMS, ochrona budynków.

Introduction

Structural health monitoring (SHM) is an active area of research devoted to systems that can autonomously and proactively assess the structural integrity of bridges, buildings, and aerospace vehicles. Recent technological advances promise the eventual ability to cover a large civil structure with low-cost sensors that can continuously monitor a building's structural health. Large civil structures such as buildings form the backbone of our society and are critical to its daily operation. Inspectors typically assess them manually, but a networked computer system that could automatically assess structural integrity and pinpoint the existence and location of any damage could measurably lengthen a structure's lifetime, reduce its operational cost, and improve overall public safety [1]. Broadly speaking, SHM research attempts to use sensors to localize damage and detect its extent through structural response (via the spatiotemporal patterns of vibrations induced throughout the structure).

Background

Now a day, safety issue related to the high-rise building or historical building is most important to the human society. The health of the civil building structural performing a key task to evaluate consistency of a structure and identify possible damaging factor that are fundamental element to define the danger level of a building. From last several years, high-rise building structural health monitoring system based on vibration become a fourth-coming issue for environmental safety purpose [2], [3]. Due to new technology materialize in the field of the structural health monitoring, measurement technique become easily accessible to assess sensing information of the structural health condition with meaningful information and analysis those information to find out the how much damage occur. An increasing amount of organized sensor depend on this the amount of information collecting data going to large and become a wholly unmanageable system that issue one of the important issue for the engineering or researcher or system developer to take out the optimization of the employed system [4]. Accelerometers sensor is the newest sensor that widely used in civil structural health monitoring and creating a new opportunity for identification of civil structural health damage and fire intensity [5]. Several types of problem arises with sensor network system among those optimization is the one of them [6].

Motivation

The human safety who lived under high-rise building is now the most danger issue over the world [7]. Due to enhance development in the field of sensor network give the easiest way to measure/monitoring of the high-rise building structural health condition [8]. Monitoring civil structural health using sensor communication network has been vastly used. ZigBee is one of the promising technologies for monitoring structural health due to its several advantages like low cost, portable, and easy to re-configurable [7]. Two environments of the structural health are required to monitor, one is outdoor environment and another is indoor environment. An autonomous monitoring system could be monitored and controlled of the monitoring system. Those sensor systems are used to measure the safety level to provide the human safety of the structural health [9]. The monitoring and control of structural health is being complex as increasing the structural size. In the case of large structural health, reliability, and accuracy of the whole transmission system is becoming challenging issue [10], [11]. M-array QAM wireless sensor network reliability and accuracy is computed by author Haque [12]. There are many factors that affect the communication system in practical environments and many researcher shows that employed with WSN numerous problems arises among those in terms of communication system [13]. A star topology based sensor network loss is computed in [14] and provided the optimum buffer mechanism technique.

Acceleration and tilt measurement Techniques

The acceleration normally refers to as vibration of the object. The following accelerometers are used to measure acceleration of the object:

- Piezoelectric accelerometer
- Piezoresistive accelerometer
- Capacitive accelerometer
- Servo force balance accelerometer
- MEMS accelerometer

The following tilt measurement techniques has been used for tilt recorded of the object:

- Liquid-level tilt
- Vibrating wire tilt-meter
- Electrolytic tilt meter

A. Acceleration Measurement Techniques

Accelerometer of the object is measured using accelerometer sensor which is a combination of electrical and electronics system with mechanical that measure the applied force. This force is an external force may be dynamic or static based on object motion. If the object is moving, the measurement system is known as dynamic and otherwise is static.

1) Piezoelectric Accelerometer:

Piezoelectric accelerometers are frequently used for acceleration or vibration measurement of any object. An electric charge is produced in piezoelectric crystal or quartz or ceramic due to force imposed by the object under some vibration. When the force applied into the piezoelectric plate it produces electric charge. This is charge output produce a voltage which is proportional to the applied force. Fig. 1 shows the basic diagram of piezoelectric mechanism where:

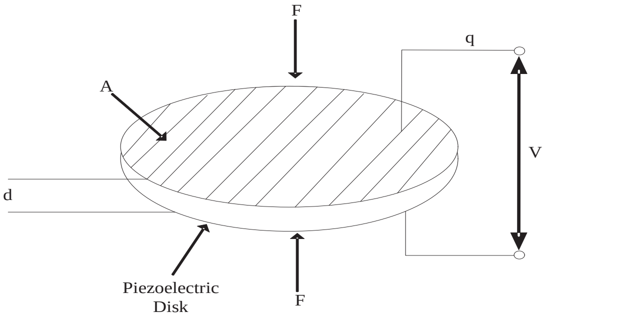


Fig. 1. Piezoelectric accelerometer.(A = Electrode Area, F = Applied Force, d = Thickness, q = Charge, V = Voltage across the piezoelectric plate, d33 and e33 = Piezo constant, q = =d33F)

The applied force can be calculated using Newton second law:

(1) $$F = ma$$

where m and a are the mass and acceleration of the object. The output voltage can be calculated using the formula (2).

(2) $$V = \frac{d33d}{e33A}F$$

Since, mass of the object is the known value, F can be calculated using (1). As the output voltage is directly proportional to the acceleration (2) indicates the acceleration of the target object. But the piezoelectric accelerometer has the following drawback.

- Required constant citation power.
- Highest operating temperature 12000C.

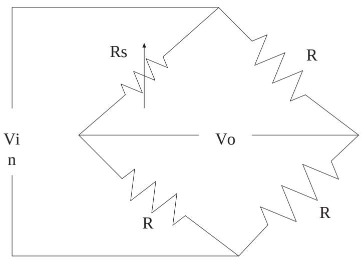


Fig. 2. Wheatstone bridge circuit.

2) Piezoresistive Accelerometer

Piezoresistive accelerometer sensor is broadly used in many sensing field among those acceleration measurement, pressure measurement, flow measurement, and gyro rotary motion remarkable. The operation of the Piezoresistive accelerometer is simply base on sensor resistivity change due to the applied force. This applied force creates a resistance change in the resistor and the register experience a deformation of its resistance. The resistance of the sensor is given by the following equation:

(3) $$R = \rho\frac{l}{A}$$

where R is sensor resistance value is determined by its length l, cross section area A and resistivity. Since, the resistivity of the register is fixed value, so it is determined by its length and cross sectional area. After applied strain, the change in resistance is related with its length and expressed by the following equation.

(4) $$\frac{\Delta R}{R} = G\frac{\Delta L}{L} \qquad G = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}} = \frac{\frac{\Delta R}{R}}{\varepsilon} = \frac{\Delta R}{R\varepsilon}$$

In equation (4), G is known as gage factor and $\varepsilon = \frac{\Delta L}{L}$ is the applied strain which indicates the amount of resistance change from its normal value. The resistance changes in the sensor are converted using Wheatstone bridge circuit. The above Fig. 2 is shown the Wheatstone bridge circuit. The sensor resistance denoted by Rs in one arm and other arm of the Wheatstone bridge circuit setup by identical circuit resistance R. The strain change of the sensor is expressed by:

(5) $$R_s = R + \Delta R$$

(6) $$V_o = \left(\frac{R}{R+R_s} - \frac{R}{R+R}\right)V_{in} = -\frac{\Delta R}{2R+\Delta R}V_{in}$$

When the bridge is in balance condition, the output voltage is equal to zero. When the sensor resistance is changed due to the applied force, this resistance varies the output voltage and from (6), we can calculate the changing value of the resistance and finally, from (2), the strain can be calculated.

(7) $$\varepsilon = \frac{\Delta R}{RG}$$

Capable to measure high shock applications and zero force acceleration are the advantages of piezoresistive accelerometer but it is unable to high frequency response.

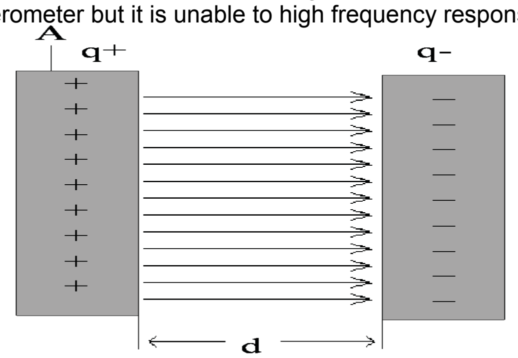


Fig. 3. Capacitive accelerometer.

3) Capacitive Accelerometer

A capacitive accelerometer measure the variation of the capacitance due to the applied target force. For a simple two parallel plate capacitor (shown in Fig. 3), the capacitance is given by:

(8) $$C = \frac{\varepsilon\varepsilon_o A}{d}$$

where A is the area of electrode and d is the distance between two parallel plates. ε and ε_o are the dielectric and vacuum permittivity respectively. From, above equation capacitance is increasing as increasing electrode area or decreasing the distance between two electrodes.

In the capacitive accelerometer, one plate acts as a fixed plate and another as a moving plate. In the moving plate the measurement object forced is applied which change the capacitance of the parallel plate. This changing of the capacitance is presented as voltage output using suitable electronics circuit formally known as an acceleration of the object. Advantage of this accelerometer is that the accuracy is more than other types of sensors and ability to measure mili-gs to micro-gs but is costly compare to others types of sensor system.

4) Servo Forced Balanced Accelerometer
A servo forced balanced accelerometer is shown in Fig. 4. When the mass experiences the acceleration, the null detector is recorded its movement and servo coil current is increased to keep the mass null position. The produced coil current provides the restoring force to keep the mass null position. This inductor coil current is directly proportional to the applied acceleration by the mass.
The advantages and disadvantages of the servo force accelerometer are given below:
Advantages:

- Ability to measure microgravity

Disadvantages:

- Low hysteresis performance
- Large size compare to other types of sensor like strain gauge
- Unable to measure high shock

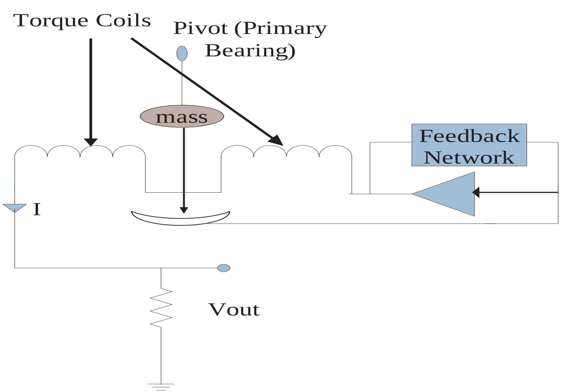


Fig. 4. Servo force balance accelerometer.

5) MEMS Accelerometer:
Due to the recent development of the smart sensor, measurement technique becomes easy and cost effective [15]. Advancement development of the MEMS technology has the capability to measure different types of damages of the civil structural (e.g. temperature, tilt, humidity, acceleration, corrosion, and deterioration etc.) [16]. Many types of the smart sensor already developed; the newest one is the dual axis accelerometer sensor. The MEMSIC 2125 accelerometer measure the object acceleration, tilt, and rotation. It is becoming popular because of its small price accomplished of dynamic and static acceleration measurement and also easy to integrate with another compatible platform.

MXD2125M MEMSIC is a two axis monolithic CMOS IC accelerometer, as shown in Fig. 5. The operation of the device based on the heat transfer of the gas inside the sensor. The gas chamber works as proof mass in the MEMS accelerometer sensor. Across cavity a single heat source is located in equal distance from both axes. Aluminium or polysilicon thermopiles are located on the two axes equidistant from gas chamber. In each axis, two thermopiles are considered and these two thermopiles are same distance from gas chamber and same things are consider in another axis. Under zero force acceleration, the heat source provides the symmetrical temperature gradient. At this situation, four thermopiles provide the same voltage output. Due to acceleration in any direction will change the temperature profile and causing the thermopiles output become asymmetric, hence the voltage output will be different. This voltage output is considered as acceleration. This acceleration is measured in a two way: one is X-axis acceleration and another is Y-axis acceleration.

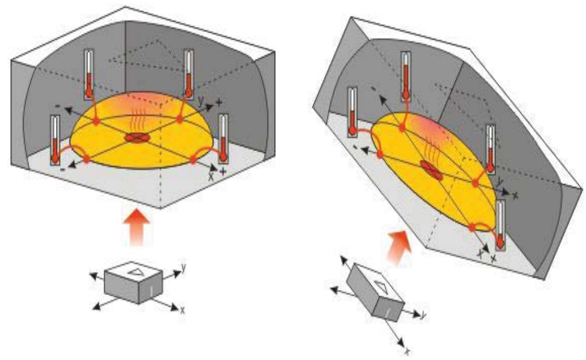


Fig. 5. Theory of MXD2125M MEMSIC accelerometer operation.

B. Tilt Measurement Techniques

The tilt of the object indicates its inclination or deformation angle. Actually, in the case of stationary or dynamic object by measuring the acceleration of earth gravity defines the tilt of the object, known as indirect measurement technique. Dynamic behaviours measuring of the historical or high-rise building structural health continuously by various damages, tilt is becoming as another important parameter that indicates the horizontal or vertical deformation from the earth surface due to any others causes like earthquake and flooding.

1) Liquid-Level Tilt: In the liquid-level tilt meter, the positions of the liquid indicate the tilt of the object. It consists of the two water tank at the end of the tube. The quantitative difference among the two water tank indicate the amount of tilt at which angle the object is inclined with the earth surface.

2) Vibrating Wire Tilt-Meter: Vibrating wire tilt meter has been designed for monitoring the various kinds of structural tilt. The tilt sensor directly attach to the measuring object to make accurate measurement. Sensor consists of pendulum mass is connected vibrating wire strain gauge. This strain gauge detects the applied force which has been produced by the mass. The water proof housing connects the sensor to the mounting bracket. To minimize the corrosion effect, the housing is constructed by steel. The vibrating wire tilt-meter is capable to measure both axes acceleration; however, the system provides inaccurate results when the pendulum mass vibration accesses the threshold of the system.

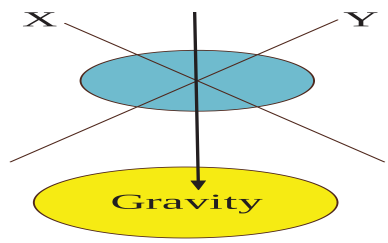


Fig. 6. Axis direction of electrolytic tilt sensor

3) Electrolytic Tilt Meter: Electrolytic tilt sensor measures the angle or null position or level of the object with respect to gravity. Axis direction of electrolytic tilt sensor is depicted in Fig. 6. The sensor tilt angle can be expressed as degree or arc minute or arc second. At the null position the tilt angle is perpendicular to the gravity. When the sensor is experienced a changed from its null position, the object experience its change and this change can be expressed as positive or negative tilt.

Validation of system and analysis

The high-rise building structural produces the physical quantity that is measured to define the acceleration and tilt level. The proposed sensor measured the acceleration and tilt of the high-rise building dynamically. The experimental setup is shown in Fig. 7. Firstly, the sensor sensed the dynamic value that was produced by the building structural. After that, the acceleration and tilt of the building structural was measured based on sensor principle. To wake the sensor system, external power source was supply to the sensor modulo. To collect the sensor acquisition data, we followed two procedures. One is based on the lab test result that validates the proposed system. Finally, using the proposed validate system, we measured the acceleration and tilt of the high-rise building structural health. The below procedure represent the lab test validation test result:

- Firstly, connect the accelerometer sensor with the bread board.
- Supply the VDD voltage to input pin as mentioned in the methodology section. The range of the VDD is between 3.3 to 5.5V.
- After that, connect the accelerometer output port to the oscilloscope channel to visualize the sensor output.
- Acquire the sensor output signal using scope software of the oscilloscope and analysis the output signal using suitable software like MATLAB.
- Finally, to check the hardware validation, vary input power supply and observe how the output signal is varying. After that, compute the acceleration using the formula:

(9) $$Acceleration = \frac{High\ Pulse\ Duty\ Cycle}{Total\ Duty\ Cycle}$$

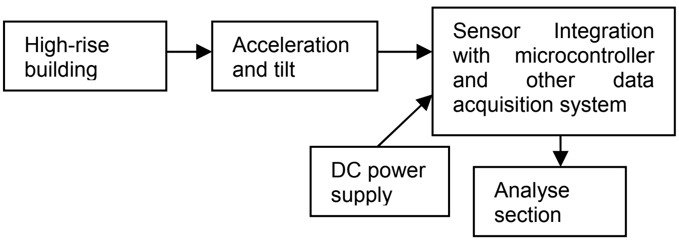


Fig. 7 Experimental setup.

A. Results

Table 1 shows the validation test result of the proposed prototype for X-axis acceleration. The input and output of the propose system is consider as voltage signal. Figure 8 shows the row data signal of the proposed sensor.

Table 1. Sensor validation test result for X-axis acceleration

V_{inx}(DC)	V_{outx}	T_{hx}	T_{lx}	Acceleration (g) = $T_{hx}/(T_{lx}+T_{hx})$
3.3	Fig.8(a)	50.70%	49.30%	0.507g
3.73	Fig.8(b)	50.20%	49.80%	0.502g
4	Fig.8(c)	50.00%	50.50%	0.49g
4.25	Fig.8(d)	50.00%	50.00%	0.5g
4.50	Fig.8(e)	50.00%	50.00%	0.5g
5	Fig.8(f)	50.00%	50.00%	0.5g

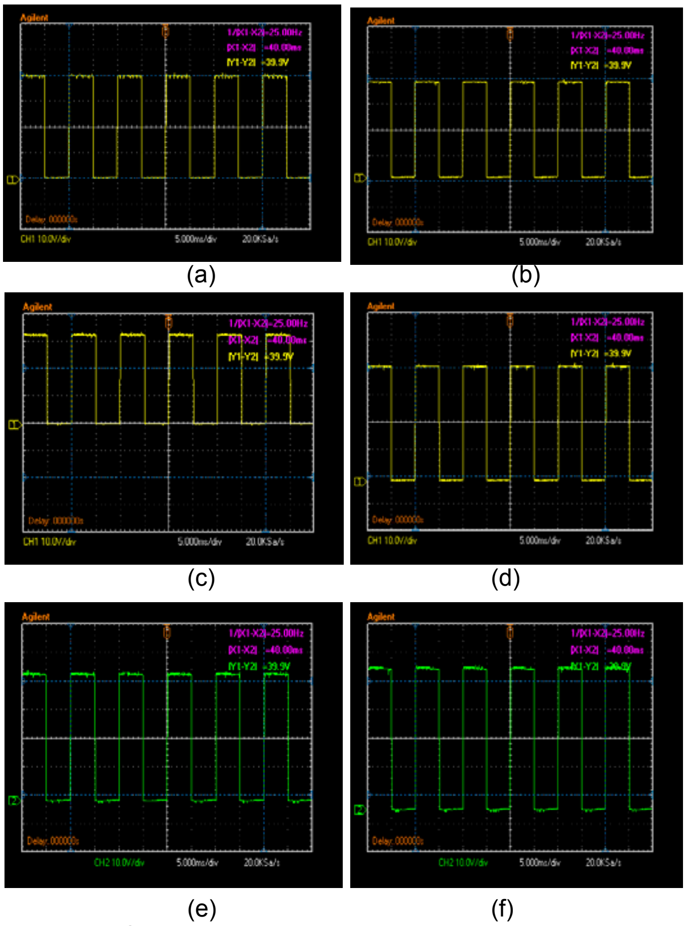


Fig. 8 MEMS accelerometer X-axis output: (a) 3.3V input; (b) 3.73V input; (c) 4V input; (d) 4.25V input; (e) 4.50V input; (f) 5V input.

Table 2 enclose the Y-axis acceleration validation test result and figure 9 shows the corresponding output.

Table 2. Sensor validation test result for Y-axis acceleration

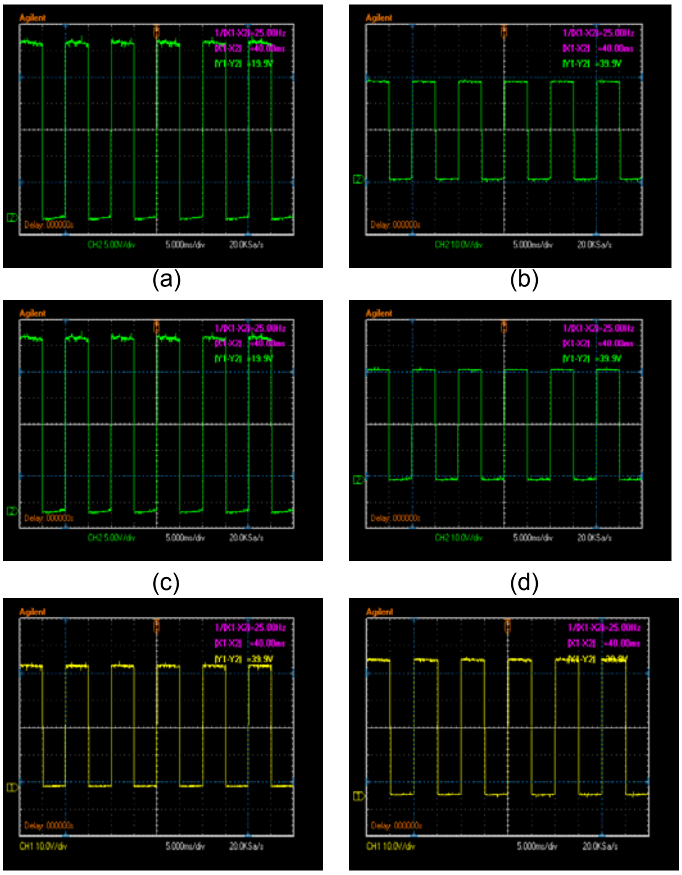
V_{iny} (DC)	V_{outy}	T_{hy}	Tly	Acceleration (g) = $T_{hy}/(T_{ly}+T_{hy})$
3.3	Fig.9(a)	50.70%	49.30%	0.507g
3.73	Fig.9(b)	50.20%	49.30%	0.505g
4	Fig.9(c)	50.20%	49.80%	0.49g
4.25	Fig.9(d)	50.00%	50.00%	0.5g
4.50	Fig.9(e)	50.20%	49.30%	0.505g
5	Fig.9(f)	50.00%	50.00%	0.5g

From validation test result, the X-axis acceleration of the object is decreases until 4.25 V supply voltage and after that a constant value is obtained as increasing the supply voltage level. For Y-axis case, the acceleration is decreases as increasing supply voltage until 4.25 V and after that it increases but the maximum value of the acceleration is recorded at 3.3V supply voltage.

The integral view of the MEMSIC accelerometer with basic stamp microcontroller shows in Figure 10.
Table 3 shows the measurement value of building beam acceleration and tilt by setting. Tilt value indicate how much inclination of the building surface with earth surface. Tilt angle 0 and 90 indicate that building surface is the parallel and perpendicular with the earth surface. Result shows that, when the Y-axis tilt value is increase, the axis acceleration is randomly changes, but Y-axis acceleration value of the beam gradually increases.The X and Y-axis acceleration specify the respective tilt acceleration value. The maximum gravity force of the building beam is found in Y-axis acceleration.

Table 3. Beam acceleration and tilt by setting X-tilt=0.

X-axis acceleration	Y-axis tilt	Y-axis acceleration
0.024g	5	0.095g
0.024g	10	0.192g
0.024g	15	0.264g
0.008g	20	0.344g
0.016g	26	0.440g
0.024g	30	0.504g
0.008g	36	0.592g
0.008g	40	0.648g
0.024g	47	0.736g
0.008g	50	0.760g
0.016g	55	0.824g
0.024g	60	0.864g
0.016g	65	0.904g
0.008g	71	0.944g
0.008g	75	0.968g
0.008g	81	0.948g
0.008g	85	1.032g



(a) (b) (c) (d) (e) (f)

Fig. 9 MEMS accelerometer Y-axis output: (a) 3.3V input; (b) 3.73V input; (c) 4V input; (d) 4.25V input; (e) 4.50V input; (f) 5V input.

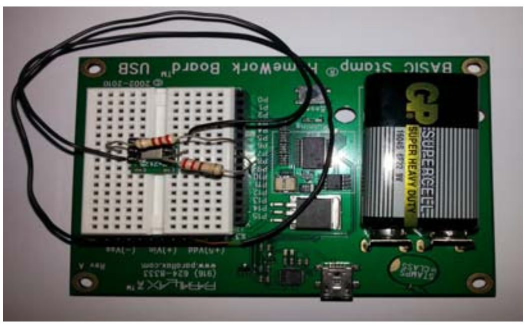


Fig. 10 Integral view of MEMSIC accelerometer with BASIC station microcontroller.

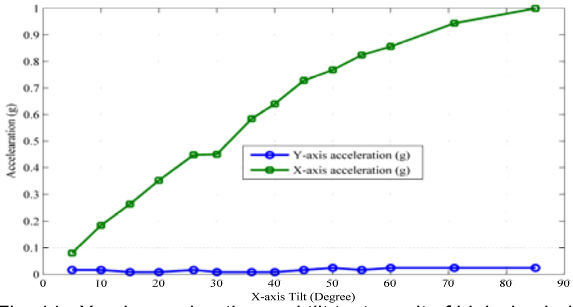


Fig. 11a X-axis acceleration and tilt test result of high-rise building.

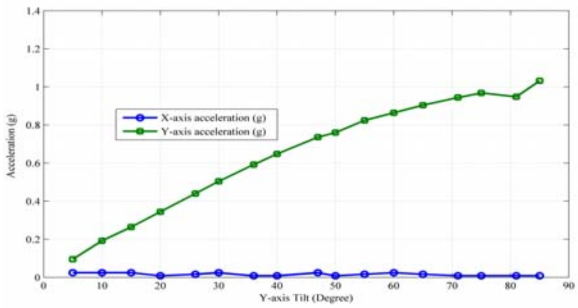


Fig. 11b Y-axis acceleration and tilt test result of high-rise building.

Table 4. Beam acceleration and tilt by setting Y-tilt=0.

Y-axis acceleration	X-axis tilt	X-axis acceleration
0.016g	5	0.080g
0.016g	10	0.184g
0.008g	15	0.264g
0.008g	20	0.352g
0.016g	26	0.448g
0.008g	30	0.450g
0.008g	36	0.584g
0.008g	40	0.640g
0.016g	45	0.728g
0.024g	50	0.768g
0.016g	55	0.824g
0.024g	60	0.856g
0.024g	71	0.944g
0.024g	85	1g

Table 4 shows the measurement value of building beam acceleration and tilt when X-tilt=0. Result shows that, when the Y-axis tilt value is increase, the axis acceleration is randomly changes, but Y-axis acceleration value of the beam gradually increases.The X and Y-axis acceleration specify the respective tilt acceleration value. The maximum gravity force of the building beam is found in Y-axis acceleration. The maximum gravity force of the building beam is found in X-axis acceleration.

Fig. 11(a) and Fig. 11(b) show the X and Y-axis acceleration and tilt of the high-rise building beam by setting Y-tilt = 0 and X-tilt = 0 respectively.

Conclusion

In this article, we have proposed the application of smart sensor in the field of civil building structural health for vibration and tilt measure. Measurement technique is based on dynamic characteristic of the civil building structure health. Our proposed prototype has low cost, low power profile and easy to maintenance over conventional measurement system. We used MEMSIC 2125M accelerometer that still research phase and basic station microcontroller. From experimental results, the proposed prototype has successfully measured the high-rise building acceleration and tilt. Our future work will focus on the integration of MEMSIC2125 accelerometer with X-Bee module.

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