FREQUENCIES AND DAMPING RATIOS OF A HIGH RISE BUILDING BASED ON MICROTREMOR MEASUREMENT

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SUMMARY

Microtremors of a high rise building have been measuring in regularly and vibration characteristics are observed periodically as the structural monitoring. This building of a moment resisting steel frame with seismic control walls made of ultra mild steels belongs to Meiji University in Tokyo, and it has rectangular plan and 120m height. In this study, it is evaluated of natural frequencies and damping ratios given by microtremor data on lower modes in two horizontal directions and torsional direction. And it is examined the changes with the passage of time for natural frequencies and damping ratios on 60 months as yet since January 1999. Relations in the damping ratios of lower modes are also discussed.

INTRODUCTION

Structural characteristics and aseismic performance of buildings, which are subjected to natural disasters such as earthquakes, strong winds and so on, are caused remarkable reduction. Therefore, it needs to observe the vibration of buildings periodically, the structural monitoring is an example. Identification of system parameters of buildings is important for the structural monitoring or the damage detection of buildings due to some excitation or the passage of time. It has been provided literature reviews of the structural monitoring or the damage detection for structural and mechanical systems as yet. A sampling of such studies can be found in Beck et al. [1], Natke et al. [2], Liu [3], Masri et al. [4], Sone et al. [5], and Arakawa et al. [6]. Representative reviews include system identifications of neural network approaches or wavelet transform analyses. Their reviews focused on methods for vibration measurements and detections on changes in several physical parameters of a system. Those parameters from vibration characteristics viewpoints are such as natural frequencies, modal shapes and modal damping ratios. Variations on vibration characteristics reflect changes in the physical parameters of the system and indicate certain cracks or damages caused by failure of members in the system.

Natural frequencies and modal damping ratios of buildings for vibration tests or vibration observations are important to grasp, and those various behaviors are also significant. The evaluation methods of natural

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frequencies are almost established, however the modal damping ratios can not be evaluated accurately in these days. The estimates of damping on the basis of measurement data in actual buildings are widely dispersed. Measured values vary according to amplitude levels, structural materials, foundation types, amount of nonstructural member, and so on. Furthermore, the modal damping ratios of buildings are due to the vibration measurement method and due to the damping evaluation method. In Japan, 1st mode damping ratios are used 2.0% in high rise steel buildings and 3.0% in reinforced concrete buildings in the design stage such as earthquake or wind action. And relations in the damping ratios of lower modes are proportional to natural frequencies. However, these values or relations have no theoretical reasons.

Evaluations of modal damping ratios on the basis of analyses using vibration measurement data are attempted recently. Jeary [7] applied the random decrement technique to structures such a building to evaluate structural damping under random excitation. Tamura et al. [8] have investigated that the amplitude was depended upon natural frequency and modal damping ratio by using the random decrement technique. Besides the complex cause of damping mechanisms, the evaluation of damping in full-scale structures has been investigated by several literature reviews as yet. A sampling of such studies can be found in Jeary [7], Davenport et al. [9], Lagomarsino [10], Kareem et al. [11], and Satake et al. [12].

This paper presents natural frequencies and damping ratios on lower modes that have given by microtremor data of two horizontal directions and torsional direction for a building. And it is examined the changes with the passage of time for natural frequencies and damping ratios on 60 months as yet since January 1999. The building is a moment resisting frame of steel framed structure. It has the rectangular plan and 120m height.

First, evaluation methods of vibration characteristics are explained. Natural frequencies and damping ratios from 1st mode to 4th mode in each direction are evaluated out of Fourier spectra made from measurement data. The damping ratios are evaluated employing $1/\sqrt{2}$ Method adapted to the Fourier spectrum. Secondly, the changes with passage of time for natural frequencies from 1st mode to 4th mode in each direction are analysed. It is decreased with the passage of time on 60 months as yet from the completion gradually and certainly. And the fluctuations on one day of natural frequencies on each mode are calculated employing the standard deviation and coefficient of variation. Thirdly, the changes with passage of time for damping ratios from 1st mode to 4th mode in each direction are analysed. It is dispersed in each measurement time or day. And tendencies with the passage of time on 60 months as yet from the completion are not evident. The fluctuations on one day of damping ratios on each mode are calculated employing the standard deviation and coefficient of variation. Lastly, relations in the damping ratios of lower modes are discussed in each direction. It is estimated Rayleigh damping type at the long length and torsional directions, and proportional to natural frequencies at the short length direction.

ANALYZING BUILDING AND MEASUREMENT METHOD

The building for using the analysis is called Liberty Tower as shown in Figure 1, which belongs to Meiji University in Tokyo, and it was completed in October 1998. The building is moment resisting frame of steel framed structure with seismic control walls made of ultra mild steels. It is 120m height, 23 floors on the ground and 3 floors under the ground, and it has the rectangular plan. The main usages of the building are laboratories, classrooms and offices. Table 1 shows the natural frequencies in a design stage from 1st mode to 3rd mode in two horizontal directions of the building.

Microtremor data of the building are measured in the midnight, once in two months. A lot of data have been collected on 60 months as yet since January 1999. The measurement floors are mainly 23rd, 20th, 16th, 14th, 12th, 8th, 1st, and so on. At the points of C, L, and R as shown in Figure 2, microtremor data on accelerations and velocities are measured for the two horizontal directions and torsional direction. The servo mechanism vibrometers are used for the instruments of the vibration observation. The low-pass

filters are set up in 10.0Hz, and the sampling frequency is 50Hz. Measurement data are divided the time into consecutive 30 minutes periods.
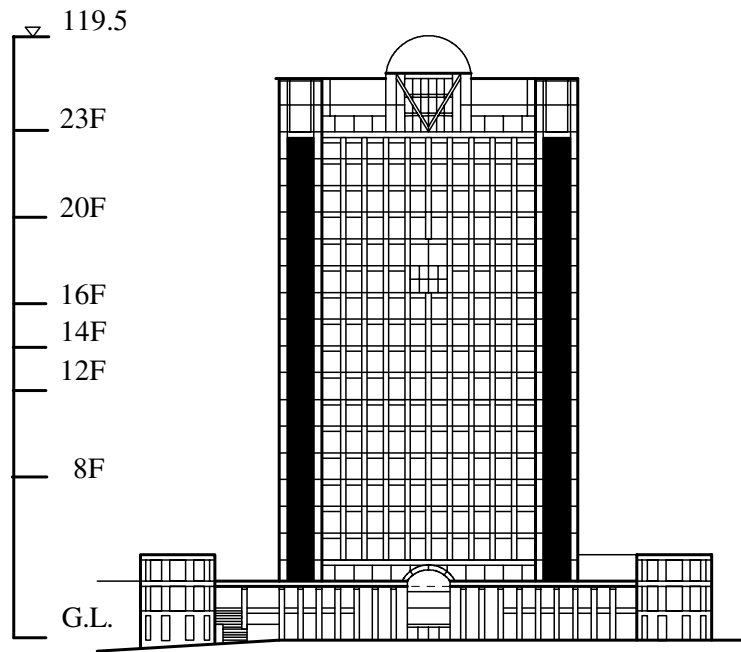

Fig. 1 The overview

Table 1 Natural frequencies in design   [Hz]

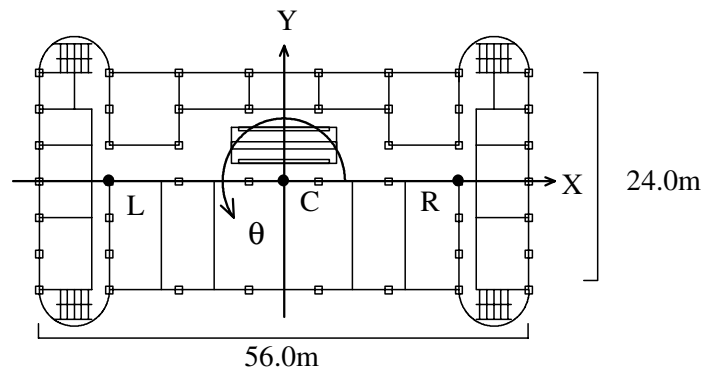| mode	Long length direction	Short length direction
1st	0.403	0.383
2nd	1.10	1.05
3rd	1.68	1.61

Fig. 2 The plan of typical floor and measurement positions

EVALUATION METHODS OF VIBRATION CHARACTERISTICS

Natural Frequencies

Microtremor data measured in the midnight at an optional day are divided the time into consecutive 30 minutes periods. Several data have been collected on one day, and were named as data A, data B, data C, data D, and so on. The natural frequencies are evaluated out of Fourier spectra made from each measurement data. Figure 3 shows the evaluation method of natural frequency using a partial frequency domain on Fourier spectrum of one data. The natural frequency is identified as the frequency of which amplitude is near to an average of five largest amplitudes in the neighborhood of an object modal natural frequency on Fourier spectrum. The five largest amplitudes are showed as black marks, and the average of five natural frequencies as vertical straight line in Fig. 3.

Damping Ratios

The modal damping ratios are evaluated employing $1/\sqrt{2}$ Method adapted to the Fourier spectrum. Figure 4 shows the evaluation method of damping ratio using $1/\sqrt{2}$ Method on Fourier spectrum of one data. Using f_n as the n-th modal natural frequency identified by above method, the n-th modal damping ratio ζ_n is given by

$$\varsigma_n = \frac{1}{2} \times \frac{\delta f}{f_n} \tag{1}$$

where δf is the band width in frequency domain at $X_{max}/\sqrt{2}$ Method as half power. X_{max} is the amplitude of the n-th modal natural frequency f_n on Fourier spectrum.
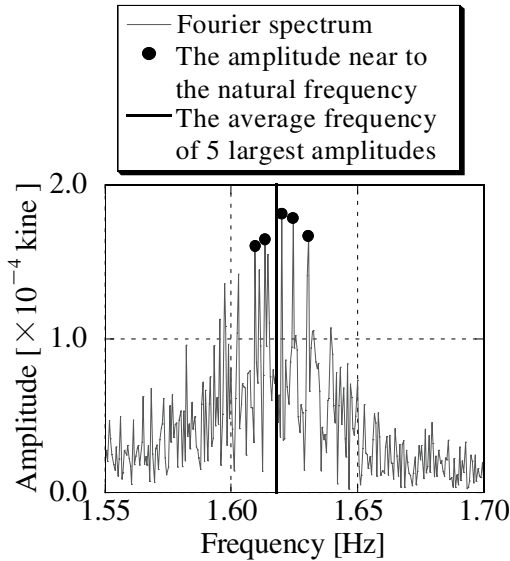

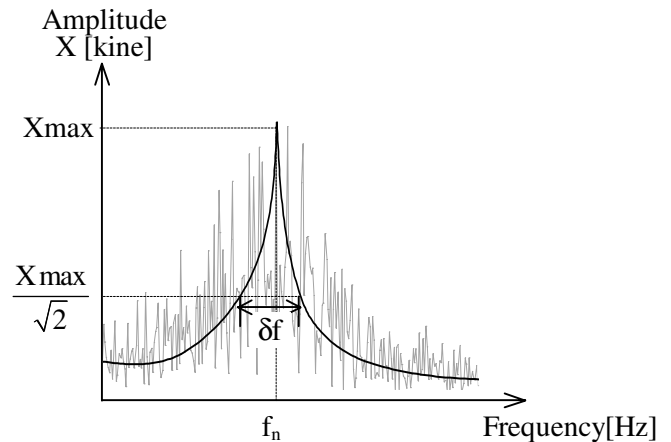**Fig. 3 The evaluation method of each mode natural frequency**

Fig. 4 The evaluation method of each mode damping ratio ($1/\sqrt{2}$ Method)

Acceleration Data and Velocity Data

Table 2 shows an example of natural frequencies of acceleration data and velocity data. And, Table 3 shows an example of damping ratios of acceleration data and velocity data. Those natural frequencies and damping ratios are from 1st mode to 4th mode on the same measurement time in November 2003, and are on same measurement position in the two horizontal directions and torsional direction. The measurement data in those tables are used data of the floor to having an articulate spectrum regarding an object mode. 1st mode is used on 23rd floor data, 2nd mode on 14th floor, 3rd mode on 8th floor, and 4th mode on 14th floor. 30 minutes period is a unit of measurement time of which data is named data A, data B, or data C. The values evaluated by acceleration data agree fairly well with those evaluated by the velocity data for both natural frequencies and damping ratios. Therefore, the following analyses in this paper are applied both the acceleration data and the velocity data.

Table 2 Natural Frequencies of acceleration and velocity data on the same measurement time and position [Hz] (Nov., 2003)

Direction			Long length			Short length			Torsional		
Data name			A	B	C	A	B	C	A	B	C
1st mode	23rd floor	Accerlation	0.51	0.51	0.51	0.50	0.50	0.50	0.60	0.59	0.60
		Velocity	0.51	0.51	0.51	0.50	0.50	0.50	0.60	0.59	0.60
2nd mode	14th floor	Accerlation	1.62	1.62	1.62	1.60	1.60	1.60	1.83	1.83	1.83
		Velocity	1.62	1.62	1.62	1.60	1.60	1.60	1.83	1.83	1.83
3rd mode	8th floor	Accerlation	2.76	2.75	2.77	2.80	2.81	2.82	3.11	3.11	3.11
		Velocity	2.76	2.75	2.77	2.80	2.81	2.82	3.11	3.11	3.11
4th mode	14th floor	Accerlation	4.08	4.09	4.07	4.28	4.26	4.28	4.57	4.61	4.59
		Velocity	4.08	4.09	4.07	4.28	4.26	4.24	4.56	4.61	4.59

Table 3 Damping ratios of acceleration and velocity data on the same measurement time and position [%] (Nov., 2003)

Direction			Long length			Short length			Torsional		
Data name			A	B	C	A	B	C	A	B	C
1st mode	23rd floor	Accerlation	0.66	1.04	0.94	0.74	0.79	0.33	0.38	0.69	0.21
		Velocity	0.66	1.04	0.94	0.74	0.80	0.33	0.38	0.69	0.35
2nd mode	14th floor	Accerlation	1.03	0.58	0.74	0.77	0.62	0.62	0.52	0.63	0.58
		Velocity	1.03	0.58	0.73	0.77	0.62	0.62	0.52	0.63	0.58
3rd mode	8th floor	Accerlation	1.20	1.22	1.50	0.65	0.97	1.21	0.55	0.89	0.57
		Velocity	1.20	1.22	1.50	0.65	0.97	1.20	0.55	0.89	0.57
4th mode	14th floor	Accerlation	1.71	1.55	1.40	2.55	2.58	2.67	2.09	1.90	0.99
		Velocity	1.69	1.55	1.40	2.55	2.34	2.70	2.09	1.90	0.75

THE CHANGES WITH PASSAGE OF TIME FOR NATURAL FREQUENCIES

The Changes along Passage of Time

The natural frequencies from 1st mode to 4th mode are analysed on 60 months as yet from the completion. Figure 5 shows the natural frequencies in long length direction(X direction on the plan), short length
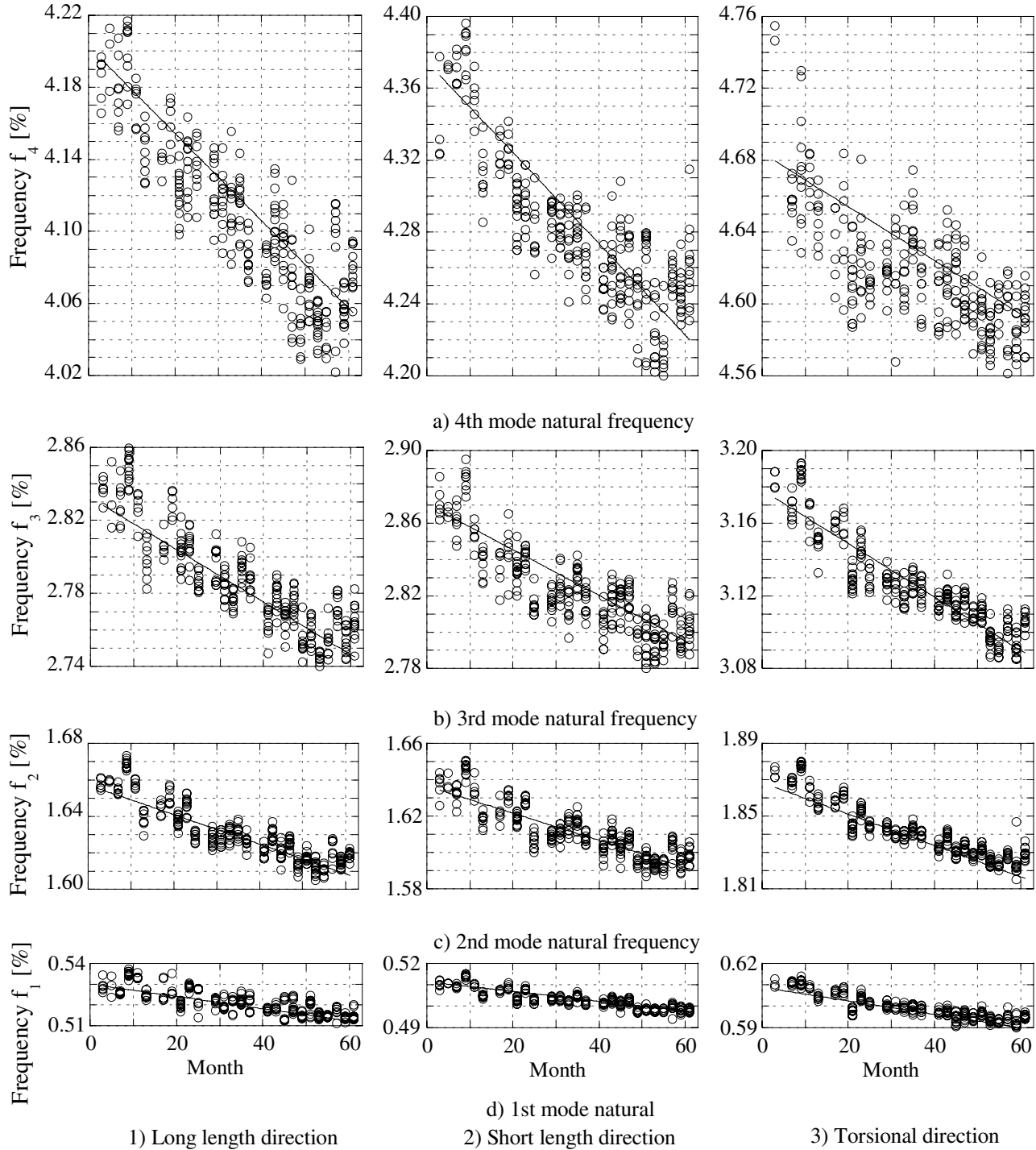

a) 4th mode natural frequency

b) 3rd mode natural frequency

c) 2nd mode natural frequency

d) 1st mode natural

1) Long length direction　　　　2) Short length direction　　　　3) Torsional direction

Fig. 5 The changes along passages of 1st mode to 4th mode natural frequencies in each direction

direction(Y direction), and torsional direction(θ direction). A circle is the natural frequency evaluated by a 30 minutes period measurement data. It can be seen from Fig. 5 that the natural frequencies decrease with the passage of time on 60 months as yet from the completion gradually and certainly. Degree of the decrease becomes large so that higher mode becomes.

Next, it is examined numerical change rate Δf of natural frequency from 1st mode to 4th mode in each direction. Figure 6 shows calculation method on the change rate Δf of natural frequency. The value Δf takes the mean of change rate Δf_y for one year by the progress the number of years. The value Δf_y is calculated using representative value f' on natural frequency of each measurement month and representative value f_0 on natural frequency of one year ago of those month as Equation (2).

$$\Delta f_y = \frac{f_0 - f'}{f_0} \tag{2}$$

The change rate Δf of natural frequency on 60 months are around 2.7-3.4% as shown in Table 4. It can be predicted future natural frequency numerical fall than tendency of these topics.
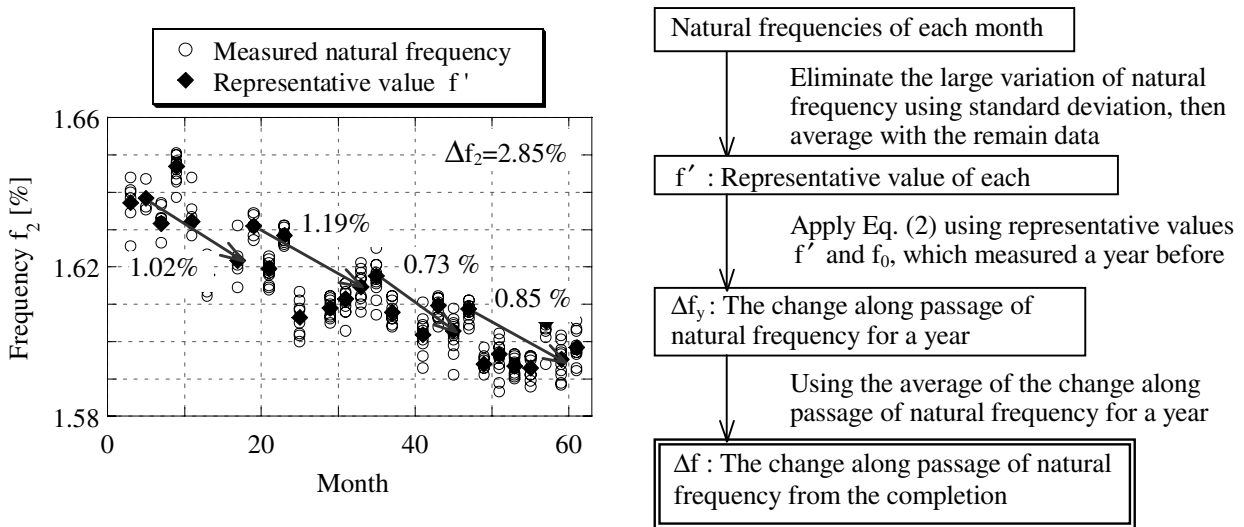

Fig. 6 The calculation method on the change along passage of natural frequencies and flow chart
(Short length direction, 2nd mode)

Table 4 The change rate Δf of 1st mode to 4th mode natural frequencies in each direction on 60 months from the completion   [%]

mode	Long length direction	Short length direction	Torsional direction
1st	3.51	2.77	3.25
2nd	3.05	2.85	2.88
3rd	3.15	2.72	2.89
4th	3.61	3.63	1.97

The Fluctuations on One Day

The natural frequencies are different every measurement time of each day. Then, the fluctuations on one day of natural frequencies on each mode are calculated employing the standard deviation and the coefficient of variation. Standard deviation and coefficient of variation to express natural frequency numerical change are given by Equation (3) and Equation (4) respectively.

$$\sigma_f = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(f_i - f_\mu\right)^2} \ [Hz] \tag{3}$$

$$\varepsilon_f = \frac{\sigma_f}{f_\mu} \tag{4}$$

where f_μ is the natural frequency numerical mean of each measurement day.

1) Long length direction

2) Short length direction
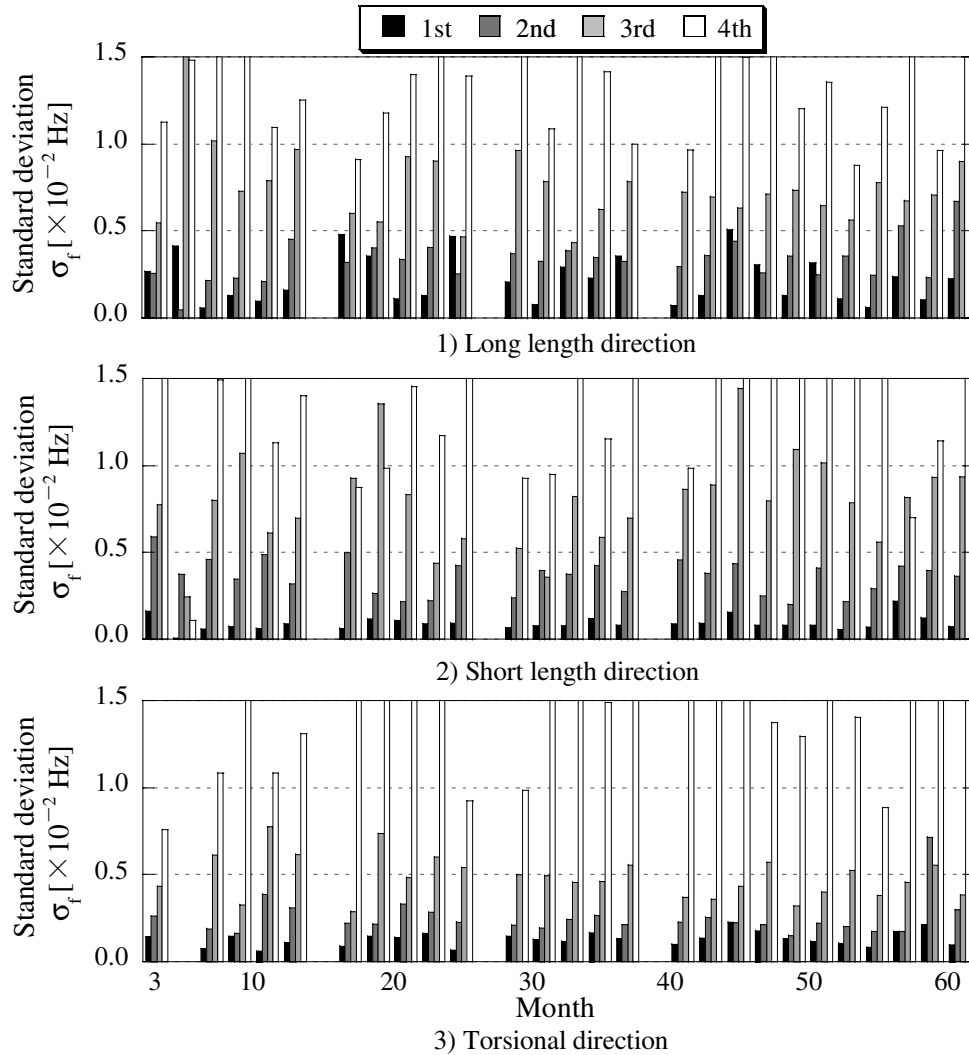
3) Torsional direction

Fig. 7 Standard deviation of 1st mode to 4th mode natural frequencies in each direction   [Hz]

Figure 7 shows the standard deviation σ_f to express of those natural frequencies for progress month of crossed axis. And, Figure 8 shows the coefficients of variation ε_f of those. Figs. 7 and 8 are the fluctuations from 1st mode to 4th mode in each direction. Although it changes in each direction in every progress month, σ_f is small with 1st mode and higher mode becomes large slightly. ε_f are 0.4% degree with each mode. However, X direction is larger slightly than Y direction and θ direction.
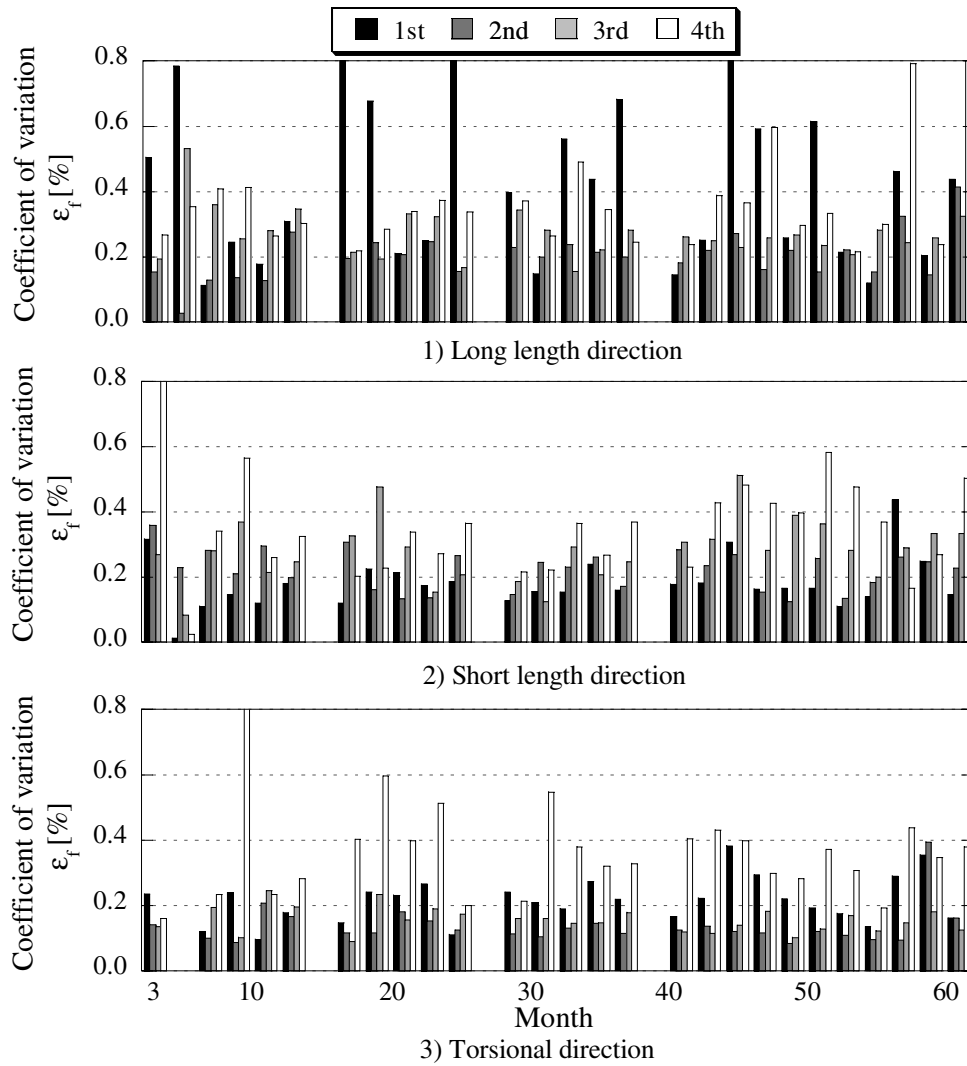
Fig. 8 Coefficient of variation of 1st mode to 4th mode natural frequencies in each direction [%]

THE CHANGES WITH PASSAGE OF TIME FOR DAMPING RATIOS

The Changes along Passage of Time

The damping ratios from 1st mode to 4th mode are analysed on 60 months as yet from the completion. Figure 9 shows the damping ratios in X direction, Y direction, and θ direction. A circle is the damping ratio evaluated by a 30 minutes period measurement data and black square is the mean of those damping ratios for one day. It can be seen from Fig. 9 that 1st mode damping ratios are 1.0% degree in X direction and θ direction, and 0.5% degree in Y direction. Those 1st mode damping ratios are less than 2.0% that are in a design stage. In addition, as for each direction from 1st mode to 4th mode, the clear change is not seen by the present for progress month from the completion.
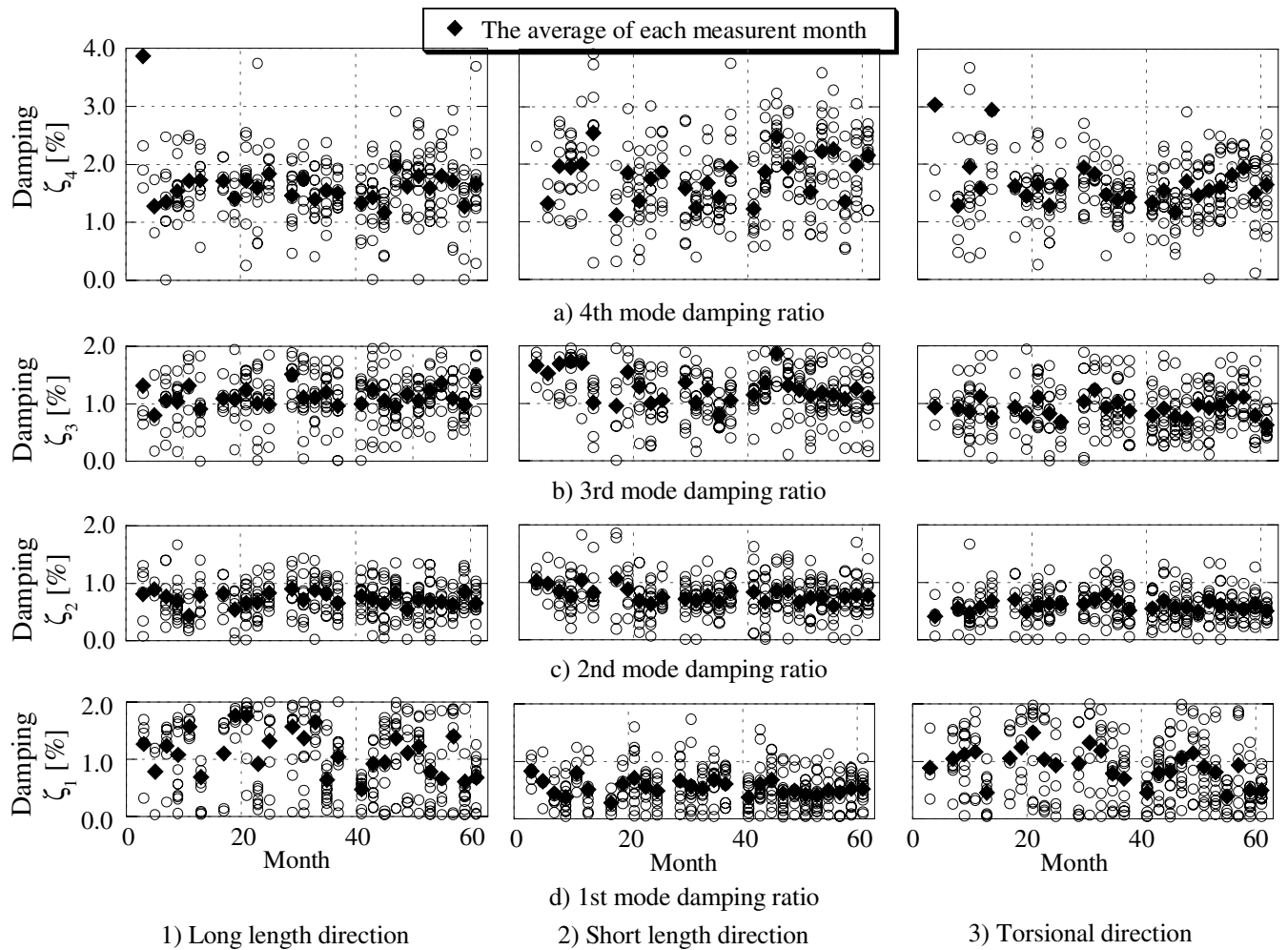

a) 4th mode damping ratio

b) 3rd mode damping ratio

c) 2nd mode damping ratio

d) 1st mode damping ratio

1) Long length direction   2) Short length direction   3) Torsional direction

Fig. 9 The changes along passages of 1st mode to 4th mode damping ratios in each direction

The Fluctuations on One Day

The damping ratios are fairly different every measurement time of each day. Then, the fluctuations on one day of damping ratio on each mode are calculated employing the standard deviation and the coefficient of variation. The standard deviation and the coefficient of variation to express damping ratio numerical change are given by Equation (5) and Equation (6) respectively.

$$\sigma_\varsigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\varsigma_i - \varsigma_\mu\right)^2} \qquad (5)$$

$$\varepsilon_\varsigma = \frac{\sigma_\varsigma}{\varsigma_\mu} \qquad (6)$$

where ζ_μ is the damping ratio numerical mean of each measurement day.

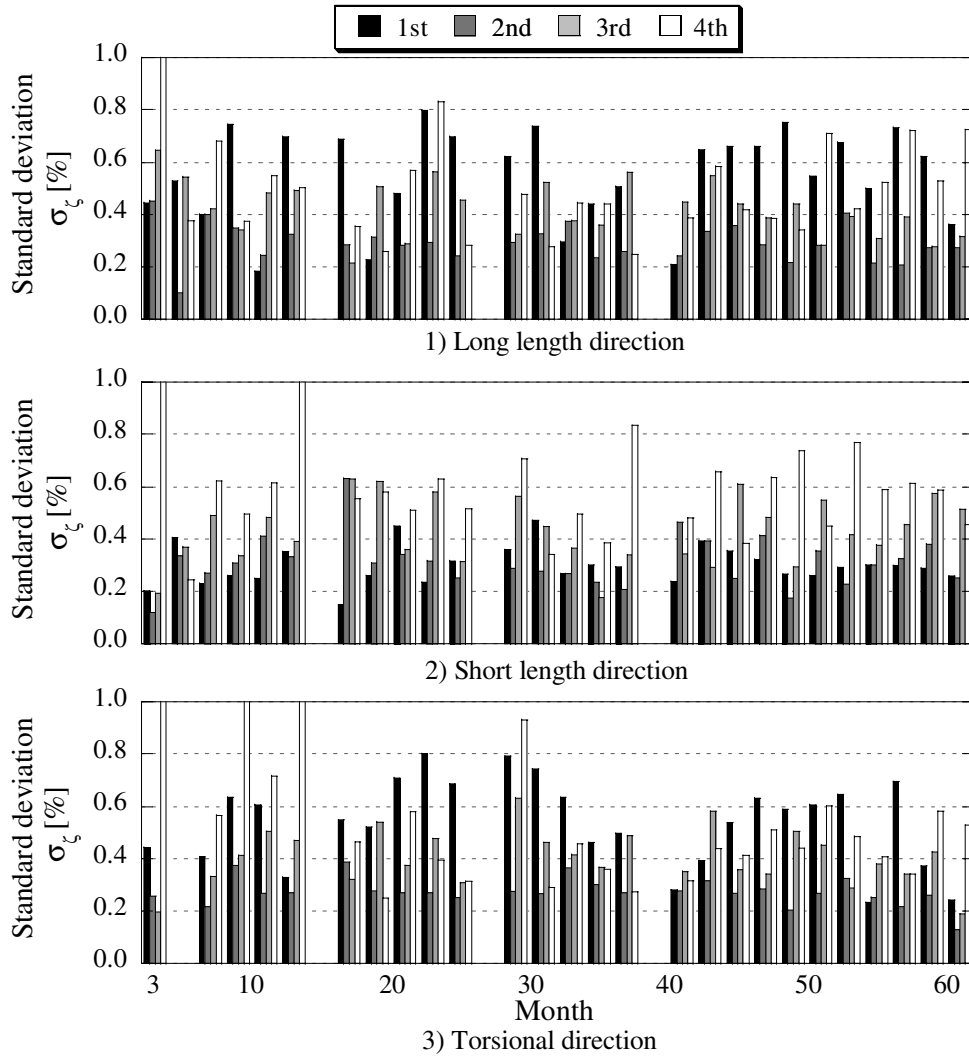
Fig. 10 Standard deviation of 1st mode to 4th mode damping ratios in each direction   [Hz]

Figure 10 shows the standard deviation σ_ζ to express of that damping ratios for progress month of crossed axis. And, Figure 11 shows the coefficients of variation ε_ζ of those. Figs. 10 and 11 are the fluctuations from 1st mode to 4th mode in each direction. In X direction and θ direction, σ_ζ for 1st mode and 4th mode are large, and σ_ζ for 2nd mode and 3rd mode are small. In Y direction, σ_ζ for 1st mode is small, and higher mode becomes large. In every direction, ε_ζ for 1st mode are large, and the higher mode becomes small. In addition, there is ε_ζ for 1st mode in X direction in the case of 100% over. It is separation nature as for the factor that ε_ζ for 1st mode in X direction is large in the 1st natural frequency neighborhood on Fourier spectrum. There are many cases that the peak of 1st natural frequency is divided into two peaks greatly as shown in Figure 12. Existence of two peaks is regarded as for the factor of dispersion of 1st mode damping ratio in X direction.
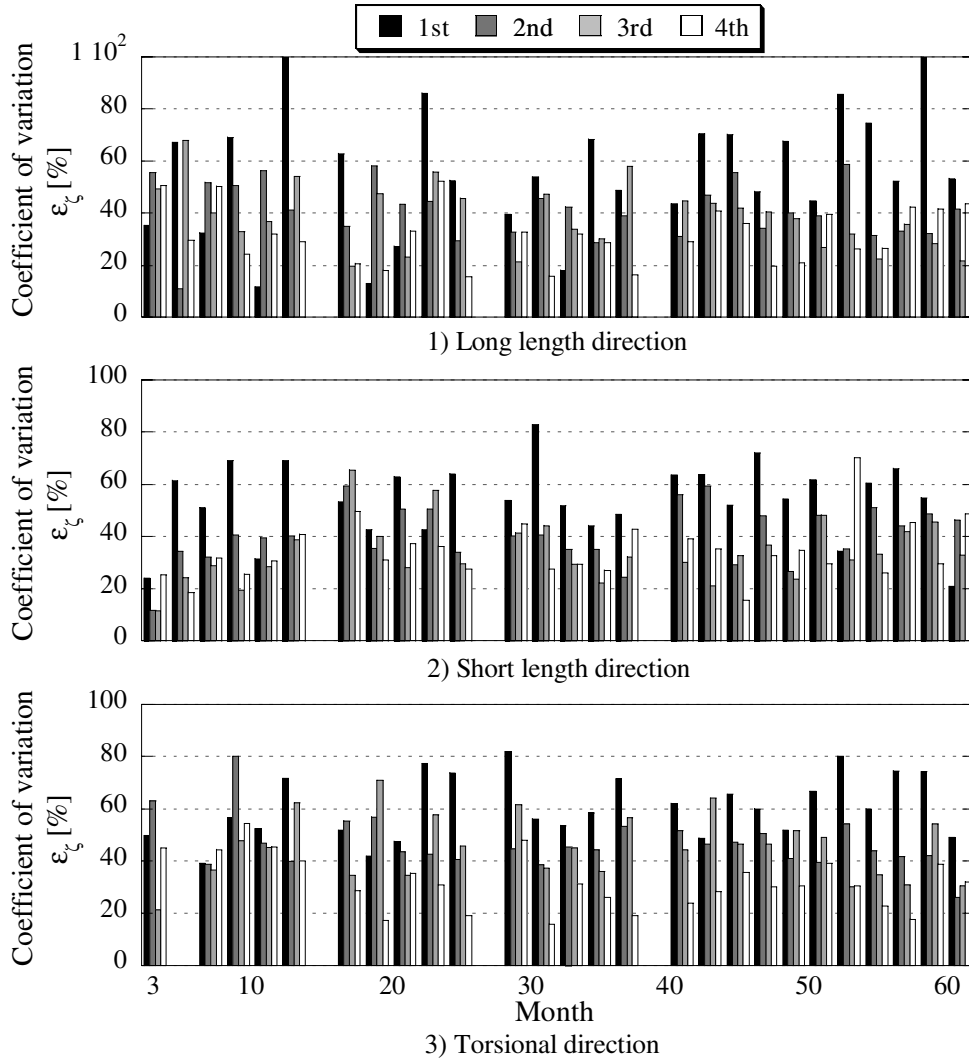

Fig. 11 Coefficient of variation of 1st mode to 4th mode damping ratios in each direction   [%]
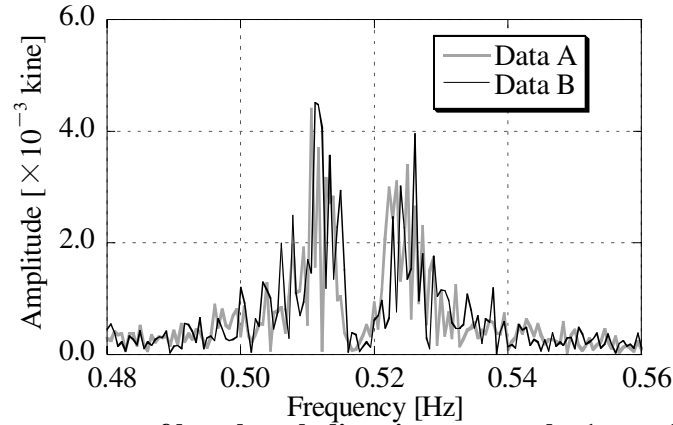
Fig. 12 Fourier spectrum of long length direction near to the 1st mode natural frequency (Nov., 2001, 23rd floor)
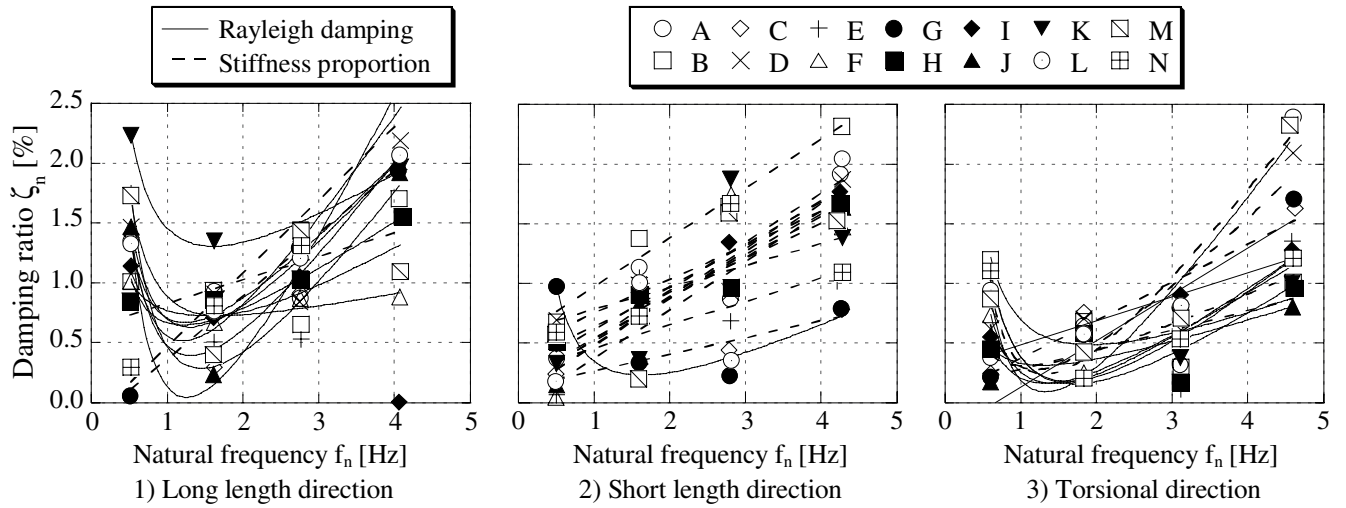

1) Long length direction   2) Short length direction   3) Torsional direction

Fig. 13 The relations along the natural frequencies and damping ratios in each direction (Jan., 2003)

RELATIONS IN THE DAMPING RATIOS OF LOWER MODES

Next, relations in the damping ratios of lower modes are analysed in each direction. Figure 13 shows an example of relations with the damping ratios for natural frequencies from 1st mode to 4th mode on the same measurement time in January 2003. Difference of marks in this figure is meaning data named from A to N on each 30 minutes period of that measurement day. It is estimated Rayleigh damping type at X direction and θ direction, and proportional to natural frequencies that is stiffness proportion type at Y direction. Rayleigh dampings are showed as solid lines, and stiffness proportion are as straight broken lines in Fig. 13.

CONCLUSIONS

Natural frequencies and damping ratios on lower modes in each direction were evaluated by Microtremor data of a high rise steel building as the structural monitoring. It was examined the changes with the passage of time for natural frequencies and damping ratios on 60 months as yet since the completion. And,

relations in the damping ratios of lower modes were also discussed. The following result was provided.

1. It is decreased with the passage of time for the natural frequencies gradually and certainly. The decreases of the natural frequencies on each mode in every direction are 3.0% on 60 months.

2. In comparison with standard deviation of the natural frequencies in every direction, 1st mode is small and higher mode becomes large slightly. However, the coefficients of variation are almost the same values on each mode.

3. The 1st mode damping ratios were dispersion in measurement time or day. Those were evaluated from 1.5% to 2.0% in long length or torsional directions and from 0.5% to 1.0% in short length direction.

4. The changes along passage of time of damping ratios were not seen. However, the fluctuation of damping ratios were large in 1st mode, small in higher mode.

5. Relation in the damping ratios of lower modes at long length and torsional directions was estimated Rayleigh damping type, and that at short direction was stiffness proportion type.

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