Edinburgh, Scotland
EURONOISE 2009
October 26-28

Human exposure to low frequency horizontal motion in buildings and offshore structures: an assessment of guidance in BS 6611 and ISO 6897

Henrietta V.C. Howarth [a]
Michael J. Griffin [b]
Human Factors Research Unit
Institute of Sound and Vibration Research
University of Southampton SO17 1BJ
United Kingdom

ABSTRACT
Building vibration produced by external sources (e.g. road and rail traffic) and internal sources (e.g. domestic equipment and footfalls) is usually within the frequency range 1 to 80 Hz. The excitation of structures by wind or waves can induce horizontal motion at frequencies less than 1 Hz. This paper reviews guidance on the measurement, evaluation and assessment of human exposure to horizontal motion over the frequency range 0.063 to 1.0 Hz as provided in British Standard 6611 (1985) and the equivalent International Standard 6897 (1984). The guidance is compared with standards applicable to exposure to vibration at higher frequencies. It is concluded that BS 6611 and ISO 6897 do not adequately allow for the effects of exposure duration or for differences in the effects of motion on different tasks. Acceleration limits for buildings proposed in BS 6611 and ISO 6897 for the worst 10 minutes of a wind storm with a return period of 5 years or more are similar to satisfactory magnitudes in BS 6472-1 (2008) and BS 6841 (1987) for 10-minute daily exposures. Mean thresholds for the perception of motion in BS 6611 and ISO 6897 are a little higher than those in ISO 2631-1 (1997), BS 6472-1 (2008), and BS 6841 (1987). The acceleration magnitudes expected to impair task performance in BS 6611 and ISO 6897 are lower than the magnitudes impairing hand control in BS 6841. Possible revisions to BS 6611 and ISO 6897 are discussed.

1. INTRODUCTION
The number of tall buildings, and the height of tall buildings, is increasing world-wide. High-rise buildings are often light-weight structures comprised of slender sections that are susceptible to movement when exposed to the forces of wind. Excitation of tall buildings by high winds induces horizontal motion at frequencies less than 1 Hz. The exposure of off-shore fixed structures to wind and waves can also result in low frequency horizontal motion. Such motions may affect habitability and interfere with task performance. British Standard 6611[1] and the equivalent International Standard 6897[2] provide identical guidance on the magnitudes of low-frequency horizontal motion expected to be satisfactory for people living and working in buildings and offshore fixed structures.

[a] Email address. H.Howarth@soton.ac.uk
[b] Email address. M.J.Griffin@soton.ac.uk

External sources, such as road and rail traffic, and internal sources such as domestic equipment and footfalls, can induce motion in buildings within the frequency range 1 to 80 Hz, with the greatest magnitude of vibration often in the vertical direction. Guidance on the evaluation of such human exposures to building vibration over the frequency range 0.5 to 80 Hz is provided in British Standard 6472-1[3].

This paper reviews the guidance in British Standard 6611, and in the equivalent International Standard 6897, for the evaluation of human exposure to horizontal motion over the frequency range 0.063 Hz to 1.0 Hz. Thresholds for the perception of vibration in British Standard 6611, British Standard 6472-1[3] and International Standard 2631-1[5] are compared. The effect of low frequency motion on task performance implied by BS 6611 and ISO 6897 is compared with guidance in BS 6841[4] and with the results of studies of motion-induced activity disturbance.

2. MEASUREMENT, EVALUATION AND ASSESSMENT ADVICE IN BS 6611 AND ISO 6897

In BS 6611 and ISO 6897 there is guidance on measurement, evaluation, and assessment of low-frequency horizontal motion. Four curves of satisfactory magnitudes for events of more than 10 minutes duration are given: one for offshore structures and three for buildings of different usage. This section summarises the advice given.

A. Motion measurement

Guidance in BS 6611 and ISO 6897 on the measurement of motion is in accord with ISO 2631 Part 2[6] and BS 6472 Part 1 for the evaluation of human exposure to building vibration. The standard states that the magnitude and direction of the greatest horizontal motion shall be determined by measurements of motion on a structural surface supporting the body at the point of entry to the body. If measurements are made at locations other than at the point of entry, transfer functions must be applied.

B. Motion evaluation

The evaluation method employed in BS 6611 and ISO 6897 is not consistent with the methods defined in ISO 2631 Part 2 or BS 6472 Part 1: there are no frequency weightings or band-limiting filters. Both BS 6611 and ISO 6897 state that the r.m.s. acceleration of motion over the frequency range 0.063 Hz to 1 Hz shall be determined. However, it is not clear what to do with motion outside the range 0.063 to 1 Hz or how to evaluate motions that have more than one frequency. If motion occurs in more than one horizontal axis, the guidance states that the components shall be added vectorially. The vector addition of two axes differs from guidance in ISO 2631 Part 2 and BS 6472 Part 1, where only vibration in the axis of greatest motion is used in the evaluation.

For the evaluation of intermittent and time-varying events, BS 6472-1 and ISO 2631-1 advise the determination of the vibration dose value:

$$VDV = \left[\int_0^T \left[a_w(t) \right]^4 \mathrm{d}t \right]^{\frac{1}{4}}$$

where $a_w(t)$ is the instantaneous frequency-weighted acceleration, and T is the duration of the measurement.

The fourth-power relationship between acceleration and time in the vibration dose value means that a doubling of the vibration magnitude is equivalent to a sixteen-fold increase in exposure duration. The vibration dose value integrates over time and therefore provides a means of accumulating exposures over a day. There is no equivalent guidance on the influence of motion duration in BS 6611 or ISO 6897. Advice is limited to the categorisation of motion as either ‘infrequently’ or ‘frequently’ induced. No account is taken of the duration of an event or the number of events in a day; it is simply stated that that “frequent occurrences refer to events of an everyday nature” and that the limits apply to events with duration in excess of 10 minutes.

C. Motion assessment

The four curves giving the limits in BS 6611 and ISO 6897 (Curves A to D in Figure 1) suggest that sensitivity to horizontal acceleration increases with increasing frequency between 0.063 and 1.0 Hz. The limits are categorized according to the use of the structure and the frequency of occurrence of the excitation forces. Curves A, B and C correspond to satisfactory magnitudes of low-frequency horizontal motion for people living or working in buildings; Curve D corresponds to satisfactory magnitudes for trained personnel on off-shore fixed structures. The limits are said to take into account the effect of motion on subjective responses (intrusion, alarm, or fear) and task performance. Information on structure type, frequency of events, and the activities of occupants relating to each curve is summarised in Table 1.

i. Perception thresholds

BS 6611 and ISO 6897 state that Curve B in Figure 1 corresponds to the mean perception threshold for horizontal motion. At the highest frequency of 1 Hz, the mean acceleration perception threshold of Curve B is 0.014 ms^{-2} r.m.s. and 40% higher than the mean perception threshold of 0.01 ms^{-2} r.m.s. at 1 Hz in British Standard BS 6841, BS 6472-1 and ISO 2631-1 (Curve 1 in Figure 1). Experimental studies report large variations between individuals in the ability to perceive vibration. International Standard 2631-1, BS 6841, and BS 6472-1 state that the inter-quartile range of weighted vertical acceleration for the threshold of perception may extend from about 0.007 to 0.014 ms^{-2} r.m.s. On this basis, the mean perception threshold for horizontal vibration in BS 6611 and ISO 6897 may correspond to approximately the 75th percentile threshold implied by ISO 2631-1 and BS 6472-1.

A “lower perception threshold” for horizontal motion is defined by Curve A in BS 6611 and ISO 6897. The limits of Curve A apply where there is a requirement for the building to be apparently stationary. At a frequency of 1 Hz, the acceleration magnitude of the lower perception threshold of 0.0036 ms^{-2} r.m.s. is half the magnitude of the 25th percentile threshold for perceiving horizontal motion implied by BS 6472 Part 1 and ISO 2631-1. At 1.0 Hz, the standards are therefore roughly consistent in saying that a building would be apparently stationary to most building occupants at the acceleration magnitudes given by Curve A.

The evidence to support any frequency-dependence in the perception of horizontal oscillation below 1 Hz is limited. The mean perception thresholds in BS 6611 are derived from laboratory studies with horizontal motion conducted by Chen and Robertson[7] (at 0.067, 0.1, and 0.2 Hz) and by Miwa[8] (at frequencies in the range 0.5 Hz to 100 Hz). Few other studies have investigated the perception thresholds of significant numbers of seated subjects exposed sinusoidal horizontal motion[9].

ii. Satisfactory magnitudes

British Standard 6472 Part 1 indicates ranges of vibration dose values corresponding to various probabilities of adverse comment. The standard suggests that in residential

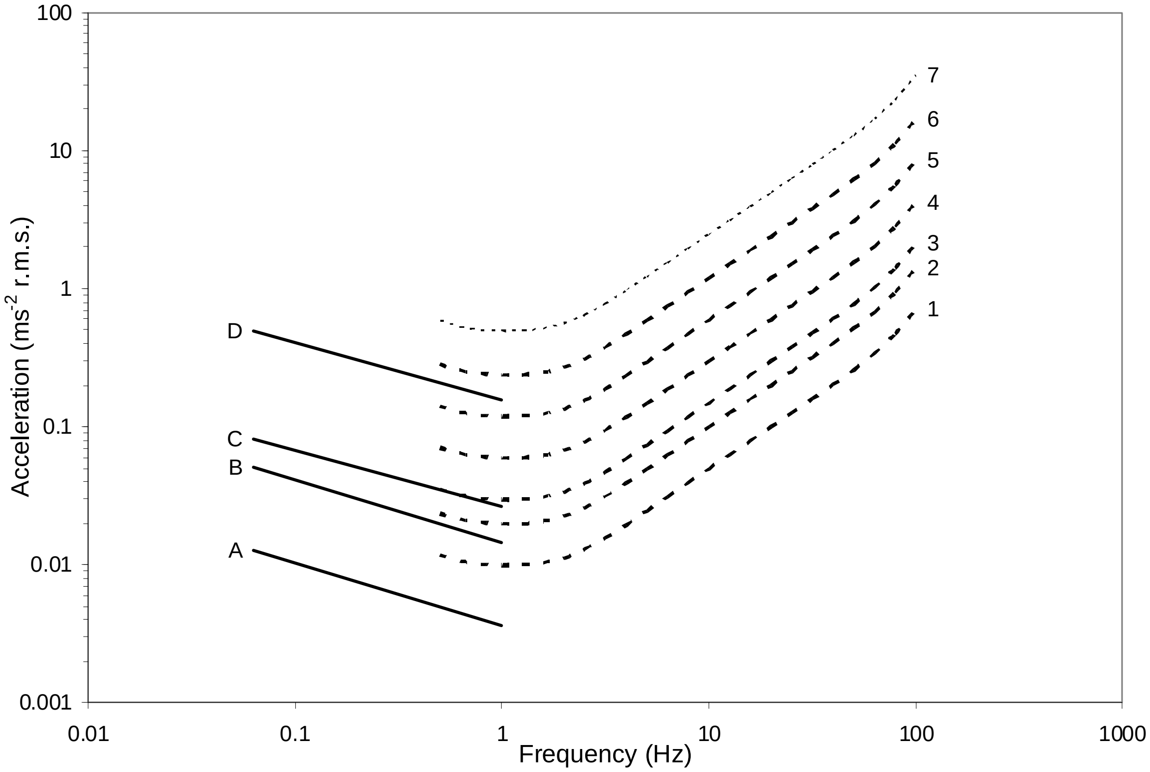

Figure 1 Limit curves for horizontal motion as given in BS 6611 and ISO 6897 (**––––**), BS 6472-1 (- - - - -) and BS 6841 (·········).

Curves A - D: BS 6611 and ISO 6897 - satisfactory magnitudes for criteria as specified in Table 1
Curve 1: BS 6472 - perception threshold
Curve 2: BS 6472 - low probability of adverse comment in residential buildings, 16-h upper limit
Curve 3: BS 6472 - low probability of adverse comment in residential buildings, 10-minute lower limit
Curve 4: BS 6472 - low probability of adverse comment in offices, 10-minute upper limit
Curve 5: BS 6472 - low probability of adverse comment in workshops, 10-minute upper limit
Curve 6: BS 6472 - low probability of adverse comment in workshops, 16-h upper limit
Curve 7: BS 6841 - limit for tasks involving hand-control

buildings there is a low probability of adverse comment for exposures in the range 0.2 to 0.4 $ms^{-1.75}$. Below this range, adverse comments are not expected. To obtain satisfactory magnitudes in offices and workshops, multiplying factors of 2 and 4, respectively, are applied to this range for residential buildings.

The time-dependency inherent in vibration dose values is represented in ‘estimated vibration dose values’, where the r.m.s. acceleration reduces in inverse proportion to the fourth power of the exposure duration. In BS 6472-1, the lower value of the range for low probability of adverse comment of 0.2 $ms^{-1.75}$ corresponds to a 1-Hz 16-h exposure to 0.01 ms^{-2} r.m.s. (i.e., the mean perception threshold given in BS 6472-1 – Curve 1 in Figure 1). A 10-minute exposure to 0.03 ms^{-2} r.m.s. at 1 Hz has the same estimated vibration dose value (Curve 3 in Figure 1).

At 1 Hz there is agreement between the lower value of the acceptable range for 10-minute exposures in residential buildings according to BS 6472-1 (Curve 3) and the limit in BS 6611 and ISO 6897 for the worst 10 minutes of motion in “buildings used for general purposes” (Curve C). According to BS 6611 and ISO 6897, at magnitudes below Curve C

Table 1 *Application of the limit curves in BS 6611 and ISO 6897 for horizontal motion events of more than 10 minutes duration (see Figure 1).*

Curve	Type of structure	Activities of occupants	Frequency of event	Criterion of limit
D	Off-shore fixed	Work of critical nature, non-routine task or skilled operation	Infrequent	Acceleration limit for the performance of specified tasks
C	Buildings	General purpose	Worst 10 minutes of infrequent events, return period at least 5 years	Adverse comment level of 2%
B	Buildings	Special purposes, routine precision work	Frequent events, everyday occurrence	Mean threshold of perception
A	Buildings	Special purposes, requirement for apparently stationary environment	Frequent events, everyday occurrence	0.25 x threshold of perception

not more than 2% of occupants comment adversely about the motion caused by the worst 10 minutes of a wind storm with a return period of five years or more.

There is scope for differing interpretations of the meaning of “buildings used for general purposes”. For 10-minute exposures, BS 6472-1 states that there is a low probability of adverse comment in residential buildings at magnitudes up to twice those of Curve C (i.e. Curve 4), and up to four times Curve C in offices (Curve 5), and up to eight times Curve C in workshops (Curve 6). Since BS 6611 and ISO 6897 say the guidance is applicable to people living and working in buildings, the “general purpose” building category of Curve C in BS 6611 and ISO 6897 may be interpreted as encompassing buildings used for residential, office, and workshop purposes. Compared with BS 6472-1, the limits in BS 6611 and ISO 6897 might be considered unduly restrictive for, at least, offices and workshops.

iii. Activity disturbance

BS 6611 and ISO 6897 define a motion limit (Curve D) for off-shore fixed structures exposed to infrequent wind-induced events. It is stated that this is to be applied where “work of a somewhat critical nature has to be performed”. For buildings used for “special purpose” that are subjected to frequent events, the limit defined by Curve B is applicable “where routine precision work in carried out”. At a frequency of 1 Hz, the performance limits of Curves B and D are, respectively, about one-thirtieth and one-third of the acceleration limit suggested in BS 6841 where hand or finger control to an accuracy of within 5 mm r.m.s. is required (Curve 7). The apparent discrepancy might be accounted for by the interpretation of the wording describing tasks relating to Curves B and D. The imprecise descriptions make it difficult to identify the types of task to which the guidance in BS 6611 and ISO 6897 applies. However, it seems unlikely that limits more restrictive than those of BS 6841 for fine hand control are necessary for any task.

The advice in BS 6611 and ISO 6897 suggests that task impairment during horizontal acceleration over the frequency range 0.063 to 1.0 Hz increases with increasing frequency. Experimental studies suggest that the frequency-dependence of impairment varies with small differences in tasks. Griffin and Hayward[10] investigated the effects of horizontal whole-body vibration on reading. Text was read from a hand-held clip-board by seated subjects during exposure to fore-and-aft and lateral narrow-band random whole-body vibration at frequencies between 0.5 Hz and 10 Hz. Horizontal vibration caused a significant reduction in reading speed over a small frequency range between 2.5 Hz and 5 Hz. Griffin and Hayward concluded that with hand-held text the slowest reading speed was at frequencies around 4 Hz because of the dynamic response of the shoulders and arms at this frequency. The frequency-dependence differs from that reported by Lewis and Griffin[11] for subjects experiencing fore-and-aft motion while reading text from a stationary display, where most reading errors occurred at 6 Hz. A study of the interference of a drinking task showed that the magnitude of seat vibration required for subjects to spill liquid from a hand-held cup was lowest at 4 Hz in each of the three translational and three rotational axes of motion[12]. Spillage was most likely at 4 Hz due to the high transmission of vibration to the hand at this frequency. The frequency-dependence of the effects of horizontal vibration on reading and drinking in the above studies differs from the advice in BS 6841 for hand control tasks where it is suggested that tasks are most impaired at frequencies between 1 Hz and 2 Hz. A comparison of the findings from studies of activity interference caused by whole-body vibration, including visual and hand tasks, concluded that the range of possible effects on performance is such that a single limit is not appropriate[13]. It was suggested that experimentally determined weightings may be appropriate for some specific tasks, but approximations based on generic tasks may be sufficient for general guidance. Guidance on the effects of low-frequency motion on well-defined categories of tasks (including those involving balance and manual control) would probably be more useful than the current advice in BS 6611 and ISO 6897 that does not state the types of tasks to which the limits apply.

4. CONCLUSIONS

The mean threshold for the perception of horizontal motion at a frequency of 1 Hz given in BS 6611 and ISO 6897 is somewhat higher than the thresholds in ISO 2631-1 and BS 6472-1. It would seem appropriate to harmonise the guidance on thresholds of perception so that it is consistent between the standards.

The method of evaluating oscillatory motion given in BS 6611 is not consistent with other current standards that define frequency weightings and band limiting filters. Compared with BS 6472-1, the guidance for acceptable magnitudes of motion in BS 6611 might be considered unduly restrictive for people working in buildings. Improved definitions are needed for the categories of buildings and tasks. Further research is needed to define appropriate frequency weightings and band-limits for horizontal motion at frequencies less than 1 Hz, and to establish guidance for well-defined categories of relevant tasks.

The method of evaluating the severity of motion in BS 6611 does not allow for the effects of exposure duration. An evaluation procedure that accumulates motion over a day (to allow for the effects of the total motion exposure) but that also identifies the worst periods of motion would appear preferable to the use of r.m.s. averaging as recommended in the present standard.

REFERENCES

1. British Standards Institution, Guide to Evaluation of the response of occupants of fixed structures, especially buildings and offshore structures, to low-frequency horizontal motion (0.063 Hz to 1 Hz), BS 6611, British Standards Institution, London 1985.
2. International Organization for Standardization, Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and offshore structures, to low-frequency horizontal motion (0.063 Hz to 1 Hz), ISO 6897, International Organization for Standardization, Geneva 1984.
3. British Standards Institution, Guide to evaluation of human exposure to vibration in buildings Part 1: Vibration sources other than blasting, BS 6472-1, British Standards Institution, London 2008.
4. British Standards Institution, Guide to Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock, BS 6841, British Standards Institution, London 1987.
5. International Organization for Standardization, Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General requirements, ISO 2631-1, International Organization for Standardization, Geneva 1997.
6. International Organization for Standardization, Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 2: Vibration in buildings (1 Hz to 80 Hz), ISO 2631-2, International Organization for Standardization, Geneva 2003.
7. P.W. Chen, and L.E. Robertson, Human perception thresholds of horizontal motion, *Journal of the Structural Division. Proceedings of the American Society of Civil Engineers* **98,** pp.1681-1695, (1972).
8. T. Miwa, Evaluation methods for vibration effect, part 1: measurements of threshold and equal sensation contours of whole body for vertical and horizontal vibrations, *Industrial Health* **2,** pp.183-205, (1967).
9. A.J. Gundry, Thresholds of perception for periodic linear motion, *Aviation, Space, and Environmental Medicine* **49**, pp.679-686, (1978).
10. M.J. Griffin and R.A. Hayward, Effects of horizontal whole-body vibration on reading, *Applied Ergonomics* **25**(3), pp165-170, (1994).
11. C.H. Lewis and M.J. Griffin, Predicting the effects of vibration frequency and axis, and seating conditions on the reading of numeric displays, *Ergonomics* **23**, pp.485-501, (1980).
12. E.M. Whitham and M.J. Griffin, "Interference with drinking due to whole-body vibration" in *Proceedings of the United Kingdom Informal Group on Human Response to Vibration Meeting 1978,* National Institute of Agricultural Engineering, Silsoe, UK*,* 18 - 20 September 1978.
13. M.J. Griffin, Handbook of Human Vibration, Academic Press, London 1990.