# The Evaluation of Dynamic Characteristics for a Middle Rise Building Made of Steel Based on Measurement Data

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#### SUMMARY:

Dynamic characteristics are evaluated from a viewpoint of structural health monitoring based on microtremor measurement for a middle rise building made of steel. The object building belonging to Meiji University in Japan is eleven stories, 44 m height. Microtremor measurement is periodically continued over 100 months. Based on those data that measured in microtremor, changes along passage and dispersions of dynamic characteristics in the building are examined. Free vibration waves employing man power excitation are measured on the measurement day as microtremor measurement. When a strong wind approached the building, strong wind observation and vibration measurement were performed. Severe vibration using earthquake observation system is also observed. Vibration amplitude levels in microtremor, free vibration wave employing man power excitation, largish vibration wave in strong wind and severe vibration wave in earthquake are different. Comparing dynamic characteristics are examined.

Keywords: Natural frequency, Damping ratios, Microtremor, Man Power Excitation, Earthquake

## **1. INTRODUCTION**

Dynamic characteristics were evaluated from a viewpoint of structural health monitoring based on microtremor measurement for a middle rise building made of steel. The object building belonging to Meiji University in Japan is eleven stories, 44 m height. Microtremor measurement are periodically continued over 100 months. Based on measurement data in microtremor, changes along passage and dispersions of dynamic characteristics in the building are examined. Dynamic characteristics are natural frequencies and damping ratios. Natural frequencies have gradually reduced with the passage of years for 20 months from completion of this building. Natural frequencies were stable in recent years. However, natural frequencies greatly reduced because the 2011 off the Pacific coast of Tohoku Earthquake on March 11 (3.11 Earthquake) occurred. Transition of natural frequencies after the occurrence of 3.11 Earthquake is examined and reported. Damping ratios in the measurement day are large. Based on data of microtremor, free vibration wave employing man power excitation, strong wind observation and earthquake observation, comparing dynamic characteristics evaluated for every vibration amplitude levels, relation between vibration amplitude levels and dynamic characteristics are examined.

## 2. OBJECT BUILDING AND VIBRATION OBSERVATION SYSTEM

The object building is Research building Annex "A" belonging to Ikuta Campus of Meiji University in Japan. This building is a rectangular plan, moment resisting frame structure, made of steel, eleven stories and 44 m height. The plan of roof floor of this building is shown in Fig. 2.1. The sectional view of this building is shown in Fig. 2.2. Black dots  $\bullet$  show the position that a 3-axis servo type



Figure 2.1. Plan of roof floor and measuring positions



Figure 2.2. Sectional view of object building (A-A')

accelerometer is set. These accelerometers are installed on the main girder of each measurement story and in the ground. The Measurement positions are J, K, L and M. The Measurement floors are roof floor, 9th floor, 7th floor, 4th floor, ground surface and 30m underground. The measurement data of microtremor, free vibration wave employing man power excitation, largish vibration wave in strong wind and severe vibration wave in earthquake can be recorded. In the case of microtremor measurement, the accelerometers are added on C at roof floor. 9th floor and 6th floor because responses of 1st - 3rd mode are dominant at these floors. Moreover, the accelerometers are added on L and R at roof floor, 9th floor and 6th floor for torsional ingredient calculation. The objects of evaluation are X direction, Y direction and  $\theta$  direction. X direction is stretcher on the plan. Y direction is header on the plan.  $\theta$  direction is torsional direction on the plan. Microtremor are measured at midnight because there are little walk, machine vibration, etc. From completion, microtremor measurement are performed once every two months, and microtremor measurement are always continuing for 100 months. Low pass filter is set as 10 Hz. Sampling frequency of Analog Digital Conversion is 50 Hz. The measuring time of one data is 20 minutes. 15 - 20 data are recorded in the day of measurement. The vibration measurement of free vibration waves employing man power excitation are targeting 1st mode. Man power excitation is performed by 10 people on the 11th floor. In the case of a typhoon approaches this building, largish vibration in strong wind are observed. The vibration measurement of strong wind observation are targeting the 1st mode. The flow from measurement to analyses is shown in this figure. The flow of the analysis of a microtremor wave is shown in left side of Fig. 2.3. The flow of the analysis of a free oscillation waveform according man power excitation is shown in right side of this figure.

#### 3. STRUCTURAL HEALTH MONITORING BASED ON MICROTREMOR DATA

Natural frequencies were calculated in two horizontal directions and torsional direction concerning 1st mode to 3rd mode using Fourier amplitude spectrum of time domain microtremor wave. One of



Figure 2.3. Process flow chart of measurement and analyses



Figure 3.1. Time domain microtremor waves (X direction, Roof floor, Dec. in 2011)

examples for a time domain wave obtained from microtremor measurement is shown in Fig. 3.1. Right side of this figure is a wave for 300 seconds, and left side of this figure is a wave for 30 seconds of the start for the 300 seconds. Concerning velocity data, 1st mode is dominant. Higher mode does not affect vibration wave. Acceleration data is dominant 1st mode similarly velocity data. Higher mode also affects vibration wave.

## **3.1.** Changes along Passages

The calculation method of natural frequency is shown in Fig. 3.2. In Fourier amplitude spectrum of each measurement story of this building, five peaks  $\bullet$  shown in this figure near the natural frequency are chosen and the nearest peak of the mean value straight line (—) shown in this figure of the frequencies of the five peaks is defined as the natural frequency. Transition of the natural frequencies concerning 1st mode to 3rd mode in each direction for 100 months from completion of this building to now is examined. The changes along passages of natural frequencies are shown in Fig. 3.3.  $\bigcirc$  shows the data measured in the measurement day, and  $\blacklozenge$  shows the mean value of those data. Natural frequencies in each direction reduce by 0.04 Hz in 1st mode, 0.10 Hz in 2nd mode and 0.15 Hz in 3rd mode for 20 months after completion of this building. Although natural frequencies were stable after 20 month from completion of this building, natural frequencies concerning 1st mode to 3rd mode in



Figure 3.2. Calculation method of natural frequency (Five peaks at near side of concerned natural frequency)



Figure 3.3. Changes along passages of 1st mode to 3rd mode natural frequencies in each direction

each direction greatly reduced because 3.11 Earthquake occurred. The amounts of reduction are 0.04 Hz in 1st mode, 0.13 Hz in 2nd mode and 0.16 Hz in 3rd mode. Natural frequencies are changing with the value after reduction still now. Damping ratios of n-th mode  $\zeta_n$  were calculated in two horizontal directions and torsional direction concerning 1st mode to 3st mode using Fourier amplitude spectrum with the  $1/\sqrt{2}$  method shown in Eqn. 3.1.

$$\zeta_n = \frac{f_n}{2\Delta f} \tag{3.1}$$

where  $f_n$  shows natural frequency in the n-th mode,  $\Delta f$  shows the interval of frequency which corresponds to  $1/\sqrt{2}$  times the amplitude of the peak. The calculation method of damping ratios is shown in Fig. 3.4. Transition of the damping ratios concerning 1st mode to 3rd mode in each direction for 100 months from completion of this building to now is examined. The changes along passages of damping ratios are shown in Fig. 3.5.  $\bigcirc$  shows the data measured in the measurement day and  $\blacklozenge$ 



Figure 3.4. Calculation method of damping ratio



Figure 3.5. Changes along passages of 1st mode to 3rd mode damping ratios in each direction

shows the mean value of those data. Damping ratios concerning 1st mode to 3rd mode in each direction are stable in constant range from completion of this building to now. Damping ratios do not changes along passages. Damping ratios of 1st mode in X direction are 0.8 - 3.0 %, namely those values have wide range. Damping ratios of 1st mode in Y direction and  $\theta$  direction are 0.5 - 1.5 %. Damping ratios of 2nd mode in X direction are 2.0 - 4.0 %. Damping ratios of 2nd mode in Y direction are 1.0 - 3.0 %. Damping ratios of 3rd mode in  $\theta$  direction are 2.0 - 4.0 %. Damping ratios of 3rd mode in Y direction are 2.0 - 4.0 %. It can be mean that there was little damage to the building by 3.11 Earthquake because characteristics of damping ratios do not have change after 3.11 Earthquake.

#### 3.2. Dispersions of Dynamic Characteristics in Measurement Day

Dispersions of natural frequencies and damping ratios are examined using coefficients of variation. The coefficients of variation of natural frequencies and damping ratios are shown in Fig. 3.6 and Fig. 3.7. The coefficients of variation of higher mode natural frequencies are large. Because the peak of dominant frequency of higher mode is not clear and an error occurs in a calculation value. However, the coefficient of variation of natural frequency is less than 1.0 % and natural frequencies do not vary in the measurement day. As for the coefficients of variation of damping ratios, low order mode is large.



1st mode  $\triangle$  2nd mode 3rd mode X 50 50 of variation [%] Coefficient 100 80 100 40 60 80 100 20 40 60 80 2040 60 20 Month Month Month 1) X direction 3)  $\theta$  direction 2) Y direction

Figure 3.7. Coefficients of variation of 1st mode to 3rd mode damping ratios in each direction



Figure 4.1. Time domain earthquake waves (Y direction, Mar. in 2011)

The coefficients of variation of damping ratios of 1st mode are 50 %. The coefficients of variation of damping ratios of 3rd mode and 2nd mode are 10 - 30 %. The coefficient of variation of damping ratios is obviously large as compared with that of natural frequencies. Damping ratios greatly vary in the day of measurement.

#### 4. EVALUATION OF DYNAMIC CHARACTERISTICS DURING EARTHQUAKE

In the chapter 3, vibration characteristics of this building in microtremor were evaluated from a viewpoint of structural health monitoring based on microtremor measurement data. In this chapter, vibration characteristics of this building during some earthquakes are evaluated based on earthquake observation data. Vibration characteristics during earthquake are evaluated based on earthquake observation data of 3.11 Earthquake, two earthquakes before 3.11 Earthquake and six earthquakes after 3.11 Earthquake. The time domain earthquake waves in Y direction of 3.11 Earthquake are shown in Fig. 4.1 as an example of measured earthquake data. The time domain earthquake wave measured at ground surface is shown in left side of this figure. The time domain earthquake wave measured at roof floor is shown in right side of this figure. Natural frequencies and damping ratios are calculated from frequency response functions. Frequency response functions are calculated using Fourier amplitude spectrum translated from time domain earthquake wave of roof floor divided by ground surface. In the case of frequency response functions are calculated, each Fourier amplitude spectrum is smoothed by Lag Window of Parzen. Frequency band of Lag Window is 0.05 Hz. Natural

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data	date	Amplitude [cm/s <sup>2</sup> ]				Natural frequency [Hz]				Damping ratio [%]			
		X		Y		Х		Y		Х		Y	
		max	rms	max	rms	1st mode	2nd mode	1st mode	2nd mode	1st mode	2nd mode	1st mode	2nd mode
Pre-1	2010.12.06.03:20	6.9	0.8	7.1	0.8	0.83	2.7	0.83	2.3	7.8	1.4	3.0	6.8
Pre-2	2011.02.05.10:56	10.8	1.9	5.5	1.4	0.82	2.5	0.79	2.5	7.6	1.0	3.3	2.5
Just	2011.03.11.14:47	402.7	65.6	357.0	54.0	0.75	2.3	0.70	2.2	3.2	1.0	4.9	2.9
Aft-1	2011.03.11.15:15	142.7	29.5	115.7	26.5	0.74	2.3	0.70	2.1	3.1	1.9	3.7	0.8
Aft-2	2011.03.15.22:31	50.0	6.5	45.7	8.5	0.74	2.3	0.69	2.3	4.6	2.9	3.4	5.2
Aft-3	2011.03.16.12:51	18.6	4.1	15.2	4.0	0.77	2.4	0.75	2.2	3.9	0.8	6.7	1.1
Aft-4	2011.03.16.22:38	8.7	2.0	13.9	2.1	0.77	2.4	0.71	2.2	3.1	1.8	6.5	2.6
Aft-5	2011.03.19.18:55	27.2	5.8	25.3	4.7	0.75	2.3	0.70	2.3	3.1	3.2	2.9	5.3
Aft-6	2011.03.24.08:55	20.4	2.8	20.2	2.2	0.76	2.3	0.85	2.2	3.3	2.0	9.6	2.7

Table 4.1. Natural frequencies and damping ratios of object building during earthquakes



Figure 4.2. Frequency response functions of object building during earthquakes (Y direction)

frequencies are dominant frequencies of frequency response functions. Damping ratios are calculated by  $1/\sqrt{2}$  method. The natural frequencies and damping ratios of this building during earthquakes are shown in Tab. 4.1. Pre-1 - 2 represent Earthquakes before 3.11 Earthquake. Just represent 3.11 Earthquake. Aft-1 - 6 represent Earthquakes after 3.11 Earthquake. The frequency response functions during earthquakes are shown in Fig. 4.2. Natural frequencies of this building during earthquakes are lower than those in microtremor before 3.11 Earthquake. Damping ratios during earthquakes are larger than damping ratios in microtremor before 3.11 Earthquake. It should be considered that damping ratios are large because Fourier amplitude spectrum is smoothed at the process of transfer function calculation.

# 5. EVALUATION OF DYNAMIC CHARACTERISTICS IN CONSIDERATION OF VIBRATION AMPLITUDE

# 5.1. Damping Characteristics in Free Vibration Waves Employing Man Power Excitation

Vibration amplitude is increased by man power excitation. Man power excitation is that some people move their weight to horizontal direction in keeping with 1st mode natural frequency of this building. Ten people participated in this experiment. Vibration amplitude of this building are increased until 50 times of those in microtremor by repeat of weight moving, then free vibration waves are obtained by stop of moving. It is examined that relation between vibration amplitude and 1st mode damping ratios in free vibration wave. Experiment of Man power excitations in each direction were performed 5 times on March, May, July, October and December in 2011. 1st mode damping ratios  $\zeta_1$  in free vibration wave were calculated using logarithmic decrement shown in Eqn. 5.1. The calculation method of damping ratio using the logarithmic decrement applied to free vibration wave is shown in Fig. 5.1.

$$\log\left(\frac{x_i}{x_{i+n}}\right) = 2\pi\zeta_1 n \tag{5.1}$$

where  $x_i$  shows *i*-th peak from 1st peak of free vibration wave.  $x_{i+n}$  shows peak after *n* periods from  $x_i$ . Calculation parameter *n* of Eqn.5.1 is verified. In the case of 1st mode damping ratios were calculated,



Figure 5.1. Calculation method of damping ratio using logarithmic decrement applied to free vibration wave



Figure 5.2. Relation between vibration amplitude and 1st mode damping ratios in free vibration waves (2011)

*n* in Eqn. 5.1 was changed from 1 to 7. In the case of n = 4, 5 and 6, 1st mode damping ratios proportionally decrease as vibration amplitude levels. It was considered that *n* which most effective in examining tendency of 1st mode damping ratios is 5. The relation between vibration amplitude and 1st mode damping ratios in free vibration waves is shown in Fig. 5.2. Data in this figure are 5 select from 25 data in each direction measured in 2011. The plots in this figure are changed for every data. Damping ratios in each direction proportionally decrease from 3.0 % to 1.0 % as vibration amplitude levels immediately after man power excitation with excitation conditions of this experiment. Because damping mechanism in free vibration wave employing man power excitation is similar to in microtremor, a reason of dispersions of damping ratios in microtremor is variation of vibration amplitude.

# **5.2.** Relation between Vibration Amplitude and Dynamic Characteristics in Each Vibration Amplitude Level

Natural frequencies and damping ratios of 1st mode evaluated based on each measurement data are examined from a viewpoint of vibration amplitude levels. Measurement data are microtremor measured on July in 2011, free vibration wave employing man power excitation measured on July in 2011, largish vibration strong wind measured on September in 2011 and severe vibration in earthquake shown in chapter 4. The maximum instantaneous wind speed at roof floor of this building during strong wind is 44 m/s. Vibration amplitude levels in microtremor, free vibration wave employing man power excitation and largish vibration in strong wind are slight. Damping mechanism in free vibration wave employing man power excitation and largish vibration in strong wind are similar to in microtremor. Vibration amplitude levels in earthquake are larger than vibration amplitude levels in microtremor, free vibration wave employing man power excitation and largish vibration in strong wind. Damping mechanism in earthquake is different from in microtremor, free vibration wave employing man power excitation and vibration in strong wind. Vibration amplitude in microtremor, largish vibration in strong wind and severe vibration in earthquake are calculated using root mean square value of time domain wave amplitude because those vibration are random vibration waves. Vibration amplitude in free vibration wave employing man power excitation are applied absolute value of zero to peak amplitude. The relation between vibration amplitude and 1st mode natural frequencies is shown in Fig. 5.3. The relation between vibration amplitude and 1st mode damping ratios is shown in Fig. 5.4. Natural frequencies in X direction in microtremor after 3.11 Earthquake were 0.89 Hz. Those in Y direction in



**Figure 5.3.** Relation between vibration amplitude and 1st mode natural frequencies in microtremor, free vibration wave, strong wind and earthquake (2011)



**Figure 5.4.** Relation between vibration amplitude and 1st mode damping ratios in microtremor, free vibration wave, strong wind and earthquake (2011)

microtremor after 3.11 Earthquake were 0.84 Hz. 1st mode natural frequencies in X and Y directions reduce at most 0.15 Hz as vibration amplitude levels increase. It can be seen from Fig. 5.3 that vibration amplitude affects natural frequencies. However, the reduction of natural frequencies never affect the response of this building during earthquake. 1st mode damping ratios increase as vibration amplitude levels increase. It can be seen that vibration amplitude greatly affects damping ratios. Especially damping ratios in Y direction proportionally increase from 1.0 % to 5.0 % as vibration amplitude levels increase during earthquakes. It is considered that the increase of damping ratios greatly affects the response of the building during earthquakes.

## 6. CONCLUSIONS

Natural frequencies concerning 1st mode to 3rd mode in each direction have gradually reduced with the passage of years for 20 months after completion of this building. Then, the degree of the reduction became slight and natural frequencies were stable. However, natural frequencies reduce remarkably because 3.11 Earthquake occurred. Natural frequencies remain low still now.

Damping ratios concerning 1st mode to 3rd mode in each direction are stable in constant range from completion of this building to now. There are no changes along passages in damping ratios. Damping ratios always greatly vary in the measurement day.

Natural frequencies in X direction in microtremor before 3.11 Earthquake were 0.93 Hz. Natural frequencies in X direction during 3.11 Earthquake were 0.75 Hz. Natural frequencies in Y direction in microtremor before 3.11 Earthquake were 0.90 Hz. Natural frequencies in Y direction during 3.11 Earthquake were 0.70 Hz. Natural frequencies in X and Y directions during 3.11 Earthquake are 0.2 Hz lower than in microtremor before 3.11 Earthquake. Damping ratios in X direction in microtremor were 1.0 %. Damping ratios in X direction during 3.11 Earthquake were 3.2 %. Damping ratios in Y direction in microtremor were 1.0 %. Damping ratios in Y direction during 3.11 Earthquake were

4.9 %. Damping ratios in X and Y directions during 3.11 Earthquake are 2.0 - 4.0 % higher than damping ratios in microtremor.

In the case of the free vibration experiment employing man power excitation, damping ratios proportionally decrease from 3.0 % to 1.0 % as vibration amplitude levels employing man power excitation decrease. Furthermore in the case of a strong wind, 1st mode damping ratios are proportional to vibration amplitude levels. Damping mechanisms in free vibration wave employing man power excitation and vibration in strong wind are similar to in microtremor. Variation of vibration amplitude levels is a reason of dispersions of damping ratios in microtremor.

Comparing natural frequencies evaluated in microtremor, free vibration wave employing man power excitation, largish vibration in strong wind and severe vibration in earthquake, natural frequencies slightly reduce as vibration amplitude levels increase. However, the reduction of natural frequencies does not affect the responses of this building during earthquake.

Comparing damping ratios evaluated in microtremor, free vibration wave employing man power excitation, largish vibration wave in strong wind and severe vibration in earthquake, damping ratios increase as vibration amplitude levels increase. In Y direction, damping ratios proportionally increase from 1.0 % to 5.0 % as vibration amplitude levels increase during earthquakes. The increase greatly affects the response of this building during earthquake.

#### AKCNOWLEDGEMENT

This study is supported by the Special Project (B) on Institute of Science and Technology in Meiji University.

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