Journal of Japan Association for Earthquake Engineering, Vol. 18, No. 3, 2018

CHANGE OF NATURAL FREQUENCY OF LOW-RISE BUILDINGS BASED ON LONG-TERM VIBRATION RECORDS

Tomoki HATAKEYAMA[1], Xing WANG[2], Susumu OHNO[3] and Masato MOTOSAKA[4]

[1] Student Member of JAEE, Graduate School of Engineering, Tohoku University, Sendai, Japan, tomoki-h@dc.tohoku.ac.jp
[2] Member of JAEE, Assistant Prof., International Research Institute of Disaster Science(IRIDeS), Tohoku University, Sendai, Japan, kin.o.a6@tohoku.ac.jp
[3] Member of JAEE, Associate Prof., IRIDeS, Tohoku University, Sendai, Japan, ohnos@archi.tohoku.ac.jp
[4] Member of JAEE, Professor, IRIDeS, Tohoku University, Sendai, Japan, motosaka@irides.tohoku.ac.jp

ABSTRACT: This paper aims to describe the changes in the dynamic characteristics of two existing buildings in Miyagi Pref., Japan. One is a reinforced-concrete(RC) structure and the other is steel one. In this study, we found that the natural frequency of the RC structure is more strongly correlated with temperature in comparison with the steel structure. The temperature dependence of the natural frequencies is included in record indicating the amplitude dependence of the building's dynamic characteristics, and corrections with temperature data can deliver more accurate estimations of a building's structural soundness.

Key Words: Long-term Monitoring, Natural Frequency, Temperature Dependence, Amplitude Dependence, Structural Hearth Monitoring

1. INTRODUCTION

After an earthquake, building damage must be inspected immediately to determine the safety and usability of the building. Simple visual inspections are widely used for this purpose. However, after destructive earthquakes, such as the 2011 off the Pacific coast of Tohoku Earthquake, timely visual inspections of the buildings are difficult to perform due to the high number of the damaged buildings[1)]. In addition, visual inspection cannot identify damages that are invisible to the naked eye. On the other hand, even if a building has not experienced any damage due to the earthquake, the structural performance will be declined due to the aging of the building.

Therefore, Structural Health Monitoring (SHM), which can provide an alternative to traditional inspection methods, is attracting great research interest[2)3)].

The International Research Institute of Disaster Science (IRIDeS), Tohoku University, Sendai, Japan has developed an Earthquake Early Warning (EEW) system that includes an on-line SHM (EEW/SHM system), and it has been installed in several buildings around Sendai[4)]. The system aims to diagnose the safety and usability of the buildings judging from the variation of the natural frequency and damping ratio due to the earthquake and aging of the building. The system continuously records the real-time vibration records from buildings, including vibrations caused by ambient vibration and earthquakes. Since the dynamic characteristics of buildings change from time to time, trends in the observed records must be understood to apply SHM accurately. Long-term records from two low-rise buildings (referred to as building A and building B), with reinforced concrete and steel structures, respectively, allow the examination of changes in dynamic characteristics of the structure.

In this paper, first, ambient vibration records were continuously recorded for one year and the changes to the natural frequency were studied to reveal the relation between the natural frequency and temperature. This analysis suggests that the natural frequency of reinforced-concrete building is strongly correlated with temperature. Second, the amplitude dependence of building natural frequency is examined using earthquake response record recorded from 2013 to 2015. Finally, this paper describes the influence of temperature on the amplitude dependence of the natural frequency. Our results demonstrate that the relation between the amplitude and natural frequency can be clarified if the temperature dependence can be corrected for.

Though several researchers have reported the dynamic characteristics of existing buildings[5) 6)], few reports about dynamic characteristics of middle- and low-rise buildings exist in the literature[7)]. Researches about middle- and low-rise buildings are very less. The proposed study increases the level of the details available about the dynamic characteristics of low-rise buildings, which are important for understanding SHM data.

2. BUILDING STUDIED

In this paper, two 3-story buildings constructed of different materials are studied, specifications of which are shown in Table 1. This study focuses on how the buildings' dynamic characteristics change in response to temperature and amplitude of earthquake response. Locations of these two buildings are marked with reverse triangles in Fig. 1. Building A is located in Ishinomaki City, Miyagi Pref., Japan.

Table 1 Description of the investigated buildings

Name of buildings	building A	building B
Structure type	RC	S
Number of stories	3F	3F
Building height (m)	17	12
Total floor area (m²)	2,222	1,673
Foundation type	Spread	Pile
Completion year	1975	2005
Type	City hall	City hall
Ground	N-value is over 50	Reference Fig. 2

Fig. 1 Locations of the building A and building B

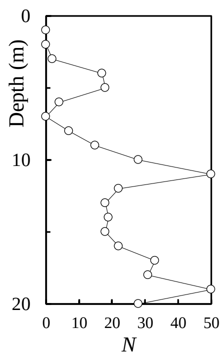
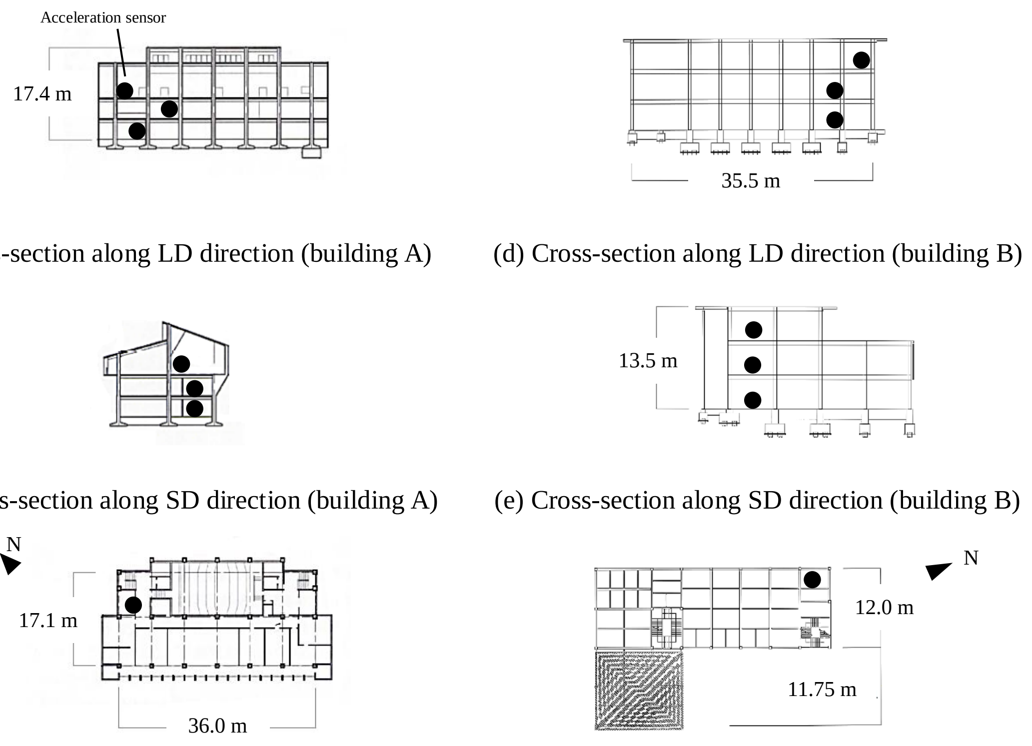


Fig. 2 Soil profiles of the site around the building B

It was built out of reinforced concrete in 1975 as the office hall of the city, and has a spread foundation. The N-value of the site is over 50. Building B is located in Osaki City, Miyagi, Japan. It has a steel structure with pile foundation, and was completed in 2005. Soil profiles for the site[10)]are shown in Fig. 2. The surface of the site is a clay layer and its N-value is around 5, and the N-value changes to over 50 when the depth exceeds 25 m. The building is supported by7- or 8-meter-long PHC piles (type B) with diameter of ϕ 0.5 or 0.6 m.

3. DATA ACQUISITION

The vibration observation system comprises of three acceleration sensors (Micro SMA), data logger (NetDAS), and communication software (GRF Tools Suite). The sensor is a MEMS sensor with a wide dynamic range of 120 dB. It can measure the vibration ranging from ambient vibration to strong motion. The data logger has a variable sampling rate from 10 Hz to 1 kHz, and was fixed to 100 Hz for the measurements in this study. The signal from each seismometer is transferred by a cable to the logger using a 24-bit A/D converter. The sensors are installed at the 1st, 2nd, and 3rd floors in each building. The sensor locations in each building are marked in Fig. 3 (LD is the longitudinal direction and SD is the transverse direction). All data are transferred to a data server at IRIDeS, and are stored automatically through the local intranet. The system records data continuously. With baseline observations of continuous ambient vibration, we conducted an analysis of the natural frequency's change with temperature, the details of which are shown in section 4. An analysis of the natural frequency's trend with driving amplitude using earthquake response records is described in section 5.



(a) Cross-section along LD direction (building A)

(d) Cross-section along LD direction (building B)

(b) Cross-section along SD direction (building A)

(e) Cross-section along SD direction (building B)

(c) 3rd floor plan (building A)

(f) 3rd floor plan (building B)

Fig. 3 Sensor locations (●) in building A (left figures) and building B (right figures)

4. TEMPERATURE DEPENDENCE OF THE NATURAL FREQUENCY

4.1 Natural frequency extraction

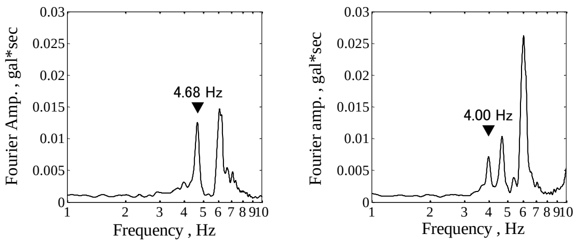
Based on the one-year ambient vibration records measured from the two buildings in 2015, natural frequencies of the building systems including soil-structure interactions were extracted, which allows us to study the relation between natural frequency and temperature. Although several periods of time include no data due to system maintenance, the amount of data collected is sufficient for the present study.

As mentioned above, this paper focuses on the natural frequency of the entire building system including soil-structure interactions. The natural frequency is measured for each hour of vibration records from the first peak of the Fourier spectrum based on ambient vibrations. The details of this calculation are as follows.

To estimate the natural frequency, each hour of ambient vibration records from the third floor is separated into forty 81.92-second-long records windows. The average of the Fourier spectra from these windows is taken and smoothing windows are applied 0.2 Hz Parzen window. One-year data sets are analyzed using the same method. The Fourier spectra results for ambient vibration records in the two horizontal directions from building A recorded at midnight of January 1st, 2015 are shown in Fig. 4 and from building B recorded at midnight of February 1st, 2015 are shown in Fig. 5, respectively. As can be seen in Fig. 4, two frequency peaks occur in the LD direction and three frequency peaks occur in the SD direction. According to the a previous study with this building[11)], the low-frequency peak (4.68Hz) in Fig. 4(a) is the natural frequency in the LD direction. The lowest-frequency peak (4.00 Hz) in Fig. 4(b) is recognized as the natural frequency in the SD direction, and includes the effect of the torsion mode. From Fig. 5, the natural frequency in the LD direction is estimated to be 2.04 Hz, and in the SD direction is estimated to be 2.36 Hz.

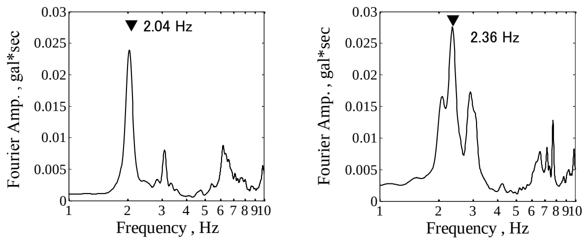
4.2 Results

One-year changes in the natural frequency of the soil-structure system for buildings A and B are shown in Fig. 6 and 7, respectively. Figure 6(a) shows the day-averaged temperatures at the JMA (Japan Meteorological Agency) Ishinomaki meteorological observatory and the JMA Kashimadai meteorological observatory, which are the nearest stations to buildings A and B, respectively. Hereafter, for the sake of brevity, this paper mentions the temperature data from JMA[12)] only. JMA Ishinomaki is located about 20 km from building A. JMA Kashimadai is about 2 km from building B. For the sake of easy comparison, the upper and the lower limits of the vertical axes of Fig. 6(b) and (c) and Fig. 7(b) and (c) are set to be ± 10% of the one-year average of the natural frequency. The records in Fig. 6 suggest that the natural frequency of building A is strongly correlated with temperature, and the natural frequency increases with an increase in temperature. The change is more obvious in the LD direction than in the SD direction for both of the buildings.



(a) LD direction (b) SD direction

Fig. 4 Fourier spectra of building A



(a) LD direction (b) SD direction

Fig. 5 Fourier spectra of building B

To evaluate the temperature-dependence quantitatively, relationships between the monthly average of the natural frequency and the temperature of the two buildings are examined for the one year data. The values for buildings A and B are listed in Tables 2 and 3 are plotted in Fig. 8 and Fig. 9, respectively. Linear regressions were applied to these records. The scales of the vertical axes of Fig. 8 and Fig. 9 are the same as those of Figs. 6 and 7. Based on the coefficient of determination (R^2) for each regression, the regressions are appropriate except the data from the SD direction in building A. However, the linear regression does at least connect all data points in the SD direction for building A. As the present study aims to understand the basic trends, this result is sufficient for the present purposes.

The slopes of the regression lines are 0.0103 Hz/°C (in LD direction) and 0.0027 Hz/°C (in SD direction) for building A and 0.0007 Hz/°C (in LD direction) and 0.0019 Hz/°C (in SD direction) for building B. As the proposed study used simple linear regression analysis, the gradient represents the

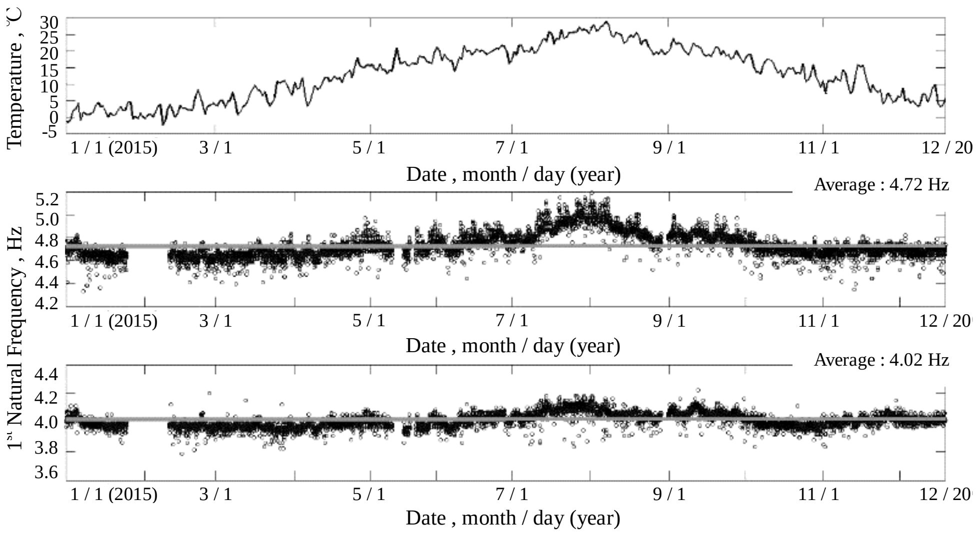


Fig. 6 Changes in natural frequency with temperature (building A
(Upper row: temperature, middle row: LD direction, and Lower row: SD direction)

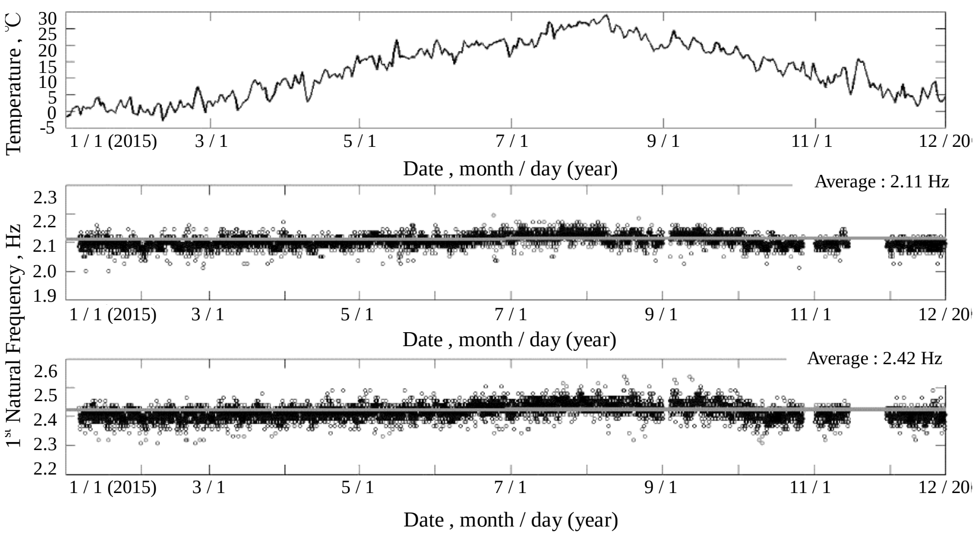


Fig. 7 Changes in natural frequency with temperature (building B)
(Upper row: temperature, middle row: LD direction, and Lower row: SD direction)

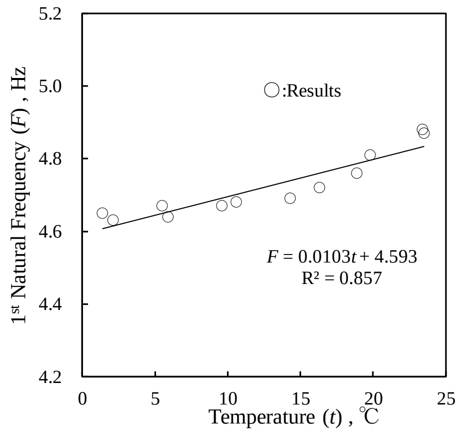
magnitude of the natural frequency's dependence on temperature. As the slope increases, the natural frequency is more dependent on temperature. Therefore, Building A is more affected by temperature than is building B, especially in the LD direction. Furthermore, the natural frequency is hardly affected by temperature in the LD direction in building B.

Table 2 Monthly average of the natural frequency (building A)

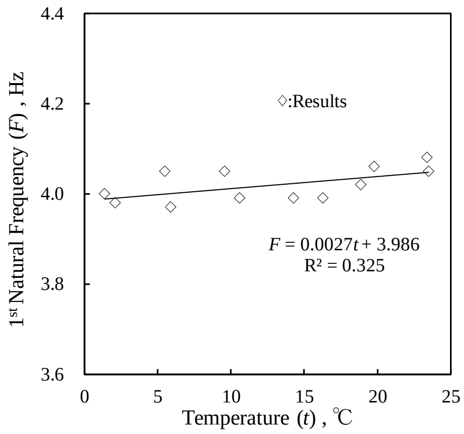
month / 2015	1	2	3	4	5	6	7	8	9	10	11	12
monthly average of temperature / ℃	1.4	2.1	5.9	10.6	16.3	18.9	23.4	23.5	19.8	14.3	9.6	5.5
monthly average of the natural frequency (LD) / Hz	4.65	4.63	4.64	4.68	4.72	4.76	4.88	4.87	4.81	4.69	4.67	4.67
monthly average of the natural frequency (SD) / Hz	4.00	3.98	3.97	3.99	3.99	4.02	4.08	4.05	4.06	3.99	4.05	4.05

Table 3 Monthly average of the natural frequency (building B)

month / 2015	1	2	3	4	5	6	7	8	9	10	11	12
monthly average of temperature / ℃	0.8	1.3	5.2	10.2	16.6	19.1	23.7	23.3	19.4	13.2	8.8	4.8
monthly average of the natural frequency (LD) / Hz	2.10	2.10	2.10	2.10	2.11	2.11	2.12	2.11	2.11	2.11	2.11	2.10
monthly average of the natural frequency (SD) / Hz	2.40	2.40	2.40	2.40	2.41	2.43	2.44	2.44	2.43	2.41	2.40	2.40

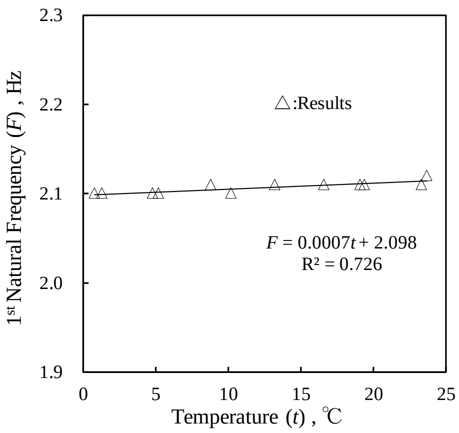


(a) LD direction

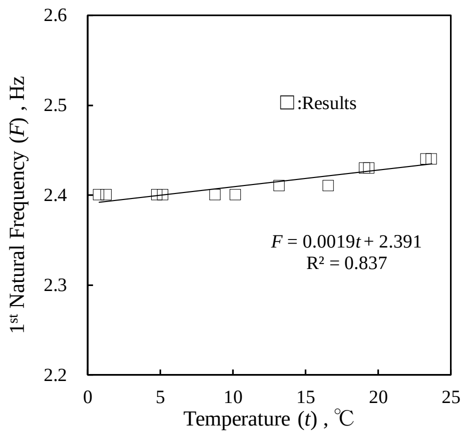


(b) SD direction

Fig. 8 Temperature dependent natural frequency (building A)



(a) LD direction



(b) SD direction

Fig. 9 Temperature dependent natural frequency (building B)

Since building A locate a rock site with N-value over 50, the effect of soil-structure interactions is small. The natural frequency extracted in this case represents the characteristics of the upper structure. Therefore, it is reasonable to consider that the heat expansion of concrete influences the temperature-dependence of the natural frequencies of concrete structures. During The 2011 off the Pacific coast of Tohoku Earthquake, severe cracks occurred in the concrete walls and floors of building A. Although these damages have been repaired by injecting resin into the cracks, to judge by the extent of the damage, micro cracks might also occur in the RC elements. These micro cracks are temporarily shrunk due to heat expansion of cracks in the RC elements could explain why the natural frequency of the buildings is so much affected by high temperatures. Though the amounts of solar radiation incident on the two directions of the building A seem to be nearly equal, the temperature dependences of the natural frequency in either direction is different. This difference may be explained if the cracks in the structure are biased to one axis or another. The relationship between cracks and dynamic characteristics should be studied further.

5. AMPLITUDE-DEPENDENT DYNAMIC CHARACTERISTICS

5.1 Earthquake records and methodology of record analysis

In this section, earthquake response records from building A and B are used to study the changes in natural frequency with increasing amplitude of earthquake responses. Considering the quality of the data available, 18 earthquake response records are chosen for building A and 40 for building B from the third floor. The maximum accelerations at the 3rd floor of building A and building B for all the studied earthquakes are listed in Table 4 and 5, respectively. The earthquake information is from JMA[13].

In this paper, these records are used to analyze the relation between the natural frequency and maximum response acceleration. To estimate the natural frequency, each 300 seconds of earthquake response records centered on the time at which the absolute value of the response acceleration becomes maximum is separated into seven 40.96-second-long data windows. The average of the Fourier spectra from these windows is taken and smoothing windows are applied 0.2 Hz Parzen window[14].

Table 4 Specifications list (building A)

No.	Eq. occurrence		Eq. information			Max. acc. at 3rd floor (cm/sec^2)		1st natural Freq. (Hz)	
	Year.month.day	Time	Epicenter	M_j	JMA Int.	LD	SD	LD	SD
1	2014.04.03	8:22	Iwate coast south	5.5	4	13.5	21.5	4.22	3.59
2	2014.04.15	10:35	Miyagi Oki	4.1	2	19.6	30.3	4.08	3.47
3	2014.04.17	2:20	Miyagi Oki	4.2	3	25.9	43.4	4.08	3.37
4	2014.06.15	2:31	Iwate island south	5.5	4	13.1	16.5	4.39	3.59
5	2014.06.16	5:14	Fukusima Oki	5.8	4	18.9	23.2	4.25	3.52
6	2014.07.12	4:22	Fukusima Oki	7	4	10.9	16.1	4.52	3.34
7	2014.11.08	8:54	Miyagi Oki	5.2	3	14.4	23.3	4.05	3.69
8	2014.12.20	18:49	Miyagi Oki	4.4	2	30.0	31.1	4.00	2.95
9	2014.12.27	6:04	Miyagi Oki	4.3	3	20.3	18.0	4.20	3.64
10	2015.02.11	4:23	Miyagi Oki	4.2	2	37.2	38.3	4.10	3.47
11	2015.02.17	8:06	Sanriku Oki	6.9	4	13.6	10.5	4.05	3.69
12	2015.02.26	10:11	Miyagi Oki	5	4	14.6	26.3	4.20	3.54
13	2015.07.02	15:05	Miyagi Oki	4.7	3	19.5	16.5	4.20	3.64
14	2015.07.04	13:23	Miyagi Oki	4.7	3	25.5	38.1	4.27	3.61
15	2015.08.01	23:24	Miyagi Oki	4.7	3	22.1	18.9	4.54	3.69
16	2015.08.03	14:30	Miyagi Oki	5.1	3	24.5	24.0	4.54	3.44
17	2015.08.20	21:57	Miyagi Oki	4.8	3	29.3	28.1	4.35	3.39
18	2015.10.06	18:32	Miyagi Oki	5	3	25.2	28.3	4.25	3.37

5.2 Results

The amplitude dependences of the natural frequency of building A and B in the LD and SD directions are as plotted in Fig. 10. The horizontal axes represent the maximum acceleration and are shown in logarithmic scale. Regression curves to evaluate the natural frequency are plotted based on least-squares fitting[15)]. The one-year average of natural frequencies analyzed using ambient vibration in section 4 are

Table 5 Specifications list (building B)

No.	Eq. occurrence		Eq. information			Max. acc. at 3rd floor (cm/sec^2)		1st natural Freq. (Hz)	
	year.month.day	time	Epicenter	M_j	JMA Int.	LD	SD	LD	SD
1	2013.07.10	14:22	Iwate south	4.9	4	14.7	10.2	1.98	2.34
2	2013.09.04	9:18	The sea near Torishima	6.8	4	20.1	32.3	1.86	2.10
3	2013.09.20	2:25	Hukushima Pref. Hama-dori	5.9	5+	24.8	17.7	1.88	2.12
4	2013.10.20	0:14	Miyagi Oki	5.1	4	30.7	78.8	1.93	1.98
5	2013.10.22	10:18	Fukushima Oki	5.3	3	6.6	9.3	1.93	2.42
6	2013.10.26	2:10	Fukushima Oki	7.1	4	55.3	32.7	1.73	2.03
7	2013.10.26	23:36	Miyagi Oki	4.4	3	5.0	10.4	1.98	2.17
8	2013.11.01	0:01	Sanriku Oki	5.2	3	7.1	9.2	1.98	2.27
9	2013.11.12	5:54	Miyagi Oki	4.5	3	9.0	8.1	2.03	2.27
10	2013.11.21	12:37	Fukushima Oki	4.9	3	5.3	8.1	1.95	2.27
11	2013.11.26	0:43	Miyagi Oki	4.9	4	14.6	13.6	2.05	2.22
12	2013.12.03	18:16	Ibaraki Oki	5.5	3	10.2	12.6	1.93	2.27
13	2013.12.18	19:14	Miyagi Oki	4.7	3	11.0	8.1	2.03	2.08
14	2013.12.29	10:22	Miyagi Oki	4.4	3	11.7	21.0	1.95	2.12
15	2014.06.08	14:24	Iwate south	5	4	28.8	31.0	1.81	2.20
16	2014.06.09	6:10	Miyagi Oki	4.6	4	17.4	11.7	2.03	2.15
17	2014.06.15	2:31	Iwate south	5.5	4	26.7	18.0	1.93	2.27
18	2014.06.16	5:14	Fukushima Oki	5.8	4	30.5	51.8	1.88	1.98
19	2014.06.27	6:55	Fukushima Oki	4.7	3	11.0	8.6	2.05	2.25
20	2014.07.05	7:42	Iwate Oki	5.9	5-	12.1	12.5	2.00	2.22
21	2014.10.15	12:51	Miyagi Oki	4.6	4	29.7	19.0	1.95	2.08
22	2014.11.08	8:54	Miyagi Oki	5.2	3	17.1	23.2	1.90	1.90
23	2014.11.20	10:51	Fukushima Oki	5.5	4	13.8	17.7	2.00	2.12
24	2014.12.12	13:07	Miyagi Oki	4.2	2	11.8	6.0	2.10	2.10
25	2015.02.17	8:06	Sanriku Oki	6.9	4	36.2	31.5	1.88	2.00
26	2015.02.17	13:46	Iwate Oki	5.7	5+	26.2	31.1	1.88	2.10
27	2015.02.26	20:11	Miyagi Oki	5	4	17.5	16.0	1.93	2.29
28	2015.03.19	10:33	Miyagi Oki	4.8	3	11.4	10.9	2.00	2.25
29	2015.03.27	2:28	Miyagi Oki	3.9	2	5.8	8.5	1.98	2.22
30	2015.04.03	4:04	Miyagi Oki	4.6	3	11.3	12.2	2.12	2.25
31	2015.05.13	6:12	Miyagi Oki	6.8	5+	95.7	113.7	1.78	1.95
32	2015.05.15	12:30	Fukushima Oki	5	4	11.0	11.2	2.03	2.27
33	2015.05.30	20:23	Ogasawara west	8.1	5+	15.5	10.1	1.95	2.34
34	2015.06.13	5:56	Miyagi Oki	4.7	3	8.2	9.8	2.05	2.34
35	2015.07.10	3:32	Iwate north	5.7	5+	13.5	14.4	1.98	2.22
36	2015.07.21	18:16	Fukushima Oki	4.9	3	9.5	11.1	2.03	2.15
37	2015.08.01	23:24	Miyagi Oki	4.7	3	10.6	12.7	1.95	2.29
38	2015.08.03	14:30	Fukushima Oki	5.1	3	14.6	17.6	2.03	2.25
39	2015.08.05	20:56	Fukushima Oki	5	3	17.2	9.1	2.00	2.39
40	2015.08.23	11:08	Miyagi Oki	4.3	3	13.1	7.6	2.03	2.27

also included in the regression. The accelerations due to ambient vibration are 0.02 cm/sec^2 for building A and 0.05 cm/sec^2 for building B.

The natural frequency decreases with increasing acceleration amplitude in both of the buildings, as can be seen in Fig. 10. Natural frequency drops significantly when the acceleration is large. And the linear regression curve does least connect all data points, the present study could describe rough trend of amplitude-dependent dynamic characteristics of two buildings in both directions.

However, as can be seen from the small values of R^2, the regression curves hardly express quantitative relationships between the acceleration and the natural frequencies. As a cause of this, obvious variation of natural frequencies is plotted even in the same acceleration. Temperature may have a clear effect on the plot for building A. Therefore, it is necessary to eliminate the effect of the temperature dependence from the analysis of amplitude dependence.

In the next section, the authors attempt to analyze the amplitude dependence eliminating the effect of temperature dependence of building A, as the natural frequency of building A depends more heavily on temperature.

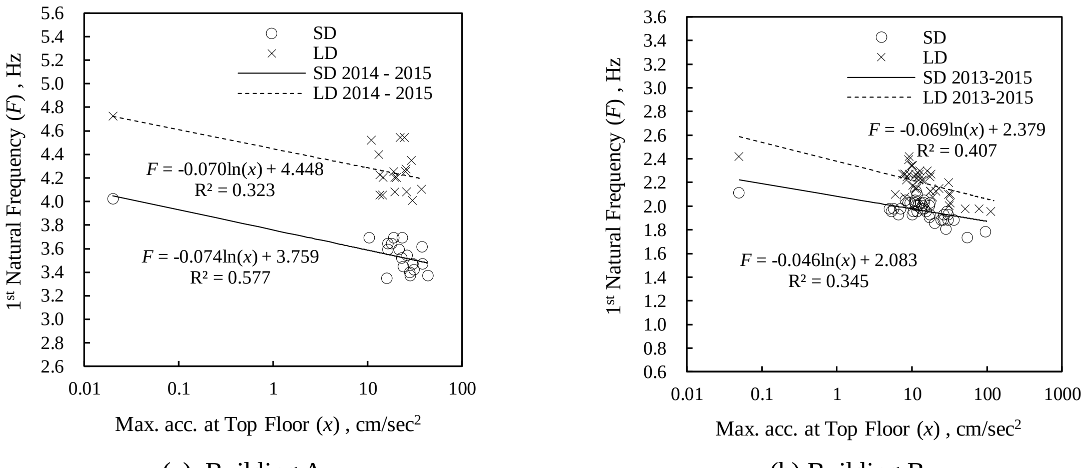
5.3 Eliminate the effect of temperature dependence

The relationship between natural frequency, maximum acceleration, and temperature is given by the summation of the amplitude dependence of the natural frequency, which has been presented in the previous section and the following function:

$$f_{\mathrm{dif}} = f_{\mathrm{mean}} - F(t) \qquad (1)$$

where f_{mean} is the average of natural frequency over a year based on the observations and $F(t)$ is given by substituting the temperature data at the time of occurring of earthquake into the regression curves discussed in section 4 (Figs. 8 and 9).

The natural frequencies modified with f_{dif} for building A (in LD direction) are plotted in Fig. 11, since this building is most affected by temperature. Weather data at this spot has been recorded by JMA[12)] at ten-minute intervals since 2010, allowing precise correlation with the earthquake timing. Fig. 11 indicates that correcting for temperature can improve the fit between acceleration and natural frequency, as the R^2 increases from 0.323 (before modification) to 0.504 (after modification). These results show that temperature may have an influence on dynamic characteristics regardless of driving amplitude, though the result is not statistically significant. This may be explained by noticing that the maximum accelerations are concentrated in the range from 10 to 35 cm/sec^2. The difference in natural



(a) Building A (b) Building B

Fig. 10 Amplitude dependent 1st natural frequency at investigated buildings frequency caused by acceleration amplitude is not clear.

However, we may predict the tendency that natural frequency will follow during an earthquake. Accurate determination of the amplitude dependence of dynamic characteristics is very useful for evaluating a building's structural integrity. By correcting for temperature, the abovementioned method may offer a rough estimate of the extent to which driving amplitude affects a building's natural frequency. Further data collection and analysis remains for future work.

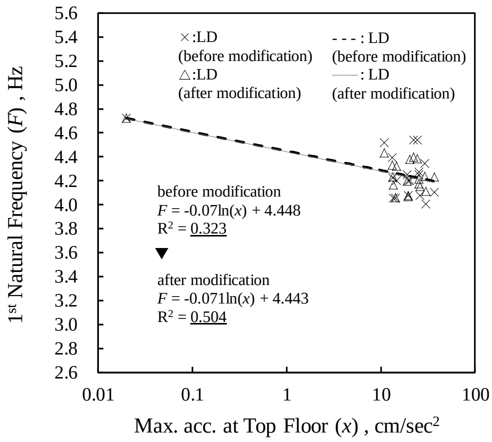


Fig. 11 Modified relationship between maximum acceleration and natural frequency (buildingA, LDdirection)

6. CONCLUSION

In this paper, the temperature dependence of dynamic characteristics of two existing buildings of reinforced concrete and steel is investigated based on the long-term continuous observations of vibrations. The amplitude dependences of the dynamic characteristics are also studied with earthquake response records. The main findings of this study can be summarized as follows:

1) Both buildings have a natural frequency, and that frequency increases with an increase in the temperature. The natural frequency of the reinforced-concrete structure is more sensitive to temperature than is the natural frequency of the steel structure.
2) Both natural frequencies depend on the driving amplitude supplied by an earthquake. Natural frequency drops significantly when the amplitude is large.
3) Since natural frequency is strongly dependent on the temperature, this effect may be eliminated to easily see how natural frequency depends on amplitude.

In this paper, it is suggested that temperature has an influence on the dynamic characteristics of buildings. Therefore, while implementing SHM, individual earthquake response records and long-term monitoring data may be both necessary for accurate evaluations of changing dynamic characteristics.
As the data considered in this paper was recorded for less than three years, the buildings should continue to be observed in the future. And this paper discusses dynamic characteristics extracted only from data recorded at the 3rd floor of the buildings. Further analysis remains for future work, such as the transfer function.

ACKNOWLEDGMENT

The support from the owners of the studied buildings is greatly appreciated. This work was supported by the Grant-in-Aid for Scientific Research(B) (No.26289187, principal investigator: Prof. Masato MOTOSAKA), and by an IRIDeS Special Project grant.

REFERENCES

1) Japan Building Disaster Prevention Association: Symposium on post-earthquake quick inspection of damaged buildings hitted by The 2011 off the Pacific coast of Tohoku Earthquake, http://www.kenchiku-bosai.or.jp (in Japanese, last accessed in December 5, 2016)
2) Maria, I., Todorovska, Mihailo D. Trifunac: Earthquake damage detection in the Imperial County Services Building I: The data and time-frequency analysis, *Soil Dynamics and Earthquake Engineering*, Volume 27, pp.564-576, 2007.
3) Kohler, M.D., Davis, P.M. and Safak, E.: Earthquake and Ambient Vibration Monitoring of the Steel-Frame UCLA Factor Building, *Earthquake Spectra*, Vol.21, No. 3, pp.564-576, 2005.
4) Masato, M., Makoto, H, Kuyuk H.S. and Arrecis F.: Development of an integrated early warning and structural monitoring system to real time earthquake information, *AIJ J. Technol. Des.*, Vol.14, No.28, pp.669-674, 2008. (in Japanese with English abstract)
5) Toshihide K., Shin K., Tatsuya A. and Namihiko I.: Change in dynamic characteristics of super high-rise buildings due to the 2011 Great East Japan Earthquake, *AIJ J. Technol. Des*., Vol.21, No.48, pp.493-497, 2015. (in Japanese with English abstract)
6) Tadayuki M., Yoshihiro S., Hiroaki R., Takehiko T. and Kazuhiro W.: Dynamic properties for the super-high-rise RC structure buildings based on long term earthquake records, *AIJ J. Technol. Des.*, Vol.20, No.45, pp.527-532, 2014. (in Japanese with English abstract)
7) Naohiro N., Toshihide K., Takuya K., Shinji I., Yasushi M., Takayuki S., Takahisa E. and Tetsushi I.: Study on horizontal first move vibration characteristics of low and middle rised RC and SRC buildings considering amplitude dependency, *J. Struct. Constr. Eng., AIJ*, Vol.81, No.721, pp.471-481, 2016. (in Japanese with English abstract)
8) Sub Committee on Earthquake Strong Ground Motion and Observation of A.I.J.: *The future of strong ground motion and observation(Draft)*, Report on Activities in Sub Committee on Earthquake Strong Ground Motion and Observation of A.I.J., 2003.3(in Japanese)
9) Building Research Institute: Research on dynamic characteristics of a residential building based on microtremor measurement, *Building Research Data*, No.122, 2009. (in Japanese with English abstract)
10) KuniJiban: http://www.kunijiban.pwri.go.jp/jp (in Japanese, last accessed in December 5, 2016)
11) Francisco A., Yoshiyuki T. Masato M.: Development of an Integrated Early Warning and Structural Health Monitoring System to Real Time Earthquake Information - Part4: The Structural Health Monitoring System, *Tohoku Journal of Natural Disaster Science*, Vol.44, pp.29-34, 2008. (in Japanese)
12) Japan Meteorological Agency: http://www.data.jma.go.jp/gmd/risk/obsdl/index.php (in Japanese, last accessed in May 12, 2017)
13) Japan Meteorological Agency: http://www.data.jma.go.jp/svd/eqdb/data/shindo/index.php (in Japanese, last accessed in May 9, 2017)
14) Motosaka, M., Ohno, S., Mitsuji, K., Wang, X. and Hatakeyama, T.: Development of Structural Health Monitoring System Combined with Earthquake Early Warning System for Real-time Earthquake Information Navigation, 16th World Conference on Earthquake Engineering, Paper ID.803, Santiago, Chile, 2017.
15) Clinton, J.F., Bradford, S.C., Heaton, T.H. and Favela, J.: The Observed Wander of the Natural Frequencies in a Structure, *Bulletin of the Seismological Society of America*, Vol. 96, No. 1, pp. 237-257, 2006.

(Original Japanese Paper Published: August, 2017)
(English Version Submitted: Nov. 6, 2017)
(English Version Accepted: Feb. 19, 2018)