17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

EXPERIMENTAL STUDIES ON PERFORMANCE OF A NEW ACCELEROMETER MADE OF CRYSTAL OSCILLATOR

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Abstract

To mitigate seismic disasters, it is very important to identify the dynamic properties of ground and structure, and to estimate their seismic responses caused by a future earthquake. Although many techniques are proposed to identify the dynamic properties, observation of their dynamic responses can be the most basic information.

Sensors for such the observations are required ideally with high sensitivity, low noise floor, large dynamic range, small and light-weight for portability, and so on. It is impossible to satisfy everything simultaneously, and we usually abandon some of them to realize an observation system. Recently, many kinds of MEMS (Micro Electro Mechanical Systems) sensors are available and satisfy many of the above requirements except for the high sensitivity and low noise floor. A kind of pendulum is used for conventional types of MEMS sensors to measure acceleration, though Seiko Epson Corp. has developed and released an accelerometer made of a crystal oscillator, which has completely different working principle from conventional MEMS sensors and has potentials to satisfy the remaining requirements such as high sensitivity and low noise floor.

The authors have evaluated the sensor to apply it to observations of gravity, microtremors, and earthquake ground motions and confirmed that it could work very well under proper situations. However, the sensor is fragile against impacts because it is made of crystal oscillator. To remedy this problem, one of the authors developed a new sensor, which is irrefrangible and provides lower noise floor. We evaluate applicability of the new sensor to microtremor survey and observation of earthquake ground motions from the viewpoints of noise floor.

We carried out observations of microtremors at some different environments, which include a site with extremely low level of microtremor. The data obtained through the already-existing and new sensors made of crystal oscillator are compared with data of high-performance accelerometers as references. The results of the observation using A351 and A352, which are already-existing and new sensors, respectively, are compared with the results from reference sensor. It is observed that only the reference sensor records ground motions of microtremors and other sensors record only circuit noise. Noise floors of each system, which consists of sensor and data logger, are obtained through the observation. Through the observations, noise floor and limitations of the new sensor are made clear.

Keywords: accelerometer; crystal oscillator; microtremor survey; noise floor; MEMS

1. Introduction

To mitigate earthquake disaster, it is very important to predict how a specific site will shake during a future earthquake. For this purpose, it is necessary to estimate ground motions for appropriate scenario earthquakes using modeled ground structure accurately in a target area. The improvement of accuracy and resolution is important for models of ground structures, because spatial variation of ground motions strongly depends on ground structures and quality of ground model affects accuracy of estimated motions by an earthquake.

Various techniques have been used for geophysical surveys to estimate ground structures. Microtremor survey technique is one of most useful methods using microtremors that can be observed anytime and anywhere. For the microtremor survey, we need to carry out temporal observations of very tiny ground vibrations for a while at many sites in a target area. Sensors for such the observations are required ideally with high sensitivity, low noise floor, large dynamic range, small and light-weight for portability, and so on. It is impossible to satisfy everything simultaneously, and we usually abandon some of them to realize an observation system.

In recent years, small and high-performance devices called MEMS (Micro Electro Mechanical Systems), in which ultra-small components are highly integrated, have been developed and put to practical use in various fields. Sensors using MEMS technology are also applied to accelerometers for seismic observation and small, light-weight, and low-power-consumption devices are easily available. However, even for sensors using MEMS technology, it is common to convert movements of a pendulum into an electric signal and apply the signal to an analog-to-digital converter (ADC) to record ground motions digitally. When converting movements of a pendulum into an electric signal, a sufficiently high signal level is required compared to the noise of the electric circuit. Therefore, in order to measure tiny ground motions accurately, a certain amount of inertial mass is required for a pendulum, making it difficult to reduce the size of sensors. This involves inherent difficulties that conflict with MEMS technology.

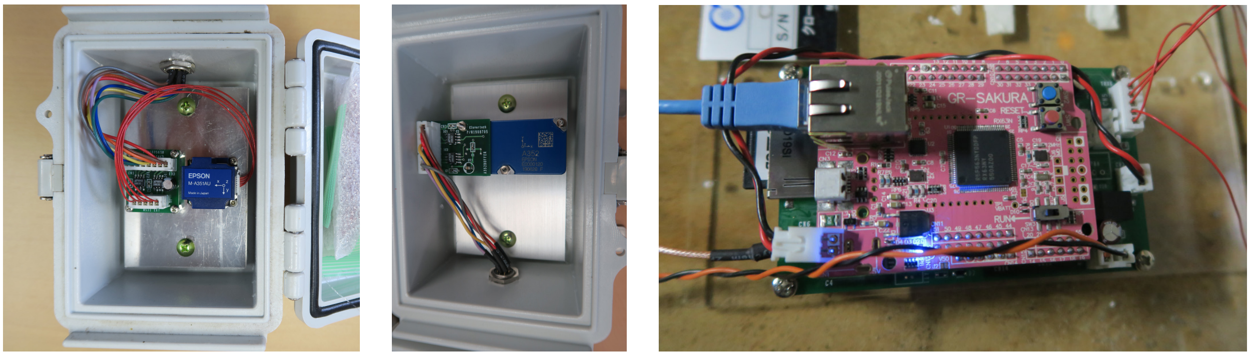
However, accelerometers using a quartz oscillator as a sensor (hereafter, called “quartz accelerometer”) have a unique operating principle. The use of a quartz accelerometer is expected to realize a completely new portable system to observe microtremors that satisfies the conflicting performances of compact, low power consumption, high sensitivity, and low noise. The authors have evaluated the sensor to apply it to observations of gravity, microtremors, and earthquake ground motions and confirmed that it could work very well under proper situations [1]. However, the sensor is fragile against impacts because it is made of crystal oscillator. To remedy this problem, one of the authors have developed a new sensor, which is irrefrangible and provides lower noise floor. We evaluate applicability of the new sensor to microtremor survey and observation of earthquake ground motions from the viewpoints of noise floor including recoding devices (data loggers). Specifically, (1) a data logger specialized for the new quartz accelerometer is developed, (2) an observation system using the new type of quartz accelerometer is assembled, (3) various observations including existing quartz accelerometers are performed, (4) basic performance of the new observation system is evaluated by focusing on overall noise level (hereafter, called “noise floor”) of the system consisting of sensors and loggers, and (5) we examine whether the new observation system is suitable for microtremor survey.

2. Developing an observation system using quartz accelerometer

2.1 Operation principles of quartz accelerometer

For developing a system to observe ground motions, which uses a quartz accelerometer as a sensor, we summarize the operating principle of the quartz accelerometer as a vibration transducer. The details are shown in previous studies [1, 2].

A quartz accelerometer is a sensor based on a completely different operating principle from conventional accelerometers, which convert the movement of a pendulum into an electric signal and output it a voltage value [2]. Quartz oscillators vibrate stably at their own natural frequency and can output a stable sinusoidal signal, if a small amount of electric power is supplied. The natural frequency depends on the temperature and gravitational acceleration, though there is apparent 1-to-1 relationships between the factors (temperature and gravitational acceleration) and the variation of the natural frequency. From this, it is possible to obtain a time history of acceleration in real time by measuring the natural frequency using a counter, correcting fluctuations of the natural frequency appropriately due to temperature.



(a) A351 (b) A352 (c) Circuit board of the data logger

Fig. 1 – Casing quartz accelerometer and circuit board of the data logger.

However, even if the target measurement signal, which is sinusoidal signal outputted from the crystal oscillator, is directly counted in a short time window, it is impossible to identify a very small change in frequency with enough accuracy. In contrast, in a case where the target measurement signal is modulated by a reference sinusoidal signal, the modulated frequency has extremely high sensitivity against the change of the frequency of the target measurement signal. Therefore, instead of directly counting the natural frequency of the crystal oscillator, the quartz accelerometer employs a method in which the change of the natural frequency is obtained by counting the modulated frequency. This method can detect small changes of the natural frequency accurately in short time window [2].

Since the quartz accelerometer can digitize change of the natural frequency directly, it is less affected by the noise caused by the analog circuit than the conventional method of converting motions of a pendulum into an electric signal. Therefore, it is expected that the quartz accelerometer can keep high sensitivity and high S/N even if size of sensor is reduced. In addition, since a crystal oscillator is excited with very small electric power, it is possible to realize a sensor with low power consumption.

A quartz accelerometer that operates on the principle described above was provided from Seiko Epson Corp. as a product (hereafter, A351), and the previous studies by the authors also targeted the A351 [1]. The quartz accelerometer has a disadvantage that it is easily broken by an impact because the sensor is made of quartz. As used as a portable system to observe earthquake ground motions and/or microtremor, it is indispensable to have an impact resistance that can withstand some impact during transportation. A352 is our main target to evaluate in this paper.

2.2 Development of a data logger for quartz accelerometer

For evaluating the quartz accelerometer, we first develop a data logger that can utilize the functions of A351 and A352 so that it can be used as a portable seismometer. VCTCXO (voltage-controlled temperature-compensated crystal oscillator) or OCXO (oven-controlled crystal oscillator) is introduced as a primary clock to control accurately clocks of both the logger and the sensor. In either case, clock is synchronized to a built-in GNSS (global navigation satellite system) receiver or external NTP (network time protocol) server. In a case where VCTCXO is used for primary clock, 1PPS (pulse per second) signal from GNSS receiver controls its oscillation frequency to ensure time accuracy. On the other hand, for primary clock of OCXO, its frequency is not controlled by 1PPS, however it can run by itself with high accuracy over for a long term, after system is synchronized with the absolute time. Thus, OCXO is effective for observation at single station where GNSS radio waves do not reach, such as tunnels.

For the prototype described in this paper, the sensor part is separated from the logger to consider less constraints for installing the quartz accelerometer. The quartz accelerometer outputs digital data serially at the 3.3V CMOS level by single-ended connections. Thus, signal is vulnerable to noise because of single-ended low voltage level signal. It means that a long signal cable cannot be used. To avoid this problem, a simple circuit for single-ended to differential conversion is attached and a long-distance transmission is realized by RS-422/485. Fig.1(a) and (b) show the quartz accelerometers and circuit boards for single-ended to differential conversion in cases, in which blue ones are sensors and green ones are board.

Table 1 – Summary of observation at Higashi-Tanzawa (OKG)

Site code: OKG
Date : Aug. 13, 2019.
Time : 1:50 pm to 2:40 pm
Place: Okunoguchi Parking Lot
Mattake-yama park,
Sagamihara, Kanagawa, Japan
Latitude: 35°31′31.6″N
Longitude: 139°11′17.2″E

Sensor	Logger	SF* [Hz]	Gain	Note
A351	Prototype	200	–	
A352	Prototype	200	–	Noise reduction is disabled.
Titan	AK-002	100	x1	Full scale in 0.25G†
Titan	Centaur	100	x1	Full scale in 0.25G†
KVS-300	AK-002	100	x256	Gain x1 for step response

*: Sampling rate, † : Setting of Titan

Table 2 – Dynamic properties of KVS-300 on the site (OKG)

Component	Natural period[s]	Damping factor
NS	0.504	0.684
EW	0.496	0.640
UD	0.508	0.671

Data logger can record the data from the sensor if it supports serial communications by RS-232/422/485 on CMOS level. Since there is no need to handle analog signals in the logger, no special consideration is required for noise. Thus, the logger can be realized by a power-saving one-board microcomputer. However, to work as an observation system, some functions should be implemented: a circuit for controlling clock described before, a storage system for saving data, and a network interface for communication for setting and data monitoring. The prototype uses GR-SAKURA by Renesas Electronics Corp. as a one-board microcomputer, and we add some peripheral circuits such as a power supply circuit, serial receiver, GNSS receiver, and crystal oscillator for clock. Fig.1(c) shows the circuit board for the data logger. The pink board is GR-SAKURA, and the green board below is the peripheral circuit board. The socket at the top right of the photo is connector for the serial communication with the sensor. On the left side of the photo you can see the network port and the SD card socket below it. Various statuses can be indicated by the four LEDs (light emitting diodes) mounted on GR-SAKURA, where only the blue glow is visible under the red and black power cables in the photo.

Since the quartz accelerometer can output digital signals, the data logger is very simple except for the clock circuit. The prototype, furthermore, records the waveform with the exact absolute time after correcting the time delay caused by the group delay time of a decimation filter of the quartz accelerometer.

3. Noise floor of quartz accelerometer

3.1 Observation settings

The noise floor of the observation system is examined using the quartz accelerometer and the prototype of data logger. Titan accelerometer by Nanometrics Corp. (hereafter, Titan) is used as a reference sensor. Two different types of data loggers are prepared, because the quality of the recorded data also depends on the noise floor of the data logger: one is AK-002 by aLab Corp. and the other is Centaur by Nanometrics. In addition, a moving-coil-type velocity sensor, which is KVS-300 with 0.5 second of the natural period by Kinkei System Corp. is used used with AK-002 for high sensitive observation.

In order for the noise floor to be clearly visible, level of microtremors should be very low. For this reason, the observation was carried out on a bedrock outcrop of Higashi-Tanzawa, Japan. Table 1 summarizes the settings of the observation and Fig.2 shows the site and the sensors.

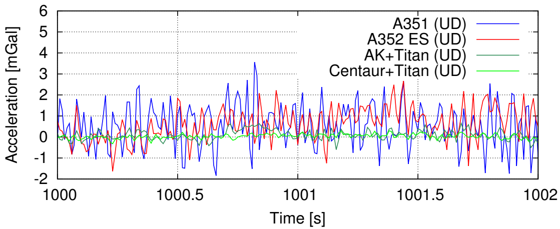
Step responses are recorded for the moving-coil-type velocity sensor (KVS-300) prior to observation in order to determine the natural frequency and damping factor in the installed state. Table 2 shows the obtained parameters. Corrections of the instrumental characteristics are performed by post-processing using the records of step responses.

3.2 Results of observation

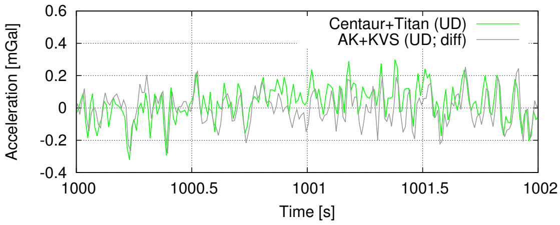
Fig.3 shows an example of the obtained time history of acceleration. The quartz accelerometers are set in the sampling frequency of 200 Hz, however they are resampled to 100 Hz after taking the moving average of

(a) site view (b) settings of sensors and loggers

Fig. 2 – Settings of sensors at site OKG. There is a rock outcrop behind the large sign shown in (a). For sensors, in the panel (b), clockwise from the left top, KVS-300 in silver, two Titans in green, skipping one, and A351 and A352 in gray . For loggers, clockwise from right bottom, two prototypes for quartz accelerometers in transparency and gray, Centaur in white, two AK-002 in brack and transparent cases.



(a) outputs from accelerometers



(b) outputs from velocity sensors

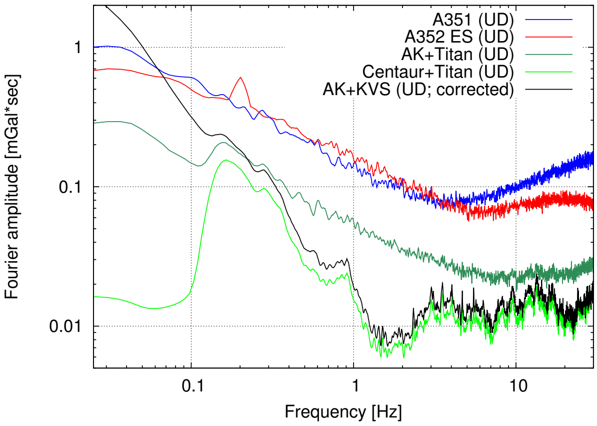


Fig. 3 – An example of time histories of acceleration at OKG (UD components).

Fig. 4 – Fourier amplitude spectra of acceleration records at OKG (UD components)

adjacent samples to make it easier to compare with other records. In addition, since some of records contains large drifts due to temperature changes, low- and high-frequency components are reduced by applying band-pass filter with cutoff frequencies of 0.025 Hz and 30 Hz.

It is observed in Fig.3(a) that the amplitudes of the quartz accelerometers are larger than ones of Titans and the waveforms are no correlation each other. On the other hand, in Fig.3(b), the output of the velocity sensor KVS-300 without instrumental correction is converted approximately to acceleration using forward difference and compared with output of accelerometer (Centaur + Titan). From this figure, it is observed that both waveforms agree well.

Since the records obtained through the combination of different sensors and loggers are consistent, it is presumed that the observation systems except for quartz accelerometers correctly record the microtremors at the site. From this, we can say that the waveforms of the quartz accelerometers shown in Fig.3(a) contains large noise, and their noise levels are about 10 times of microtremor signal in time domain.

Table 3 – Summary of observation at Laser Tunnel, Tokyo Institute of Technology (TUN)

Site code:	TUN
Date & Time:	from 11:00 am, Aug. 22, 2019. to 9:00 am, Sep. 2, 2019
Place:	Laser Tunnel, Suzukake-dai Campus, Tokyo Institute of Technology Midori-ku, Yokohama, Japan
Latitude:	35°30′58.3″N
Longitude:	139°29′4.3″E

Sensor	Logger	SF* [Hz]	Gain	Note
A352	Prototype	200	–	Noise reduction is enabled.
Titan	Centaur	100	x1	Full scale in 0.25G†

*: Sampling rate, † : Setting of Titan

To confirm this, the observed data are compared in frequency domain. The procedure for the analysis is as follows:

(1) Applying a band-pass filter with cutoff frequencies of 0.025 and 30 Hz in the time domain to reduce a large drift due to temperature change,
(2) Choosing a 30-minute length data of signal which is not affected by the filter,
(3) Picking up 12 portions with 163.5-second length and applying Fourier transform to each portion,
(4) Applying the Hanning window 5 times to the Fourier amplitudes of each portion to obtain smoothed spectrum,
(5) Squaring the obtained Fourier amplitudes and taking their arithmetic mean,
(6) Multiplying its square root by the duration time 163.5 seconds to obtain a Fourier amplitude spectrum.

Fig.4 shows Fourier amplitude spectra (UD component) of accelerations. In this figure, the Fourier spectrum of KVS-300 is obtained by multiplying the inverse of the frequency response function of a one-degree-of-freedom system in the frequency domain using the parameters as shown in Table 2. Furthermore, multiplying it by the circular frequency ω, Fourier spectrum of acceleration is obtained.

As shown in Fig.3(b), AK-002 + KVS-300 and Centaur + Titan agree well in most of the target frequency range such as 0.15 to 30 Hz. In contrast, the quartz accelerometers (A351 and A352) and AK-002 + Titan show Fourier amplitudes that change almost linearly on a log-log axis. This indicates that only the 1/f noise of the observation system is recorded, and signal of microtremors, which is our target, is buried in the noise and is not recorded at all. This can be understood from the fact that the Fourier amplitude of Centaur + Titan is smaller than that of AK-002 + Titan over the entire frequency range. The noise floor of the AK-002 is about 1/10 of that of the quartz accelerometers, and this corresponds that the amplitude of AK-002 + Titan is almost the same as Centaur + Titan in Fig.3(a). In addition, the noise floor of the A352 is significantly improved over the A351 in the high-frequency range above 5 Hz.

The noise floor of AK-002 + KVS-300 is apparently lower than that of AK-002 + Titan, because KVS-300 is a velocity sensor and signal is gained 256 times at the gain stage of the logger. However, in the frequency range lower than 0.1 Hz, the Fourier amplitude becomes larger and deviates from that of Centaur + Titan. AK-002 + Titan shows almost the same Fourier amplitude as Centaur + Titan only in the frequency range from 0.15 to 0.3 Hz. On the day of the observation, Typhoon No. 10 was stagnant near the Ogasawara Islands, Japan. Thus it is considered that the level of microseisms, which is microtremors with slightly long-period about 0.1 to 1 Hz originating off the Pacific Ocean, was enough higher than the noise floor of AK-002 in the specific frequency range.

From the above, the noise floor of the observation system can be clearly known and the noise floor of the quartz accelerometers can be clarified in an environment where the microtremor level was extremely low, such as peak-to-peak amplitude of less than 0.5 mGal in time domain. It is found that Centaur + Titan and AK-002 + KVS-300 can be reliably used as a reference, even at extremely small levels of microtremors by applying appropriate settings and post-processing as needed.

4. Microtremor observation

4.1 Observation settings

We investigate if the quartz accelerometers can be used for the observation of microtremors on sediments. Level of microtremor is generally very large at a place where the sedimentary layer is thick, and it is too rough

Fig. 5 – Settings of sensors at site TUN (Laser tunnel). An aluminum plate of 20mm thickness was fixed by anchoring the concrete floor of alcove, where is located at center of the laser tunnel, and the sensor was screwed on it. For sensors, anti-clockwise from right top, Titan in green and A352 in gray. For loggers, left top is Centaur and left bottom is the prototype for A352.

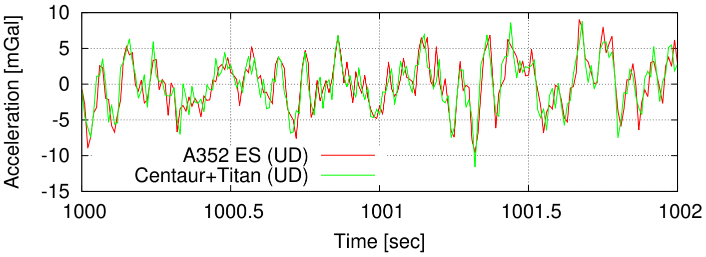


Fig. 6 – An example of time histories of acceleration at TUN (UD components)

and less meaning in order to know the sensor performance such as sensitivity. Therefore, in this section, the observation is performed at a place where the soft soil layer is thin and there is less traffic, that is, microtremor level is low. If microtremors can be observed correctly at such the place, there should be almost no problems for microtremor survey on sedimentary layers.

Although it seems to difficult to find such a convenient place, we believe that the laser tunnel of Suzukakedai campus, Tokyo Institute of Technology is one of such a place.

For the observation, an aluminum plate of 20mm thickness is fixed by anchoring to the concrete floor of the alcove, where is located at the center of the tunnel, and the chassis containing the sensor is fixed to the aluminum plate with screws. The observation at OKG described in the previous section showed that Centaur + Titan can be used as a reference, and we will compare the output from A352 with one from Centaur + Titan for the observation at TUN.

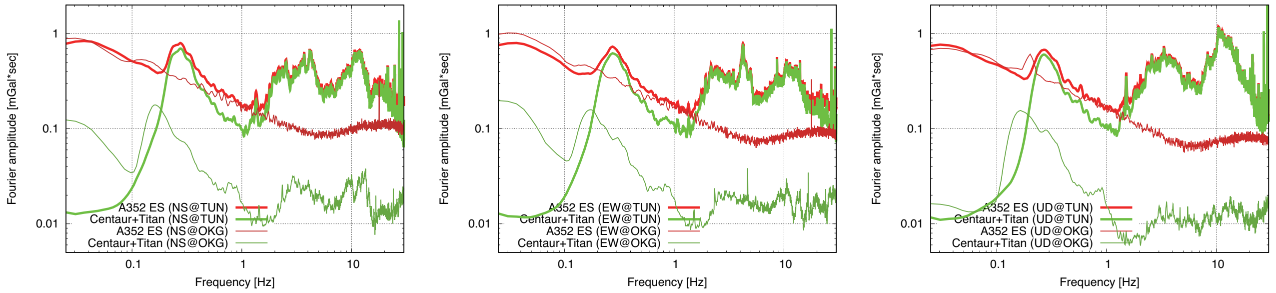
Table 3 summarizes the settings of the observation at TUN and Fig.5 shows the sensors used for the observation. The photo also includes some sensor which are not discussed in the study and our targets are described in the caption of Fig.5.

4.2 Results of observation

Fig.6 shows an example of the observed time histories of acceleration. The waveforms shown in the figure are a portion of two-second length from a one-hour record beginning from 1:00 am on August 24, 2019. The data processing in the time domain is the same as that for the record obtained at OKG.

Although output from A352 was a random waveform and showed no correlation with the output from Centaur + Titan, the waveforms obtained at TUN agree well in both amplitude and phase as shown in Fig.6.

Fig.7 shows the Fourier spectra of the acceleration obtained at TUN together with those at OKG for corresponding sensors. The analytical procedure to obtain the Fourier amplitude spectra is same as that for OKG, though the length of the record used for the analysis is 60 minutes, not 50 minutes. 18 portions are chosen for the Fourier transform from 60-minute data beginning from 1:00 am on August 24, 2019. In the figure, a specific color of line corresponds to a specific sensor and logger. Fourier amplitudes are higher at TUN drawn in thick lines than at OKG in thin lines which are same as Fig.4. From the Fourier amplitude of Centaur + Titan shown in Fig.7, it is observed that level of microtremors at TUN is almost an order of magnitude



(a) NS component (b) EW component (c) UD component

Fig. 7 – Fourier amplitude spectra of acceleration at OKG and TUN.

higher than that at OKG. This is consistent with the fact that the amplitude of time history at TUN (Fig.6) is more than 10 times of that at OKG (Fig.3(a)).

5. Discussion

As shown in Fig.7, the Fourier spectrum of A352 at OKG is quite different from that of Centaur + Titan, though the one at TUN corresponds well with one at OKG. However, it is observed in the frequency range from 0.5 to 1.5 Hz that the Fourier spectrum of A352 is about 1.5 times larger than Centaur + Titan and changes linearly.

It can be seen that the shape of the Fourier spectrum of A352 around 1 Hz at TUN almost coincides with one at OKG. This clearly shows that the signal is buried under the noise, because the amplitude of microtremors is lower than the noise floor of the A352 revealed by the observation at OKG.

Fig.7 also shows that the Fourier amplitude of A352 is slightly larger than that of Centaur + Titan in the frequency range higher than 15 Hz, especially, for EW component. In this frequency range, since the level of microtremors is sufficiently higher than the noise floor of the sensor, the differences may be caused by any influence of external noise in high frequency range besides the circuit noise of the sensor. This may suggest that further measures are required such as casing and grounding, because the quartz accelerometer is very sensitive to installation conditions.

It is observed from the Fourier amplitude spectra at OKG shown in Fig.4 that the noise floor is V-shaped with a peak at around 5 Hz for the quartz accelerometers (A351 and A352). Noise in low frequency range is ”1/f noise,” which is a typical noise generally found in analog circuits. As already mentioned, output signal of the quartz accelerometer should be not affected by any analog circuit, because the quartz accelerometer directly digitizes the variation of natural frequency of the quartz oscillator. Nevertheless, the reason why 1/f noise is observed is that the oscillation of the reference oscillator used to measure the variations of the natural frequency of the quartz oscillator has 1/f fluctuation. Therefore, 1/f noise can be reduced in the low frequency range by using a reference signal generator with smaller 1/f fluctuation.

On the other hand, the noise floor increases as higher frequency in high frequency range. In a case where a combination of a conventional accelerometer and a data logger is used to record data, the noise in this frequency range is generally the quantization noise of ADC and takes usually a constant value regardless of the frequency. For the quartz accelerometer as well, the noise in high frequency range is due to quantization noise, but is unique to digitization using frequency modulation. Thus, the quantization noise in high frequency range can be reduced by increasing the parallelization order of the parallel processing to perform phase modulation in the frequency modulation.

6. Conclusions

To examine applicability of a quartz accelerometer to the microtremor survey, we evaluate its performances through observations at two sites, where the level of microtremors are significantly different. The results obtained through the study are summarized below.

- The noise level of the quartz accelerometer is much higher than level of microtremors at a place where the amplitude of microtremors are about 0.5 mGal in peak-to-peak. As a result, the noise floor of the quartz accelerometer is clarified.
- Noise floor of the new quartz accelerometer A352 is significantly improved in the high frequency range comparing the existing one A351.
- In the frequency range around 1 Hz in which the microtremor level is particularly low at a place where microtremor level is very low in spite of presence of the sedimentary layer, noise floor of the quartz accelerometer and microtremor level are almost comparable, or the noise floor is higher than microtremor level and noise is dominant. Therefore, Fourier amplitude is considerably affected by internal noise of the sensor.
- It highly suggests potentialities that quartz accelerometers can be used to observe signals in large dynamic range from microtremors to strong ground motions, in a case where we understand accurately the noise characteristics of the sensors.
- For microtremor survey, the quartz accelerometer can be a one of realistic choices, considering performances of an entire system including portability and low power consumptions.

Acknowledgments

A part of this work is supported by JSPS KAKENHI Grant numbers JP19H02400, JP17H02064, and JP19H02406.

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