Vibration Perception and Comfort Levels for an Audience Occupying a Grandstand with Perceivable Motion

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Abstract

This paper reports a controlled laboratory investigation on the evolution of human vibration-perception and comfort states as a result of a change in the vibration levels of an occupied grandstand structure. Our structural dynamics laboratory is equipped with a fully instrumented real-life grandstand whose motion could be controlled to simulate a vibrating structure. Students were recruited to participate as a seated and a standing audience and to provide feedback on the state of their comfort and vibration perception during exposure to different vibration levels. After applying frequency weighting filters specified in different standards to each vibration level, charts are presented to describe vibration perception and comfort levels of the audience given a prescribed movement of the structure. The charts indicate that the perception variable takes on its extreme state sooner than the comfort variable, confirming that vibrations are felt long before they are generally deemed uncomfortable. This makes the assessment of human perception of vibrations to be of primary importance in establishing safety criteria. Finally, the results were compared with recommendations of several international standards and design guidelines in the same area of research. The results of the comparison showed serviceability data obtained from our grandstand study to be lying significantly below the recommended limits for transportation structures (BS6841) but significantly above the recommended limits for most classes of buildings (BS6472). This implies a serviceability limit state for grandstand-design lying somewhere between the recommended limits of the two standards. These results are an important contribution to the establishment of serviceability requirements for grandstand structures.

Introduction

Experimental data related to levels of perception and comfort during exposure to whole body vibration finds many applications such as among other things, the assessment of ride quality and incidents of motion sickness in the automotive industry [9]. Data collected over the years for defining limits of vibration exposure to ordinary humans, workers handling vibrating machinery, and human subjects participating in experiments involving exposure to vibration have also resulted in a set of vibration criteria specified in ISO 2631, ISO 8041, BS 6472, BS 6841, BS 7085 and other relevant standards [2, 3, 4, 12, 13]. In structural engineering, the awareness of the importance of such data has come about because of the realization and world wide evidence that modern slender structures can undergo perceivable motion due to crowd induced vibrations, leading to human discomfort or crowd panic [5, 7, 11].

It has been pointed out many times that modern grandstand structures are especially vulnerable to excessive crowd-induced vibration due to their low natural frequencies [11, 14]. However, apart from a few case studies [7], there is currently little research data on which to base serviceability requirements for the design of grandstands [1, 14, 15]. The few available case studies only focus on real-life accidental accounts of crowd behavior following exposure to extreme vibrations [7]. While these accounts have been significantly instrumental in shaping our awareness of the potential danger of excessive crowd induced vibrations in slender structures, they currently lack the experimental rigour necessary to form a definitive design guideline. For instance, in the majority of the case studies the reaction of the crowd following exposure to uncomfortable vibration levels may be reported, but the characteristics of the vibration levels are often unknown or are crudely estimated from the reaction of the crowd [7].

A series of threshold values for human perception of vibrations in grandstands have also been suggested by Kasperski [14] based on tests carried out on a permanent grandstand in 1996. In defining these limits, Kasperski used peak accelerations as a measure of vibration exposure, concluding that vibrations become disturbing at 5%g (g = 9.81 m/s^2), unacceptable at 18%g and are likely to induce panic at values exceeding 35%g. The National Building Code of Canada [6] and Browning *et al.* [1] also used an evaluation approach based on peak accelerations. However an evaluation approach based on peak accelerations is not a universal measure of vibration exposure because it does not take into account the duration of exposure. In 2004, Ellis and Littler [8] promoted the use of vibration dose values (VDV) as a way of assessing vibrations in grandstands. The VDV measure incorporates a time variable and a root mean square (RMS) value of the acceleration. This approach is consistent with many international standards (ISO 2631, ISO 8041, BS 6841, BS 7085), which define and adopt the VDV or RMS value of the acceleration as a measure of vibration exposure.

The aim of this paper is to report a controlled laboratory investigation on the evolution of human vibration-perception and comfort states as a result of a change in the vibration levels of an occupied grandstand structure. In order to maintain consistency with many international standards, a vibration evaluation approach based on the use of the VDV or acceleration RMS value, has been used throughout the paper. Our structural dynamics laboratory is equipped with a fully instrumented real-life grandstand whose motion can be controlled to simulate a vibrating structure. Student were recruited to participate as a seated and a standing audience and to provide feedback on the state of their comfort and vibration-perception during exposure to different vibration levels. After applying frequency weighting filters specified in different standards to each vibration level, charts are presented to describe vibration-perception and comfort levels of the audience given a prescribed movement of the structure. Finally, the results are compared with recommendations of several international standards and design guidelines in the same area of research and conclusions are drawn from the comparison. The results presented here are an important contribution to the establishment of serviceability requirements for grandstand structures. The following section discusses a particular research approach (used as a basis for this investigation) on evaluation of human vibration-perception and comfort and the reasons for adopting this approach.

Evaluation of Human Vibration-perception and Comfort

There are several reasons why evaluation of human response to vibration may be desirable, namely (a) to understand human subjective impressions of the characteristics of vibration; (b) to determine the relationship between the subjective perception of some aspect of the vibration and its physical or quantitative characteristics; and (c) to establish target values for design of vibration environments in terms of human sensation of vibration characteristics [9, 10]. This paper is concerned with the latter. In order to understand the relationship between a physical measure of the mechanical vibration and their subjective correlates, or percepts, two types of psychophysical experimental methods have been used, namely constant measurement and subjective scaling methods [10]. While the use of a particular method may be a simple matter of choice, the aim of the investigation will also influence the choice of the method. Constant measurement methods are suitable in the case of (a) or (b), while subjective scaling methods could be used for (b) or (c). A brief overview of these methods is provided by Guilford [10].

Category judgment is a type of subjective scaling method which is widely used when the aim of evaluating human response to vibration is to obtain target values for use in the design of vibration environments. Consistent with the aim of this research, this method was chosen as an appropriate and preferred method for the work discussed in this paper. The method requires subjects to select their subjective perception and or state of comfort during exposure to vibration from a range of text descriptors written in natural language [3, 9, 10]. The general principles of this method are illustrated in the flow chart shown in Figure 1. In our study, the vibration source is a sinusoidal-driven grandstand. Two categories of subjective responses or output were requested from the participants, namely the degree or state of vibration perception and state of comfort. Figure 1 shows the range of text descriptors considered as well as the exact language used. The phrase words were slightly modified from [3] so that they could be clearly understood by all our participants, which were drawn from a very diverse student body in the department.

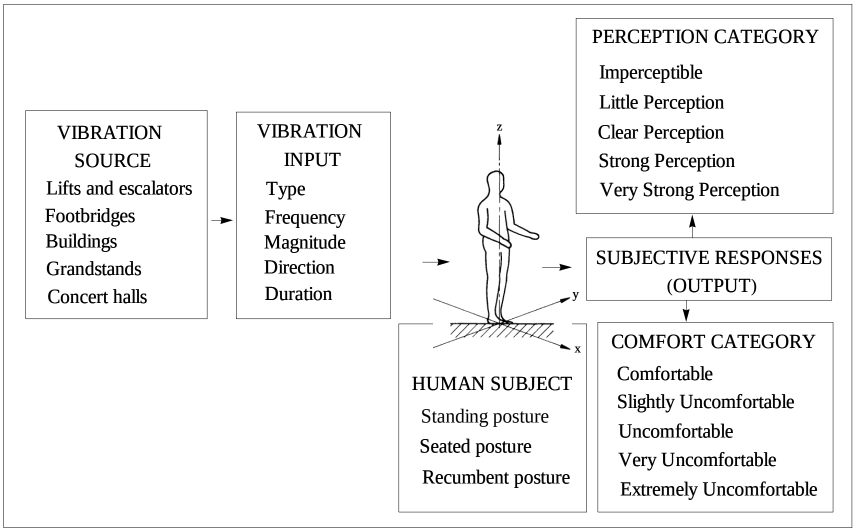

Figure 1 Illustration of category judgment method

Description of Test Structure, Participants and Methodology

Our structural dynamics laboratory is equipped with a fully-instrumented prototype grandstand rig which is described in detail in one or more publications [6]. This is an aluminium raked grandstand with 15 seats to accommodate a maximum audience of 15 occupants (refer to Figure 2). The grandstand is capable of undergoing motion of a real-life structure. Simulation of structural motion of a real-life grandstand is achieved by 4 linear electro-magnetic actuators that support the rig's deck and control its vertical motion. In addition, displacement transducers record and monitor the deck's movement (vibration dose) to which occupants are subjected, while flagging dangerous vibration levels which are beyond the scope of our research. In the latter case the instrumentation allows for automatic shut down of a test, allowing the test structure to come immediately to rest, thus ensuring the safety of the occupants.

Figure 2: Picture of the test structure

Post graduate students were recruited to participate as a seated and a standing spectator audience. The age of the recruited audience typically lies between mid twenties and late twenties. The availability of postgraduate students allowed us to have the same individuals and roughly the same number of participants for all test sessions. Following exposure to a minute long vibration level, the participants are prompted to provide feedback on the state of their comfort and vibration perception during the exposure period using the category judgment approach explained in the previous section.

In our study, a typical test session is at most 90 minutes and comprises several tests of over a minute each. In a typical test the grandstand rig (occupied by seated or standing participants) is subjected to a minute-long sinusoidal vertical vibration of specified or intended frequency and amplitude. The intended vibration motion can be completely described by a single acceleration RMS value referred to here as the *target acceleration RMS value*. Due to feedback forces from the participants and slight imperfections in the actuator control and driving mechanism, the actual motion of the grandstand is not perfectly the same as the user specified or intended motion. However, displacement transducers record the actual motion of the grandstand rig. This data is stored as non-volatile memory and later used to assess the actual vibration dose to which the participants were subjected. Again a single acceleration RMS value referred to here as the *measured acceleration RMS value* is used to describe the actual motion of the grandstand during a test. At the end of each test the participants are given a little time to rest before the next test begins. At the same time they provide feedback on the state of their comfort and vibration perception during the vibration exposure period by filling in a response sheet handed out to each individual participant. This card contained the exact subjective response information or text described earlier and shown in Figure 1.

Figure 3 shows the mean vertical motion of the grandstand deck recorded during one particular test. Table 1 and Table 2 lists all the tests conducted for the work discussed in this paper. A complete description of grandstand motion during each test is indicated by an acceleration RMS value. Note the slight differences between the intended or targeted motion of the structure and the actual motion. This is indicated by the slight differences between target and measured acceleration RMS values.

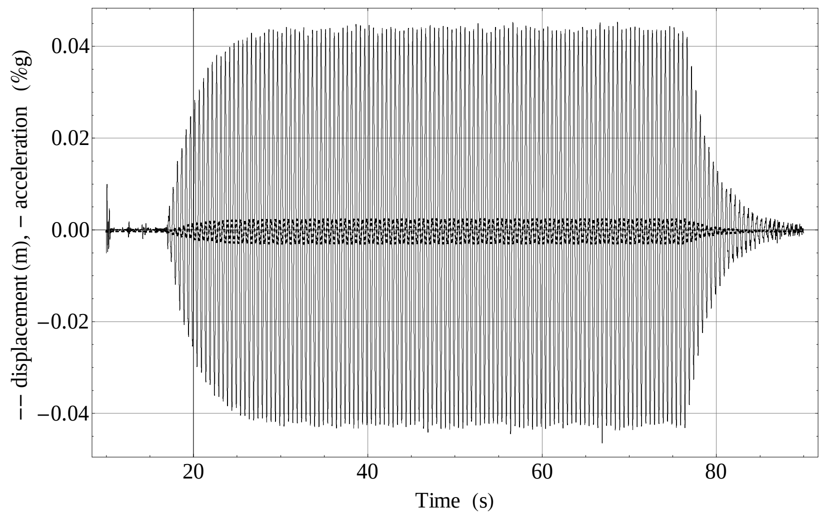

Figure 3 Graph showing typical vertical motion of the rig deck, acceleration (solid line), and displacement (dashed line)

Table 1 Range of Grandstand Vibration Motion Considered for the Sitting Tests

Test Description	*Frequency* (Hz)	*Vertical Displacement* (mm)	*Target acceleration R.M.S Values* (%g)	*Measured acceleration R.M.S Values* (%g)
2Hz/1mm		1	1.138	1.001
2Hz/1.5mm		1.5	1.707	1.516
2Hz/2mm		2	2.276	2.032
2Hz/2.5mm	2	2.5	2.846	2.552
2Hz/3mm		3	3.415	3.055
2Hz/4mm		4	4.553	4.102
2Hz/5mm		5	5.691	5.026
3.3Hz/0.5mm		0.5	1.581	1.52
3.3Hz/0.5mm		0.5	1.581	1.632
3.3Hz/0.75mm	3.3	0.75	2.371	2.49
3.3Hz/1mm		1	3.161	3.294
3.3Hz/2mm		2	6.322	6.579
4Hz/0.15mm		0.15	0.683	0.776
4Hz/0.15mm		0.15	0.683	0.781
4Hz/0.15mm		0.15	0.683	0.744
4Hz/0.25mm		0.25	1.138	1.278
4Hz/0.5mm	4	0.5	2.276	2.51
4Hz/1mm		1	4.553	4.621
4Hz/1.5mm		1.5	6.829	6.838
4Hz/1.5mm		1.5	6.829	6.871
4Hz/2.5mm		2.5	11.382	10.802
6Hz/0.15mm		0.1	1.024	0.978
6Hz/0.25mm		0.25	2.561	2.536
6Hz/0.5mm	6	0.5	5.122	5.244
6Hz/0.5mm		0.5	5.122	5.444
6Hz/0.75mm		0.75	7.683	8.449
6Hz/1mm		1	10.244	10.911

Table 2 Range of Grandstand Vibration Motion Considered for the Standing Tests

Test Description	*Frequency* (Hz)	*Vertical Displacement* (mm)	*Target acceleration R.M.S Values* (%g)	*Measured acceleration R.M.S Values* (%g)
2Hz/1.5mm		1.5	1.707	1.571
2Hz/3.5mm	2	3.5	3.984	3.616
2.67Hz/1.5mm		1.5	3.036	2.784
2.67Hz/3.5mm	2.67	3.5	7.084	6.506
3.3Hz/1mm		1	3.161	2.971
3.3Hz/1.5mm	3.33	1.5	4.742	4.472
3.3Hz/2mm		2	6.222	5.879
4Hz/0.5mm		0.5	2.276	2.205
4Hz/1.5mm	4	1.5	6.829	6.643
4Hz/1.5mm		1.5	6.829	6.722
4Hz/2.5mm		2.5	11.382	11.294
6Hz/1mm	6	1	10.244	13.983

Test Results and Analysis

(a) Sitting Tests

Figures 4 and 5 show data relating to levels of vibration-perception and comfort obtained from all sitting tests. For each vibration motion (acceleration RMS) the participants were subjected to, Figures 4 and 5 show the break down of responses obtained from the participants as a percentage of the total number of participants. Note that because some tests had acceleration RMS values very close to each other (refer to Table 1) some lines plotted on top of each other. Nevertheless it is clear from both figures that the responses from the participants are dependent on the measured acceleration RMS value.

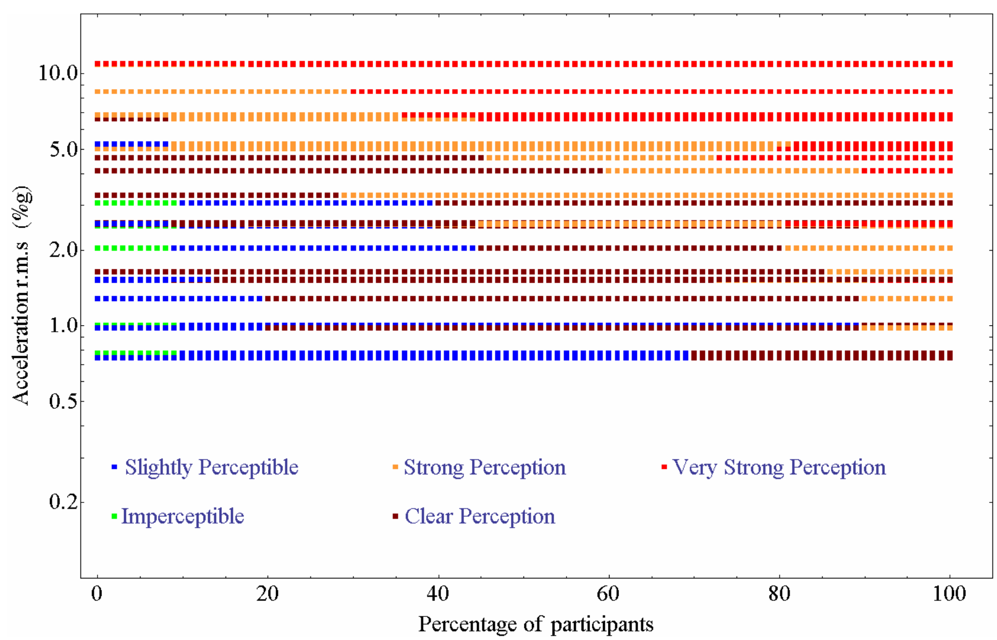

Figure 4 Sitting perception data

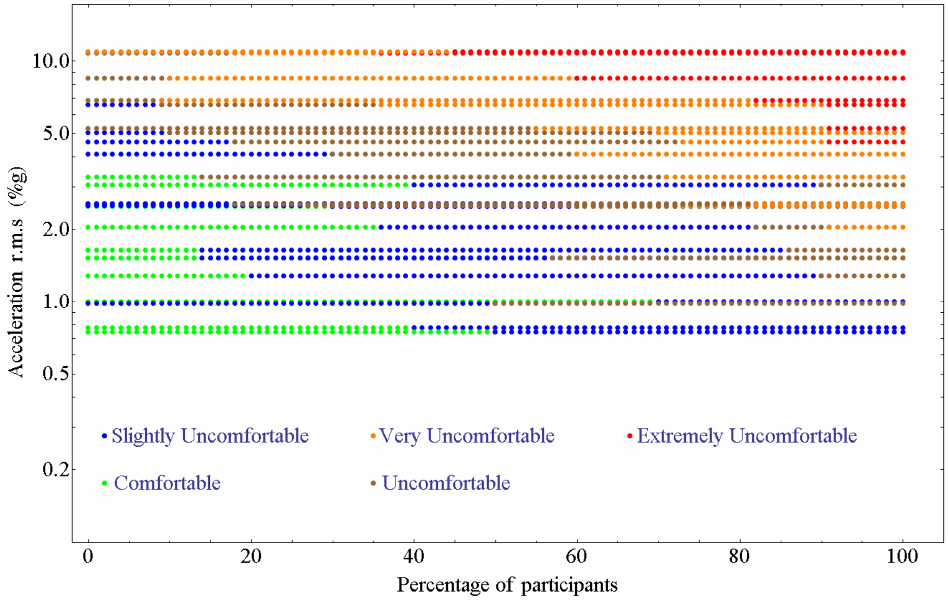

Figure 5 Sitting comfort data

Since human response to vibration is a function of the frequency of vibration, it is customary to "weight" measured data to give greater prominence to frequencies where humans are most sensitive [9, 17]. In this research it was decided to "weight" the data of figures 4 and 5 using frequency weighting filters specified in three different standards that are relevant to whole body vibration and building vibration. The weighting filters and the standards from which the filters were drawn are shown in Figure 6. Detailed numerical description of the filters can be found in the relevant standards. Derivation and guidance on the use of some of the filters can be found in the work of other investigators [17].

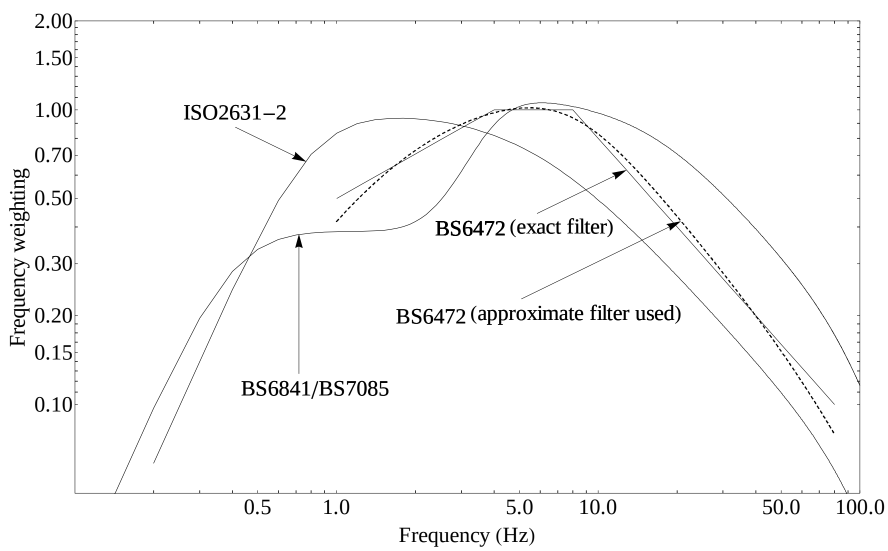

Figure 6 Frequency weighting filters relevant to whole body and building vibration

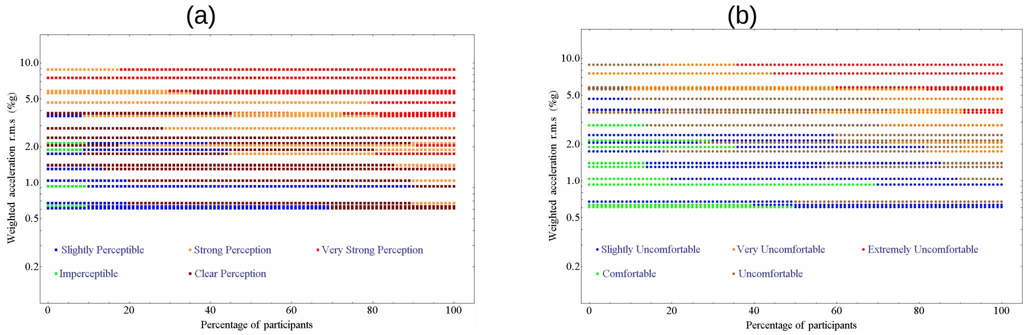

Figure 7 Sitting data after applying weighting filters of ISO 2631-2: (a) perception data, (b) comfort data

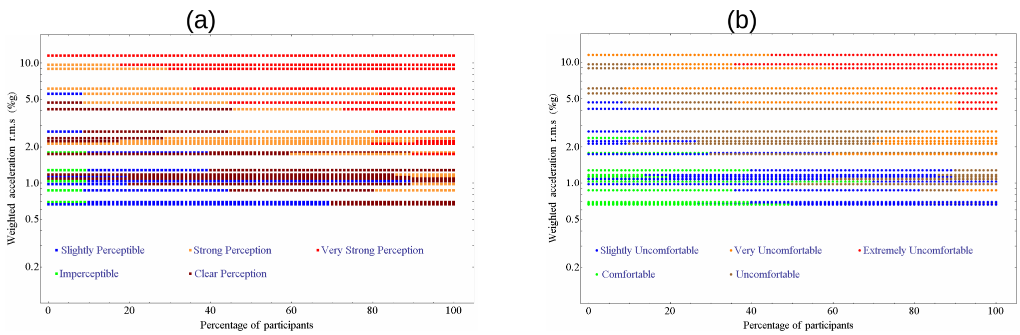

Figure 8 Sitting data after applying weighting filters of BS 6841/BS7085: (a) perception data, (b) comfort data

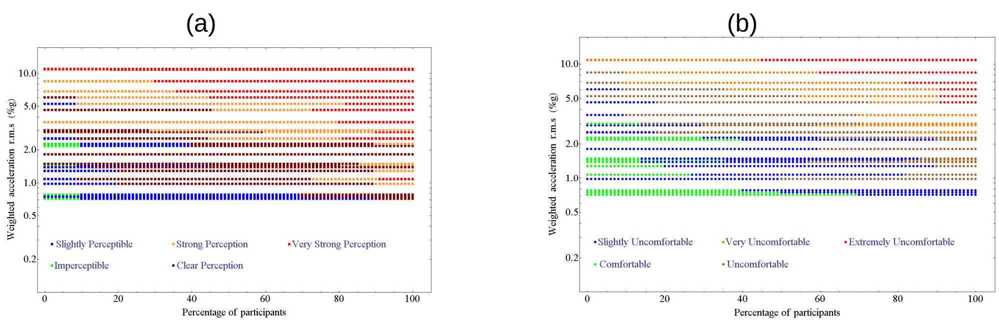

Figure 9 Sitting data after applying weighting filters of BS 6472: (a) perception data, (b) comfort data

Figures 8 to 10 show the effects of applying different frequency weighting filters (shown in Figure 6) to the perception and comfort data of Figures 4 and 5. When comparing perception and comfort states, all graphs (Figures 7-9) show that the perception variable takes on its extreme state sooner than the comfort variable, confirming that vibrations are noticed (felt) long before they are generally deemed uncomfortable [11]. This makes the assessment of human perception of vibrations to be of primary importance in establishing safety criteria.

For the frequencies of structural motion investigated (2-6Hz), there are significant differences in the weighting mechanisms of the filters used. At vibration frequencies of motion around 2Hz, the filter of BS6841 suppresses vibration amplitudes more than all the filters used. The filter of BS6472 does a moderate suppression, while the filter of ISO2631-2 does little or no suppression. By suppressing vibration amplitudes at frequencies around 2 Hz, the filters of

BS6841 and BS6472 take into account human tolerance of vibrations around the 2Hz frequency. On the other hand the filter of ISO2631-2 assumes greater sensitivity to vibration motion around 2Hz by allowing little or no suppression of vibration amplitudes. This approach seems more sympathetic to low frequency structures because they are prone to excitation by humans. Because it does not take into account human tolerance of motion around 2Hz, the filter of ISO2631-2 adopts a more conservative approach that is likely to lead to uneconomical or expensive structural designs. At frequencies of structural motion around 6Hz, the performance of BS6841 and BS6472 filters is nearly the same (allowing no suppression), while the ISO2631-2 filter attenuates vibration amplitudes significantly.

(b) Standing Tests

A similar procedure was followed for the standing tests, trends similar to the sitting tests were found, but the results are not included here for reasons of space. The results from the standing tests are also discussed in detail in the accompanying research paper [16].

Comparison of Results with Relevant Standards

In Figure 10, the sitting and standing comfort data is shown along side and compared with the limits recommended in BS6841. While this standard contains provisions for dealing with vibrations encountered in transportation structures and industrial activities, the comparison is still meaningful for benchmarking our results. The standard specifies frequency weighted acceleration limits (in term of RMS values) at which vibrations becomes uncomfortable, very uncomfortable, etc. These limits are indicated by solid lines in the figure. The sitting and the standing data obtained in our grandstand study is indicated by the markers shown. The markers show only the comfort state reported by the majority of the subjects when subjected to a particular vibration level. In line with the provisions of BS6841 the data from both types of tests is plotted here after frequency-weighting the vibration level using the appropriate filter in the standard. Data from both types of tests appear significantly below the specified limits. For a standard whose guidance is directed at vibrations encountered in transportation structures this is not surprising since humans naturally show greater tolerance of vibrations when commuting. Comparison of the standing and the sitting data (Figure 10), reveals that the subjects showed more tolerance to vibrations when standing than when seated. This means that the design criteria for public facilities where occupants are expected to be standing only should be different to those facilities where sitting only is expected.

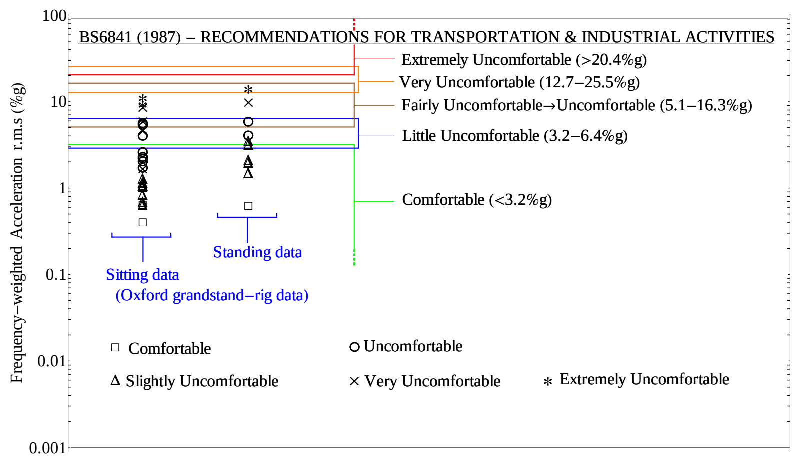

Figure 10 Comparison of sitting and standing comfort data with recommendations of BS6841

Figure 11, compares the sitting comfort data (plotted using different markers) with the unweighted acceleration limits (shown in solid lines) recommended in BS6472. The acceleration limits recommended in this standard relate to vibration serviceability limit state for different classes of buildings as shown in Figure 11. However the standard makes no provisions for grandstand structures. The sitting comfort data from our grandstand study has been superimposed on the provisions of this standard for comparison. The markers in Figure 11 show only the comfort state reported by the majority of the subjects when subjected to a particular vibration level (unweighted acceleration RMS). In the figure, if the location of the "slightly uncomfortable" state of comfort (as obtained from our study) is used to define the serviceability limit state for grandstand structures, then the current study suggest the design curve shown in a broken line as a basis for grandstand design.

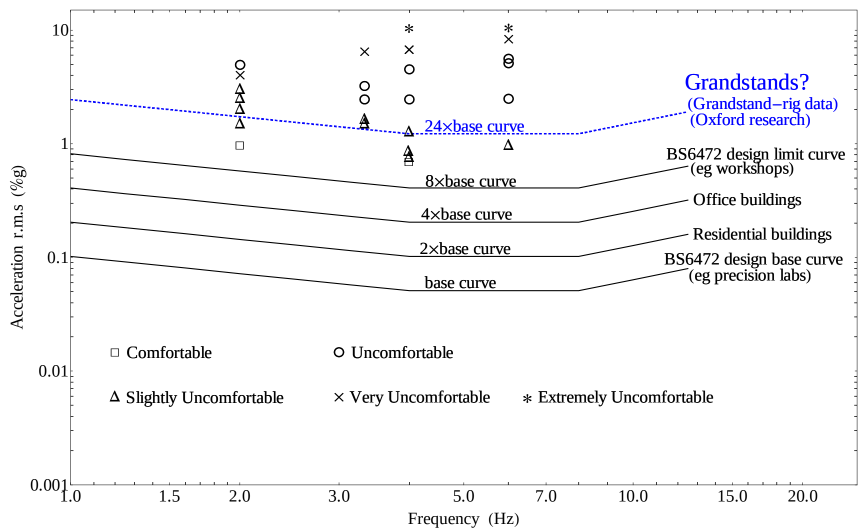

Figure 11 Comparison of sitting comfort data with design guidelines of BS6472

Finally, when comparing Figures 10 and 11, the grandstand data from our study, lies significantly below the recommended limits for transportation structures (BS6841) but significantly above the recommended limits for most classes of buildings (BS6472). This seems to suggest that the serviceability limit state for grandstand design lies somewhere between the recommended limits of the two standards.

Conclusions

This paper has used a controlled laboratory study to investigate changes in the levels of human vibration perception and comfort as a result of a change in the vibration levels of an occupied grandstand whose motion could be controlled to simulate a vibrating structure. The results are an important contribution to the establishment of serviceability requirements for grandstand structures. Charts were presented to describe vibration perception and comfort levels of human subjects given a prescribed movement of the structure. The charts indicated that the perception variable takes on its extreme state sooner than the comfort variable, confirming that vibrations are noticed (felt) long before they are generally deemed uncomfortable. This makes the assessment of human perception of vibrations to be of primary importance in establishing safety criteria. Finally, it was shown that the serviceability data from our grandstand study lie significantly below the recommended limits for transportation structures (BS6841) but significantly above the recommended limits for most classes of buildings (BS6472). This seemed to suggest that the serviceability limit state for grandstand design lies somewhere between the recommended limits of the two standards.

Acknowledgements

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