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MEMS−based Tri−Axial Seismometer for Estimation of Natural Frequency of Buildings

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Summary

In the field of health monitoring of building structures, one of the most efficient method to determine the natural frequency of building is microtremor measurements. To determine natural frequency of many buildings of urban areas in a short time it is necessary to use fast, more effective and simple method which can determine natural frequency in−situ. In view of this situation, we have developed the portable tri−axial seismometer using micro electromechanical system (MEMS) acceleration sensor and tested for fast determination of the natural frequency of building in situ. MEMS sensor used is Silicon Designs Inc. model 1221 low noise analog accelerometer, which is a highly sensitive seismic sensor characterized by rugged construction and proven reliability. Full scale range of our seismometer is ±2g with 20Hz pass band mainly for seismic and structural application. We have mounted three accelerometers orthogonally on three sides of a single cube and housed in a case for recording all three components of accelerations simultaneously. We calibrated and tested the seismometer by using gravitational field of the earth and shaking table and applied it for determination of natural frequencies of existing buildings. The results obtained from buildings showed good repeatability, which provide the possibility to spread the application scope.

Keywords: Microtremor, MEMS, Health monitoring, Natural frequency, Accelerometers

1. Introduction

For the last decades micro electromechanical system (MEMS) acceleration sensors were used in many branches including aerospace, railway, automotive, IT, advanced industrial and instrumentation, and so on. Now, low noise MEMS−based accelerometers are starting to replace traditional, expensive, and fragile electromechanical devices, offering same or even better performances at small size, lower power consumption, lower cost and much better environmental survivability. In geophysics and seismology, sophisticated MEMS−based accelerometers combined with advanced electronics, which have extreme low noise, high resolution, and large dynamic range, are replacing traditional geophones or seismometers. In the building industry, seismic accelerometers in the form of structural health monitoring (SHM) systems are increasingly being installed throughout the world. SHM system is especially important in areas vulnerable to high−level seismic activity for seismic pre−mapping and intensity measurements. Within large structures such as buildings, dams, bridges and nuclear plants that are subject to subsurface landslip or externally induced stress and vibrations SHM system is used to determine the structural integrity.

In the field of health monitoring of building structures, microtremor measurements are used as one of the most efficient method to determine the natural frequency of building because no special vibration sources like a moving car are necessary.[4, 7, 9] Microtremors in the general sense are very small vibration generated by various natural and artificial sources, such as tidal waves, traffic disturbances, heavy machinery, cultural activity, factories, industrial vibration, etc. The dynamic structural characteristics of buildings including natural frequency and mode shape can be easily obtained by microtremor measurements. Natural frequency of building obtained by microtremor measurements is used in estimating danger of soil−structure resonance of existing buildings.[6, 8]

Last few decades several types of instruments have been used in microtremor measurements.[3, 5, 11] The instruments mainly used were seismometers (3−component velocity meters or accelerometers).

Bour et al. have used a three−directional Güralp CMG−5T accelerometer and an autonomous Lennartz Mars88 recorder including GPS system in microtremor measurements.[2]

Gosar have used two Tromino seismographs, which were composed of three orthogonal electrodynamic velocity sensors, a GPS receiver, digitizer and recording unit with a flash memory card, in microtremor measurements.[4] Gaudio et al have also used Tromino, which had a good instrumental response in a wide frequency interval, small size (10×14×7.7 cm) and light weight (1.1kg). They said that Tromino is particularly suitable for measurements in rough terrain conditions like those of landslide prone slopes [13].

On the other hand, Uhean et al. have proposed an accurate method for remotely measuring structure microtremors by using an improved Laser Doppler Velocimeter (LDV) that had a vibration sensor and telephoto lens.[14] They removed the LDV vibrations which influenced the recorded data and accurately estimated dynamic characteristics, such as the natural frequency and mode shape by using one or two LDV sensors. From the result obtained in model and actual RC rigid−frame structure they said that the proposed microtremor measuring method was a fine and accurate tool for vibration diagnosis of structure.

Recently, seismic sensor technology is evolving rapidly and traditional electromechanical sensors, such as force balanced accelerometers (FBA), are increasingly being displaced by more cost−effective and robust MEMS−based sensors.[1, 13, 15]

Pakzad have developed a MEMS–based wireless sensor node as part of a wireless sensor network and deployed it on a Golden Gate Bridge for structural health monitoring of bridge. [10] Using Low–level Silicon Designs 1221 MEMS sensors, they have made sensor board and performed extensive laboratory testing to validate the hardware system and evaluated its performance under different excitation and environmental circumstances. [12] From the tests in a laboratory in McCone Hall and in a vault at Berkeley Seismological Laboratory facilities under ambient vibrations in an active environment of an academic building they have obtained the result that 1221 sensor had a RMS noise level of 71μg/$\sqrt{}$Hz in the very low frequency range (below 0.1Hz) which linearly reduced to 10μg/$\sqrt{}$Hz for larger frequencies.

Torfs et al. have proposed a wireless sensor network for monitoring buildings to assess earthquake damage. The proposed sensor nodes used custom–developed capacitive MEMS strain and acceleration sensors and a low power readout circuit for a battery life of up to 12 years.[13]

Estimating danger of soil–structure resonance of existing buildings in urban areas vulnerable against average earthquakes is very important for mitigation of seismic hazard. On the basis of these estimation results we can design new building or retrofit the existing building, pull down and rebuild if necessary. To determine natural frequency of many buildings of urban areas in a short time it is necessary to use fast, more cost effective and simple method which can determine natural frequency in–situ.

In view of this situation, we have developed MEMS–based integrated seismometer for fast determination of natural frequency of building in–situ. Our seismometer has the full scale range of ±2g and 20Hz pass band. We have calibrated and tested the seismometer by using gravitational field of the earth and shaking table and applied it for determination of natural frequencies of existing buildings. The test results showed that the repeatability and resolution of the seismometer were satisfactory for determination of natural frequency of building.

This paper is organized in the following ways. Section 2 concentrated with the system overview. Section 3 described experimental results. Last section dealt with the conclusion.

2. System Overview

The system is composed of two parts: the tri–axial acceleration sensor and a data acquisition unit (Fig. 1).

The three analog outputs of the sensor are fed to a signal conditioning circuit. Cutoff frequency of anti–aliasing low–pass filter is 20 Hz. The filtered analog signal is fed to 24–bit Δ–Σ analog–to–digital (A/D) converter for each of the three channels. The ADS1252 is a precision, wide dynamic range A/D converter and has an effective resolution of 19 bits (2.5ppm of rms noise) for conversion rates up to 40 kHz. The converter includes a flexible, two–wire synchronous serial interface for low–cost isolation, which is connected with control unit. Control unit controls A/D conversion process and send conversion results to ARM11 kit.

2.1 Acceleration Sensor

The most significant advantages of MEMS accelerometer over traditional electromechanical devices are its small size, light–weight and compactness.

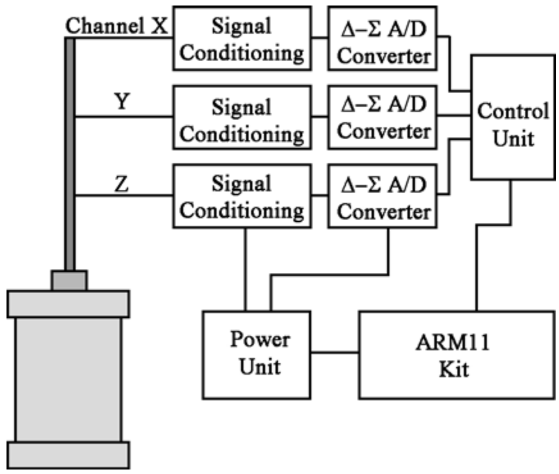

Figure 1. Block diagram of the seismometer

Because of its small size and light weight, MEMS sensor is suitable for portable instrument which require light–weight and low power consumption. We used Model 1221 MEMS accelerometers (Silicon Designs 2007) as sensor of the seismometer. They are low–cost, integrated accelerometers suitable for instrumentation applications that require extremely low noise. Among Model 1221 series, the 2g version 1221L–002 is ideally suited for seismic applications. Each miniature package is hermetically sealed. It combines a micro–machined capacitive sense element and an integrated circuit that includes a sense amplifier and differential output stage. This sensor is relatively insensitive to temperature changes. It contains a temperature dependent current source, which is useful for precise measurement of acceleration. Frequency response of 1221 sensor is linear from DC to about 500Hz, which is the one of the most important advantages that makes it suitable for application in geophysics and seismology.

Fig. 2 shows a Silicon Designs 1221 sensors mounted orthogonally on three sides of a steel cube. The sensor provides acceptable sensitivity for low–level ambient structural vibrations. This single–axis sensor also responds to both static and dynamic vibrations, provides the sensitivity required for ambient vibrations, and has a nominal noise level of 5 μg per root–square Hz.

Figure 2. Sensors mounted orthogonally on three sides of a single cube (size 4×4×4cm)

Three PCBs of each sensor (size 3×3cm) are stuck on three sides of cube with epoxy resins. This sensor block is fixed on the bottom of sensor box.

2.2 Signal Conditioning and A/D Converter

Three outputs of sensor box in Fig.1 are analog voltages. Each voltage is fed to an anti–aliasing low–pass filter with a cutoff frequency of 20Hz. The filter cutoff frequency was set in consideration of range of natural frequency of buildings.

The filtered analog signal is fed to 24–bit Δ–Σ A/D converter ADS1252 for each of the three channels. The ADS1252 is a precision, wide dynamic range, Δ–Σ A/D converter with 24–bit resolution operating from a single +5V supply. For maximum conversion rates (40kHz) an effective resolution is 19 bits. Signal is oversampled at a high frequency of 2.5 kHz and then the digitized signal is down sampled by averaging 25 samples. This method of oversampling improves the dynamic range of a digital signal and reduces the Gaussian noise level by a factor of five. Combination of anti–aliasing filter, oversampling and down sampling provides efficient approach for high–resolution measurement.

2.3 Control Unit and ARM11 Kit

The micro–controller in control unit controls three A/D converters and performs averaging operation and send down sampled result to ARM11 kit. The core of ARM11 kit is S3C6410 CPU. The S3C6410 is a 16/32–bit RISC microprocessor, which is designed to provide a cost–effective, low–power capabilities, high performance application processor solution for mobile phones and general applications. The ARM11 kit includes many hardware peripherals such as a TFT 24–bit true color LCD, 4–channel UART, USB host, 3–channel SD/MMC host and so on. All software including calibration, FFT, data manage and user interface program are embedded in flash memory of the kit. In consideration of the power consumption of seismometer we selected 12V/20Ah sealed lead–acid battery for power supply.

3. Experimental Results

In experiment, the noise characteristic of recorder was studied first and then the frequency response of the tri–axial acceleration sensor was determined by the shaking table tests. From the analysis of the noise characteristic (Fig.3), we have determined the resolution and dynamic range of recorder including signal conditioning and A/D converter (120dB).

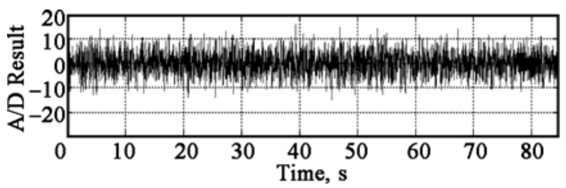

Figure 3. Noise in signal conditioning and A/D converter.

Although three sensor boards are stuck on three sides of cube, three axes of sensors may not be orthogonal owing to a defect in manufacturing and installation. In this case the values measured by the acceleration sensors do not represent the correct orthogonal components of acceleration applied on the sensor (Fig. 4). In order to calibrate this error, we propose the calibration method using the Earth's gravitational field. Suppose the acceleration vector applied on the sensor is **a.**

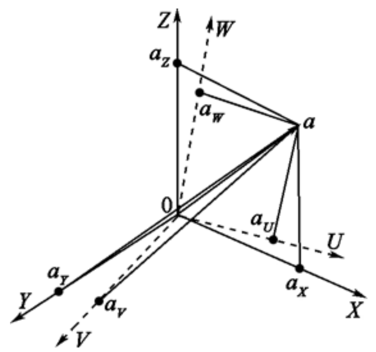

Figure 4. Tilted Axes of accelerometers

Three components of the acceleration vector a are (a_X, a_Y, a_Z) in orthogonal coordinate XYZ and (a_U, a_V, a_W) in non–orthogonal coordinate UVW of the sensor. In order to obtain correct orthogonal components of acceleration from the measured components, we should determine the transform matrix **k**.

$$(a_X\,,\ a_Y\,,\ a_Z) = \begin{pmatrix} k_{11}k_{12}k_{13} \\ k_{21}k_{22}k_{23} \\ k_{31}k_{32}k_{33} \end{pmatrix} \cdot \begin{pmatrix} a_u \\ a_v \\ a_w \end{pmatrix} \tag{1}$$

Now, X axis is set in such a way that its direction should be towards land. At this state, if we denote the measured values as (u_x, u_y, u_z), then

$$\left(g,\ 0,\ 0\right) = \begin{pmatrix} k_{11}k_{12}k_{13} \\ k_{21}k_{22}k_{23} \\ k_{31}k_{32}k_{33} \end{pmatrix} \cdot \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} \tag{2}$$

We can use the same manner as Eq. (2) for Y and Z axes. Thus we obtain the following equation.

$$\begin{pmatrix} g & 0 & 0 \\ 0 & g & 0 \\ 0 & 0 & g \end{pmatrix} = \begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix} \cdot \begin{pmatrix} u_x & u'_x & u''_x \\ u_y & u'_y & u''_y \\ u_z & u'_z & u''_z \end{pmatrix} \tag{3}$$

From Eq. (3), we obtain

$$\begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix} = \begin{pmatrix} g & 0 & 0 \\ 0 & g & 0 \\ 0 & 0 & g \end{pmatrix} \cdot \begin{pmatrix} u_x & u'_x & u''_x \\ u_y & u'_y & u''_y \\ u_z & u'_z & u''_z \end{pmatrix}^{-1} \tag{4}$$

The matrix k in Eq. (4) is used to calculate orthogonal components (a_x, a_y, a_z) from measured components (a_U, a_V, a_W).

We can obtain information about the noise characteristics and transform matrix for calibration of non–orthogonal components from static tests of the tri–axial acceleration sensor, but it is necessary to test sensor under dynamic excitation to get a frequency response of sensor. The frequency response of sensor can be determined by the shaking table tests. The VEB 11075 shaking table was used to subject the sensors in the horizontal direction to harmonic vibrations with varying amplitudes. We placed the tri–axial acceleration sensor and a reference broad band seismometer (Güralp CMG–6TD) on the shaking table and obtained simultaneous records. Broad band seismometer CMG–6TD provides complete seismic information from about 0.03Hz to 100Hz.

A harmonic function generator 200MSTPC and power amplifier LV102 were used to dynamically drive the shaking table at various frequencies, each for approximately 3 minutes. Changing the frequency in 1Hz step, we have recorded the vibration of shaking table in each frequency step.

Because CMG–6TD is seismometer with velocity output, we converted the original digitally recorded signal of it to acceleration. On the basis of simultaneous records of our sensor and CMG–6TD, we have determined the overall sensitivity of sensors and frequency response.

Final equation for acceleration is

$$Acc = 0.000\ 292N(\mathrm{cm/s^2})$$

where *Acc* is acceleration, and *N* original digitally recorded value from A/D converter. Non–zero initial value in A/D converter is eliminated by software.

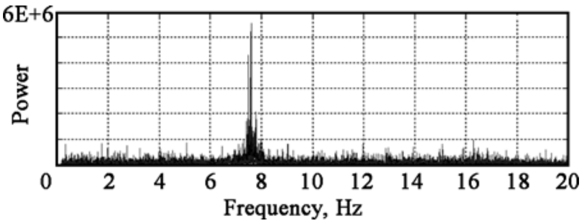

Figure 5. Power spectra of record in a building.

Our tri–axial acceleration sensors showed negligible variation of output value with temperature. From a large number of repeated measurements under the static condition, we have found that within the ambient temperature range of –20 to 30 ºC, the percentage error was less than 0.3. The output value seems to decrease slightly in low temperature but no significant difference was observed between the values in –20ºC and 30ºC. The variation of output with temperature can be easily removed by using the temperature compensation software, if necessary. After indoor test and calibration, we have used developed seismometer for determination of the natural frequencies of existing buildings in urban area (Fig. 5). We have used CMG–6TD for the purpose of comparison in some buildings. The obtained results showed good coincidence of natural frequencies calculated from CMG–6TD records and ours.

5. Conclusions

We have here described MEMS–based integrated seismometer for fast determination of natural frequency of building in–situ. The result to emerge from the test is that the developed MEMS–based integrated seismometer is one of the fast, simple, and cost effective solutions for determination of natural frequencies of existing buildings in urban areas. Our seismometer has the full scale range of ±2g and 20Hz pass band. In the developed seismometer, all functions such as recording, FFT, calculation of natural frequency, display, and so on are softly aggregated in seismometer, which provide the possibility to spread the application scope.

Acknowledgements

The authors would like to thank Jang Jong Nam, Kim Dong Gwang and Kim Hyok Chol of the Korean Earthquake Administration and Yu In Chol, Technical Exchange Office, Kim Chaek University of Technology for their contribution during the development of instrument and experimental performance evaluation processes. The authors also wish to acknowledge Mirae Company, Kim Chaek University of Technology for their assistance in conducting this research project.

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