Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 69 (1993)

Artikel: Human response to horizontal motion of tall buildings

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DOI: https://doi.org/10.5169/seals-52545

Human Response to Horizontal Motion of Tall Buildings

Réaction humaine aux mouvements horizontaux des gratte-ciels

Menschliche Reaktion auf Horizontalschwingungen in Hochhäusern

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SUMMARY

The authors have conducted experiments on human response to typical horizontal biaxial motions in order to clarify the effects of the motions of tall buildings induced by wind on habitability. The tests proved the following by the experience of discomfort, difficulty and uneasiness and the balance of standing persons: Human response to biaxial motions, especially to circular and linear motion, is much greater than that to linear motion; and, the relation between balance shift index and psychological response can be approximated by one logarithmic function.

RESUME

Les auteurs ont mené des essais sur le comportement humain par suite de mouvements horizontaux biaxiaux, engendrés par l'effet du vent sur les immeubles de grande hauteur. Il en résulte que les humains réagissent plus fortement aux mouvements biaxiaux, tout spécialement à la combinaison des mouvements circulaires et de roulis, qu'aux mouvements uniquement linéaires. Les essais ont montré que le déplacement du centre de gravité de l'être humain concorde de manière quasiment logarithmique avec sa réaction psychologique. Les degrés d'inconfort, d'inquiétude et de difficulté à conserver l'équilibre ont servi à chiffrer cette évaluation.

ZUSAMMENFASSUNG

Versuche zur menschlichen Reaktion auf typische Horizontalbewegungen in beiden Achsrichtungen in Hochhäusern haben ergeben, dass Menschen stärker auf biachsiale, Kreisel- und Schlingerbewegungen reagieren als auf Linearschwingungen und dass die Schwerpunktsverlagerung fast logarithmisch mit der psychologischen Reaktion übereinstimmt. Zur Bewertung wurde dabei das Ausmass des Unbehagens, der Beklemmung und der Gleichgewichtsstörungen verwendet.

1. INTRODUCTION

The history of tall building construction began with an encounter of our admiration for height with advanced technology. Authors of this paper have been engaged in the development of a 100 story multi-purpose building which has dwelling floors on its upper stories. The building is 480 meters high and has a high aspect ratio, therefore, the upper part of the building can be subject to complex and large motion with long period when strong wind blows. Accordingly, the vibrations give some influence on the serviceability, especially habitability of the rooms in the building.

There are guidelines[1) 2)] for the evaluation of the human response to horizontal motion provided by the International Organization for Standardization (referred to as ISO for the rest of this paper) and the Architectural Institute of Japan (referred to as AIJ for the rest of this paper). These guidelines suggest that tests should be performed on threshold of perception to horizontal uniaxial motion. Whereas, tests performed in this manner are thought to be inadequate because tall buildings are subject to complex horizontal motion in actuality.

In this paper, tests are conducted on human response to horizontal biaxial motion using a motion simulator. In the tests, the psychological response of subjects was surveyed by conducting questionnaire and the physical response of subjects was obtained by measuring the balance shift of the subjects. After obtaining test data, habitability to horizontal biaxial motion is studied on the basis of available data on those with horizontal uniaxial motion. Then the test results are compared with existing guidelines, and the correlation between physical response and psychological response is studied.

2. PLANNED BUILDING AND MOTION

The planned building is 100 storied and 480 meters high. It is composed of vertically dissectioned four blocks (see Fig.1) so that vibrations caused by strong wind are attenuated and structural safety is ensured.

According to the model test and analysis, the top of the planned building causes largest displacement to the wind direction of 0°, when response wave forms indicate an extreme motion around the first natural period (8.0sec) of the building. Fig.2 is the locus of the top displacement of the building when the wind velocities with a return period of one year (level 0), and those with a return period of 100 years (level 1), are applied in Tokyo. When the wind velocities of level 1 are applied, vibrations are extreme in the cross wind direction and show an elliptic response. When the wind velocities of level 0 is applied, vibrations show a circular response.

For the reasons mentioned above, habitability can not be assessed adequately by human response to uniaxial motion, and human response to horizontal biaxial motion must be evaluated.

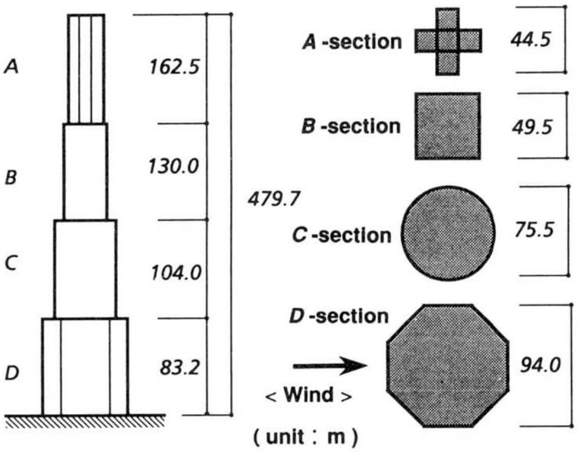

Fig.1 Planned building

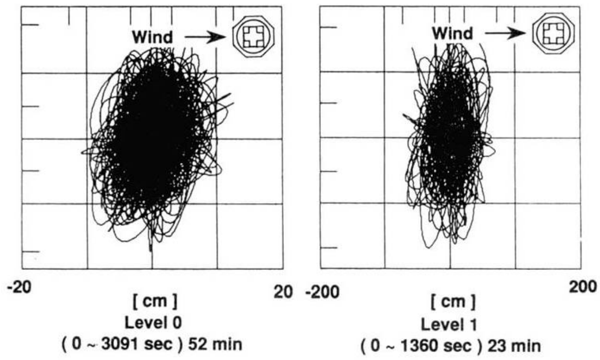

Fig.2. Locus diagram of top displacement of the building

3. HUMAN RESPONSE TEST

3.1 Test equipment

Tests are performed in a testing room (2.4m x 2.4m x H2.4m) installed on the six-degree of freedom motion simulator (in Hosei University, Tokyo, Japan) (see Fig.3).

3.2 Human subjects

Twenty subjects are chosen from female aged between 37 to 58. House wives, who most stay at home, are selected because a daily life environment is assumed in these tests.
Subjects are divided into groups of four members.

3.3 Conditions

Test conditions are determined so that acceleration amplitudes of motion are in accordance with ISO curve 1 (suggested satisfactory magnitudes of horizontal motion of building used for general purposes) and AIJ H-4 curve. Vibration period is set to five to ten seconds, which covers the first natural period of the planned building. Motion types are linear, elliptic, circular, and eight-figure, each of which has sinusoidal motions. Detailed conditions are given in Table 1. The order of motion conditions for tests are decided using a table of random numbers and so that each group of subjects has a different order.

3.4 Procedure

The testing room has no window so that subjects can not visually perceive vibrations. Subjects stand still with their eyes opened in the testing room. Each motion lasts for ten minutes. After one minute from the start of each test, balance shifts of the subjects are measured for one minute, and after five and ten minutes, they are requested to vote each item of discomfort, difficulty, and uneasiness they perceived on five levels. The category scale is shown in Fig.6.

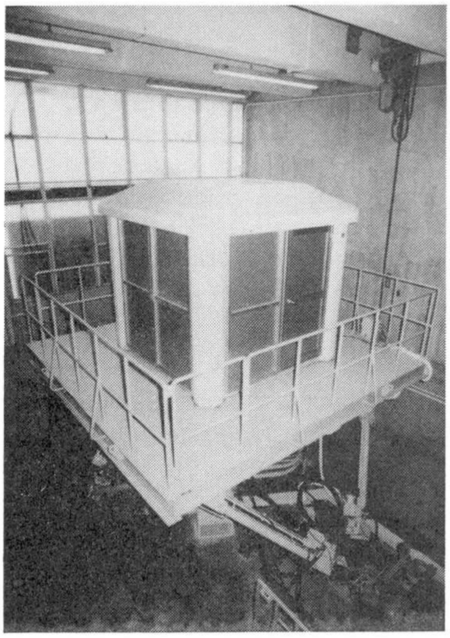

Fig.3 Motion simulator

Table 1 Motion conditions of the test

Figure of Motion	Period (sec)	Maximum Acceleration of X-direction (cm/s^2)	Ratio of Maximum Acceleration of two direction : R_{XY} 1)
Linear	10.0	9.1~14.2	0.0
	8.0	8.0~12.3	
	6.0	6.6~8.8	
	5.0	4.7~7.9	
Circular	10.0	9.1~14.2	1.0
	8.0	8.0~12.3	
	6.0	6.6~8.8	
	5.0	4.7~7.9	
Elliptic	10.0	9.1~14.2	0.5
	8.0	8.0~12.3	
	6.0	6.6~8.8	
	5.0	4.7~7.9	
Eight - figure 2)	10.0	9.1~14.2	0.2
	8.0	8.0~12.3	
	6.0	6.6~8.8	
	5.0	4.7~7.9	

1)Ratio of Maximum Acceleration of two direction

$$RXY = \frac{\text{Maximum Acceleration of Y-Direction}}{\text{Maximum Acceleration of X-Direction}}$$

2)Period of Y-Direction is half for that of X-Direction

4. VIBRATION AND BALANCE SHIFT

Fig.4 is the typical locus curve of balance shift of subject with each motion type. In all cases, balance shift indicates the locus similar to the motion type. It should be noted that a half moon shaped locus in the case of eight-figure motion is due to phase shift of X direction and Y direction.
Fig.5 shows the balance shift (r.m.s. value) of human subjects in each of the X direction and Y direction. Values are the average of all

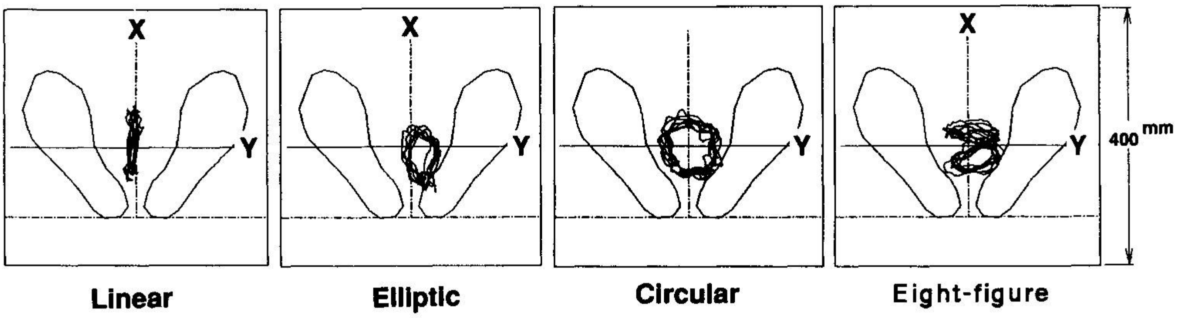

Fig.4 Locus diagram of balance shift of subjects

subjects.
Each motion type(linear, elliptic, circular, eight-figure) has the same amplitude of acceleration in the X direction but the different amplitude of acceleration in the Y direction. Therefore, balance shift shows little difference in the X direction but considerable difference in the Y direction with the motion type.

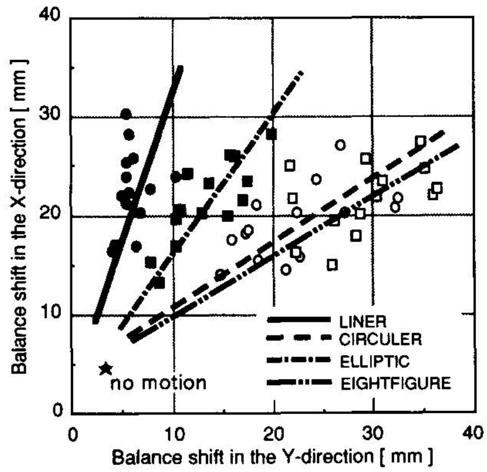

Fig.5 Balance shift in X/Y directions

5. VIBRATION ACCELERATION AND VOTINGS OF PSYCHOLOGICAL RESPONSES

When the voted value obtained after 5 minutes and that 10 minutes are compared, the later is slightly lower than the former. This may be caused by the habituation of the subjects. Hereafter, the values obtained after 5 minutes are used for examination.

Biaxial motions, especially circular and eight-figure motions, have more influence on human response than linear motion does, by about 0.6~0.8 rank in the five level voting system in this paper. This is because circular and eight-figure motions cause balance shift in both Y and X directions while linear motion causes balance shift mainly in the X direction as shown in Fig.4 and 5.

The relationship between the vibration acceleration amplitude and voting of psychological response can be approximated by the Weibull curve as shown in Fig.6. The vibration acceleration amplitude which corresponds to a certain voting level at each vibration frequency can be obtianed from using this relationship.

In Fig.7, the vibration acceleration amplitude in the X direction which corresponds to the voting of 2.5 is shown together with ISO curve 1 and AIJ H-4 curve.

The voting of 2.5 refers to the level between "slightly perceptible" and "clearly perceptible".

ISO curve 1 is the criterion that probably not more than 2% of those occupying the parts of the building where the motion is greatest comment adversely about the motion caused by the peak 10 minutes of the worst wind storm with a return period of 5

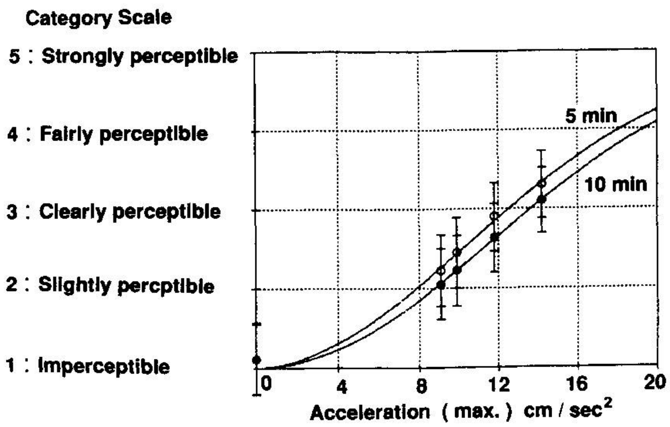

Fig.6 Vibration acceleration amplitudes and votings

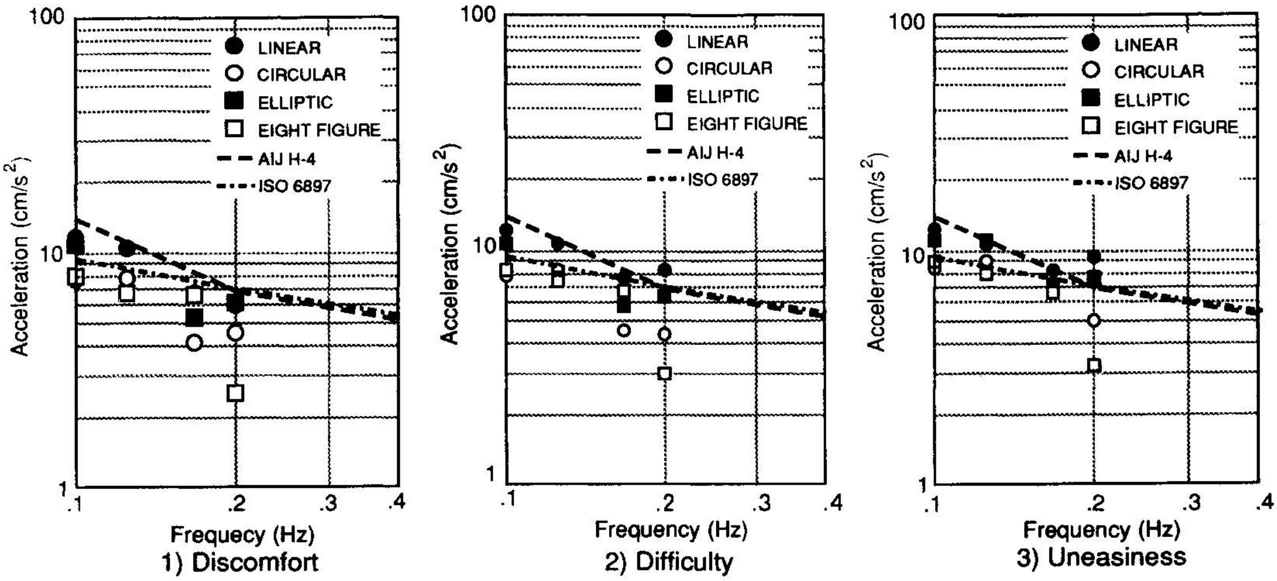

Fig.7 Relationship between vibration acceleration amplitudes rated 2.5 and existing guidelines

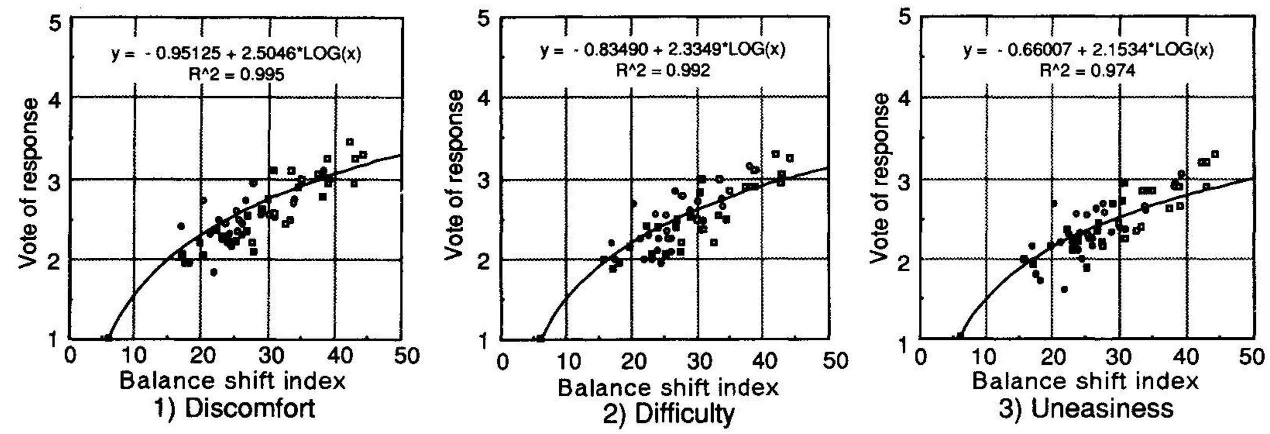

Fig.8 Balance shift indices and votings

years or more. AIJ H-4 curve is 1.75 times of the average threshold of perception obtained by human response tests to sinusoidal motions. Complaint categories dealt with in this paper, discomfort, difficulty, and uneasiness, can not be compared absolutely but it is possible to compare them relatively.

The vibration acceleration amplitudes which received the psychological voting of 2.5 almost agree with ISO curve 1, but there exist slight differences with the 3 items above.

However, a ratio of the increasing perceptible acceleration amplitude to the decreasing frequency, namely the incline of the curve, is similar to AIJ H-4 curve. Comparing with the complaint categories, perceptible acceleration amplitude increases in order of discomfort, difficulty, and uneasiness with all motion types. That means subjects feel discomfort before feeling difficulty, and feel difficulty, before feeling uneasiness. This result is in line with authors' expectation, however, it should be noted that subjects do not feel uneasiness so much because they know it is a test.

6. BALANCE SHIFT AND VOTINGS

Next, psychological response (ratings) is considered in relation to balance shift. Fig.8 shows the relationship between the balance shift index and voting. The

balance shift indices are the square root of the variance of balance shift in both X and Y direction. With all complaint categories, the balance shift index and voting decrease in order of linear, ellipse, circular, and eight-figure motion. The relationship between the balance shift index and voting can be approximated by one logarithmic function for all motion types, and used for explaining the relationship between physical and psychological response to biaxial motion.
Comparing the voting with balance shift index, the voting decreases in order of discomfort, difficulty, and uneasiness with a certain balance shift index.

7. CONCLUSION

Tests were conducted on human response to typical horizontal biaxial motion. The psychological response of subjects was surveyed by conducting questionnaire and the physical response of subjects was obtained by measuring the balance shift of the subjects.
Comparison of the test results with existing guidelines for the evaluation of habitability and study on the relationship between balance shift and psychological response brought about the following conclusions:

(1) The vibration acceleration amplitude which received the voting of 2.5 (the level between "slightly perceptible" and "clearly perceptible") for all cases of discomfort, difficulty, and uneasiness agrees with perceptible acceleration amplitude ISO curve 1. But, a ratio of the increasing perceptible acceleration amplitude to the decreasing frequency, namely the incline of the curve, is similar to AIJ H-4 curve.
(2) With all motion types, biaxial motions increase in order of discomfort, difficulty, and uneasiness. This is in line with authors' expectation though it might be difficult for subjects to feel uneasiness because of the test settings.
(3) Horizontal human response, especially circular and eight-figure, have more influence on humans than horizontal linear motion does, by about one rank in the five level voting system in this paper.
(4) The relationship between the balance shift index which is the square root of the variance of balance shift levels in both X direction and Y direction and voting can be approximated by one logarithmic function for all motion types, and used for explaining the relationship between physical and psychological response to biaxial motion.

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