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Author(s)	AIZAWA, Takao; KIMURA, Toshinori; MATSUOKA, Toshifumi; TAKEDA, Tetsuya; ASANO, Youichi
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Application of MEMS accelerometer to geophysics

Takao AIZAWA*, Toshinori KIMURA**, Toshifumi MATSUOKA***,
Tetsuya TAKEDA**** and Youichi ASANO*****

* Member of ISRM: Suncoh Consultants Co. Ltd., Koto-ku, Tokyo, 136-8522 Japan

**Non-member of ISRM: Suncoh Consultants Co. Ltd., Koto-ku, Tokyo, 136-8522 Japan

*** Member of ISRM: Dept. of Civil and Earth Resource Engineering, Kyoto University, Nishikyo-ku, Kyoto 615-8540 Japan

****Non-member of ISRM: Earthquake Research Dept., NIED, Tsukuba, Ibaraki 305-0006 Japan.

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ABSTRACT

We developed several types of MEMS accelerometers using commercial MEMS elements for trial use in seismic surveys. Field experiments and earthquake observations were carried out for investigating the capabilities of the MEMS accelerometers. The results of these experiments and observations show that the properties of these MEMS accelerometers are similar and that they are about 1.5-3.0 times as sensitive as conventional geophones used in seismic surveys. The noise level of the MEMS 3-C accelerometer in natural earthquake observation was about 10^{-4} kine (cm/s), and the useable frequency band extends to below 1Hz. For future works, we will further investigate the characteristic of MEMS geophones in low frequency band using earthquake records. In addition, we will reexamine the electronic circuit and the MEMS elements in order to attain high sensitivity.

Keywords: MEMS accelerometer, Geophone, Field experiments, Seismic survey, Earthquake observation, Sensitivity

1. INTRODUCTION

Micro Electro Mechanical Systems (MEMS) is a platform technology to create small electrical devices in the order of micrometers to millimeters in size. Use of MEMS technology includes many electrical devices such as inkjet printer, gyroscope, pressure sensor and accelerometer. In this paper, we discuss MEMS accelerometer.

MEMS accelerometers are used in shake prevention of a camera, a game controller and the air bag of a car. Because of its small size and light weight, MEMS sensor element can save the weight and power consumption of a measuring instruments. Moreover, since the single crystal silicon used in MEMS is a stable substance, a MEMS product is excellent in long-term endurance. A MEMS sensor has small distortion in phase spectrum and linear response in amplitude spectrum (Yu et al., 2008). These are desired characteristics for measuring ground motion.

In the petroleum exploration, data acquisition systems which use MEMS have already been developed. A MEMS sensor is also used as a sensor in the earthquake disaster prevention and damage mitigation.

Taking the advantage of its long-term stability and spectral characteristics, we envisage to use the MEMS technology for monitoring underground spaces, base rock slopes and life cycle cost management of infrastructures as well as conventional geophysical fields such as seismic reflection surveys (Niitsuma, 1997). With this vision, we

carried out field experiments and earthquake observation using some MEMS accelerometers developed for trial, and investigated the capabilities of MEMS accelerometers for these applications (Aizawa et al., 2007a, Aizawa et al., 2007b).

2. CHARACTERISTICS OF MEMS ACCELEROMETER

A MEMS accelerometer has some significant advantages over conventional geophones: light-weight and compactness. Therefore, a small and light 3-C sensor using MEMS accelerometers is more easily assembled than conventional geophones. An existing 3-C geophone is heavy and large, causing low productivity in the field. As a MEMS accelerometer can be incorporated with a tilt sensor, horizontal setting does not have to be so stringent.

One of the most important advantages of a MEMS accelerometer is that it has linear frequency response from DC to about 500Hz (Figure 1). This broadband capability offers dramatic improvement in measuring ground motion at lower frequency band. In seismic reflection surveys, data in low frequency band contain important information such as shear waves and reflection waves returning from deep layer boundaries. In earthquake seismology, low-frequency (long-period) data are important for characterizing ground motion to reveal the mechanism of the earthquake, as the low frequency component is sometimes dominant in earthquake, especially when the source is far away. Stability of MEMS

accelerometer is important for long term monitoring, too. MEMS accelerometer has some disadvantages: it requires a power supply; and gravitational acceleration has to be calibrated.

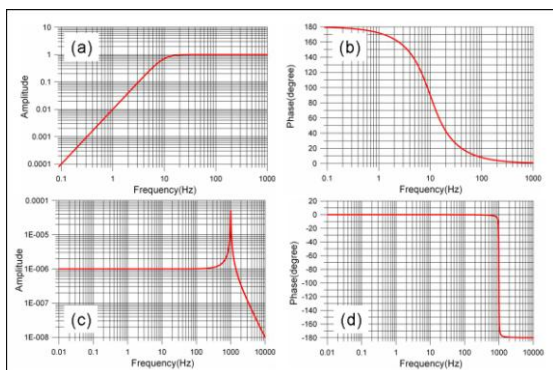


Figure 1. Amplitude and phase response of MEMS accelerometer and 10 Hz geophone (Speller and Yu,2004). (a)Amplitude response of geophone. (b)Phase response of geophone. (c)Amplitude spectrum of MEMS accelerometer. (d)Phase response of MEMS accelerometer.

3. FIELD EXPERIMENTS

We developed some MEMS accelerometers using commercially available MEMS elements. Field experiments were carried out for comparison between the developed MEMS accelerometers and the conventional geophone. We conducted three experiments as follows.

3.1 Field experiment 1: using single-component sensors

To compare single-component (1-C) sensors, array experiments were carried out with three kinds of sensors: conventional 10 Hz geophones, (I/O SM-7); two commercially available MEMS accelerometer geophones V- and M-brands. These MEMS elements were installed to geophone cases with simple electrical circuits. Arrays of 24 receivers were laid with geophone interval of 1m. Figure 2 shows the survey line of the array experiments, Figure 3 shows the sensors used for the experiment and Figure 4 shows raw shot records of these sensors. Hammer impacts were used as a source. In Figure.4, the surface wave vibration is clearly seen in all the shot records. A 70-250 Hz band-pass filter was applied to each record. Figure 5 is an enlargement of the filtered records from 0 to 0.15 second. In Figure 5, reflection waves from shallow reflectors are clearly seen in the shot records of geophone and V-brand MEMS accelerometer. However, no reflection waves were found in the shot record of M-brand MEMS accelerometer. In another experiment, the bunching experiment, five kinds of sensors (Geophone, V-brand MEMS, M-brand MEMS, C-brand MEMS and “High-sensitivity MEMS”) were fixed to the ground with plaster in a small area about 15 x 15 cm. Three of the geophones used are the same as used in array experiments: a conventional 10Hz and V-brand and M-brand MEMS. In addition, a commercially available MEMS accelerometer specialized in seismic survey, C-brand MEMS, was also used. The “High-sensitivity MEMS” was assembled using V-brand MEMS element with our electrical circuit. Because they are fixed to the ground with plaster, the



Figure 2. The survey line of array experiment



Figure 3. Sensors used for the experiment. Left: conventional geophone. Middle: V-brand MEMS accelerometer. Right: M-brand MEMS accelerometer.

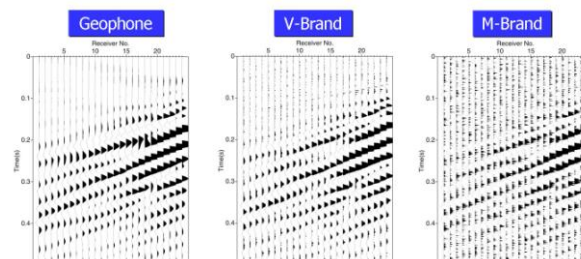


Figure 4. Comparison of shot records. The source is hammer impact.

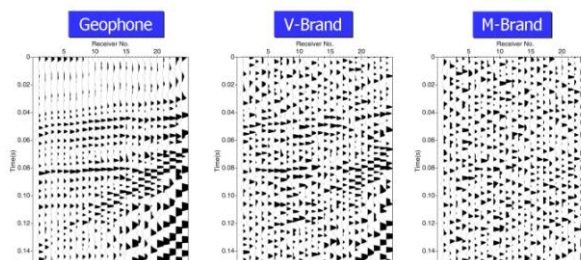


Figure 5. Enlargement of the shot records in Figure 4 from 0 to 0.15 second with 70-250 Hz band-pass filter.

conditions of the setting of the sensors are identical (Figure 6).

The MEMS accelerometer measures acceleration while the conventional geophones output velocity. For this comparison, the MEMS output was integrated over time by numeric calculation. Figure 7 shows raw shot records and integrated records of these sensors generated by hammer impacts 2.5 m away from sensors.



Figure 6. Five sensors fixed to the ground with plaster.

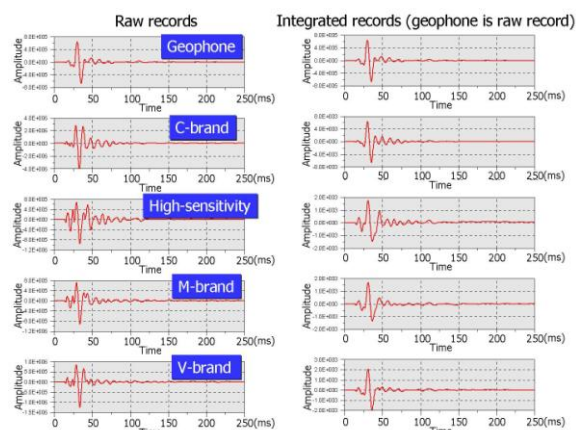


Figure 7. Comparison of raw shot records and integrated records of the five sensors. A source used is a hammer at 2.5 m away from sensors.

In the integrated records, all the records are very similar. For comparison of the sensitivities, S/N ratios of shot records are calculated by dividing signal component by noise component. Here signal component is defined as the maximum of values after the first break, and noise component is defined as the average of the absolute values before first break. S/N ratio and relative ratio are shown in Table 1.

Table 1. Result of the field experiment 1.

Sensor	Signal	Noise	S/N ratio	Sensitivity relative to conventional geophone
Geophone	186346	533	349.62	1.000
C-brand	557133	931	598.42	1.712
High-sensitivity	275333	2103	130.92	0.374
M-brand	190122	9744	19.51	0.056
V-brand	186714	2137	87.37	0.250

In Table 1, the following features became clear: the C-brand MEMS accelerometer has the sensitivity 1.7 times that of geophone; The S/N ratio of the high-sensitivity MEMS accelerometer is about 1/3 of that of conventional geophone; the V-brand MEMS accelerometer has sensitivity 1/4 times of conventional geophone and M-brand MEMS accelerometer has S/N ratio only 1/20 of geophone.

3.2 Field experiment 2: using 3-C sensors

Another field experiment was carried out using two types of MEMS three-component (3-C) accelerometers (C-brand and S-brand), MEMS 1-C accelerometer (C-brand) and the conventional geophone. The 1-C accelerometer and the conventional geophone are same as used in the previous experiments. The S-brand MEMS accelerometer is a

commercially available MEMS accelerometer that has almost the same sensitivity as the C-brand one. As a trial, 3-C MEMS accelerometers, 3-axis MEMS elements (C-brand and S-brand) and electrical circuits were installed to plastic cases. Figure 8 shows a scene of the experiment. Figure 9 shows integrated shot records and spectra generated by hammer impacts at about 1m away from sensors.



Figure 8. A scene of the experiment

As seen in Figure 9, the C-brand MEMS 1-C accelerometer used in field experiment 1 has the same waveform as that of the geophone. However, the C-brand and S-brand MEMS 3-C accelerometer has different waveforms from that of the geophone especially in the range after 150 milliseconds. It appears that the difference is caused by the difference of the setting condition of sensors, and the setting condition depended upon their shapes. In the frequency domain, the dominant region around 100 Hz of the spectrum of shot records have the similar shapes. There are many similarities between the spectrum of the conventional geophone record and that of C-brand MEMS 1-C accelerometer. However, the spectra of other two MEMS (C-brand 3-C and S-brand 3-C) accelerometers have different shapes from others. It appears that the difference of the spectra is caused by the difference in setting condition of sensors. It is consistent with the case of the shot records.

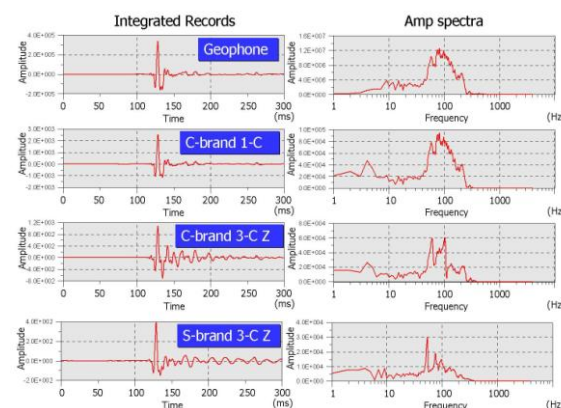


Figure 9. Comparison of integrated shot records and spectra (only vertical (Z) component is shown).

Table 2. Result of the field experiment 2.

Sensor	Signal	Noise	S/N ratio	Sensitivity relative to conventional geophone
Geophone	502801	738	681.65	1.00
C-brand 1-C	3411621	1817	1877.23	2.80
C-brand 3-C Z	1429238	2925	488.55	0.71
S-brand 3-C Z	487540	908	536.67	0.79

S/N ratios calculated by the same way as field experiment 1 are shown in Table 2. As a result of the field experiment 2, the following features became clear: the sensitivities of the C-brand MEMS 3-C accelerometer and the S-brand MEMS 3-C accelerometer were nearly the same; And C-brand MEMS 1-C accelerometer was about three times more sensitive than the conventional geophone.

3.3 Earthquake observation using 3-C sensors

In Japan, there are two broad band seismograph networks of the National Research Institute for Earth Science and Disaster Prevention (NIED): the Hi-net, a high-sensitivity network; and the F-net, a full range network. There are around 600 stations distributed evenly in the whole Japanese Islands with an average spacing of 20–30 km. At each station a velocity seismometer is installed at the bottom of borehole at a depth of 100 m or deeper.

Records of a natural earthquake observed at the Tsukuba observatory (Figure 10) by C-brand MEMS 3-C accelerometer and the broad band seismographs were compared.

An earthquake (M 5.5) occurred on August 1st, 2007, and it was recorded by MEMS accelerometer, Hi-net and F-net (Figure 11). The hypocenter was 383 km below southeast seabed off Mie Prefecture. The epicenter of this earthquake was about 350 km southwest of Tsukuba.

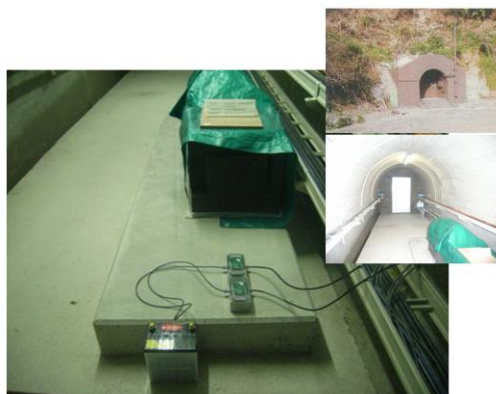


Figure 10. MEMS accelerometer at the Tsukuba observation point .

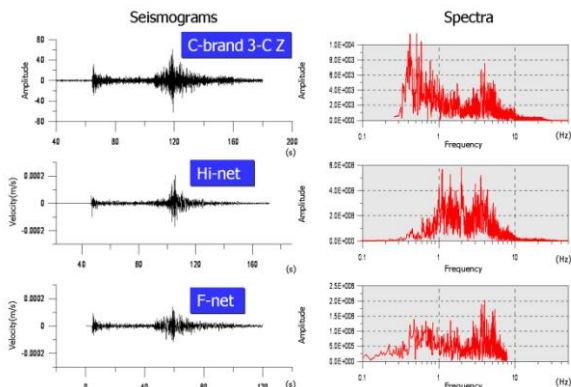


Figure 11. Comparison of seismograms and spectra.

In Figure 11, all the seismograms and the spectra from 1 Hz to 10 Hz appear similar. In the lower frequency band from 0.6 Hz to 1 Hz, the spectra of C-brand MEMS 3-C accelerometer and the F-net are similar. The reason why the spectrum of the Hi-net appear different from others is because the seismometers used in the Hi-net have natural frequency of 1 Hz, and the frequency response decreases exponentially in the region less than 1 Hz. The noise level of C-brand MEMS 3-C accelerometer calculated by normalizing to maxima is about 10^{-4} kine. This compares with the noise level of the Hi-net about 10^{-5} kine. Therefore, it appears that the MEMS accelerometer has the sensitivity about 1/10 times that of the Hi-net seismometer.

4. CONCLUSIONS

The field experiments showed that some MEMS accelerometers developed for trial are as sensitive as or more sensitive than the conventional geophones, but that many of them are less sensitive. However, we consider that geophone, C-brand 1-C, C-brand 3-C and S-brand 3-C MEMS all have similar sensitivities. The different appearance is considered due to the field condition, because these field experiments were carried out by using simple hammer stroke in actual ground condition which were not identical.

From the earthquake observations, the MEMS accelerometer has the linear frequency response in the low frequency band below 1 Hz. The MEMS accelerometer has the sensitivity about 1/10 times that of the Hi-net seismometer.

For future works, we plan to continue earthquake observation and compare seismograms from the MEMS accelerometers and the F-net seismometer to confirm characteristic in the low frequency band of MEMS accelerometers. In addition, electrical circuits and elements in the MEMS sensor have to be improved for practical use.

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