# Evaluation of Dynamic Characteristics and their Variation of a Seismically Isolated Building Using Health Monitoring Data

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## ABSTRACT:

A structural health monitoring system was developed and installed in a six-story seismically isolated building located in Tokyo, Japan. There are two types of data in the monitoring wave history: One is the daily data, which are two-minute wave histories recorded twice a day at midnight and noon. The other is the event-driven data, which are records of events such as earthquakes. The daily data which cover over three years were analyzed and the natural frequency and the damping ratio of the building were identified from each record using polynomial models of modal analysis. The modal parameter estimates were found to fluctuate for many reasons. In addition to the variation derived from estimation error, there are dependency on response amplitude, possible changes after earthquakes, effects of temperature variation, etc. This paper also proposes a framework for structural health diagnosis taking those factors into account.

## INTRODUCTION

In recent years, many structural health monitoring systems have been installed in buildings. These installations have been enabled by the development of the next generation of sensors such as optical fiber sensors and MEMS sensors which are already available for practical use, and by new developments and improvements in information technology which enable the transmission and processing of enormous amounts of data.

Research has also been conducted on methods for damage diagnosis of buildings in severe events such as huge earthquakes. Many of those methods utilize system identification techniques and estimate damage by evaluating changes in the stiffness or the natural frequency of buildings [e.g 1-6].

However, a standardized framework for the daily soundness diagnosis of buildings using microtremor observation data has not yet been established. Even studies of estimation utilizing the daily monitoring data are rather sparse and comprise a very few cases [7, 8].

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This is can be due to the difficulties in structural identification of dynamic characteristics in minute levels of vibration and the difficulties of automating evaluations that deal with an enormous amount of monitoring data.

The daily diagnosis is essential, however, because the damage diagnosis in severe events cannot be done properly without the background data that support the reliability of a damage estimation.

In this paper the daily monitoring data of a six-story seismically isolated building, which have been stored for over three years, are analyzed and the natural frequency and the damping ratio of the building are identified from each record. The stochastic characteristics of the modal parameters are investigated taking many factors into account such as temperature, response amplitude, aging, etc.

## OUTLINE OF MONITORING SYSTEM

A structural health monitoring system was installed in the main building of the Institute of Technology, Shimizu Corporation in Tokyo.

All the data collected from the building is transmitted to an online server for unified data management. The transmitted data is compiled into a database containing various fields of data so users can retrieve any data on demand using an Internet browser.

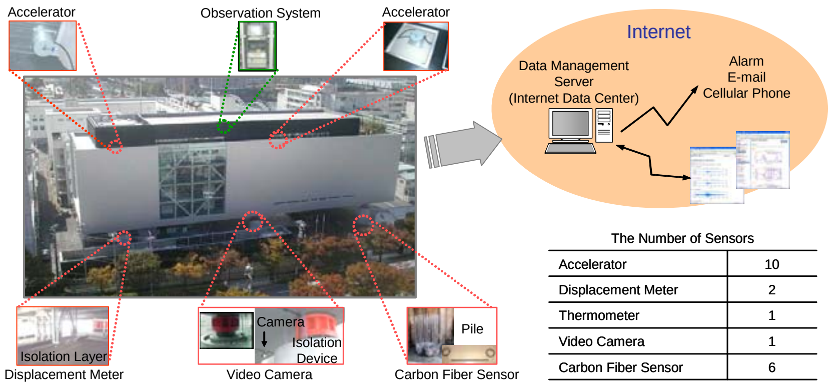
Data transmission between the observation systems and the server is automatically processed. The server for the data management is installed in an Internet Data Center in Nihonbashi, Tokyo. The configuration of the whole system is shown in Figure 1.

### Target building

The target building is a 6-story base isolation structure with LRB (lead rubber bearing). Each base isolation device is installed on the six RC piers of the piloti part of the 1st floor, and the upper steel structure from the 2nd floor to the 6th floor is mounted on that: the gross floor area is 9,066 m$^2$, and with total height of the structure is 27.4 m.

### Sensor installation

Ten accelerometers, two displacement meters, a thermocouple thermometer and a



The Number of Sensors

| | |
|---|---|
| Accelerator | 10 |
| Displacement Meter | 2 |
| Thermometer | 1 |
| Video Camera | 1 |
| Carbon Fiber Sensor | 6 |

Figure 1: Configuration of the structural health monitoring system

video camera were installed in the building and connected to the observation system to conduct continuous monitoring.

The accelerometers are located on the 6th floor, 4th floor and 2nd floor of the upper structure, and in the top and bottom of the 1st floor piers to detect two or three-dimensional vibrations of the building. The displacement meters were installed in the base isolation layer to verify the performance of the base isolation devices. The thermometer is also equipped to monitor the atmospheric temperature around one of the base isolation devices. The video camera is installed against one of the devices to capture an image of any deformation.

### Observation system

There are two types in the monitoring wave history data: One is daily data, which consists of two minute wave histories recorded twice a day at midnight and noon. The other is event-driven data, which are records of events such as earthquakes using the acceleration amplitude as a trigger.

The signals of four sensors located on 6th floor and basement in each horizontal direction are divaricated and amplified by 100 times to achieve high resolution in the microtremor wave history for the daily monitoring.

## ESTIMATION OF DYNAMIC CHARACTERISTICS OF TARGET BUILDING

### Target mode for estimation

We conducted the system identification analysis of this building using event data during a small earthquake [7]. According to the result it was found that there are three fundamental modes in the building as shown in Figure 2. These modes are also the target of the estimation using daily microtremor monitoring data.

### Identification method

Although there are sensors with high resolution signals both on the 6th floor and in the basement, only signals of two sensors on the 6th floor in each horizontal direction are used for identification, since the input-output relationship was not clear when the signals of the basement sensors were utilized as input.

The time domain system identification method using a polynomial model was employed to estimate the modal parameters, i.e. natural frequencies and damping ratios. Since the 2nd mode is a torsional mode and has components in both horizontal directions, the identification should preferably be done using signals in both directions simultaneously. Thus the Multi-Input-Multi-Output ARX model of Modal Analysis (MIMO-ARX-MA), a polynomial model [9], which enables us to estimate the modal parameters from multi-output data, was applied.

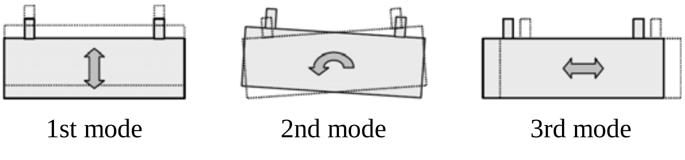


Figure 2: Three fundamental modes

All the data were low-pass filtered with a cut-off frequency of 5 Hz and re-sampled at 0.05 s from the original sampling interval of 0.01 s before the identification process.

The order of the model, na, is so determined that the sum of the AIC is minimized, which is calculated by the identification from 100 randomly chosen data sets as the order is changed sequentially. The order is thus selected to be 48 throughout the analysis.

### Estimation results

The natural frequency and damping ratio of the 1st, 2nd and 3rd mode of the building are identified and shown in Figures 3-4.

Values of natural frequency and damping ratio are estimated properly although they fluctuate due to the estimation error. Besides that the evaluated value of the natural frequency has some oscillation with annual period, which is not clearly seen in the case of the damping ratio. In addition the natural frequency of each mode shows a tendency to decrease its values over time, which might be due to structural aging.

Since the period of movement of the natural frequency is about one year and the peak comes in winter and summer, it can be surmised that the fluctuation is related to the seasonal variation in temperature.

Therefore the values of natural frequency and damping ratio are represented in relation to the temperature in Figures 5-6.

From these figures it can be said that the natural frequency has a strong correlation with the temperature, where the values of natural frequency get lower as the temperature increases, while the damping ratio seems to have no relationship to the temperature.

The same assessment was done for the influence of response amplitude. The natural frequency and the damping ratio are also represented in relation to the root mean squares of the acceleration response in both directions in Figures 7-8. It can be seen from Figure 7 that the natural frequency is affected by the response amplitude and the values of the 2nd and 3rd mode tend to increase as the response increases, though the values of the 1st mode show the opposite tendency. From Figure 8, the damping ratio does not seem to have any correlation with the response amplitude.

In order to diagnose the aging effect on the building appropriately, the influence of temperature and response amplitude on the change of natural frequency should be removed. Therefore the compensation of temperature and response amplitude was attempted in the following way: to minimize the influence of change due to aging, the data of natural frequency are divided into three parts of every one year for each mode. Then the average is removed from each data set on which linear regression was done by the least squares method for each mode fitting the equation below.

$$\Delta f = \alpha_1 T + \alpha_2 \log_{10} R + \alpha_3 \tag{1}$$

where $\Delta f$ is the natural frequency from which the average is removed in each section of one year, $T$ is the temperature in degree Celsius, $R$ is the rms of response amplitude in cm/s$^2$, and $\alpha_j$ ( $j$ = 1, 2, 3) are the regression coefficients to be estimated.

The fitting results are presented, in relation to the temperature with the mean response amplitude in Figure 9, and in relation to the response amplitude with the mean temperature in Figure 10, respectively. The data are well fitted by the linear regression for both factors. The evaluated coefficients are shown in Table 1.

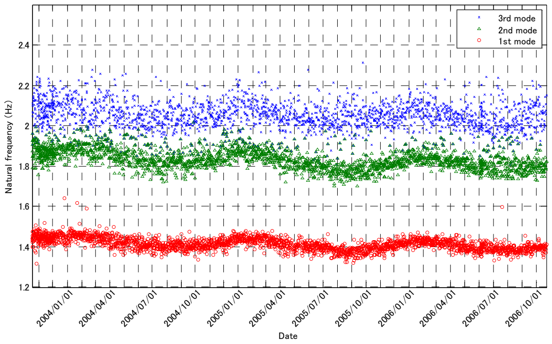


Figure 3. Identification result of natural frequency

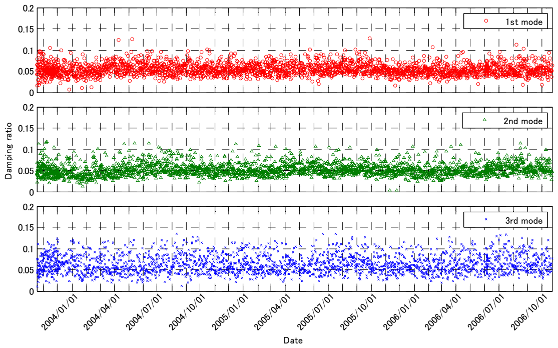


Figure 4. Identification result of damping ratio

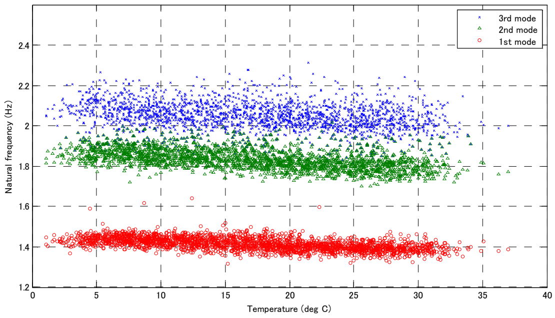


Figure 5. Natural frequency in relation to temperature

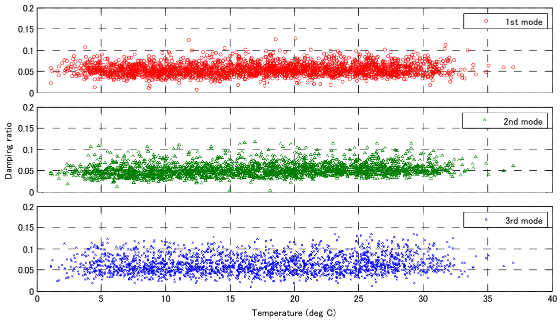


Figure 6. Damping ratio in relation to temperature

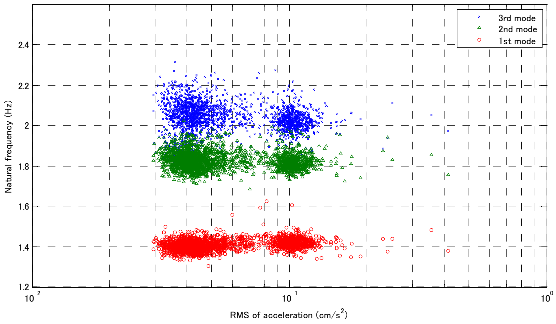


Figure 7. Natural frequency in relation to response amplitude

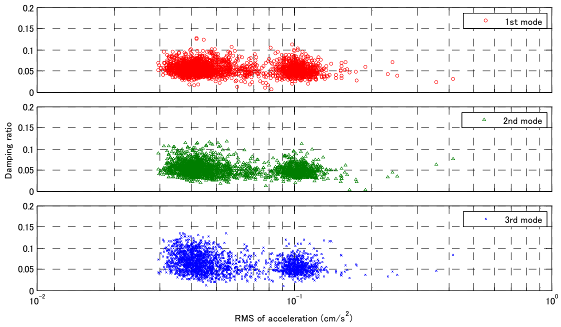


Figure 8. Damping ratio in relation to response amplitude

By using these coefficients the natural frequency in each mode is compensated for so it is equivalent to the value of a temperature of 20 degree Celsius and a response amplitude of 0.05 cm/s$^2$. The compensated natural frequency is now shown in Figure 11. The periodic fluctuation due to temperature change disappears and the dispersion depending on the response amplitude is removed, so that the long-term decreasing trend of natural frequency can clearly be picked out.

To verify whether the reduction in natural frequency is related to the earthquakes the building has experienced, the earthquake records stored in the structural health monitoring

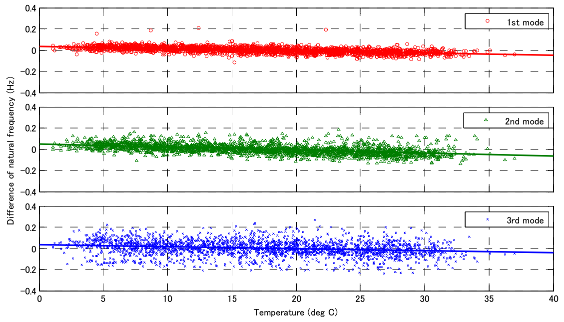


Figure 9. Linear regression of deviation of the natural frequency in correlation to temperature with average response amplitude

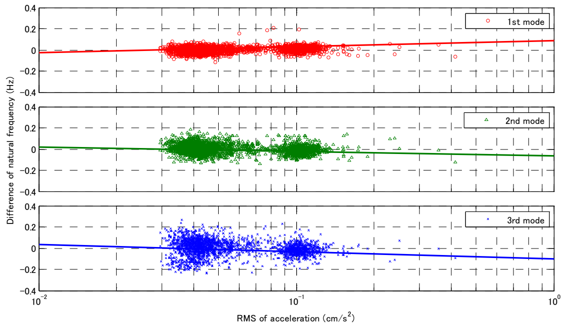


Figure 10. Linear regression of deviation of natural frequency in correlation to response amplitude with average temperature

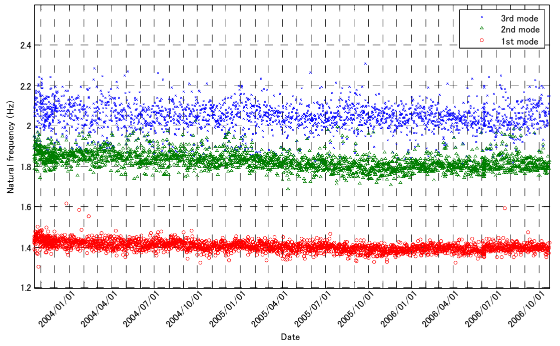


Figure 11. Natural frequency compensated for at temperature of 20 deg C and with a response amplitude of 0.05 cm/s$^2$

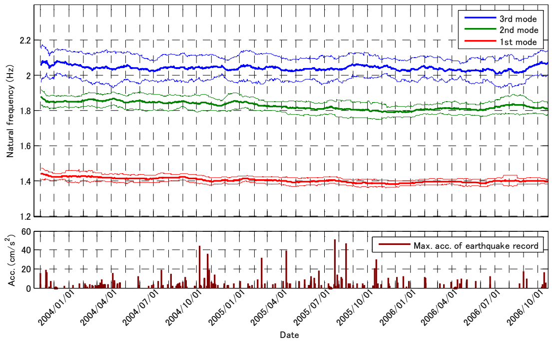


Figure 12. Monthly average and standard deviation of compensated natural frequency with amplitude of recorded earthquakes

Table 1. Regression coefficients for change of natural frequency

| mode | 1st | 2nd | 3rd |
|---|---|---|---|
| coefficient $\alpha_1$ ($10^{-3}$ Hz/deg) | -2.14 | -2.93 | -1.91 |
| coefficient $\alpha_2$ ($10^{-2}$ Hz/log$_{10}$[cm/s$^2$]) | 3.89 | -2.74 | -4.54 |

system were investigated and the root of sum of squares of maximum absolute values in both horizontal directions on the 6th floor for each earthquake was extracted. These values are shown in Figure 12 with the moving average and standard deviation of natural frequency calculated using data over the past one month.

In regards to this figure even earthquakes imparting more than 20 cm/s$^2$ response to the building do not seem to cause any acute reduction in natural frequency directly when compared to the breadth of standard deviation.

## CONCLUSIONS

The modal parameters, especially the natural frequency and the damping ratio, of a six-story seismically isolated building are estimated using microtremor observation data recorded twice a day for over three years by the structural health monitoring system installed in the building. The multi-output AR model of modal analysis is used for the system identification, which enables us to identify all fundamental modes utilizing the wave histories in both horizontal directions simultaneously.

According to the identification results the natural frequency is affected by both the temperature of surrounding air and the response amplitude besides the dispersion due to estimation error. In addition there also seems to be a long-term decreasing tendency in the natural frequency, although it is somewhat hidden by the influence of the temperature and the response amplitude. On the other hand the damping ratio does not seem to have much influence on those factors or any long-term trend.

Therefore the natural frequency is compensated for so the influence of the temperature and the response amplitude is removed, which shows a clear tendency for the natural frequency to be gradually reduced over the three years of observation.

To verify the relationship between the long-term reduction of natural frequency and earthquakes experienced, the monthly average and standard deviation of natural frequency was checked with reference to the maximum response of each earthquake observation record. The earthquakes, including some over 40 cm/s$^2$, however, did not seem to cause any acute reduction in natural frequency directly, compared to the range of standard deviation.

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