WIRELESS VIBRATION SENSOR FOR TUNNEL CONSTRUCTION

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Abstract:
During and after tunnel construction, many problems including civil petitions and construction delay result from tunnel deformation, ground settlement, ground vibration, and tunnel lining crack. In relation to tunnel construction and maintenance, this study explains a development background of small wireless vibration sensors and their applications based on RF(Radio Frequency)-MEMS (Micro Electro Mechanical System) technology. The advantages and usefulness of the wireless automatic monitoring system is addressed compared with the conventional wired or survey measurement systems. Thus, the study provides a framework of the process for monitoring, manipulating, and transferring data from MEMS sensor and explains the application of the new developed automatic monitoring system for tunnel construction and maintenance.
Keywords: Mems, Sensor Networks, Structural Health Monitoring

1. Introduction

Tunnel construction is gradually increasing due to the development and upgrade of infrastructures in Korea where 70% of the nation is composed of mountain area, and the maintenance of tunnel in operation is also becoming more important due to the complex environment change in vicinity of the existing tunnel and the deterioration of tunnel structure. At the same time, public concerns have risen over tunnel construction because of the effect of the tunnel-induced many problems such as damage in nearby structures and utilities, vibration, noise, and environmental impact.

Peck (R. B. Peck) stated three issues in tunneling, which are first, maintaining stability and safety during construction, second, minimizing unfavorable impact on third parties, and finally performing intended function over the life of a project [1]. Terzaghi (K. Terzaghi) pointed out that nearly all questions raised during tunnel design and construction may not be answered without field measurements and tests[2]. And as many other tunnel engineers have been experienced, monitoring is a key element to better accomplish tunnel construction and maintenance, and a systematic monitoring plan should be carried out for acquisitioning useful and reliable field measurement data.

Monitoring of tunnel during construction includes the measurement of ground displacement and pore water pressure in the vicinity of a tunnel, the measurement of stress and strain in tunnel structure, and the measurement of the displacement in adjacent structures or utilities along the tunnel route. Data acquisition obtained from a systematic monitoring plan plays many important roles in various aspects[3][4]. The data can be used to provide a guide of modification of construction methods or procedures to complete tunnel construction more safely and economically and to minimize the construction-induced third party impact. Besides that the data record may be used for the research purpose and the design of similar tunnel construction in the future. For tunnels constructed with the blasting method, noise and vibration could induce significant problems and their effects should be monitored.

Monitoring of tunnel in operation is related to the inspection of the existing state in a tunnel. The construction activities such as new tunnel or building construction in the vicinity of the existing tunnel can significantly change the stress and strain state in the existing tunnel structure, frequently inducing tunnel stability and safety problems. In addition, as time goes on, a tunnel structure becomes deteriorated and the surrounding environment can change physically or chemically. Thus, the existing tunnel structure could be in the condition of instability. Again, the monitoring of tunnel in operation should also be kept on in a systematic monitoring plan to have the existing tunnel in better quality and in case to provide the appropriate repair or reinforcement measures.

Monitoring instruments have been changed from the conventional devices such as the level survey to the automatic devices using the electric cables and sensors. The automatic monitoring systems can provide more effectively the data acquisition in extensive area and continuous real time. However, up to date, most monitoring of tunnel is wire-based systems for acquisitioning and transferring the field data. The wire-based systems frequently interrupt construction procedure, causing construction delays, and are expensive to install and maintain the systems during the measurement period. In addition, the wire-based systems can only be applied for a limited area and the systems become incapable if the wire is cut, which happens frequently.

To overcome those disadvantages and limitations of monitoring systems, the wireless-based monitoring systems, which are based on small wireless vibration sensors and RF (Radio Frequency)-MEMS (MicroElectroMechanical System), have been developed. This paper describes the background of the system development and the applications to tunnel monitoring and provides a framework of the process for monitoring, manipulating, and transferring field data using the new developed systems.

2. MEMS-based vibration sensor module

2.1 Development objective

Blasting has always been the most prevalent and effective means of destroying rocks. However, several problems arise from blasting, such as vibration of the ground, scattering of rock fragments and the long-lasting sound. In particular, according to the Review of Noise and Vibration Tolerance Standard of Blasting [5], low vibration can lead to serious damage to livestock, including pigs and roe deer, as well as to the human body. The standard for vibration tolerance suggested by the Ministry of Environment appears to be V=0.09cm/sec (70dB), which cannot be met when blasting is implemented in an urban area. Consequently, civil petitions and lawsuits against blasting ceaselessly take place.

Blasting vibration is measured to obtain data that can be utilized to understand the vibration around the blasted area and the structure in a construction site and to elucidate the adverse impact of vibration. In addition, accurate blasting vibration data can be used to calculate the optimal blasting pattern, as well as to yield the appropriate amount of gunpowder to be loaded for a time. A wide range of efforts is being made to utilize the data to validate its influence on the concrete lining during tunnel construction and to yield the safe distance from the area where concrete is being put.

Thus, measuring the blasting vibration is a very significant and fundamental item in tunnel digging. Therefore, great and far-reaching effects are expected from the development of a MEMS-based vibration sensor with simple installation to measure vibration in a more convenient and less expensive way. The objective of this research is to develop a MEMS-based wireless acceleration sensor and implement experiments to verify the possibility of replacing the functions and performance of conventional blasting vibration sensors. Furthermore, it also aims to easily and conveniently obtain blasting vibration data by realizing a wireless sensor network through MEMS sensors equipped with a wireless RF module.

2.2 Problems of existing vibration sensors

Conventional vibration sensors are composed as shown in Figs. 1 and 2 and are designed to simultaneously measure vibration and noise. They may vary depending on type, but in general, it has 1 to 8 input channels so that a variety of types of sensors for vibration measurement (acceleration, velocity and others) can be connected. A vibration sensor module is comprised as a package consisting of a sensor to measure vibration and noise, a cable and a data logger for data analysis. In the investigation, an expert is required to operate a vibration sensor module for blasting and one to two sensors for vibration measurement can be attached to an instrument.

As for the experimental blasting in a tunnel, a vibration sensor equipped with two sensors, one for vibration and the other for noise, is evaluated for operation in the center of a security building. (When blasting a tunnel, 4 to 5 vibration sensors are needed and as many people are also required. The purchase price for a vibration sensor module is KRW 8 to 10 million and the value of lease per month is KRW 600,000 and 800,000).

The problem with conventional vibration sensors is that many people and many gauges are needed due to its constraint of only a maximum of one or two sensors can be equipped even if vibration needs to be measured at several points. Therefore, when complicated vibrations need to be measured at different positions, as many vibration sensors as sensors must be purchased, which is tremendously expensive

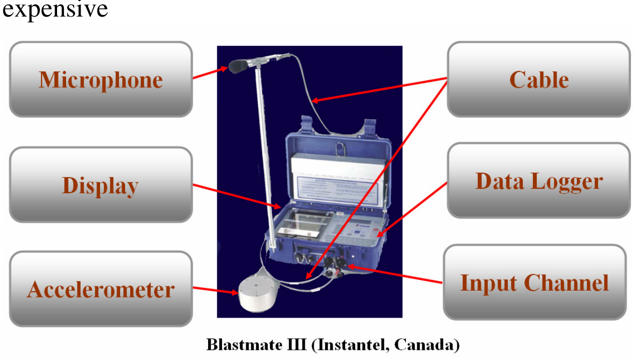

Figure 1. Composition of a conventional vibration sensor module

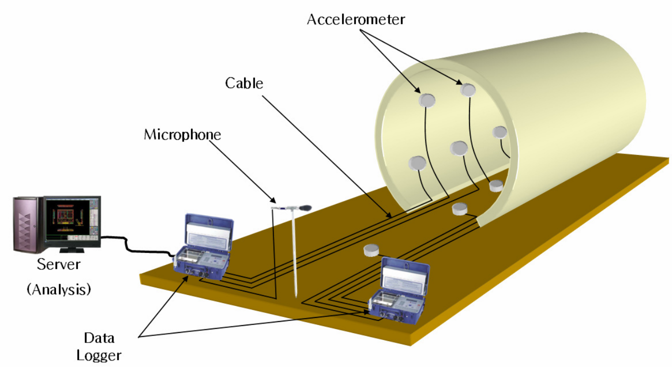

Figure 2. Installed shape of conventional vibration sensor modules

3. Development of a prototype MEMS-based vibration sensor module

3.1 Design and Manufacture of MEMs Vibration Sensor

The accelerometer is a capacity-type vibration sensor that can read changes in the sensing capacitance in accordance with input acceleration as shown in Figure 3.4..

The accelerometer consists of one inertia mass and four support beams. The sensing electrodes are arranged at the right and left of the inertia mass and designed so that the movement direction of the inertia mass is reverse to the direction of the changes in the sensing capacity. This is called the differential capacitance sensing method, which has the advantage of increased linearity in comparison with the single capacitance sensing method.

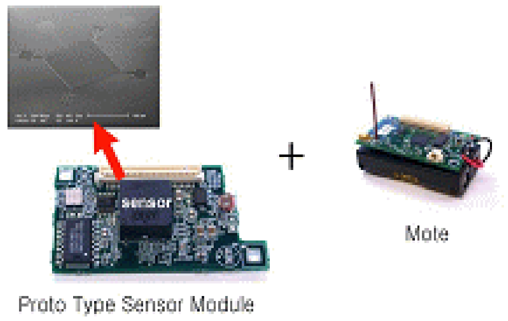

Figure 3. Conceptual map of a prototype MEMS sensor

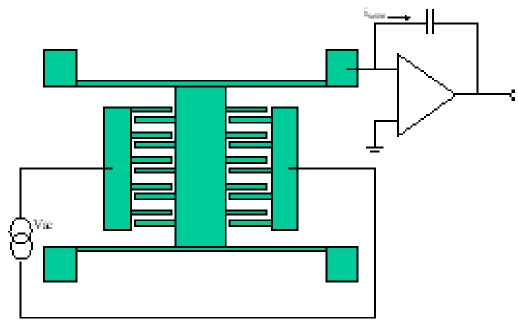

Figure 4. Signal processing of an accelerometer

Vibration sensor is manufactured using MEMS manufacturing technology with a semiconductor manufacturing process. The sensor was made through a total of two lithographic processes and a total of three etching processes. A thin gold film was formed on the SIO (Silicon On Insulator) wafer, and then the thin film became the gold pad that would connect to the external signal processing circuit through lithography and etching processes. The pad was changed into a sensor-type through lithography and etching processes, and finally, when the silicon dioxide film that fixes the moving part of the sensor is removed in the last etching process, the vibration sensor is completed. The manufactured MEMS-based vibration sensor is used by packaging with a silicon DIP(dual in-line package).

3.2 Test Methods for the Mems Sensor

In order to evaluate the performance of the manufactured sensor based on MEMS technology and identify improvements, we conducted a precision test at the Korea Testing Laboratory (KTL). The purpose of the test was to precisely analyze the vibration measurement capacity of the MEMS-based vibration sensor module. The test of the MEMS-based vibration module was conducted by attaching the vibration module to a vibrator as shown in Figure 5, which can provide standard vibration, and vibrating it up and down. A reference accelerometer was also attached in order to compare the measured values.

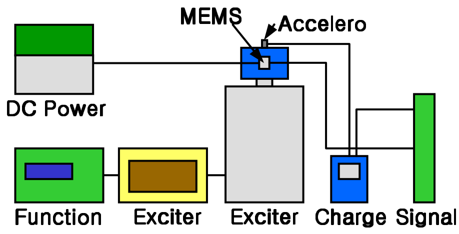

Figure 5. Composition of Test Equipment

3.3 Results and analysis of the performance test

It was analyzed that the deviation in the output signal was not regular in comparison to the sensors currently in use. The error rate was shown at 3% and 4% for #2 and #4, respectively as shown in Figure 6 and 7. The reasons were interpreted to be the noise of the circuit, non-homogeneity during the manufacturing process, and non-homogeneity of the property of silicon, which was used as the MEMS element.

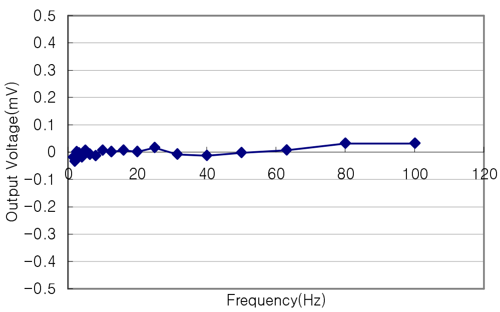

Figure 6. Measurement deviation of the #2 sensor(mV)

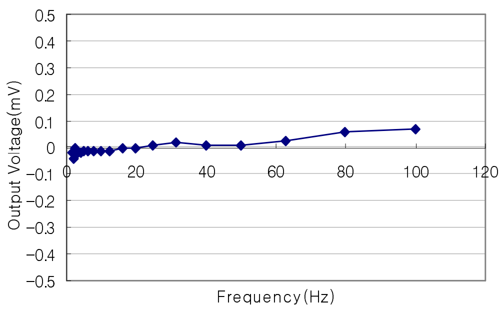

Figure 7. Measurement deviation of the #4 sensor(mV)

3. Improvement of elements for the MEMS-based vibration sensor

3.1 1st design and manufacture

Based on the performance analysis and improvements of the vibration sensor developed during the first year of research, we exerted efforts to improve the elements for the MEMS sensor. The research was largely performed in two types – horizontal and vertical. In particular, the horizontal type was improved from the type studied in the first year. It is a method to detect changes in capacitance resulting from the gap between electrodes during the vertical vibration of a mass, which is shown in Fig. 8.

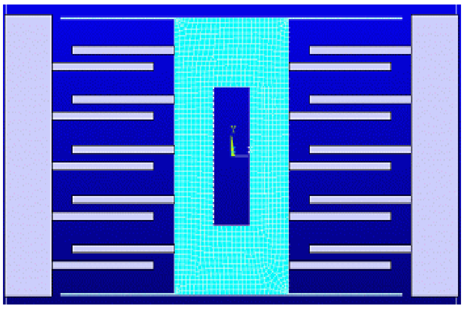

Figure 8. Design improvement for the horizontal type (1st)

The sensing electrodes are arranged at the right and left of the inertia mass and designed so that the movement direction of the inertia mass is reverse to the direction of the changes in the sensing capacity. This is called the differential capacitance sensing method, which has the advantage of increased linearity in comparison with the single capacitance sensing method.

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$$\frac{\Delta C}{g} = \frac{C_l - C_r}{g} = \frac{2N\frac{\varepsilon_0 A \Delta d}{d_0^2}}{\frac{k\Delta d}{m}} = \frac{2N\varepsilon_0 A}{d_o^2}\frac{m}{k} \qquad \text{Eq.1}$$

ΔC : difference of capacity of accelerometer, g: approved accelerometer, C_l: capacity of left comb, C_R: capacity of right comb, d_0: initial gab of comb, Δd : difference of comb gab, m: magnitude of accelerometer, k: rigidity of spring in accelerometer, ε_0 :a dielectric constant of air, A: area of overlap of comb

In accordance with the sensing principles of a vibration sensor, the relation between input acceleration and capacitance change is shown in Eq. 1. As shown in the equation, sensitivity is in proportion to the area of the comb and the mass of the inertial mass, while in inverse proportion to the gap between the sensing electrodes and the stiffness of the support beam. The horizontal type was designed in three different types depending on the acceleration range and frequency, as shown in Table 1.

A vertical type was newly developed during the second year of research. As shown in Fig. 9, it is a method of vibration measurement using the changes in capacitance when the sensing electrodes attached in the same direction to the vibration of the mass is inserted between the fixed electrodes. In the design, it was expected that the mass and the number of electrode can be added enough to demonstrate the desired performance, and it is no longer necessary to design different types like the horizontal type. Therefore, it was designed as a single type. In addition, MEMS is one of the semiconductor manufacturing processes and it is possible to design and implement different types of elements on a Wafer at a time, so that the horizontal and vertical types are reflected in designing the wafer.

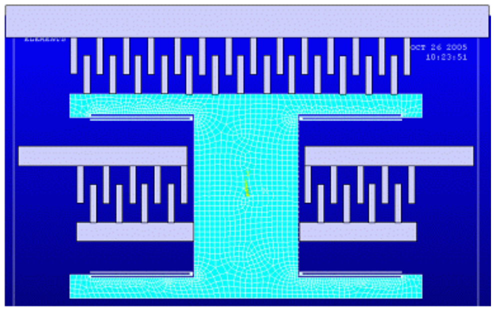

Figure 9. Design improvement for the vertical type (1st)

3.2 2nd design and manufacture

The yield rate, the rate of complete products obtained from a wafer, was shown to be very low and the problem of durability occurred in the form of an inner short during operation.

The causes of the problem found with the elements manufactured during the first year of research were analyzed to be as follows:

① Gold powder accrues in the course of the laser-dicing process (the final process of cutting a sensor from a wafer) and causes contamination between electrodes.

② The spring structure of a sensor is easily broken in the wafer-handling process, but it is not found during the microscope inspection.

③ Abnormality of the etch profile during the deep si-etch process

A new design was implemented by taking the abovementioned items into consideration.

① Inspection of the laser-dicing equipment and split test on the laser power

② Resetting of the safety factor based on the ratio of the moving mass against the spring stiffness in the 3rd accelerometer

③ To prevent the pull-in phenomenon between the moving comb and the fixed one, the tip structure was added to each of them.

④ Progression of the process after confirming the SEM image of the etch profile in the deep si etch process

Above all, there were no structural changes in the horizontal type, but the number and width of the spring and the moving displacement of the mass were optimized and 4 different types were designed to fit into three different sensing areas, as shown in Fig. 10.

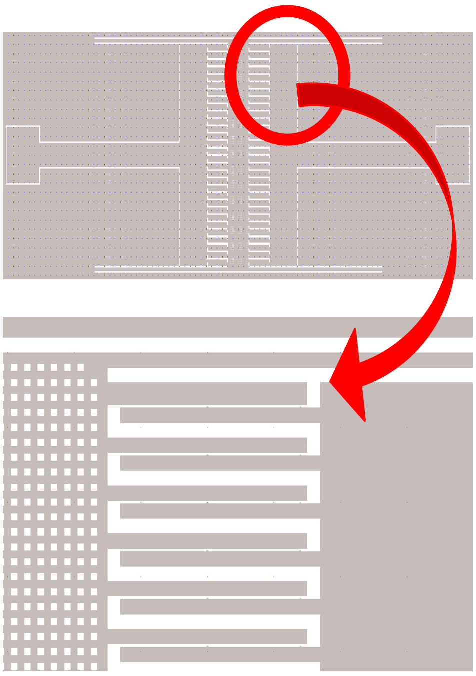

Figure 10. Design improvement for the horizontal type (2^{nd})

Next, the design of the vertical type developed during the first year of research was changed by eliminating the upper electrodes and inserting the electrodes inside the mass, as shown in Fig. 11. In addition, the number and width of the spring and the moving displacement of the mass were optimized, as shown in Table 2. We obtained satisfactory results from the tests by designing and manufacturing a test rig in the abovementioned manner. We plan to verify the performance of the test rig by conducting a precision test at the Korea Testing Laboratory

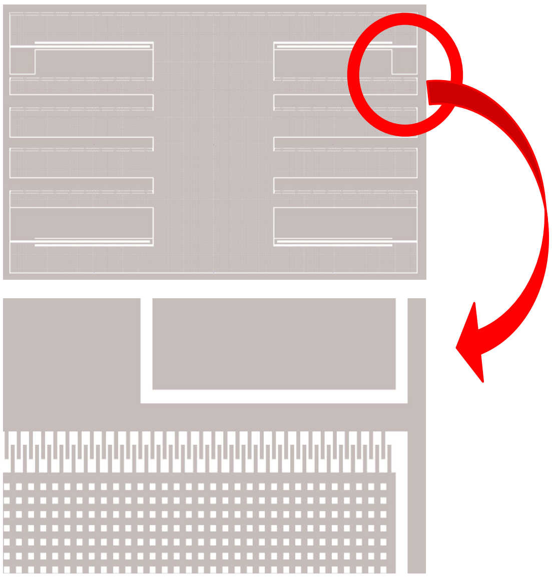

Figure 11. Design improvement for the vertical type (2^{nd})

3.3 Development of a MEMS-based wireless blasting vibration sensor

The system suggested in the paper is equipped with a MEMS-based acceleration sensor, a miniaturized data logger, and a Zigbee-based wireless sensor network chip, as shown in Fig. 12. To develop a small sensor like this, the three cutting-edge technologies – MEMS-based vibration sensor, development of the MCU in replacement of the data logger, the Zigbee-based wireless sensor network technology - are required.

The wireless blasting vibration sensor presented in the paper consists of a number of sensors and a notebook computer (or a PC). The sensor can be added up to a maximum of 255. Each sensor has a Zigbee-based wireless sensor network chip inside so that the sensors can wirelessly send and transmit the sensed data among each other. An amplifier can be additionally equipped to send and receive distant data, which does not require an additional data logger or another power facility.

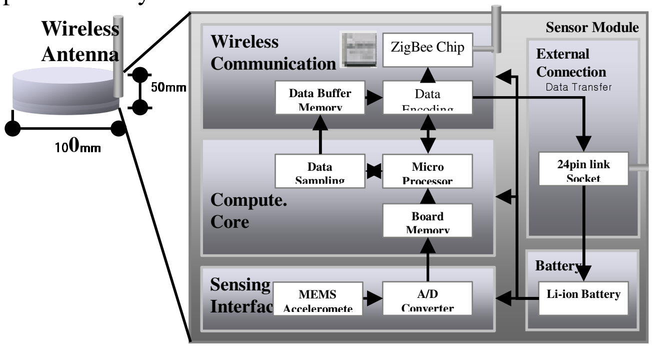

Figure 12. Sensor structure

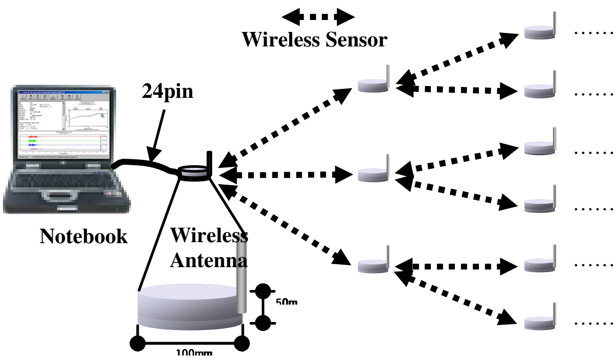

Figure 13. Composition of the wireless blasting vibration .sensor

4. Conclusion

The final developed product of this study is a MEMS-based vibration sensor module that can be applied in the construction of a wireless sensor network for the monitoring of a structure. This module is a SoC product (System on a Chip) where a sensor, signal processing circuit, wireless transmitter/receiver and self-driving power are on a chip. We tried to determine the appropriate performance with the prototype of the developed MEMS-based vibration sensor in order to use the result in designing the complete product. The results consist of the layout of the MEMS-based vibration sensor, related data and the complete product (including packaging). The MEMS-based vibration sensor can be used with a commercial wireless transceiver module where there is a MEMS sensor part and a signal processing circuit and its driving power uses the power of a wireless transmitter/receiver Mote. The prototype of the MEMS-based vibration sensor senses and measures one-way acceleration within the range of -50 and +50g (g: acceleration of gravity) and has a vibration measurement bandwidth between 0Hz up to 1kHz at 10mg of resolution. The changes in the measured acceleration of gravity will be exchanged as data after being interpreted over the wireless transceiver. We will stabilize the performance of the device and enable it to measure 2-axial and 3-axial acceleration in succeeding studies.

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Table 1. Functional Improvements of Mems Vibration Sensor (by Type) – 1st

Division	Voltage Sensitivity		Measurement Range		Frequency Range	Mass (L*W*D, ㎛)	Spring (L*W*D, ㎛)	Comb (No.)
Type1	400mV/G	40.8 mV/m/s2	5G	49m/s	0 ~ 100Hz	2000*500*40	1000*10*40	60(*2)
Type2	100mV/G	10.2 mV/m/s2	20G	196m/s	0 ~ 300Hz	2000*1000*40	1000*10*40	60(*2)
Type3	40mV/G	4.08 mV/m/s2	50G	490m/s	0 ~ 1000Hz	3000*1000*40	1000*10*40	90(*2)

Table 2. Functional Improvements of Mems Vibration Sensor (by Type) -2nd

Division	Voltage Sensitivity		Measurement Range		Frequency Range	Mass (L*W*D, ㎛)	Spring (L*W*D, ㎛)	Comb (No.)
Type 1-1	400mV/G	40.8 mV/m/s2	5G	49m/s	0 ~ 100Hz	2000*500*40	1000*5*40	30(*2)
Type 1-2	400mV/G	40.8 mV/m/s2	5G	49m/s	0 ~ 100Hz	2000*500*40	1000*10*40	43(*2)
Type2	100mV/G	10.2 mV/m/s2	20G	196m/s	0 ~ 300Hz	2000*1000*40	1000*10*40	30(*2)
Type3	40mV/G	4.08 mV/m/s2	50G	490m/s	0 ~ 1000Hz	3000*1000*40	1000*10*40	43(*2)