Footfall Vibration and the Dynamic Response of Different Structures – A case study comparing predicted and measured results

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ABSTRACT

Excessive floor vibration in buildings can adversely impact on human comfort or the operation of vibration sensitive equipment. Design procedures with varying degrees of sophistication have been developed over the last decades for both concrete and steel building structures. Key input parameters are the dynamic floor properties (with required information ranging from the fundamental frequency to a mobility spectrum of up to 4 times the fastest stepping frequency) and footfall characteristics (from stepping frequency only to a force spectra of up to four times this frequency). This paper discusses floor vibration criteria for human comfort. Footfall vibration measurements taken on different suspended floors (concrete and composite structures) are presented. The measured results are compared against different prediction methods of varying degrees of sophistication. The effects of individual and two person walker combinations are discussed as well.

INTRODUCTION

Excessive floor vibration due to footfalls is a common problem. Allen and Pernica (1998) write

> Floor vibration generally makes people uneasy and creates fear of structural collapse, although such fear is usually unwarranted because of the small displacements and stresses that are actually produced. Nevertheless, perceptible vibration is usually considered to be undesirable because it affects people's sense of well being and their ability to carry out tasks.

Consequently, reliable prediction methods *and* suitable floor vibration goals are required to minimise the likelihood of complaints. Various prediction methods with differing degrees of complexity have been developed in the past. Closed analytical solutions can be derived when reducing the excitation-response problem to single degree of freedom system (eg Allen, 1990; Murray et al, 1997). More sophisticated assessment methods have emerged as the Finite Element method has become more widely used. These approaches allow for predicting footfall vibration of complex structures as well as predicting vibration at response locations away from the walker (eg Wilford, 2006).

This paper presents a footfall vibration case study and compares predicted and measured results for individual walkers and a pair of walkers.

A brief discussion on human comfort is provided covering baseline and multiplier approaches and a vibration dose value based approach. The discussion focuses on office space human comfort considerations.

The dynamic properties of two test floors are discussed and walker vibration for two single walkers and a pair of walkers are presented. Subsequently, three prediction methods are briefly outlined and these predictions are compared against the measured levels for these floors.

HUMAN COMFORT

Acceptance criteria for human comfort are difficult to define and quantify because of the complexities involved in the human response to vibration. Influencing factors include the vibration characteristics of the source (frequency content, vertical or horizontal, duration, continuous or intermittent), the individual’s expectations (private residence, office or workshop) and the type of activity taking place. Specific responses also depend on the individual’s relationship to the source, health and vibration perceptibility. A detailed discussion and extensive lists of references can be found in Griffin (1986, 1996).

Many Standards utilise the concept of baseline curves and multipliers for specifying floor vibration criteria. A baseline marks the threshold of perception. The black line in Figure 1 shows (part of) the baseline for vertical vibration given in BS 6472-1992 (baseline extends to 80 Hz one-third octave band). It shows that humans are most sensitive from 4 Hz to 8 Hz and higher vibration amplitudes are tolerable outside this range. A vibration criterion for a specific vibration source and a specific receiver environment can be obtained by multiplying the baseline by an appropriate factor.

Recommended baseline multipliers for offices range from 4 to 8 (Table 1). The BS 6472-1992 multiplier of 4 is for continuous vibration and applying this multiplier to footfall vibration results in a conservative assessment of human response. Adjusting the multipliers to accurately capture non-continuous events (such as footfall vibration with ill defined start and end points and irregular occurrence) is difficult.

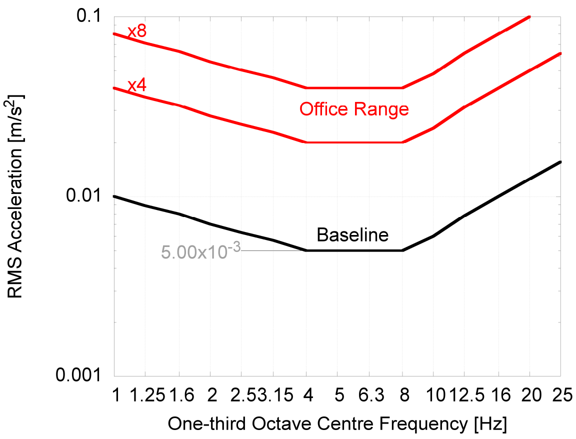

Figure 1. Office Criteria

Table 1. Recommended multiplying factors for offices

Source	Multiplier
BS 6472-1992	4
Concrete Design Guide (Willford et all, 2006)– Standard Office	4^(*) to 8
Steel design guide 11 (Murray et al, 1997)	7^(**)

^(*) Premium quality open-plan offices; Open plan offices with busy corridors near midspan; Heavily trafficked public areas with seating
^(**) Defined as peak acceleration 10 times greater than RMS baseline criterion.

The method of baselines and multipliers is somewhat outdated and is mentioned here to provide reference levels for gauging the measured vibration levels; and also because the prediction procedures use criteria derived from the baseline method.

The Vibration Dose Value (VDV) provides an alternative metric for assessing human comfort. The VDV accumulates the vibration energy received over an exposure time and aims to accurately account for the trade-off between the number of events per day and their magnitude. Recently, many Standards (including BS 6472:2008, superseding the 1992 version), adopted this descriptor to assess the impact of vibration events.

The VDVs recommended in BS 6472:2008 for offices are presented in Table 2. It is worthwhile pointing out that the lastest revision of BS 6472 not only represents a shift away from the baseline approach towards VDVs, but also recommends different frequency weightings with maximum sensitivity to vertical acceleration in the frequency range 4 Hz to 12.5 Hz (Allan, Duschlbauer, Harrison, 2010).

Table 2. Recommended VDVs for offices

Low probability of adverse comment	Adverse comment possible	Adverse comment probable
0.4 to 0.8 $ms^{-1.75}$	0.8 to 1.6 $ms^{-1.75}$	1.6 to 3.2 $ms^{-1.75}$

INVESTIGATED FLOORS

The tested floors were a concrete floor (Floor 1) and a concrete/steel composite floor (Floor 2), both supported on concrete columns. Impact tests were conducted to determine the dyamic properties of the floors. The accelerances in the centre of each floor are presented in Figure 2. The static stiffness and modal parameters at the dominant floor mode were extracted and are presented in Table 3.

Table 3. Modal parameters

Parameter	Floor 1	Floor 2
Fundamental Frequency, f_n	8 Hz	9.2 Hz
Modal damping	1.8%	1.3%
Modal mass	20t	50t
Dynamic stiffness at fundamental	50 MN/m	180 MN/m
Static stiffness	18.5 MN/m	37 MN/m

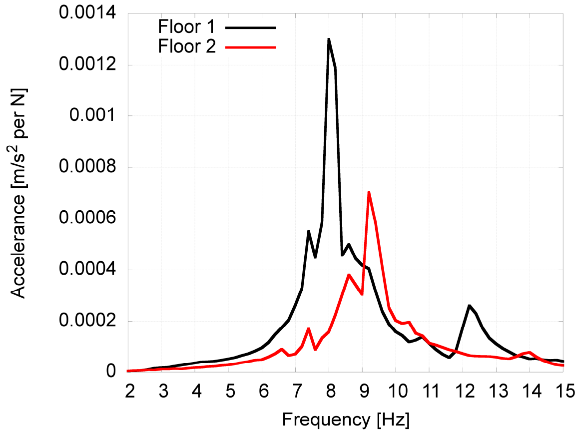

Figure 2. Measured floor accelerances

MEASUREMENT RESULTS

Footfall vibration was measured in the centre of each test floor with an accelerometer. The sampling frequency was 256 Hz and continuous, unweighted acceleration timetraces were recorded. Measurements were conducted at night to minimise external influences. A test walker would start from close to the centre of the adjacent bay, walk through the centre of the test floor passing by the accelerometer, continue to walk towards the centre of the next bay, turn around and return to the startpoint in a similar fashion. This approach yielded result sets containing two walk-through events. Tests were conducted for two walkers; Walker 1 weighed 75 kg and Walker 2 weighted 115 kg. Individual walking as well as combined synchronous walking was also tested. Each floor was tested at five discrete stepping frequencies starting from 72 beats per minute (bpm) (1.2 Hz) up to 120 bpm (2 Hz) in 12 bpm (0.2 Hz) increments. The test walkers were assisted by a metronome to keep a constant pace.

Figure 3 shows a typical result (Walker 2 walking on Floor 1 at 120 bpm). The unweighted acceleration timetrace is plotted in grey. The thick black line shows the running unweighted 1 second RMS acceleration (75% overlap is used). The thick red line shows the running 1 second RMS acceleration (75% overlap) of the bandpass filtered (corner frequencies 6.3 Hz and 10 Hz) acceleration timetrace. The two accelerometer pass-bys are clearly discernible and exhibit similar vibration levels.

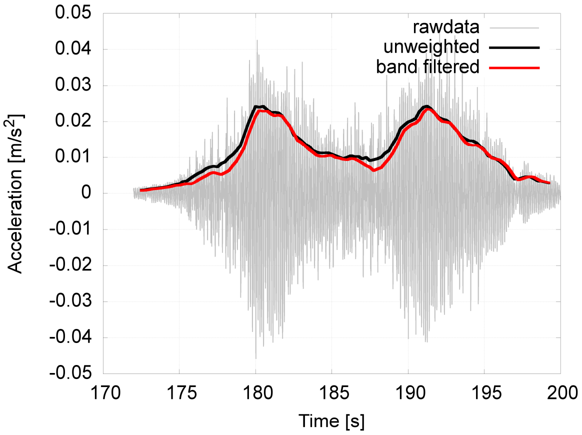

Figure 3. Unweighted acceleration timetrace (grey) and 1 second running RMS acceleration (black, red).

Figure 4 and Figure 5 show peak-hold one-third octave RMS acceleration spectra for Walker 1 and Walker 2 on Floors 1 and 2, respectively.

The spectra clearly show that the dominant response occurs at the floor fundamental frequency independent of the footfall frequency. Footfall frequencies and their first harmonics (ie twice the footfall frequencies) can be identified. The running 1s RMS levels were found to be generally within 15% of the maximum peak-hold one-third octave RMS acceleration levels for all results.

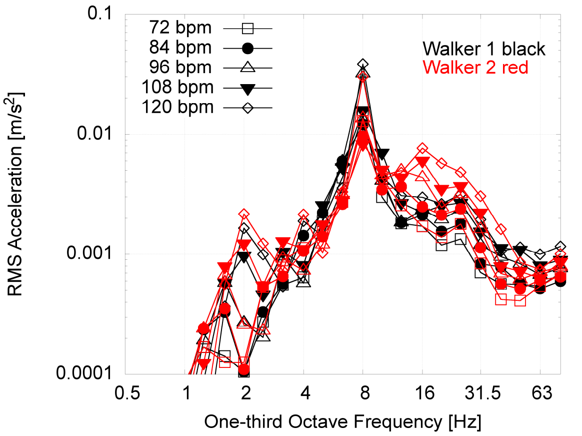

Figure 4. Unweighted peak-hold spectra for Walker 1 (black) and Walker 2 (red) on Floor 1.

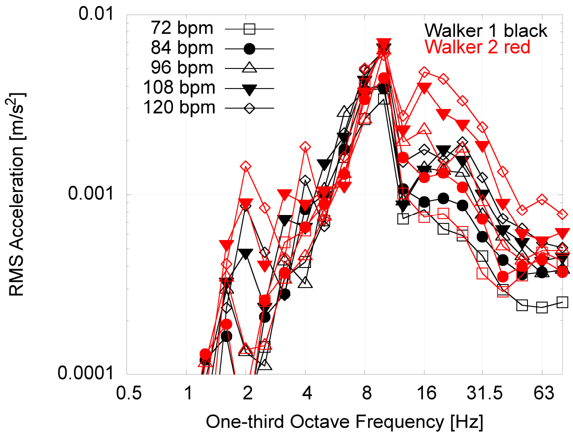

Figure 5. Unweighted peak-hold spectra for Walker 1 (black) and Walker 2 (red) on Floor 2.

DISCUSSION OF MEASUREMENTS

RMS Acceleration Levels

Figure 6 and Figure 7 show the maximum peak-hold one-third octave RMS acceleration levels for individual walking as well as combined walking on Floors 1 and 2, respectively. Figure 6 also indicates the Office Criteria range outlined in the Human Comfort Section. The Floor 2 vibration levels are well below the office criterion but exceed the threshold of perception (0.005 m/s^2).

The levels presented occurred in the one-third octave band corresponding to the fundamental frequency of the floor, specifically the 8 Hz band for Floor 1 and the 10 Hz band for Floor 2.

Floor 1 vibration is greater than Floor 2 vibration for all of the walker configurations and stepping frequencies; in most cases by a factor greater than 2. These decreased vibration levels in Floor 2 are expected, due to its reduced accelerance (demonstrated in Figure 1) and its higher fundamental frequency, while exhibiting similar damping levels (indicated in Table 3).

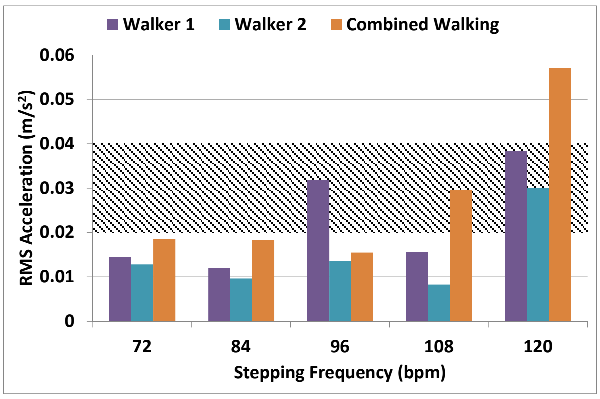

Figure 6. Maximum 1/3 Octave band acceleration for W1, W2 and both walkers on Floor 1.

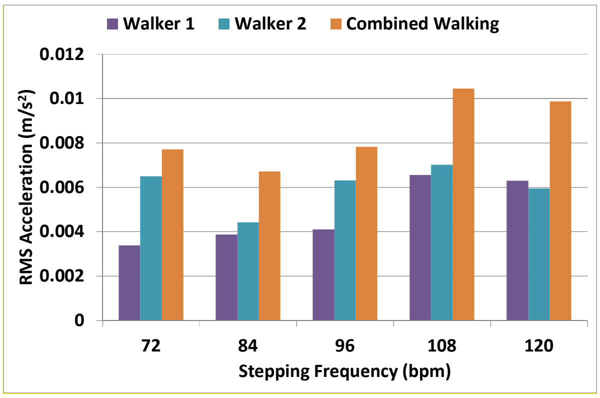

Figure 7. Maximum 1/3 Octave band acceleration for W1, W2 and both walkers on Floor 2.

Both of the floors responded differently to the varying individual walking styles. Floor 1 was more responsive to Walker 1 at all stepping frequencies, and Floor 2 was more responsive to Walker 2 at all stepping frequencies up to 120 bpm (2 Hz). This 'responsiveness' to walker style is surprising and for the investigated floors it proved to be sufficient enough to overcome a 50% difference in walker weight. The reasons for the varying response of the floors are not understood but most likely originate from differences in individual walking styles and footfall characteristics.

Combined walking generally resulted in higher vibration levels on both floors, compared with individual walking. The levels were generally less than the cumulative level of the individual walkers. Literature suggests increases in the range of $N^{0.5}$ to N (where N is the number of walkers) for completely uncoherent and coherent walking, respectively (Hauksson, 2005).

The vibration levels for Floor 1, and in particular Floor 2, show very little increase with stepping frequency. Both floors exhibit slightly elevated vibration levels at a particular stepping frequency: 120 bpm (2 Hz) and 108 bpm (1.8 Hz) for Floors 1 and 2, respectively, because integer multiples of the stepping frequencies coincide with the floor fundamentals.

Vibration Dose Values

The VDVs associated with double crossings were calculated using W_b frequency weighting and trapezoidal integration. Detailed information on weighting functions can be found in BS 6841:1987 and it suffices to state that the W_b weighting function has a unity response from approximately 5 Hz to 16 Hz. For the considered floors it was found that the weighted and unweighted floor responses are almost identical because both floor fundamentals are well inside the 5 Hz to 16 Hz band of unity weighting.

The VDVs associated with a double crossing for Floor 1 for single walkers ranged from 0.014 $m/s^{1.75}$ (W2, 84bpm) to 0.0526 $m/s^{1.75}$ (W1, 120bpm) and for Floor 2 for single walkers ranged from 0.0068 $m/s^{1.75}$ (W1, 72bpm) to 0.012 $m/s^{1.75}$ (W2, 120bpm).

The VDVs associated with individual passbys were used to calculate the range of total accumulated VDVs over a 16 hour period (see Figure 8). Figure 8 also shows the recommended VDV range for offices for low probability of adverse comment.

Receivers on Floor 2 will not exceed vibration dose recommendations in typical office environments as the number of bay crossings per hour generally would be less than 1000. Similarily, receivers on Floor 1 are unlikely to exceed the vibration dose recommendations.

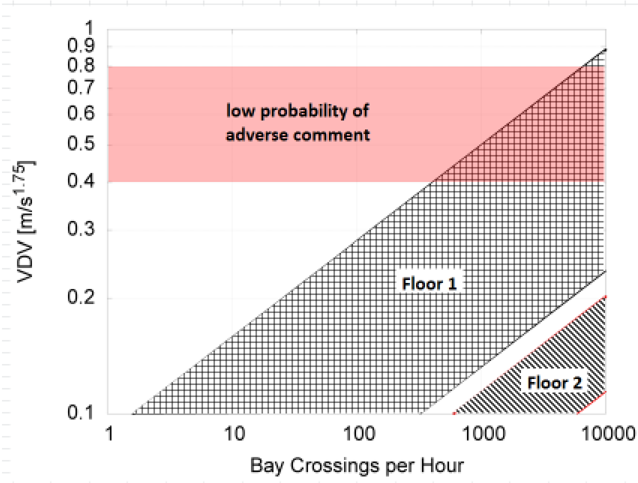

Figure 8. Accumulated VDV ranges versus number of bay crossings per hour for Floors 1 and 2.

PREDICTION MODELS

Footfall prediction methods can be split into two groups; resonant response approaches and impulse response approaches. The applicability of the two methods is not clearly defined. According to Ellis (2003) floors with fundamentals greater than 7 Hz or 8 Hz do not encounter a resonance situation from walking. BS 6472:2008 (referring to "low frequency floors" and "high frequency floors") provides a cut-off range of 7 Hz to 10 Hz. Willford and Young (2006) provide a cut-off limit of about 10 Hz, depending on the maximum expected footfall rate.

In this paper, simple to use resonant response approaches and impulse response approaches are used. All results are presented for a 95 kg walker, ie the average weight of Walker 1 and 2. All required data to perform the calculations is presented in Table 3.

The first method used calculates one-third octave band velocity based on the static floor stiffness and the fundamental frequency. The formula provided by Brownjohn and Pavic (2006) calculates vibration velocities and multiplication by the circular fundamental floor frequency yields accelerations (and eliminates the dependence on the floor fundamental, Equation 1).

$$a_{RMS} = 2\,\pi\, C_w \;/\; k_0 \;. \qquad (1)$$

In Equation 1, k_0 is the static floor stiffness and C_w equals 70,000. Equation 1 expresses floor acceleration in terms of static stiffness only. The predictions do not depend on walker weight or stepping frequency. It is very simple to use.

The second and third methods are the Chapter 2 and Chapter 6 method of the AISC Design Guide 11 (Murray et al, 1997).

The AISC Chapter 2 formula is presented in Equation 2. The actual formula calculates peak acceleration and hence the division of sqrt(2) to convert to RMS acceleration. For a 95 kg walker the dynamic force P_0 is 0.39 kN, β is the modal damping, f_n is the floor's fundamental frequency and W is the effective weight of the floor.

$$a_{RMS} = g / sqrt(2)\ P_0\ exp(-0.35\ f_n) / \beta / W\ . \quad (2)$$

Similar to Equation 1, predictions do not depend on the stepping frequency. However, the walker weight is an input parameter.

The AISC Chapter 6 formula is based on the static stiffness of the floor, the fundamental frequency and the dependence of maximum force on the stepping frequency from Galbraith and Barton, 1970. The maximum displacement is expressed as

$$X_{max} = F_m\ \Delta_p\ f_0^2 / (2\ f_n^2)\ . \quad (3)$$

In Equation 3, F_m is the maximum force, f_0 the inverse of the footfall rise-time and Δ_p is the inverse of the static floor stiffness. The maximum displacement can then be transformed to accelerations by multiplications of the circular floor fundamental frequency squared. Equation 3 predicts peak levels and a series of transient impulses was calculated (using exponential decay) and from this train of impulses the 1s RMS value was calculated. This method does account for the effects of different stepping speeds and walker weights.

Prediction Results

Figures 9 and 10 compare prediction results and measured vibration levels.

For stepping frequencies of less than 120 bpm the AISC Chapter 2 method gives the most conservative results (ie this method predicts the highest levels). This method predicts 0.046 m/s^2 for Floor 1 (shown as a solid black line in Figure 9). For Floor 2, this method predicts 0.017 m/s^2 and is approximately 3 times greater than the measured levels.

The method presented in Brownjohn et al. yields 0.024 m/s^2 and 0.011 m/s^2 for Floor 1 and Floor 2, respectively (shown as dashed grey line in Figures 9 and 10). This method fits the measured data, in particular Floor 2, better than the AISC Chapter 2 method. This method generally overpredicts by less than a factor of two.

The AISC Chapter 6 predictions are shown as black dashed lines for each stepping frequency. This method matches the Floor 1 measurements quite well and captures the trend of increasing vibration with increasing stepping frequencies. Similarly, for low to moderate stepping frequencies (less than 100 bpm) the Floor 2 response is captured reasonably well. For walking at higher footfall frequencies, however, this method overpredicts Floor 2 vibration significantly (by a factor of 4 at 120 bpm).

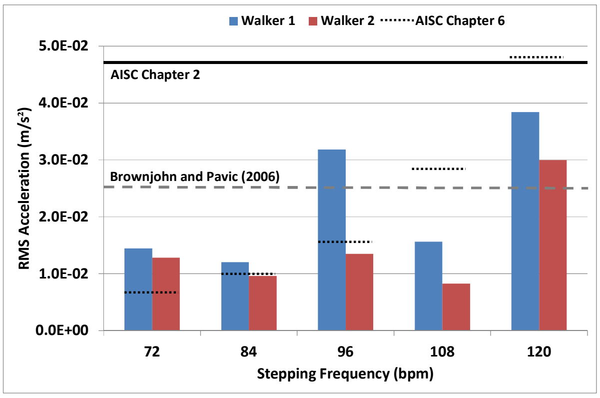

Figure 9. Predicted and measured footfall vibration for individual walkers on Floor 1.

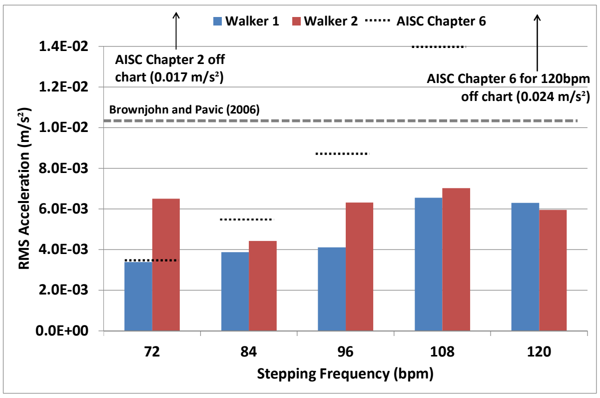

Figure 10. Predicted and measured footfall vibration for individual walkers on Floor 2.

In summary, predictions for Floor 1 generally show better agreement with data than predictions for Floor 2. In particular the lack of an increase in vibration levels with increasing footfall frequencies exhibited by Floor 2 is not understood.

CONCLUSIONS

Perhaps the most important conclusion to be drawn from this study is that footfall vibration varies greatly; not only from individual to individual independent of the floor, but also that the floor's response to an individual's walking style is important.

In this study the difference in walker mass was some 50% (Walker 1 weighed 75 kg and Walker 2 weighted 115 kg). Footfall vibration of Walker 1 was greater than that of Walker 2 on Floor 1 and the opposite trend was observed on Floor 2. This shows that a particular combination of an invidual's walking style and dynamic floor properties can outweigh effects associated with substantial differences in walker mass.

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