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# HEALTH MONITORING OF NATIONAL HERITAGE FIVE STORY WOOD PAGODA BY IMAGE PROCESSING AND VIBROMETERS

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## ABSTRACT

This Five storied pagoda is built of wood and is known as a high earthquake proof structure. The pagoda is composed of the frame and the center column. The center column is structurally independent of the frame structure. Many researchers have mainly been interested in its characteristics under natural forces; such as earthquakes and strong winds. We began the monitoring of acceleration responses of national heritage five storied pagoda which is located in Ichikawa City close to Tokyo and constructed in 1622; Hokekyo-ji Pagoda. In addition, image procession monitoring is also conducted. An motion capture camera which shoots the several illuminating marker on each story, is installed at first story beam. The marker positions are obtained instantly in site PC, and stored in site PC hard disk, in 10Hz sampling, continuously. Using the maker positions, the each story displacements to first story are calculated. The relative displacements are compared with two time acceleration integral displacement using filtering. From the setting of camera, two earthquakes of about 0.6cm/s and strong wind of about 25m/s were obtained. The comparisons were reasonable. Image processing displacements are indicating long term period structure deformations.

## Introduction

The In Japan, there are five storied pagodas of more than 22, which were built before 1850. Although there are many reports of its dynamic characteristics under the earthquake and strong winds, there are a few reports on them under both the seismic load and wind load. Many micro tremor measurements of the real pagoda were conducted (Kanai and Yamabe 1988, Fujita 2004). Shaking table tests of scale models were also done. Seismic response of new-built five storied pagoda was obtained under an actual seismic event of the intensity level 5. Our response observations are on the Nakayama Hokekyo-ji Pagoda, which is located at Ichikawa-shi in Chiba Prefecture which is close to Tokyo. It is a statue of Buddha and was dedicated in the 1622. Micro tremor measurement of this pagoda has already been conducted. Natural frequency and vibration mode of the frame and the center column were reported.

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In half century, computing and image processing technology have progressed very much. Image processing techniques was applied to displacement measuring in many areas. In seismic response tests using shaking tables, the image processing displacements have been reported . In this research, we monitored not only its response characteristics under seismic load but also under the strong wind load by using vibrometers and image processing.

## Hokekyou-ji Temple Fiveried Pagoda

The pictures of Hokekyo-ji Pagoda and its location are shown in Fig. 1 and 2. It is a five storied pagoda and built of wood without the use of nails. It is a 30.76m-high statue of Buddha. It was dedicated in 1622 and renovated several times, in 1743, 1864 and 1912. The pagoda is composed of a frame and a center column. On the top of the center column, a metal ornament called a sourin is attached. The structure has a square and symmetrical plan. The front of the pagoda is face to the southwest. The difference between pagoda axis and compass axis is 40. Fig.3 shows the cross section of the pagoda. The frame is composed of 5 blocks (stories) and the blocks are simply piled together. Each block of the frame is able to move independently from each other and it becomes a flexible frame structure. The center column is hung with the suspension system made up of 4 units of steel plate with two steel rings at the third story of the frame. The bottom head of the center column is not fixed and it is structurally restricted to move freely by the iron dowel. The center column is structurally independent from the surrounding frame.

Fig.1. Hokekyou-ji Five Storied Pagoda

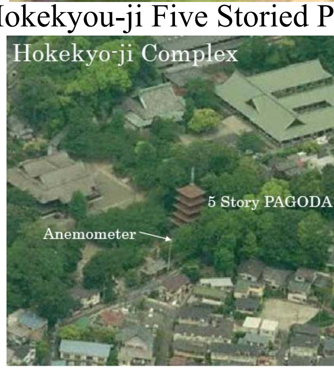


Fig.2. Location of the Five Storied Pagoda

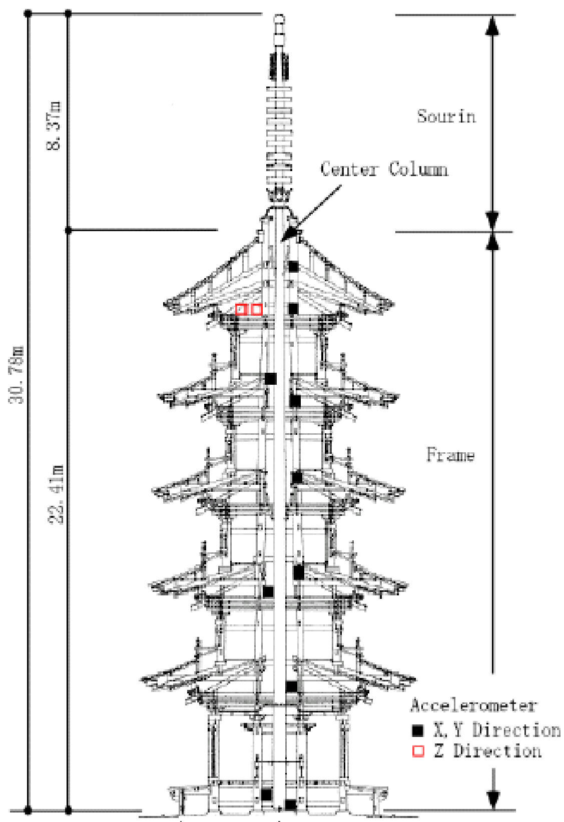


Fig.3. Structure Outline of Hokekyou-ji Five Storied Pagoda and Vibrometer Position.

## Monitoring System

At first, vibrometers were installed in Hokekyou-ji Five Storied Pagoda. In a year, image processing system was installed.

### Vibrometer System

Vibrometers and digital recorders were used in the monitoring system. Horizontal accelerations are measured at several points on the frame and center column. Two accelerometers are set on the fifth story to measure the vertical acceleration. These are shown in Fig.3. Sampling frequency of the record was set to 100Hz at first and missing data was observed in the recorded data of the center column. It was changed to 1000Hz now. Fig.4 is the Fourier spectra of center column which include frequency components of more than 100Hz. The system is going at all times.

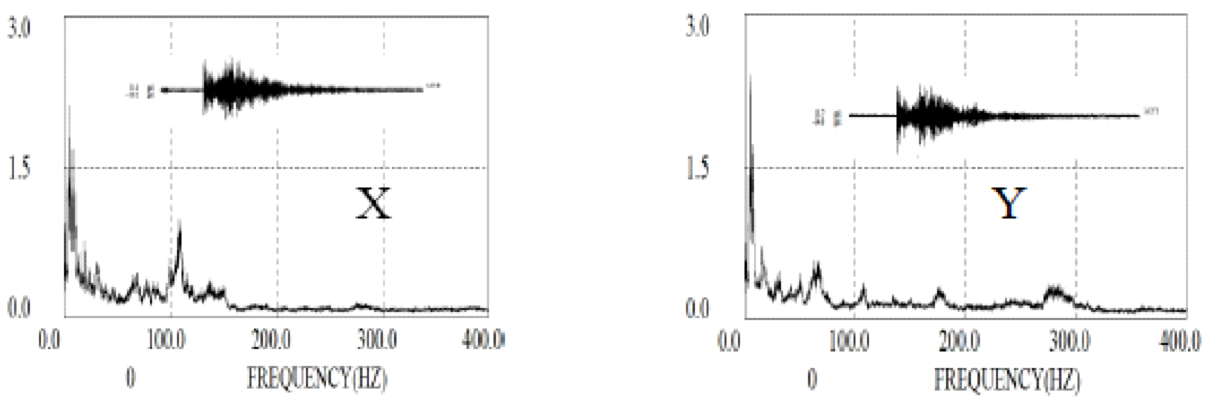


Fig.4. Fourier Spectra of Center Column Responses to a earthquake

To understand the response of the structure, the displacement wave is important. In vibrometer system, the displacement was obtained by integrating the recorded acceleration data two times. The recorded acceleration was low level one. The fluctuation was clearly observed in the displacement data. In this case, a high pass filter and a low pass filter were adapted to the recorded data. Low pass filter $\dot{x} + h\omega x = h\omega y$ and high pass filter $\dot{x} + h\omega x = \dot{y}$ were used. Where y is input, x is output, $\omega$ is circular frequency, and h is coefficient. In this case, h=1.4, fo=20Hzin low pass filter and fo=0.3Hz in high pass filter were used. Fig. 5 showed the results of filtering the data three times.

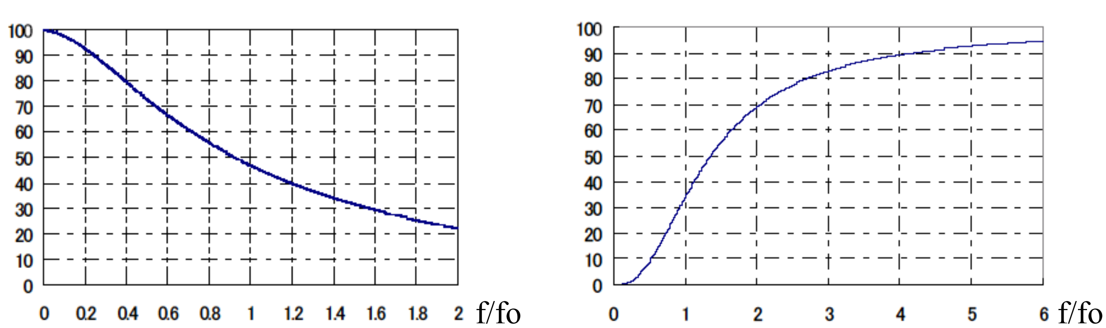


Fig.5 Low Pass Filter Gain % High Pass Filter Gain %

**Image Process System**

Image procession monitoring system consists of CCD camera, LED makers and data acquisition computer. Fig.6 shows outline of image procession monitoring system for Hokekyou-ji five storied pagoda. Multiple markers (monitoring targets) are fixed at each story beam of five storied pagoda as shown in Table 1 and Fig.7. And the motions of the markers are captured by a CCD camera placed at first story beam. Each marker position (pixels) in camera image is calculated instantly in data acquisition personal computer on site. Performances of camera and PC are shown in Table 2. The marker position data are stored in hard disk, every hour. It takes one second to store one hour data in hard disk. One year data length is about 70GB.

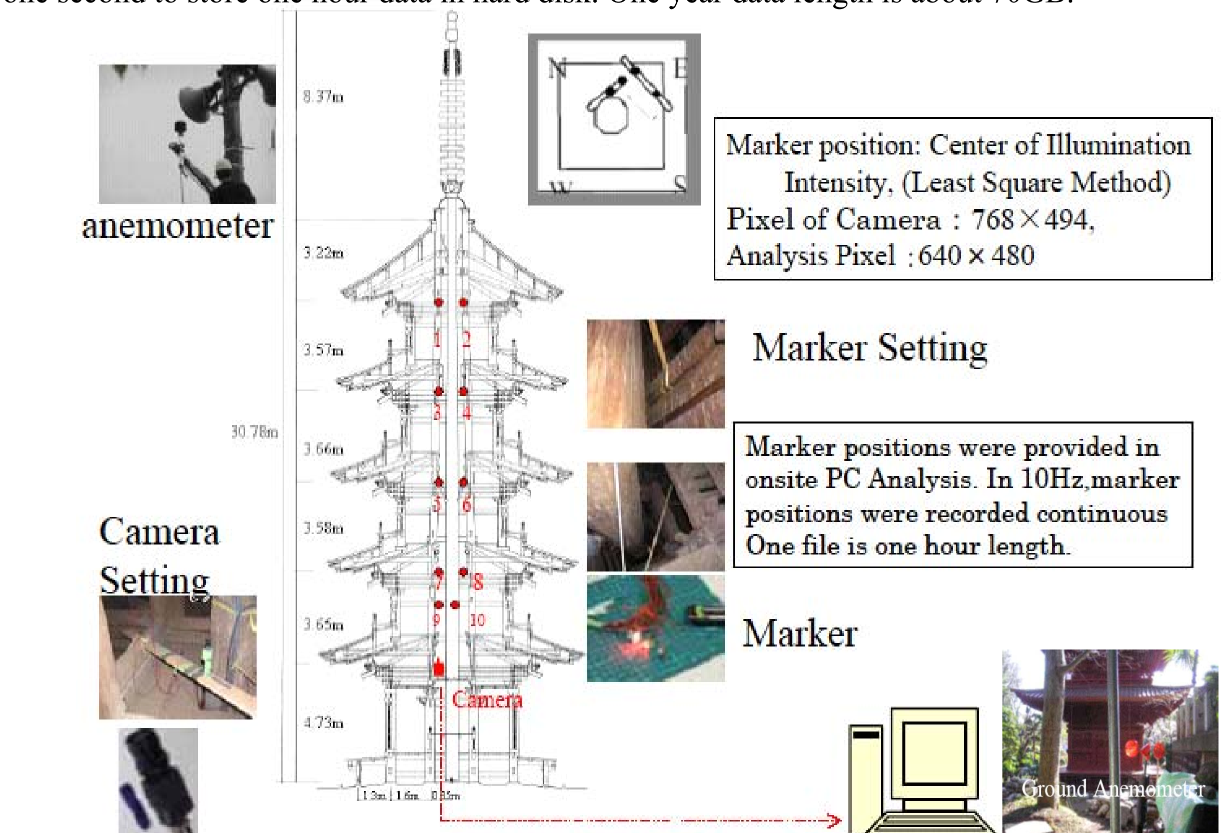


Fig.6. Image procession monitoring system for Hokekyou-ji Five Storied Pagoda

Table 1. Marker Position

| Marker No | Height (Distance from Camera)(mm) | Distance of two markers L (mm) | Distance on Image D (pixels) | Coefficient L/D (mm/pixel) |
|---|---|---|---|---|
| 1,2 | 14,479 | 500.0 | 79.27 | 6.3076 |
| 3,4 | 10,891 | 500.0 | 103.87 | 4.8135 |
| 5,6 | 7,265 | 500.0 | 158.29 | 3.1588 |
| 7,8 | 3,628 | 500.0 | 322.90 | 1.5484 |
| 9,10 | 2,208 | 200.0 | 216.52 | 0.9237 |
| 11 | - | - | - | about 1.8 |

Table 2. Performance of Camera and PC

| | |
|---|---|
| Camera | Monochrome 1/3 inch CCD made by Toshiba |
| Signal | NTSC Analog, 30 frame / sec |
| Lens | F12.5mm, F1.4, C-Mmount |
| Computer | Pentium4HT, 3.0GHz, 1GBMemory, 250GBHDD |
| Resolution of Capture | 640 X 480 pixels 8 bits |
| Processing Speed | 10 frame / sec (Sampling Speed) |

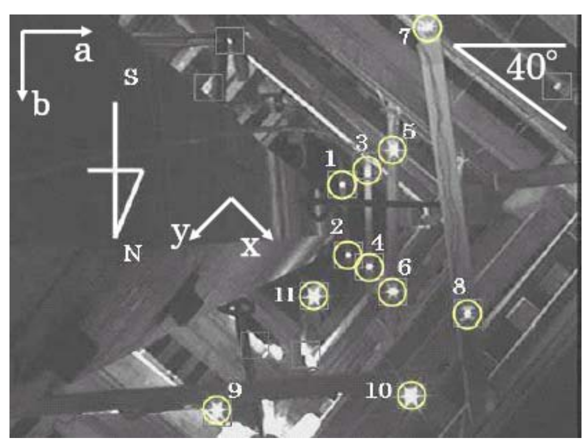


Fig. 7 Captured Multiple Markers Image

**Image Processing**

Fundamentally, the marker in camera image is not a point light source, and it was designed to have a resultant spread light area of some pixels on the camera image. Therefore, the light source is blurred in the camera image, and the luminance distribution of the pixels can be obtained from the pixels which were recognized as an image of marker.

The m-th marker position $\left(p_a^{(m)},\ p_b^{(m)}\right)$ is calculated in pixels as follows. The position of the marker on the camera image with some pixels is given by the luminance $f_{ij}$ distribution of the marker which is over the threshold level $f_{threshold}$. In the monitoring, $f_{threshold}$ is given like this,

$$f_{threshold} = \lambda \cdot \left(f_{\max} - f_{average}\right) + f_{average} \qquad (1)$$

$$\lambda = 0.1 \sim 0.3$$

Luminance is denoted again.

$$f_{ij}^{*} = \begin{cases} f_{ij} \cdots\cdots f_{ij} \geq f_{threshold} \\ 0 \cdots\cdots f_{ij} < f_{threshold} \end{cases} \qquad (2)$$

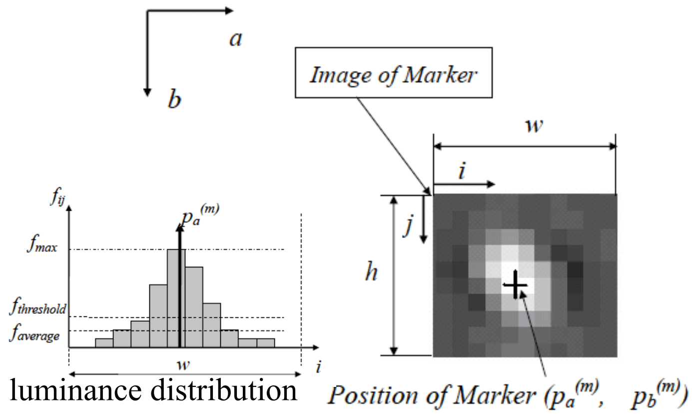


Fig.8 Marker recognition method on two-dimensional camera image

Next, the position of the marker on the images is obtained using centre of gravity calculation method. The positions of $a,b$ directions are given as follow.

$$\left(p_a^{(m)},\ p_b^{(m)}\right) = \frac{\sum_i \sum_j (\ell i,\ \ell j) \cdot f_{ij}^{*}}{\sum_i \sum_j f_{ij}^{*}} \qquad (3)$$

Calculation area (h, w) have the height of 32 pixels and the width of 32 pixels in the monitoring. $f_{ij}$ in the monitoring is 8bits data.

Pagoda displacements are calculated as follows. Pagoda axes are x, y. (m) is maker number. $\left(\delta_a^{(m)},\ \delta_b^{(m)}\right)$ are displacements in screen axes for m-th marker. $\alpha^{(m)}$ is coefficient given by L/D of Table 1. $\theta$ is the angle between pagoda axes and screen axes, 40degree. $\left(\delta_x^{(m)},\ \delta_y^{(m)}\right)$ is displacements in pagoda axes for m-th marker. In the monitoring, there are two LED markers in each story, with distance of 500mm.

$$\left(\delta_a^{(m)},\ \delta_b^{(m)}\right)[mm] = \alpha^{(m)} \cdot \left(\Delta p_a^{(m)},\ \Delta p_b^{(m)}\right)[pixels] \qquad (4)$$

$$\begin{pmatrix} \delta_x^{(m)} \\ \delta_y^{(m)} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \delta_a^{(m)} \\ \delta_b^{(m)} \end{pmatrix} \qquad (5)$$

## Long Term Continual Recoding of Image Processing Data

The image processing would be able to give the long term horizontal deformation data. In Fig. 9 and 10, deformations from camera position (first story), wind speed and wind direction (WDIR) are shown with average of 2 minutes. The Full monitoring; image processing system and vibrometer system with anemometers was completed, and recording was started. Initial states are at 0am, on June 1st 2009. Trial recording began from January 2009. The observation with vibromaters started in June 2007.

**Anemometers**

Two anemometers are used in the monitoring. One is set at back yard, about 15m apart from the pagoda, about 1.5m height from ground, which is a generator type with three cups, as shown in Fig 6. The other is set on an electric pole at front yard, about 15m apart from the pagoda, about 13m height from ground, which is ultra sonic type with 4Hz sampling, as shown in Fig.2 and 6. According to June wind speed of Fig.9 , the wind speed ratio of 13m high and 1.5m high anemometer is about 2.5 ~ 3.5. at time of low wind velocity level, wind direction are unstable. Day fluctuating deformations about 1mm are found in Fig. 9 and 10. Shifts of monitoring deformation lines would be caused by climate changes. Rainy and Cloudy days continued to July 11. Days from July 11 to July 20 were hot. From July 21, cloudy days continued again. It is clear that deformations of the pagoda related strong with wind characteristics.

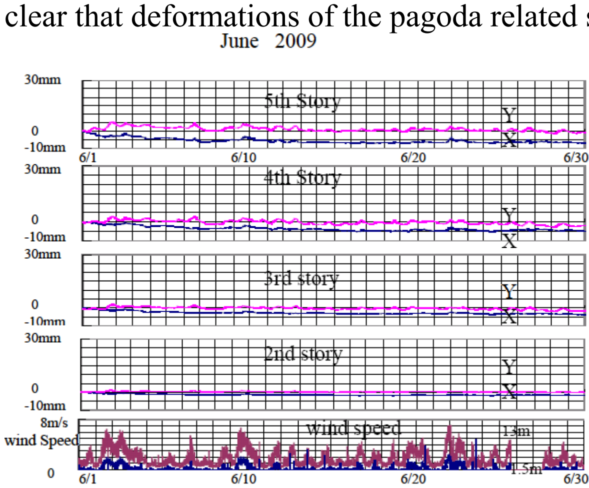


Fig. 9 June Pagoda deformation and wind speed.

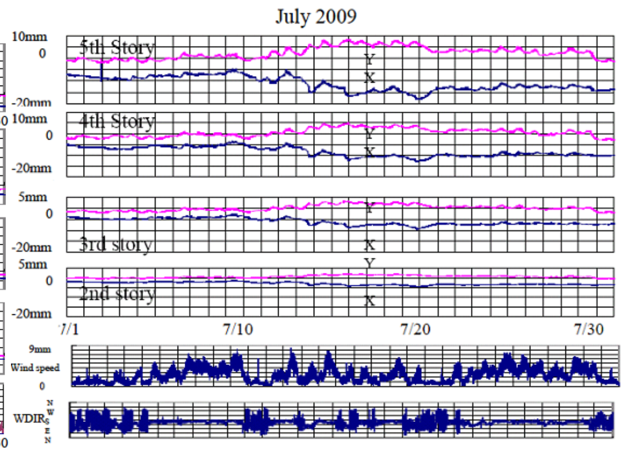


Fig. 10 July Pagoda deformation and wind Speed and wind direction.

## Earthquake Response Record Results

Several earthquake responses of more than 10cm/s/s were recorded. In 2007 Chuetsu-oki earthquake, M=6.8, depth about 17km, about 250km northwest from Hokekyou-ji, horizontal ground motions of x=10.9cm/s/s, y=10.4cm/s/s were observed. In the earthquake on May 8th 1:45am, 2008, M=7.0, depth about 45km, 150km northeast, accelerations of x=39cm/s/s, y=28.3cm/s/s were observed.

The dynamic characteristics of Hokekyou-ji Five Storied Pagoda in 2007 Chuketsu-oki Earthquake is described. Acceleration response time histories are shown in Fig. 11. Fourier amplitudes on X and Y components are shown in Fig.12. There would be no difference of X and

Y characteristics. First and second vibration mode frequencies are estimated about 0.8Hz. and about 2.4Hz. In Fig.13, vertical distributions of pagoda deformation during 2.5second are shown with step interval time 0.1second. The maximum deformation of top sensor position gave 5mm in X direction and 7mm in Y direction. The vertical distribution clarified the first mode response dominance in strong earthquakes. In the earthquake on May 8th 1:43am, 2008, the maximum deformation of top sensor position gave 9.5mm in X direction and 10.1mm in Y direction. Second vibration mode was also observed in the Earthquake on May 1st 7.34am, 2008, M=4.6, depth=36km, about 50km southeast. Fig. 14 is the vertical distributions of pagoda deformation duration 2.5second with step time interval 0.1second, which would be the verification of second vibration mode generation.

In the earthquakes on August 9th 19:55 2009, M=7, depth=333km, about 350km southwest, and August 11th 5:07am 2009, M=6.5, depth=23km, 150km west, image processing system obtained pagoda response deformations to the earthquakes. Ground accelerations of August 9 earthquake are x: 19.8cm/s/s, y: 20:5cm/s/s z: 8:4cm/s/s. Ground accelerations of August 11 earthquake are x: 5.4cm/s/s, y: 11:9cm/s/s z: 4:5cm/s/s. Image processing data of each pagoda story are compared with the two time integral displacement of vibrometer data. Image processing data are relative displacements to 1st story. In order to compare the image processing data, 1st story two times integral displacement data have to be subtract from east story one. Fig. 15 is August 9 data.

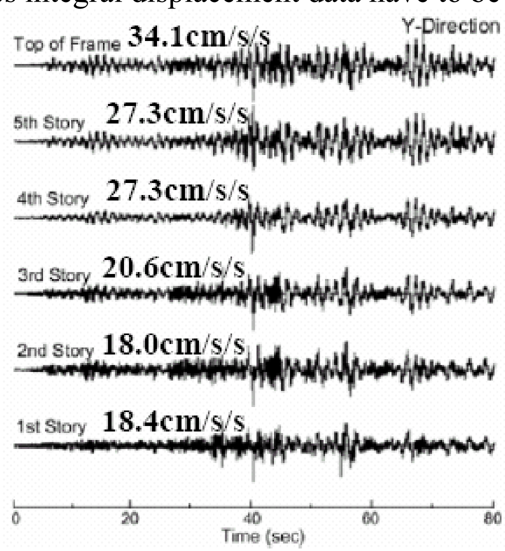


Fig.11 Pagoda Acceleration Response Time Time history to 2007 Chuetsu-oki Eq.

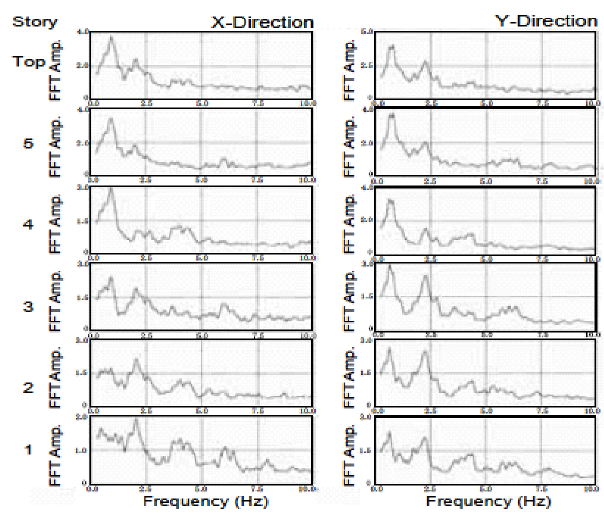


Fig.12 Fourier Spectra of Pagoda Response Time History of 2007 Chuetsu-oki Eq.

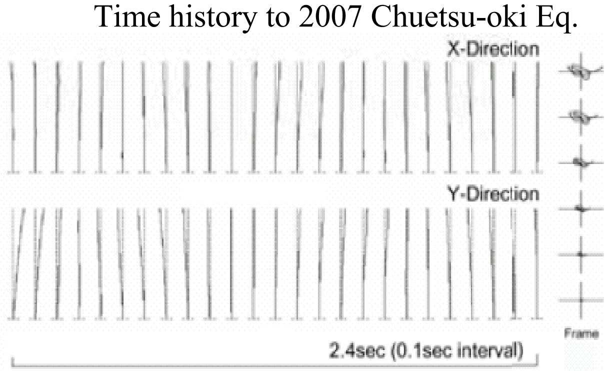


Fig.13 Vertical Distribution of Pagoda Deformation in 2007 Chuetsu-oki Eq.

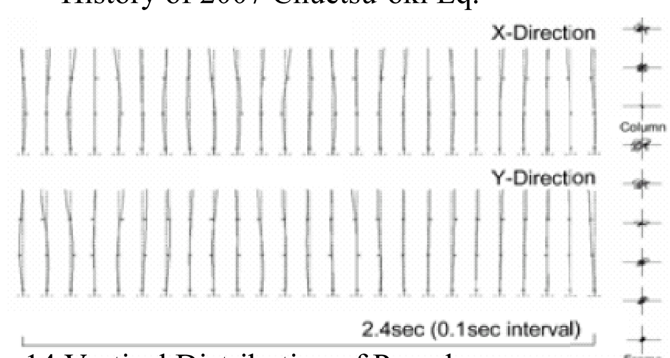


Fig.14 Vertical Distribution of Pagoda Deformation in Eq. of May 1st 7:34 2008

Fig. 16 is August 11 data. Image processing data are less than 4mm. In August 9th data, at 20:00, the data was sent from PC memory to hard disk. One second data blank occurred during the earthquake. Fig. 17 is August 19 data. Image processing data are less than 5mm. The 5th and 4th story data shows relatively good agreements of two systems: image processing and vibrometer system. However, in 3rd and 2nd story data in both figures, two system agreements would not be good. The reason of two system difference is brought by noises and reliabilities of vibrometers ( accelerometer), two times integral and filtering. In reliability, image processing is preferable to two times integral displacements.

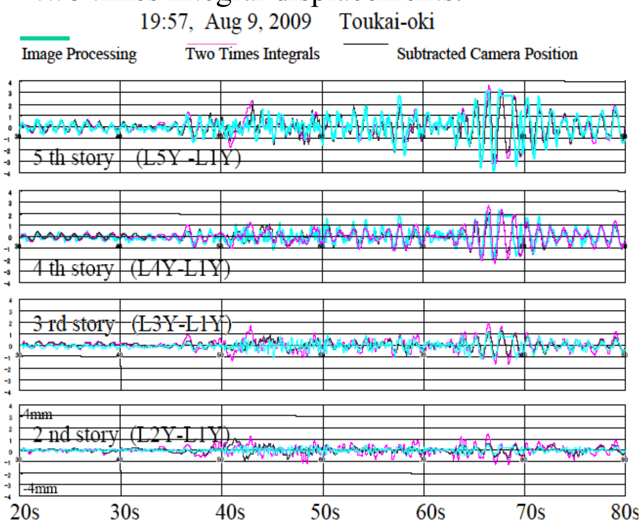


Fig. 15 Image Processing and Two Times Integral of August 9th 2009 Earthquake

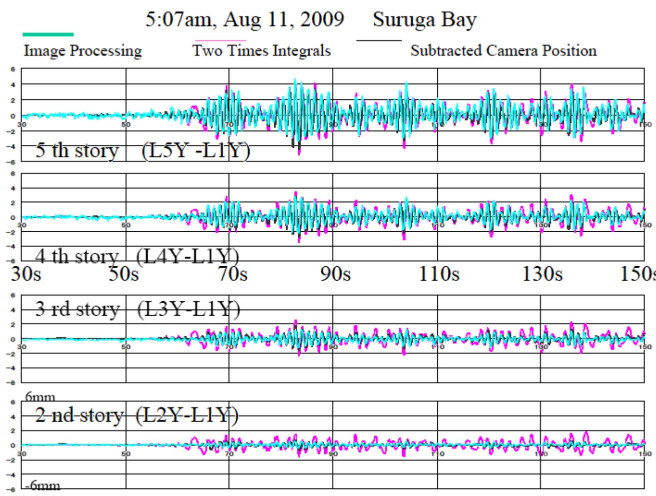


Fig. 16 Image Processing and Two Times Integral of August 11th 2009 Earthquake

## Wind Response Record Results

The vibrometer system records not only earthquake responses, but also strong wind responses of five storied pagoda. On February 24th 2008, strong winds hit Japanese Islands. The vibrometer system records presented larger responses than ever recorded earthquake responses .Fig. 17 is the two times integral displacements with different High Pass Filter frequencies (HPF).

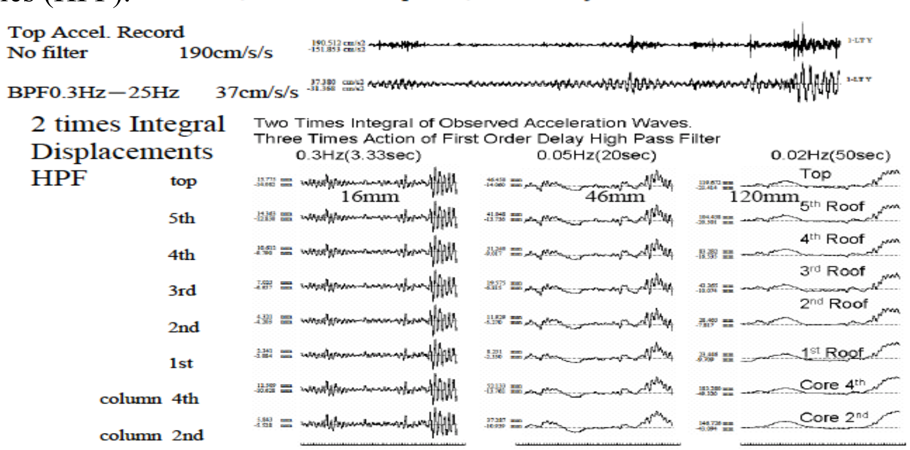


Fig.17. Two Times Integrals of Feb. 24 Strong Wind Response Data

The displacements of top position are 16mm with HPF 03Ha, 46mm with HPF 0.05Hz and 120mm with 0.02Hz. To get real displacements at strong winds, direct displacement measurement is desired. So, we decided to use image processing for the Hokekyou-ji monitoring. The other way, the dynamic period of Hokekyou-ji five storied pagoda increased in accordance with increase of response amplitudes. In Feb. 24$^{th}$ 2008, a first vibration period changed from 1.3second to 1.6second as shown in Fig.18.. The rigidity decrease in accordance with increase of response amplitude was verified.

In the reason, an image processing system was installed. After full system completed, a typhoon hit the pagoda on October 8$^{th}$ 2009. Fig.19 is wind records from Oct. 1 to Oct.10, which shows maximum wind speed of 26.8m/s of the typhoon. Fig.20 are deformations records corresponding to Fig.19. The maximum deformations of 5$^{th}$ story form 1$^{st}$ story are about 40mm in both x, y directions, including static deformations. Fig. 20 is two times integral displacements of vibrometer records; accelerations, with HPF of 0.2Hz, about 40seconds. This would be dynamic relative displacements to ground. Fig.21 is the image processing deformation corresponding to Fig21. The records are relative displacement to 1$^{st}$ story. Therefore, at time of comparing Fig.20 and Fig.21, 1$^{st}$ story amplitude value have to be subtracted from each story amplitude in Fig.20. So, wind response time histories of Fig.20 and 21 show good agreements in x and y directions. Vibrometer system monitoring in Fig. 20 describes short period fluctuation, probably a few times larger structure fundamental period. Image processing system monitoring describes fluctuation including long term, and perhaps static deformation from camera position..

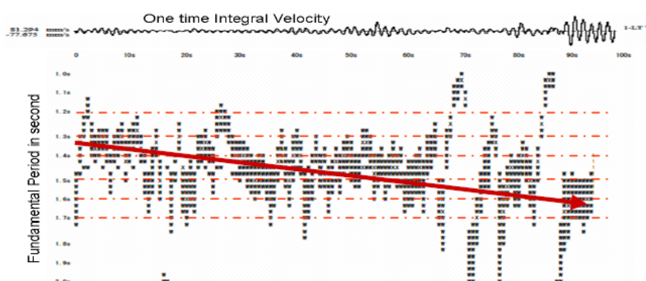


Fig. 18 Running Spectra of Top Story Response in Feb. 24$^{th}$ 2008 Strong Wind .

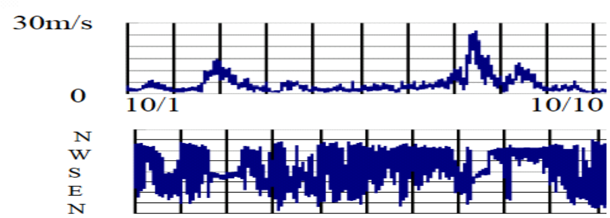


Fig.19 Wind Records of 13m Anemometer in October1 ~10

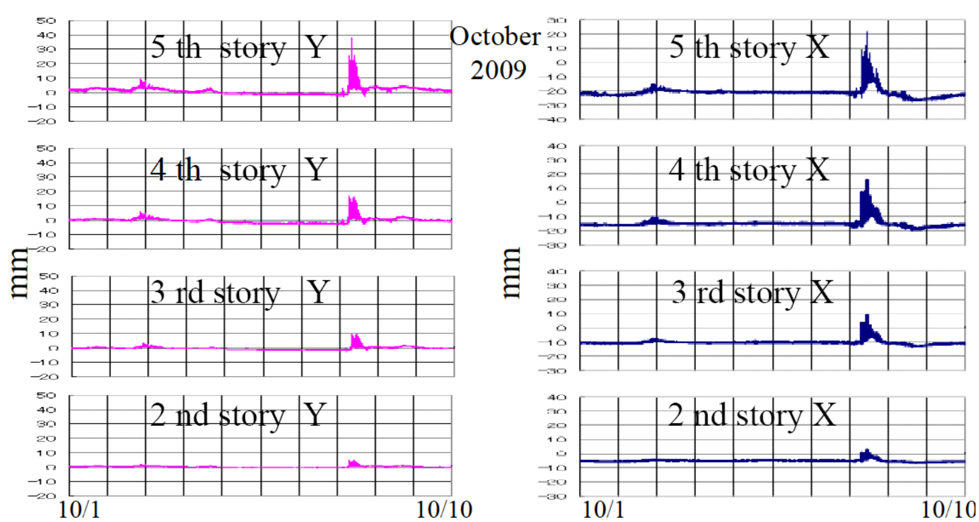


Fig. 20 Image Procession Deformation Records of Each Story from 1$^{st}$ Story in October 1-10.

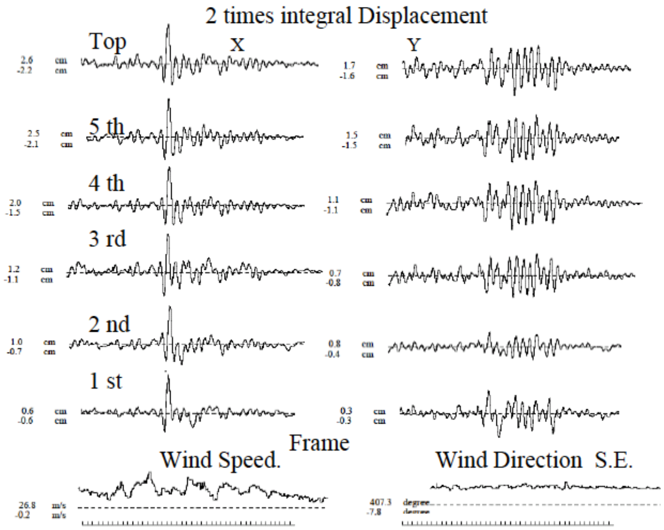


Fig. 20 Two Times Integrals of Vibrometers with Filtering at Typhoon of 40seconds.

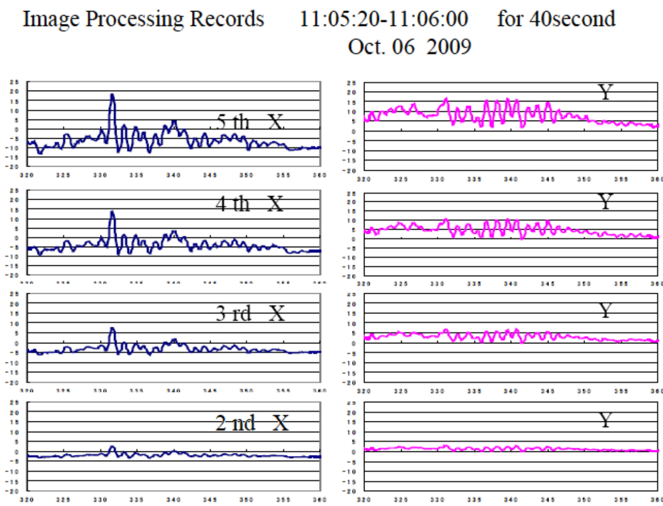


Fig.21 Each Story Image Processing Deformations at Typhoon of 40sec.

## Conclusions

Earthquake and strong wind responses of Five Storied wood Pagoda were monitored and recorded. About 1cm deformation in half amplitude in earthquake motion of about 40cm/s/s was observed. Supposing strong earthquake motions of nearly 1G and proportional deformations, five storied pagoda would make deformation about 0.3m, which would not bring serious damages to the pagoda. Deformation nearly 4cm under strong wind of about 25m/s were observed. Supposing strong wind about 60m/s. Deformation nearly 20cm would be bought.

Image Processing Monitoring is useful for estimating long term deformation of structures. More investigations and theoretical analysis are required to clarify the five storied wooden pagoda.

## Acknowledgments

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