Australian Earthquake Engineering Society 2011 Conference, 18-20 November, Barossa Valley, South Australia

Evaluation of footfall induced vibration in building floor

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Abstract

Disturbing walking-induced vibrations have been observed more frequently in recent times on long span lightweight floor systems as evidenced by the development of a number of new design guidelines for floor vibration assessment. This paper discusses a simple probability-based vibration analysis of a real office composite floor, taking into account the variability in walking excitation and dynamic characteristics of the floor. Some aspects of randomness in gait parameters are determined via a statistical analysis of measured gait data obtained from a biomedical research program; and the likely change in serviceability load and the uncertainty in the estimation of floor damping and frequency are considered. Consequently, the probability distribution of the floor response is determined with good agreement between the predicted and measured floor responses. However, response levels can be translated inconsistently in terms of human comfort by various acceptance criteria.

Keywords: Floor vibrations, acceptance criteria, gait parameters, walking force, probabilistic design.

1. INTRODUCTION

Modern floor systems can be more vibration-vulnerable due to trends in design and construction leading to longer spans, lighter weight and lower damping. New design guides for human-induced floor vibrations have been developed in response to the increasing number of problematic floors. One of the most widely used guidelines is the AISC DG11 developed by the American and Canadian Institute of Steel Construction (Murray et al. 2003). The AISC DG11 is currently used for vibration assessment of composite floors in North American, Australia and some other countries. In the UK, there are two widely recognised design guides introduced by the Concrete Society (Willford and Young 2006) and the Steel Construction Institute (Smith et al. 2009). Another significant contribution to this research topic comes from European research projects which resulted in a number of floor design procedures, which are now referred to as the EUR DG (European Commission 2006, 2008; Feldmann et al. 2009).

Floor vibration design guidelines usually incorporate human comfort criteria and methodologies to determine the floor response to be checked against these criteria. The AISC DG11 suggests that floor peak acceleration should not exceed an appropriate limit shown in Figure 1(a), depending on various human activities in different environments. A tolerable peak acceleration of 0.5% g (i.e. 0.05 m/s^2) is typically recommended for offices with frequency ranging from 4 to 8 Hz. The EUR DG, on the other hand, utilises the root mean square velocity v_{RMS} as a design value. This value covers the velocity response of the floor for a significant step with an intensity of 90% of a person's step when walking normally. Floor classification as per this guideline can be seen in Figure 1(b) by which classes A, B, C and D are suitable for general office floors, implying an acceptable velocity of up to 3.2 mm/s.

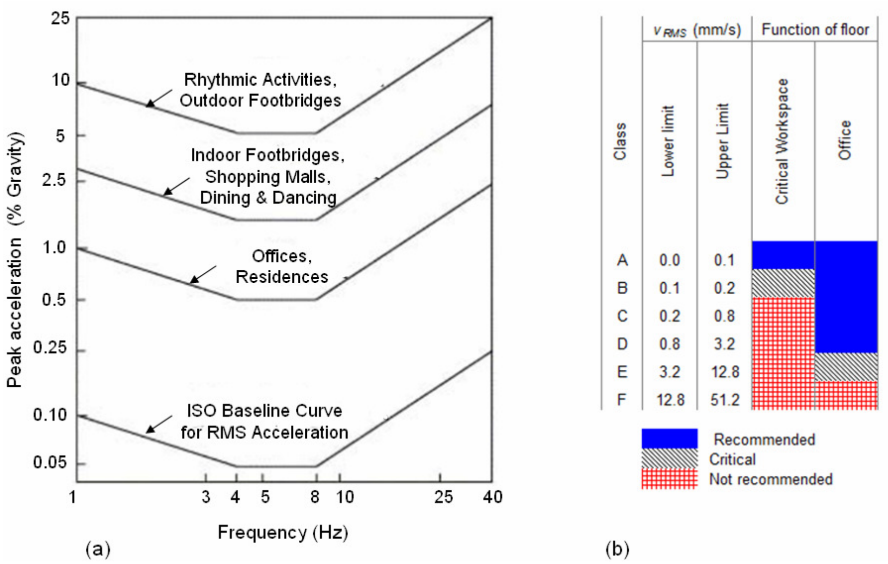


Figure 1: (a) Peak acceleration for human tolerance recommended by AISC DG11 (Murray et al. 2003); (b) RMS velocity and classification of floor response suggested by EUR DG (European Commission 2008).

This paper first presents basic gait parameters obtained from experimental work and statistical analysis. This is followed by a walking-induced vibration assessment for a real office floor that includes results from both a probabilistic analysis and field tests. The two comfort criteria suggested by AISC DG11 and EUR DG are compared and contrasted via their application to this case study.

2. DETERMINATION OF BASIC GAIT PAMARETERS

A biomedical research program using the GAITRite electronic walkway system with pressure activated sensors (CIR 2010) was conducted to investigate the basic spatial and temporal gait measures of about 900 participants of which 90% were primary school-aged children. The participants, recruited from Australian schools, completed a series of walks at self-selected free (normal), fast and slow gait speeds across the GAITRite walkway (Lythgo et al. 2009, 2011). This paper utilised only the measured data relating to a sample of 90 healthy young adults with an average age of 26. These data were statistically analysed to determine some parameters contributing to the characterisation of walking force.

Table 1 reports mean and standard deviation values for the walking speed v_p, step frequency f_p, and step length L_p associated with various walking conditions. The obtained mean step frequency for normal walk is 1.98 Hz with a standard deviation of 0.13 Hz, which compares well with values reported by Bachmann and Ammann (1987) and the European Commission (2006). The probability distribution of step frequency for a normal walking pace is shown in Figure 2(a). A relationship with strong linear association ($R^2 = 0.80$) between the step frequency and walking speed was obtained as Equation 1 and Figure 2(b).

$$v_p = 1.268 f_p - 0.935 \qquad (1)$$

Table 1: Basic gait parameters: mean (SD)

Walking condition	v_p (m/s)	f_p (Hz)	L_p (m)
Slow	1.18 (0.16)	1.72 (0.14)	0.69 (0.07)
Normal	1.56 (0.16)	1.98 (0.13)	0.79 (0.07)
Fast	1.98 (0.18)	2.24 (0.17)	0.89 (0.07)

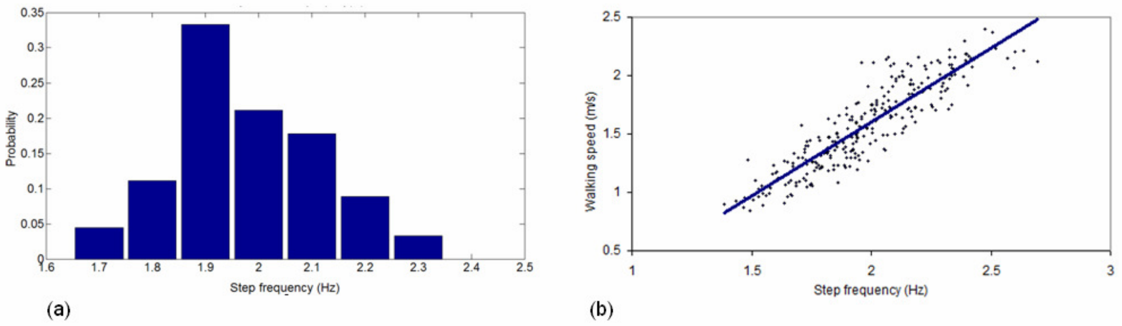


Figure 2: (a) Probability distribution of step frequency for normal walk; (b) relationship between step frequency and velocity for all walk conditions: slow, normal, and fast walk.

To investigate intra-subject variability, the standard deviation in the gait parameter was also determined for each test subject, resulting in a standard deviation of up to 0.08 Hz for the step frequency for a single walker. This figure is based on 95% confidence for all 90 subjects.

3. DESCRIPTION OF CASE STUDY FLOOR

Disturbing walking-induced vibrations were reported from tenants occupying a particular office floor of a multi-story building in Melbourne’s CBD. The most annoying area was located at the north-west corner of the building with floor beam spans of up to 12.7 m and two long perpendicular corridors as shown in Figure 3(a). A number of physical heel drop tests were performed on the problematic floor bay, revealing a natural frequency of about 6.2 Hz and a modal damping value of around 2.5-3%. A detailed FE model of the floor was created and calibrated which predicted a natural frequency of 6.22 Hz, modal mass of 20600 kg, and a mode shape as shown in Figure 3(b), for the resonant mode of the problematic floor bay.

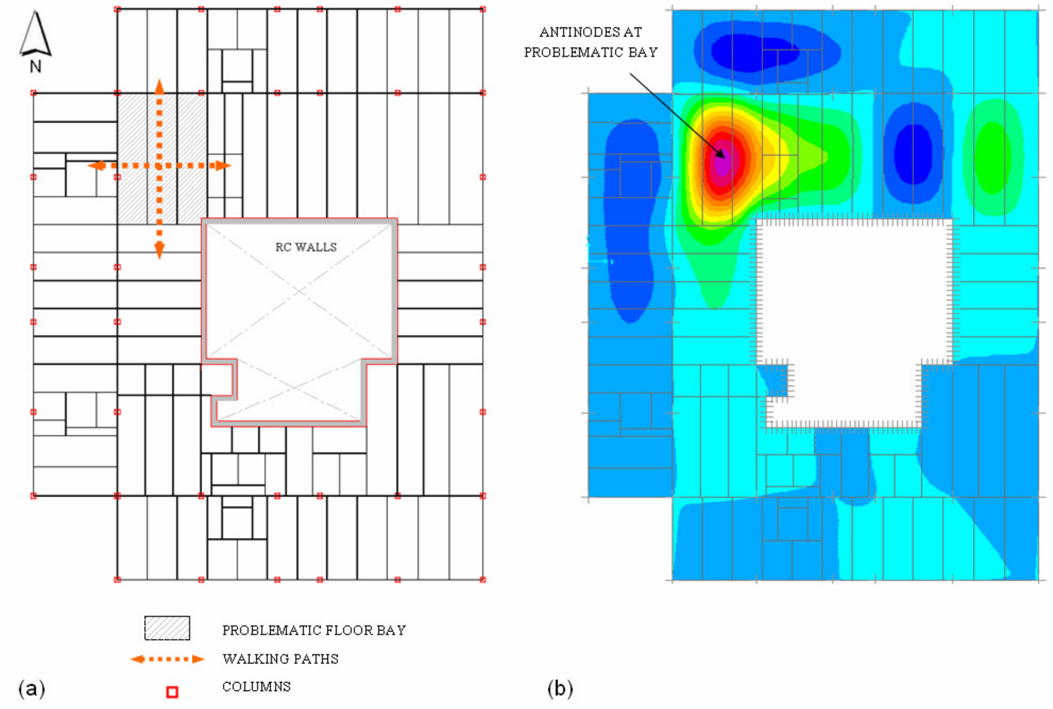


Figure 3: (a) Floor plan; (b) a mode shape which is critical to the problematic bay.

4. PROBABILISTIC PREDICTION OF FLOOR VIBRATION

The case study floor bay is idealised as a SDOF system with the governing equation of motion as:

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{2}$$

in which x, m, c, k, F are the displacement, mass, damping coefficient, stiffness, and walking force, respectively. The forcing function $F(t)$ includes the first four harmonics of the walking excitation and can be expressed by Equation 3.

$$F(t) = P\sum \alpha_i \cos\left(2\pi i f_p t + \phi_i\right)u \tag{3}$$

where P is the walker's weight. The Fourier coefficient α_i can be taken as 0.5, 0.2, 0.1 and 0.05 for the first, second, third and fourth harmonic, respectively (Murray et al. 2003). Phase angles ϕ_i can be taken as 0 for the first harmonic and $\pi/2$ for the others (Bachmann and Ammann 1987). To model a person walking from one end of the floor span to the other, the floor mode shape value u is incorporated into the forcing function of Equation 3. For simplicity, modal displacement along the walking path with a length of L is assumed to follow the mode shape configuration of a simply-supported beam in the form of a half-sine function as shown in Figure 4(a). Moreover, the coordinate z in Figure 4(a) can be calculated from the walking speed v_p, which relates to the step frequency f_p via Equation 1, so that u can be essentially represented as a function of time.

A large number of Monte Carlo simulations were used to probabilistically predict the floor response from this modelling procedure. Random values were used with the specified limits below:

(i) Modal mass of the floor:
Based on FE modal analysis of the floor, it was estimated that its modal mass could be in the range of 19,000 to 23,000 kg. This variation is primarily due to the possible range of service loads that the floor would experience. The change in modal mass translated to a variation in fundamental natural frequency of between 5.9 and 6.5 Hz.

(ii) Damping ratio:
Most design guidelines and the relevant literature would estimate the floor damping ratio to be in the order of 2% to 3%. The measured damping was also found to be within this range.

(iii) Walking force function $F(t)$:
A walker's weight in the range of 650 to 850 N was used. To take into account the inter-and-intra subject diversity in gait parameter, first a "basic" step frequency at normal walk was randomly selected from Figure 2(a). This was followed by generation of a set of step frequencies for all footsteps constituting a walking activity from one end of the floor span to the other. These step frequencies vary around the previously selected basic step frequency with a standard deviation of 0.08 Hz, as a result of the intra-subject variability mentioned in Section 2. Figure 4(b) shows an example of the simulated continuous walking force. Figure 4(e) illustrates a simulation case where the floor frequency is 6.47 Hz and a perfect resonance condition would not occur because the randomly generated step frequencies differ from the "critical" imaginary step frequency of 2.16 Hz which is one third of the floor frequency.

A numerical integration method (Clough and Penzien 1993) was used to solve Equation 2 with input parameters already determined via items (i), (ii) and (iii). Examples of the resultant acceleration and velocity response time histories are shown in Figures 4(c) and (d). The response solutions from 500,000 samples from within the specified ranges in items (i) to (iii) were analysed from which the cumulative probabilities of the floor responses were obtained as shown in Figures 4(f) and (g).

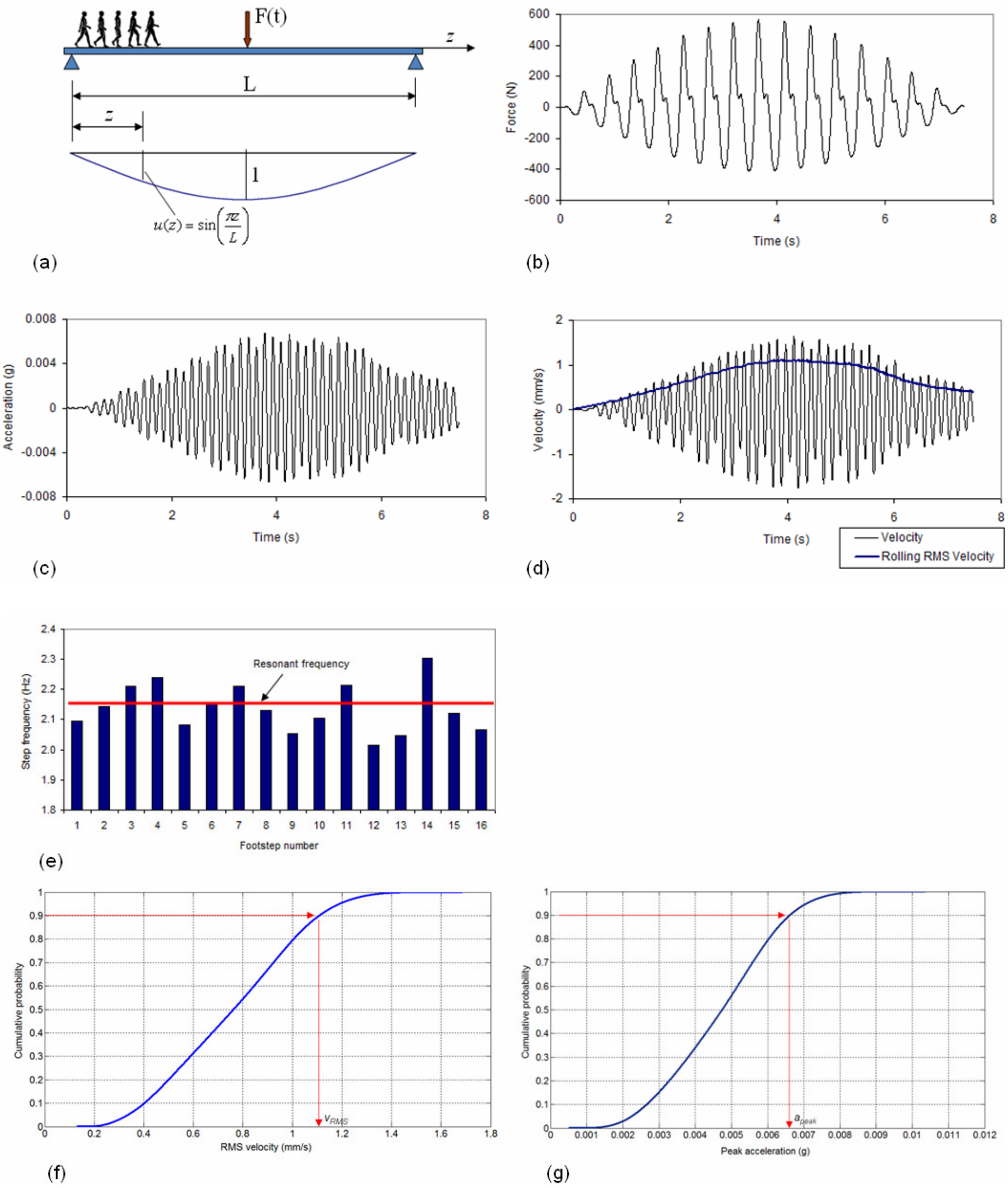


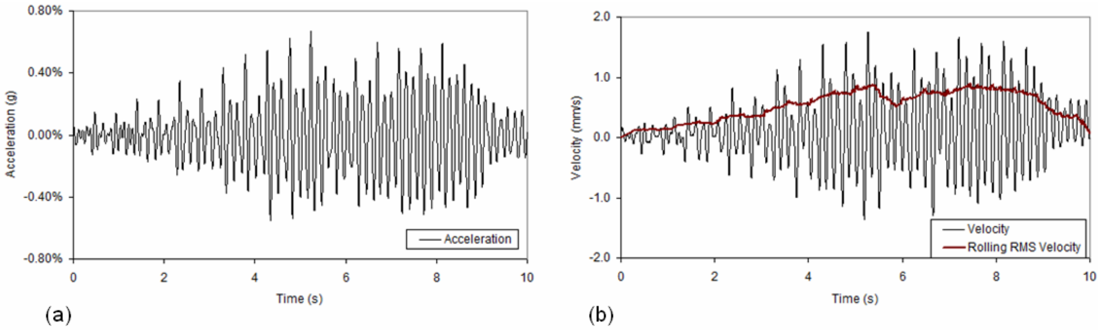
Figure 4: Probabilistic analysis of walking-induced floor vibration: (a) simplified fundamental mode shape; (b) an example of walking force; (c) an example of acceleration response; (d) an example of velocity response; (e) an example of variability of step frequency during a walk activity; (f) cumulative probability of RMS velocity; (g) cumulative probability of peak acceleration.

It can be seen from Figure 4(g) that the 90% fractile peak acceleration is 0.66% g, which exceeds the threshold of 0.5% g as per AISC DG11. Hence the floor is classified as unacceptable in terms of human comfort by this guideline. On the other hand, the 90% fractile RMS velocity of 1.1 mm/s obtained from Figure 4(f) is well below the upper velocity limit of 3.2 mm/s suggested by the EUR DG, i.e. the floor would be deemed acceptable by this criterion. The two guidelines clearly exhibit inconsistency in the assessment of floor acceptability. However, Figures 4(f) and (g) also reveals interestingly that the cumulative probability of an acceleration limit of 0.5% g and that of a lower velocity limit for class D floor of 0.8 mm/s are almost the same (about 55%). The EUR DG lower velocity limit is thus more comparable to the AISC DG11 criterion. The upper velocity limit is much less stringent and is likely to reflect the behaviour of much more tolerant occupants to vibrations.

5. EXPERIMENTAL DETERMINATION OF FLOOR RESPONSE

Walking tests were conducted on the real floor where the walker attempted to maintain a pacing rate of around 2 Hz to match the dominant natural frequency of about 6 Hz. Typical time traces for the filtered floor response measured at the critical antinode location in Figure 3(b) are shown in Figure 5 with a peak acceleration of 0.67% g and RMS velocity of 0.87 mm/s. Figure 6 shows the peak acceleration and RMS velocity obtained from different tests. Further details related to the experimental results can be found in Nguyen et al. (2011).

It can be seen that the measured responses are in good agreement with the predicted ones. And once again, while the peak acceleration can exceed a threshold of 0.5% g suggested by the AISC DG11, the RMS velocity is far below the upper limit of 3.2 mm/s allowed by the EUR DG. However, floor acceptability assessment using the lower velocity limit of 0.8 mm/s is more comparable to that using the AISC DG acceleration limit. A response level can thus be translated inconsistently as either acceptable or unacceptable by various acceptance criteria, which may confuse designers. It should be noted that the tenants associated with the case study floor did express their concerns over the clearly perceptible walking-induced annoying vibrations they had been experiencing.



(a) (b)

Figure 5: An example of measured floor response time histories: (a) acceleration; (b) velocity.

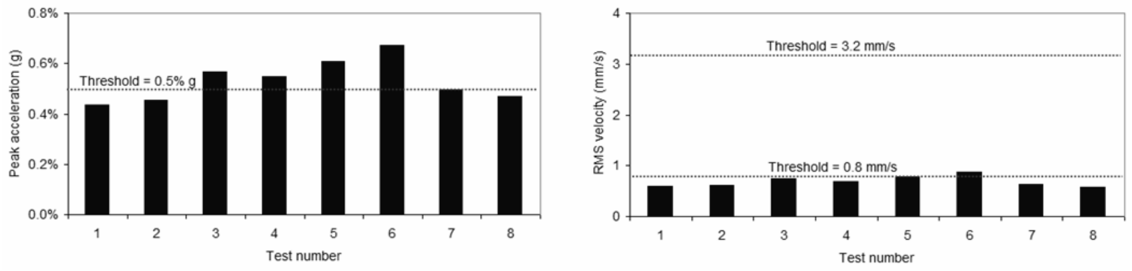


Figure 6: A sample of measured floor peak acceleration and velocity, compared with acceptance criteria.

6. CONCLUSIONS

A simple probability-based prediction of footfall-induced floor vibration using Monte Carlo simulations has been presented with the forcing function considering the inter-and-intra subject variability in footstep frequency and applied to a case study floor. An appropriate range of the floor dynamic properties, estimated from both FE modelling and field tests, also served as the inputs for the probabilistic analysis. The predicted response was found to compare well with the measured one. However, the two most currently used human comfort criteria (EUR DG and AISC DG11), were found to provide conflicting conclusions about floor response acceptability, which would place designers in a dilemma. Based on this investigation, use of the lower velocity limit in the EUR DG (as opposed to the upper velocity limit) is suggested to provide a more comparable outcome to the AISC DG11.

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