Fundamental Tests on Structural Performance Monitoring System of Building Structures Using Gyro Sensor

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SUMMARY:
In this study, MEMS-based gyro sensors are employed as a new device on structural performance monitoring of building structures, and calculation methods of response displacements using gyro sensors are proposed. In order to verify measuring accuracy of response displacements and natural periods of specimens, fundamental vibration tests on gyro sensors are performed in comparison with acceleration sensors. Vibration tests are carried out using two types of specimens with four kinds of different natural periods, which imitate building structures and/or structural control devices. The calculating method is proposed to convert inclination angles measured by gyro sensors into response displacements according to spatial geometric relation. It is clarified that response displacements using proposed method have reasonable accuracy, and the orbital diagrams in X-Y plane also can be simply and properly obtained. Therefore, the proposed measuring system is considered to be applicable to structural performance monitoring and popularization in practical due to high cost performance.

Keywords: Structural performance monitoring, Gyro sensor, Response displacements, Measurement accuracy, Natural period, Orbital diagrams

1. INTRODUCTION

Nowadays, the monitoring on structural performance of buildings in life cycle is becoming increasingly important, especially during extreme motions caused by earthquakes. In the Great East Japan (Tohoku-Chiho Taiheiyo-Oki) Earthquake and Tsunami (2011), not only the many building structures were damaged severely, but also some of the isolation devices needed to be replaced. A quick emergency inspection including damage detection and residual seismic capacity after earthquake should be developed for assessing structures and carrying out appropriate anti-seismic retrofit rapidly and properly.

Sensor network system using strain gages and/or acceleration sensors have been studied experimentally and utilized in practical building recently, and numerous communication technologies such as RFID and wireless networks have also been introduced into monitoring systems by Tani et al. (2005, 2007a, 2007b), Murakami et al. (2007) and Ugaji et al. (2008). In these studies, commonly, relative story displacements are employed as important seismic indexes of structural performance assessment. However, in order to calculate relative response displacements based on data measured by accelerometers, it is necessary to perform post-processing including double integration and proper filter processing. Furthermore, structural monitoring systems have not been adopted in general buildings in Japan because these systems are expensive and low cost performance. Therefore, it is necessary to develop better and more extensive monitoring system with simple processing and high cost performance.

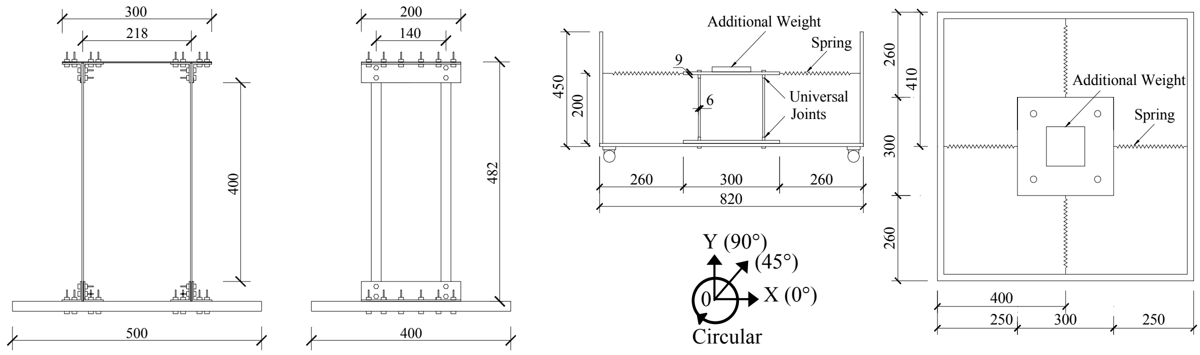
To achieve this objective, in this study, gyro sensors are employed as a new device to perform monitoring on structural performance of building structures, and a calculation method of response displacements using gyro sensors are also proposed by the authors (Liang et al. 2011). Gyro sensors, also known as angular rate sensors or angular velocity sensors are devices that detect rotation and return a value representing the number of degrees per second of rotation. They have been used in various fields and a variety of types are supplied for different applications. The gyro sensor used in this study is a MEMS-based type applied widely in car navigation systems, game controllers, cellular phone, vehicle control, and so on. In this study, fundamental vibration tests using gyro sensors are performed to verify measuring accuracy using proposed calculation method, and to identify natural period of specimens by FFT analyses. Based on results obtained through tests, the applicability of gyro sensors to structural performance monitoring system is verified and discussed.

2. OUTLINE OF EXPERIMENT

2.1 Test Specimens

Two types of specimens (Series A and B), which imitate building structures and/or structural control devices, are employed. Details of these specimens are shown in Fig. 1(a) and (b). Specimen Series A is a 1-story frame structure with 1-degree-of-freedom and its top board and columns of the specimen consist of steel and aluminium plates, respectively. The top board and columns are connected by angle plates and M5 bolts. By changing the internal length of column (400mm and 600mm), two types of specimens with different natural periods (A-1 and A-2) are tested. Specimen Series B is a 1-story rigidly rotated specimen with 2-degree-of-freedom. Column of the specimen consists of an aluminium bar and universal joints; the top board is connected to the supporting frame by springs. Two types of specimens with different natural periods (B-1 and B-2) are tested by adding different additional weight on the top board.

In case of Specimen Series A, shaking table tests are performed and specimens are subjected to seismic loading. Regarding seismic loadings, four earthquake wave models are used: El Centro NS (1940), Taft EW (1952), Hachinohe NS (1968), and JMA Kobe NS (1995). While in case of Specimen Series B, tests are carried out by man-power excitation in four horizontal vibration directions. Outline of vibration tests are summarised in Table 2.1.



(a) Specimen A (b) Specimen B

Figure 1. Dimensions of test specimens (Unit: mm)

Table 2.1. Outline of Vibration Tests

Specimen	Additional Weight	Internal Height	Natural Period*1	Vibration Method	Input Seismic Waves or Vibration Directions
A-1	4640.8 g	400 mm	0.371s	Shaking Table	JMA Kobe NS(1995), Taft EW (1952)
A-2		600 mm	0.737s		Hachinohe NS(1964), El Centro NS(1940)
B-1	-	200 mm	X*2: 0.366s Y*2: 0.347s	Man-power Excitation	0° (X), 45°, 90° (Y), Circular direction (Y (90°), (45°), X (0°), 0, Circular)
B-2	3680.1 g		X*2: 0.952s Y*2: 0.949s		
*1: average value calculated by FFT using angular velocity data			*2: X, Y represent X and Y direction		

2.2 Gyro Sensors

Gyro sensor used in this study is shown in Fig. 2, and electric characteristics of the gyro sensor are also shown in Table 2.2. It has following special features: 1) small size, 2) low price, and 3) commercially available. By measuring the output voltages V_{out} (V), instantaneous value of angular velocity $d\omega$ (deg./sec.) is calculated by Eqn. 2.1, where V_0 is the static output voltage (V) and R_g is the sensitivity of gyro sensor. The rotation angle is obtained by accumulating the angle per interval of time dt (sec.) using the measured angular velocity $d\omega$ as shown in Eqn. 2.2, in which θ_i and θ_{i-1} (deg.) denote the angles at time t_i and t_{i-1} (sec.), respectively.

Table 2.2. Electric Characteristics of Gyro Sensor

Supply Voltage (DC/V)	Static Output (DC/V)	Measuring Range (deg./sec.)	Sensitivity (mV/deg./sec.)	Linearity (%)	Weight (g)
5	1.35	±300	0.67	±5	0.2

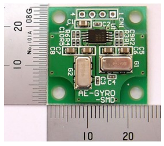


Figure 2. Photo of gyro sensor

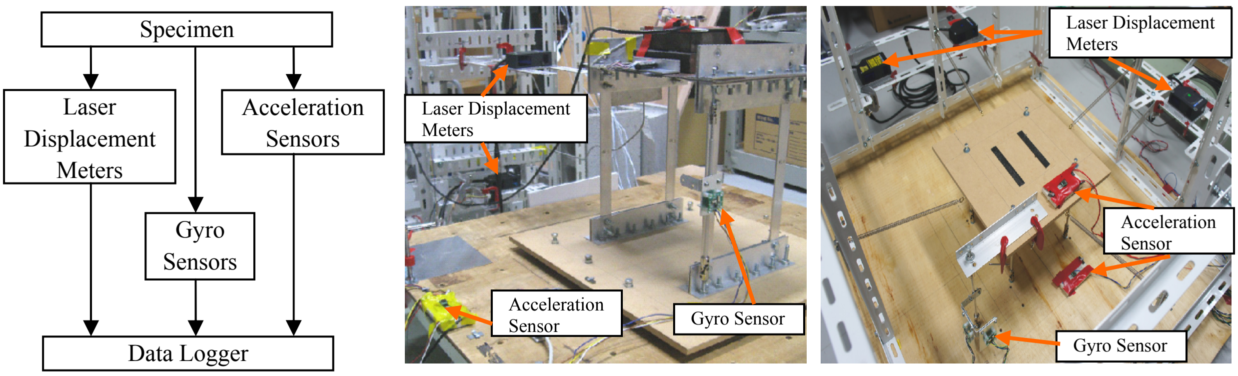
$$d\omega = \frac{(V_{out} - V_0) \cdot 1000}{R_g} \tag{2.1}$$

$$\theta_i = \theta_{i-1} + d\omega \cdot dt \tag{2.2}$$

2.3 Experiment System

The measuring system consists of an aluminium bar connected to specimen with two universal joints and gyro sensors are installed on the bar. In case of Specimen Series A, the aluminium bar was fabricated to be telescopic due to the specimens deformed like a frame structure. To measure the inclination angles of the specimens, one gyro sensor is used for single direction in Specimen Series A with 1-degree-of-freedom. On the other hand, in case of Specimen Series B with 2-degree-of-freedom, two gyro sensors are utilized for two orthogonal directions. In order to verify measuring accuracy of gyro sensors in comparison with acceleration sensors, relative response displacement and response acceleration data of the top board of specimens are also collected in this study using laser displacement meters and acceleration sensors.

Fig. 3 shows the outline of the experiment system and the photos for Specimen Series A and B. In this study, all gyro sensors, acceleration sensors and laser displacement meters are connected to the data logger, and synchronized data are stored in flash memories connected to the data logger. Sampling interval of data is 0.01 seconds, and the duration time is 20 seconds. Details of the data logger are shown in Table 2.3.



(a) Outline of Experiment System (b) Specimen Series A (c) Specimen Series B

Figure 3. Experiment system

Table 2.3. Details of Data Logger

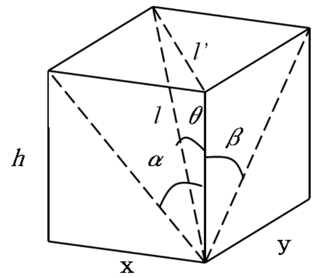
Supply Voltage (DC/V)	Memory Size (Mega Byte)	A/D Converter (bit)	Analog Input (Channel)	Sampling Interval (Second)
5	256	16	8	0.01

3. CALCULATION OF RESPONSE DISPLACEMENT AND NATURAL PERIOD

3.1 Calculation of Response Displacement

According to spatial geometric relation as shown in Fig. 4, inclination angles measured by gyro sensors can be simply converted into relative response displacements. Relative response displacements x and y of Specimen Series B in X and Y directions can be calculated using following equations in Eqn. 3.1, where α and β denote the inclination angle in X and Y directions measured by gyro sensors (deg.), respectively. θ is spatial inclination angle of specimen (deg.). In case of Specimen Series A with single degree of freedom, relative response displacements are also calculated by Eqn. 3.1, where let β be equal to 0.

In this calculating method, the orbital diagrams in X-Y plane can be simply obtained by using response displacements x and y, and conveniently applied for assessing the damage of isolation devices after earthquake.



$$\begin{cases} l' = \sqrt{x^2 + y^2} = h \cdot \sqrt{tan^2\,\alpha + tan^2\,\beta} \\ tan\,\theta = l'/h = \sqrt{tan^2\,\alpha + tan^2\,\beta} \\ \theta = tan^{-1}(\sqrt{tan^2\,\alpha + tan^2\,\beta}\,) \\ h = l \cdot cos\,\theta \\ x = h \cdot tan\,\alpha \\ y = h \cdot tan\,\beta \end{cases} \quad (3.1)$$

Figure 4. Spatial geometric relation on measurement

3.2 Calculation of Natural Period

In structural performance monitoring, natural periods are also one of seismic indexes of structures. In order to identify natural periods, generally, Fast Fourier Transform (FFT) is performed using measured acceleration data. The peak values of obtained Fourier spectrum are determined as natural frequencies of structures. Gyro sensors are also desired to determine natural periods of structures when being applied in structural performance monitoring. In this study, FFT analyses are also performed using response angular velocity data measured by gyro sensors. Natural periods of specimens identified using measured data by gyro sensors are also compared with those by acceleration sensors, and identification accuracy of gyro sensors are also verified.

4. TEST RESULTS AND DISCUSSION

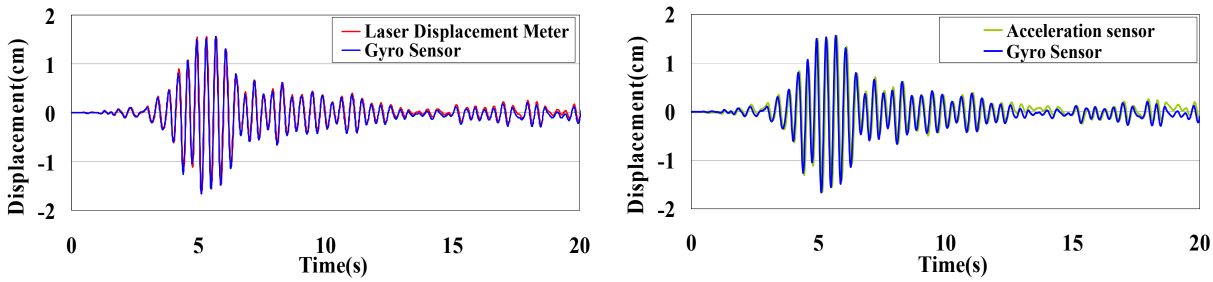
4.1 Test Results of Response Displacement

Time historical response displacements of Specimen A-1 in the case of Hachinohe NS are shown in Fig. 5. Results of gyro sensors are compared with those by laser displacement meters in Fig. 5 (a), and compared with those by acceleration sensors in Fig. 5 (b). It is obvious that response displacements by gyro sensors almost coincide with those by laser displacement meters regarding with phase and amplitude. However, small differences in amplitude are observed in comparison with results of gyro sensors and acceleration sensors. Fig. 6 (a) and (b) show the time historical response displacements of

Specimen B-1 in X and Y directions, respectively. In both figures, results calculated by gyro sensors have reasonable accuracy in phase and amplitude in comparison with the results measured by laser displacement meters. The orbital diagram of Specimen B-1 in X-Y Plane is shown in Fig. 6 (c). The orbit by gyro sensors well coincides with that of laser displacement meters.

Measurement errors of all specimens are shown in Table 4.1. Errors in the table are calculated using Eqn. 4.1, where $DISP_{Acc}$, $DISP_{Laser}$ and $DISP_{Gyro}$ denote the response displacements collected and calculated by the acceleration sensors, laser displacement meters and gyro sensors, respectively. 'Max' and 'Min' in Table 4.1 denote the maximal and minimal values of measured response displacement data. Table 4.1 shows the measuring accuracy of acceleration sensors and gyro sensors, and it is clarified that obtained results by gyro sensors have almost the same accuracy as those by acceleration sensors, and gyro sensors are applicable to structural monitoring systems within the allowable range. However, in some cases, errors become large. Reasons of these errors are considered to be experimental error such as improper human-powered excitation, flaw of measurement systems and so on, and it is necessary to improve experimental systems.

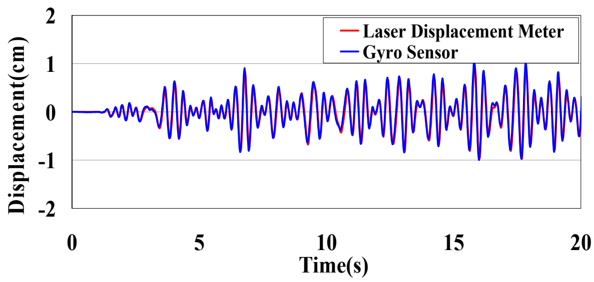
$$\begin{cases} Error_{Acc}(\%) = (DISP_{Acc} - DISP_{Laser}) / DISP_{Laser} \times 100 \\ Error_{Gyro}(\%) = (DISP_{Gyro} - DISP_{Laser}) / DISP_{Laser} \times 100 \end{cases} \quad (4.1)$$



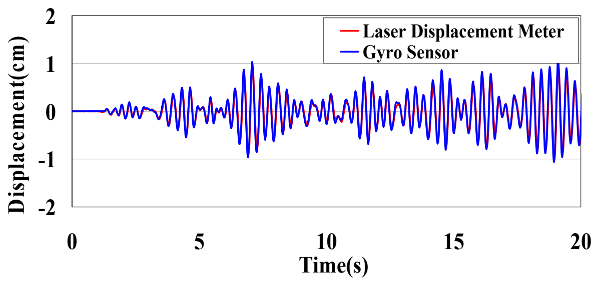
(a) Comparison of Gyro Sensor and Laser Displacement Meter (A-1, Hachinohe)

(b) Comparison of Acceleration Sensor and Laser Displacement Meter (A-1, Hachinohe)

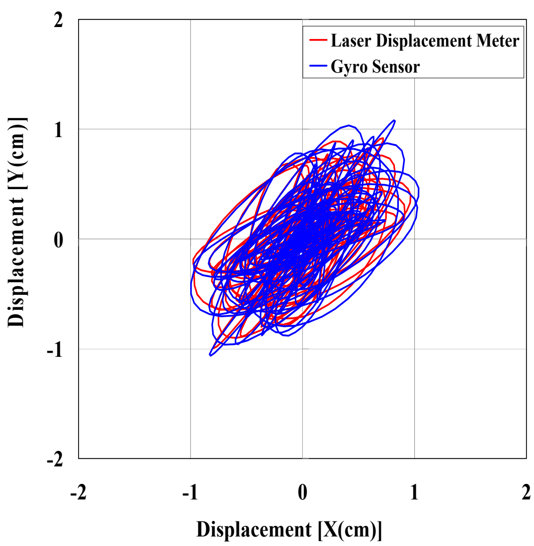
Figure 5. Results of response displacement of specimen A-1



(a) Comparison on B-1 (X direction)



(b) Comparison on B-1 (Y direction)



(c) Orbital Diagram in X-Y Plane (B-1)

Figure 6. Results of response displacement of specimen B-1

These results show that structural monitoring by gyro sensors is applicable to structures with natural periods under approximately 1 second. Applicability for structures with longer period is needed to be discussed in the further studies. This method is considered effective not only for the rigidly rotated structures, but also for frame structures which has different curvature in column, by using device free in expansion and contraction.

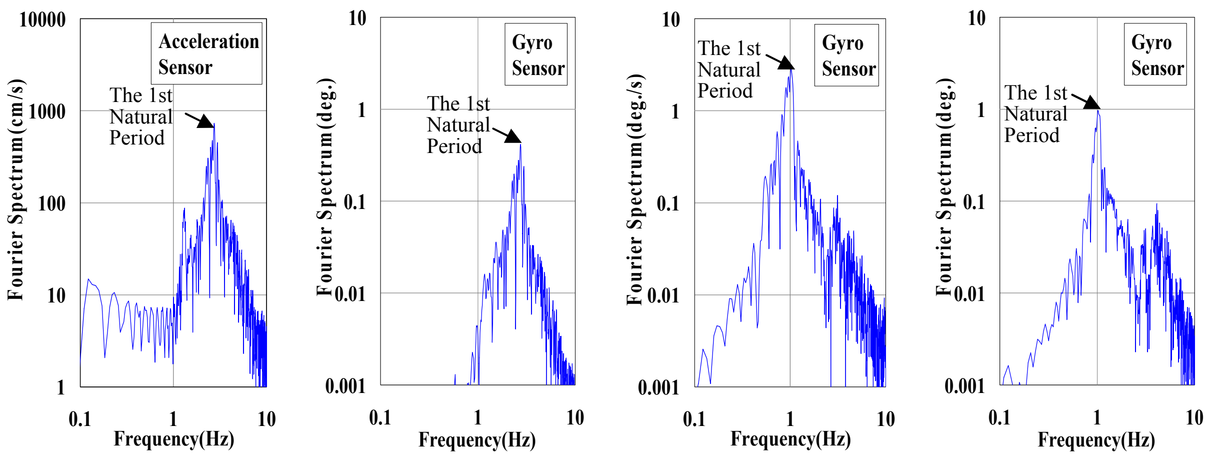
Table 4.1. Displacement Errors of Specimens (Unit: %)

Error (%)	Input Seismic Wave	A-1		A-2		Vibration Directions	B-1		B-2	
		Acceleration Sensor	Gyro Sensor	Acceleration Sensor	Gyro Sensor		X	Y	X	Y
Max	JMA Kobe	0.11	3.66	1.08	7.68	0°	4.41	2.26	1.47	14.8
Min		5.29	2.94	5.85	7.52		1.24	17.0	10.7	1.08
Max	Taft	8.75	3.75	0.83	5.49	90°	8.54	14.1	20.4	6.52
Min		8.58	0.05	3.48	7.44		1.92	7.62	34.6	6.02
Max	Hachinohe	0.20	0.06	4.51	5.21	45°	7.42	17.6	13.2	9.05
Min		2.75	1.98	8.93	10.9		0.61	6.93	14.4	0.34
Max	El Centro	5.63	2.13	1.61	8.16	Circular	4.44	4.03	0.32	7.17
Min		5.57	3.92	6.13	4.35		0.04	10.8	6.67	0.27

4.2 Test Results for Natural Period

The FFT analyses are performed using time historical data collected by acceleration sensors and gyro sensors. The results of Specimen A-1 in case of Taft EW wave and A-2 in case of circular direction are shown in Fig. 7, in which Fig. 7 (a) is the FFT results using acceleration data and Fig. 7 (b), (c) and (d) are the FFT results using angular velocity data. FFT results of gyro sensors also have apparent peak value at predominant period as well as those by acceleration sensors. These results mean that natural periods of specimens can be identified using obtained Fourier spectrums. In this study, natural periods of all specimens can be identified, and effects of signal-noise cannot be observed.

The 1st natural periods of Specimen Series A and B identified by FFT analyses are shown and compared respectively in Tables 4.2 and 4.3, in which the identified values by gyro sensors are basically identical to those by acceleration sensors. It is clarified that natural frequency is also identifiable by angular velocity data measured by gyro sensors, and accuracy of this method is verified.



(a) Specimen A-1, Taft

(b) Specimen A-1, Taft

(c) Specimen B-2, Circular, X-direction

(d) Specimen B-2, Circular, Y-direction

Figure 7. Results of FFT analyses in case of specimen series A and B

Table 4.2. Identified Natural Periods of the Specimen Series A (Unit: s)

Specimen	Input Seismic Wave	Natural Period		Specimen	Input Seismic Wave	Natural Period	
		Acceleration Sensor	Gyro Sensor			Acceleration Sensor	Gyro Sensor
A-1	JMA Kobe	0.388	0.364	A-2	JMA Kobe	0.694	0.694
	El Centro	0.364	0.364		El Centro	0.780	0.780
	Hachinohe	0.379	0.378		Hachinohe	0.780	0.780
	Taft	0.376	0.376		Taft	0.694	0.694
	Average	**0.377**	**0.371**		**Average**	**0.737**	**0.737**

Table 4.3. Identified Natural Periods of the Specimen Series B (Unit: s)

Specimen	Vibration Directions	Natural Period		Specimen	Vibration Directions	Natural Period	
		X-Axis	Y-Axis			X-Axis	Y-Axis
B-1	0°	0.378	0.378	B-2	0°	1.011	1.011
	90°	0.347	0.349		90°	0.975	0.975
	45°	0.334	0.334		45°	0.845	0.836
	Circular	0.406	0.325		Circular	0.975	0.975
	Average	**0.366**	**0.347**		**Average**	**0.952**	**0.949**

5. CONCLUSIONS

As described in this paper, aiming at the popularization of the health monitoring system on buildings using sensor systems with convenience and high cost performance, fundamental tests of performance of MEMS-based gyro sensors are performed. Based on experimental results, following conclusions can be obtained:

1) The proposed system using gyro sensors provides a new method to measure response displacements without complicated post-processing such as double integration, filter processing and baseline correction. According to spatial geometric relation, inclination angles measured by gyro sensors can be simply converted into relative response displacements and the orbital diagrams in X-Y plane can also be conveniently obtained. Therefore, employed system using gyro sensors can be used to improve and speed up the quick emergency inspection including damage detection and residual seismic capacity after earthquake.

2) Measured results by gyro sensors approximately coincide with those by acceleration sensors and laser displacement meters in amplitude and phase with acceptable measuring errors of 0.06～34.6% in a range of natural period approximately from 0.3 to 1 seconds. Large measuring errors observed in some cases are considered to be strongly affected by experimental conditions such as improper human-powered excitation, flaw of measurement systems and so on. Furthermore, the orbital diagrams in X-Y plane can be obtained easily and can be used for monitoring such as base isolation devices.

3) The response angular velocity data recorded by gyro sensors can be processed to determine natural period of specimens by using FFT analysis, and the results of natural periods are almost identical with those using data recorded by response acceleration sensors. The proposed system is considered to be applicable to detect changes of natural period and assess the damage to building structures.

4) The proposed method using gyro sensors is proved to have convenience in measuring and high cost performance, and is suitable and applicable for structural performance monitoring as same as those using acceleration sensors. Applicability for structures with longer natural periods and practical methods of installation are needed to be discussed and developed in the further studies.

As mentioned above, proposed monitoring system using gyro sensors can measure the relative displacements directly and conveniently identify natural periods with a reasonable accuracy. Therefore, proposed system is considered to be suitable not only to monitor building structures in daily, but also to assess the performance of building and/or structural control devices immediately during extreme motions caused by earthquakes and strong winds. Engineers and building owners or managers can make decisions to future repair and retrofit based on monitoring information on the responses of the structure. It is considered that monitoring system using gyro sensors have the potential for improving the safety of public in structural performance monitoring.

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