

Investigation of a Semi-FE Approach to Prediction of Floor Response to Walking



Huu-Anh-Tuan Nguyen

Abstract Contemporary guidelines for evaluation of human-induced floor vibrations normally introduce simplified hand calculation methods for prediction of dynamic characteristics and response of floor systems. On the other hand, finite element (FE) modeling is more suitable for analysis of floors with complex geometry and irregular framing layouts. Vibration prediction using the FE approach usually involves both a modal analysis and a time history analysis that requires modeling of the time dependent walking force for calculation of the resultant floor response. The present paper investigates the efficiency of a semi-FE approach to predicting the vibration response due to walking of a real office floor. This method combines the modal properties calculated via an FE model with manual equations established by two widely recognized design guides to obtain the floor response. The contribution of multiple vibration modes and multiple harmonic components of the foot-step frequency to the total response is considered. The response calculated using the semi-FE approach is found to compare well with that obtained from the time history analysis for a practical range of pacing rates covering both resonance and off-resonance conditions. In addition, the predicted response is reasonably conservative when compared with the response level measured on the test floor.

Keywords Floor vibrations · Walking excitation · Finite element · Design guides

1 Introduction

Technology has seen an increase in floor spans and the use of lighter and higher strength materials, which has resulted in a growing concern for floor vibrations. Several design guidelines which provide methodologies for the assessment of footfall-induced floor vibrations have been developed [1–3]. Floor vibration design guides usually include simplified hand calculation procedures for the determination of the modal properties and vibration response of the floor. The Steel Construction

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Institute Publication P354 (SCI DG) [2] and the Concrete Centre Industry Publication 016 (CCIP DG) [3] are the two widely recognized design guides in the UK and other countries. In addition, a number of researchers have dedicated their work to the improvement of finite element (FE) techniques for floor vibration analysis [4–7]. Evaluation of footfall induced floor vibrations using FE modeling normally involves both modal analysis and time history analysis. The natural frequencies obtained from a modal analysis could suggest whether the floor should be treated as a low frequency or high frequency floor. The material covered in this paper relates to low frequency floors (fundamental frequency less than about 10 Hz) in which resonance may cause severe vibration amplification, rather than high frequency floors where resonance becomes less important compared with transient response [2].

The paper examines the accuracy of a semi-FE approach, in comparison with the time history analysis, in predicting the floor response to walking excitation. The semi-FE method incorporates the floor modal properties obtained from an FE modal analysis into hand calculation formulas suggested by the SCI DG and CCIP DG for response prediction. The footfall-induced vibration of an actual office floor is investigated and the results from various prediction methods along with some experimental findings are discussed.

2 Contemporary Guidelines for Floor Vibration Evaluation

2.1 Walking Force Model

The continuous steady state walking excitation is represented by a Fourier series of sine waves:

$$F(t) = P \left[1 + \sum_{i=1}^H \alpha_i \sin(2\pi i f_p t + \phi_i) \right] \quad (1)$$

where f_p is the step frequency; P is the standard pedestrian's weight, normally taken as 746 N (76 kg); α_i and ϕ_i are the dynamic load factor and phase angle of the i -th harmonic component. The forcing function consists of four harmonics ($H = 4$) with the dynamic load factor α_i corresponding to the i -th harmonic given in Table 1 as

Table 1 Dynamic load factors for walking excitation

Harmonic, i	α_i from SCI DG	α_i from CCIP DG
1	$0.436(if_p - 0.95)$	$0.41(if_p - 0.95) \leq 0.56$
2	$0.006(if_p + 12.3)$	$0.069 + 0.0056if_p$
3	$0.007(if_p + 5.2)$	$0.033 + 0.0064if_p$
4	$0.007(if_p + 2.0)$	$0.013 + 0.0065if_p$

suggested by the SCI DG and CCIP DG [2, 3]. The phase angles are taken as $0, -\pi/2, \pi$ and $\pi/2$ for the first, second, third and fourth harmonics respectively.

2.2 Response Calculation

SCI DG. The response in each vibration mode of the floor to each harmonic component of the walking force is calculated. The total acceleration response due to all harmonics in all modes is then combined using the following expression:

$$a_{RMS} = \frac{1}{\sqrt{2}} \sqrt{\sum_{i=1}^H \left(\sum_{n=1}^N \left(\varphi_{e,n} \varphi_{r,n} \frac{\alpha_i P}{m_n} D_{i,n} \lambda_i \right) \right)^2} \tag{2}$$

where a_{RMS} is the root-mean-square acceleration; H, N are the number of harmonics and modes to be considered, respectively; $\varphi_{e,n}, \varphi_{r,n}$ are the normalized mode shape values at the point of excitation and the point of response in mode n , respectively; m_n is the modal mass of the floor in mode n . As human would be most sensitive to vibrations in the frequency range of 4–8 Hz, a code-defined frequency weighting factor for human perception λ_i is introduced, which is equal to 1.0 for frequencies within this range and less than 1.0 for those outside the range [2, 8]. Let f_n and ζ be the natural frequency and damping ratio of the floor in mode n . The dynamic magnification factor $D_{i,n}$ in mode n to harmonic i is computed using Eq. 3 in which $r_{i,n}$ is the ratio of the forcing frequency if_p to the floor frequency f_n . Moreover, a resonant build-up factor (≤ 1) can be included in Eq. 2 to allow for the case where a walking path is sufficient short and a steady-state condition may not be reached.

$$D_{i,n} = \frac{r_{i,n}^2}{\sqrt{(1 - r_{i,n}^2)^2 + (2\zeta r_{i,n})^2}} \tag{3}$$

CCIP DG. The real and imaginary acceleration ($a_{real,i,n}$ and $a_{imag,i,n}$) due to each harmonic, i , in each mode, n , are calculated as:

$$a_{real,i,n} = \varphi_{e,n} \varphi_{r,n} \frac{\alpha_i P}{m_n} \left[\frac{r_{i,n}^2 (1 - r_{i,n}^2)}{(1 - r_{i,n}^2)^2 + (2\zeta r_{i,n})^2} \right] \tag{4}$$

$$a_{imag,i,n} = \varphi_{e,n} \varphi_{r,n} \frac{\alpha_i P}{m_n} \left[\frac{r_{i,n}^2 (2\zeta r_{i,n})}{(1 - r_{i,n}^2)^2 + (2\zeta r_{i,n})^2} \right] \tag{5}$$

The total real and imaginary acceleration ($a_{real,i}$ and $a_{imag,i}$) due to each harmonic i in all modes are then computed using Eq. 6 from which the magnitude a_i of the response to this harmonic can be obtained as Eq. 7.

$$a_{real,i} = \sum_{n=1}^N a_{real,i,n} \dots \dots \dots a_{imag,i} = \sum_{n=1}^N a_{imag,i,n} \tag{6}$$

$$a_i = \sqrt{a_{real,i}^2 + a_{imag,i}^2} \tag{7}$$

A multiplying factor of 0.71 ($=1/\sqrt{2}$) is needed to obtain the RMS acceleration $a_{RMS,i}$ from the peak acceleration a_i . Also, a frequency weighting factor λ_i may also be multiplied by $a_{RMS,i}$ as described in the SCI DG. Finally, the total response a_{RMS} to all harmonics is estimated by combining the $a_{RMS,i}$ values using the Square Root of the Sum of the Squares (SRSS) method.

Acceptance Criteria. The SCI DG and CCIP DG use the baseline for perception of vibration given in the standard ISO 10137 [9]. A response factor RF is defined as the ratio of the frequency weighted acceleration a_{RMS} to the “base value” of 0.005 m/s^2 . From human comfort perspective, the limit $RF = 8$ is suggested for general offices.

3 Vibration Analysis of a Case Study Floor

Figure 1 shows the framing layout of a typical floor in a real office building. The floor was fully fitted with demountable partitions, ducting, ceiling, services and

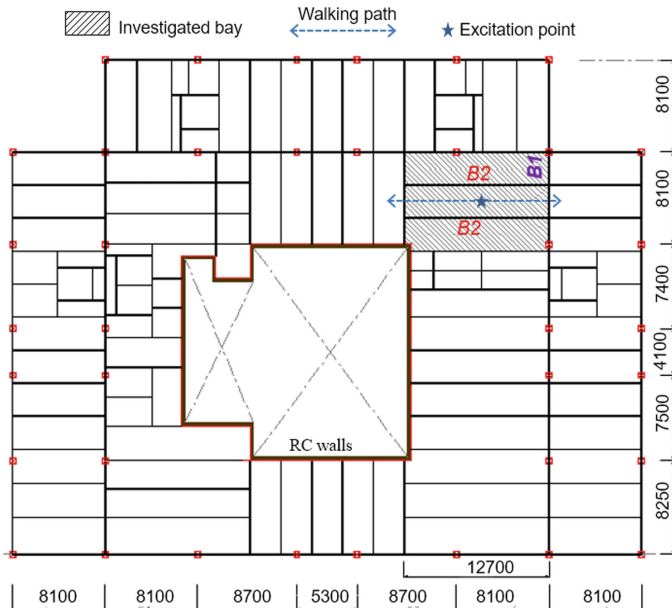


Fig. 1 Plan view of floor framing layout

a raise floor above the concrete slab. The present study focused on a floor bay, shown shaded in Fig. 1, with beam spans of up to 12.7 m and with long corridors crossing the midspan. The walking path was long enough for the vibration energy to build up and a walking induced steady state vibration to occur. The floor is of composite construction, consisting of a 120 mm lightweight concrete slab supported on 610UB101 (approximately 610 mm deep I-section with a weight of 101 kg/m) secondary steel beams B2 which are in turn supported on 610UB113 primary steel beams B1 spanning 8.1 m between columns or concrete walls.

3.1 Modal Analysis

An FE model of the floor was created using SAP2000 software [10]. Figure 2 depicts the selected four mode shapes with significant participation of the investigated bay. The corresponding natural frequencies f_n , modal mass m_n , and modal displacement at the bay center φ_n are given in Table 2. The 6.22 Hz mode was found to be the resonance mode which showed antinodes with maximum modal displacements being located around the center of the bay of interest. The fourth mode (8.37 Hz) was still worth being considered as it could match the fourth harmonic of a common step frequency of around 2.1 Hz. However, natural modes higher than four were found to have either too high frequencies to be excited by normal walking or negligible modal displacements at the bay of interest (Fig. 2).

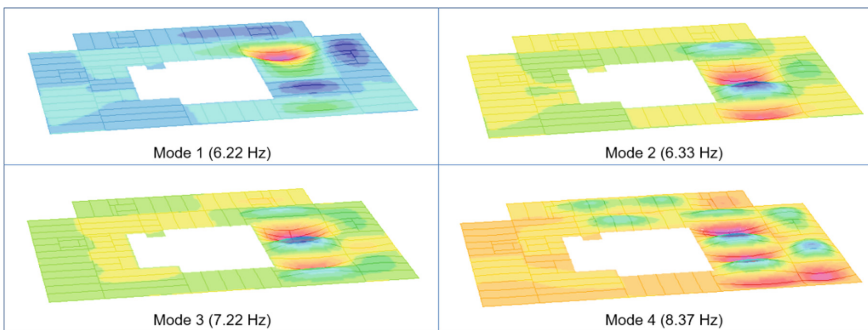


Fig. 2 Mode shapes critical to investigated bay

Table 2 Modal properties of case study floor

Mode	f_n (Hz)	m_n (kg)	φ_n
1	6.22	20,600	1
2	6.33	35,020	0.599
3	7.22	31,610	0.435
4	8.37	56,290	0.570

3.2 Semi-FE Versus Time History Analysis in Prediction of Footfall-Induced Floor Vibration

Semi-FE Analysis using SCI DG and CCIP DG. The modal frequencies, masses and displacements of the four natural modes determined from the FE modal analysis were utilized in the determination of floor response using Eqs. 2 and 3 from the SCI DG and Eqs. 4–7 from the CCIP DG. Both $\varphi_{e,n}$ and $\varphi_{r,n}$ were taken as φ_n given by Table 2 for a simple and conservative design. The damping ratio was assumed to be 3% as recommended by the guidelines for composite floors with typical fitout [1–3].

Time History Analysis. For a walking event at a step frequency f_p , an equivalent concentrated time-dependent force was applied at the floor bay center in the FE model. Let v_p and L be the walking speed and length of the floor span. The relationship between the step frequency and speed is given by [2]:

$$v_p = 1.67 f_p^2 - 4.83 f_p + 4.5 \tag{8}$$

The excitation time for a walking event was taken as L/v_p , the duration required for a person to walk from one end of the span to the other end. A half-sine function, which was a simple representation of the fundamental mode shape configuration, was incorporated to the dynamic part of the one-spot walking force of Eq. 1 to allow for the movement of the walker along the walking path. An example of the simulated walking force is shown in Fig. 3a, which can be applied to the midpoint of the span to represent a walking event. This force was for step frequency of 2.07 Hz and used the dynamic load factors suggested by the SCI DG.

Once the acceleration time trace was obtained from the time history analysis, a rolling RMS acceleration trace can be produced using Eq. 9 in which each $a_{RMS}(t)$ value was calculated from a set of acceleration values with the integration time T being taken as 1 s [2, 3, 9]. Figure 3b shows the time history and rolling RMS acceleration for walking at the resonance step frequency of 2.07 Hz.

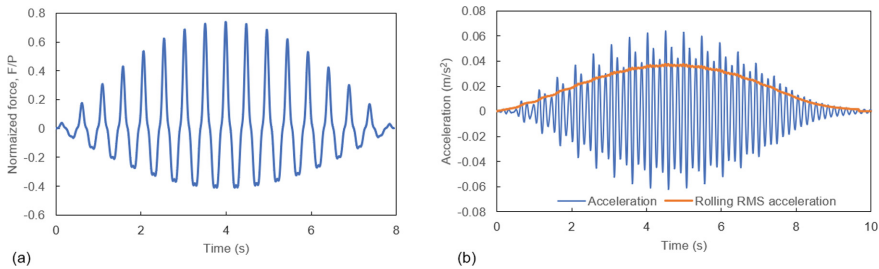


Fig. 3 Walking force and floor response time histories ($f_p = 2.07$ Hz)

$$a_{RMS} = \sqrt{\frac{1}{T} \int_0^T a(t)^2 dt} \tag{9}$$

Comparison of Predicted Response. A step frequency range of 1.5–2.4 Hz was used in the vibration analysis to cover pacing rates from slow to normal and fast walking. The variation of the maximum RMS acceleration as a function of the step frequency was found as shown in Fig. 4 where each point on the plot was obtained from an appropriate semi-FE analysis or time history FE analysis. The response spectrum shows two peaks at the 1.55 and 2.07 Hz step frequencies. The third harmonic of the normal walk 2.07 Hz step frequency and the fourth harmonic of the slow-walk 1.55 Hz pacing rate matched the fundamental frequency of the floor bay, thus producing a resonance condition. The resonance at the third harmonic was more critical than the resonance at the fourth harmonic. The worst-case RMS acceleration ($f_p = 2.07$ Hz) was estimated at 0.0348 m/s^2 ($RF = 6.96$) and 0.0382 m/s^2 ($RF = 7.64$) using the time history analysis with dynamic load factors based on the CCIP DG and SCI DG respectively. The response levels acquired from the semi-FE approach was 5–10% higher, being 0.0364 m/s^2 ($RF = 7.28$) and 0.0422 m/s^2 ($RF = 8.44$) as per the CCIP DG and SCI DG formulas respectively.

It would now be useful to discuss the contribution of multi modes and multi harmonic forcing components to the total response when using the semi-FE approach. In the event that a simplified prediction considered only the fundamental vibration mode (6.22 Hz) and the harmonic component in resonance with that frequency (the third harmonic), the calculated RMS acceleration would be 0.0312 m/s^2 for the CCIP DG ($\alpha_3 = 0.073$) and 0.0341 m/s^2 for the SCIDG ($\alpha_3 = 0.080$). These response values were 14–19% lower than those obtained using multi modes and multi harmonics (Fig. 4).

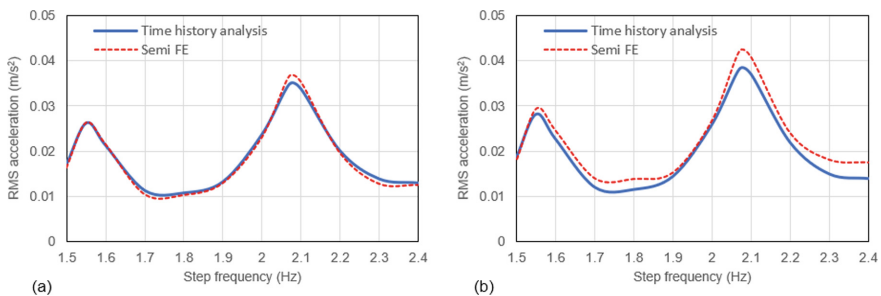


Fig. 4 Predicted floor response spectrum **a** CCIP DG, **b** SCI DG

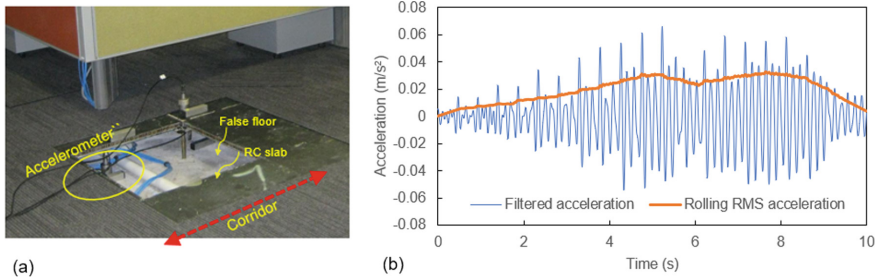


Fig. 5 Measured response to walking

3.3 Measured Response

Several walking tests were carried out in which the test person managed to maintain a normal pacing rate of around 2.0–2.2 Hz when walking along the bay's corridor. The recorded acceleration response was filtered to remove high frequency content above 15 Hz to which humans are insensitive [1]. The response was also scaled to take account of the difference between the weight of the test person and the standard pedestrian weight of 746 N. Figure 5 depicts the accelerometers installed on the test floor and a typical acceleration time trace due to walking excitation. A rolling acceleration time history was generated using Eq. 9 from which the maximum RMS acceleration was found to be 0.032 m/s². Higher response levels would, however, be expected because it was unlikely that the exact resonance step frequency was continuously performed on the test floor. A good agreement between the predicted response and the measured one was hence achieved (Figs. 4 and 5).

4 Conclusions

The semi-FE analysis which does not require a time history analysis and modeling of walking force may be an efficient approach in predicting the floor response to walking excitation. The presented semi-FE method involves utilizing the SCI DG and CCIP DG equations with modal properties obtained from an FE modal analysis, considering multi mode responses to multi harmonic components of the footstep frequency. The dynamic load factors in accordance with the CCIP DG are a bit lower than those given by the SCI DG, hence the corresponding predicted response levels. Comparisons between the semi-FE method and the full time history analysis were made for both resonance and off-resonance walking excitations. It was found that the discrepancy in response calculation between the semi-FE method and the time history analysis was insignificant for the case study floor with a straight walking path. Furthermore, response prediction using either the semi-FE approach or time history analysis was reasonably conservative when compared with the vibration level

measured on the real floor. Of the two UK guidelines discussed, the CCIPDG method appeared to exhibit a more accurate response prediction for the floor examined.

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