Evaluation of a practical automatic damage assessment system using a single accelerometer for wooden frame houses

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Abstract In recent years, Structural Health Monitoring (SHM) has been attracting more attention as a method to determine the existence of the damage and its extent. The typical SHM system employs many sensors to assess the damage quantitatively and qualitatively. However, such a system is not appropriate for wooden houses as it is very costly despite the strong demand. Therefore, developing a low-cost SHM system for wooden houses is necessary. We have been working on algorithms that automatically determine the degree of damage from the maximum inter-story drift angle and natural frequencies using two accelerometers and evaluate the accuracy of the results by applying them to full-scale shake table experimental data.[1] Then, we evolved the system to use only a single accelerometer. In this advanced method, we estimate the first natural frequency without being annoyed by the fundamental frequency of ground motion, which often deteriorates frequency estimation accuracy. In this paper, we demonstrate the applicability of the SHM system using only one sensor in practical scenarios. Firstly, we examined the proposed method using only one accelerometer through the simulation approach. Secondly, we test the system's applicability utilizing a series of large-scale shake table test data. Finally, we examine this method's validity and economic feasibility, contributing to cost reduction and simplification of the algorithm for practical use.

Introduction

In April 2016, the Kumamoto earthquake occurred in Japan, causing multiple large earthquakes in a short period of two days. In particular, many people returned to their homes from evacuation places after the first main shock. They lost their lives due to the collapse of their wooden houses caused by the second major earthquake. This tragic event was caused by the fact that after the first earthquake, people returned to their homes from the evacuation site, unaware that the wooden building had lost its bearing capacity. Usually, after the main shock, the building capacity is checked by experts, which takes about one month on average. In other words, visual checks by experts alone are not enough to cope with such a huge earthquake in an extremely short period such as this one. The need is evident for a system that can automatically and quickly estimate the degree of damage to a building after the main shock by installing accelerometers inside the building. In addition, there is currently little research on automatic damage assessment systems using a single acceleration sensor in wooden houses, and further studies are needed for practical use.[2] Our research is precisely in this field (SHM), and we are researching the evaluation of building resistance using acceleration sensors. The fewer the number of accelerometers, the better, in terms of installation cost, etc., and the simpler the program, the better the management by residents through maintenance, etc. The fewer number of accelerometers, the better from the point of view of installation cost, etc. Considering these factors, we show their effectiveness and usefulness in this paper.

The proposed method

Previous issues with the method using a single accelerometer

A method for estimating the maximum inter-story drift angle of a building using a single accelerometer has been proposed. However, there was a problem that the ground's natural frequency affected the building's first-order natural frequency estimated by system identification, as shown in Figure 1 below. How to remove this effect remained an issue. Therefore, we propose a method for estimating the first-order natural frequencies of buildings, which is one factor in determining the degree of damage.

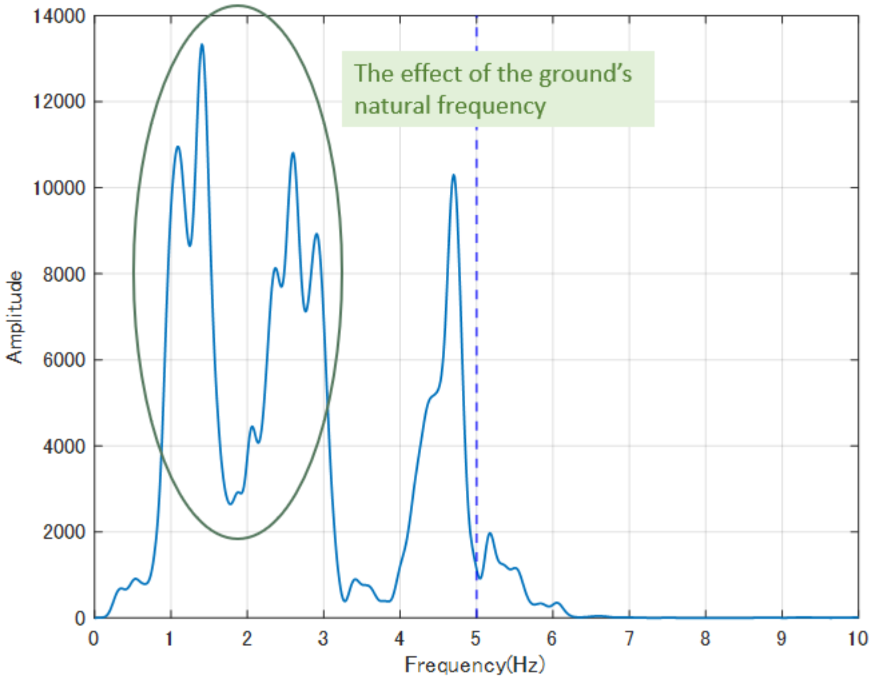

Fig.1 A problem with the effect of the ground's natural frequency

Use of the initial tremor interval

During our research, we discovered that it is possible to estimate the primary natural frequencies of buildings by extracting the response acceleration of buildings to the initial microtremor section of a large earthquake and performing spectral analysis to remove the effect of the ground. First, the initial microtremor time is calculated by the following Omori formula.

$$D = k \cdot \tau \tag{1}$$

D is the hypo central distance, τ is the initial microtremor duration, and k is the Omori coefficient. The Omori coefficient varies from 4 to 9 km/s depending on the location. It can be assumed to be 8 km/s for the Japanese Islands.

Next, a spectral analysis using power spectral density is performed on the response acceleration data of the building, from which the initial microtremor interval is extracted to estimate the primary natural frequencies of the building. Equation (2) below represents the Fourier transform, where $X(\omega)$ is the Fourier spectrum. The power spectral density (PSD) is calculated by equation (3) below. It can be obtained by dividing the mean of the squares of the Fourier spectrum by the frequency resolution Δf, which is determined by the length of the time history T with$\Delta f = \frac{1}{T}$.

$$X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-i\omega t}dt \qquad (2)$$

$$PSD(\omega) = |X(\omega)|^2/\Delta f \qquad (3)$$

In this study, we will examine the method using simulation data and experimental data. Figure 2 below summarizes the flow of this approach.

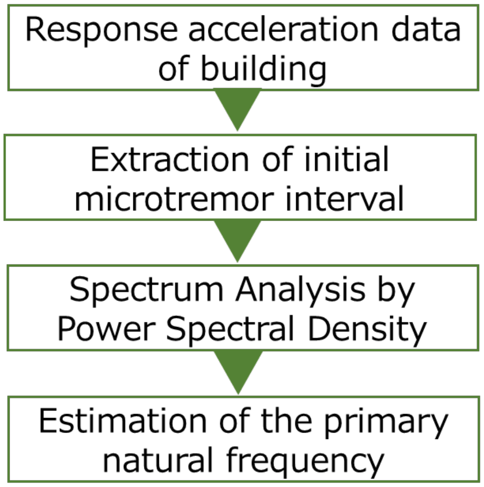

Fig.2 Flow-chart of the proposed approach

Estimation results

Full-scale shaking table experiment

The actual data used in this study are based on experiments conducted at E-defense, a full-scale 3D seismic rupture test facility at the National Research Institute for Earth Science and Disaster Prevention (NIED) Hyogo Earthquake Engineering Center. Among them, we will use data from a vibration test titled "Verification of Seismic Transfer Structural Safety of Detached Houses against Large-Scale Earthquakes" conducted in 2015.

The subject of this study is a wooden house with a two-story 2×6 panel structure and no vibration control system installed. Figure 3 below shows the south and east elevations, and Figure4 shows a photograph of the specimen.

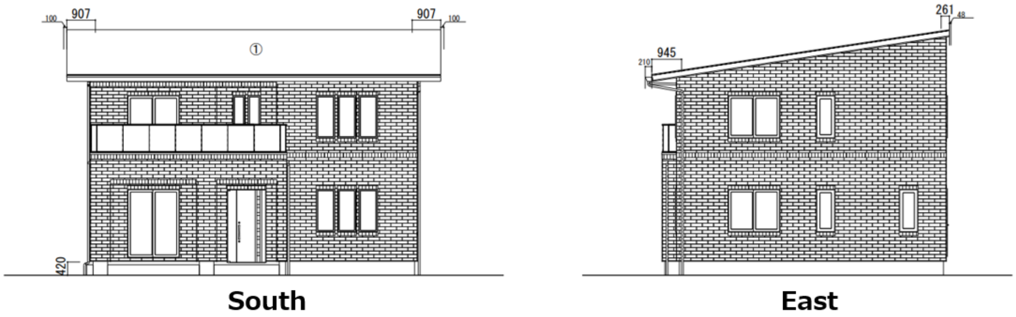

Fig.3 South and east elevations

Fig.4 Two test buildings on the table

Fig.5 Accelerometer used in the tests

On each first and second floor, servo accelerometers were installed at the northwest, center, and southeast locations. The accelerometer is a 3-axis servo-type accelerometer, TA-25E, manufactured by TOKYO KEIKI CORPORATION, and Figure 5 shows a photograph of it. This study uses four types of seismic motions from these excitation experiments, as shown in Table 1 below.

Table.1 Seismic waves

Earthquake	Input scale	Input Directions
JR Takatori	100%	XYZ
JMA Kobe	100%	XYZ
K-net Hitachi	100%	XYZ
K-net Mito	100%	XYZ

Result of the simulation

In studying a method for automatic determination of the degree of damage using a single accelerometer, a two-mass linear numerical simulation modeling a wooden house is designed. Table 2 below shows the design parameters for the simulation.

Table.2 Simulation parameters

mass ratio(m_1, m_2)	2 : 1
rigidity ratio(k_1, k_2)	1 : 0.7
primary natural frequency	5Hz
damping ratio	5%

Figures 6 and 7 below show the input and output waveforms of building response acceleration and the red line in it means the period of extracting the initial tremor interval. Figure 8 below shows PSD results when input by JMA Kobe seismic acceleration data. The building response acceleration is for the first-floor horizontal direction.

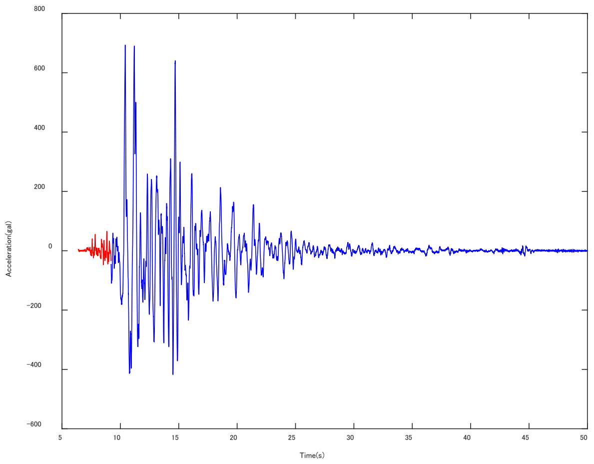

Fig.6 Input waveforms

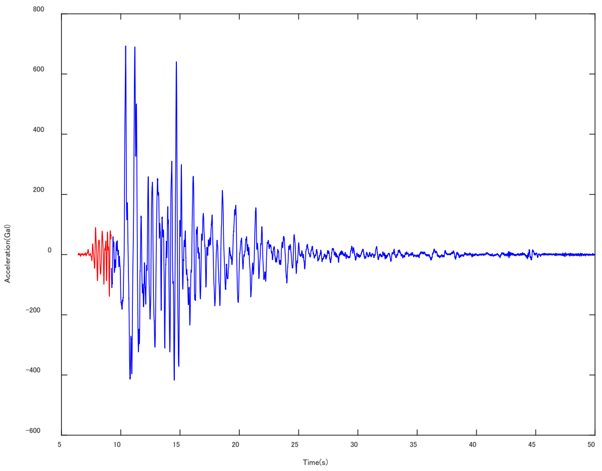

Fig.7 Output waveforms obtained by simulation

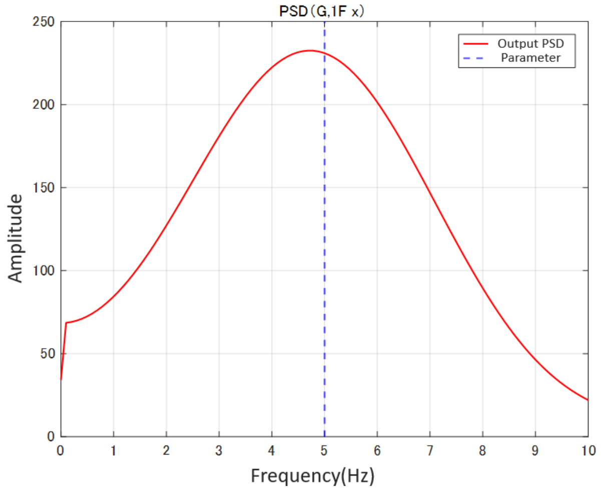

Fig.8 PSD result

The estimated primary natural frequency was 4.69 Hz, close to the parameter setting value of 5 Hz. Since the initial microtremor interval is extracted, it is clear that the low-frequency component, which has a strong ground component, has almost no effect.

Next, we tested how much the estimated results deviated from the set value when the parameter set value for the primary natural frequency of the simulation varied between 2 Hz and 8 Hz for the four seismic data. Next, we tested how much the estimated results deviated from the set value when the parameter set value for the primary natural frequency of the simulation varied between 2 Hz and 8 Hz for the four seismic data. The results are shown in Table 3 below. If the error in the estimated results is within 1 Hz, it is indicated as 0, if it is within 2 Hz, it is indicated as △, and if it is larger than that, it is indicated as ×.

Table.3 Simulation results for applicable frequencies

Earthquake	Primary natural frequency[Hz]						
	2	3	4	5	6	7	8
JR Takatori	△	×	○	○	×	○	○
JMA Kobe	△	○	○	○	△	○	○
K-net Hitachi	△	○	○	○	○	○	○
K-net Mito	△	○	○	○	○	○	○

The results in the table above show that the method applies to most seismic motions. Still, it does not apply to the 3 Hz and 6 Hz of the JR Takatori seismic motions because the estimation error is more than 2 Hz.

Use of full-scale shake table test

Finally, the initial microtremor interval is extracted, and PSD is applied directly using the full-scale shake table test. Figure 8 below shows the results of building response acceleration for the JR Takatori seismic data. Figure 9 below shows the PSD results of it.

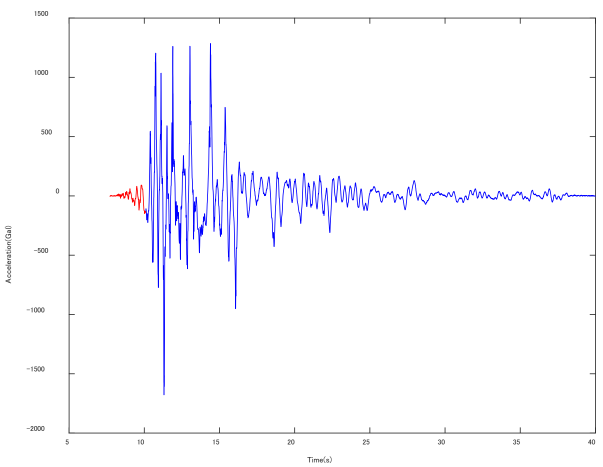

Fig.8 Output Waveforms

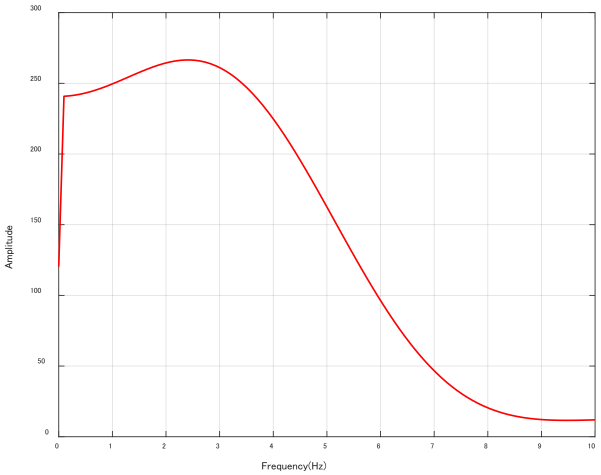

Fig.9 PSD results of building response acceleration for the JR Takatori seismic data

The estimated primary natural frequency obtained from this result is 2.44 Hz, which, compared with the reference value calculated by the transfer function and ARX method, is shown in Table 4 below.

Table.4 Comparison between the estimated value and reference value

estimated value	reference value	
PSD	ARX	transfer function
2.44Hz	2.56Hz	2.44Hz

The comparison results in the table above indicate that the difference between the estimated and reference values of the primary natural frequencies is less than 0.2 Hz, suggesting that our method is effective for recording actual data building response acceleration.

Conclusion

In this paper, we have studied the usefulness of an automatic damage assessment system for wooden wall houses using a single acceleration sensor. In estimating the first-order natural frequencies, we compared the values with the set values in simulations and with reference values obtained using building response acceleration data from full-scale shaking table experiments. The results showed that the difference between the estimated and reference values was minimal, indicating that the method is applicable.

References

[1] Yu Suzuki, Akira Mita: Output only estimation of inter-story drift angle for buildings using small number of accelerometers, J. Struct. Constr. Eng., AIJ, Vol.81, No.725, 1061-1070, Jul.,2016. https://doi.org/10.3130/aijs.81.1061

[2] Kangqian Xu, Akira Mita: Maximum drift estimation based on only one accelerometer for damaged shear structures with unknown parameters, Journal of Building Engineering, 46, (2022), 103372, Sep.,2021. https://doi.org/10.1016/j.jobe.2021.103372

[3] Yuichi Furukawa, Ko Horita, Akira Mita: Proposal and Evaluation of Practical Automatic Damage Assessment System for Wood Frame Houses, AIJ, Summaries of Technical Papers of Annual Meetng, Hokkaido, #1164, Sep., 2022