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ESTIMATION OF STRESS DISTRIBUTION BY MICRO STRAIN MEASUREMENT IN SEISMIC REINFORCEMENT STEEL BRACE

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Abstract

An acceleration and strain measurement system using inexpensive MEMS accelerometers, inexpensive AD conversion chips equipped with an dynamic strain amplifier, and highly sensitive semiconductor strain gauges is developed and applied to seismic reinforcement steel braces installed in a 9-story reinforced concrete building in order to measure the acceleration response and the strain response during microtremor and small earthquakes.

It is shown that the primary fundamental frequency determined from microtremors using strain measurements from semiconductor strain gauges almost coincides with the natural period of the building, confirming that the proposed measuring system is applicable to the measurement of strain in steel member even under extremely small motion. Fourier analysis of 7 recorded small earthquake histories is conducted, and the ratio between the peak magnitude of the Fourier coefficient of the strain and peak magnitude of the Fourier coefficient of the relative acceleration, which can be considered as an index of the effectiveness of the brace as a force resisting member, is evaluated. The obtained ratio is almost constant irrespective of the input time history and has a value approximately half of that obtained from a simple structural model of which the discrepancy can be attributed to an oversimplification in the structural model. The ratio for the four steel braces in the seismic reinforcement are similar in value, implying that the braces equally resist the lateral force.

Keywords: Structural health monitoring; Strain measurement;Steel member

1. Introduction

In recent years, structural health monitoring of building structures has attracted a great deal of attention, and many monitoring systems for buildings have become commercially available. However, many of them measure the acceleration response to estimate the overall behavior of the building, such as natural period, attenuation, and inter story drift, and cannot directly measure the stress state or damage state of individual structural members.

An alternative and better measurement index to determine the state of individual structural members may be strain. The advantage of strain measurement over acceleration is its capability in assessing local internal forces in members enabling one to directly measure the stress and force distribution within a structure. Though measuring strain by strain gauges is simple and straightforward, there exist few examples of measuring strain in actual steel building structures. The reasons for this may be that the strain that occurs in the structural frame on a daily basis is extremely small and difficult to measure, the long term durability of strain gauges is low, and the data acquisition system of dynamic strain is expensive. In addition, local strains are likely to be affected by the measurement position and the surrounding environment and it may be difficult to interpret the measured values compared to existing more understandable indexes. As a result, the data analysis method and the utilization method of such measured strain have not been established.

In this paper, an example of measuring microstrain vibration as well as acceleration under microtremor or small earthquakes using a low-cost dynamic strain measuring device and high precision semiconductor strain gauges is presented. The semiconductor gauge is capable of capturing extremely small strain amplitudes under microtremor as well as small earthquakes with high accuracy compared to standard foil strain gauges[1]. The measuring system is based on advances made in the IT and IoT technology, reducing the cost and increasing the feasibility in the measurement of actual building structures. The proposed system along with MEMS accelerometers are installed in a 9 story RC building. The sensors are attached to the steel reinforcement braced frame within the building, and time histories of microtremors as well as small earthquakes are obtained. The validity of the measurements are investigated through Fourier analysis of the measurements and the internal force distribution between the braces in the frame is obtained.

2. Measurement method

2.1 Measurement system

Fig. 1 shows the configuration of the entire measurement system. One sensor unit consists of one Raspberry Pi Zero W[2] connected to either one MEMS accelerometer or 4 strain gauges. Each sensor unit sends measurement records to the server via the Ethernet at any time using the MQTT protocol[3]. Although strict time synchronization is not established between each acceleration measurement unit and strain measurement unit, the data transmitted to the server has a time stamp synchronized in sub-second units to an operating NTP client.

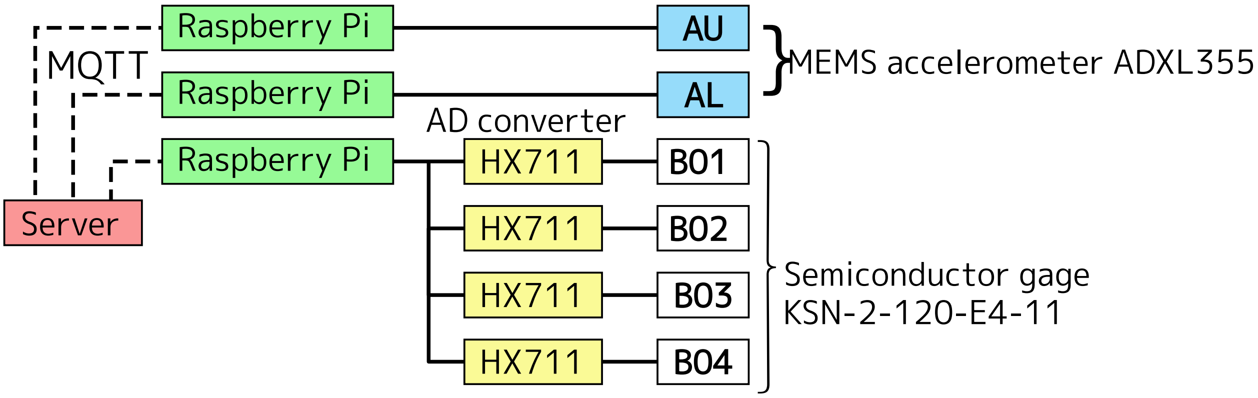

Fig. 1 – Configuration of the measuring system

2.2 Dynamic strain measurement unit

The dynamic strain measurement unit used in this study is designed with an HX711[4], a microchip whose main purpose is to measure the differential potential in a Wheatstone bridge configuration of devices such as a load cell or a strain gauge. Its nominal sampling frequency is either 10Hz or 80Hz. Many applications of this chip can be found for static load measurements using its 10Hz sampling function, but the number of applications found using the 80 Hz sampling function is few and its applicability to building structure measurement has not been established. From the viewpoint of functionality, the chip does not have a feature to allow time synchronization with other chips and is much inferior to commercially available dynamic strain measurement systems. However, the price of the chip is very low. If this can be used effectively, an inexpensive structural monitoring system can be realized. Under such expectations, in this study, a dynamic strain measurement unit using 4 HX711s in collaboration with a Raspberry Pi Zero W micro controller is designed and fabricated. The circuitry of the system almost follows the reference circuit displayed in the manual attached to the HX711, and a voltage of about 2.5V, generated by a regulator (constant voltage circuit) built into the chip, is supplied to the bridge.

2.3 Acceleration measurement unit

For the acceleration measurement, a unit using the MEMS accelerometer ADXL355 was created and employed. The ADXL355 has a function to measure 3-axis acceleration, perform AD conversion, and output it to a micro controller, which is a Raspberry Pi Zero W in the proposed system. In this study, the sampling frequency was set to 62.5Hz, and the minimum resolution for the accelerometer is 0.0037[gal].

3. Measurement target

The measurement target is a steel braced frame installed as a seismic reinforcement on the 6th floor of a 9-story reinforced concrete building. Figure 2 shows the outline of the shape and the measurement location. In order to measure the axial force of the diagonal braces, strain gauges are attached to the top and the bottom flange of the H-shaped steel members. There are 4 gauges in a section in order to verify the deviation of the stress distribution in the section from a purely axially loaded state. To focus on accurate response measurements due to microtremors and small earthquakes, a semiconductor strain gauge (KSN-2-120-E4-11 manufactured by Kyowa Electronic Instruments Co., Ltd) was used. This has a gauge factor of approx. 100, and thus has a precision of about 50 times that of normal foil strain gauges which have gauge factors of approx. 2. The minimum resolution for this semiconductor gauge is 1.81x10^{-5}[μstrain]. Four measurement units are installed in the 4 braces.

Two acceleration measuring units are installed at the top and bottom of the column in the steel frame to calculate the interstory drift.

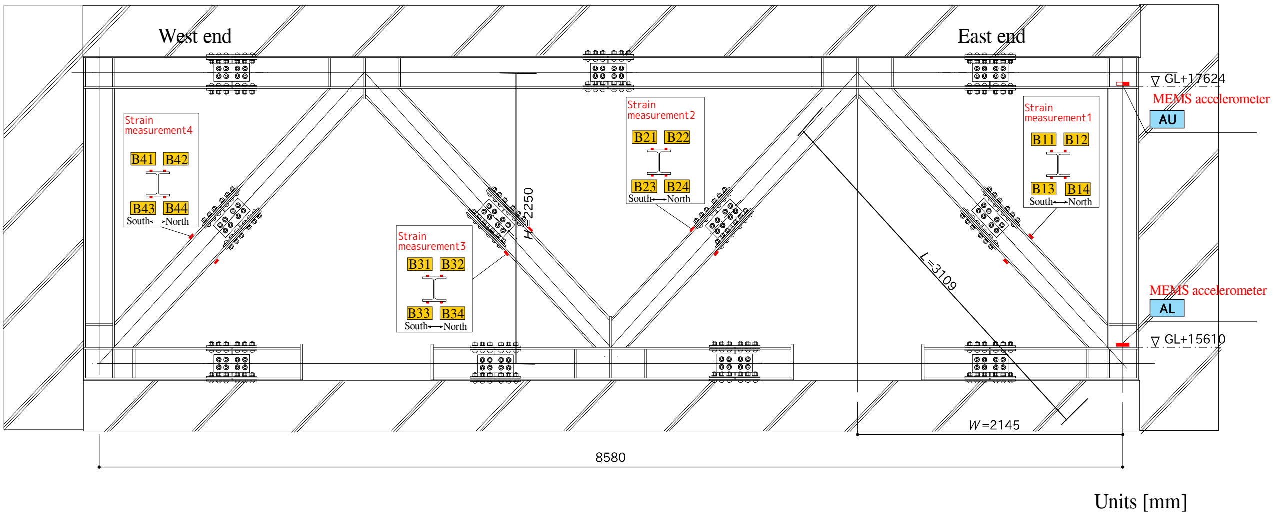

Fig. 2 – Measurement target : steel brace frame serving as seismic reinforcement in a RC building

4. Measurement result

4.1 Measured time history

A summary of the measured time histories is shown in Table 1. The first data is a microtremor measurement and thus does not have an epicenter. The 2nd through 7th data are earthquake measurements ranging from extremely small to small. The maximum acceleration recorded at the top of the steel frame (AU) is listed as a reference to show how much the building shook under the earthquake.

Table 1 – Summary of the measured time histories

No.	Date	Epicenter location	Magnitude	Max. JMA intensity scale	Onsite max. JMA intensity scale	Max. acc (AU) [gal]
1	2020/2/9	- (Microtemor)	-	-	-	0.23
2	2019/7/8	Western Kanagawa	4.3	3	1	2.14
3	2019/8/4	Off the coast of Fukushima	6.2	5-lower	2	16.5
4	2020/1/21	Off the coast of Ibaragi	4.3	4	-	1.02
5	2020/2/1	Northeastern Chiba	5.1	3	1	4.10
6	2020/2/1	Southern Ibaragi	5.3	4	2	21.5
7	2020/2/9	Northeastern Chiba	4.0	2	-	1.12

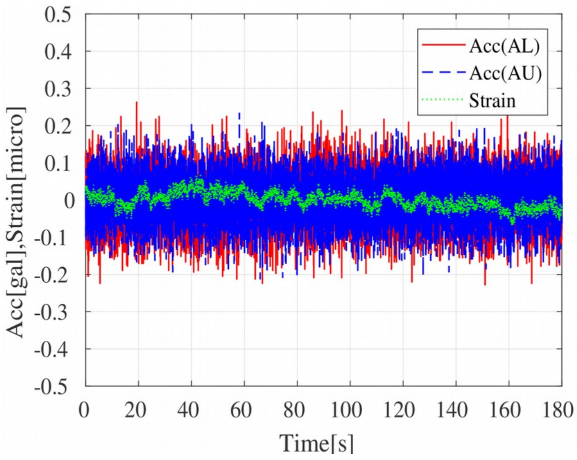

Fig.3 – Time history of acceleration (AL,AU) and strain(B11) for record No.1

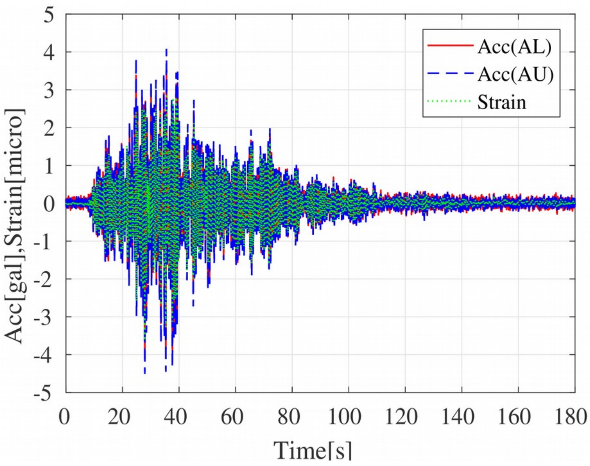

Fig.4 – Time history of acceleration (AL,AU) and strain(B11) for record No.5

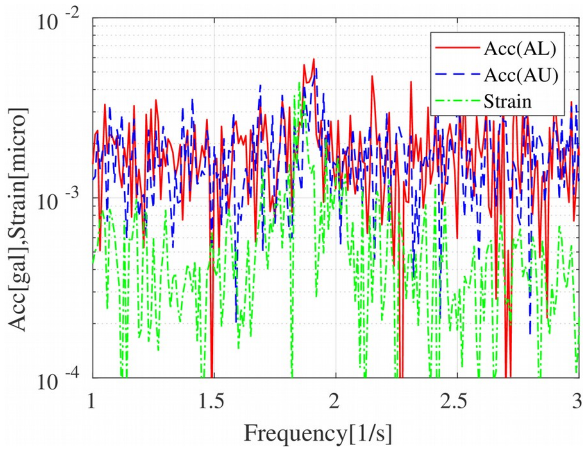

Fig.5 – Fourier coefficients of acceleration (AL,AU) and strain(BS11) for record No.1

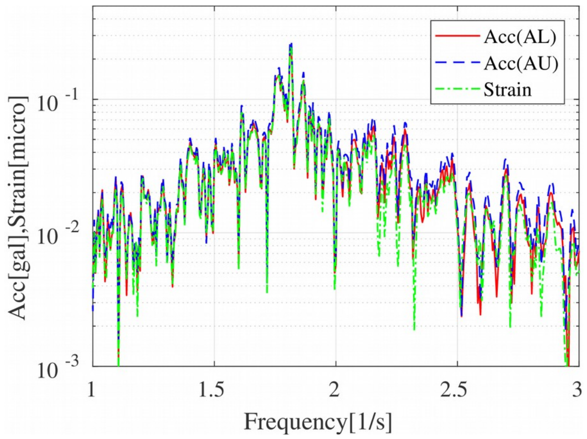

Fig.6 – Fourier coefficients of acceleration (AL,AU) and strain(BS11) for record No.5

The measured time histories of the acceleration(AL,AU) and strain(at location B11) for record No. 1 (microtremor) and record No. 5 are shown in Fig. 3 and Fig. 4. From Fig.3, one sees that the acceleration time histories contain much noise such that the resolution of the accelerometers is not sufficient to capture the microtremor motion. However, the strain measurement using the semiconductor gauge has enough sensitivity to record the small microtremor motion. Observation of Fig. 4 reveals that under earthquake induced motion, both accelerometer and strain measurement seem to be able to record the motion properly. The validity of the measurements will be further confirmed in the Fourier analysis of the measurements.

4.2 Fourier analysis of measured acceleration and strain

A Fourier analysis of the measured acceleration and strain are conducted to investigate their spectral properties. Here a discrete Fourier analysis is conducted, in which the measured signals $a(t)$ is treated as a discrete sequence $a(t_j)$ with $j=0\sim N-1$ and $t_j=j\Delta t$, and decomposed into its Fourier series.

$$a(t_j)=\frac{A_0}{2}+\sum_{i=1}^{N-1} A_i \cos\left(\frac{2\pi i}{N\Delta t}t_j-\varphi_i\right) \tag{1}$$

Here N is the number of data, Δt is the sampling time step, and A_i and φ_i are the Fourier coefficient and phase angle corresponding to the frequency $\frac{2\pi}{N\Delta t}i$, respectively. The Fourier coefficients of data record No. 1 and data record No. 5 are shown in Fig. 5 and Fig.6. It is clear from Fig.5, that the accelerometer does not have enough resolution to measure the response of the structure. On the other hand, the strain measurement using the semiconductor gauge is able to produce a clear peak near the fundamental frequency of the building at approximately 1.8[Hz] which is close to the value of 1.88[Hz] obtained from an eigenvalue analysis of a stick model. Fig.6 shows that under small earthquakes, the accelerometer and strain measurements show equivalent results. Thus in order to conduct analysis between the two measurements, motion under at least small earthquakes must be considered.

4.3 Relation between Fourier coefficients of acceleration and strain

The previous section revealed that the accelerometer and strain measurements show the same spectral trend. Here the validity of their magnitude is investigated by comparing the ratio between the Fourier coefficients of measured acceleration and strain. The configuration shown in Fig. 7 is a simplified line model of the steel braced frame in Fig. 2. All connections are assumed pinned, the outer rectangular frame is assumed rigid, and only the braces are expected to extend or contract. Under these assumptions along with the small deformation assumption, the interstory drift (shear deformation) of the frame d is related to the brace deformation Δ through the relationship $\Delta = \frac{B}{L} d$. The relationship between the brace strain and deformation is given as $\Delta = \varepsilon L$, and the relationship between relative acceleration and interstory drift d is $a = a_U - a_L = \ddot{d}$. Combining these three equations results in the following relationship between the magnitude of the Fourier coefficients for the relative acceleration A and brace strain E,

$$\mathrm{E} = \frac{B}{L^2} \frac{1}{(2\pi f)^2} A . \tag{2}$$

For a fundamental frequency of 1.8[Hz], the theoretical ratio E/A is approximately 17.3[μstrain/gal]. This ratio between the magnitude of the Fourier coefficient of the strain divided by the magnitude of the Fourier coefficient of the acceleration reflects the local stiffness of the structural member, i.e., the amount of deformation that occurs for a certain amount of load, near the location where the strain gauge is pasted. A low ratio would imply low effectiveness as a force resisting member.

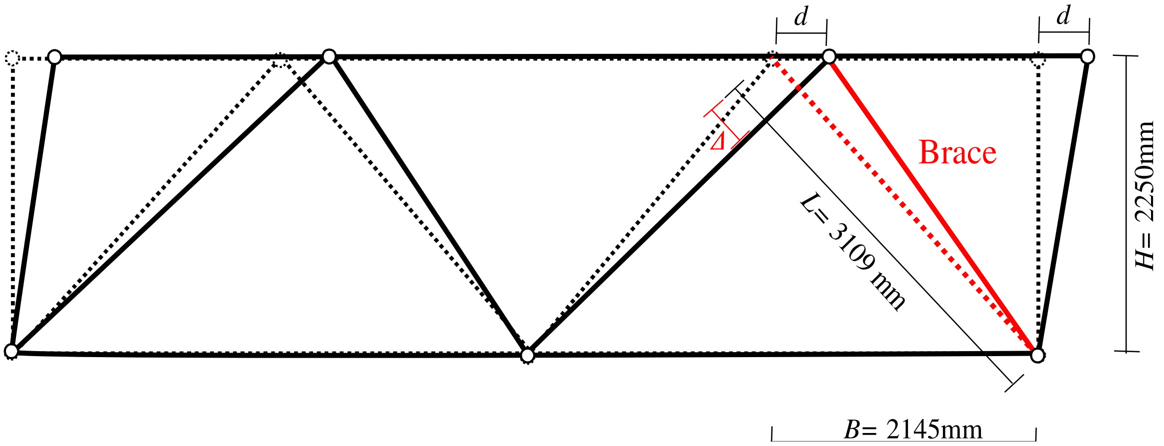

Fig. 7 – A simplified model of the steel braced frame

Since the E/A ratio involves the magnitude of the Fourier coefficients E and A which depend on the length of the signal analyzed, the dependence of the E/A ratio on the signal duration is investigated using earthquake record No. 5 shown in Fig. 4. A fixed time interval centered at the peak in the strain history (approx. t=28[s] in Fig. 4) is extracted from the earthquake and the ratio E/A is computed. The fixed time interval is varied from 10[s] to 180[s]. The magnitude of the Fourier coefficients E, A_L, A_U, and relative acceleration A(=A_L-A_U) at the fundamental frequency and the ratio E/A for record No. 6 with signal duration of 180 seconds is shown in Fig. 8. Since the measurement system employed in this paper does not have the ability to synchronously sample data, first the acceleration and strain data are aligned based on their time stamp set by the NTP client. Next a fixed time interval of the data is extracted and the Fourier coefficients are computed. The building is assumed to vibrate mainly in its first fundamental mode, such that the acceleration data at the top and bottom of the column be in phase. This allows one to compute the magnitude of the relative acceleration A by taking the difference between the magnitudes of the accelerations, A_L-A_U.

The relationship between the size of the extracted time interval and the magnitude of the Fourier coefficients E and A at the fundamental frequency and the ratio E/A is shown in Fig. 9. As the duration of the extracted signals increases the magnitudes of the Fourier coefficient decrease, since more data including less motion contribution near the peak frequency is included. On the other hand, the ratio E/A takes an almost constant value of approximately 7 and is fairly insensitive to the duration of the signal. The theoretical value for the ratio based on the simple model of Eq. (2), which depends on the peak frequency takes an approximate value of 17. The cause of this discrepancy can be attributed to the oversimplification employed to develop Eq. (3), such as a rigid outer frame and pinned joints as well as the constraint from the exterior reinforced column elements.

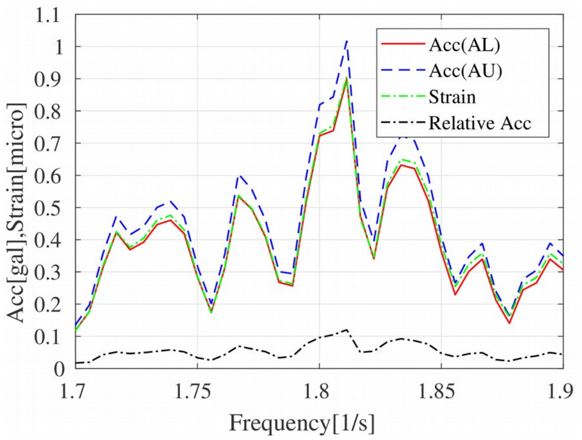

Fig.8 – Fourier coefficients of acceleration (AL,AU) and strain(B11) and relative acceleration for record No.6

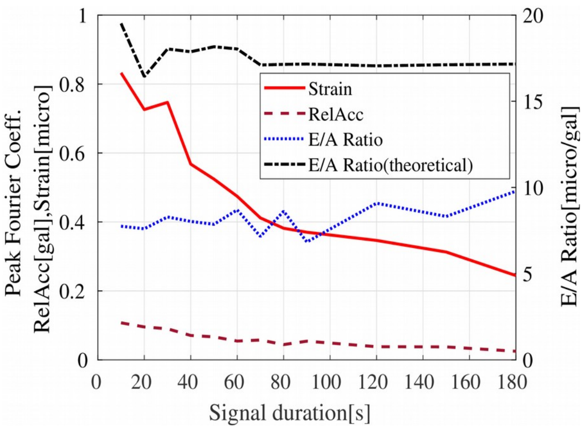

Fig.9 – Variation of the peak Fourier coeffs. of relative acceleration and strain(B11) and their ratio for record No. 5(the theoretical value from Eqn. (3) is shown in black)

In order to investigate the sensitivity of the E/A ratio to the input earthquake, the E/A ratio is computed for earthquake record No. 2 through 7 using a signal duration of 100[s]. The relationship between the peak magnitude of the Fourier coefficient of the strain E, which is an index of the intensity of the building response, and the corresponding peak frequency, which should coincide with the fundamental frequency of the building, is shown in Fig. 10. Though the number of data is limited, the extracted fundamental frequency has a value close to 1.8[Hz] and displays a decreasing trend with an increase in the peak magnitude of the Fourier coefficient of the relative acceleration. The relationship between the peak magnitude of the Fourier coefficient of the strain E and the E/A ratio is shown in Fig. 11. The E/A ratio also seems to be fairly insensitive to the magnitude of the response of the building.

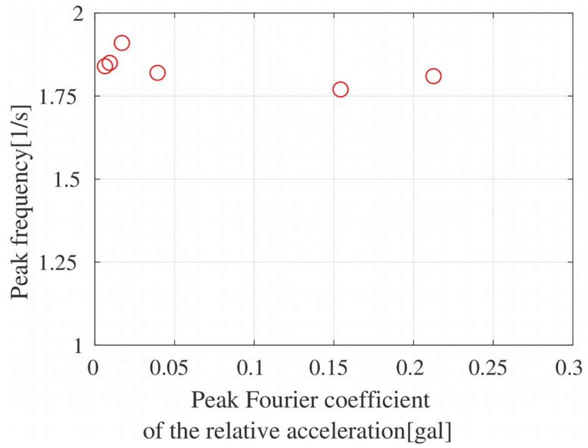

Fig.10 – Relationship between peak Fourier coefficient for the relative acceleration and corresponding frequency (signal duration 100[s])

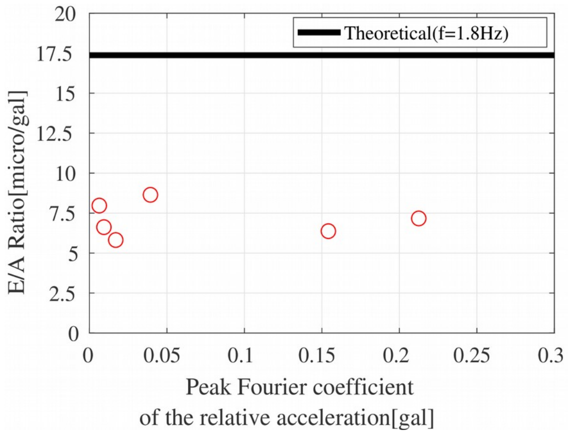

Fig.11 – Relationship between peak Fourier coefficient for the relative acceleration and E/A ratio (signal duration 100[s])

Lastly, the axial force distribution among the braces is investigated. For this study, only record No. 4,5,6,7, which have measured data for all 4 braces, are treated. Since each brace has 2 strains gauges attached to each flange (see Fig. 2), their average value corresponds to a measure of the axial force acting within the brace. The relationship between the peak magnitude of the Fourier coefficient of the relative acceleration and its E/A ratio for each brace is shown in Fig.11. One observes that the discrepancy in the E/A values between the braces is small, such that major dependence of the axial force distribution on the magnitude of the response of the building cannot be seen.

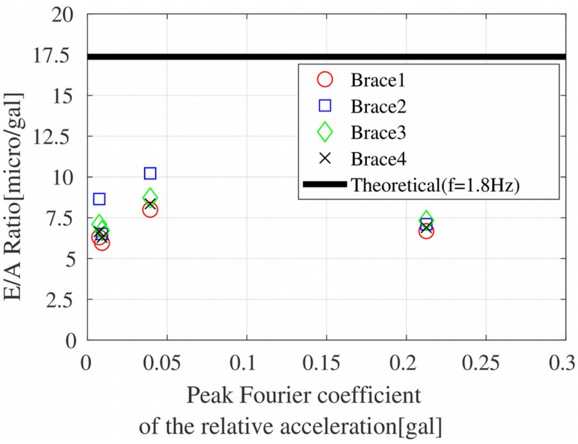

Fig.11 – Relationship between peak Fourier coefficient for the relative acceleration and E/A ratio of each brace (signal duration 100[s])

5. Conclusion

An acceleration and strain measurement system combining an inexpensive MEMS accelerometer and AD conversion chip with semiconductor strain gauges was created and used for measurement of acceleration and strain of a seismic reinforcing steel frame member under microtremor or small earthquake motion.

The highly sensitive strain measurement system is able to capture the motion under microtremors as opposed to the acceleration measurement system. But both systems perform equally well under small earthquakes and are able to estimate the fundamental frequency of the building as well as have similar trends in the magnitudes of the Fourier coefficients.

Though the proposed systems is low cost, it lacks the ability to strictly perform time synchronization between the various sensors. In the case that the building structure mainly vibrates under the primary fundamental frequency in the same phase, one can assume that the phase angles of the strain and the accelerations decomposed into their Fourier series are identical in the frequency range close to fundamental frequency. This allows one to perform addition and multiplication of the magnitude of the Fourier coefficients. Based on this assumption, the relative acceleration can be obtained and be compared with the strain. The ratio between the magnitude of the Fourier coefficient of the strain and the magnitude of the Fourier coefficient of the acceleration reflects the local stiffness of the structural member near the location where strain gauge is pasted. This ratio is evaluated for 6 different small earthquake histories an results in an almost constant value irrespective of the input earthquake. The constant value is almost approximately half of that obtained from a simple structural model to which the discrepancy can be attributed to an oversimplified structural model. The ratio obtained for the four braces in the steel braced frame showed similar values, implying that the braces all shared the load equally.

There are still many issues to be solved such as the low accuracy in time synchronization, the durability of semiconductor strain gauges, and the uncertainty in the long-term stability of the chip used for measurement. However, the obtained data shows stable trends. Further accumulation of data and improvement of accuracy of the method will be conducted through continuing long-term measurements using this system.

Acknowledgments

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