Research on vibration criteria from the viewpoint of people living in high-rise buildings. Part 1. Various responses of humans to motion

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T. GOTO

RESEARCH ON VIBRATION CRITERIA FROM THE VIEWPOINT OF PEOPLE LIVING IN HIGH-RISE BUILDINGS (PART 1) VARIOUS RESPONSES OF HUMANS TO MOTION

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PREFACE

A special problem for inhabitants of tall buildings is the perception of motion induced by external forces, such as wind and earthquake. To ensure that tall buildings will be comfortably habitable, limits to building vibration are required, but as yet there has been little information published on which to base design criteria.

This paper by Takeshi Goto summarizes extensive Japanese studies on human response to horizontal sinusoidal motion with periods of 1 - 10 seconds and amplitudes of 1 - 50 cm. The results are interpreted in biomechanistic terms as a basis for establishing habitability criteria.

The Division of Building Research is pleased to make this research information available to other Canadian research workers through the Technical Translation series of the National Research Council. The contribution of the translator, Dr. Alice Tsai, is gratefully acknowledged, as is that of W.A. Dalgliesh of this Division, who checked the translation.

Ottawa
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C.B. Crawford
Director
Division of Building Research

NATIONAL RESEARCH COUNCIL OF CANADA
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RESEARCH ON VIBRATION CRITERIA FROM THE VIEWPOINT OF PEOPLE LIVING IN HIGH-RISE BUILDINGS
(PART 1) VARIOUS RESPONSES OF HUMANS TO VIBRATION

1. Introduction

High-rise buildings are flexible structures. Therefore, natural forces, such as earthquake and wind, introduce the new problem of building vibration, which may have various effects on living conditions for occupants.

In a study of the safety and various vibrations of high-rise buildings, habitability must be considered first, and demands our urgent investigation. In order to study the fundamental criteria, the physiological response of occupants to the physical stimuli of vibration must be understood. In other words, this can be achieved from the biomechanistic point of view.

In view of the above, the end objective of this study dealing with the safety and comfort of high-rise buildings vibrating under the action of external natural forces is to propose habitability criteria. The study consists of the following two parts:

1) Various human responses to vibration.
2) Effect of external natural forces on vibration of buildings and occupants.

However, this paper reports only on Part 1. The remainder will be reported in the next paper.

2. Method and Objectives

The period of vibration of low solid buildings is usually less than 1 sec, and the single amplitude (displacement) is at most within a range of several mm. On the other hand, for high-rise buildings the period for horizontal vibration caused by strong earthquake and wind is 1 - 8 sec (first natural period) and the amplitude may reach several tens of cm (Note 1). These vibrational characteristics being different, the measurement of response in terms of perceptibility and perception threshold is generally used as the criterion for the vibration of tall buildings. However, when the vibration is very strong, the horizontal vibration of high-rise buildings not only causes stimulation of the senses, but also inhibits the activity and movement of people. Furthermore, prolonged vibration even within the nonperceptible range may sometimes cause symptoms of seasickness.

The conditions for the vibration of high-rise buildings in this study are that the period is 1 - 10 sec and the single amplitude is 1 - 50 cm, assuming horizontal sine wave motion. Experiments were carried out to study the degree of influence on occupants by the application pf psychological, physiological, kinesiological and engineering methods. A vibration simulator is used as shown in Photo 1. The experimental items are shown in Table I. The results have been reported at conferences of the Japanese Architectural Society[1-7].

After briefly outlining the experimental conditions and methods of this research, the first part of this paper correlates the results of major experiments and explains them from the biomechanistic point of view. The second part then investigates habitability limits for the vibration of buildings based on results of the first part.

3. Biomechanistic Response to Vibration

1) Complex human sensory response to vibration

The human sensory response to vibration varies profoundly with different individuals.

Figure 1 shows the average male and female perception curves which express the relationship between the period of floor vibration caused by the simulator and the maximum amplitude (abbreviated as amplitude below). Perceptibility (I) is in the range where the vibration is completely imperceptible. (II) (i) is the range where the vibration is beginning to be perceptible, and (II) (ii) is the range where the vibration is strongly perceptible. (II)* is the range where the

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* Translator's note: This is an error. According to Figure 1, this range should be (III).

vibration becomes unbearable. Therefore, the boundaries of perceptibilities (I) and (II) as well as (II) and (III) are designated as perception threshold (Note 2) and tolerance threshold (Note 3), respectively. In general, the curve for females is below the curve for males. In other words, females are more sensitive to vibration than males. Furthermore, results obtained from different age groups, postures and vibrational directions are compared, as summarized in Table II. The table indicates a consistent trend that the female is more sensitive than the male, children are more sensitive than adults, and people in standing positions are more sensitive than those in sitting positions to short-period vibration or vehicle vibration[8-10]. However, if a person taking part in the experiment is sitting in a chair with a back support, this sitting position will be more sensitive than the standing position.*

The perception threshold and tolerance threshold for all items in Table II are shown in the same graph, Figure 2, as dotted lines. It should be noted that, for example, when the period is 10 sec, although in some cases when the amplitude is 5 cm (point M), the vibration is perceptible, in other cases the amplitude can be increased 5 times (point N, about 25 cm) before it begins to be perceptible. The perceptibility to vibration varies greatly due to differences in physical condition from one individual to another. On the other hand, the perceptibility of the same individual may also vary from time to time due to variation in his or her physical and mental states.

It is very difficult to determine the perception threshold and tolerance threshold for an actual building vibration from experimental results. This is because the vibration generated is not necessarily similar to the actual vibration of buildings. Meanwhile, people taking part in the experiment are notified of the content of the experiment beforehand. In this case, people already become very attentive as soon as the vibration starts. The perception threshold in Figure 2 is considered to be more sensitive than that obtained from the actual building vibration without warning. On the other hand, the tolerance threshold is accompanied by visual and auditory stimuli due to the movement of household objects. One feels rather safe during the experiment and is not horrified as in the situation of actual building vibration. The experimental

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* Translator's note: This statement disagrees with the results shown in Table II which indicates that the standing position is more sensitive to vibration than the sitting position.

results should perhaps be considered to be on the unconservative side. Due to the diversity of conditions, it is very difficult to make a judgement. For example, should the sitting criterion or the standing criterion be used? Many items like this should be investigated. Under these circumstances it was decided to base the perception threshold and tolerance threshold on the average values of all the fundamental criteria. The final perception threshold and tolerance threshold are shown as the solid lines in Figure 2 (—o—).

2) Perception zone in which people are sensitive to vibration

The average perception threshold and average tolerance threshold are shown in Figure 2. The floor vibration of a house is expressed by the amplitude (A). The maximum acceleration (α which will be called simply acceleration) may be expressed in the following equation if the vibration is a sine wave,

$$\alpha = \left(\frac{2\pi}{T}\right)^2 \times A \tag{1}$$

Where T is the period. The average perception threshold and average tolerance threshold derived from this are shown in Figure 3 (—o—).

Human perception to vibration of long duration is known to vary with acceleration. In the acceleration perception zone, it is sensitive to the magnitude of the period. For example, the left-hand side of point E, which is on the tolerance threshold line with a period of 5 sec and acceleration of 65 gal, is in the perceptibility (III) zone when the acceleration is kept constant. However, the right-hand side of point E is in the perceptibility (II) zone. The same trend is also observed for the perception threshold. The tolerance threshold calculated by Dr. Ishimoto(11) is shown in Figure 4. As shown in the figure, the curve becomes convex upward when the period is below 0.3 sec. This is the area where the perceptibility is sensitive to changes of the period. In other words, when the acceleration is kept constant at 1.0 gal, the vibration is imperceptible at point A, while the vibration is perceptible at point B.

Furthermore, the horizontal straight lines (screen tone) in Figure 3 represent the rankings (levels). Dr. Chang investigated experimental results of many researchers who studied vibrations with periods less than 1.0 sec and proposed that vibrations with periods lower than 1.0 sec are suitable for ranking determination[12].

3) Human perceptibility to vibration controlled by head acceleration

The sensing of vibrations of long period and large amplitude is determined by the head acceleration which results from the strong floor (or leg) vibration.

The analogous results can then be derived. The perceptibilities (I), (II)-i, (II)-ii and (III) were studied by measuring the accelerations of heads of people taking part in the experiment. The results obtained are plotted in the graph as shown in Figure 5. The same perceptibilities caused by the acceleration of heads are distributed in almost the same acceleration zones.

The human perception to the acceleration of his body is sensed by the vestibule in the inner ear (Figure 6) and this is related to the movement of the head.

Various body senses are characterized as shown in Figure 7.

The term with a dot • in the front indicates that it is related to a sensing of vibration. In addition to skin, visual and auditory senses, people can also perceive linear vibration by the vestibule of the inner ear, especially the utriculus. The utriculus is shown in Figure 6. There are hair cells on the tip of nerve fibres. These hairs protrude from lymphs. There are calcareous small particles (otolith) which are enclosed in membrane[13,14] at the tips. The movement of the head, which induces the movement of these particles, thus controls the sensing of vibration (Note 4).

From the engineering point of view, this is equivalent to an inverse pendulum in a liquid. This phenomenon is also similar to the structural response of a one-storey building to viscous damping (Figure 8). The following expression (2) describes the equation of motion of this system (Figure 8). The displacement and acceleration may be derived[15].

$$m(\ddot{X} + \ddot{x}) + c\dot{x} + kx = 0 \qquad (2)$$

Since the viscosity constant of lymph in the utriculus (c), the elasticity constant (k) of hair cells and the mass of otolith (m) are known, the corresponding movement of otolith which is caused by movement of the head may be calculated.

The human sensation of vibration may be understood scientifically through this biomechanism.

In addition to those described above, the skin sense is the major sense organ which perceives vibration of short period and small amplitude. Vibration of long period and large amplitude may greatly upset the body balance. Therefore, other sense organs such as muscles, tendons and joints are also involved in the perception of vibration.

4) People are sensitive to the sensation of vibration

The average perception threshold and tolerance threshold are proposed above (Figure 3). Objects which begin to move at this boundary are compared.

Forty-five general household kitchen, dining room and living room objects, such as dinnerware, cooking utensils, cooking appliances, furniture, etc. are selected as shown in Table III. Their movement during vibration is analyzed. The analysis of motion is based on three stages, i.e., the boundary where objects begin to shake, the boundary where objects begin to rattle, and the boundary where objects begin to topple.

The physical phenomenon for the movement of household objects is compared with the perception of body response as shown in Figure 9. The perception threshold is below the first limit of movement of household objects, i.e., when the objects start to shake. People can detect the vibration even before the household objects start to shake.

Similarly, in an actual earthquake, people subconsciously notice the vibration and then ask anybody who happens to be around for confirmation, or observe the movement of household objects. From this information, people gradually confirm their perception.

People are sensitive to vibration. Before household objects start to move, people can already perceive the vibration. This agrees with the hypothesis in Section 3) that people can perceive vibration even if the visual, auditory and skin senses are eliminated.

5) Symptoms of seasickness vary greatly with different individuals

In the perceptible vibrational range, persons who have never experienced vehicle sickness before do not usually react to vibrations of long period with seasickness symptoms. In the imperceptible vibrational range, nobody reacts to it with seasickness symptoms regardless of one's previous vehicle sickness experience.

Figure 10 shows the symptoms people experienced during vibrations with a period of 6 sec and amplitudes of 20 cm (Exp. 1) as well as 37.5 cm (Exp. 2) respectively. People with previous vehicle sickness experience exhibit seasickness symptoms 10 - 20 min after vibration starts. The symptoms are increasingly worsened with prolonged vibration. However, those people without previous vehicle seasickness experience exhibit slight symptoms of seasickness momentarily, but soon recover. No seasickness symptoms were observed.

As far as symptoms of seasickness are concerned, some people are easily afflicted with it but some people are not. It all depends on the individual. For those people with severe seasickness symptoms, the blood pressure, breathing and heartbeat become obviously abnormal.

Physiological changes are caused. As discussed previously, the vestibular organ is excited. The effect of strong excitement is transmitted not only to the spinal nervous system but also to the autonomic nervous system, thereby inducing reflexion, especially the so-called reflexion phenomenon through the vagus nerve. Therefore, it was previously proposed[16] that for the prevention of seasickness, the otolith could be dissolved to eradicate the perception of vestibular stimuli. This may be interpreted from the engineering point of view as setting the mass of Figure 8 to zero, i.e., $m = 0$. This means that the motion equation cannot be established.

Figure 11 shows the results of experiments investigating whether the vibration in the vicinity of the perception threshold causes symptoms of seasickness. The relationship between period and amplitude is presented. The black dots in the figure indicate the experimental points. The surrounding circles represent the number of people who took part in the experiment. The large black dots indicate that persons who took part in the experiment exhibited obvious seasickness symptoms and left the house in the middle of the experiment.

The sign ◆ represents those persons who seemed to develop seasickness symptoms but remained in the house until the end of the experiment (2 hours). The open circle (o) indicates that nothing abnormal was observed.

Based on this, the curve for the boundary of seasickness symptoms caused by vibration is shown as the thin line curve in the figure (— + —). The curve is situated above the perception threshold (—o— in the figure). Therefore, one perceives vibration before exhibiting seasickness symptoms.

6) Ability to work is related simply to floor (table) acceleration, whereas ability to move is related in a complex way to floor acceleration.

Ability to work is tested by tracing a simple diagram, as shown in Figure 12. Walking ability was tested by walking on a flat surface and climbing up and down stairs. Figure 13 shows the experimental results of walking on a flat surface. The trails of both head and feet are shown in the figure. Based on the results of the tracing test, the ability to work is judged by three arbitrary degrees of difficulty: □ without deviation from normal state (degree of difficulty [I]); ▨ partially deviated from the base line (degree of difficulty [II]); ■ obviously deviated from the base line (degree of difficulty [III]) (cf. Figure 12). The relationship between period and acceleration is shown in Figure 14. The degrees of difficulty shown as dotted lines in the figure are controlled by floor acceleration.

As to the effect on walking ability (✡), the experimental results for walking on a flat surface (Δ) and those for climbing up and down stairs (∇) are rather similar. The degree of difficulty in ability to walk is chosen, on the safe side, below each curve. Similarly, the relationship between period and acceleration is shown in Figure 15. Furthermore, the degree of difficulty in walking up and down stairs and walking on a flat surface is rather similar. This may be explained as follows: the staircase is 120 cm wide with walls on both sides. This has a psychological effect on people taking part in the experiment because when they are off balance they can rely on walls on both sides. During the experiment some people actually stretched out their hands to get support from the wall. In the experiment of walking on a flat surface, there is no side wall within reach. This makes the persons who took part in the experiment feel unstable. The staircase with walls on both sides within reach is actually used in the experiment. The degree of difficulty in walking is determined according to the previous method.

As shown in Figure 15, the response in walking ability to the floor acceleration is complex. The curves obtained tend to be quite similar to the perception curves of Section 1). These curves are known to be influenced periodically by the period. Unlike the static state, this complexity may be due to the additive periodic effect of the floor vibration and foot-stepping.

On the contrary, the ability to work at a desk is affected by fixed factors. It is mainly controlled by acceleration.

4. Investigation of Vibration Limits and Habitability

This section investigates the significant biomechanistic response of people to vibration as a means of evaluating habitability. The experiments on items encircled with o listed in Table I were carried out. The relationships between period and acceleration for these experiments are shown in the same graph, Figure 16. The ranges between these curves (and also straight lines) are designated for convenience as Ⓐ - Ⓘ. The content for each of these areas will be described as follows.

Ⓐ: In this range, most people do not perceive vibration. The vibration of buildings caused by an unwarned earthquake or storm is even more imperceptible.

Ⓑ: In this range, most people are aware of the slight vibration, and start to talk about it. The boundary between ranges Ⓐ and Ⓑ is called the perception threshold. To ensure comfort and habitability, the vibration should be within the weak range. The limit where comfort is lost depends on the perception of each individual. Therefore, the perception threshold is the first limit for the investigation of comfort. These curves are based on people's feeling. The index may be established from the following equation[17] which is expressed in terms of acceleration (α) and period (T).

$$\alpha = 0.38 \times 1.3^{T} \qquad (3)$$

where $1 \leqslant T \leqslant 10$ (sec).

In the (B) range with acceleration of 5 - 10 gal, the water in the water tank which was installed with a pendant light began to shake gently. This is detected visually, but the vibration is not yet perceived. This phenomenon has been confirmed.

(C): In this range, the vibration of the surroundings is discernible even without household objects. Everyone can feel the vibration. Ability to work at a desk is slightly interfered with. Ability to walk is equivalent to the curve for the first degree of difficulty, i.e., is nearly normal. However, prolonged vibration causes seasickness symptoms for certain people. This is the boundary for areas (B) and (C) . Since most of the above items are concentrated on this curve, it is established as the second limit for the comfort investigation. To be on the safe side, the limit should be established below each curve.

(D): In this range, it is still possible to move around, but with great difficulty. In addition to the difficulty in movement, the occupants feel unsafe due to violent shaking of the building. The last comfort limit (the third) should be assigned below this range. Beyond this range, the investigation on habitability should be switched from comfort to safety. Therefore, the third comfort limit is also the first safety limit. This is the basis for establishing the curve of difficulty in movement.

Beyond the (C) range of 35 gal acceleration, desk work becomes difficult. The limit for which desk work becomes impossible is set at 35 gal. However, it is pointless to set the working limit when it already exceeds the comfort limit.

(E): At 40 gal, household objects start a clearly audible rattling. It becomes increasingly difficult to move around. It is almost impossible to maintain balance even if one tries to stand still. Above 40 gal, one has to be very careful to maintain balance in moving around. The lower limit of this area is established as the second safety limit.

(F): In this range, movement is possible to some degree but the degree of perceptibility is intolerable.

(G): Movement becomes impossible. However, the perceptibility is in the "strongly perceptible area". In actual building vibration, the occupants start to escape, fearing that the violent vibration may throw them out. The above observation is confirmed by two accidents during the experiment. In the (F) and (G) ranges, movement is suppressed. From the above discussion, the third safety limit, in which movement is prevented, is established below the lower limit of the previous two areas.

(H): In this range, the response to vibration is greater than that in (F) and (G) areas. It is understandable that its vibrational condition is also more severe than that of the other two ranges.

(I): In this range, household objects start to topple. The occupants have to escape or else the objects may fall and hit them. From the viewpoint of living conditions, the acceleration caused by the building vibration in this area is unfavorable for living. In other words, the lower limit of this range is the final safety limit for occupancy. It is assigned as the 4th safety limit.

5. Conclusion

From this viewpoint of habitability, the comfort and safety limits for vibration of long period and large amplitude are proposed based on the above observations as shown in Figures 17 and 18. Figure 17 shows the relationship between period and acceleration. Figure 18 shows the relationship between the period and amplitude (displacement).

In the next paper, the limits obtained from the actual vibrations of buildings and the analysis of response to vibration will be compared. The final criteria concerning building vibrations will then be proposed.

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Notes

1. The vibrational characteristics of high-rise buildings due to natural forces will be discussed in Part 2. The explanation of data is therefore omitted.

2. The perception threshold is defined as the minimum vibration at which it is perceived when the imperceptible vibration is gradually increased.

3. The tolerance threshold is defined as the minimum differential point at which tolerance and intolerance are distinguished.

4. Dr. S. Takeshita's helpful advice is appreciated.

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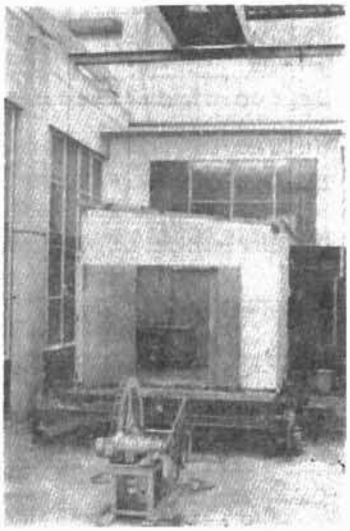


Photo 1

Vibration simulator

Table I

Items of experimental objects

State of persons in experiment	Experiment No.	Items of experiment	Symbol representing the results
Static state	①	Perceptibility[1,4]	○———○
	2	Analysis on the state of body shaking[1]	□———□
	3	Acceleration produced in various parts of body	◇———◇
	④	Effect on ability to work[6]	—— · ——
	5	Effect on vision	⬠
	⑥	Symptoms of seasickness and physiological changes[5]	+
Mobile state	⑦	Degree of difficulty in walking	△———△
	⑧	Degree of difficulty in walking up and down the stairs[3]	▽———▽
Changes of the indoor state	⑨	Disturbance of household objects[7]	---------

The number indicated in the upper right corner in column 3 indicates the Reference No.

Table II

Results of experiments on perceptibility

Items compared	Experimental results
Difference in perceptibility due to sex	Female > male
Difference in perceptibility due to age	Children > adolescents > adults
Difference in perceptibility due to direction	Back-front > left-right
Difference in perceptibility due to posture	Standing > sitting with back support > sitting position

The open side of the unequal sign represents the higher sensitivity.

Table III

Household objects

№	Items	Measurement	№	Items	Measurement	№	Items	Measurement
1	食卓	a=60.0, b=90.5, c=72.5, w=11.0	16	茶筒	c=18.0, d=9.0	31	額縁	a=36.5, b=49.0
2	イス(食卓用)	a=34.0, b=35.0, c=72.0, w=3.3	17	茶ぶ台	a=74.0, b=74.0, c=32.0, w=9.1	32	電燈	c=14.0, d=30.0, e=44.0
3	ガステーブル	a=42.0, b=87.0, c=78.0, w=16.0	18	サイドボード	a=17.5, b=145.0, c=90.0, w=12.6	33	洋ダンス	a=53.0, b=88.0, c=172.0, w=35.3
4	流し	a=56.0, b=120.0, c=80.0, w=27.5	19	事務机	a=72.5, b=106.0, c=73.0, w=44.5	34	整理ダンス	a=41.0, b=68.0, c=128.0, w=34.8
5	冷蔵庫	a=18.0, b=49.0, c=97.0, w=43.3	20	イス(事務机用)	a=35.0, b=38.5, c=75.0, w=7.7	35	ベビーダンス	a=43.0, b=87.5, c=117.0, w=23.3
6	食器戸棚	a=40.5, b=86.0, c=121.0, w=24.5	21	本箱	a=20.0, b=59.0, c=114.0, w=31.1	36	電気スタンド	a=17.0, b=16.0, c=42.0
7	茶ダンス	a=33.0, b=74.5, c=104.0, w=15.1	22	石油ストーブ	a=53.0, d=39.0, w=6.3	37	ハンガー	—
8	バケツ	c=30.0, d=24.0, w=0.6	23	ガスストーブ	a=17.0, b=76.0, c=62.0, w=19.0	38	下駄箱	a=38.0, b=71.0, c=87.0, w=13.4
9	バケツ内の水	—	24	電気ストーブ	a=17.0, b=40.5, c=28.5, w=2.3	39	キャタツ	a=130.0, b=57.0, c=172.5, w=10.0
10	電気ポット	c=20.0, d=11.0, w=0.6	25	テレビ	a=28.0, b=50.0, c=37.0, w=16.3	40	三面鏡	a=30.0, b=72.5, c=109.0, w=13.7
11	ジャー	c=30.0, d=12.0, w=1.1	26	扇風機	a=25.0, b=18.0, c=54.0, w=6.8	41	ミシン台	a=42.0, b=84.0, c=78.0, w=28.2
12	食器・コップ類	—	27	置時計	a=6.5, b=23.5, c=20.0, w=1.3	42	空キ箱	—
13	ナベ・ヤカン	—	28	ゴミ箱	c=28.0, d=20.0, w=0.6	43	ロッカー	a=51.0, b=87.5, c=178.5, w=72.5
14	ビン類	—	29	スタンド式灰皿	d=23.0, c=55.0, w=1.9	44	帽子掛ハンガー	a=40.0, b=34.0, c=120.0, w=3.1
15	カン類	c=18.0, d=9.0	30	花ビン	d=7.0, c=20.0	45	揺りカゴ	a=128.0, b=51.0, c=40.0, w=5.3

(*a*: length; b: width; c: height; d: diameter of the base;
e: length of cord; w: weight; unit: cm, kg)

1. Dining table
2. Dining chair
3. Gas table
4. Sink
5. Refrigerator
6. China cabinet
7. Tea-set cabinet
8. Bucket
9. Water in the bucket
10. Electric pot
11. Jars
12. Dinnerware, cups
13. Pans, kettle
14. Bottles
15. Cans
16. Teapot
17. Tea table
18. Sideboard
19. Desk
20. Desk chair
21. Bookcase
22. Oil stove
23. Gas stove
24. Electric stove
25. Television
26. Electric fan
27. Clock
28. Trash can
29. Upright ashtray
30. Vase
31. Frame
32. Electric bulb
33. Dresser
34. Make-up dresser
35. Baby dresser
36. Electric stand
37. Hanger
38. Wooden-shoe rack
39. Step ladder
40. 3-way mirror
41. Sewing-machine stand
42. Empty boxes
43. Locker
44. Hanger for hat
45. Swing for baby

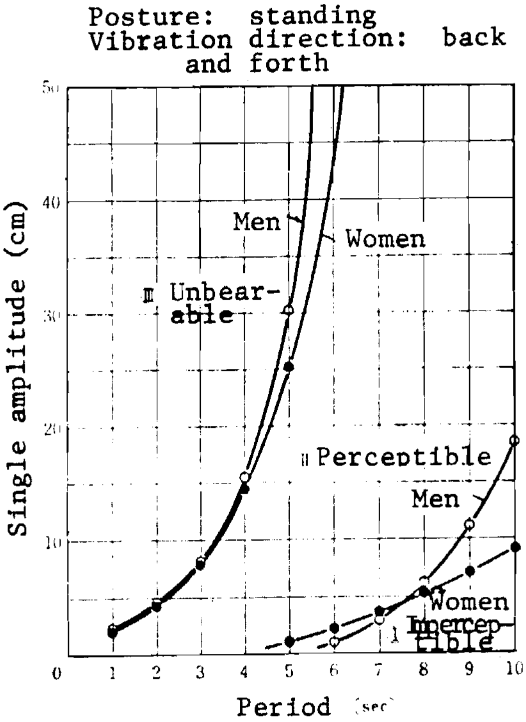


Fig. 1

Difference in perceptibility due to difference in sex

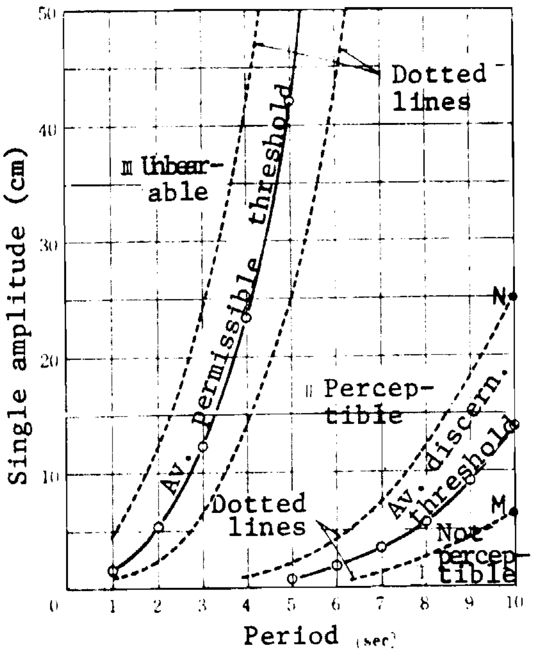


Fig. 2

Average perception threshold and average tolerance threshold

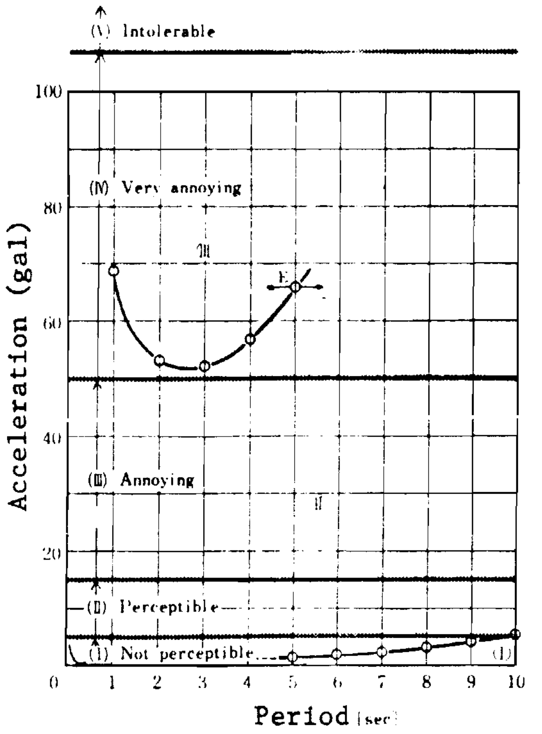


Fig. 3

Comparison on perceptibility
obtained by other researchers

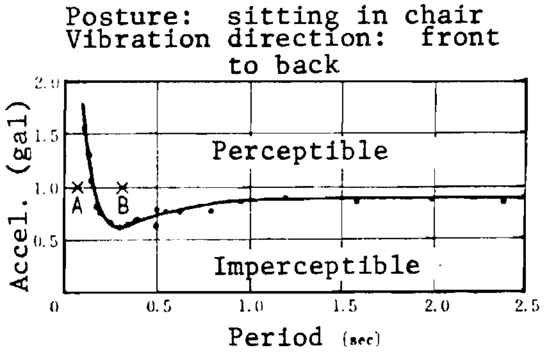


Fig. 4

Perception threshold calculated by Dr. Ishimoto

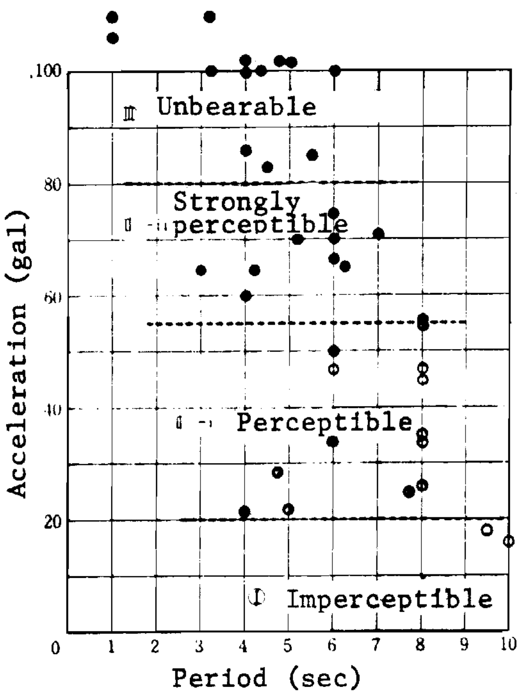
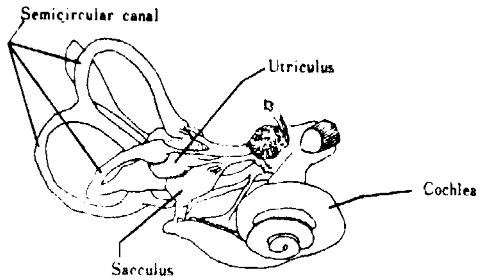


Fig. 5

Acceleration of head and the corresponding perceptibility

(1) Vestibular organ



(2) Utriculus

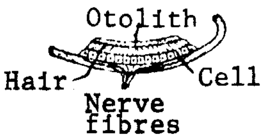


Fig. 6

Vestibular organ (1) and utriculus (2)

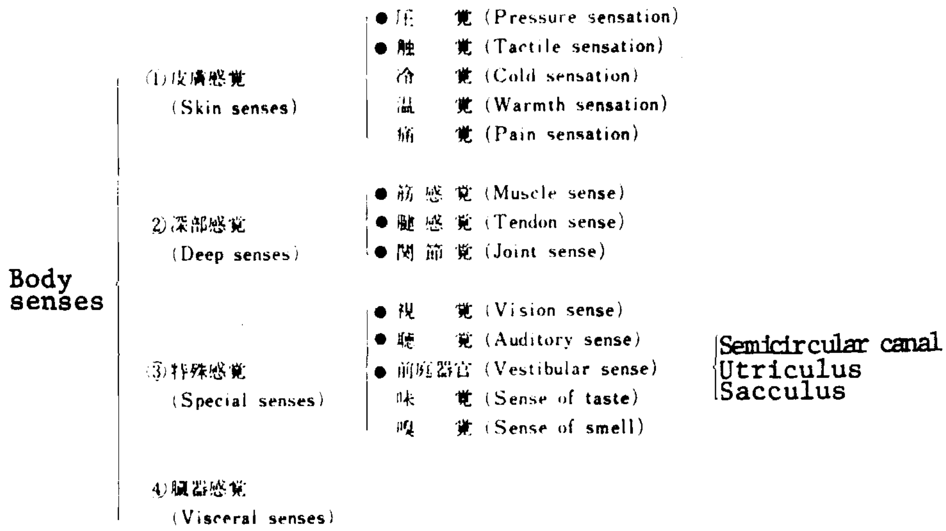


Fig. 7

Characterization of body senses

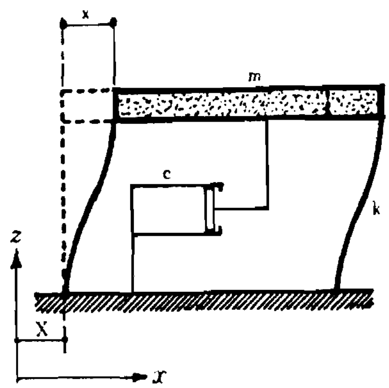


Fig. 8

Viscous damping for a vibrational system of one-storey building

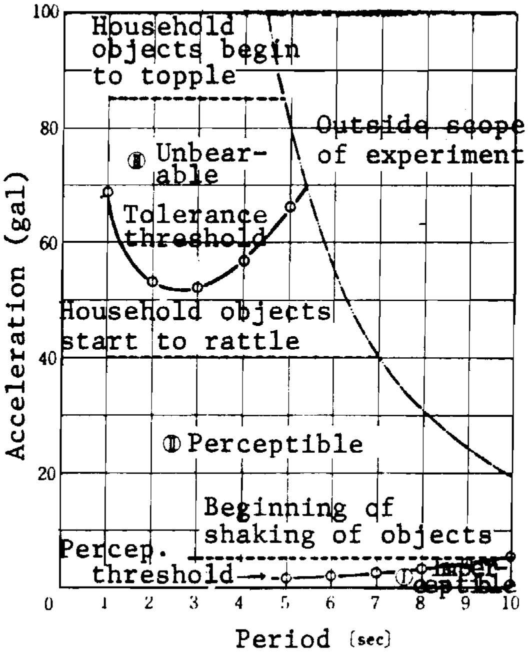


Fig. 9

Motion of household objects and the corresponding human perception

Experiment 1. Amplitude: 20 cm; period: 6 sec

Type of people		0	10	20	30	40	50	60	70	80	90	100.....150
		Experiment (vibration) starts ▽									Vibration stops ▽	End of experiment ▽
People with previous seasickness experience	A			Feel heavy in head ▽	Headache ▽			Nauseous ▽	Strongly nauseous ▽		Vomit ▽	
	B					▽ Momentarily nauseous, increasingly nauseous in every 10 min interval						
People without previous seasickness experience	C			Feel heavy in head ▽	▽ Headache momentarily, headache again later							
	D			(No symptoms at all)								
Time course (sec)		0	10	20	30	40	50	60	70	80	90	100.....150

Experiment 2. Amplitude: 37.5 cm; period: 6 sec

Type of people		0	10	20	30	40	50	60	70	80	90	100.....150
People with previous seasickness experience	E		Δ Nauseous Δ	14 min after vibration started, nauseous feeling worsened and people left vibrating house								
	F		Δ Headache	Δ Nauseous		Δ Left vibrating house						
People without previous seasickness experience	G			Δ Headache, but soon recovered								
	H				Δ Unpleasant feeling, but soon recovered							
	I				Δ Headache, but soon recovered							
Type of people		Δ Experiment (vibration) starts					Δ Vibration stops				Δ End of experiment	

Fig. 10

Symptoms of people taking part in the experiment during the vibration

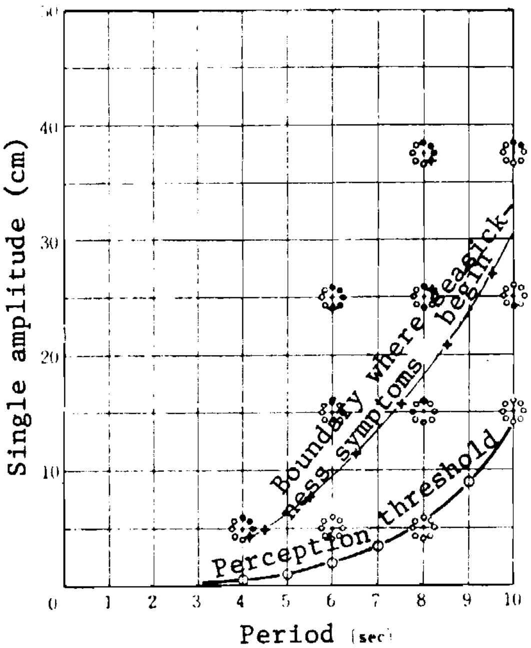


Fig. 11

Boundary where seasickness symptoms begin to develop

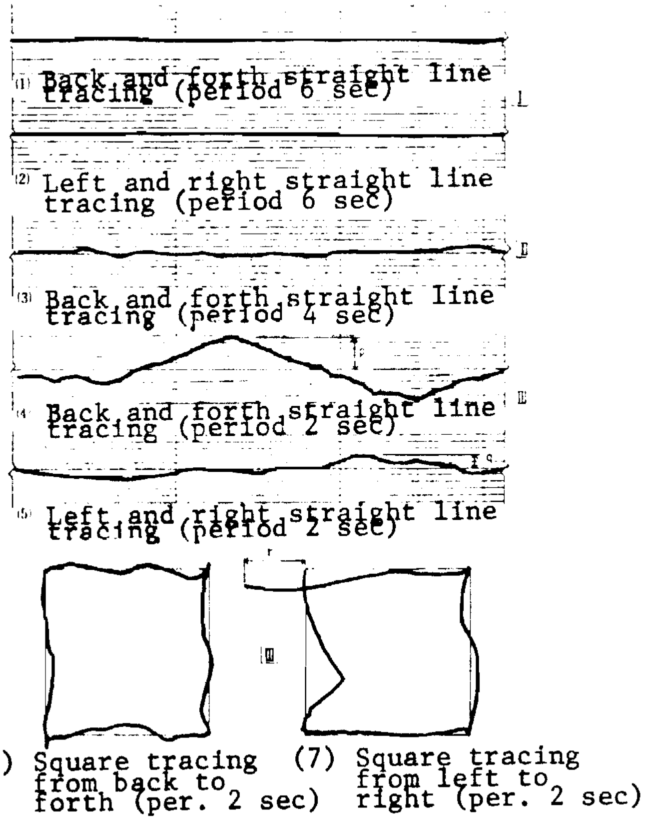


Fig. 12

One of the examples of tracing at a desk

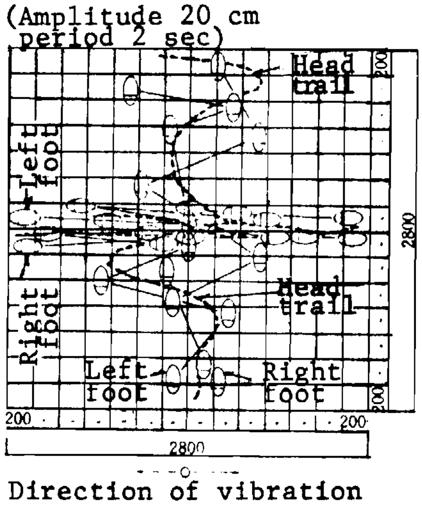


Fig. 13

Walking trail

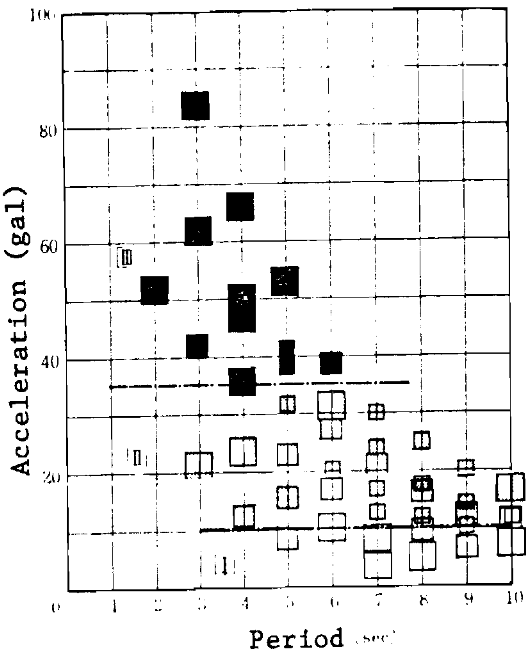


Fig. 14

Period-acceleration and the degree of difficulty

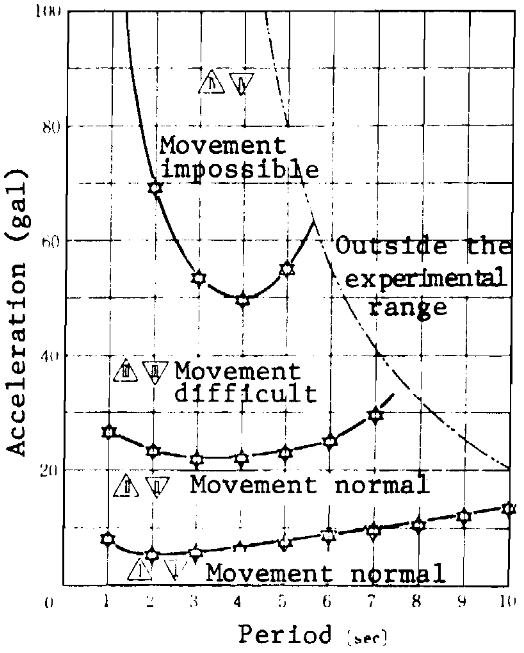


Fig. 15

Evaluation of ability to walk

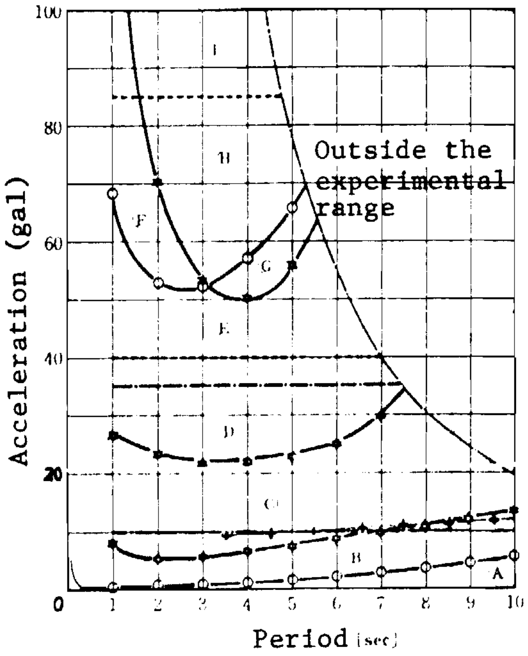


Fig. 16

Final considerations

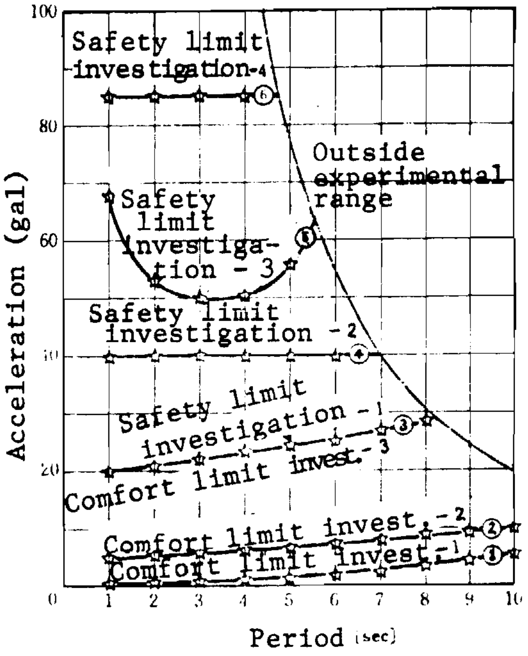


Fig. 17

Investigation on the limits of habitability 1

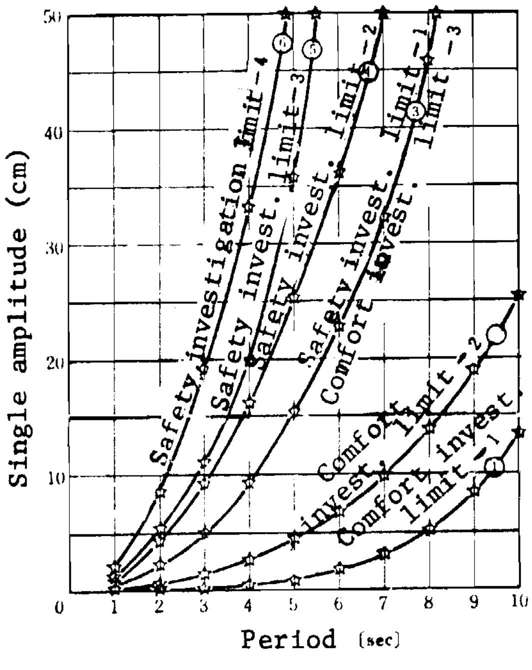


Fig. 18

Investigation on the limits of habitability 2