EVALUATION OF VIBRATION CHARACTERISTICS OF TRADITIONAL THATCHED ROOF HOUSES IN JAPAN

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Abstract

Thatched roof houses can be found all over Japan as well as European countries and other Asian countries. Thatched roof in Japan is a part of traditional wooden houses. Thatched roof is supported by roof truss structure which is composed of many wood or bamboo members connected by ropes. Then, traditional thatched roof houses have diversity in terms of roof shapes and construction methods. Namely, the slope of the roof, planar shapes of the houses and the number of stories in the roof are different place to place in Japan. The difference is dependent on the regional history, lifestyle and the use of roof space and so on.

In the seismic performance evaluation of thatched roof houses, roof trusses are usually modeled as rigid bodies for simplicity, because the sectional size of each truss member is different and ununiformed and it is difficult to evaluate the in-plane shear stiffness of thatch covering trusses. However, there are very few studies about the stiffness evaluation or the vibration characteristic evaluation of the thatched roofs. Therefore, we conducted ambient vibration tests of thatched roof houses with various types of roof shapes and structure.

Measurement were conducted for several thatched roof houses, which differ in the slope of the roof, the planar shape (e.g. L-shaped and U-shaped), and the number of stories in the roof trusses. We use small highly precision wireless acceleration sensors capable of detecting 3 components including 2 horizontal components and 1 vertical component. The measurements were performed several times by changing the arrangement of 17 acceleration sensors. Thus, the sensors are distributed on the roof plane with high density. Using all the acceleration records of the measurements, natural vibration modes and natural frequencies of the roofs were identified by modal Frequency Domain Decomposition (FDD). On the other hands, we have investigated the structures of the measured houses. Especially, arrangement and dimensions of the structural members are investigated. Then, the relationship between the natural vibration modes and structural characteristics are clarified.

(1) The fundamental peak frequencies of the Fourier spectrum ratio were mainly in the range of 3.0 to 3.5 Hz.

(2) The private house, which has single floor inside the roof truss and simple planer shape, did not show any torsional vibration, and it was confirmed that the roof structure generally behaved as a rigid body.

(3) In private houses with several floors inside the hut, the structure cannot be considered as a rigid body. Their vibration modes show great deformation in the lateral direction, along with coupled vibration in the lateral direction and longitudinal direction.

(4) In private houses with complicated planer shapes, complex vibration modes were confirmed in which vibrations in the longitudinal direction and lateral direction are coupled, or connection between two buildings vibrated greatly.

Keywords: traditional house; thatched roof; natural frequency; vibration mode; ambient vibration test

1. Introduction

In Japan, many traditional thatched roof houses still remain today, and the seismic performance evaluation of them is an important issue. A thatched roof is supported by roof trusses which consist of woods and bamboos tied with ropes. Thatched roof houses have various styles by region and history. The difference can be seen in roof slope, planar shape and the number of stories in the roof. In the seismic performance evaluation of thatched roof houses, roof trusses are usually modeled as rigid bodies and only the mass are modeled for simplicity. This is because stiffness evaluation of a thatched roof is difficult for the following reasons: the number of structural member is too many, each truss member has different sectional size and structural members are tied with ropes. However, there are very few experimental studies about the stiffness evaluation or the vibration characteristic evaluation of the thatched roofs. Therefore, we have conducted ambient vibration tests of thatched roof houses with measurement points distributed densely on roof plane. We have chosen 5 targeting houses with several stories in the roof or complicated planar shape. From the measurement results, the vibration modes of thatched roof houses are understood in detail.

2. Target private houses

Photo 1 shows the appearance of target study houses and Figs. 1 to 5 show their plan and sectional views.

PH-M is a private house located in a mountainous area in northern Kyoto prefecture in Japan. PH-M was rebuilt 16 years ago after being destroyed by fire and is now being used as an ethnographic museum. The roof structure consists of trusses supported by king posts on a base ridge. The first floor is for residential and its floor plan is characterized by quadrant floor plan and "*tsumairi*" style, a Japanese traditional style that main entrance is placed on the gabled side. The inside of the hut is originally used for preserving thatch for rethatching roof. Square cross section timber is used for the roof purlin and logs are used for the rafters. The king posts are connected by penetrating joint to diagonal member, which are parallel to the rafters, via the lateral beams ("tie beam") at an intermediate portion. The diagonal member is inserted into the girder, and the diagonal member and roof beams are connected to the roof purlin by a rope. Therefore, the vertical load from the roof is transmitted to the girder via the diagonal member and the king posts, and the resistance of roof structure to thrust is low.

PH-G is a private house called *Gassho*-style with a steep gable roof. In the gable roof, the upper ends of two logs, "*gassho*", cross at the ridge, and the lower ends are inserted into a beam to form a truss. The lower part of the hut structure is residential space. Formerly used for sericulture, the gables provide lighting and ventilation. The structural walls below the hut are composed of wood siding walls for both the inner and outer walls. There is a girder on the wall in the long side direction, on which the beams in the short side direction are placed. The *gassho, diagonal member,* is inserted into the end of the short beams. The two *gassho* are connected to each other by a beam at the middle of them. Thin wood boards are laid at intervals on the beams as a floor dividing the hut into two layers as shown in photo 2(a). Therefore, the stiffness of the floor in the hut can hardly be expected. In addition, the longitudinal girders and roof purlins are connected along the way. Roof purlin, rafters and *gassho* are all made of small diameter logs. On the first floor of the hut, there are braces along the roof surface.

PH-K had a hipped roof at first, but the roof was remodeled for sericulture in Meiji period (1868~1912). The openings are provided by cutting off the lateral side or pushing up a part of the long side of the hipped roof surface. The first floor of two story wooden frame is for residential use and the second floor (bottom floor of the hut) is residential and working space for employees. The second floor is almost inside the hut structure. An opening ceiling section installed to a living room on the first floor is open to the second floor. The third floor is divided into two layers: a space for sericulture and a space for storage. Roof purlins, rafters and are logs and *gassho* are square timbers. They are tied each other with ropes. The all floors have wooden floor (Photo 2 (b)).

PH-T is the one-story private house called *Nito*-style distributed along the Pacific coast of Japan. PH-T consists of raised floor area, "*omoya*", and earth floored area, "*kamaya*", each area has independent thatched roof. The *omoya* and *kamaya* are arranged in parallel, and a gutter installed between them.

PH-U is the one-story private house called *Kudo*-style, found in northern Kyushu. The shape of the thatched roof viewed from above is U-shaped. When viewed from the front or side, the PH-U looks like a hipped roof style with a squared floor plan, but from the back, it can be seen that PH-U is composed of the front area, and the areas arranged both sides of the front area and orthogonal to the front area, and tiled lean-to roof area arranged between them.

(a) PH-M

(b) PH-G

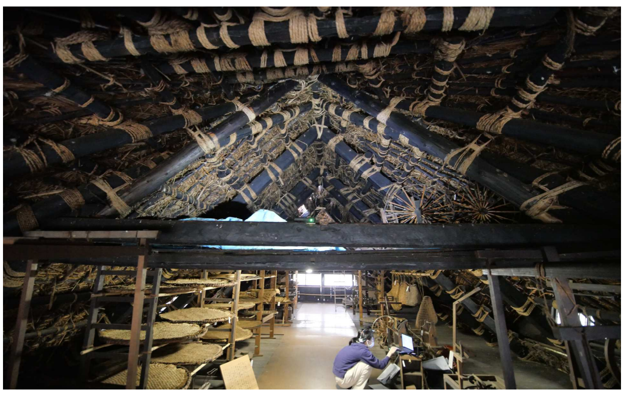
(c) PH-K

(d) PH-T

(e) PH-U

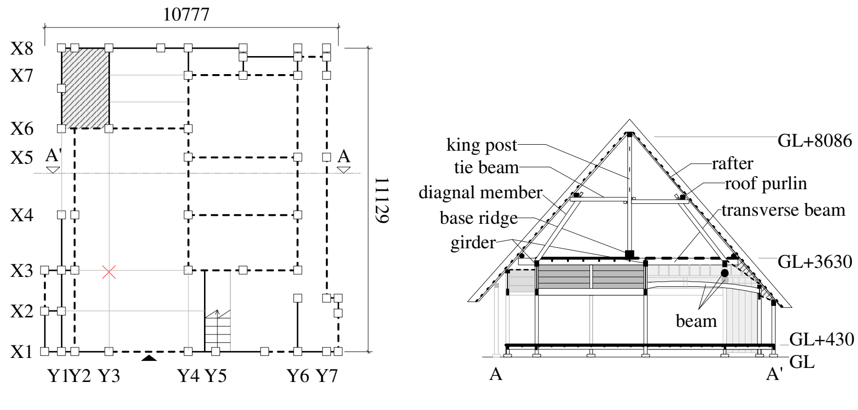
Photo 1 – Appearance of investigated private houses

(a) PH- G



(b) PH-K

Photo 2 – Roof truss structures



(a) 1st floor plan (b) Sectional view

Fig. 1 – Floor plan and sectional view of PH-M

unconfirmed area

<floor plan>

column ■ strut

△column added later

beam

wall

hanging wall
low wall

joint where beam is not on column

Non thatched roof area

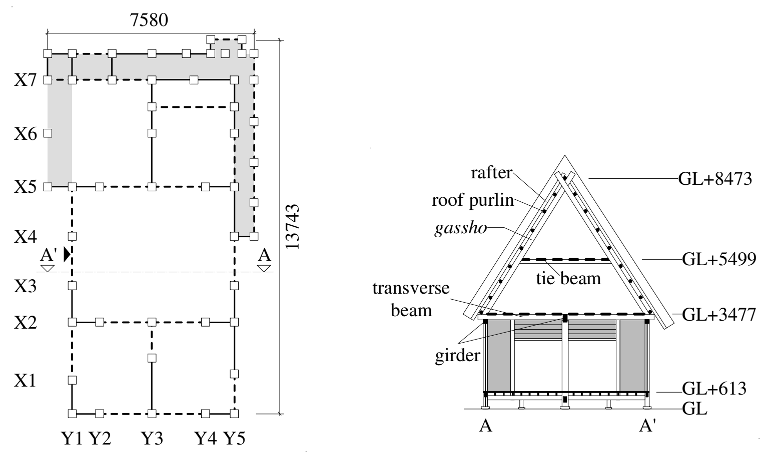
<vertical section>

floor

slotted floor

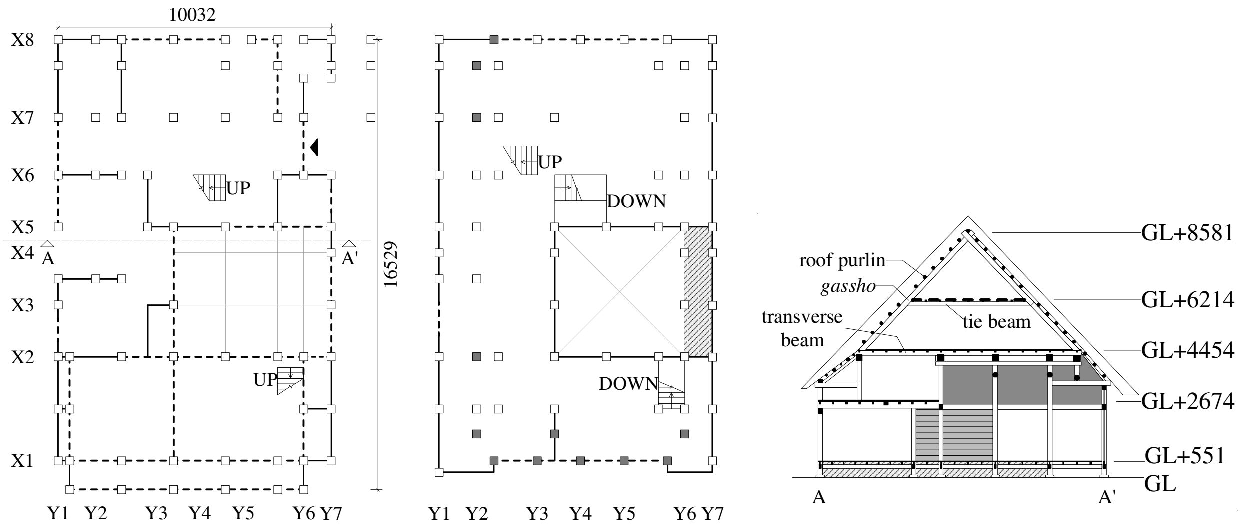
ceiling

Symbols in Fig. 1~ Fig. 5



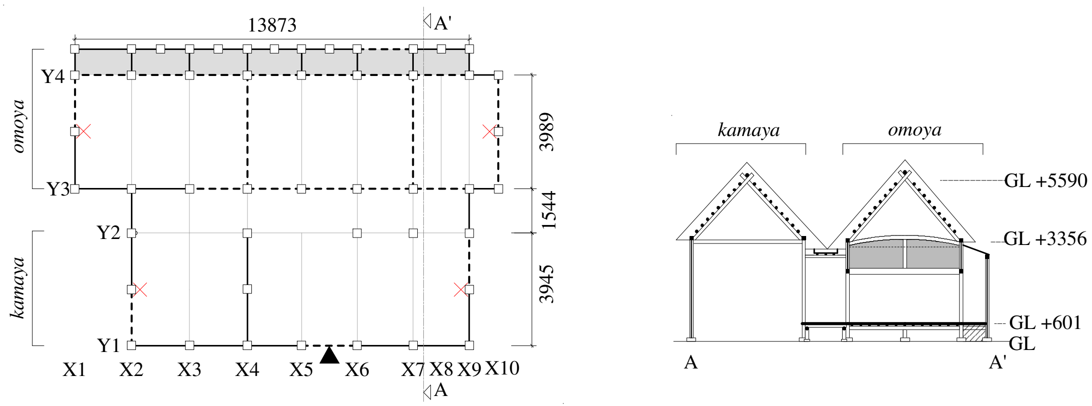
(a) 1st floor plan (b) Sectional view

Fig. 2 – Floor plan and sectional view of PH-G



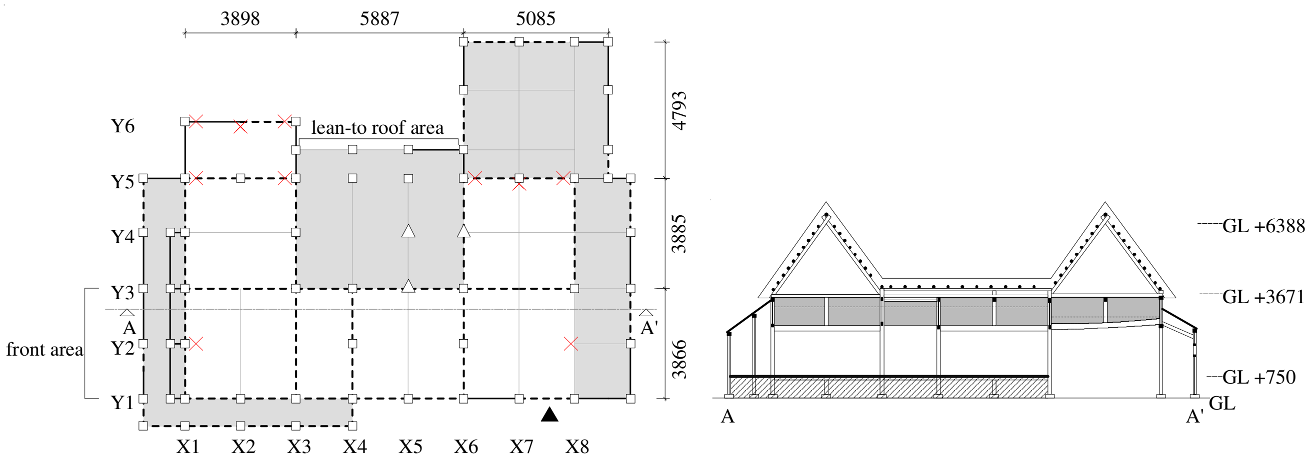
(a) 1st floor plan (b) 2nd floor plan (c) Sectional view

Fig.3 – Floor plans and sectional view of PH-K



(a) 1st floor plan (b) Sectional view

Fig. 4 – Floor plan and sectional view of PH-T



(a) 1st floor plan (b) Sectional view

Fig. 5 – Floor plan and sectional view of PH-U

3. Outline of survey

3.1 Investigation methods

First, we checked the arrangement and dimensions of structural members in the houses, and the details of the beam-column joints. Especially for the hut construction, the slope and thickness of the thatched roof and the dimensions, number and arrangement of purlins and roof truss are investigated.

Next, ambient vibration measurements are performed for each private house. In each ambient vibration test, measurements have been performed using 16 to 17 high-accuracy wireless acceleration sensors capable of detecting three components. Measurements are performed up to three times for a house. The sampling frequency was basically 100 Hz, and the duration time of a measurement is basically 10 minutes. The acceleration sensors were installed on a beam near the intersection of each structure plane. If possible, acceleration sensors are tied to the side of the columns, or installed on installation tables mounted at a purlin. The measurement points are selected so that the vibration characteristics of each structural plane and the roof vibration characteristics can be grasped as much as possible. The acceleration sensors are arranged on the assumption that the deformation of the horizontal structural member in the axial direction is negligible, that is, the displacement at the same level in the same structure plane is equal. The number of measurement points for each private house was 12 to 23 points. Namely, very high-density measurements are performed compared with building size. Photo 3 shows an example of the measurement condition.

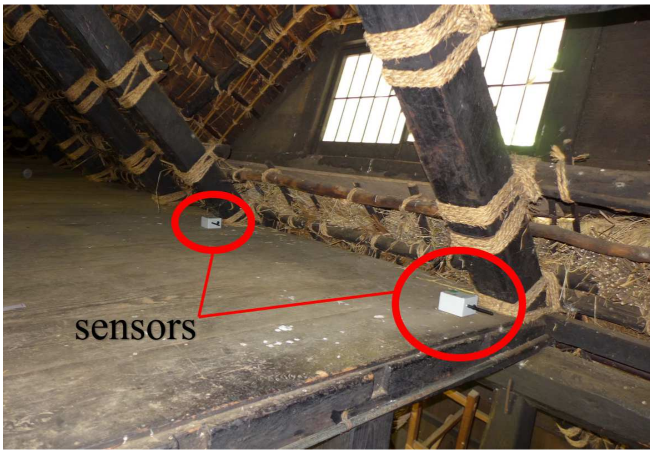


Photo 3 – Example of measurement condition

3.2 Analysis method

In this section, we analyze the vibration characteristics of thatched private houses with natural frequency obtained from Fourier spectrum ratio and natural vibration modes obtained from Frequency Domain Decomposition (FDD) method. The FDD method is a method proposed by Brinker et al.[1]. In FDD method, natural vibration modes are obtained only by performing singular value decomposition of a cross spectrum matrix of acceleration data in a building. In the Fourier spectrum ratio, horizontal components of acceleration data measured in a building and on the ground are used. On the other hand, in the FDD method, only the acceleration data of the horizontal components measured in a building are used. Therefore, if the number of measurement points in a building is N, 2 (N + 1) components are used for analysis in the Fourier spectrum ratio, and 2N components are used for analysis in the FDD method. Here, $x_i(t)$ is the acceleration time history measured on the ground, and $y_j(t)$ is the acceleration time history measured in a building. The Fourier spectrum ratio used in this analysis and the calculation procedure of the FDD method are shown below. Here, i and j represent measurement components, and i = 1~2, and j = 1~2N. In this section, bold letters indicate vectors and matrixes. As a pre-process applied to all acceleration, the acceleration waveforms are baseline-corrected with an average value, and a band-pass filter with cut-off frequency of 0.2 Hz and higher corner frequency of 20 Hz is applied by using Butterworth filter.

(1) Fourier spectrum ratio

1) The acceleration time history $x_i(t)$ and $y_j(t)$ are divided into divided time history of 40.96 seconds ${}_kx_i(t)$ and ${}_ky_j(t)$ allowing 30.72 seconds overlap. Here, k = 1 to K (K is the number of divisions).
2) Perform Fourier-transformation at the acceleration time history ${}_kx_i(t)$ and ${}_ky_j(t)$. After Perform Fourier-transformation, the waveforms are smoothed by Parzen window having a bandwidth of 0.2 Hz. The smoothed Fourier-transformation are described as ${}_kX_i(\omega)$ and ${}_kY_j(\omega)$.
3) As shown in equation (1), the Fourier spectrum ratio $H_j(\omega)$ of the component j measured in the building is obtained by ensemble-averaging the ratio of the absolute values of the Fourier-transformation ${}_kX_i(\omega)$ and ${}_kY_j(\omega)$. When calculating $H_j(\omega)$, the component i measured on the ground uses the same direction as the component j.

$$H_j(\omega) = (1/K)\Sigma_k \left(|{}_kY_j(\omega)| \,/\, |{}_kX_i(\omega)|\right) \tag{1}$$

(2) FDD Method

1) Perform Fourier-transformation to the acceleration time history $y_j(t)$. The $Y_j(\omega)$ represents the Fourier-transformed $y_j(t)$, and $\mathbf{Y}(\omega)$ represents Fourier transformation of all the measurement points as in Eq. (2). For a given circular frequency ω, $\mathbf{Y}(\omega)$ is a $2N$-dimensional column vector.

$$\mathbf{Y}(\omega) = \{Y_1(\omega), Y_2(\omega), \dots , Y_{2N}(\omega)\}^{\mathrm{T}} \tag{2}$$

2) With $\mathbf{Y}(\omega)$, find a cross spectrum matrix $\mathbf{G}(\omega)$ as in Eq. (3). Here, $\mathbf{Y}^*(\omega)$ represents the complex conjugate of $\mathbf{Y}(\omega)$, and the superscript T indicates the matrix is transposed. For a given circular frequency ω, $\mathbf{G}(\omega)$ is a $2N \times 2N$ square matrix. The $\mathbf{G}(\omega)$ is smoothed by Parzen window of which bandwidth is 0.2 Hz.

$$\mathbf{G}(\omega) = \mathbf{Y}^*(\omega)\, \mathbf{Y}(\omega)^{\mathrm{T}} \tag{3}$$

3) Decompose the singular value of $\mathbf{G}(\omega)$ as in Eq. (4). The $\mathbf{U}(\omega)$ and $\mathbf{V}(\omega)$ are a left singular value matrix and a right singular value matrix, respectively, and are $2N\times2N$ square matrices for a certain circular frequency ω. The $\mathbf{S}(\omega)$ is a $2N\times2N$ square matrix in which diagonal matrix components are singular values $S_j(\omega)$ and the rest are 0. Here, the singular values are arranged in the descending order of $S_1(\omega)$, $S_2(\omega)$, ….

$$\mathbf{G}(\omega) = \mathbf{U}(\omega)\, \mathbf{S}(\omega)\, \mathbf{V}(\omega)^{\mathrm{T}} \tag{4}$$

4) The peak circular frequency ω_{max} is specified by the frequency distribution of the maximum singular value $S_1(\omega)$. Assuming that the left singular value matrix $\mathbf{U}(\omega)$ has $2N$-dimensional column vectors $\mathbf{U}_j(\omega)$ arranged along j = 1 to $2N$ as in Eq. (5), the natural vibration mode corresponding to the peak circular frequency ω_{max} is $\mathbf{U}_1(\omega_{max})$.

$$\mathbf{U}(\omega) = \{\mathbf{U}_1(\omega), \mathbf{U}_2(\omega), \dots , \mathbf{U}_{2N}(\omega)\} \tag{5}$$

4. Ambient vibration test result

Figures 6 to 10 show the arrangement of acceleration sensors and the Fourier spectrum ratios of representative points to the ground. Figures 11 to 15 show the vibration modes at the peak frequency of the maximum singular value obtained by the FDD method. The peak frequencies obtained by the FDD method are almost identical to those by Fourier spectral ratios. The vibration characteristics of each private house are described below.

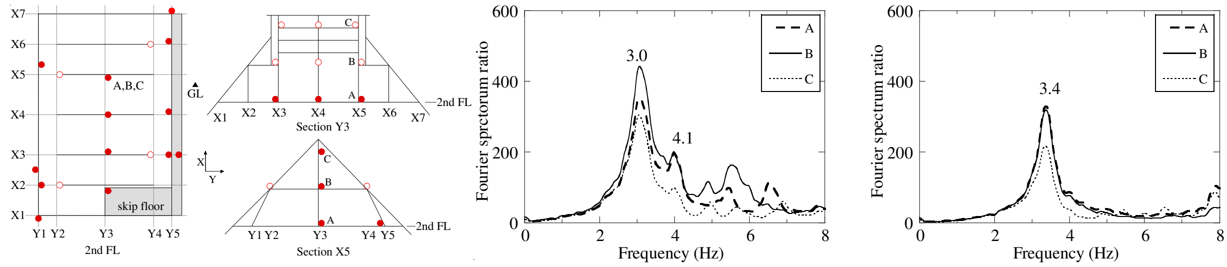
For PH-M, the longitudinal direction of the private house is the X direction, and the lateral direction is the Y direction. The fundamental peak frequency is clear in both directions, 3.4 Hz in the X direction and 3.0 Hz in the Y direction, and the fundamental frequency is slightly higher in X direction. In the vibration mode obtained by the FDD method, almost no torsion is observed. Looking at the natural vibration modes in Y direction, the response at the tie beam level in the middle of the kingpost is slightly larger than that at the girder level or ridge level, but not so large.

For PH-G, the longitudinal direction of the private house is the X direction, and the lateral direction is the Y direction. The Fourier spectrum ratio has a relatively clear fundamental peak frequency at 3.5 Hz in both directions. There are also peaks at 4.6 Hz and 5.7 Hz. Looking at the fundamental vibration mode, it can be seen that the roof truss is greatly deformed in the Y-direction at the middle level of the roof. Looking at the vibration mode at 4.6 Hz where the maximum singular value peaks, you can see a twisted vibration mode with an opposite phase in the Y direction at the girder level and a large wavy vibration mode at the middle level of the roof. From the above, it can be understood from the vibration mode in the Y direction that the restraint effect by the gable wall can be confirmed at the 1st floor level inside the hut, but the floor stiffness at the middle level of roof is not sufficient. Furthermore, it can be seen that the *Gassho*-style hut structure is greatly deformed at the same frequency as the room space, and cannot be regarded as rigid body.

For PH-K, the longitudinal direction of the private house is the *X* direction, and the lateral direction is the *Y* direction. In the Fourier spectrum ratio in the *X* direction, adjacent peaks at 2.9 Hz, 3.2 Hz, and 3.4 Hz can be confirmed. In the *Y* direction, peaks at 3.1 Hz and 3.4 Hz can be confirmed. Therefore, the fundamental peak frequency in the *X* direction is considered to be 2.9 Hz. Also, 3.1 to 3.2 Hz and 3.4 Hz are considered to be the vibration deformations in which the *X* and *Y* directions are coupled. As is clear from the vibration mode, it can be seen that the vibration characteristics (vibration mode and peak frequency) greatly change across the opening ceiling section. Therefore, it is considered that torsional vibration is caused by the opening ceiling section. However, there is no vibration mode in which the hut was deformed into a bow shape in the short side direction as seen in the PH-G of the *Gassho*-style. This is understood by the following structural features: the framework has almost reached the inside of the hut, the sectional dimensions of the timber that make up the hut is large, the floor stiffness is relatively large, horizontal structural members in the longitudinal direction is composed of one timber member without joints.

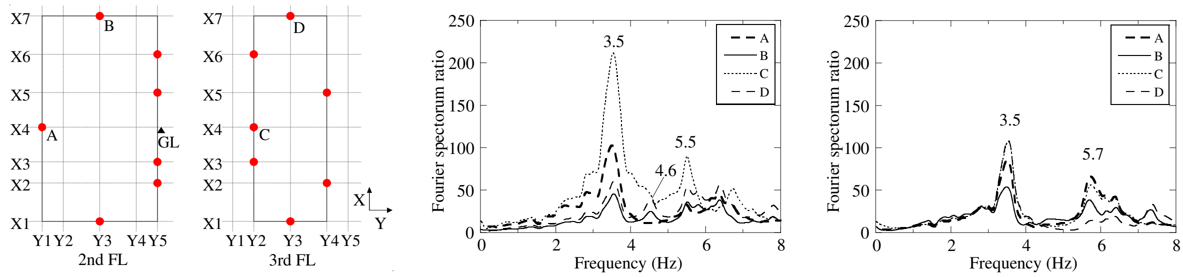
For PH-T, the longitudinal direction is the *X* direction, and the lateral direction is the *Y* direction. From the Fourier spectrum ratio to the ground, the fundamental peak frequency in the *Y* direction is 2.6 Hz, and clear peaks at 3.5 Hz and 4.6 Hz in the *X* direction can be found. It is considered that the fundamental peak frequency in the *X* direction is larger than that in the *Y* direction because the wall length in the *X* direction is longer. In the fundamental peak frequency in the *Y* direction, *omoya* and *kamaya* deform in the same phase in the lateral direction. In the fundamental peak frequency in the *X* direction, the middle part between *omoya* and *kamaya* where there are a few walls vibrates greatly. At the secondary peak frequency, the outer walls on both sides in the *X* direction vibrate greatly. It is considered that the coupling effect in the *X* direction and the *Y* direction is not so large.

For PH-U, the girder direction of the front house is the *X* direction, and the orthogonal direction to the *X* direction is the *Y* direction. From the Fourier spectrum ratio to the ground, the Fourier spectrum in the *X* direction and the *Y* direction both have peak frequencies near 3.3 Hz. In the Y direction, a clear peak can be also seen at 4.4Hz. Around 3.3 Hz, it vibrates greatly in both *X* and *Y* directions. Also, at 4.4 Hz, it can be seen that the left and right sides of the front area vibrate in opposite directions of the Y direction.



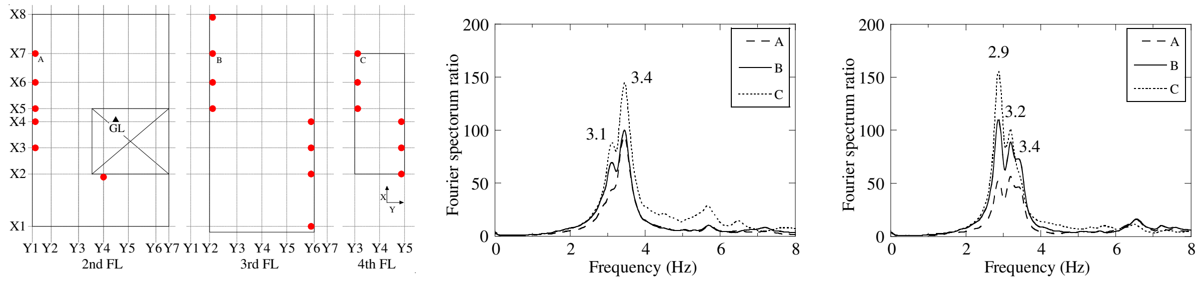
(a) Sensor arrangement (b) Y direction (c) X direction

Fig. 6 – Sensor arrangement and Fourier spectrum ratio of PH-M



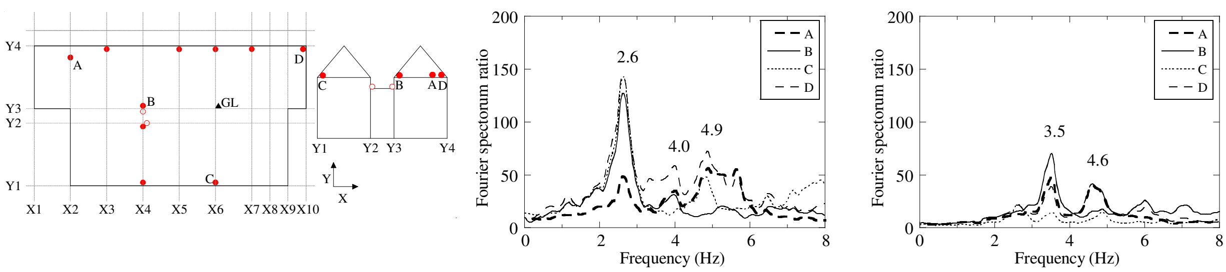
(a) Sensor arrangement (b) Y direction (c) X direction

Fig. 7 – Sensor arrangement and Fourier spectrum ratio of PH-G



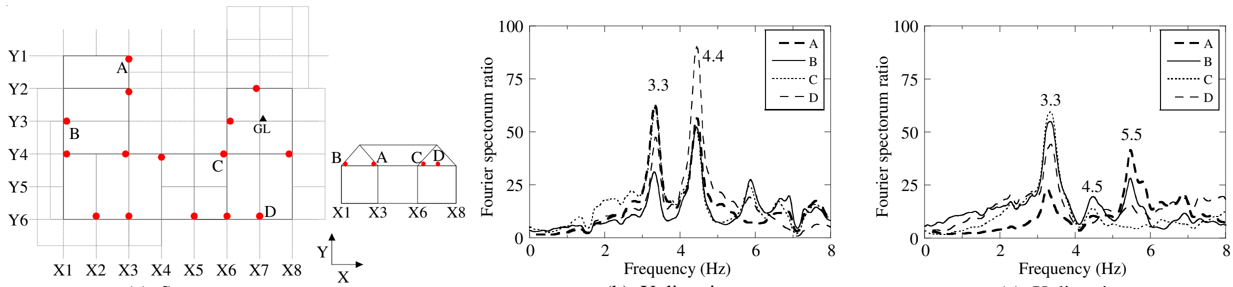
(a) Sensor arrangement (b) Y direction (c) X direction

Fig. 8 – Sensor arrangement and Fourier spectrum ratio of PH-K



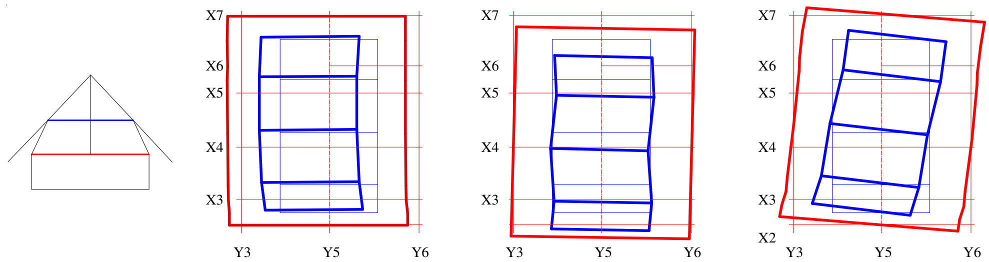
(a) Sensor arrangement (b) Y direction (c) X direction

Fig. 9 – Sensor arrangement and Fourier spectrumr ratio of PH-T



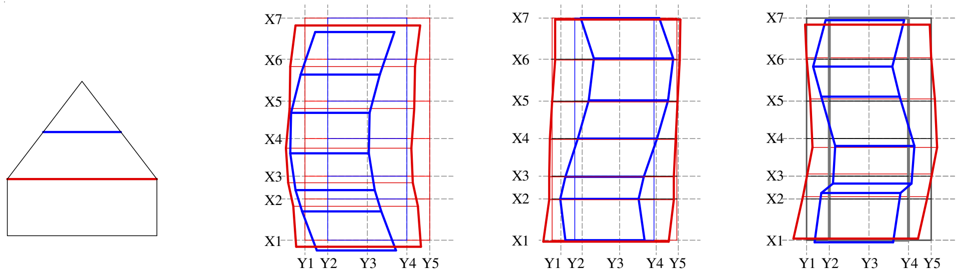
(a) Sensor arrangement (b) Y direction (c) X direction

Fig. 10 – Sensor arrangement and Fourier spectrum ratio of PH-U



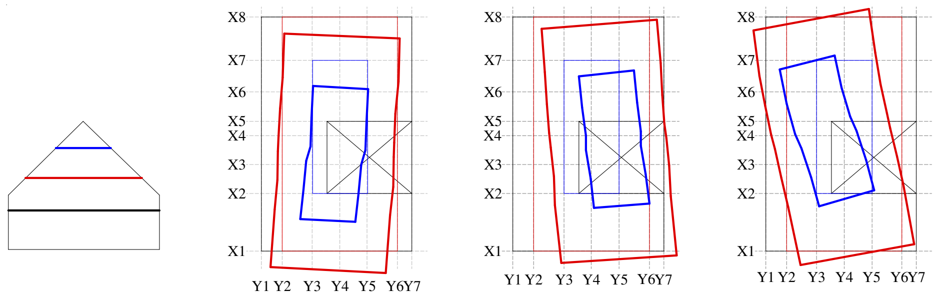
(a) Measurement level (b) 3.1 Hz (c) 3.4 Hz (d)4.1 Hz

Fig. 11 – Vibration modes of PH-M



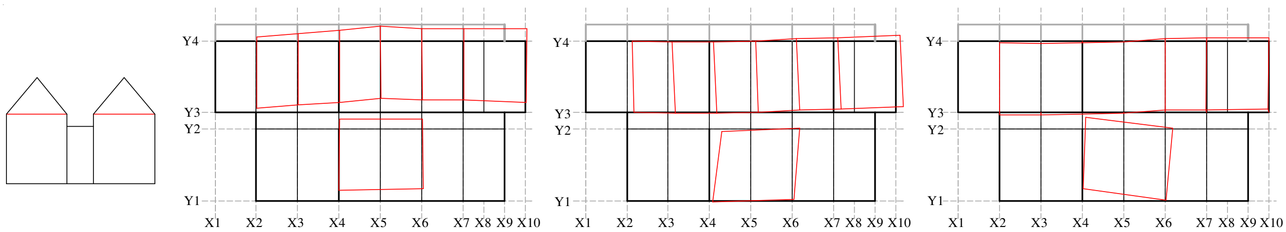
(a) Measurement level (b) 3.5 Hz (c) 4.6 Hz (d) 5.5 Hz

Fig. 12 – Vibration modes of PH-G



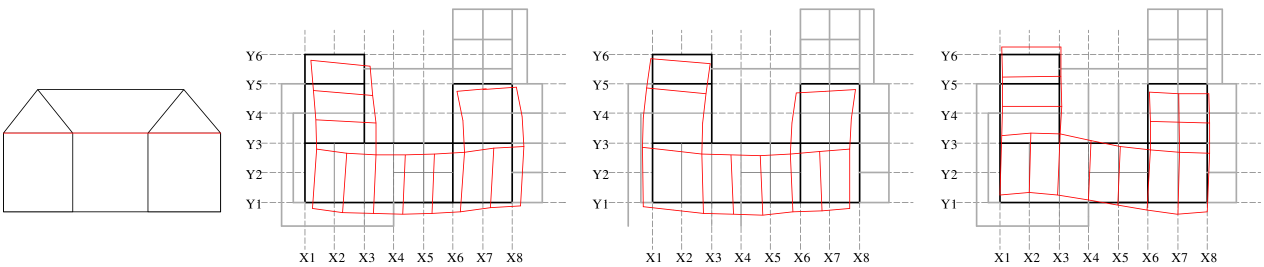
(a) Measurement level (b) 2.9 Hz (c) 3.1 Hz (d) 3.5 Hz

Fig. 13 – Vibration modes of PH-K



(a) Measurement level (b) 2.6 Hz (c) 3.5 Hz (d) 4.0 Hz

Fig. 14 – Vibration modes of PH-T



(a) Measurement level (b) 3.2 Hz (c) 3.4 Hz (d) 4.4 Hz

Fig. 15 – Vibration modes of PH-U

5. Conclusion

In this study, we reported the results of a high-density ambient vibration test focusing on traditional Japanese-style private houses with thatched roofs. We chose 5 target private houses, including houses with multiple layers inside thatched roof and houses with a complicated thatched roof. This study aims at grasping the complicated vibration mode of the thatched roof. By applying the FDD method to the results of the ambient vibration tests in which acceleration sensors were distributed at high density, we were able to understand the complex vibration characteristics of thatched roofs. The main conclusions obtained in this study are as follows.

(1) The fundamental peak frequency of the Fourier spectrum ratio is slightly lower at 2.6 Hz in the lateral direction of PH-T, but in other private houses they are in the range of 3.0 to 3.5 Hz.

(2) The PH-M, which has single floor inside the hut and simple planer shape, does not show any torsional vibration, and it is confirmed that the roof structure generally behaved as a rigid body.

(3) In private houses with several floors inside the hut, the structure cannot be considered as a rigid body. In particular, it is confirmed that in the case of a *Gassho*-style PH-G, the vibration mode of the middle level of the hut, away from the gable wall, deforms greatly in the lateral direction. In the case of a helmet-style private house PH-K, close vibration modes are observed around 3.0-3.5 Hz, and coupled vibration modes in the lateral direction and longitudinal direction are also found.

(4) The PH-U with a U-shaped thatched roof shows complex coupled vibration modes between longitudinal and lateral direction. On the other hand, the PH-T which was sectioned by two parallel buildings, the vibration modes observed show that two parallel buildings deforms differently.

6. References

[1] Brincker, R., Zhang, L., and Andersen, P.: Modal Identification from Ambient Responses Using Frequency Domain Decomposition, Proceedings of 18th International Modal Analysis Conference, San Antonio, Texas, pp.625-630, 2000

