An investigation of human comfort criteria for footfall induced floor vibrations

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Abstract. Human comfort is becoming a vital serviceability requirement when it comes to design of long-span floor systems, as evidenced by the development of international standards on human exposure to vibrations. This paper discusses experimental findings derived from dynamic testing of a real office floor of steel-concrete composite construction where annoying footfall-induced vibration had been reported by the floor tenants. The fundamental frequency of the problematic floor was determined using measurements obtained from a series of simple heel drop tests. The observed vibration levels of the floor under normal walking excitations was then benchmarked against acceptance criteria suggested by a number of widely used floor vibration design guides. From a human comfort perspective, it is found that the same floor can be classified as unacceptable by some guidelines but deemed extremely acceptable by the others. As response levels are translated inconsistently by various acceptance criteria, designers would hence be placed in a dilemma when deciding whether the existing floor really needs modification to enhance its serviceability.

1. Introduction

Long-span lightweight floor systems have increasingly been utilized for construction of offices and commercial retail buildings that require larger column-free spaces. Moreover, a reduction in both floor mass and damping could result from changes in modern electronic office layouts relating to the removal of full height partitions, large bookshelves, heavy filing cabinets and other architectural elements. Modern floor constructions would hence be more vibration-vulnerable regardless of their ultimate strength capacity being assured by higher strength materials. Floor systems can be subjected to dynamic forces generated by various human activities such as walking, running and dancing. Resonant vibrations can arise in low frequency floors when natural frequencies of the floors closely match the excitation frequency or its harmonics [1].

Human response to floor motion is not easy to predict because of its involvement in many psychological and physiological factors. The characteristics of the excitation source, the environment surrounding the person, and the person himself all contribute to human tolerance to floor vibrations. Visual and acoustic cues caused by floor vibrations would also worsen human comfort [2]. Figure 1 depicts a lumped mass model that represents the human body as a mechanical system, revealing that frequencies below 10 Hz seem to be most critical when matching the resonant frequencies of main internal body organs. As a result, human comfort criteria usually set the most stringent vibration limits...
for the 4–8 Hz frequency range whilst higher vibration levels can be tolerated for frequencies outside this range. Response to less sensitive frequencies can be taken into account by frequency weighting values such as those introduced in BS 6841 [4] and ISO 2631 [5]. The perception of vibration also depends on the direction of motion to the human body posture defined by the basicentric co-ordinate system of figure 2. Offices may primarily be designed for vertical vibrations whilst the vibrations in residences and hotels should be checked for all three directions in order to assure human sleeping comfort. Numerous efforts have been made to identify factors affecting human response to vibrations, as evidenced by the development of international standards on human exposure to vibrations [4-10]. It should be noted that the acceptance criteria discussed here are derived from a human comfort perspective rather than structural strength or integrity.

This paper discusses the results of vibration testing performed on an actual office floor which was reported to have annoying walking-induced vibration. The measured vibration levels were checked against various commonly used human comfort criteria to investigate the extent of consistency among these criteria when assessing the same floor.

2. Methods

2.1. Acceptance criteria for floor vibrations
Current guidelines normally quantify vibration levels in relation to peak acceleration, root-mean-square (RMS) acceleration or velocity whose acceptable limits are adjusted from and multiple of the baseline curve of figure 3 recommended by ISO 10137 [6]. This section outlines the acceptance criteria against which the experimental results obtained from testing the case study floor are benchmarked.

The design guide AISC DG11 [8], which is widely used in North American and other countries including Australia, suggests peak acceleration limits for human comfort as shown in figure 4. The acceleration thresholds, expressed as a fraction of the acceleration of gravity g, relate to various human activities in different environments. For instance, a peak tolerable acceleration of 0.5% g (i.e. 0.05 m/s²) is typically used for offices with frequency ranging from 4 to 8 Hz whilst the limit for shopping malls is three times higher.
The use of RMS acceleration would enable evaluation of vibration levels not to be influenced by one unrepresentative peak in the response time history. The limits of RMS acceleration for human comfort can be expressed in terms of multiplying factors of the ISO 10137 baseline curve. The “base” RMS acceleration for the 4-8-Hz frequency range is 0.005m/s² (i.e. 0.05% g) as shown in figure 3. In the United Kingdom, the popular design guide SCI P354 suggests baseline multiplying factors of 8 and 4 be used for design of offices and shopping malls respectively [9]. Therefore the RMS acceleration limit for 4-8-Hz office floors as per the SCI P354 would be about 0.4% g (= 8 × 0.005 m/s²). Several countries including Denmark use the vibration threshold recommended by the ISO 10137 as briefly reproduced in table 1. Adopting this table for general office floors would result in an allowable multiplying factor of 4 or RMS acceleration of 0.2% g, i.e. half of the values suggested by the SCI P354.

A number of guidelines resulted from extensive European research projects on human-induced floor vibrations suggest using a design value termed one-step root-mean-square velocity as the benchmark for assessment of floor acceptability. This value covers the RMS velocity response of a floor to a step of people walking normally on the floor. Table 2 shows classification of floors in which each class corresponds to a range of velocity response specified by the lower and upper limits. Furthermore, the shaded cells in table 2 provides guidance for the application of classes suitable for floor usage [10,11]. According to the European research documents, briefly named the EUR DG in this paper, classes A, B, C and D are recommended for general office floors whilst only class A is suggested for critical workplaces such as hospital operating theatres or precision laboratories.

![Figure 3. ISO 10137 Base curve for acceleration, foot-to-head vibration direction [6].](image)

![Figure 4. AISC DG11 peak acceleration limit [8].](image)

| Place                  | Time               | Multiplying factors |
|------------------------|--------------------|---------------------|
| Critical working areas | Day, Night         | 1                   |
| Residential            | Day                | 2 to 4              |
|                        | Night              | 1.4                 |
| Quite office, open plan| Day, Night         | 2                   |
| General office         | Day, Night         | 4                   |
| Workshops              | Day, Night         | 8                   |

Table 1. ISO 10137 Multiplying factors for continuous and intermittent vibration [6].
Table 2. Classification of floor response based on RMS velocity [10,11].

| Class | Lower limit (mm/s) | Upper limit (mm/s) | Critical workplace | Health, Education | Residential, Office | Industrial, Sport |
|-------|--------------------|--------------------|-------------------|------------------|-------------------|-------------------|
| A     | 0                  | 0.1                |                   | Health, Education |                   |                   |
| B     | 0.1                | 0.2                |                   | Health, Education |                   |                   |
| C     | 0.2                | 0.8                |                   | Health, Education |                   |                   |
| D     | 0.8                | 3.2                |                   | Residential, Office |                 |                   |
| E     | 3.2                | 12.8               |                   | Residential, Office |                 | Industrial, Sport |
| F     | 12.8               | 51.2               |                   | Residential, Office |                 | Industrial, Sport |

2.2. Description of case study floor and experimental setup

Troubling vibrations due to normal footfall were reported from the occupants of an office floor of a multi-storey building located in Melbourne, Australia. The floor was of composite construction consisting of a 120 mm concrete slab supported on secondary steel beams which were in turn carried by primary steel beams spanning between columns or concrete walls. A plan view of the floor framing is shown in figure 5 with the most annoying floor bay having two long corridors perpendicular to each other as indicated by the arrows. For the investigated floor bay, the available paths for continuous walking were quite long with the span lengths being about 13 m and 9 m for secondary and primary beams respectively. The distance from the intersection of these corridors to the closest work station was just about 1 m, which was too short to alleviate the vibration effects.

![Figure 5. Plan view of floor framing details.](image)

Floor testing including heel drop tests and walking tests was performed to determine the dynamic characteristics and response to walking of the problematic floor bay. In the heel drop tests, an 85-kg person rose onto his toes with his heels about 65 mm off the floor and suddenly dropped his heels to the floor. The walking tests were conducted by the person walking along the corridors. Utilising a metronome, the walker attempted to maintain a pacing rate of around 2 Hz which was about one third of the measured dominant natural frequency of the problematic floor bay. The floor response was recorded at a sampling rate of 128 Hz by Dytran seismic accelerometers of 5 V/g sensitivity located
around the floor bay centre. A laptop that controlled National Instruments data acquisition system was utilised at test site, allowing real-time observation of the floor response.

3. Results

3.1. Floor fundamental frequency

Figure 6(a) shows a typical filtered acceleration time history due to an actual heel-drop excitation, having the form of a decaying curve of free vibration following the initial peak. Fourier transformation was then applied to the acceleration time trace to obtain its associated transfer function in the frequency domain as shown in figure 6(b). The sharp peak in the frequency response spectrum indicated the first natural frequency $f_n$ of approximately 6.20 Hz for the investigated floor bay. Since the observed fundamental frequency of the floor was less than 9−10 Hz, the floor can be considered as a low-frequency floor by current design guidelines [8, 9]. Therefore, the possibility of resonant build-up of response under repeated footfall should be examined carefully.

![Figure 6](image1.png)

**Figure 6.** Floor response to a heel impact: (a) Time domain, (b) Frequency domain.

3.2. Floor response to walking

Although the walker managed to maintain his pacing of around 2.0 Hz so that the third harmonic of footfall (approx. 6.0 Hz) could be close to the fundamental frequency of the floor (6.2 Hz), a perfect resonant condition could not be achieved. The measured peak acceleration fluctuated between different tests and could reach a maximum of 0.671% g. Figure 7 presents a typical acceleration time history recorded at a position close to the centre of the problematic bay. Whilst extraction of the peak acceleration was straightforward from the response time history, the determination of RMS values required more work. A rolling RMS of the acceleration time history $a_{RMS}(t)$ was produced in which each $a_{RMS}$ point was calculated from a set of acceleration values $a(t)$ using the following expression:

$$a_{RMS} = \sqrt{\frac{1}{T} \int_0^T a(t)^2 \, dt} = \sqrt{\frac{\sum_{n} a(t)^2}{n}}$$

(1)

in which $n$ is the number of samples within the time interval for averaging $T$ taken as 1.0 second [9].

In order to obtain velocity time traces $v(t)$ from the measured acceleration traces $a(t)$, a numerical integral procedure of the acceleration was performed using Matlab [12]. Similar to the determination of $a_{RMS}$ values, the rolling RMS velocity $v_{RMS}(t)$ was constructed from the velocity time history using equation (2). The time interval $T$ for velocity averaging was, however, taken as 0.5 seconds which was approximately the duration of a typical footstep, as recommended by the European guidelines [10]. Figure 8 shows the resulting velocity time history associated with the acceleration trace of figure 7.
\[ v_{\text{RMS}} = \sqrt{\frac{1}{T} \int_0^T v(t)^2 \, dt} = \sqrt{\frac{\sum_{i=1}^{n} v_i^2}{n}} \]  

(2)

**Figure 7.** Typical acceleration time trace due to walking.

**Figure 8.** Typical velocity time trace due to walking.

**Table 3.** Maximum response due to walking.

| Test | \(a_{\text{peak}}\) (g) | \(a_{\text{RMS}}\) (g) | \(v_{\text{RMS}}\) (mm/s) | MF |
|------|----------------|----------------|----------------|----|
| 1    | 0.468%         | 0.219%         | 0.647          | 4.38 |
| 2    | 0.546%         | 0.235%         | 0.682          | 4.70 |
| 3    | 0.497%         | 0.239%         | 0.639          | 4.78 |
| 4    | 0.671%         | 0.330%         | 0.874          | 6.61 |
| 5    | 0.436%         | 0.217%         | 0.596          | 4.34 |
| 6    | 0.566%         | 0.274%         | 0.753          | 5.49 |
| 7    | 0.455%         | 0.222%         | 0.610          | 4.43 |
| 8    | 0.609%         | 0.290%         | 0.789          | 5.80 |
| 9    | 0.563%         | 0.256%         | 0.720          | 5.29 |
| 10   | 0.585%         | 0.279%         | 0.756          | 5.62 |
The same analysis procedure was repeated for all experimental data obtained from 10 walking tests. Maximum response measures in terms of peak acceleration $a_{\text{peak}}$, RMS acceleration $a_{\text{RMS}}$ and RMS velocity $v_{\text{RMS}}$ for each test were then collected as summarised in table 3. The multiplying factor $MF$ which is the ratio of $a_{\text{peak}}$ to 0.05% $g$ is also presented. Some observations can be made:

- The average ratio of $a_{\text{RMS}}$ to $a_{\text{Peak}}$ was experimentally found to be 0.48 whereas popular design guides assume a value of $0.7 (= 1/\sqrt{2})$ for that ratio when using simple hand-calculation methods of vibration prediction [8,9];
- If $v_{\text{RMS}}$ was directly estimated from $a_{\text{RMS}}$ assuming steady state harmonic vibration at resonance then, taking test 4 for example, the velocity level would be $v_{\text{RMS}} = a_{\text{RMS}}/(2\pi f_n) = 0.33\% \times 9810 / (2\times 3.14 \times 6.2) = 0.831 \text{ mm/s}$ which is just 5% away from the value of 0.871 mm/s resulting from the complex analysis procedure discussed above.

3.3. Assessment of floor acceptability

The measured floor responses were compared with different acceptance criteria outlined in section 2 to examine the suitability of the case study floor for general office usage from a human comfort perspective. Table 4 presents the assessment results and also defines a “safety factor” which is the ratio of the guideline-specified threshold to the measured response.

| Test | AISC DG11 Safety factor | Comment | SCI P354 Safety factor | Comment | ISO 10137 Safety factor | Comment | EUR DG Class | Comment |
|------|-------------------------|---------|------------------------|---------|-------------------------|---------|-------------|---------|
| 1    | 1.07                    | Pass    | 1.83                   | Pass    | 0.91                    | Fail    | C           | Pass    |
| 2    | 0.91                    | Fail    | 1.70                   | Pass    | 0.85                    | Fail    | C           | Pass    |
| 3    | 1.01                    | Pass    | 1.67                   | Pass    | 0.84                    | Fail    | C           | Pass    |
| 4    | 0.75                    | Fail    | 1.21                   | Pass    | 0.61                    | Fail    | D           | Pass    |
| 5    | 1.15                    | Pass    | 1.85                   | Pass    | 0.92                    | Fail    | C           | Pass    |
| 6    | 0.88                    | Fail    | 1.46                   | Pass    | 0.73                    | Fail    | C           | Pass    |
| 7    | 1.10                    | Pass    | 1.81                   | Pass    | 0.90                    | Fail    | C           | Pass    |
| 8    | 0.82                    | Fail    | 1.38                   | Pass    | 0.69                    | Fail    | C           | Pass    |
| 9    | 0.89                    | Fail    | 1.57                   | Pass    | 0.78                    | Fail    | C           | Pass    |
| 10   | 0.86                    | Fail    | 1.43                   | Pass    | 0.72                    | Fail    | C           | Pass    |

4. Discussion

It was found that current human comfort criteria can provide conflicting conclusions about floor response acceptability, which may confuse designers. Using the “Peak acceleration criterion” proposed by the AISC DG11, the floor would be deemed to be unacceptable for general office usage as only 40% of the tests revealed vibration levels below the code-specified limit. However, the “RMS acceleration criterion” as per the SCI P354 would classify the floor as acceptable for office usage since the vibration levels obtained from all of the walking tests were well below the tolerable limit, i.e. all the safety factors were greater than 1. The discrepancy between the two criteria may be attributed to the following reason. The ratio of the SCI P354 vibration threshold to the AISC DG11 limit is as high as $0.8 (= 0.4\%g / 0.5\%g)$ whilst the $a_{\text{RMS}}$-to-$a_{\text{peak}}$ ratio obtained from floor testing was much lower at 0.48. Therefore, if a measured peak response exceeds the peak limit then it does not necessarily mean that the corresponding measured RMS response would also exceed the RMS limit.

By contrast to the SCI P354, when the same RMS acceleration levels were benchmarked against the ISO 10137 comfort threshold then none of the tests passed the criterion, i.e. the floor was considered to be unsatisfactory. It should be noted that the SCI P354 allowable limit is twice higher than the ISO 10137 threshold suggested for general offices.
Regarding the “RMS velocity criteria” as per the EUR DG, 90% of the tests proved that class C can be assigned to the investigated floor. Since the EUR DG suggests the vibration level of general office floors can be up to the limits specified for class D showed in table 2, the vibration measured on the case study floor can be classified as extremely acceptable as per this guideline. Surprisingly, even if the vibration level in the most critical test (0.874 mm/s) had increased by a factor of 3.5 then the floor would still have been considered acceptable because the upper limit for class D is set as high as 3.2 mm/s.

5. Conclusions
This paper presented an overview of popular floor vibration guidelines and provided details on dynamic testing of a real office floor subjected to footfall. The current design guidelines were found to exhibit inconsistency in the assessment of floor acceptability from a human comfort perspective. Assessments using the SCI P354 and EUR DG criteria would confirm the acceptability of the case study floor whereas both the AISC DG11 and ISO 10137 comfort criteria considered the floor to be unacceptable for office usage. Since the tenants of the investigated floor did complain about the annoying vibrations they had experienced due to people walking normally on the floor, it is likely that the SCI P354 and EUR DG acceptance criteria reflect the behaviour of much more tolerant occupants to vibrations. The EUR DG was found to be the least stringent benchmark for this particular floor. Finally, as human response to floor vibrations is a very complex phenomenon, the presented study is instructive and does not aim to claim that one design guide or the other is more accurate.

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