International Journal of High-Rise Buildings
December 2012, Vol 1, No 4, 283-300

International Journal of
High-Rise Buildings
www.ctbuh.org

Study on Vibration Perception by Visual Sensation Considering Probability of Seeing

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Abstract

Wind-induced vibrations of buildings can be perceived when movement of objects caused by the vibration is seen. However, movement of objects that would normally be expected to trigger visual perception of building vibrations is not necessarily seen in actual building environments. Therefore, to evaluate habitability to building vibrations, it is necessary to examine the influence of movement of objects on vibration perception taking into account probability of seeing the objects. As the first step in this study, those data necessary to estimate probability of vibration perception from seeing of swaying objects have been measured during normal activities in actual buildings. In addition, statistical analysis of the data has also been carried out. As the second step in this study, the probability distribution of vibration perception by visual sensation is estimated using the series of data measured in the first step. Probability of seeing object is considered in the estimated probability distribution.

Keywords: Habitability to building vibrations, Vibration perception, Visual sensation, Visual cues, Probability of seeing

1. Introduction

Concerns about vibration perception and the unpleasantness of building vibrations have been expressed, and the number of complaints and discussions have been increasing. One report stated that 11.4% of 1483 cases were sent to a Japanese organization concerned with vibration problems (Inoue, 2004), and many of these were concerned by wind-induced vibrations. It is an important factor to consider in the design stage of buildings and maintenance. Thus, habitability to wind-induced vibrations of buildings is often evaluated before or after building construction, and countermeasures based on the evaluation results are carried out (Ohkuma et al., 1996). Several methods for evaluating habitability to building vibrations based on the vibration perception amplitude level have been also published (AIJ-GEH-2004, ISO 2631-2, ISO 6897). In addition, much research has been carried out for investigating human reactions to building vibrations in an attempt to develop evaluation methods (e.g. Jeary et al., 1988; Irwin, 1975; Griffin and Whithman, 1980; Ishikawa et al., 1993).

Building vibrations are perceived by body sensation when the vibrations are passed to them via body parts in contact with the building (expressed as "vibration perception by body sensation" hereafter). Building vibrations can also be perceived when objects inside buildings and scenery outside windows (expressed as "visual cues" hereafter) are seen to be swaying because of building vibrations (expressed as "vibration perception by visual sensation" hereafter) (Nakamura et al., 1995, Kawana and Hisada, 2002). Furthermore, there is a possibility building vibrations would be perceived by visual sensation, although the vibrations are not big enough to be perceived by body sensation.

Some medical experiments have shown that passive vibration of human bodies is a major cause of human balance unsteadiness and unpleasant feelings due to vibration. Passive vibration of human bodies is generated when vibration feelings felt by each sensations are clearly different (Takahashi, 1995, 1997). The situation between vibration sensation felt by body sensation and vibration sensation felt by visual sensation is a main causes why passive vibration of the human body occurs. Therefore, vibration perception by body sensation and vibration perception by visual sensation should be investigated statistically and quantitatively to determine methods for evaluating habitability to building vibrations. In previous research, vibration perception by body sensation has been investigated and analyzed using statistical methods, taking into account individual differences of vibration perception and other influential factors (Shioya et al., 1994, 1996, Ishikawa and Noda, 1998, 1999). However, there have been few studies of visual sensation effects on vibration perception (Shindo and Goto, 2002; Ishikawa and Noda, 1999). In addition, the following three factors have not been considered in previous studies. Therefore, the results of previous studies are not accurate enough:

1) Visual cues under experimental conditions are differ-

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ent from real visual cues in an actual building environment. The visual cues were not sufficiently realistic.

2) Effects of visual sensation on vibration feelings were experimentally investigated under the condition visual cues were always seen. However, the visual cues are not necessarily seen in normal condition of actual buildings.

3) In questionnaires about vibration feelings in actual buildings, vibrations were perceived more often by seeing sways of objects inside rooms than by seeing the sway of scenery outside windows (Ishikawa et al., 1993; Nakamura et al., 1995; Kawana and Hisada, 2002). However, previous experimental studies have been concerned with only visual cues of scenery outside windows.

Thus, for evaluation of habitability under building vibration, statistical analysis of vibration perception by visual sensation yielding results that can be easily compared with those of previous researches on vibration perception by body sensation should be conducted considering probability of seeing visual cues.

Building vibrations are perceived by visual sensation in two ways: 1) by accidental seeing of visual cues without any vibration perception by other sensations, and 2) by other sensations first, and then visually from active observation of visual cues to confirm the vibration perception. The medical reports (Takahashi, 1995, 1997) have shown their findings under a condition those two vibration perceptions by visual sensation are intermingled. In this study, vibration perception by visual sensation by accidental seeing of visual cues is focused upon, under a condition that lighting is turned on. When building vibrations are perceived by other sensations first and visual cues are actively observed, the statistical results become different. In this case, it is necessary to do the same investigation under the condition that visual cues are actively observed at each vibration amplitude of buildings. However, the active observation of visual cues to confirm initial uncertain vibration perceptions due to the other sensations should be the subject of a future study.

As the first step of this study, a series of data necessary to estimate a probability distribution of vibration perception by visual sensation considering probability of seeing visual cues are measured during normal activities in actual buildings. Statistical analysis is then carried out to investigate statistical values of those data. The results of statistical analysis of vibration perception by visual sensation are influenced by mean values, coefficients of variation and shapes of relative frequency distributions of the measured data. Thus, these statistical parameters are investigated. Identification of the most appropriate probability distribution model for the obtained data has also been investigated. In this paper, outline of the investigation is described. Detail of the first step is already described in the reference (Kawana et al. 2008).

As the second step of this study, a probability distribution of vibration perception by visual sensation is estimated using the series of data measured in the first step. The probability of seeing visual cues is considered in the results. Furthermore, the results are compared with the probability distribution of vibration perception by body sensation, and the possibility of vibration perception by visual sensation against probability of vibration perception by body sensation is investigated.

In this study, selected visual cues would sway because of airflow from air conditioners and open windows. However, it is natural to perceive the airflow by hearing noise made by air conditioners and by body sensation. It is considered that people notice swaying of the visual cues occurs because of this airflow, if vibrations of the visual cues correspond to the feeling about airflow. Thus, vibration perception by visual sensation of visual cues by airflow is discriminated from vibration perception of buildings, and is not considered.

2. The Research in Context

Figure 1 summarizes our understanding of vibration perception phenomena and the relationship to the research of this investigation.

According to previous studies (e.g. Ohyama et al., 1994; Leibowitz, 1955; Johnson and Leibowitz, 1976; Finlay, 1982) on cognitive psychology, the distance of observers from an seen visual cue and the length of time during which it is seen, are important parameters for estimating the minimum vibration amplitude of an seen visual cue that is necessary for that vibration to be perceived by visual sensation (this amplitude is referred to as "visual perception threshold" hereafter). Knowledge of visual perception thresholds and vibration characteristics of seen visual cues is necessary for estimating the probability of vibration perception of buildings by visual sensation. Length of time to see visual cues and the number of times they are seen are also important data for estimating the probability of vibration perception by visual sensation. In the first step of this study, three following three data are

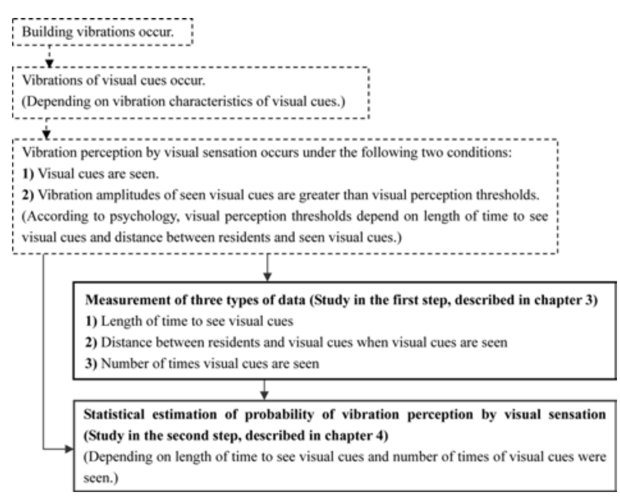

Figure 1. Research in context.

measured under normal activities in actual buildings and they are statistically analyzed:

1) Length of time to see visual cues

2) Distance between subjects and visual cues while the visual cues are being seen

3) Number of times visual cues are seen

In this study, visual cues were seen many times during the measurement period. The length of time to see visual cues and the distance between subjects and seen visual cues for each event of seeing were measured and statistically analyzed. The measurement methodology and investigated results are shown in chapter 3.

According to previous studies on cognitive psychology (Finlay, 1982; Johnson and Scobey, 1980; Post and Leibowitz, 1981; Duncker, 1929), visual perception thresholds vary under different situations as follows.

1) Differences between seeing of visual cues on the foveal visual field (central part of visual field) and on the peripheral visual field (edge of visual field).

2) Differences between existence and non-existence of stuck objects near visual cues that would become reference lines for perceiving vibration of visual cues

In previous studies, no clear difference between visual perception thresholds was found for the cases of "gazing" and "not gazing". No academic proof of other factors that would influence visual perception thresholds could be found. Thus, obtained data in the first step of this study was categorized into the following two groups for statistical analysis in the second step of this study. Furthermore, these two different situations and individual differences are considered in the process of the second step of this study.

1) Categorized into the two cases of seeing of visual cues either on the foveal visual field or on the peripheral visual field

2) Categorized into the two cases of seeing of visual cues under either existence or non-existence reference lines

In the second step of this study, probability of vibration perception by visual sensation was investigated based on the measurement and investigation results in chapter 3. Investigation methodology and results are shown in chapter 4.

3. Measurement and Statistical Analysis of Length of Time to See Visual Cues

3.1. Measurement methodology

It is anticipated that measured data and the probability of occurrence of vibration perception by visual sensation would vary greatly under different circumstances (for instance, differences in kinds of activities being undertaken, and differences in the positions of objects inside rooms). Thus, the following types of measurements were carried out in residences and offices separately, places where people usually stay for the longest periods. Deskwork is mainly done in offices.

1) A small camera is set between the eyes of subjects who work in office buildings and subjects who live in residences. Where they look during their normal activities is recorded as a movie. The length of measurement period is set at 80 minutes to suit the realities of the durations in which people stay in the same location.

2) A researcher stays with the subjects in the same rooms. The researcher notes the positions of the subjects and the situations of objects that might become visual cues on plans of those buildings. Postures of subjects and the contents of their activities during the measurement period are also noted in time series on the plans of buildings.

3) Based on the recorded movies and plans of the buildings, the three types of data cited above are collected.

A picture of a small camera set on the face of a subject is shown in Fig. 2. The camera is set between the eyes of the subject, and is connected by a cable to batteries and a video camera in a shoulder bag. Subjects are asked to perform their normal activities while the video camera and the small camera record the places looked at by the subject.

If there is free eyeball movement, the data on what is being watched cannot be relied on. The subjects are therefore asked to refrain from eyeball movement, and asked instead to maintain their line of vision in the same direction in which the camera is recording. In addition, they are asked to directly face the place they are looking at.

The angle of the visual field is about ±45 degrees horizontally and about ±25 degrees vertically, from the direction of the line of vision. However, the angle of the movies range recorded by the small camera was ±30 degrees horizontally, and ±22 degrees vertically, from the center point. Thus, the range of the recorded movies is narrower than that of the actual visual field, especially taking eyeball movement into account. However, the range of visual field that is thoroughly seen is recorded on the movie.

3.1.1. Outline of buildings and subjects

The numbers of subjects and rooms where subjects stayed

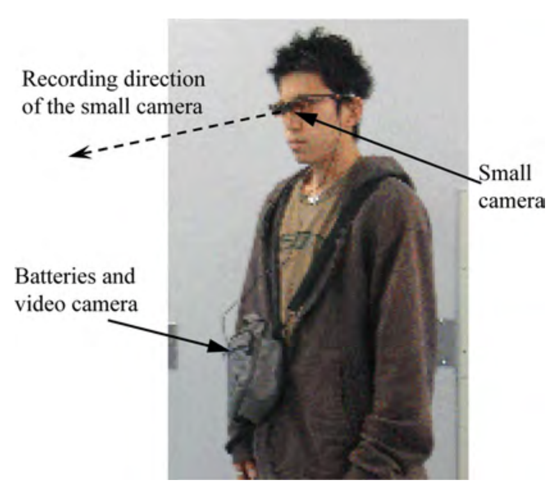

Figure 2. Situation of small camera set on face of subject.

Table 1. Number of subjects according to sex and age

	Residences		Offices	
	Men	Women	Men	Women
10's	0	1	0	0
20's	4	0	7	3
30's	2	2	9	1
40's	0	0	0	0
50's	1	3	0	0
60's	4	3	0	0
Total	11	9	16	4
	20		20	

Table 2. Sizes of rooms, where subjects stayed during the measurement period

Each room size in residences (m^2)	10.8
Total room size in residences (m^2)	38.4
Each room size in offices (m^2)	39.7

during the measurement period are outlined in Table 1 and Table 2, respectively. There were 20 subjects in 11 houses and apartments. Their ages were between 12 and 69. The number of rooms in which any subject stayed during the measurement period was between 3 and 7. There were 20 subjects in 3 office buildings. Their ages were between 22 and 39. The number of rooms in which any subject stayed was between 1 and 3.

3.1.2. Selected visual cues

Objects fitting the following two conditions were chosen as visual cues.

1) The same objects that seemed to be swaying under actual building vibrations. These were obtained from questionnaires about sensitivity to wind-induced vibration vibrations in actual buildings (Ishikawa et al., 1993; Nakamura et al., 1995; Kawana and Hisada, 2002). The installation situations of experimental and questionnaire objects also had to be the same.

2) Similar objects whose installation situation was similar to the above situation.

Objects fitting the above two conditions are listed below.

Residences

1) Curtains hung from the tops of windows
2) Lights hung from ceilings
3) Blinds hung from the tops of windows
4) Hangers and clothes on hooks on walls
5) Hung calendars
6) Towels hung from hooks on walls
7) Picture frames hung on walls
8) Message boards hung on walls

Offices

1) Blinds hung from the top of windows
2) Hung calendars
3) Strings hung from ceilings for lighting power supply
4) Papers hung on walls
5) Message boards and amulets hung on hooks on walls
6) Curtains hung from the tops of windows
7) Towels hung from hooks on walls
8) Notebooks hung from hooks on walls

3.2. Measurement result

3.2.1. Postures of subjects

The ratio of the time spend in each posture to the length of the total measurement period (80 minutes for one subject) is shown in Table 3. Time spent sitting is the longest, followed by time standing.

3.2.2. Main activities of subjects

Conversation with families and friends (18 subjects per 20), eating (17 subjects) and watching TV (10 subjects) were the most common activities in the residences. 17 subjects were eating while they were making conversation and watching TV. The other subjects were observed smoking, ironing, taking care of plants, or brushing their teeth. In the offices, all subjects were observed doing their computer work, such as checking e-mail, searching references using web sites of libraries, or writing reports. 15 subjects were observed reading books and making conversation. 5 subjects were observed arranging books and papers, and 4 subjects were observed relaxing. These activities were performed whether visual cues were seen or not.

3.2.3. Length of time to see visual cues

An example of a seeing time history for a subject is shown in Fig. 3. This figure shows that hung curtains are the most seen visual cues. It was found that hung curtains are seen the most in residences, and hung blinds are the most seen in offices, in the case of other subjects. Hung curtains and hung blinds are bigger than the other visual cues. Therefore, it can be said that hung curtains and hung blinds could be seen more easily and more often than the other visual cues.

Figure 4 shows a comparison between a lognormal distribution of the relative frequency distribution of the length of time to see visual cues for each event of seeing for residences. The type of seen visual cues and the age and

Table 3. Time sent in each posture as a percentage of the total measurement period

	Lying	Sitting on a Floor	Sitting on Chars	Standing	Walking
Residences	1%	33%	42%	19%	5%
Offices	0%	1%	90%	8%	1%

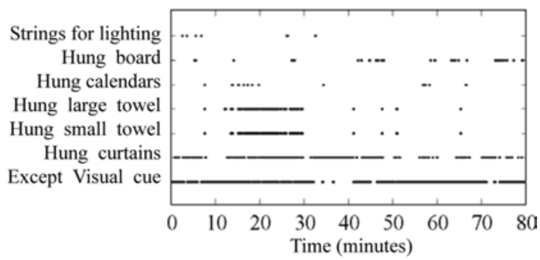

Figure 3. Example of an observation time history (case of a residences).

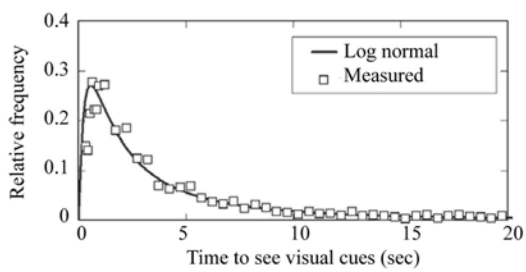

Figure 4. Comparison of lognormal distribution and relative frequency distribution of time to see visual cues (Case of residences. Types of visual cues not considered).

sex of subjects are ignored. The type of seen visual cue is not considered hereafter. Figure 4 shows that the lognormal distribution fits well with the relative frequencies of the length of time. A similar result is obtained for offices. It can be said that the lognormal distribution is a good approximation for the probability distribution model of the lengths of time to see visual cues. When the time length of seeing are categorized according to subjects' sex and age, the same result is obtained. For residences, time to see visual cues is 7.1 seconds on average and the coefficient of variation (COV) is 3.5. For offices, average time is 6.9 seconds and the coefficient of variation is 2.0.

The mean values and coefficients of variance of the length of time to see visual cues are shown in Table 4. They are categorized according to sex and age of subjects. The table shows that mean values are not obviously affected by age or sex. Differences of mean values are not clear between residences and offices. However, the coefficients of variation for residences are bigger than those for offices.

Table 4. Comparison of mean values and coefficients of variation of length of time to see visual cues, categorized according to sex and age of subjects

	Residences				
	All	Women	Men	10s-30s	40s-60s
Average	7.1	7.7	6.7	6.7	7.7
COV	3.5	3.5	3.4	3.4	3.5
	Offices				
	All	Women	Men	20s	30s
Average	6.9	5.8	7.1	7.1	5.8
COV	2.0	1.9	2.0	2.0	1.9

3.2.4. Distance between subjects and visual cues

The relative frequency distribution of distances between subjects and seen visual cues was examined by Chi-square tests for goodness of fit to normal, lognormal and Rayleigh distributions (Alfredo and Wilson 1977). Table 5 shows the results of the Chi-square tests. They show that all of these probability distribution models fit well within a 5% significance level. However, the Rayleigh distribution shows the best fit for residences, and the lognormal distribution shows the best fit for offices. Some other probability distribution models (e.g. Gumbel and Weibull distribution) were also tested. However, the results were inferior to the results shown in Table 5. Therefore, it can be said that the lognormal distribution and the Rayleigh distribution are the most appropriate probability distribution models for distances for residences and offices respectively.

Figure 5 compares the relative frequencies, average values, and coefficients of variation of distances between subjects and seen visual cues. They are categorized according to sex and age of subjects. When the age and sex of subjects are not considered, the distance is 2.3 meters for residences on average, and the coefficient of variation is 0.50. The distance is 2.5 meters for offices on average and the coefficient of variation is 0.76. If the environmental conditions of the buildings are the same, the relative frequencies, mean values and coefficients of variation are almost the same for all subject ages and for both sexes. The mean values were almost the same for both residences and offices, although the coefficients of variation for offices were bigger than those for residences. This is because the relative frequencies at around 1m were greater than those for other distances.

3.2.5. Number of times visual cues were seen

The numbers of times visual cues were seen by each subject during the measurement period (80 minutes for one subject) were statistically analyzed. The results for residences are shown in Fig. 6. The cumulative frequency distribution of the number of times is compared with the cumulative probability distribution model of a normal distribution and of a lognormal distribution. Sex and age of subjects are not considered in the figure. The lognormal distribution model fits better than the normal distri-

Table 5. Result of Chi-square test for goodness of fit for relative frequency of distance and some probability distribution models

	5% Significant level	Normal	Lognormal	Rayleigh
Residences	9.26	0.07	0.08	0.04
Offices	10.5	0.41	0.19	0.57

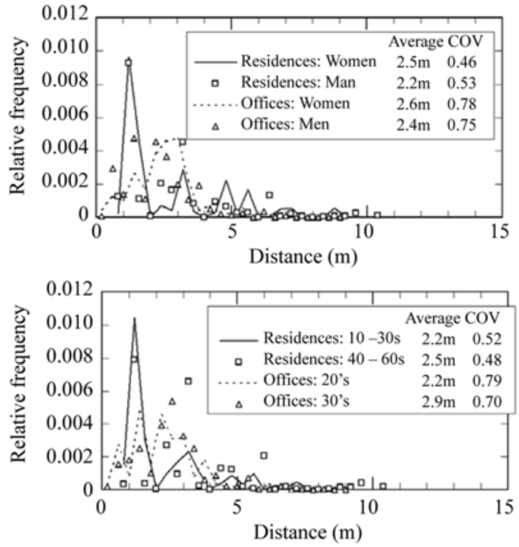

Figure 5. Comparison of relative frequencies of distance between subjects and visual cues categories according to sex and age of subjects.

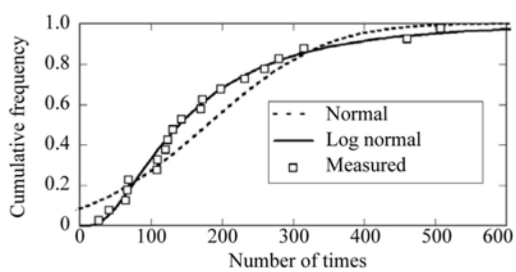

Figure 6. Comparison of cumulative frequencies of number of times visual cues were seen, 'normal distribution' and 'lognormal distribution' (Case of residences, types of visual cues not considered).

bution model for the cumulative frequency distribution. The same result is obtained for offices.

The mean values and coefficients of variation of the number of times to see visual cues, categorized according to age and sex of subjects, are shown in Table 6. When they are categorized according to sex and age, the statistical stability of the results is not good enough, since there were not enough data samples. However, the number of times for offices is clearly smaller than that for residences for all subjects as shown in Table 6. The difference occurs because the number of objects that can be visual cues in offices is smaller than that for residences. The number of objects that can be visual cues is 7.8 in residences and 3.5 in offices on average.

Table 6. Comparison of 'mean values' and 'coefficient of variation' of number of times visual cues were seen, categorized according to sex and age of subjects

	Residences				
	All	Women	Men	10s-30s	40s-60s
Average	180	161	197	250	133
COV	0.73	0.83	0.67	0.57	0.68
	Offices				
	All	Women	Men	20s	30s
Average	111	103	142	126	97
COV	0.81	0.87	0.69	0.62	1.0

4. Estimation of Probability of Vibration Perception by Visual Sensation Taking into Account Probability of Seeing Visual Cues

In previous studies (Shioya et al., 1994, 1996; Ishikawa and Noda, 1998, 1999; Shindo and Goto, 2002), vibration perceptions by body sensation have been investigated over a range of peak accelerations and natural frequencies that would be expected to occur in actual buildings. Thus, the probability distribution of vibration perception by visual sensation should be investigated in the same range to get results that can be easily compared to those of the previous studies.

In the previous chapter, length of time to see visual cues and distances between subjects and seen visual cues were measured for each event of seeing visual cues, during normal activities in actual residences and offices. The number of times visual cues were seen during measurement was also obtained. Environmental conditions in those residences and offices (for instance, room size, illuminance in rooms and activities of subjects) are almost the same as those of general residences and offices.

In this chapter, the following two things have to be clear in the process of estimating probability distribution of vibration perception by visual sensation taking into account probability of seeing visual cues.

1) Relationship between each event of seeing and visual perception threshold as velocity amplitudes of each event.

2) Relationship between visual perception threshold of each event of seeing visual cues and acceleration amplitude of building rooms vibration, which is necessary to generate the perception thresholds.

In this study, measured data of 20 subjects in the chapter 3 is brought together as measured data of one subject. Furthermore, vibration perception by visual sensation is statistically investigated using this series of data. The flow of the investigation is as follows:

1) Visual perception thresholds of each event of seeing visual cues under the condition that lighting is turned on are estimated. In this process, length of time to see visual cues and distance between subjects and seen visual cues under each event, and results from previous studies (Ohyama et al., 1994; Leibowitz, 1995; Johnson and Leibowitz, 1976; Finlay, 1982; Johnson and Scobey, 1980; Post and Leibowitz, 1981; Duncker, 1929; Mack et al., 1975) are used. (Details of the process are described in Chapter 4.1)

2) Acceleration amplitudes of building room vibrations necessary to generate the visual perception thresholds of each event of seeing visual cues estimated in process 1) are estimated. In this process, visual perception thresholds of each event of seeing and vibration characteristics of seen visual cues are used. (Details of the process are described in Chapter 4.2)

3) Probability of vibration perception by visual sensation in either events of seeing visual cues is estimated for each vibration amplitude of building rooms. The estimation is carried out separately for each natural frequency of building room vibration, using three types of data (length of time to see visual cues of each seeing event, length of measurement period, and estimated data in the above processes). (Details of the process are described in Chapter 4.3)

The details of each process are described as follows.

4.1. Estimation of visual perception thresholds for each event of seeing visual cues

Figure 7 shows the relationship between length of time to see movement of visual cues and visual perception thresholds as angular velocity amplitudes obtained from previous studies on cognitive psychology (Ohyama et al., 1994; Leibowitz, 1995; Johnson and Leibowitz, 1976; Finlay, 1982; Johnson and Scobey, 1980; Post and Leibowitz, 1981; Duncker, 1929; Mack et al., 1975). The perception thresholds as angular velocity amplitudes are a value θ, against a head of a person, distance L between the head of a person and a seen visual cue that seems to sway, and

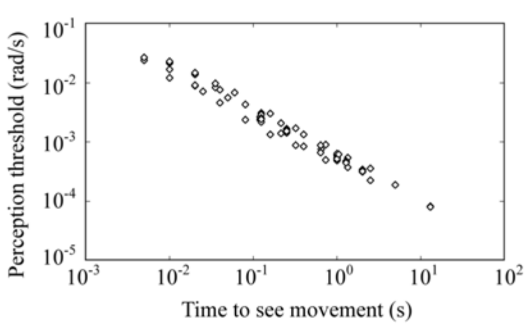

Figure 7. Relationship vetween length of time to see movement and perception thresholds as angular velocity amplitudes (e.g. Ohyama, Imai, and Waki, 1994).

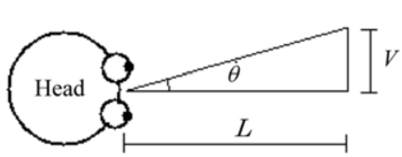

Figure 8. Relationship between a human head, a perception threshold as angular velocity amplitude ($\dot{\theta}$) and a perception threshold as velocity amplitude (V).

a minimum velocity amplitude of the seen visual cue to perceive sway of the visual cues V (expressed as "vibration perception threshold as a velocity amplitude" hereafter) as shown in Fig. 8.

In those previous studies, the perception thresholds as angular velocity amplitudes were measured for each time to see swaying visual cues, under the condition that subjects were not swayed and that they saw swaying visual cues. When the length of time to see is shorter than 1 second, the perception thresholds have a dependency on angular displacement amplitudes. However, when the length of time to see is longer than 1 second, the perception thresholds have a dependency on angular velocity amplitudes. In some of those previous studies (Ohyama et al., 1994), visual perception thresholds are investigated using angular velocity amplitudes for all time length. Thus, in this study, visual vibration perception is investigated based on the perception thresholds as angular velocity amplitudes.

In those studies, the perception thresholds as angular velocity amplitudes are investigated under different illuminance between 0.02 and 1500 lx. When the length of time to see swaying visual cues was 1 second, it was found that the perception thresholds for an illuminance of 0.02 lx was about 6.6 times bigger than those for an illuminance of 1500 lx (Ohyama et al., 1994). On the other hand, illuminance in rooms under the condition of lighting turned on was measured at several points of rooms when the investigation of the previous chapter in this study was conducted. As a result, the average value (411 lx in offices and 231 lx in residences) was close to the illuminance standard of JIS Z 9110-1979 (Tanaka et al., 1996). Figure 7 shows visual perception thresholds as angular velocity amplitudes, which correspond to an average value ± the standard deviation of illuminance measured in the previous chapter. It is assumed that visual cues were seen under the illuminance range. Furthermore, visual perception thresholds of each event of seeing visual cues as velocity amplitudes (V shown in Fig. 8) are estimated using three data: visual perception thresholds as angular velocity amplitudes shown in Fig. 7, length of time to see visual cues and distance between subjects and seen visual cues of each event of seeing measured in chapter 3.

The visual perception thresholds as angular velocity amplitudes have individual differences under the same illuminance condition. In the previous studies (Finlay, 1982; Johnson and Scobey, 1980; Post and Leibowitz, 1981; Duncker, 1929; Mack et al., 1975), it was experimentally found that there are clear differences between the perception thresholds of seeing visual cues on foveal and peripheral visual fields, and between existence and non-existence of stuck objects near visual cues that would become reference lines for perceiving vibration of visual cues. However, in previous studies, no academic proof of other factors that would influence visual perception thresholds could be found. Thus, in the step of estimation of visual perception thresholds as velocity amplitudes, the following three things are considered.

a) Individual differences

b) Differences between foveal and peripheral visual fields

c) Differences between existence and non-existence of stuck objects as reference lines

Details of the consideration methodology are described below.

In this study, the estimation is carried out under the assumption that all visual cues sway from right to left direction from the viewpoint of subjects. There is a possibility that the visual cues sway backward and forward. However, no reasonable academic proofs concerning differences in perception thresholds have been found between right and left direction and backward and forward direction, under the condition that vibration amplitudes are smaller than 15 cm(Ohyama et al., 1994). Thus, between these two modes are not considered.

4.1.1. Consideration of individual differences

There are individual differences between visual perception thresholds. Thus, all people do not necessarily perceive vibration of visual cues via a specific visual perception threshold as angular velocity amplitude under the same conditions of illuminance, distance between subjects and seen visual cues, and length of time to see. Figure 9 shows a cumulative distribution function of the perception thresholds that describes individual differences, in a case where length of time to see swaying visual cues is 0.125 sec. Figure 9 shows that both normal and lognormal distributions are appropriate for the cumulative distribution function. The same results are obtained for all the other time of seeing. The following handling is carried out to consider individual differences of perception thresholds as angular velocity amplitudes.

1) The cumulative probability distribution of the perception thresholds as angular velocity amplitudes for the same length of time is estimated using the lognormal distribution model. Perception thresholds as angular velocity amplitudes are extracted for 10%, 30%, 50%, 70%, and 90% perception probabilities.

2) The same handling is carried out for several different lengths of time. Furthermore, regression equations for the five perception probabilities are calculated(Alfredo and Wilson, 1977).

Figure 10 shows the regression equations. Perception thresholds as angular velocity amplitudes for every events of seeing visual cues are calculated for all five perception probabilities, using the five regression equations and length of time of each event of seeing measured in chapter 3. Table 7 shows an example of the calculation results where length of time to see visual cues is 2 sec.

The following assumption is made, and the individual differences for each event of seeing visual cues are considered in the process of estimating probability of vibration perception by visual sensation.

1) People who can perceive vibration by perception thresholds where the perception probability is between 0% and 20%, perceive vibration by perception thresholds, which are calculated from the regression equation whose perception probability is 10%. The ratio of the number of those people is 20%.

2) The same assumption is made for the range of perception probabilities from 20% to 40%, from 40% to 60%, from 60% to 80%, and from 80% to 100%.

In a previous study (Ohoyama et al., 1994), it was found that perception thresholds as angular velocity amplitudes are constant regardless of length of time to see movement, when the length of time is longer than 13 seconds. Thus, it is assumed that perception thresholds as angular velocity amplitudes are constant for each event of seeing

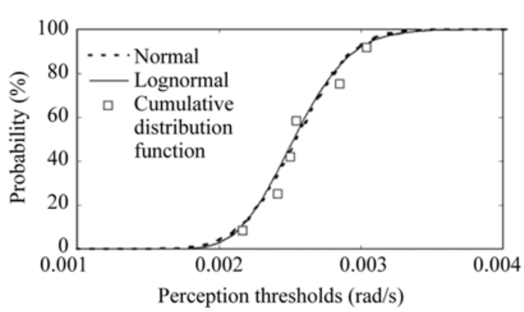

Figure 9. Probability distribution of perception thresholds as angular velocity amplitudes (a case of time length is 0.125 sec) (e.g., Ohyama, Imai, and Waki, 1994; Leibowitz, 1955; Johnson and Leibowitz, 1976; Finlay, 1982).

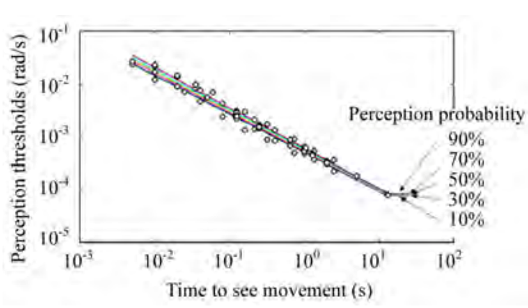

Figure 10. Regression equations of perception thresholds as angular velocity amplitudes for each perception probability (e.g., Ohyama, Imai, and Waki, 1994; Leibowitz, 1955; Johnson and Leibowitz, 1976; Finlay, 1982).

Table 7. Example of estimated perception thresholds as angular velocity amplitudes for time length 2 sec

Perception probability	Perception threshold (rad/s)
10%	1.01
30%	1.09
50%	1.12
70%	1.16
90%	1.22

Table 8. Perception thresholds as angular velocity amplitudes for observation times longer than 13 sec

Perception probability	Perception threshold (rad/s)
10%	0.00007692
30%	0.00007895
50%	0.00008076
70%	0.00008263
90%	0.00008507

visual cues, if the time length of the event is longer than 13 seconds. Table 8 shows the perception thresholds as angular velocity amplitudes for lengths of time longer than 13 seconds.

Figure 11. Examples of objects that reference lines.

4.1.2. Consideration of differences between foveal and peripheral visual fields

To perceive vibration of visual cues for seeing in the peripheral visual field, vibration amplitudes of visual cues have to be bigger than perception thresholds for seeing in the foveal visual field. According to previous studies (Finlay, 1982; Johnson and Scobey, 1980; Post and Leibowitz, 1981), the visual perception threshold in the peripheral visual field is about 2.6 times bigger than that in the foveal visual field under the same conditions of length of time to see motion, distance between subjects and seen motion, and illuminance. Here, the angle of the foveal visual field was less than 20 degrees, and the angle of the peripheral visual field was greater than 20 degrees from the line of vision. The visual field with angle less than 20 degrees corresponds to the central part of the recorded movies in the previous chapter. The visual field with angle greater than 20 degrees corresponds to the corners of the recorded movies. Thus, 2.6 times multiplication (α_1 in Eq. (1)) is carried out for perception thresholds as angular velocity amplitudes, if visual cues were recorded only in the range of recorded movies with angles greater than 20 degrees to the center of the movies for each event of seeing visual cues.

4.1.3. Consideration of differences between existence and non-existence of reference lines

Where unmoving reference lines exist close to seen motion (nearer than 2 cm from the motion), visual perception thresholds are much smaller (about 1/6) than when there is not fixed reference lines, for the same length of time to see motion, distance between subjects and the seen motion, and illuminance (Duncker, 1929). Vibrations of visual cues are perceived with smaller vibration amplitudes if fixed objects (e.g. window frames and change of wall color) exist around the seen visual cues. Figure 11 shows an example of this kind of object, which becomes a reference line. If fixed objects are exist near seen visual cues (nearer than 2 cm from the visual cues) as shown in Fig. 11, vibrations of the seen visual cues would be perceived by smaller vibration amplitudes of the visual cues. Thus, 1/6 times multiplication (α_2 in Eq. (1)) is carried out for perception thresholds as angular velocity amplitudes if fixed objects that would become reference lines are existed around visual cues each event of seeing visual cues.

Five different perception thresholds as velocity amplitudes of each event of seeing visual cues (V in Fig. 8), whose perception probabilities are different, are estimated from Eq. (1) and two data: perception thresholds as angular velocity amplitudes of each event of seeing that considers the above three things, and distance between subjects and seen visual cues for each event of seeing visual cues.

$$V = L\alpha_1\alpha_2\dot{\theta} \tag{1}$$

where V is perception threshold of each event of seeing visual cues as velocity amplitudes (minimum vibration amplitudes necessary to perceive vibration of seen visual cues), L is distance between subjects and seen visual cues for each event of seeing, $\dot{\theta}$ is perception threshold of each event of seeing as angular velocity amplitudes calculated from length of time to see visual cues and regression equations in Fig. 10, α_1 is a coefficient that expresses different conditions described in Chapter 4.1.2 (2.6 or 1), α_2 is a coefficient that expresses different conditions described in Chapter 4.1.3 (1/6 or 1).

Two data measured in chapter 3 of this study (length of time to see visual cues, and distance between subjects and seen visual cues) are different for each event of seeing visual cues. Those two measured data are used directly to estimate perception thresholds as velocity amplitudes for the each event, using Eq. (1). Thus, estimated perception thresholds as velocity amplitudes for each event of seeing visual cues vary widely because of differences in length of time to see and distance between subjects and seen visual cues.

4.2. Estimation of acceleration amplitudes of building rooms necessary to generate visual perception thresholds

In this process, it is necessary to obtain damping ratios and natural frequencies of all visual cues first. Thus, free damped vibrations of all visual cues are measured by a laser displacement sensor. The damping ratios and natural frequencies are estimated from adjoining peak displacement (y_1, y_2), reciprocals of time between adjoining peak displacement, and Eq. (2). Table 9 shows a list of the estimated damping ratios and natural frequencies (Ohkuma et al., 1996; Shibata, 1981).

$$h=\ln(d)/2\pi \quad d=\frac{y_1}{y_2} \tag{2}$$

where h is damping ratio, π is the circular constant, and y_1, y_2 are adjoining peak displacements.

Acceleration amplitudes of building room vibrations necessary to generate perception thresholds as velocity amplitudes are estimated for each of five different perception probabilities for every event of seeing visual cues from Eq. (3)(Ohkuma et al., 1996; Shibata, 1981). Eq. (3) is generated based on an equation of the response magnification factor of absolute acceleration.

$$A=\frac{2\pi fV}{\sqrt{\frac{1+4h^2(f_0/f)^2}{\{1-(f_0/f)^2\}^2+4h^2(f_0/f)^2}}} \tag{3}$$

where A is acceleration amplitude of building room necessary to generate perception threshold as velocity amplitudes of each event of seeing visual cues, V is perception threshold of each event of seeing as velocity amplitude, h is damping ratio of seen visual cue for each event of seeing, f is natural frequency of seen visual cue for each event of seeing, f_0 is natural frequencies of building room, and π is the circular constant.

Table 9. List of damping ratio and natural frequencies of visual cues for houses and offices

Residences		
	Damping ratio	Frequency (Hz)
Thick hung curtains	11.1%	0.4
Thin hung curtains	11.5%	0.4
Hung lights	1.2%	0.82
Hung blinds	4.1%	0.6
Hung clothes	2%	0.65
Hung calendars (1)	6%	0.73
Hung calendars (2)	16.8%	1.07
Hung calendars (3)	9.5%	0.67
Hung towels (1)	11%	1.11
Hung towels (2)	12.9%	2.08
Hung towels (3)	10.7%	1.1
Hung frames (1)	7.6%	1.5
Hung frames (2)	0.3%	0.51
Hung strings for switch of light	6.8%	1.43
Offices		
	Damping ratio	Frequency (Hz)
Hung blinds (1)	0.4%	0.34
Hung blinds (2)	10.3%	0.45
Hung calendars (1)	9.7%	0.69
Hung calendars (2)	10.2%	0.38
Hung strings for switch of light	7.8%	1.52
Hung papers	2.1%	1.19
Hung boards	4%	0.99
Hung amulet	2.1%	1.19
Hung towels	11.6%	1.08

Here, ten different natural frequencies between 0.10 and 6.3 Hz of building rooms that queued on the logarithm axis with the same intervals are used for the natural frequency of building rooms f_0. This estimation methodology is carried out for each natural frequency of building rooms.

In the process of estimating the acceleration amplitudes, it is assumed that every visual cue sways as a single lumped mass system. It is also assumed that the edge of visual cues whose vibration amplitudes are the largest is seen, and the acceleration amplitudes of a building room necessary to generate the vibration perception thresholds of visual cues as velocity amplitudes at the edge are estimated. Whole visual cues were seen for every event of seeing visual cues measured in chapter 3 of this study, except hung curtains and blinds. However, there are two different conditions for curtains and blinds. One is that the edge of the curtains and blinds whose vibration amplitudes would be the largest were seen. The other is that only the central parts of the curtains and blinds whose vibration amplitudes were not the largest were seen. Where only the central parts of the curtains and blinds were seen, the acceleration amplitude necessary to generate perception thresholds at the central parts of visual cues is twice bigger than that of the edge. Thus, acceleration amplitudes of rooms necessary to generate perception thresholds estimated by Eq. (3) are multiplied by two for every event of seeing visual cues where only the central parts of the curtains and blinds were seen.

Differences between seeing in foveal and peripheral visual field and between existence and non-existence of reference lines are already considered in the process of estimating perception thresholds as velocity amplitudes. Thus, the estimation in chapter 4.2 is carried out without any relation to differences of seeing in fovea and peripheral visual field, and differences between existence and non-existence of reference lines. Table 10 shows some examples of the estimated acceleration amplitudes of rooms necessary to generate visual perception thresholds as velocity amplitudes. In two cases of Table 10, acceleration amplitudes necessary to generate visual perception thresholds are 46.6 cm/s^2 and 29.9 cm/s^2. The acceleration amplitudes are bigger than that of other cases. In these 2 cases, visual cues are seen in the peripheral visual field and fixed reference lines did not exist. It is the most difficult case to perceive vibration of visual cues. Thus, visual vibration thresholds of the cases are bigger than that of other cases and calculation results shown in Table 10 also became bigger than other cases.

Table 10. Examples of estimated acceleration amplitudes necessary to generate visual perception thresholds as velocity amplitudes

Residences	Length of time to see (s)	Acceleration (cm/s^2)
Thick hung curtains	17.75	1.4
Thin hung curtains	21.2	1.1
Hung lights	7.91	9.4
Hung blinds	5.55	1
Hung clothes	0.99	8.1
Hung calendars (1)	2.22	19.1
Hung calendars (2)	5.67	46.6
Hung calendars (3)	8.55	2.5
Hung towels (1)	2.7	9.2
Hung towels (2)	1.19	29.9
Hung towels (3)	2.84	3.8
Hung frames (1)	82.78	1.4
Hung frames (2)	3.37	2.9
Hung strings for switch of light	9.52	4.8

Offices	Length of time to see (s)	Acceleration (cm/s^2)
Hung blinds (1)	1.02	0.3
Hung blinds (2)	1.01	3.8
Hung calendars (1)	1.51	5.3
Hung calendars (2)	21.3	1.3
Hung strings for switch of light	15.56	5.7
Hung papers	1.96	2.1
Hung boards	5.61	2.3
Hung amulet	4.38	2.4
Hung towels	6.4	2.6

4.3. Estimation of probability of vibration perception by visual sensation

Probability distributions of vibration perception by visual sensation are estimated by the following methodology (Mark et al., 1975), using three data: acceleration amplitudes necessary to generate perception thresholds as velocity amplitudes of each event of seeing visual cues, length of time to see visual cues of each event of seeing visual cues, and length of measurement period of the experiment in chapter 3 of this study (80 minutes for one subject).

1) Probabilities of vibration perception by visual sensation for each event of seeing visual cues are estimated for each acceleration amplitude of building rooms. (described in chapter 4.3.1.)

2) Using the series of data obtained in 1), probabilities of perceiving vibration in either of many event of seeing visual cues that existed in the measurement period are estimated for each acceleration amplitude of buildings rooms. (described in chapter 4.3.2.)

3) Probability estimation described in 1) and 2) is conducted for each natural frequency of building rooms. Furthermore, probability distribution models of vibration perception by visual sensation taking into account a probability of seeing visual cues are estimated, based on results of the above steps. (described in chapter 4.3.3.)

Here, it is assumed that vibrations of building rooms are sinusoidal waves whose durations are optionally limited. The estimation is carried out separately, for each of 10 natural frequencies of building rooms. The natural frequencies queue up on the logarithm axis with the same intervals between 0.10 and 6.3 Hz. Details of the methodology are described as follows.

4.3.1. Estimation of probability of vibration perception for each event of seeing visual cues

Probability of vibration perception of each event of seeing visual cues is estimated from Eq. (4) for each acceleration amplitude of building rooms.

$$P_i = \beta_i \times \frac{t_i}{T} \quad i = 1,\ 2,\ 3,\ \cdots,\ n \tag{4}$$

where, P_i is probability of vibration perception of each event of seeing visual cues, β_i is probability of vibration perception under the condition that each event of seeing visual cues and building vibrations occur at the same time, t_i is time length of each event of seeing visual cues measured in chapter 3, and T is length of measurement period of the experiment conducted in chapter 3.

In chapter 3 of this study, the measurement period was 80 minutes for one subject. Furthermore, the experiment was conducted for 20 subjects for residences and offices, respectively. Thus, the length of measurement period T is 1600 minutes for this estimation.

It is assumed that β_i becomes one of 6 different numbers between 0 and 1 according to the following condition.

1) If velocity vibration amplitudes of seen visual cues generated by the target acceleration amplitude of building rooms are smaller than perception thresholds as velocity vibration amplitudes whose perception probability is 10%, β_i of each event of seeing visual cues is 0.

2) If velocity vibration amplitudes of seen visual cues generated by the target acceleration amplitude of building rooms are greater than perception thresholds whose perception probability is 10% and smaller than perception thresholds whose perception probability is 30%, β_i of each event of seeing visual cues is 0.2.

3) Similarly, β_i becomes 0.4 for perception thresholds whose perception probability is between 30% and 50%. β_i becomes 0.6 for perception thresholds whose the perception probability is between 50% and 70%. β_i becomes 0.8 for perception thresholds whose the perception probability is between 70% and 90%. If velocity vibration amplitudes of observed visual cues are bigger than perception thresholds whose the perception probability is 90%, β_i becomes 1.0.

It is assumed that vibrations of building rooms are sinusoidal waves whose durations are optionally limited. Thus, visual cues are not necessarily seen for each event of seeing during vibrations of buildings that generate vibration amplitudes of visual cues greater than perception thresholds. Thus, β_i is multiplied by t_i/T. Here, t_i/T is the probability of seeing visual cues of each event of seeing during building vibrations. The perception probabilities of every event of seeing visual cues are estimated by the same methodology for every acceleration amplitudes of building rooms.

4.3.2. Estimation of probability of vibration perception by either event of seeing visual cues

Events of seeing visual cues measured in chapter 3 of this study are not necessarily independent statistically. Thus, the probability of which building vibrations are perceived by visual sensation by either of the event of seeing visual cues is calculated from Eq. (5) for each acceleration amplitude of building rooms. The probability of an event's occurrence that is not statistically independent can be calculated accurately for Eq. (5).

$$P_V = P_1 + P_2 + \ldots + P_i - p_{12} - p_{13} - \ldots - p_{ij} \tag{5}$$

$$+p_{123} + p_{124} + \ldots + p_{ijk} \ldots \quad i,\ j,\ k = 1,\ 2,\ 3,\ \ldots,\ n$$

where P_i is perception probability of each o event of seeing visual cues estimated in chapter 4.3.1., p_{ij} is probability of seeing visual cues by either two events of seeing and visually perceiving vibrations by both of the events of seeing, p_{ijk} is probability of seeing visual cues by either three events of seeing and of visually perceiving vibrations by all three events of seeing, and P_V is the probability of perceiving vibration by visual sensation by either events of seeing visual cues.

In the measurement in chapter 3 of this study, two events of seeing visual cues occurred in the same time. Thus, to estimate probability p_{ij}, the length of time during which two events of seeing visual cues occurred at the same time was measured from the movies recorded in chapter 3 of this study. Furthermore, the probability p_{ij} is estimated from Eq. (6).

$$p_{ij} = \beta_{ij} \times \frac{t_{ij}}{T} \quad i,\ j = 1,\ 2,\ 3,\ \ldots,\ n \tag{6}$$

where p_{ij} is probability of seeing visual cues by either of two events of seeing visual cues and of visually perceiving vibration by both of the events of seeing, t_{ij} is length of time during which two events of seeing occurred at the same time, T is length of measurement period of the experiment conducted in chapter 3 of this study (1600 minutes for residences and offices respectively), and β_{ij} is a smaller probability of vibration perception of two β_i under the condition that seeing visual cues and building vibrations occur at the same time.

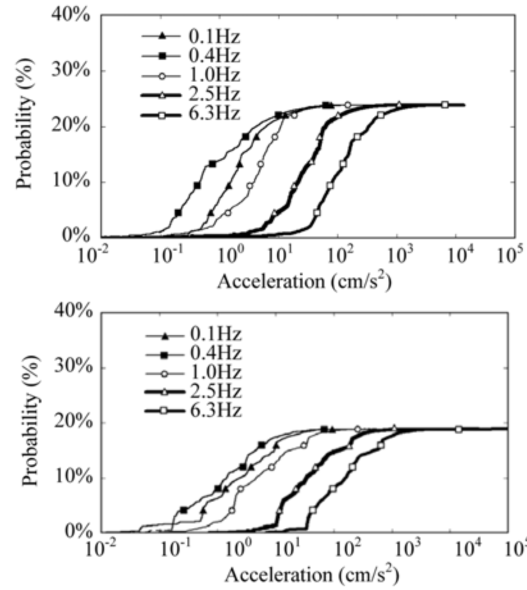

Figure 12. Estimation results of probability distribution of vibration perception by visual sensation from Eqs. (5) and (6) (top: residences, bottom: offices).

If more than two events of seeing visual cues occur at the same time during the measurement, the same consideration has to be carried out for that situation. However, in this study, this situation did not occur, so it is not considered.

The probability of vibration perception by visual sensation is estimated using Eqs. (5) and (6) for each acceleration amplitude and each natural frequency of building rooms. Figure 12 shows five examples of estimated probability distributions.

In this results, individual differences of vibration perception, differences between seeing visual cues on foveal and peripheral visual fields, differences between existence and non-existence of reference lines, and differences between seeing central parts or edge of visual cues are considered for each event of seeing visual cues. Length of time to see visual cues and distance between subjects and seen visual cues vary widely for each event of seeing visual cues. The variations are considered in the process of estimating perception thresholds as velocity amplitudes.

4.3.3. Probability distribution model of vibration perception by visual sensation

Estimated results shown in Fig. 18 are directly estimated using a series of data measured in chapter 3 of this study. Thus, it is necessary to estimate a probability distribution model of the vibration perception by visual sensation based on the results.

In Fig. 12, the maximum probability of vibration perception by visual sensation is not 100%. This is because visual cues are not necessarily seen during building vibrations. Here, the maximum probability is equal to the ratio of total length of time to see visual cues by each event of seeing to the measurement period, which can be calculated by Eq. (7). It is the same as the probability that subjects see visual cues by either event of seeing visual cues.

$$p_w = \frac{\sum_{i=1}^{n} t_i - \sum_{i=1}^{n}\sum_{j=1}^{n} t_{ij}}{T} \quad i, j = 1, 2, 3, ..., n \tag{7}$$

where p_w is probability of seeing visual cues by either event of seeing visual cues, t_i is length of time to see visual cues in each event of seeing visual cues measured in chapter 3 of this study, and t_{ij} is length of time to see visual cues during which two events of seeing visual cues occurred at the same time, and T is length of measurement period of the experiment conducted in chapter 3 (1600 minutes for residences and offices respectively).

Curves with ruggedness are drawn between 0% and maximum probability of visual vibration perception. Visual cues are seen in the range of this probability. However, there are two conditions in which vibration amplitudes of seen visual cues are greater or smaller than perception thresholds. The curves are drawn since the two conditions are intermingled and the situations differ according to acceleration amplitude of building rooms.

In this case, probability distribution models of the following two things are estimated using three data: length of time to see visual cues in each event of seeing visual cues, length of measurement period of experiment conducted chapter 3 of this study, and probability distribution of vibration perception by visual sensation shown in Fig. 12.

1) Probability of seeing visual cues by either event of seeing visual cues

2) Probability of vibration perception by visual sensation by either event of seeing visual cues under a condition visual cues are seen

Furthermore, the following two things are multiplied to estimate probability distribution models of vibration perception by visual sensation in consideration of probability of seeing.

1) Average probability of seeing visual cues by either event of seeing

2) Probability distribution model of vibration perception by visual sensation by either event of seeing visual cues under a condition visual cues are seen

4.3.3.1. Probability distribution model of seeing visual cues

Probability of seeing visual cues by either event of seeing visual cues for each subject is estimated using a series of measured data in chapter 3 and Eq. (7). Here, length of measurement period of the experiment T is 80 minutes. This is the measurement period for one subject. Furthermore, frequency distribution of the probability of seeing visual cues is estimated and examined by Chi-square tests for goodness of fit to normal, lognormal, and beta distribution. Table 11 shows results of the Chi-square tests.

Table 11. Results of Chi-square tests for probability of seeing visual cues

	5% significance level	Lognormal distribution	Normal distribution	Beta distribution
Residences	10.9	1.6	3.11	1.46
Offices	10.9	3.96	4.42	2.85

The upper and lower bound values of beta distribution are set as 1 and 0, since it is obvious that the probability of seeing is between 0 and 1.

Table 11 shows that all probability distribution models are appropriate within 5% significance level. However, it can be said that beta distribution is the most appropriate as a probability distribution model for the probability of seeing visual cues. Some other probability distribution models (for instance, Gumbel and Rayleigh distribution) were also tested. However, the results were inferior to those in Table 11. It is thought that beta distribution is the most appropriate probability distribution model, since it is also obvious that the upper and lower bound values of the probability of seeing visual cues is 1 and 0.

Here, the probability of seeing visual cues for 20 subjects calculated by Eq. (7) is 23.8% on average for residences and 18.4% on average for offices. The coefficient of variation is 0.88 for residences and 1.07 for offices.

4.3.3.2. Probability distribution model of vibration perception under the condition that visual cues are seen

The probability distributions of vibration perception shown in Fig. 12 are divided by the maximum probability. These are probability distributions of vibration perception under the condition that visual cues are seen by either event of seeing visual cues. Mean values and standard deviations of the probability distributions are not known. Thus, it is necessary to estimate the mean values μ and standard deviations σ by the least square method (Tanaka, 1977). Furthermore, some probability distribution models are calculated based on the mean values μ and standard deviations σ, to investigate the most appropriate probability model.

In the least square method, standard points Z_j are esti-

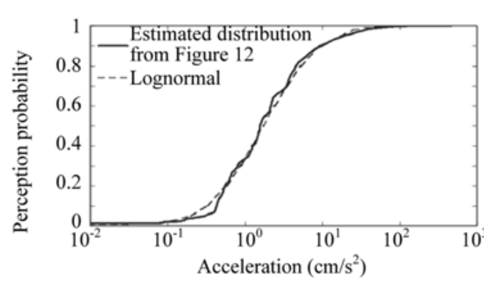

Figure 13. Comparison of probability distribution of vibration perception by visual sensation under the condition that visual cues are seen by either event of seeing and lognormal distribution (Residences, 0.10 Hz).

mated using some stimulus values S_j (they correspond to accelerations on the horizontal axis of Fig. 12) and cumulative probabilities P_j correspond to the stimulus values (they correspond to values in which the probability on vertical axis of Fig. 12 is divided by maximum probability). Furthermore, the mean values μ and the standard deviations σ are estimated using the three types of data, Eqs. (8) and (9) (Alfredo and Wilson, 1977).

$$\mu=\overline{S}-\overline{Z}\sigma \tag{8}$$

$$\sigma=\frac{\Sigma S_j^2-n(\overline{S})^2}{\Sigma S_j Z_j-n\overline{S}\overline{Z}} \tag{9}$$

where μ is mean value, σ is standard deviation, S_j is stimulus value, P_j is cumulative probability corresponding to stimulus value S_j, Z_j is standard point corresponding to cumulative probability P_j, n is number of stimulus values used for the estimation, $\overline{S}$ is mean value of stimulus values S_j, and $\overline{Z}$ is mean value of standard value Z_j.

In Fig. 13, the probability distribution model of lognormal distribution estimated by calculated mean value μ, standard deviation σ, and Eqs. (10) and (11) is compared with probability distributions of vibration perception under the condition that visual cues are seen by either event of seeing visual cues. It shows the case of 0.1 Hz for residences.

$$f_x(x)=\frac{1}{\sqrt{2\pi}\zeta x}\exp\left[-\frac{1}{2}\left(\frac{\ln x-\lambda}{\zeta}\right)^2\right] \tag{10}$$

$$\lambda=\ln(\mu)-\zeta^2/2 \qquad \zeta^2=\ln(1+\sigma^2/\mu^2) \tag{11}$$

It is clearly understood that the lognormal distribution is appropriate as a probability distribution model. Some other probability distribution models (for instance, normal distribution and Rayleigh distribution) are compared with the probability distributions to confirm their appropriateness. However, it was found that the results were inferior to those for the lognormal distribution. The same results are obtained for every other natural frequency of residences and offices. Thus, the probability distribution model of vibration perception by visual sensation under the condition that visual cues are seen by either event of seeing visual cues is estimated by lognormal distribution for every natural frequency of residences and offices.

The following two things are multiplied together to estimate the probability distributions of vibration percep-

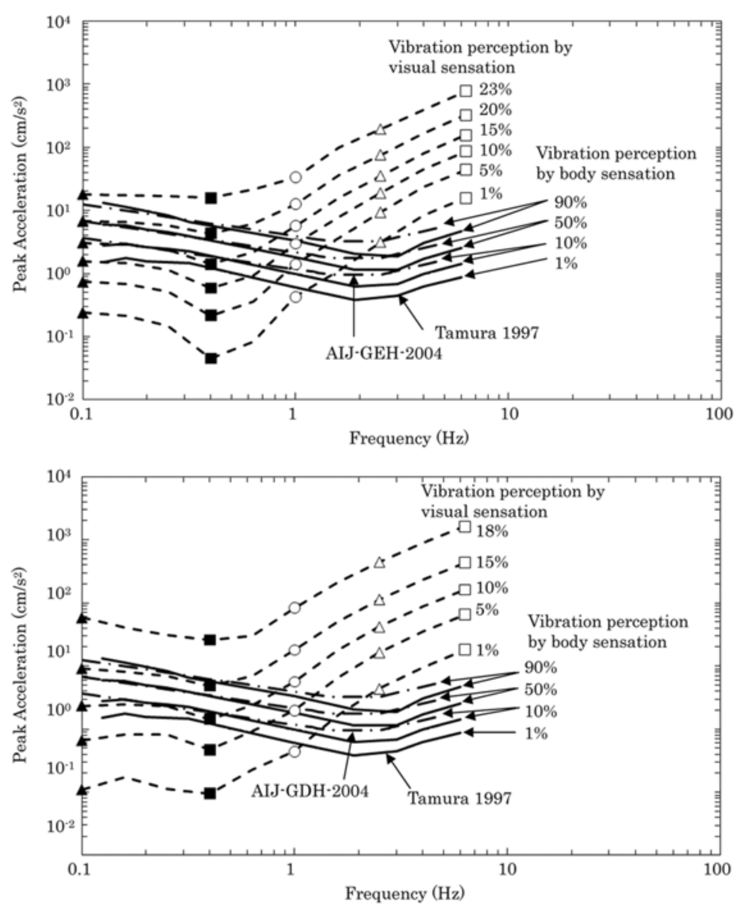

Figure 14. Comparison of probability curves of vibration perception by only visual sensation and vibration perception by only humans (AIJ-GDH-2004, 2004; Tamura, 1997) (top: residences, bottom: offices).

tion by visual sensation taking into account probability of seeing visual cues.

1) Mean values of probability of seeing visual cues by either event of seeing visual cues

2) Probability distribution model of vibration perception by visual sensation under condition that visual cues are seen by either event of seeing visual cues (estimated by lognormal distribution)

Acceleration amplitudes that correspond to probabilities queued up at the same intervals are found from the probability distributions of vibration perception by visual sensation. The probabilities are 1%, 50%, 10%, 15%, 20% and 23% for residences, and 1%, 50%, 10%, 15% and 18% for offices. Furthermore, curves of the same probabilities of vibration perception by visual sensation are drawn and compared with curves of probabilities of vibration perception by body sensation (AIJ-GEH-2004, Tamura, 1997). The comparison is shown in Fig. 14. The solid lines indicate probability distributions of vibration perception by body sensation (results of previous studies), and the dotted lines are probability distributions of vibration perception by visual sensation taking into account probability of seeing visual cues (results of this study).

In this study, it is assumed that building vibrations are sinusoidal vibration with durations optionally limited. In some previous studies(Jeary et al., 1988; Irwin, 1975; Griffin and Whithman, 1980; Nakamura et al., 1995; Shioya et al., 1994, 1996; Ishikawa and Noda, 1998, 1999; Denoot et al., 2000; Kwok et al., 2007), vibration perceptions by body sensation were investigated for maximum acceleration amplitudes of random vibration. However, it was found that there are no clear differences between vibration perceptions by body sensation for sinusoidal vibration and that of a random vibration (Shioya et al., 1994, 1996). Thus, in this study, difference of sinusoidal and random vibrations is not considered.

4.4. Discussion

By comparing the probability curves of vibration perception by visual sensation with those of vibration perception by body sensation (AIJ-GEH-2004, Tamura, 1997) shown Fig. 14, the following can be deduced.

1) In the range of natural frequency of building below 1.0 Hz and peak acceleration below 2 cm/s^2, the probability curves of vibration perception by visual sensation are in the range of smaller peak acceleration. In this range, it can be said that vibration perception by visual sensation would occur more often than vibration perception by body sensation.

2) In the range of natural frequency below 1.0 Hz and peak acceleration above 10 cm/s^2, the probability of vibration perception by body sensation is greater than 90%. However, the probability of vibration perception by visual sensation is 23% for residences and 18% for offices. Visual cues are not necessarily seen when building vibrations occur. Thus, it can be said that the probability of vibration perception by visual sensation does not increase with increase in peak acceleration, compared to the increase of probability of vibration perception by body sensation.

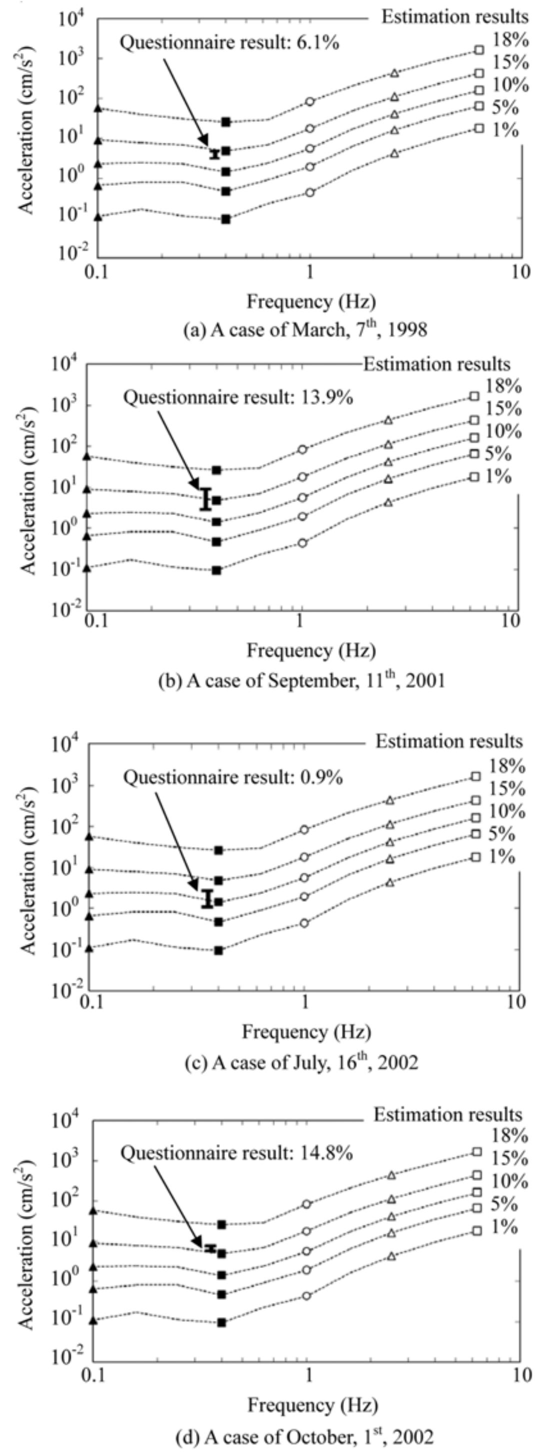

Figure 15. Comparison of estimation results in this study and questionnaire results of a previous study (dotted line: estimation results of this study, thick solid line: questionnaire resuluts (Kawana, Tamura, and Matsui, 2008)).

3) In the range of natural frequency higher than 2.5 Hz, probability curves of vibration perception by visual sen-

sation are in the range of bigger acceleration amplitude than probability curves of vibration perception by body sensation, for both residences and offices. In the range of natural frequency, the probability of vibration perception by body sensation is greater than 90% for 10 cm/s^2 of acceleration amplitude. However, the probability of vibration perception by visual sensation is less than 1% for the same acceleration amplitude. In this range of natural frequency, vibration perception by visual sensation rarely occurs, compared with vibration perception by body sensation, since very large acceleration amplitudes of buildings are necessary to generate minimum vibration amplitudes of visual cues to perceive the vibration by visual sensation.

4) Maximum probability of vibration perception by visual sensation is 23.9% for residences and 18.4% for offices. The probability for offices is smaller than that for residences. The difference occurred because the number of visual cues for offices was smaller than that for residences. Furthermore, subjects saw visual cues less often in offices, while they were concentrating on their work. In buildings where the measurement in chapter 3 of this study was conducted, the number of visual cues was 3.5 in offices and 7.8 in residences on average. The number of times visual cues were seen during the measurement was 126 times for offices and 180 times for residences on average. When the number of visual cues is increased from 6 to 10, the maximum probability of vibration perception by visual sensation is increased from 23.2% to 24.7%, even in the same circumstance of residences. When number of visual cues is increased from 2 to 5, the maximum probability of visual vibration perception is increased from 16.7% to 21%, for the same circumstance of offices. It seems that the maximum probability would increase if the number of visual cues was increased.

5) Probability curves of vibration perception by visual sensation for residences are at slightly smaller acceleration amplitude than those for offices. Furthermore, variation of vibration perception by visual sensation for offices is bigger than that for residences.

6) The authors of this paper conducted a full-scale measurement of wind-induced vibration and questionnaires about vibration perception simultaneously in an actual high-rise building. Furthermore, ratios of occupants who saw swaying of objects inside the building were investigated (Kawana et al., 2008). The ratios and estimation results of this paper were compared as shown in Fig. 15. Dotted lines are estimation results of this paper, and thick solid lines are questionnaire results. The questionnaires and full-scale measurement were conducted 4 times on March 7th 1998, September 11th 2001, July 16th 2002, and October 1st 2002. Time history of acceleration amplitudes of the same building floor was measured in the same day. However, the questionnaires were not necessarily conducted on the same floor of the high-rise building. Thus, the questionnaire results are shown based on peak accelerations amplitude measured on the nearest floor of which the questionnaires were conducted. In this study, probability distribution of vibration perception by visual sensation was estimated separately for residence and office. The questionnaire results are compared with the probability distribution for offices, since environmental conditions of a building for which questionnaires were conducted was very similar to the condition of offices. It was found that all questionnaire results and estimation results of this study correspond with each other well.

5. Conclusions

This study focused on vibration perception by visual sensation by accidental seeing of visual cues as the first perception of vibration, under a condition that lighting is turned on.

In the first step of this study, three types of data necessary to estimate the probability of vibration perception by visual sensation taking into account probability of seeing visual cues were measured using a small camera during normal activities in actual residences and offices. Probability distribution of vibration perception by visual sensation depends upon mean values, coefficients of variation and shapes of relative frequencies of the measured data. Thus, these statistical parameters were investigated. The most appropriate probability distribution models were also investigated. A Rayleigh distribution shows a good approximation as a probability distribution model of the distance between subjects and seen visual cues for residences. However, a lognormal distribution shows the best approximation as the probability distribution model for all other measured data. Mean values of the length of time to see visual cues for each event of seeing visual cues is the same, regardless of age and sex of subjects and type of building. However, the coefficient of variation for residences is bigger than that for offices. Mean values of distance between subjects and seen visual cues are almost the same for both residences and offices, regardless of age and sex of subjects. The number of times visual cues are seen in measurement period for offices is smaller than that for residences, for all subjects.

In the second step of this study, probability distribution of vibration perception by visual sensation by accidental seeing of visual cues was estimated using a series of data measured in the first step of this study. Individual differences of vibration perception, variation of measured data, and different way of seeing visual cues which influence to vibration perception by visual sensation are considered in the process of the estimation. As a result, it was found that the relationship between vibration perception by visual sensation and vibration perception by body sensation varies greatly, according to natural frequencies and acceleration amplitudes of building rooms.

Acknowledgements

The authors gratefully acknowledge the 40 subjects who cooperated for a long time in the measurements using a small camera. The study in the second chapter was conducted by financial support of Grant-in-Aid for Scientific Research by Japanese Society for the Promotion of Science. The study in the third chapter was conducted by financial support of 21st Century Center of Excellence Program by Japanese ministry of education, culture, sports, science and technology. The authors also gratefully acknowledge the supports.

References

Alfredo, H. S. A. and Wilson, H. T., interpreted by Ito, M. and Kameda, H. (1977). *Probability Concepts in Engineering Panning and Design*, Maruzen Co. Ltd. (in Japanese).

AIJ-GEH-2004. (2004). *Guidelines for the Evaluation of Habitability to Building Vibration.* Maruzen Publishing, Architectural Institute of Japan. (in Japanese).

AIJ (2004). *Guidelines for the evaluation of habitability to building vibration*, Architectural Institute of Japan. (in Japanese).

Burton, M. D., Kwok, K. C. S., Hitchcock, P. A., and Denoon, R. O. (2006). "Frequency Dependence of Human Response to Wind-Induced Building Motion." *Journal of Structural Engineering*, ASCE, 132(2), pp. 296~303.

Denoon, R. O., Roberts, R. D., Letchford, C. W., and Kwok, K. C. S. (2000). Effects of Wind-Induced Building Motion on Cognitive Performance, Research Report No. R804, October.

Duncker, K. (1929). "Uber induzierte Bewegung." *Psychologische Forschung*, 12, pp. 180~259.

Finlay, D. (1982). "Motion perception in the peripheral visual field", *Perception*, 11, pp. 457~462.

Griffin, M. J. and Whithman, E. M. (1980). "Discomfort produced by impulsive whole-body vibration." *Journal of Acoustical Society of America*, 68(5), pp. 1277~1284.

Inoue, K. (2004). "Troubles and performance evaluations of environmental vibrations." *Proceedings of environmental engineering section panel discussion in Annual conference of Architectural Institute of Japan in 2004,* September, pp. 3~8. (in Japanese).

International Organization for Standardization. (1989, 2). *ISO 2631-2, Evaluation of human exposure to whole body vibration Part2- Evaluation of human exposure to vibration in buildings.*

International Organization for Standardization. (1984, 8). *ISO 6897, Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and off-shore structures, to low frequency horizontal motion (0.063 to 1 Hz).*

Irwin, A. W. (1975). "Human reactions to oscillations of buildings – Acceptable limits." *Build International*, 8, pp. 89~102.

Ishikawa, T. and Noda, C. (1998). "Sensory assessment of horizontal vibration over a wide frequency range." *Journal of Architecture Panning Environment and Engineering*, AIJ, 506, April, pp. 9~16. (in Japanese).

Ishikawa, T. and Noda, C. (1999). "Influence of the subjects' situation on perception threshold of horizontal vibration." *Journal of Architecture Panning Environment and Engineering.*, AIJ, 524, October, pp. 9~14. (in Japanese).

Ishikawa, T. and Noda, C. (1999). "Influence of visual sensation on sense of horizontal vibration." *Journal of Architecture Panning Environment and Engineering*, AIJ, 525, November, pp. 15~20. (in Japanese).

Ishikawa, T., Uekusa, T., Ichiriki, Y., and Noda, C. (1993). "A study on vibration sensation considering habitability of high rise dwelling -Part 1 Outline of the research and the result-." *Summaries of Technical papers of Annual Meeting Architectural Institute of Japan, Environmental Engineering*, September, pp. 95~96. (in Japanese).

Jeary, A. P., Morris, R. G., and Tomlinson, R. W. (1988). "Perception of vibration-tests in tall buildings." *Journal of Wind Engineering and Industrial Aerodynamics*, 28, pp. 361~370.

Johnson, C. A. and Leibowitz, H. W. (1976). "Velocity-time reciprocity in the perception of motion: Foveal and peripheral determinations." *Vision Research*, 16, pp. 177~180.

Johnson, C. A. and Scobey R. P. (1980). "Foveal and peripheral displacement thresholds as a function of stimulus luminance, line length and duration of movement." *Vision Research*, 29, pp. 709~715.

Kawana, S. and Hisada, Y. (2002). "Study on habitability in high rise buildings during wind-induced vibration." *Proceedings of Master's thesis at KOGAKUIN University in 2002*, pp. 193~196. (in Japanese).

Kawana, S., Tamura, Y., and Matsui, M. (2008). "Study on visual vibration perception -Measurement and statistical analysis of length of time to see visual cues-." *Advances in Structural Engineering*, 11(8), pp. 411~423.

Kawana, S., Tamura, Y., and Matsui, M. (2008). Study on visual vibration perception -Full-scale measurement of vibration perception and time to see visual cues-. *Proceeding of the 4th International Conference on Advances in Wind and Structures (AWAS'08)*, pp. 1415~1425, Jeju, Korea.

Kwok, K. C. S., Burton, M. D., and Hitchcock, P. A. (2005). Human Perception of Tall Building Motions in Strong Wind Environments, The Sixth Asian-Pacific Conference on Wind Engineering (APCWE-VI), Seoul, Korea, September 12-14, pp. 248~262.

Kwok, K. C. S., Burton, M. D., and Hitchcock, P. A. (2007). Occupant Comfort and Perception of Motion in Wind-excited Tall Buildings, *12th International Conference on Wind Engineering*, Cairns, Australia, July 1-6, pp. 101~115.

Kwok, K. C. S., Burton, M. D., and Hitchcock, P. A. (2007). Human Perception of Tall Building Motions in Strong Wind Environments, COE International Advanced School Wind Effects on Buildings and Urban Environment Course A: Wind Resistant Design, March 5-9, pp. 225~240.

Leibowitz, H. W. (1955). "The relation between the rate threshold for the perception of movement and luminance for various durations of exposure." *Journal of Experimental*

Psychology, 49(3), pp. 209~214.
Mack, A., Fisher, C. B., and Fendrich, R. (1975). "A re-examination of two-point induced movement." *Perception and Psychophysics*, 17, pp. 273~276.
Nakamura, T., Kanda, J., Shioya, K., and Nagaya, M. (1995). "Statistical survey on human perception criteria for earthquake motions in base-isolated buildings." *Journal of Structure Construction and Engineering*, *AIJ*, 472, pp. 185~192. (in Japanese).
Ohkuma, T., Kanda, J., and Tamura, Y. (1996). *Wind resistant design of buildings*, Kajima institute publishing Co., Ltd.
Ohyama, T., Imai, S., and Waki, N. (1994). *Handbook of sense and sensory psychology.* Seishin Shobo. (in Japanese).
Ooyama, T., Imai, S., and Waki, Y. (1994). *New volume of the handbook for sense and cognitive psychology.* Shinseisyobo. (in Japanese).
Post, R. B. and Leibowitz, H. W. (1981). "The effect of refractive error on central and peripheral motion sensitivity at various exposure durations." *Perception and Psychophysics*, 29, pp. 91~94.
Shibata, Y. (1981). *The latest, structural analysis for seismic-resistant design*. Morikita publishing Ltd. (in Japanese).
Shindo, S. and Goto, T. (2002). "Effect of long period torsional motion on human visual perception." *Journal of Architecture Panning Environment and Engineering*, AIJ, 533, pp. 23~28. (in Japanese).
Shioya, K., Fujii, K., Tamura, Y., and Kanda, J. (1994). "Human perception thresholds of two-dimensional sinusoidal motion in horizontal plane." *Journal of Structure Construction and Engineering,* AIJ, 461, pp. 29~36. (in Japanese).
Shioya, K., Fujii, K., Tamura, T., and Kanda, J. (1996). "Human perception thresholds of two-dimensional random motion in horizontal plane." *Journal of Structure Construction and Engineering,* AIJ, 485, pp.35~42. (in Japanese).
Takahashi, M. (1995). "Relationship of various symptoms of motion sickness and sense of balance." *Practica oto-rhino-laryngologica*, 3711, October, pp. 13~19. (in Japanese).
Takahashi, M. (1997), *Motion sickness*, Tsukiji Shokan. (in Japanese).
Tanaka, T., Takeda, Z., Adachi, T., and Tsuchiya, T. (1996). *Environmental engineering for architecture*, Inoue-syoin. (in Japanese).
Tanaka, Y. (1977). *Measurement methodology for psychology*, University of Tokyo Press. (in Japanese).
Tamura, Y. (1997). *Application of Damping Devices to Suppress Wind-Induced Responses of Buildings*. Proc. 2nd European & African Conference on Wind Engineering, Palazzo Ducale, Genova, Italy, June 22-26, pp. 45~60.

Appendix: Notation

A : Acceleration amplitude of building room necessary to generate perception threshold as velocity amplitudes of each observational condition
f : Natural frequency of seen visual cue for each event of seeing
f_0 : Natural frequencies of building room
h : Damping ratio of seen visual cue for each event of seeing
L : Distance between subjects and seen visual cues for each event of seeing
n : Number of stimulus values used for estimation of mean values and standard daviations
P_i : Probability of vibration perception of each event of seeing visual cues
p_{ij} : Probability of seeing visual cues by either two events of seeing and visually perceiving vibrations by both of the events of seeing
p_{ijk} : Probability of seeing visual cues by either three events of seeing and of visually perceiving vibrations by all three events of seeing
P_V : the probability of perceiving vibration by visual sensation by either events of seeing visual cues.
p_w : Probability of seeing visual cues by either event of seeing visual cues,
$\overline{S}$: Mean value of stimulus values S
S_j : Stimulus value
T : Length of measurement period of the experiment conducted in the first step of this study
t_i : Time length of each event of seeing measured in the first step of this study
t_{ij} : Length of time to see visual cues during which two events of seeing occurred at the same time
V : Perception threshold of each event of seeing visual cues as velocity amplitudes (minimum vibration amplitudes necessary to perceive vibration of seen visual cues)
y_1, y_2 : Adjoining peak displacement amplitudes
$\overline{Z}$: Mean value of standard value Z_j.
Z_j : Standard point corresponding to cumulative probability P_j
$(1-\alpha)$: Cumulative probability of Chi-square distribution
α_1 : A coefficient that expresses different conditions described in Chapter 4.1.2 (2.6 or 1)
α_2 : A coefficient that expresses different conditions described in Chapter 4.1.3 (1/6 or 1)
β_i : Probability of vibration perception under the condition that each event of seeing visual cues and building vibrations occur at the same time
β_{ij} : A smaller probability of vibration perception of two β_i under the condition that seeing visual cues and building vibrations occur at the same time
θ : Perception threshold of each event of seeing as angular velocity amplitudes calculated from length of time to see visual cues and regression equations in Fig. 10
π : The circular constant
μ : Mean value
σ : Standard deviation