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Acceleration Indexes for Human Comfort in Tall Buildings—Peak or RMS?

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Abstract Traditionally, the effect of vibration on human comfort has been evaluated using the rms value of acceleration. More recently, a widely used criteria in North America has utilized the peak value of acceleration. The differences between these two methods are examined, and the importance of making a rational selection of the appropriate motion index for future standards is emphasized. It is proposed that, until additional research in this field demonstrates otherwise, the rms value be adopted as the best available index.

Introduction

Human response to wind-induced vibration in tall buildings has traditionally been evaluated by the acceleration in the horizontal plane. Two different measures of acceleration have been used: the peak value which occurs during a period of time—say 20 to 60 minutes—or the rms value averaged over this same period. These distinctions have arisen because of the different waveforms, or acceleration signatures, which must be addressed. Characteristic signatures are shown in Figure 1. All of these signatures can be characterized as narrow-band vibration at the same frequency, with differences in the envelope uniformity.

The first signature of Figure 1 is harmonic (sinusoidal) vibration. Harmonic acceleration of this nature does not occur in real buildings, but it has been widely used in laboratory "moving room" experiments aimed at determining human thresholds of perception of small vibrations, or tolerance of larger vibrations, under controlled conditions. The uniformity of this signature can be characterized, on a first-order basis, by the ratio of peak value to rms value. This ratio, commonly referred to as the *peak factor* and designated g, is $\sqrt{2}$ for sinusoidal signatures.

The second signature was recorded from an accelerometer in a wind-tunnel model of a tall building, measuring the crosswind vibration while "locked-in" to vortex shedding forces. The signature is nearly harmonic but slightly more random, with a correspondingly higher peak factor; $g = 2.0$. Acceleration of this type is rare in typical buildings, but could occur in special structures such as tall slender towers.

The third signature was obtained from an accelerometer in the same model under the same conditions, but it was oriented parallel to the wind direction. This motion is characteristic of tall building motion in the alongwind direction. It is more random than the above and has an even higher peak factor; $g = 3.1$.

The fourth signature is another idealized case which does not occur in practice. Conceptually it represents the transient response to a uniform impulse train. Signatures of this nature are commonly considered when dealing with human response to floor vibrations due to, say, walking motions or heavy machinery. This signature is the least uniform and has the highest peak factor; $g = 4.0$.

The four signatures in Figure 1 have all been scaled so as to have an rms value of unity. In Figure 2 the same signatures are repeated, but scaled so as to have a peak value of 1.414. In other words, the magnitude of the signatures is smaller in Figure 2 by a factor of $1.414/g$. The first "laboratory" curve is the same in both figures, while the "transient" curve has been reduced the most.

Two schools of thought have developed in applying acceleration waveforms to evaluate the induced human response. In the first, it is reasoned that the degree to which a person *objects* to a particular magnitude of vibration will be determined by some averaged effect over a period of time; for example, some weighted sum of the number of cycles above some threshold of perception and the intensity of those cycles. For the sake of simplicity, the root-mean-square value has been adopted as a concise measure of this effect. In the second school, it is reasoned that a person is affected most by the largest individual peak cycles, and will tend to "forget" about all lesser cycles. The "peak value" has been adopted as the concise measure of this effect. Strictly speaking, this is defined as the expected value of the largest single cycle of vibration which will occur during a reference period T (typically 20 to 60 minutes). If a wind storm has a stationary duration of 8 hours, for example, the peak value is the average of the 8 maximum cycles observed, one each hour. Depending on the uniformity of the waveform, of course, there may be many other cycles each hour of a magnitude nearly as great as the peak value; so the peak value is, to varying extents, an indication of an averaged effect also. Conversely, the rms value is fundamentally an index of the average effect, but is also an indication of the extreme peaks, to varying degrees, depending on waveform.

So there is some overlap between the two schools of thought, and neither is so pretentious as to claim that it is absolutely the correct viewpoint. Nevertheless, it is desirable to choose one or the other for practical reasons. This begs consideration of the idealized, fundamental nature of each school. In addition, there are practical issues to consider, such as the difficulty of predicting each index, which exert additional pressure to select one method or the other.

The Application of Research Information

A large amount of information has been compiled by researchers aimed at predicting human response to motion in tall buildings. But several issues which must be addressed, and there are difficulties to be overcome, before this information can be applied. Of these, that of the waveform is now addressed through specific examples.

Perhaps best defined is the *threshold of motion perception*, which has been studied by a number of researchers (Soliman 1963; Chen & Robertson 1972; Chang 1973; Irwin 1978; CTBUH 1981; Kanda et al. 1994). These studies utilized "moving room" experiments, in which subjects were placed in a room subjected to simple harmonic motion of varying amplitude. The subjects were asked at what point they were able to sense that the room was moving, and probability distributions fit to the responses allowed prediction of the motion amplitude which can be sensed by various percentages of the population. The results of several studies are compiled in Figure 3. Note that the frequency of motion is apparently a significant parameter, with more-or-less consistent results obtained from completely independent studies. Also, since the motion was in all cases sinusoidal, the motion intensity can be easily and interchangeably described by either the peak value (as on the left scale) or rms value (as on the right scale).

Motion perception threshold levels may be important in establishing limiting criteria for motions which might occur very frequently (such as a monthly basis) in residential or office buildings, or perhaps infrequently in critical buildings where sensitive work is expected (such as hospitals or air-traffic control towers); or in characterizing the serviceability of very stiff (or short) buildings which never experience very much motion. What is the influence of waveform regularity? It would seem as though a perception threshold, by definition, is the intensity of a single cycle of motion which can be detected. Therefore, the peak acceleration which occurs in a tall building should be compared to the peak scale in Figure 3, to determine the recurrence interval at which occupants will be able to sense motion. Is it not possible, or even likely, however, that some repetition of the motion is necessary before the subject can correlate the stimulus to a definite response? It is easily imagined that, if only one cycle per hour exceeds a subject's threshold, that he will notice it but likely dismiss or forget it much as one who captures some minor action by peripheral vision, then "checks again" to see if the stimulus was really there. There is some argument, then, that the rms motion expected in the building at various recurrence intervals should be compared against the right scale in Figure 3 to predict the interval at which occupants will be able to reliably sense motion. For reasons discussed in the previous section, these two approaches will usually result in very different conclusions.

An additional shortcoming in most of these moving-room experiments is that the motion was unidirectional. Little information is available to evaluate human response to simultaneous acceleration in multiple directions, such as usually occurs in tall buildings. As will be seen below, this shortcoming is especially significant because the effect on the rms index is different from the effect on the peak index.

Hansen et al. (1973) performed, in the early 1970's, a landmark experiment in which characteristic motions in two actual tall buildings were related to the degree of occupant discomfort. Occupants were interviewed, after experiencing a wind storm involving perceived motions, to determine the recurrence interval at which they would tolerate the experience. The motion intensity was determined in one case by accelerometer recordings at the top of the building, and in the other case by motions predicted by a wind tunnel study related to the measured wind speed. Their results are shown in Figure 4. The suggested comfort criteria, based on a 2-percent level of objection and indicated by the dashed lines, is that an acceleration of 0.005 g rms should occur no more than once every 6 years on average. Only the rms value of the vector resultant acceleration, averaged over the top floor, was considered. It is not possible to provide a secondary y axis calibrated in the alternate peak index, as in Figure 3, because the peak factor of the resultant motion was not reported. Approximate peak values of the individual component accelerations can be ascertained from the presented waveforms, or an analytical peak factor could be computed from the natural frequencies of motion which were reported; however, the process of combining these component peak values to obtain the resultant peaks is complex (see discussion below).

Two other researchers combined the work of Hansen et al. with already-established perception threshold criteria to propose other comfort criteria. Irwin (1978) reasoned that the comfort criteria curve should have the same variation with frequency as the perception threshold, but that it should be "calibrated" by passing through Hansen's curve at the frequency of Hansen's building (building B). A slight adjustment was also made to reference a 5-year recurrence interval rather than 6. The rms acceleration index was used. Irwin's proposal, which was later adapted by ISO 6897 (1984), is shown in Figure 5.

Davenport (1975) proposed two curves relating acceleration to recurrence interval, representing objection by 2 and 10 percent of the population (Figure 6). The curves were drawn to agree with Hansen's criteria at the two acceleration levels of Hansen's case studies, and were also forced tangent to the perception thresholds (according to Chen & Robertson) for very frequent (approx. weekly) occurrences. However, in apparent subscription to the belief that isolated peaks are more relevant than longer-term averages, all accelerations were expressed as peak values. To accomplish this, Hansen's rms accelerations were simply multiplied by 3.5. This is a typical peak factor for buildings having a natural frequency of about 0.07 Hz, although it is often used as a "universal" value appropriate for tall buildings in general. Davenport's 2-percent curve eventually developed into the Boundary Layer Wind Tunnel Laboratory (BLWTL) criterion of 0.020 g peak acceleration at a 10-year recurrence (which was later refined to apply to office occupancy only, with a reduced value of 0.015 g for residential occupancy). This criterion became widely used in North America (Griffis 1993).

Converting the BLWTL criterion to one based on rms rather than peak accelerations for a specific building is not straightforward, because the question arises as to whether the peak value should be divided by the building's true peak factor to obtain the corresponding true rms value, or whether it should be divided by 3.5 to obtain a "quasi" rms value consistent with Hansen's, on which the criterion was originally based.

Regardless of which of the above three criteria is favored, it has been universally recognized that they all are based on insufficient data, because the critical issue is of motion *tolerance* rather than *perception*. Since the 1970's, further research aimed at extending this data base has occurred in Japan, primarily in the form of additional laboratory moving room experiments. These were performed using sinusoidal motion over extensive ranges of acceleration, and the effects on test subjects was categorized into a number of ranges from perception threshold to intolerable ranges such as "cannot walk" to "induces nausea."

Figure 7, compiled by CTBUH Committee 36 (1981), summarizes some of this research. The wide range of acceleration and induced symptoms may be particularly useful in judging the acceptability of structures which occasionally undergo extreme motions, such as those caused by earthquakes or infrequent violent winds. They are primarily the results of research test programs by Goto Kojima & Yamada (Kojima et al. 1973; Goto et al. 1973; 1974). They have also formed the basis for proposed criteria for tall building motions in Japan.

Because these test results were based on sinusoidal waveforms, a secondary *y* axis may be calibrated in rms units, by dividing the primary axis values by 1.414. Such an axis has been added to the CTBUH compilation for Figure 7.

Figure 8*a* illustrates the difficulty of applying this research information to a case study. From the merging of a wind-tunnel model study and a study of local climatological data, the top-floor acceleration of a special-purpose tower is plotted against mean recurrence interval. The tower is quite wind-sensitive and frequently experiences high accelerations. The peak factor from the wind-tunnel results (in this case about 3.8) has been used to express the acceleration as both peak and rms values, on the left and right ordinates, respectively. Superimposed on the building response curve are various acceleration effects, all obtained from the studies described above in Figure 7. Because the peak factor for this tower differs from the sinusoidal basis of those data, the effect is plotted at two different acceleration levels depending on whether the peak or rms value is taken as the appropriate index. For example, the limit of "desk work difficult" for this building is projected to be about 0.035 g peak = 0.009 g rms if peak acceleration is used to interpret the research information (based on the left ordinate in Figure 7), but 0.090 g peak = 0.024 g rms if rms acceleration is used (based on the right ordinate in Figure 7). In fact, there is a range of a factor of nearly 3 (= $g/\sqrt{2}$) in this structure's acceleration corresponding to all of the limit states, depending on the significance of peak vs. rms indexes. Vertical lines have been formed to "box" the region where these two acceleration limits intersect the structure's response curve, thus showing, for example, that the mean recurrence interval for "desk work difficult" may range from about 0.07 years (monthly) to 50 years. Obviously, this range is too wide to be of significant use in evaluating this structure's serviceability. Other limit states display a similar range of recurrence.

Note that, in Figure 8*a*, the "dangerous" state has not been given a range as has the other states. This is because, in the research behind Figure 7 as reported by the CTBUH, this state is defined as "objects begin to fall." The interpretation here is that a single cycle of a peak acceleration of such a magnitude may cause "some object to fall," and thus constitutes a danger irrespective of how many or how frequently objects might fall. A similar interpretation *could* be given to the thresholds of motion perception, but this has not been done in Figure 8*a*, for reasons discussed earlier.

Figure 8*b* shows similar results obtained for a more typical building. Note that the 5-, 6-, and 10-year accelerations almost exactly coincide with the limiting criteria proposed by Irwin, Hansen, and BLWTL (which, of course, is not coincidental). However, the lower limit of nausea may occur every 0.2 to 40 years, depending on whether the information of Figure 7 is applied on the basis of peak or rms values respectively; similarly the limit of normal walking may be reached at intervals ranging from about 1 month to 7 years. Obviously, such wide ranges in occurrence rates compromises the usefulness of research performed on the basis of sinusoidal vibration. Also, it would seem that applying the research results of Figure 7, using peak acceleration as a basis, would lead to unusually severe evaluations which are counter to experience in most tall buildings.

Qualitative Arguments

There appear to be no documented studies at this time which address the dependence of waveform or peak factor on human response to vibration, at least in a context directly applicable to horizontal motions in tall buildings. How, then, is the selection of an appropriate measurement index to be made? It can only be done on a qualitative or practical basis. Qualitative, or intuitive, considerations are discussed in this section. Practical issues, associated with the technical feasibility of implementing these indices, are addressed in the following section.

Historically, most criteria for human response to vibration of various natures have been based on the rms index. This includes ISO 6897 and ISO 2631 (in which the "effective acceleration" is defined as the rms value), and ANSI S3.18 and S3.29, as well as Hansen et al. The reasons for this are not well documented, however, and the simple fact that rms has been used should not necessarily be inferred as having a rational basis. It is of interest to note, however, that Irwin (1978) stated "accelerations much in excess of the suggested average [rms] magnitudes will occur for short periods but these higher levels, briefly experienced, are not considered to have any great contribution to the memory of the storm...Short periods of higher acceleration which occur during the worst 10 minutes of the storm occurrence are accounted for in the rms value of the vibration of the structure for the storm peak." This rationale has also been reiterated in ISO 6897. Hansen et al. state, without justification, that “It is assumed that the motion intensity, averaged over a reasonable period during the storm peak, is the significant variable to consider” and “The rms acceleration obtained at the storm peak and averaged over the top floor area appears to best characterize the storm's severity in relation to human discomfort.” However, on a more practical level they continue, “It is closely related to the average peak acceleration, but the latter statistic is considerably more difficult to deal with during the process of temporal and spatial averaging.”

Floor vibrations due to walking (such as depicted in curve 4 of Figures 1 and 2) have been studied quite extensively (Reiher & Meister 1931; Lenzen 1966; Wiss & Parmelee 1974; additional discussion & references in Chang 1973), and it now seems to be well established that transient effects are less significant than steady state effects. Chang reports, from Lenzen's study, “Transient vibrations…are only important if the vibration induced persists more than five cycles (if the vibration persisted above 12 cycles, the occupant responded to the vibration just as to a steady-state vibration).” Wiss & Parmelee, from a series of laboratory tests of humans subjected to floor impacts, state “A very significant result of this investigation has been to show that transient vibrations of a particular frequency and peak displacement are progressively less perceptible as the damping increases. For a given [tolerance] rating, the product of frequency and displacement may be approximately twice as much when the damping is increased from 0.02 to 0.20 of critical.” For a given frequency, the acceleration producing a constant tolerance rating was found to vary approximately as the 1/4 power of damping. The Canadian Standards Association implies an even stronger dependence, with a specified allowable peak acceleration which varies as the 1.6 power of damping. It can be shown that the peak factor of a damped impulse, such as the bottom signals in Figures 1 and 2, is approximately proportional to the square root of the damping ratio, so that human sensitivity to the 0.5 power of damping would imply sensitivity to the rms value of vibration.

Human response to complex spectra motions and multiple-axis motions was extensively studied in the 1970’s, as reported by Griffin & Whitman (1980): “These earlier studies suggest the rms procedure provides a useful estimate of the discomfort produced by such motions.” In their own tests using vertical motions at a constant frequency of 8 Hz but varying amplitude, they found that human perception correlated well with rms acceleration, but increased slightly with the peak value. As the peak factor of test motions increased gradually from 1.41 to 8.51--a 6-fold increase in peak acceleration while maintaining constant rms value--the discomfort experienced was equivalent to a uniform sinusoidal acceleration increasing from 1 unit to only 1.5 to 2 units. They introduced and proposed the *rmq* index, defined just as the rms value but using the 4th root and power instead of the 2nd, which correlated well with this human response. When compared with the earlier research however, “In retrospect it appears that the rmq procedure may not have been an improvement for the multiple frequency sinusoidal motions or random motions...”

The AISC LRFD Commentary (1986) states “Generally, occupants of a building find sustained vibrations more objectionable than transient vibrations.” Qualitative comments of a similar nature have also been heard by the ASCE Task committee on Motion Perception Criteria from one researcher who has experienced both real and simulated tall building motion, to the effect that “sinusoidal acceleration is much worse than random motions”; presumably this means for a given peak value; i.e. the commentator was comparing curves 1 and 4 (or 3) in Figure 2. If he were able to compare waveforms having an equal rms value (as in Figure 1), it is likely that this commentator would have considered the effects more nearly equivalent.

All of the above observations seem to be related to the intuitive significance attributed to the *duration* of a physical stimulus instead of—or at least in addition to—its intensity. The observation was stated succinctly by Alexander et al. (1945) in connection with studies of nausea induced by vertical motions:

> Common observation suggests the conclusion that the time character of stimulation and not its intensity is the critical consideration. Large magnitude of peak accelerations is not the cause of nausea. Many vehicles and movements which yield large vertical or rotary accelerations are rarely nauseating; all have brief phases: farm wagons, motorcycles, horseback riding, rowboats on choppy waves, motor launches, running, normal quick head movements, and whirling by dancers where the head is jerked around. Other vehicles and movements, some having relatively low accelerations, are frequently nauseating; all have long phases: autos with "soft" long period swings, camels (according to hearsay), rowboats on long swells, ocean boats, elevators, stalls, spins, lazy eights, etc., in airplanes, autos on mountain-road curves, and whirling without jerking the head around.

The writer believes that intuition, along with the scant and hearsay reports that are available, support the contention that the waveforms of Figure 1 are more likely to be interpreted similarly than are the waveforms of Figure 2, if they represent a stimulus of virtually *any* physical stimulus—for example, sound intensity, pain, or motion intensity.

Technical Arguments

There are several arguments from a technical standpoint that favor the use of the rms index. These center around the fact that the rms index is more straightforward to measure and/or predict, in either analytical or wind-tunnel studies, and is therefore more likely to result in uniformity among predicting agencies.

Dynamic response predictions are most often made from model tests in which the power spectral density of the aerodynamic loading is measured, to which theoretical random vibration techniques are applied to obtain the mean square or rms response. This is performed separately for the x, y components of motion (generally torsion is also included but only two components are considered here for simplicity). This procedure is well understood and all wind tunnel laboratories utilize basically the same methodology (differences will occur due to the equipment used, the physical wind model, proximity model, means of accounting for nonideal mode shapes, etc., but these are incidental to the issue of concern).

Methodical differences are likely to arise in the determination of peak values, however, which are obtained by multiplying the rms value by a peak factor g. Some labs, for example, may simply assume $g = 3.5$. This is a simplistic approach, but it is common nevertheless and is consistent with Davenport's criterion as described above. It can thus be argued that, even though the resulting peak estimate may be biased (by using a different value for g in the analysis than occurs in the structure), it is in fact the value which should be compared to Davenport's or the UWO criteria. On the other hand, many labs will estimate the peak value by using the relation

$$g = \sqrt{2 \ln \nu T} + \frac{0.5772}{\sqrt{2 \ln \nu T}}$$

This generally results in a more accurate estimate, but there are still variations related to how the mean cycling rate ν is obtained. Usually it is assumed that this is adequately approximated by the building's natural frequency, but slightly different expressions are sometimes used depending on whether the factor is to be applied to displacement or acceleration (Simiu 1974; Simiu & Lozier 1975; Solari 1982; Simiu & Scanlan 1986). These differences can be significant for shorter buildings, or those having an unusually high natural frequency, which have a high background response in comparison to the resonant response.

Sample peak values can also be measured directly, for each component of motion, by using an aeroelastic model. But these measurements are subject to wide statistical fluctuations related to the duration of the sample, and "population" peak values must be estimated from the sample peak(s). Because of various (and legitimate) methods used, there is less uniformity in the determination of peak values than in rms values.

Technical complexities are further compounded when motions in different directions or component sources are combined. The resultant of two perpendicular motions is defined by

$$a^2 = a_x^{\ 2} + a_y^{\ 2}$$

Averaging this equation, and using a tilde to signify rms, results in

$$\tilde{a} = \sqrt{\tilde{a}_x^{\ 2} + \tilde{a}_y^{\ 2}} \tag{1}$$

Thus the rms resultant can be obtained from the rms components by simple mean square addition, regardless of the degree of correlation between them (torsional contributions can also be accommodated if the correlation is accounted for, or by mean square addition if uncorrelated). It is tempting to use a similar relation for peak values, i.e.

$$\hat{a} = \sqrt{\hat{a}_x^{\ 2} + \hat{a}_y^{\ 2}} \tag{2}$$

or, by definition of peak factors,

$$g_c\tilde{a} = \sqrt{g_x^{\ 2}\tilde{a}_x^{\ 2} + g_y^{\ 2}\tilde{a}_y^{\ 2}} \tag{3}$$

where g_c represents the "combination" peak factor. If the component peak factors are equal, $g_x = g_y = g$, then the two equations above imply that $g_c = g$, and thus

$$\hat{a} = g\tilde{a} \tag{4}$$

Unfortunately, while Eq. (1) is true in general, Eq. (2) is invalid except in the unlikely event of perfect correlation between x and y motions. Therefore, Eq. (4) is generally invalid as well. It can be shown by time series analysis of test data (Isyumov 1994) that the true peak resultant is less than that implied by Eq. (2), and may be expressed as

$$\hat{a} = \phi\sqrt{\hat{a}_x^{\ 2} + \hat{a}_y^{\ 2}} \tag{5}$$

where ϕ is a "joint action factor" which ranges from 0.7 to 1.0, and typically 0.8 to 0.9. For the special case of $g_x = g_y = g$, this implies $g_c = \phi g$. An appropriate value of ϕ could be determined by (relatively time consuming and expensive) time series analysis of model test data, or from a chart of typical results as presented by Isyumov.

The above discussion has considered only two modes of vibration in orthogonal directions. The complexity of the issue increases considerably when a third torsional mode is considered, or for the coupled three-dimensional modes often required to describe the vibration of unsymmetric structures.

In summary, there are at least three methods by which peak resultant accelerations can be determined: Eq. (2); Eq. (4) with a peak factor g subject to all of the variability of the ordinary component peak factors discussed in the first part of this section; and Eq. (5), with additional "sub-choices" for a value of ϕ. In practice, various wind-tunnel laboratories (or other predictors) will use any one of these methods, with the result that the predicted peak acceleration will be subject to a range of perhaps 30–40 percent, even when rms values would be in perfect agreement. What is an owner to do who requests a second or even third opinion on the health of his building, when all the doctors are using different methodologies to evaluate it? It will be especially difficult to sort out which is the "best" opinion if the predicted value is to be compared to a peak criterion which contains an implicit assumption of the appropriate method.

Conclusion

Some assessment of the effect of waveform must be made to relate the sinusoidal acceleration signatures, which have traditionally been used in laboratory research, to the random signatures encountered in real structures. More research is needed to quantify the effect of this waveform. It may be hypothesized that the best index to indicate human tolerance to motion lies somewhere between the extreme indexes of expected peak and rms values, averaged over a period of say 20 to 60 minutes. Feasible indexes might be, for example, the mean of these two extremes, the rms value over a much shorter interval such as 1 minute, or the rmq value. Alternatively, it may be that instantaneous peak and longer-term rms values are each valid criteria, and that both must be satisfied to ensure serviceability.

However for practical purposes, such as codification, it is desirable to choose between the extreme indexes of peak value and rms value. It is recommended herein that the rms index be adopted for the purpose of evaluating serviceability for occupant comfort. The reasons for this recommendation are as follows:

- Most criteria used historically, and throughout the world, have been based—either explicitly or implicitly—on the rms index.
- Applying some laboratory test results based on peak acceleration, rather than rms acceleration, results in unrealistically severe evaluations in real buildings which are inconsistent with observation.
- On an intuitive basis, it is believed that some form of the averaged motion intensity over a period of, say 20–60 minutes, is better correlated to human response symptoms than is a (possibly isolated) peak intensity value over the same period. This speculation also seems to be supported by the little evidence which exists.
- The rms value is much simpler to evaluate, and more likely to result in consistency and uniformity among various agencies engaged in predicting vibration in a proposed building, or in evaluating the vibration in an existing building.

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Figures

Figure 1. Characteristic acceleration signals, scaled to have equal rms values

Figure 2. Characteristic acceleration signals, scaled to have equal peak values

Figure 3. Threshold of motion perception

Figure 4. Human tolerance to motion in tall buildings, according to Hansen Reed & Van Marcke, and proposed serviceability criterion

Figure 5. Serviceability criterion proposed by Irwin [ISO 6897–1984]

Figure 6. Serviceability criterion used at BLWTL, U. of Western Ontario

Figure 7 Effects of horizontal low-frequency vibration over a wide range of acceleration in laboratory experiments

Figure 8 Attempt to characterize random wind-induced acceleration in a tall structure based on the laboratory experiments using sinusoidal acceleration. The lower limit for each characterization results from equating the peak value of sinusoidal acceleration in Figure 7 to the peak acceleration in the structure; the upper limit results from equating the rms values. (a) Special-purpose tower undergoing frequent extreme motions; (b) Typical tall building which meets several popular motion-limiting criteria.

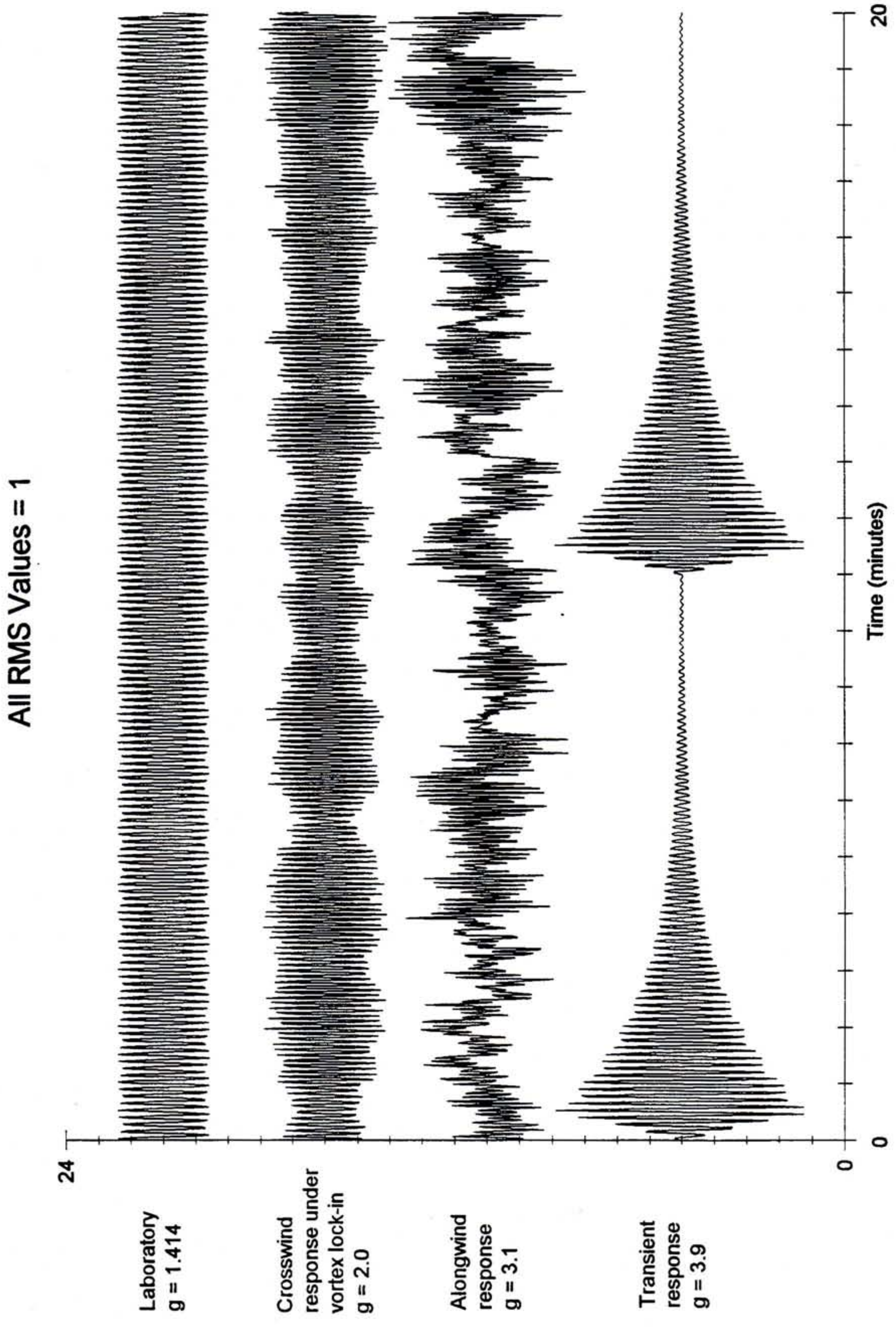
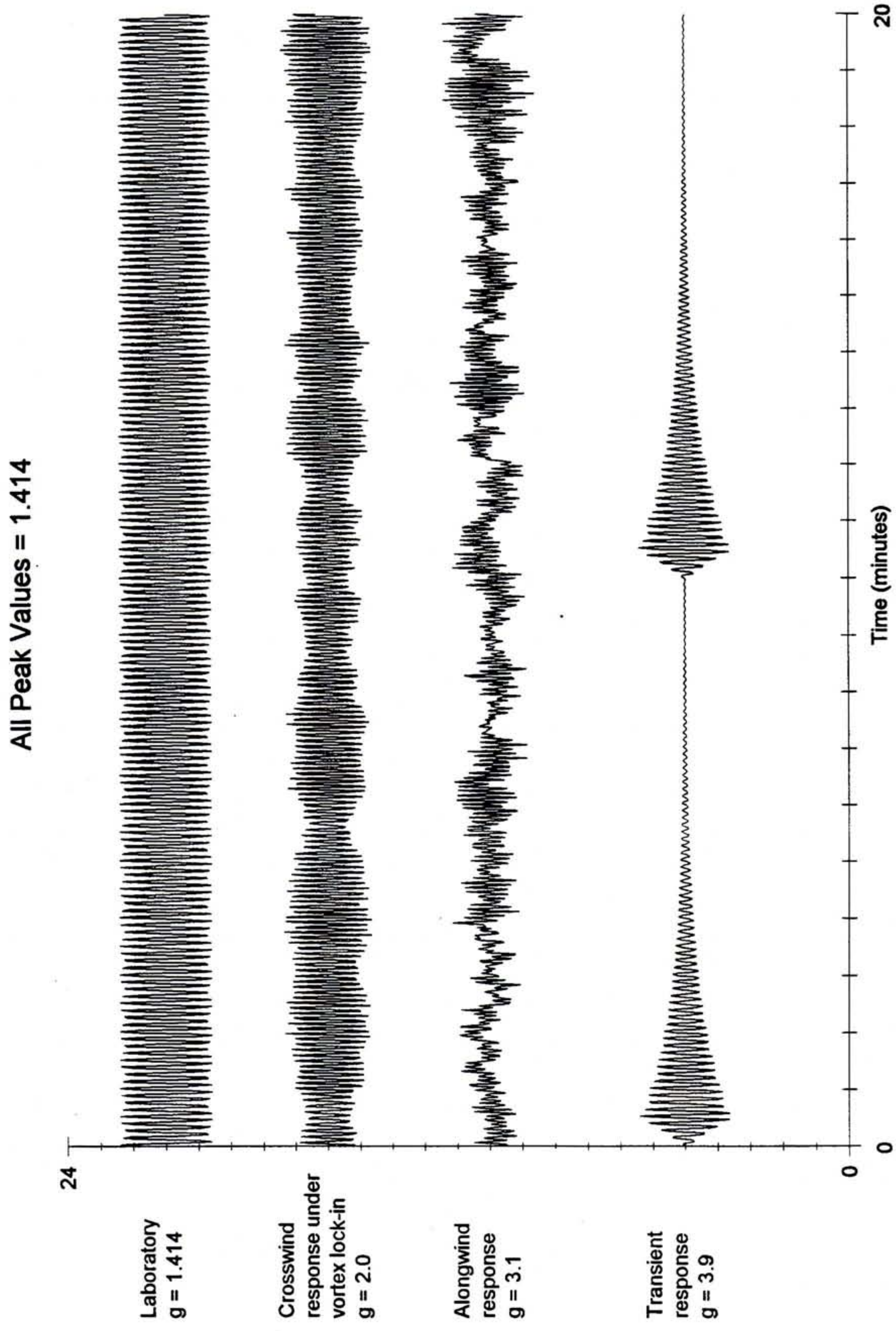
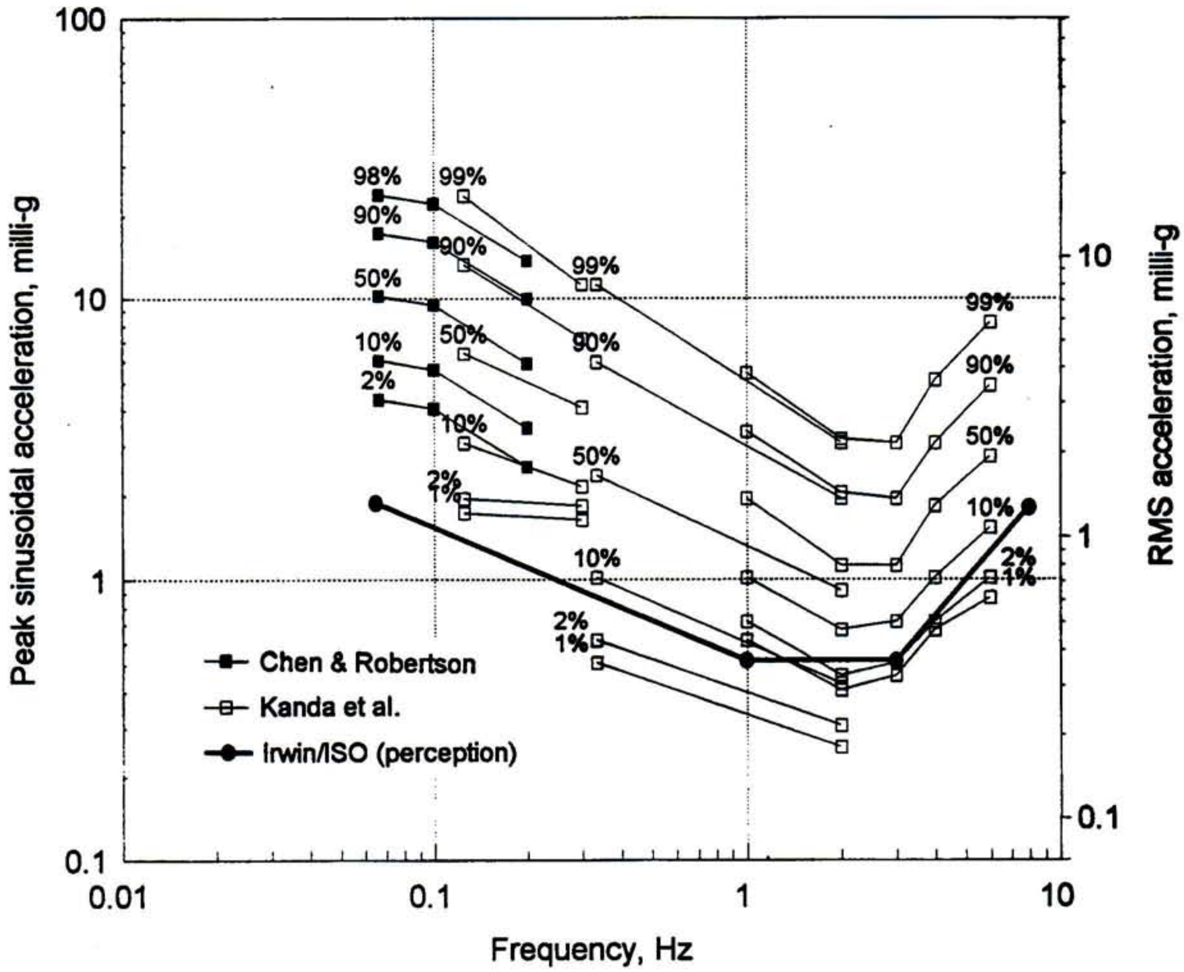

All RMS Values = 1
24
0
20
Time (minutes)
Laboratory
g = 1.414
Crosswind
response under
vortex lock-in
g = 2.0
Alongwind
response
g = 3.1
Transient
response
g = 3.9

Figure 1.



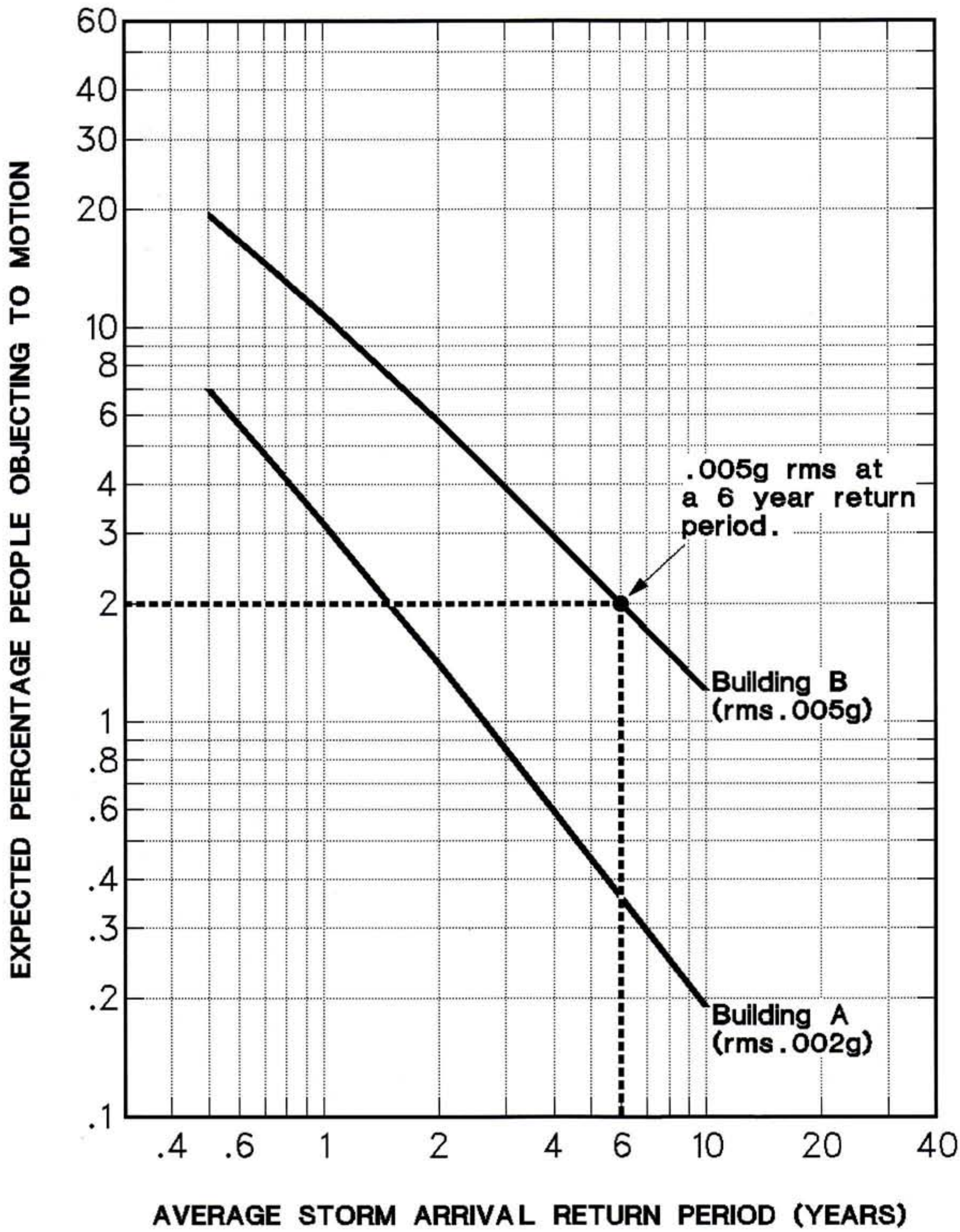
All Peak Values = 1.414
Laboratory
g = 1.414
Crosswind
response under
vortex lock-in
g = 2.0
Alongwind
response
g = 3.1
Transient
response
g = 3.9
24
0
0
20
Time (minutes)

Figure 2.



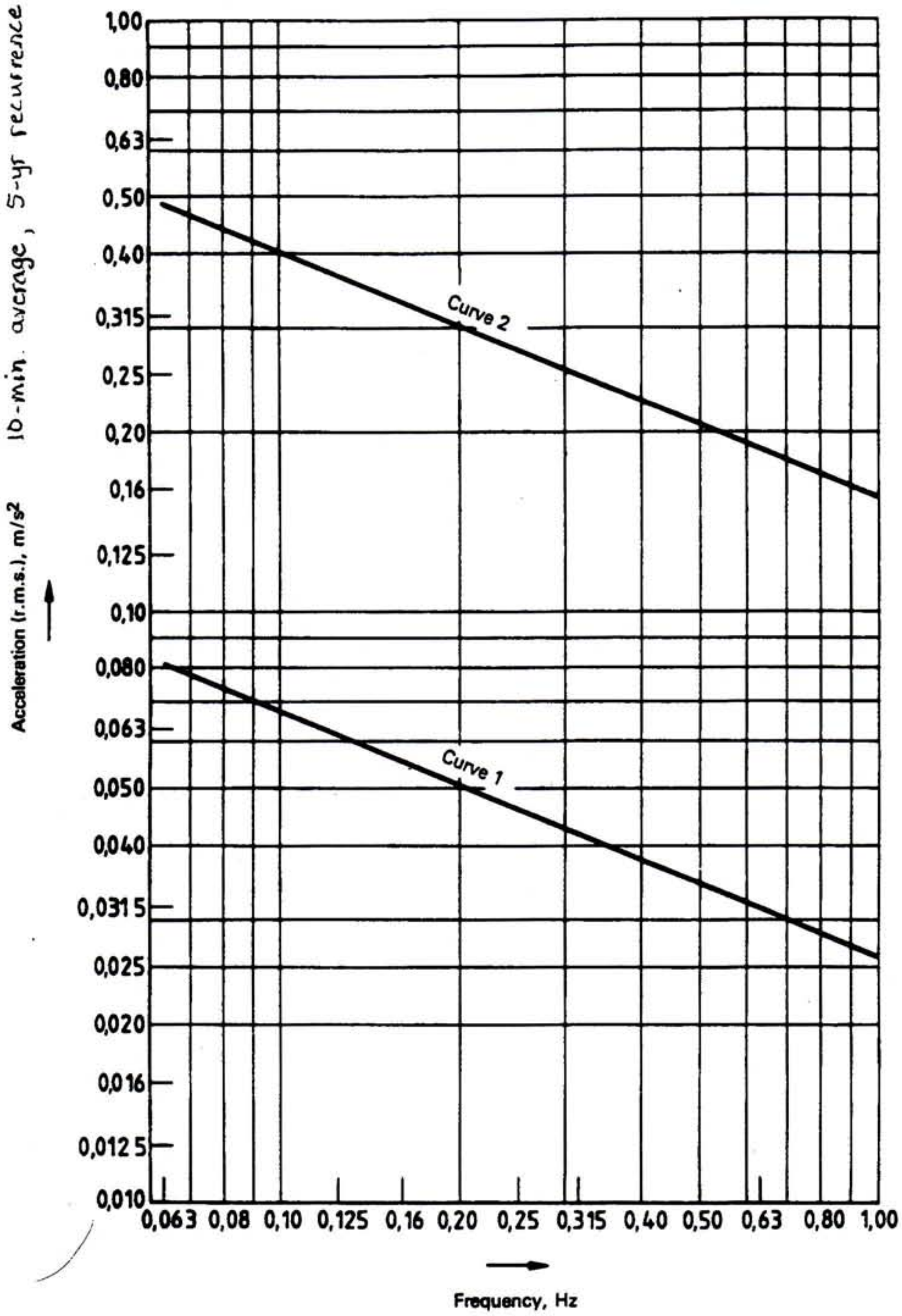
Peak sinusoidal acceleration, milli-g
RMS acceleration, milli-g
Frequency, Hz
100
10
1
0.1
0.01
0.1
1
10
Chen & Robertson
Kanda et al.
Irwin/ISO (perception)
98%
99%
90%
50%
10%
2%
1%

Figure 3.



60
40
30
20
10
8
6
4
3
2
1
.8
.6
.4
.3
.2
.1
EXPECTED PERCENTAGE PEOPLE OBJECTING TO MOTION
.4
.6
1
2
4
6
10
20
40
AVERAGE STORM ARRIVAL RETURN PERIOD (YEARS)
.005g rms at a 6 year return period.
Building B (rms.005g)
Building A (rms.002g)

Figure 4.



Suggested satisfactory magnitudes of horizontal motion of buildings used for general purposes (curve 1) and of off-shore fixed structures (curve 2)

Figure 5.

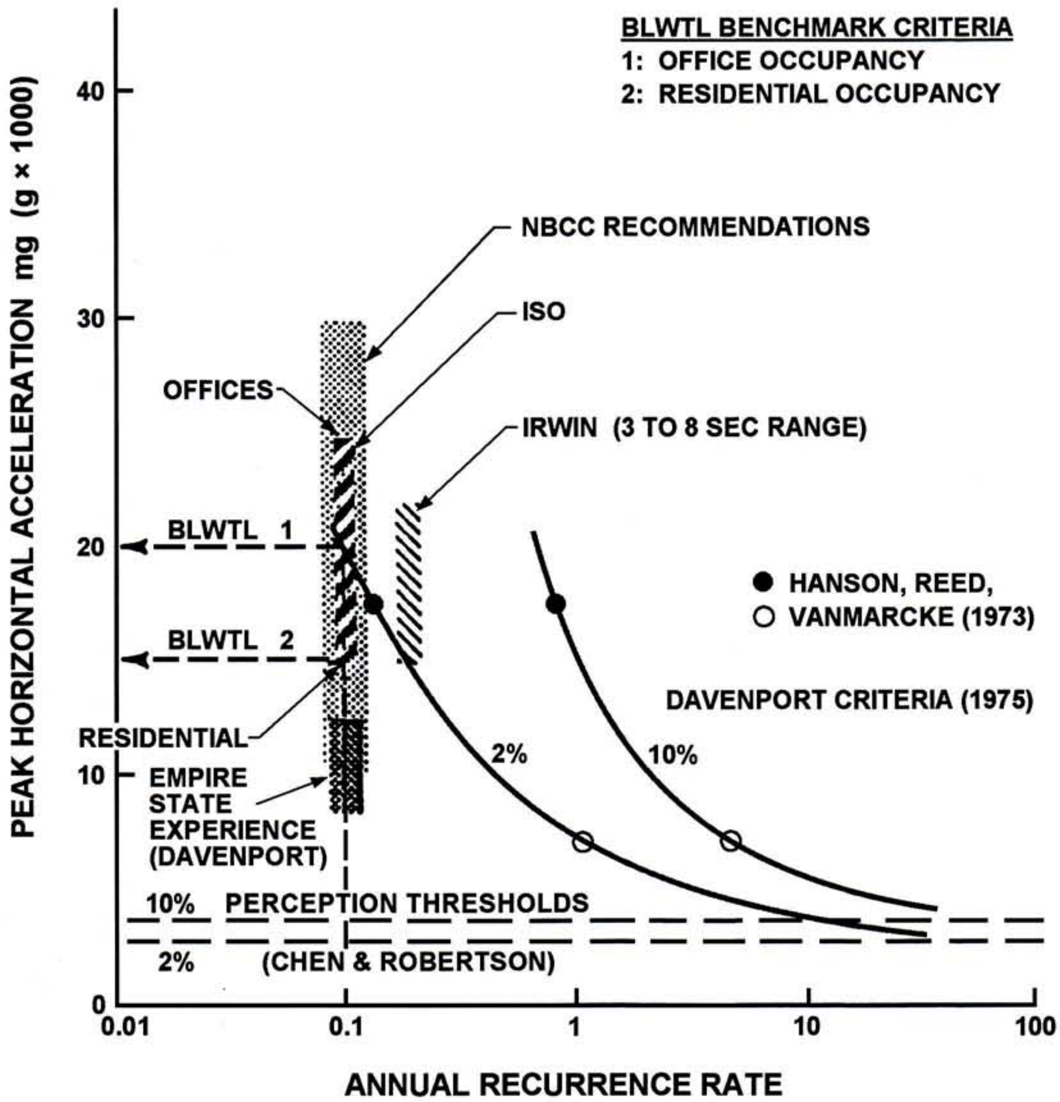
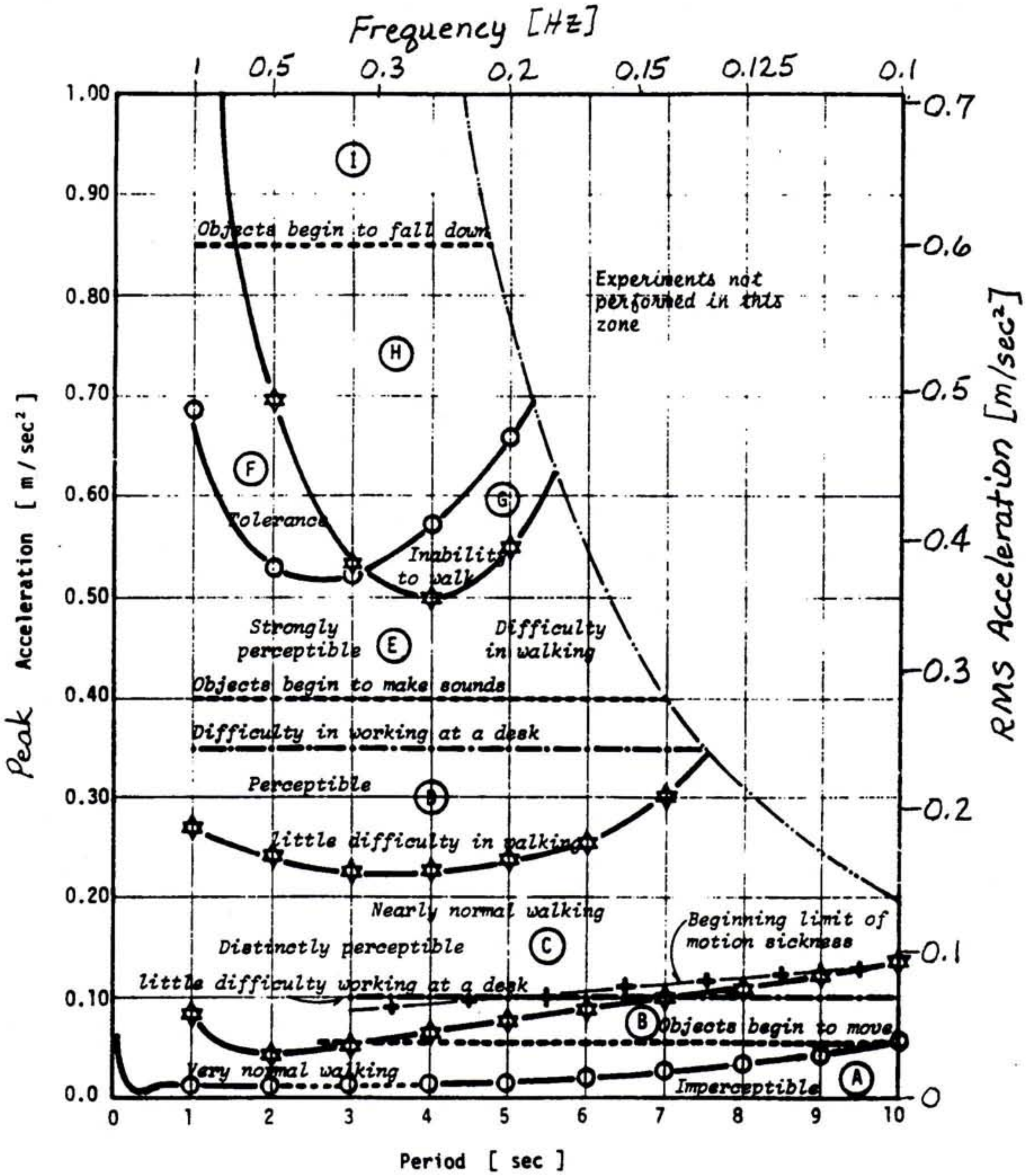

BLWTL BENCHMARK CRITERIA
1: OFFICE OCCUPANCY
2: RESIDENTIAL OCCUPANCY
NBCC RECOMMENDATIONS
ISO
OFFICES
IRWIN (3 TO 8 SEC RANGE)
BLWTL 1
BLWTL 2
HANSON, REED,
VANMARCKE (1973)
DAVENPORT CRITERIA (1975)
RESIDENTIAL
2%
10%
EMPIRE
STATE
EXPERIENCE
(DAVENPORT)
10% PERCEPTION THRESHOLDS
2% (CHEN & ROBERTSON)
PEAK HORIZONTAL ACCELERATION mg (g × 1000)
0
10
20
30
40
0.01
0.1
1
10
100
ANNUAL RECURRENCE RATE

Figure 6.



Frequency [Hz]
1
0.5
0.3
0.2
0.15
0.125
0.1
Objects begin to fall down
Experiments not performed in this zone
Tolerance
Inability to walk
Strongly perceptible
Difficulty in walking
Objects begin to make sounds
Difficulty in working at a desk
Perceptible
Little difficulty in walking
Nearly normal walking
Beginning limit of motion sickness
Distinctly perceptible
Little difficulty working at a desk
Objects begin to move
Very normal walking
Imperceptible
Peak Acceleration [m / sec²]
RMS Acceleration [m/sec²]
Period [sec]

Figure 7.

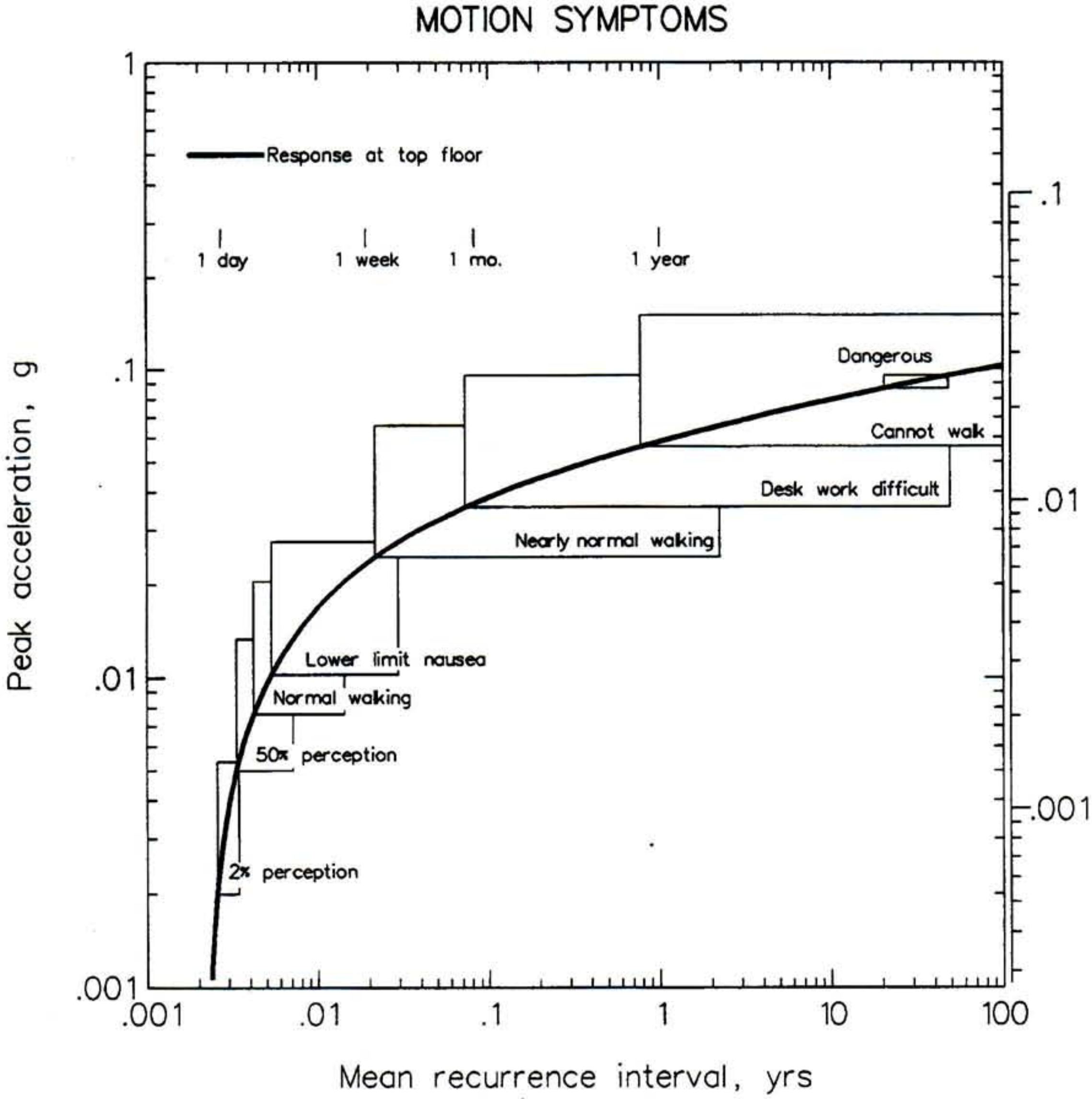

MOTION SYMPTOMS
Response at top floor
1 day
1 week
1 mo.
1 year
Dangerous
Cannot walk
Desk work difficult
Nearly normal walking
Lower limit nausea
Normal walking
50% perception
2% perception
Peak acceleration, g
RMS acceleration, g
Mean recurrence interval, yrs
1
.1
.01
.001
10
100

Figure 8(a).

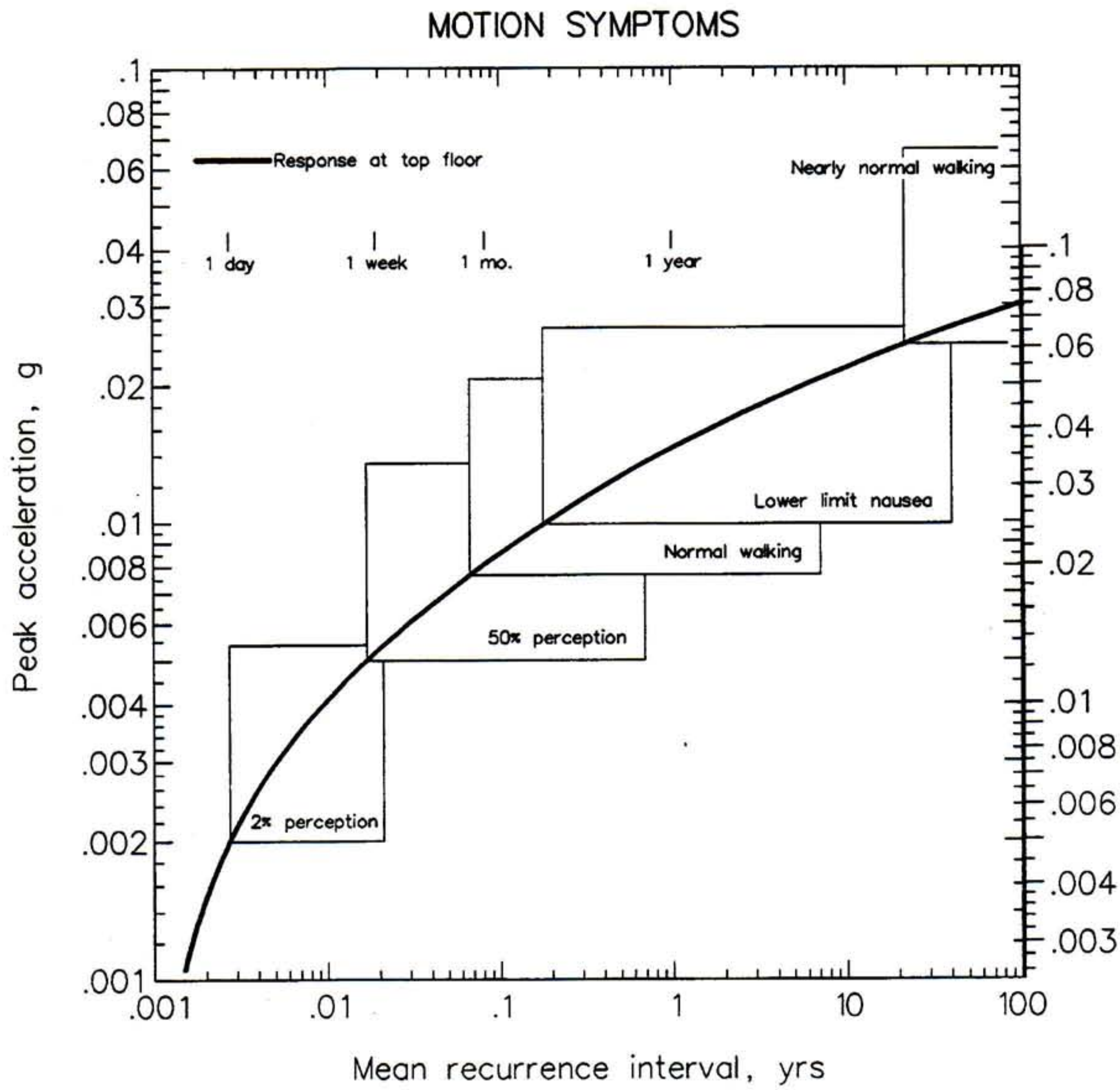

MOTION SYMPTOMS
Response at top floor
Nearly normal walking
1 day
1 week
1 mo.
1 year
Lower limit nausea
Normal walking
50% perception
2% perception
Peak acceleration, g
RMS acceleration, g
Mean recurrence interval, yrs
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
.001
.001
.01
.1
1
10
100

Figure 8(b).