vibration

Review

Review of Pedestrian Load Models for Vibration Serviceability Assessment of Floor Structures

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Abstract: Innovative design and technological advancements in the construction industry have resulted in an increased use of large, slender and lightweight floors in contemporary office buildings. Compounded by an ever-increasing use of open-plan layouts with few internal partitions and thus lower damping, floor vibration is becoming a governing limit state in the modern structural design originating from dynamic footfall excitations. This could cause annoyance and discomfort to building occupants as well as knock-on management and financial consequences for facility owners. This article presents a comprehensive review pertinent to walking-induced dynamic loading of low-frequency floor structures. It is intended to introduce and explain key walking parameters in the field as well as summarise the development of previous walking models and methods for vibration serviceability assessment. Although a number of walking models and design procedures have been proposed, the literature survey highlights that further work is required in the following areas; (1) the development of a probabilistic multi-person loading model which accounts for inter- and intra-subject variabilities, (2) the identification of walking paths (routes accounting for the effect of occupancy patterns on office floors) coupled with spatial distribution of pedestrians and (3) the production of a statistical spatial response approach for vibration serviceability assessment. A stochastic approach, capable of taking into account uncertainties in loading model and vibration responses, appears to be a more reliable way forward compared to the deterministic approaches of the past and there is a clear need for further research in this area.

Keywords: vibration; floors; multiple pedestrian; walking load model; vibration responses; probabilistic approaches; monitoring techniques

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1. Introduction

1.1. Background

Vibration serviceability has become increasingly important in recent years and it is now a critical design aspect of modern civil engineering structures. Nowadays, buildings and their constituents, especially floors, are becoming increasingly slender, flexible and lightweight as well as having open-plan layouts, as a result of architectural trends and much lighter forms of construction (Figure 1). These factors all result in significant reductions in mass and stiffness as well as low inherent damping. These tendencies and expectations on modern structures have set forth in-service functioning increasingly important [1] due to the undesirable vibration originating from human-induced loadings.

Excessive vibration in building floors [1–5], footbridges [6], staircases [7,8] and stadia [9,10] are examples of civil engineering structures, where normal human activities (i.e. walking, crowds bouncing and jumping) can cause significant annoyance to occupants and knock-on management and financial consequences for facility owners.

Human movements, such as walking, a common load case scenario on floor structures, can produce resonant, near-resonant or impulsive structural vibrations. These are uncomfortable and intolerable for some occupants [11], may cause psychological fear or panic [12] and can adversely affect the performance of sensitive equipment or machinery [13,14]. Some serviceability problems have required structural retrofits [15,16], which may be difficult and expensive to implement. Hence, understanding and avoiding these problems is imperative at early stages of design, requiring development of improved methodologies for prediction of vibration response and also novel techniques for mitigation of human-induced vibrations.

Disturbing vibrations under human excitations in building floors have also been observed despite the prevalence of contemporary design guidelines [17–19]. Notwithstanding a number of attempts in recent years, one of the key deficiencies is the lack of realistic walking patterns. This is essential to provide a realistic assessment of floor structures under pedestrian loadings. In this work, office building floors are considered under walking-induced dynamic loading, since they are more likely to suffer vibration serviceability problems due to modern efficient construction. They are used mostly by professionals for long periods of time each day hence, maximizing exposure to problematic vibrations [20,21].

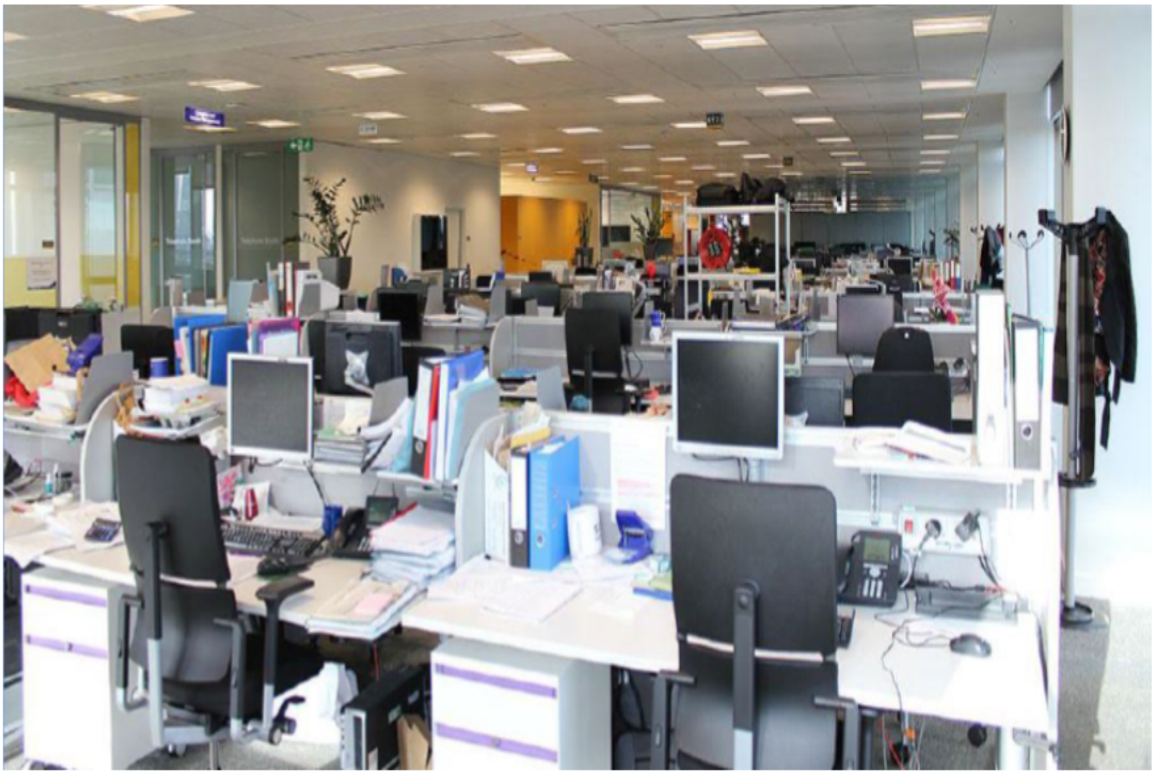


Figure 1. Typical modern office floor with open-plan layout.

1.2. Key Problems

Predicting vibration magnitude in floors is an important step so that possible problems may be anticipated and, if necessary, reduced. Annoyance or discomfort has been reported in various types of floors such as shopping malls, office buildings, residences, restaurants and airport terminals [22–25]. Building floors for which available guidelines for floor vibrations [17–19,26–28] have been applied have often been found to have unacceptable performance [29,30], thereby demanding costly remedial measures [31,32].

An ideal approach would be to cater for realistic walking excitations at early stages of design via appropriate probabilistic walking models. Such forcing models should be amenable for design engineers to estimate a realistic vibration exposure [33]. It is well known that human walking is a significant source of excitation for floors [2,18] and load models derived to date can be categorised into two broad classes; deterministic load models and (more recent) probabilistic load models. The former have been used by almost all guidelines to date [17,18,26–28], yet the latter approach has attracted increasing interest in recent years [5,34,35]. Walking has been proven to be a stochastic phenomenon or narrow band random process [36], which implies that there are clear variations during walking among pedestrians and even within the same person.

In modern office floors the mass of non-structural elements has decreased due to the tendency for more open and multifunctional space environment, which increases the likelihood of unpleasant vibrations [37]. Also, it is now widely known that in building floors the modes of vibration are often closely spaced [38]. Thus, methods to predict the vibration response should yield results that reflect actual floor behaviour in a statistical sense rather than an accept-reject method based on discrete excitation frequencies. An improved method would consider a probabilistic assessment of structural responses to walking-induced forces applied probabilistically both temporally and spatially to the structure.

In general, floors are often categorised into two types, namely, low-frequency floors (LFFs) and high-frequency floors (HFFs). Floors below the frequency threshold of approximately 10 Hz are termed as LFFs and they tend to develop a resonant build-up response. However, when the frequency threshold exceeds approximately 10 Hz the floor does not undergo a resonant response, but rather a transient response due to individual footfall impacts [13,39]. This work will focus on existing walking models pertinent to low-frequency floors as they are more frequent in modern office floors [40].

This paper serves as a comprehensive review of preceding studies on approaches for modelling human loads suitable for office buildings. The intent is to identify limitations of the available walking models and the corresponding vibration response assessment and to propose where future research and direction efforts may be targeted. In particular, it is also to highlight the need for models of statistical multiple pedestrian walking characterised by incorporating probabilistic aspects of both temporal and spatial entities of human loading and including randomness in walking paths on floor structures. These have not been covered comprehensively by any previous reviews [2,3,15,41] into human pedestrian loadings of floors. With probabilistic forcing functions established, a statistical spatial response assessment can be produced. This probabilistic framework will be the most reliable assessment tool for vibration serviceability assessment of floors.

2. Characteristics of Vibration in Floors

Modern methods of vibration serviceability assessment should, if properly formulated, define three key parameters; the vibration source, the vibration transmission path and the vibration receiver [42]. Rationalisation of floor vibration serviceability into these three characteristics is simple in concept, but can be difficult to implement in practical analysis and design [1].

2.1. Vibration Source (Input)

According to ISO 10137:2007 [42], the vibration source inside buildings can be defined as a force that generates dynamic actions that have both temporal variations (i.e., vary with time) and spatial variations (i.e., move in location) [1]. Examples are walking, which varies in both time and space and stationary equipment operation, which varies in time only. A single pedestrian is considered to be the most appropriate source of excitation for floors typically found in quiet offices [40,43] due to lack of synchronisation among a group of people in this environment. However, there is an increasing realisation [35,44] that a single person loading is rather rudimentary for assessment of vibration serviceability of floors and a more realistic approach is needed. Hence, the focus of this research study is on more sophisticated modelling of the vibration source for walking on floors.

2.2. Transmission Path (System)

The physical medium through which the vibration source is transmitted (conveyed) to the receiver can be defined as the transmission path [42]. Such a path incorporates all structural and non-structural elements attached to floor systems [1]. Dynamic properties of the transmission path are crucial to vibration serviceability. Mass can be computed fairly accurately from available physical and mechanical characteristics of floors, whereas stiffness is subjected to a high degree of uncertainty due to the influence of support conditions. Damping, a key parameter when resonance occurs, is not estimated as accurately [45]. Hence, information on floor system, mass, stiffness, damping and support conditions has to be taken into account as precisely as possible to estimate reliably the dynamic properties and thus vibration responses [46,47]. Typically, the lowest natural frequencies and mode shapes of floor structures can be obtained to a reasonable degree of accuracy using detailed numerical models but there is much more uncertainty with other dynamic properties such as modal masses [48] and hence, magnitudes of frequency response functions, particularly for higher modes. As such, there is more research required in this area.

2.3. Receiver (Output)

The vibration receiver is a person or an instrument within a building that experiences the structural motion [42]. Human comfort to floor vibrations is a subjective assessment based on the magnitude and perhaps the occurrence rate of vibration, whereas the performance of sensitive equipment may be impaired if the vibration magnitude is high. There are several established criteria in various design guidance documents, using various descriptors and metrics, to evaluate the vibration for human comfort. However, the available vibration assessment procedures and associated criteria are reported to be unreliable [30,49,50] and fail to deliver a satisfactory evaluation when compared to the actual human perception of vibrations in real life environments [51]. Therefore, improved understanding and reliable limits need to be produced to reflect more accurately the actual vibration experience of the receiver.

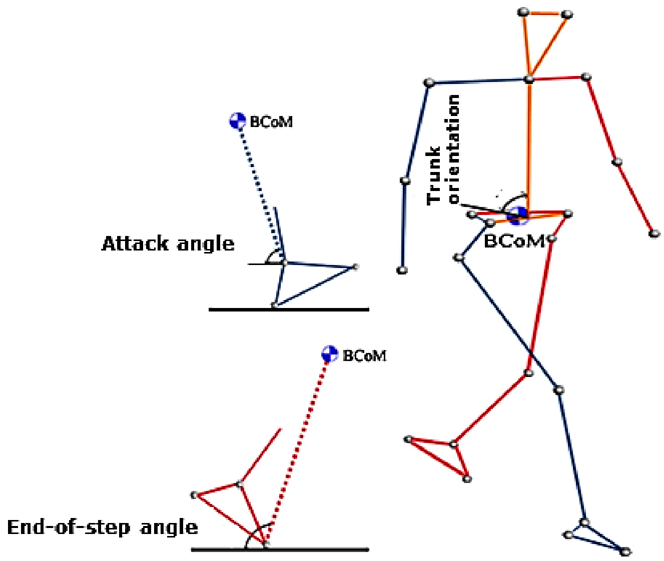
3. Human Induced Loading

3.1. Walking Parameters

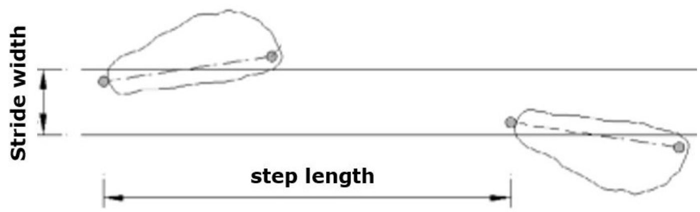
Human dynamic loading on floors can be categorised into two broad areas; walking and aerobic (rhythmic) loading. The former is when people walk on floors in different patterns, which may cause annoyance to occupants in quiet environments; this is a serviceability problem. The latter occurs when people exercise or perform strenuous physical activities on floors due to groups and crowds bouncing and jumping. In such cases, the force magnitude is relatively high and, if resonance occurs, it might cause the floor to suffer excessive movements thus becoming both a serviceability and strength issue at the same time [46]. It is argued that human-induced dynamic loads are complex due to individual pedestrian effects and their manner of dynamic excitation [52,53]. Such complexity can be attributed to the dependency of human-induced dynamic loading on a large number of parameters. Information on these parameters, well recognised in biomechanics [54,55], yet less well recognised in civil engineering, is of paramount importance in better understanding walking force functions and therefore floor vibration responses under walking excitation [56]. The reader is referred to [57] for more details.

3.1.1. Spatio-Temporal Gait Parameters

Walking is considered to be a temporal-spatial phenomenon [55]. This means that it can be described in terms of temporal and spatial parameters in addition to characteristics of a pedestrian (i.e., height, weight and so on). Temporal parameters can be grouped as: step frequency (cadence), speed, stride time, stance time, swing time, single and double support and similar. Spatial parameters, whose values change with location, are: step length, step width, foot angle, attack angle, end-of-step angle and trunk orientation [54,55,58], as shown in Figure 2. The reader is referred to [57] for more information on gait cycle.



(**a**)



(**b**)

Figure 2. Spatial walking parameters (after [58]). (**a**) Angle of different parameters with respect to Body Center of Mass (BCoM); (**b**) Step width and step length in one step cycle.

The temporal parameters are familiar to engineers, in particular step frequency and walking speed. The spatial gait parameters, however, are not fully investigated or incorporated in the context of vibration serviceability [58]. Lack of thorough studies for gait parameters may in fact result in inadequate walking force model.

3.1.2. Controlled Walking vs. Free Walking

The findings of gait parameters in available studies, for example [5,59–62], in many instances are inconsistent. Such discrepancies could be attributed to several aspects. Firstly, the diverse environments and methods of experimentation, which often are rather artificial. For example, the majority of the studies paid attention to temporal parameters measured mostly in laboratories. It is reported that in controlled environments and/or using metronome "high level of vibration are preserved and variabilities are missed" [44]; thus, pedestrians may not walk "naturally" [61]. Also, lack of extensive experimental data due to inadequate technology in different environments has resulted in a limited number of or insufficient parameters. Secondly, it is acknowledged that people from different locations have dissimilar parameters [34], which may be due to differences in lifestyle and characteristics of walking. Lastly, the inability to describe the inherent variability that occurs for walking pedestrians. These variations in walking have a great effect on the walking forcing function, which will be discussed in detail in Section 3.1.3. Therefore, it can be concluded that identification of characteristic features of the walking process is a crucial stage in developing a walking model. In fact, past studies have not yet reached a consensus regarding which are the critical parameters. Although correlations can be observed between walking parameters and pedestrian forcing functions, there is no single parameter that can individually provide a complete description of the walking process by itself [63]. The spatial parameters have just as much influence on walking as temporal parameters [58], in particular in floors where different walking patterns usually occur. Hence, a way forward might be to implement monitoring exercises, for example in real office environments, with advanced motion tracking technologies (presented in Section 6) in order to advance our knowledge of these phenomena.

3.1.3. Subject Variability

It has been reported that there are variations between real walking and mathematical models which result in mismatch of vibration responses. The differences are mainly due to subject variabilities and human-structure interactions [64]. The aspect of human-structure interaction (HSI) is not covered in this study since in normal office floors their effect is insignificant. The reader is referred to [65] for more information on HSI. Hence, this section provides insights into definition of two main subject variabilities in human walking. The occurrence of variabilities is caused by complexity of walking, which arises from inherent randomness within the bipedal locomotion. The intra-subject variability is variations that occur within the same pedestrian during walking. The variation that exists between pedestrians, such as walking speed and step frequency, is named inter-subject variability [13,47,57,58,64,66,67]. The variances that exist between individuals are a result of differences in gender, age, fitness, location, etc. [61]. These are uncertainties in walking that have a significant influence on vibration response level and its assessment [2].

For assessment of vibrations induced by walking, accurate prediction of vibration responses depends on a walker, in terms of force level, body weight, pacing frequency, walking velocity and so on [52,68]. Although there are suggestions [69] to choose a "sensible" value that can be applied to account for walking variabilities, no information is given for an appropriate range. These variabilities by their nature affect the real walking model, whereas previous studies that used Fourier series lost this significant information and hence, inaccurate data reduction was made [32].

3.2. Walking Models

Dynamic loading induced by pedestrians in normal walking involves loadings in the vertical, lateral and longitudinal directions. The vertical direction is exclusively considered in this study since it is the major component that causes vertical vibration and it is the most common source of annoyance and discomfort in floors [22,70]. In the literature, available models for forcing functions are generally expressed in two forms; deterministic and probabilistic. The former have been given significant attention in past research whereas the latter is relatively less well researched. Each of these groups of load models can either be expressed in the time domain or frequency domain.

3.2.1. Deterministic Walking Models

It is commonly assumed that the force generated in the time domain by a single walking person can be approximated by a perfectly repeating footstep at the pacing frequency [56]. The assumption of perfect repetition is also used in modelling loads generated by small groups. Hence, this type of forcing model is deterministic. The force produced by a person walking consists of distinct frequency components at integer multiples (harmonics) of the pacing frequency [56,71].

Using Fourier analysis, any periodic loading can be represented as the sum of a series of simple harmonic components and the response will also occur at these same frequencies for a linear structural system. Any forcing function $F(t)$ that is periodic and has a period T can be represented by a Fourier series as given by Equation (1). In 1972, Jacobs et al. [63] were the first ones who, in the biomechanics field of study, proposed and used the Fourier series to express the walking forcing function and it was supported by [72,73]. This method was then adopted by Blanchard et al. [74] for application in civil engineering to footbridge structures. Later, many researchers adopted the same method to produce a dynamic forcing function, to name a few [11,46,59,75–77]. Equation (1) consists of two main parts; a static part related to the weight of an individual and a time-varying part associated with the dynamic load [53]. As such, the dynamic load of the walking force is represented as follows:

$$F(t) = G\left[1 + \sum_{n=1}^{N} \alpha_n \sin(n2\pi f_p t + \Phi_n)\right] \quad (1)$$

where, $F(t)$ is the dynamic load (N); G is the static weight of a person (often assumed between 700 N and 800 N); n is order of harmonic of the pacing rate (integer multiples) (n = 1, 2, 3. . .); α_n is the Fourier coefficient (also known as Dynamic Load Factor - DLF) of harmonic n; f_p is pacing frequency (Hz); t is the time variable (s); Φ_n is the phase angle of harmonic n; N is the total number of harmonics considered.

It has been considered that the most significant parameters are DLFs and pacing frequency, since they are the main inputs in Fourier series. Hence, the focus of much prior research has been computing DLFs based on Fourier decomposition of measured time histories. Such quantifications of DLFs are the most common model when assuming deterministic dynamic forces [34] under walking. There are different suggestions on how many harmonic components, with corresponding DLFs, should be used. Previous studies considered different number of harmonics which generated deterministic values of DLFs, such as [56,59,71,75,76,78]. Although methods of measurements used and the number test subjects were different, the results exhibit clear indications of variation of DLFs among people during walking. The reader is referred to [5,6,56] for more insights.

It is noted that LFFs tend to exhibit near-resonant behaviour due to pedestrians walking where the step frequency or one of its harmonics matches a natural frequency of the floor. Conversely, HFFs tend to exhibit transient responses to individual footfalls. As such, two types of loading were deemed necessary [39] for LFFs and HFFs. This is owing to the lack of fundamental walking data and adequate mathematical models to describe the full amplitude spectrum of individual walking loading [57]. Nevertheless, there are indications [29,31,79] that walking has significant energy both at low harmonics and also at higher frequencies and hence, the demarcation between LFFs and HFFs lacks "scientific basis" [29], despite the fact that the cut-off frequency is commonly used.

From a frequency domain standpoint, a number of studies have remarked that footfall forces may be well represented in frequency domain [2,11,36,37,80]. Ohlsson [81] and Eriksson [43] used power spectral density to examine the energy of walking in frequency domain. Eriksson [43] concluded that walking is a narrow-band random process. As such, Brownjohn et al. [36] emphasised that, using power spectra, walking is a stochastic phenomenon and any forcing model should reflect the natural randomness in forcing function. Frequency domain analysis for LFFs is carried out by [29]. It is shown that frequency domain approach is less expensive in terms of time and storage spaces than the time domain analysis for a single person excitation. However, the extent of analysis was not investigated for multiple pedestrians.

It can be concluded that there is a need for more actual walking datasets to be expressed statistically, even though studies to date have shown the actual nature of walking to an extent and provided some useful data. Also, deterministic force models for floors, in their current forms, are no more an effective method to be used by design engineers, since they contain many simplifications, such as stationary excitations, a single average person and so on. These are not realistic representations of the actual loading [57]. It is noted that the majority of studies address walking of a single person in spite of existing multiple pedestrians traversing floors in daily uses of floors. There are indications showing that a single person excitation force model is not the best way of loading scenario, especially for office floors where many routes of walking are excited [35].

3.2.2. Probabilistic Walking Models for Individual Pedestrians

Probabilistic walking models can be regarded as statistical approaches in which the randomness of walking parameters, such as pacing frequency, weight, walking speed and so on, are taken into account. These approaches provide an equivalent model of walking of an individual that, in principle, is incapable of producing a perfectly periodic load time history.

Early works of probabilistic approaches were provided by [11,82,83], who considered step length, step duration and footfall function for individuals walking as a function of pacing frequency. Moreover, Brownjohn et al. [36] highlighted that past researchers had given little attention to the randomness of walking forces found in the various measurements of higher harmonics. They used an instrumented treadmill to measure the continuous walking force of three test subjects walking freely to investigate actual nature of walking. Due to the stochastic nature of walking loads and energy dispersion (see Figure 3a), a frequency domain model was proposed as an alternative approach to most previous work where time domain analyses were implemented to derive deterministic load models (as shown in Figure 3b). This study showed that there is a leakage of energy around the main harmonics of the pacing rate [13], which is due to the inherent randomness in walking. It is worth noting that the randomness has different levels at various pacing rates. Hence, a load model was proposed to include this randomness using pacing frequency as the input. This model lacks adequate statistical data to include subject variability due to a limited number of test subjects in the experiments. A number of investigations of subject variabilities have tended to use a large number of individuals to represent the variability of real walking, such 73 participants in [62], 80 in [32], 85 in [79] and 90 in [5].

Several studies have proposed that different parameters in the Fourier series, which is used primarily in the deterministic methods, should be modelled probabilistically [31,66,67,84]. The parameters are DLFs, human weight, arrival time, walking frequency and phase angle. It was claimed [85] that a 'fully' stochastic loading model, based on walking parameters, can be established for footbridges. The proposed model used only step frequency as the most significant parameter affecting the response rather than other parameters, which were used deterministically. This seems not to be a reliable method since in statistical modelling, there are some interconnections which cannot be defined deterministically [86], or at least they vary from one structure to another. In addition, Racic and Brownjohn [32] proposed a synthetic loading model based on a database of forces from an instrumented treadmill. The walking load model relies on random parameters being drawn from the experimental database, resulting in a detailed representation of both temporal and spectral features of the walking force. However, access to the experimental database is a prerequisite to implement the above model, which is not available to the public domain. A possible improvement would be to provide open-access measured walking datasets so as to use the model appropriately. Middleton [48] proposed a footfall model using a quadratic spline to model walking that is suitable for floors. However, this model relied on several fixed points to reconstruct the dynamic load based on the force level. This model can be improved by incorporating a wider range of frequency energy content and including subject variabilities in a statistical manner.

Recently, a study on a composite steel floor was conducted by Nguyen [5] in which a probabilistic force model based on Fourier series was proposed that defines both inter- and intra-subject variation. The weight of the human body was considered to be a mean weight of 750 N and standard deviation of 50 N. The intra-subject variability was considered by using a standard deviation (of 90 biomechanic participants) on step frequency, walking speed and step length of each participant with a probability of 5–10% chance of being exceeded; for example, the standard deviation of the step frequency is 0.083 Hz.

This model is lacking in several ways. Firstly, as mentioned earlier using Fourier series approach fundamental variability in walking will be lost. Secondly, the method assumed a straight walking path in the considered office floor, which appears to be unrealistic due to obstacles usually present in office developments that can have a significant effect on the floor response. Thirdly, the walking model was only applied on one configuration of floor and the effectiveness of the model on other floor systems is not clear. Hence, further investigations are required to include these parameters statistically since as far as modelling of walking is concerned, a stochastic approach is more appropriate as random walking paths and random parameters are considered [87,88].

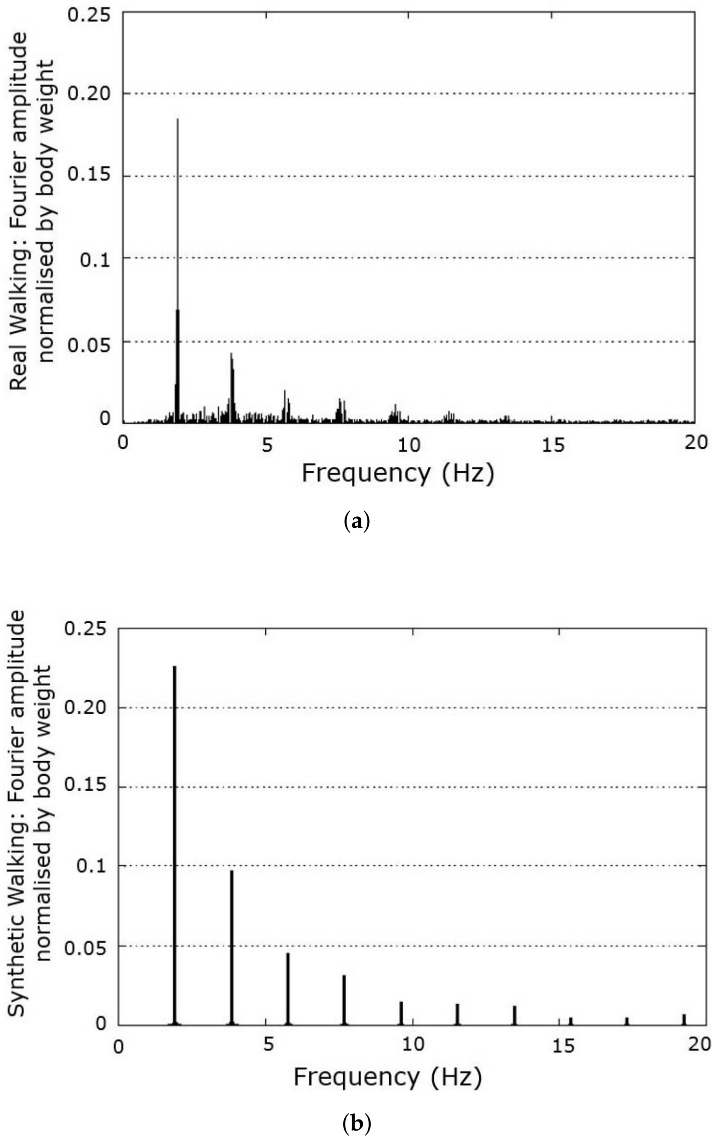


Figure 3. Frequency component of measured walking and deterministic models (after [36]). (**a**) Fourier amplitude of measured walking; (**b**) Fourier amplitude of synthetic walking from deterministic models.

In the light of the above discussion, it is obvious that vibration response of floors is sensitive to forcing function and simplified forcing models may not be reliable for assessment of floor vibration serviceability. A probabilistic approach is essential to better estimate the floor response under human walking excitation. To achieve that, actual floors, in terms of construction materials and configurations, should be monitored and numerical simulations developed based on a universal load model under a probabilistic framework.

3.2.3. Response Spectrum in Walking Models

Similar to other dynamic forces, such as seismic and wind, a number of researchers have been inspired by the response spectrum method, which is widely used in earthquake design. Despite the inherent simplifications in response spectra as it is only applicable to single degree of freedom (SDOF) structures [89], the intent is to produce a unified load model for excitation and hence, response estimation [79].

Georgakis and Ingolfsson [90] proposed a response spectrum approach based on the probability of occurrence of an event of response using numerical simulations. Mashaly et al. [89] proposed a response spectrum approach via a deterministic walking model on a footbridge to find vertical acceleration response. However, the forcing function was assumed to be stationary at the midspan. Chen et al. [62] paid attention to measured forces, using force plates and optical motion capture, to acquire statistics of test subjects for two sets of walking. One set was guided by a metronome and the other was free walking. Then, a response spectrum load model for DLFs was proposed, as shown in Figure 4.

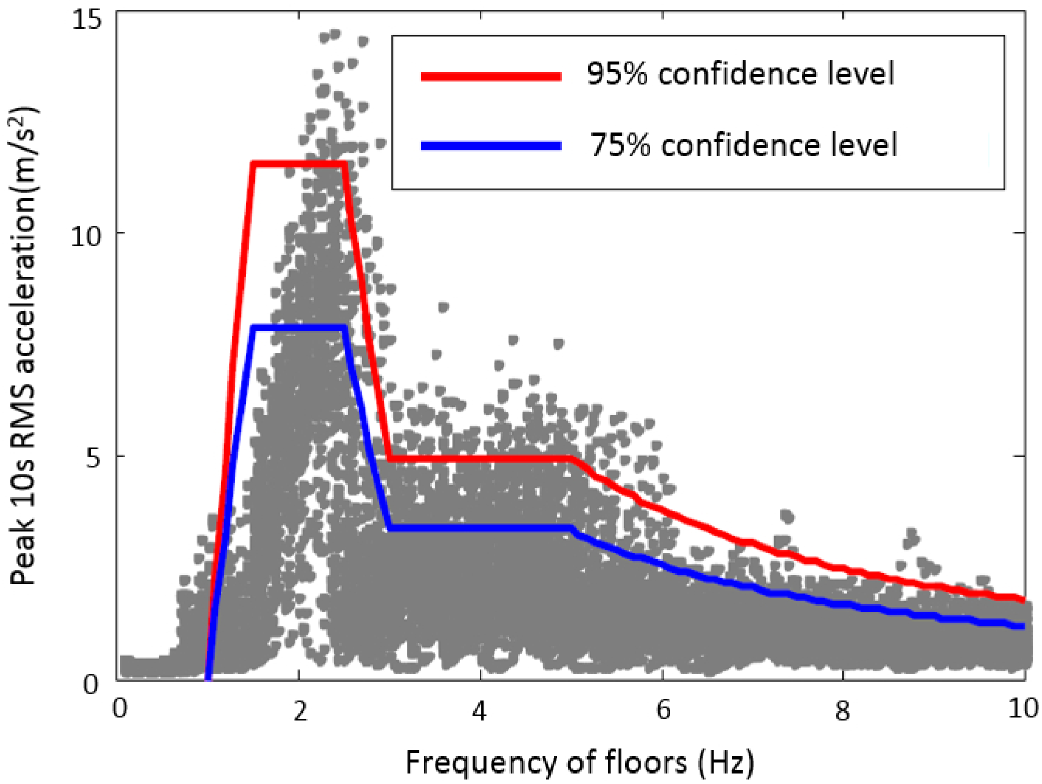


Figure 4. Response spectrum for floors under walking loading (after [62]).

An interesting observation made by this study is that there are sub-harmonics between the main harmonics, which are due to imperfection of the right and left steps in the gait cycle and thus a statistical method was deemed more appropriate.

Based on a large database of records from treadmills, Brownjohn et al. [79] proposed a response spectrum method for floors to evaluate vibration response measurements. This approach considers mode shape configurations and modal mass as important information to produce reliable vibration responses. It can be said that the response spectrum approach is actually a deterministic method since both the input and output are actual maximum values. Hence, the application of this methodology may not provide realistic vibration serviceability assessment of floors for actual multiple pedestrians, despite being flexible and fast for vibration response estimation [79,90].

3.3. Statistical Modelling Approaches for Multiple Pedestrians

Floors are usually used by a number of people, who they walk across the structure within certain existing walking paths [91]. Although, some multi-pedestrian loading models are available for crowd loads on footbridges [92,93] and grandstands [94], there is a considerable lack of information about realistic multi-pedestrian loading in floors [44]. So, the resulting response could potentially lead to human discomfort and adverse comments.

Existing guidelines [17–19,27,28,61] specify walking loading for individual pedestrians, where the load models consider a person as a stationary harmonic force. There are, however, indications [29,30] that none of the guidelines deliver a reliable vibration assessment process that allows a designer to predict realistically the vibration performance of a structure [31,44,49]. The main reason is that there is not a multiple pedestrian loading model available for floors for analysis of vibration response at the design stage, uncertainties related to dynamic properties and a lack of understanding associated with tolerance levels of occupants. In other words, the actual loading situations are simplified to an average single person loading, which does not represent reality use of floors. Also, the available single person force models in design guidelines are applied at a stationary position. However, spatial positions at different time instants would be imperative for multiple pedestrian walking excitation for which stationary harmonic forces cannot serve as a base function for such loading scenarios. Hence, the aforementioned load models do not tend to reflect the true nature of pedestrian excitation. These mechanisms to apply a probabilistic design process considering spatial patterns in walking excitation are not available and hence, the methods ignore human walking variabilities with respect to a walking path, duration of action performed and the actual frequency content of forces generated in the process [82]. Generally, pedestrians walk across floors randomly at different patterns (i.e., start point and end points [35]), walking paths (discussed in Section 3.4), entry into or exit from room, the number of active people at a particular time, walking characteristics, walking habits of people using the floor and so on [95].

There are some experimental data regarding the stochastic treatment of people arrival time in general [96] and particularly for floors [91,95], which follows a Poisson distribution. However, there is no experimental study to take into account spatial walking patterns of multiple pedestrians to drive a realistic relationship for existing patterns. In the case of insufficient experimental data, further developments use a probabilistic approach and numerical simulations to represent various start and end points within a typical office floor [35]. This approach is utilised to introduce parameters to quantify the main characteristics of walking and derive stochastic loads for various walking patterns.

The importance of numerical simulations, primarily Monte Carlo (MC) simulations, has been emphasised by many researchers, especially when the performance of a structure is of concern and experimental data are scarce. Although Sim et al. [94] point out that a sufficiently large dataset should be used for statistical analyses, MC simulations are in widespread use with random values generated from assumed normal distributions. Substantial simulations are chosen to get robust results by [5,97]. It was reported around 500,000 MC simulations is found to be a reasonable value to stably estimate statistical response distribution [85]. However, it is obvious that such a large number of simulations would be time-consuming, which is a downside of the MC approach. Therefore, a better pedestrian simulation model is needed to account for multiple pedestrians' pattern upon using floors. Pedestrian models exist based on techniques such as agent-based modelling [98] and social force modelling [99,100]. These models have been regarded to be effective in the context of human-induced bridge vibrations [65,93,101].

Actual walking paths and activities of occupants along different routes are a crucial step to establish a reliable and stochastic load model in contemporary design. This should include the randomness in walking paths (covered in the next section) chosen by different individuals and both temporal and spatial features of the force. There is a lack of fundamental data for many relevant load case scenarios, especially for multiple pedestrians, where different walking patterns are chosen by individuals. As a result, more experimental data are required over long periods so that realistic multiple pedestrian excitations and corresponding vibration responses can be collected. Utilising a sophisticated load model is essential to generate multiple pedestrian loads and predict the vibration response in a sufficiently accurate manner, i.e., significant overestimation and considerable underestimation of the response should be avoided. More advanced numerical modelling of multiple pedestrians could pave the way for more reliable estimates of floor vibration response.

3.4. Walking Path (Route of Pedestrian)

In the context of vibration response prediction, the walking path plays a major role [102], yet has not received attention in previous research. Most studies consider route of walking as a deterministic parameter based on the assumption that a particular walking path produces a worst case-scenario. This is an inherent simplification which raises concerns about the reliability of the response assessment.

It has been reported that the walking path is an important parameter in considering vibration of a floor; the path can traverse several mode amplitudes of a mode shape which in turn could generate resonance or near resonant response. This will vary according to which mode needs to be excited [87]. For a vibration floor assessment conducted by Reynolds and Pavic [40], pre-determined walking paths and pacing frequencies were used to create worst-case scenarios for vibration response measurements. Three walking paths, one through the middle and the other two along the diagonal of a floor, were used based on engineering judgements to excite the vibration modes of interest. Other researchers have sought a relation between walking path and entering time of individuals [11]. Through this it is assumed that the randomness of arrival time amongst multiple pedestrians is defined. However, this alone is not a realistic estimation of various paths and their realistic effect on the response prediction, since different individuals have different excitation potentials along various paths [52].

Willford et al. [69] stated that pedestrian walking paths are one of the parameters that is difficult to obtain or define at the design stage, which makes vibration response prediction difficult. Hicks and Smith [102] ascertained that different walking paths considerably affect vibration responses. However, no explanation has been given on how the route of walking can be included or estimated. The significance of walking path, particularly in low frequency floors, is that a pedestrian traversing a floor can cause resonant build-up of response if the walking path is sufficiently long. The duration of walking and the relevant mode shape modulation need to be considered along the walking path. However, it is acknowledged that the modulation of mode shape is not easily accounted for in the current forms of vibration serviceability assessment. As a consequence, overestimation and underestimation of the response have been reported in the current guidelines [13,29,30]. Smith et al. in the Steel Construction Institute publication (SCI P354) [18] stated that the walking path along with the length of walking have effects on the vibration response, yet no comprehensive procedure is given on how they can be incorporated into the vibration assessment. Only very rudimentary techniques formulated in terms of “build up factors” are given in some of the design guidance documents.

In his doctoral thesis, Nguyen [5] assumed that the walking path “follows the configuration of a mode shape”. The walking path was considered to excite the “relevant” mode shape, which was thought to produce maximum response. However, this assumption results in no definitive outcome since in floors the vibration mode shapes are quite closely spaced. Therefore, walking path should be considered on that part of a floor where the vibration “tolerance” is expected to be low. In other words, the walking path should represent the worst case scenario, yet in a statistical manner that would induce the most annoying vibration on the floor via a spatial distribution of the walking paths. This approach will take into account probabilistic distribution of various (random) routes across the whole floor, including the obstacles avoided by the pedestrians.

Considering floor monitoring, Živanović et al. [44] monitored an office floor during a normal working day. The focus was more in preselected paths with controlled walking which were thought to be most responsive. The study points out that usually a single pedestrian excitation would not give realistic estimates when compared with actual in-service vibrations of floors. It is argued that [44,95] all responses measured during single person walking tests had considerably less than 1 percent chance of being exceeded during normal daily use of an office floor. Therefore, the single person loading scenario is not the best way to estimate vibration serviceability of floor structures (as discussed in Section 3.3).

In a comprehensive way, Hudson and Reynolds [35] implemented various start and end points in an actual office floor where office occupants used the most; for example, near corridors are considered as walking paths. This approach gave more realistic consideration of the most used paths and gave good probabilistic assessment of the response. Thus, such an approach can be improved upon to obtain a probabilistic unified walking load model through which cumulative probabilistic responses are generated, not only at a sole location, but over the entire floor area. The probabilistic approach could entail realistic paths through a spatial distribution of multiple routes traversed by floor occupants. This in turn can generate a spatial response distribution (as discussed in Section 5) so that response assessment can be carried out on the basis of probability of exceedance. Thus, a more reliable vibration assessment of floors can be obtained.

In conclusion, the walking path has a significant effect on the vibration response on floors. This parameter, along with other walking parameters, should be considered statistically in the forcing function. The way forward is to develop a walking model in which spatial walking paths and walking parameters are characterized by their stochastic nature. There is a need for including pedestrian paths into walking models so that a more accurate yet reliable approach is utilised in the context of probabilistic response assessment. As such, a statistical approach would result in a better estimate of floor performance when subjected to multi-pedestrian walking. In addition, acquisition of experimental data on floor responses via monitoring techniques (covered in Section 6) accompanied by occupant activities and actual walking paths utilised during normal working days are of crucial importance to establish reliable and non-conservative models.

4. Contemporary Design Guidelines and Codes of Practice

This section considers briefly currently available guidance documents [17–19,26–28,103–105] used for vibration serviceability assessment of floors at the design stage. A more rigorous analysis of these guidance documents is presented in [30].

A range of footfall loading functions have been presented from vibration design guidelines that are deemed to be applicable to a range of structural systems. These guidelines demonstrate clear differences with respect to the frequency threshold (cut-off frequency), which are not realistic [106], nor in accordance with scientific method [29]. The key deficiencies of these guidelines can be summarised in a few points. Firstly, the walking model is considered to be periodic and a single pedestrian is the only loading scenario. All of the design procedures introduced assume that walking is deterministic. Not all guidelines provide necessary information to model inherent variabilities, which results in errors in vibration response estimation. Secondly, the walking path is noted to be of great importance but existing guidelines nevertheless lack procedures to incorporate it. In other words, the excitation force is generally assumed to be stationary. Thus, significant overestimation or underestimation of responses predictions are often produced by the guidelines. Finally, a single peak value of the response is the sole descriptor for vibration assessment, which is not representative of the overall temporally varying vibration environment to which occupants are exposed and hence, is unrepresentative and unreliable [44,51,69,102,107,108].

5. Probabilistic Response Distribution

Stochastic nature of walking will yield profiles of a response that is non-deterministic and can more appropriately be defined in a statistical sense [109]. In essence, the response, in any metrics, of human-induced loading should be considered probabilistically for vibration serviceability assessment.

In order to assess the vibration serviceability of floors and its effect on occupants, there are well-known existing metrics, such as R factors, acceleration, root-mean-square acceleration (RMS) and vibration dose values (VDVs) [1]. Reynolds and Pavic [40] highlighted that there seems to be difficulty in defining which parameter provides the best response evaluation. Currently, R factors are used by some guidelines (Concrete Society 2005 [26], Concrete Centre 2006 [27], SCI P354 2009 [18]). R factors are calculated by a running RMS with 1 s or 10 s integration time and the peak of this running RMS (termed maximum transient vibration value (MTVV)) divided by the baseline acceleration is used for assessment [40,110]. However, it is reported that assessment of responses based on peak acceleration is "highly sensitive" to short duration peaks in the response [49,50]. Hence, it is stated that assessing vibration responses using peak RMS is not a "reliable" descriptor and a more appropriate parameter should be defined [87,111].

The vibration dose value (VDV) is currently considered to be the most appropriate evaluation parameter in assessing vibration serviceability, as it takes into account duration of exposure and is applicable for all types of vibration (periodic, transient and random) [1,69,111–115]. A potential problem with VDVs is that the available limits (such as limits in BS6472 [116]) are considered to be too high when compared with actual in-service monitoring of floors [49]. It is observed that a reasonable VDV limit for 16-h daytime exposures in office buildings is around 0.15 $m/s^{1.75}$, above which adverse comment might be expected [49], which is far less than the available limits (0.4–0.8 $m/s^{1.75}$). In addition, Setareh [115] has recently proposed a new VDV limit for footbridges, which is 0.2 $m/s^{1.75}$ for low possibility of adverse comment of a standing person. Hence, vibration measurements of existing structures have revealed that the current limits, both for the VDVs and R-factors, are inaccurate and may result in clearly unsatisfactory structures to be deemed satisfactory. It should be stressed that the design guidelines ([17,18,26–28]) provide some of the aforementioned metrics with various limits without giving distinction of their interpretations in assessment procedures. Pedersen [117] accordingly stated that the reason that several codes and guidelines propose various parameters to assess vibrations imply that there is not a "consensus" among international committees to use a unified parameter, let alone a probabilistic assessment.

In this context, the majority of studies either use RMS or R factor in assessing vibrations. However, an important question may arise in which whether a single maximum value of these parameters or a cumulative probability distribution will yield better results. Increasing studies [31,35,65] indicate that a single value evaluation does not represent actual responses. For example, Reynolds and Pavic [49] as well as Hudson and Reynolds [35] produced a cumulative probability distribution function (PDF) of the R factors of an office floor monitored under normal operation for several days, as shown in Figure 5. Such probabilistic response distribution gave a realistic insight into the response over a long period of time in actual environments. Similarly, Živanović and Pavic [31] generated the cumulative distribution of the running RMS. These studies highlight that a single maximum value of R factor is unrepresentative and inaccurate compared to the actual response, for it tends to occur only at rare time intervals. However, the running R factor using cumulative distribution gives better impression of the response distribution with a probability of exceedance.

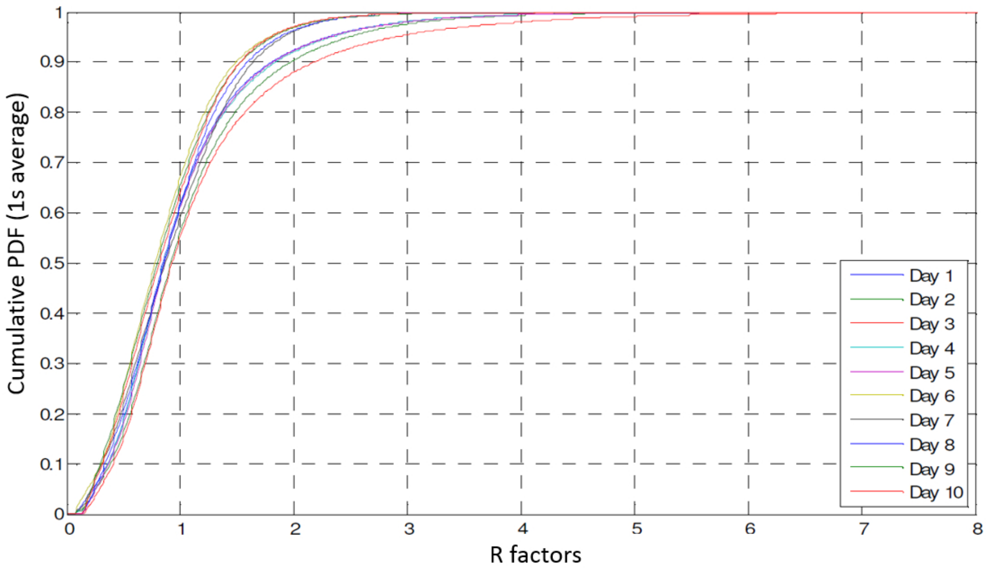


Figure 5. Cumulative distribution of R factors in office floor buildings (after [49]).

The majority of available literature considers evaluation of responses over time, this could be a single peak value or a statistical evaluation which is still under investigation. However, it is also imperative for accurate prediction of the response to take into account the spatial distribution of the vibration response. This is particularly essential where multiple pedestrians are crossing floors in normal operations and stay on their desks for a long period of time, which maximise their dose exposure to vibration. Combining both the spatial and the temporal response over the floor areas at the design stage may predict the possible areas with higher responses and their occurrence rates. This area of research is lacking thorough examination. Hudson and Reynolds [35] indicated that the spatial distribution of response can be very reliable as it highlights which areas experience higher vibrations (Figure 6). Of these areas, the vibration response may have a predetermined limit in order to be assessed and if that limit exceeded what would be the probability of occurrence. Devin et al. [118] also ascertained this method under a single person loading to produce a "contour plot of responses". In addition, there are a number of commercial software packages, such as Oasys GSA [119], Autodesk Robot Structural Analysis [120], SAP2000 [121] and ETABS [122], that define harmonic footfall analysis for a single person excitation at stationary positions based on design guidelines, such as Concrete Centre [27], SCI P354 [18] and AISC DG11 [17]. Results of the analysis produce contour plots of vibration responses at all nodes in terms of peak R factor or acceleration. However, there is no mechanism to include moving pedestrians along different walking paths.

Identifying spatial response distributions of floors seems to provide better indications of the level of response expected for assessment in accordance with the relevant vibration criterion. Pedestrian pattern modelling, i.e., microscopic and macroscopic models [101], for multiple pedestrians movements can provide significant insights for spatial response distributions. The way forward therefore would be to include knowledge of spatial positions of pedestrians at different time instants combined with a stochastic walking load model to generate vibration responses. Introducing spatial response distributions would capture the exposure route and exposure time under actual loading scenario.

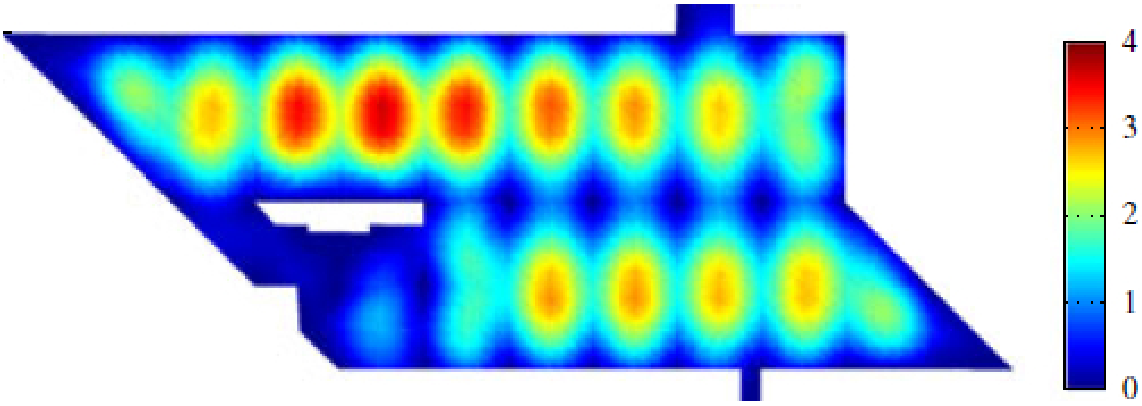


Figure 6. Spatial distribution of R-factor in a typical office floor (after [35]).

Therefore, it is necessary to evaluate vibration response of floors in a probabilistic framework, similar to the loading function. Better assessment of floors may be achieved by using the appropriate metric parameters and their values should be on the basis of probability of occurrence over the floor area, where multi-pedestrian walking occur. The spatial response coupled with the cumulative distribution of vibration responses might provide a more reliable and realistic approach for use at the design stage, for which there currently is no analytical procedure. As such, development of analytical techniques verified through experimental investigations might provide a mechanism for improved vibration response assessment.

6. Pedestrian Monitoring Techniques

A range of monitoring techniques have been discussed (e.g., [123–126]) to obtain walking patterns of relevant walking entities. This section gives an overview of existing in-service monitoring techniques using motion tracking. The main purpose is to better utilise these new techniques in establishing spatio-temporal variation data of walking and thereby developing a realistic loading model. However, the rational for using the monitoring techniques is to take into account the unconstrained floor spaces; that is experimental data should reflect the natural environments of the structures being monitored.

Monitoring tracking techniques can be categorised into the following systems for the purpose of acquiring pedestrian data. Vision-based motion tracking systems that use tracking markers, called marker-based systems, such as Codamotion and Vicon [62]. Video cameras, termed as marker-free systems, which involve image processing. The third category is motion tracking inertial sensors. These can be wired (standard accelerometers) and wireless (such as inertial sensors Xsens and Opal). It is noted that using these technologies are situation-dependent [127] and their use can be limited in different environments. For example, marker-based systems tend to become less effective in areas where there is daylight interaction, whereas wireless inertial sensors are costly and the wireless range is limited [127]. Video cameras coupled with vision tracking system have been used mainly for indoor activities. Extra care should be taken to avoid occlusion of cameras field of view when this system is deployed. Thus, selection of any of these systems should be able to capture spatio-temporal data realistically and as accurately as possible.

Use of motion monitoring techniques to track human walking on building floors is rare. Several researchers [91,123,128] have utilised video cameras to investigate normal pedestrian traffic, walking parameters and the vibration of as-built footbridges. Kretz [129] attempted to investigate the counterflow of people walking, using three cameras, in a 1.98 m wide by 34 m long corridor. The study focused more on the walking speed, passing time and the effect of a large flux of people. In office floors, however, the situation is different due to the open-plan layout and various routes of walking. Thus, it is important to implement a number of video cameras coupled with vision tracking software to track pedestrian routes and hence, produce a spatial distribution of different paths, which can be described with the probability of occurrence.

Most recently, vision based motion tracking systems have made significant advancements due to developments in computer sciences requirement for security (surveillance) purposes, where special cameras are integrated with in-built software or wireless markers. However, there seems to be no application of using a tracking system for people in civil engineering structures. Such systems would create a potential for studying human walking on floors and their movements [124]. Recently, Chen et al. [62] used a Vicon motion capture system in a laboratory to monitor the spatial trajectory of 73 test subjects during walking. Dang and Živanović [58] used a motion tracking system coupled with a treadmill in a laboratory to monitor body movements and hence, key elements of walking parameters were focused on. Also, Van Nimmen et al. [125] used motion tracking system in a laboratory to obtain step frequency of test subjects. The findings of the laboratory results were then used on a full-scale footbridge. Another contribution related to human evacuations of buildings has used Microsoft Kinect system [130] in a corridor to track the "head trajectory" of people's location, where pedestrian flow and counter flow were of interest.

There are other methods in which CCTV cameras are linked with vision tracking software. For example, Brandle et al. [131] used IP surveillance cameras with human tracking software in a railway station to capture where people stop and which areas are more concentrated. It was concluded that number and location of cameras are important. However, multiple human tracking was not included due to the complexity.

A more thorough study was carried out by [127], in which a method is proposed based on video-based algorithm to detect people on a camera then validated by Codamotion and Opal ground data (marker-based). The conclusion was that the vision-based system has the potential to be used without any markers attached to people, in spite of some possible errors.

Therefore, use of new advancements and techniques in vision tracking system to capture key parameters of human walking in as-built floor structures will, possibly, pave the way for better understanding of occupants' location and their walking paths on floors. Despite challenges and errors that are inevitable in any new system, the vision tracking systems might be feasible for use on floor structures to further investigate their vibration behaviour.

These technologies and techniques can provide information regarding the location of people, patterns of walking under normal working days and the statistical distribution of walking paths. These data assist in producing a probabilistic spatial variation of walking patterns where floor occupants using most. Thus, a better, yet realistic pedestrian load model can be developed based on the data collected from the vision tracking systems.

7. Conclusions

This paper has presented a comprehensive and state-of-the-art review on pedestrian load models proposed for assessing vibration serviceability of floors. It has addressed the importance of available walking parameters and walking paths in order to develop a sensible probabilistic model. Although none of the existing models is regarded as the most reliable and accurate in predicting vibration responses, the temporal coverage of walking parameters may be inadequate alone for a spatio-temporal loading such as walking.

A number of models have been reported to model walking of a single pedestrian, both deterministic and probabilistic. Many of these either have no pedestrian subject variabilities included and contain unrepresentative simplifications or are probabilistic in the sense that they focus on particular walking parameters and neglect other important entities. In particular, the spatial parameters and walking paths are not covered by all of these models, i.e., the routes covered by floor occupants in normal floor operations are not incorporated. Typical floors often accommodate multiple pedestrians with various walking patterns. Actual walking path and activities of occupants along different routes are a crucial step to establish a reliable loading model. This should include the randomness in walking paths chosen by different individuals and both temporal and spatial features of the force. As a result, more experimental data collected over long periods are required so that realistic multiple pedestrian excitations and thus corresponding vibration responses could be measured. Utilising a probabilistic loading model is essential to generate multiple pedestrian loads and predict the vibration response sufficiently accurately, i.e., large overestimation and considerable underestimation of the response should be avoided. The loading model integrated with numerical simulations would pave way for more reliable estimates of the vibration response of floors. It is suggested that a spatio-temporal multiple pedestrian loading of walking could be a more reliable model in vibration assessment and further work should focus on developing such models.

Following the review of different walking models, a review of vibration response assessment has been presented. Most of the vibration descriptors and tolerance limits provided by the prevalent guidelines and studies are highly dependent on a single peak value, where the assessment procedure fails to deliver a reliable prediction. However, as walking is a spatio-temporal dynamic load, the vibration response tends to become a spatial distribution of response. A more reliable load model with response prediction can be developed to obtain a probabilistic unified walking loading model through which cumulative probabilistic responses are generated, not only at a sole location, but over the entire floor area. The probabilistic approach could entail realistic paths through a spatial distribution of multiple routes traversed by floor occupants. This in turn can generate a spatial response distribution so that the response assessment can be carried out on the basis of probability of exceedance. This provides motivation for further research on the statistical relationships and development of improved spatio-temporal models for both the load and response. A probabilistic response distribution may have a predetermined limit with a probability of exceedance in order to assess floors adequately with respect to a vibration criterion.

It is essential to merge experimental and analytical activities in the research and definition of spatial distribution of walking paths traversed by floor occupants in order to produce methods for calculation of probabilistic spatial response. Experiments can inform the development of analytical models to describe the actual walking paths obtained utilising advanced vision tracking technologies. A stochastic approach, in both the walking loading and the vibration response will serve design engineers sufficiently precise in predicting the response and hence, a more reliable vibration assessment.

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