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Invited paper

Emerging research on vibration serviceability assessment of pedestrian structures

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ABSTRACT

Despite an increasing number of reported vibration serviceability problems caused by pedestrians walking on newly built footbridges, floors, and staircases around the world, there is still a lack of adequate codes of practice. There are three key issues that a new generation of relevant design guidelines should urgently address: (1) the absence of a universal model that accounts for the entire energy spectrum of walking loading as well as inter- and intra-subject variability of individual walking forces; (2) the effect of human bodies on the dynamic properties of a structure; and (3) pedestrian "intelligent" interaction with the surrounding people and environment. This article provides a brief overview of the relevant state-of-the-art research that has great potential to change this unsatisfactory state of affairs.

1 Introduction

Substantial developments in workmanship and structural materials aided by digitalisation of structural analysis have enabled daring architects and structural engineers to promote elegant but lightweight and flexible structures. As structures are becoming slenderer than ever, vibration serviceability assessment under pedestrian-induced dynamic excitation has become a routine requirement requirement in contemporary design [1-5]. While running and jumping produce more dramatic vibration responses [6,] walking is the most common form of locomotion and can be sustained for longer periods of time. Having reduced the natural frequency, this means an increased likelihood of a resonant response.

Predicting vibration responses reliably is a vital component of structural design. Retrofits after construction come at a high price and take time. For example, using tune-mass dampers to solve the lateral sway problem of the London Millennium Bridge increased the structure's cost by 30% and took two years to complete [7, 8]. Extra material is frequently added in common engineering practice to increase stiffness and/or mass in order to shift natural frequencies. For instance, an additional concrete topping is frequently placed on floor slabs and bridge decks to increase their weight. Regarding the global campaign to urgently reduce unnecessary embodied carbon emissions from the structure, the addition of excess material is increasingly deemed unacceptable [9].

Generally speaking, the formal procedure for the design of any structure for which pedestrian dynamic loading is a major concern involves: (1) establishing acceptance criteria, (2) determining the dynamic design loads, (3) creating a structural model, (4) simulating the structure´s response to the loads, (5) comparing results against the acceptance criteria, and (6) if necessary, adjusting the structural model, then repeating steps (4), (5) and (6) until satisfactory performance is achieved. Of all these steps, determining the design load has the greatest uncertainty, and to this end, there have been numerous attempts to provide reliable and practical descriptions of pedestrian induced forces. This issue will be elaborated in Section 2.

There is a widespread yet utterly wrong assumption that walking people affect structural vibrations only through the inertia of their moving body mass, thereby acting only as the dynamic excitation [6]. In reality, human bodies are mechanisms with mass, stiffness, and damping. When attached to the structure, they have the power to alter the modal properties of the empty structure [10]. Generally known as “human-structure interaction” (HSI), this aspect of the human influence on structural vibration will be discussed in Section 3.

A single pedestrian walking is a hardly relevant load case scenario for footbridges. Pedestrian groups and ultimately crowds are a far more likely source of dynamic excitation in urban environments. However, due to multiple pedestrian occupants, there is a severe lack of reliable force and HSI models, as will be revealed in Section 4.

2 Dynamic loading due to individuals walking

The modern design guidelines and codes of practice model a pedestrian as a moving force F(t) generated at the point of contact between the feet and the supporting structure, known as "ground reaction force" or GRF (Figure 1). It is traditionally modelled as a deterministic and perfectly periodic function (Figure 2), presentable by the sum of the first few dominant Fourier harmonics [6, 11, 12]:

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$$F(t) = W + \sum_{n=1}^{N} A_n \sin(2\pi n f_p + \theta_n) \quad (1)$$

Here, f_p is walking frequency (also called pacing rate), W is the mean value (equivalent to the body weight of a pedestrian), A_n are harmonic amplitudes, θ_n are the corresponding phase angles, and N determines the number of harmonics considered in a model. One harmonic is tuned to match the frequency of a target mode of the structure to induce resonance (Figure 1a). The simplest such model is a single sinusoidal function and can be found in the current UK [13] and Canadian [14] design codes for footbridges. On the other hand, vibration design guidelines primarily for floors [15-18] provide for up to four harmonics. There are models comprising even the sixth harmonic [19]. In the time domain, vibration analysis of the structure is assumed to be linearly elastic. Based on the principles of modal decomposition, the vibration response of each mode can be studied separately using harmonic loads described by the appropriate mode shape to account for the moving load [20].

The weight-normalised coefficients $\alpha_n = A_n/W$ are commonly reported in the literature as dynamic load factors (DLFs), which depend on walking frequency f_p and a person's manner of walking [6]. In a comprehensive experimental study of walking DLFs, Kerr [21] observed a wide variability of DLF values among different pedestrians while walking at different walking frequencies, so called “inter-subject variability”. Based on Kerr’s dataset, Young [22] fitted a frequency-dependent mean and coefficient of variation for the first four DLFs. These deterministic DLF functions are most widely used in the design of pedestrian structures [6]. Deterministic means that there is a uniform force model for naturally diverse individuals, thereby neglecting the true stochastic nature of walking loading.

The random nature of phase angles θ_n has been utilised very little in design practice. This is because vibration analysis focuses mostly on the resonance due to a single harmonic, so the phase angles have no influence on the overall response. However, when the modes are closely spaced phase angles determine if the responses due to each harmonic result in an increase or decrease in the overall vibration level.

The Fourier modelling approach described by Equation (1) seems too good to be true. Years of experimental and analytical research, as well as application in design practice, have shown that the Fourier characterization is insufficient to reliably describe walking loading. Brownjohn et al. [23] showed that perfect periodicity oversimplifies reality, yielding inaccuracies as high as 50% between simulated and measured vertical vibrations. Rare studies [24] addressed the randomness of inter-subject variability by providing statistical distributions of DLFs. However, a model of intra-subject variability that would address the near-periodic nature of successive footfalls is yet to be seen.

Modern research laboratories and hospitals increasingly accommodate equipment sensitive to even micro-levels of non-resonant vibration. The high-frequency content of walking has become relevant for the design of “high-frequency floors”, i.e., when the natural frequency of the fundamental mode of vibration is far above the average pacing rate. Their vibration response has a series of transient decays due to each footfall (Figure 1c). No resonant buildup of vibrations (Figure 1a) can be developed due to the high level of damping that is typical for HFF [25].

The difference in the nature of resonant and transient vibration responses (Figure 1a and 1c) has led to a requirement for two conceptually distinct walking force models used in the design guidelines of low-frequency and high-frequency structures. For floors, the most-up-to date guidance is available in Appendix G [17] of the Concrete Society Technical Report 43 (CSTR43). It provides design values of DLFs for single pedestrians on low-frequency floors (i.e., if f_n<10 Hz) and equivalent impulse values (Equation 2) for high-frequency floors (i.e., if f_n>10 Hz).

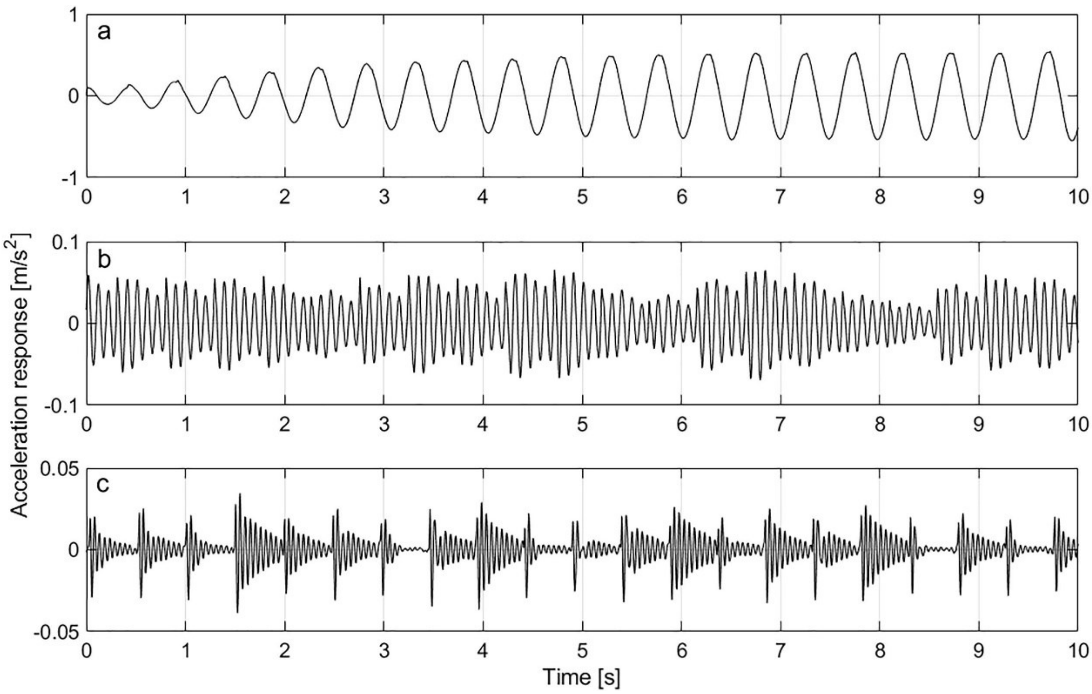

Figure 1. Measured vibration responses of a floor with the fundamental frequency a) 2 Hz, b) 10 Hz and c) 20 Hz due to an individual walking at f_p=2 Hz (after [33])

$$I_{eff} = 54\frac{f_p^{1.43}}{f_n^{1.3}} \quad (2)$$

This artificial division proves unreliable when the fundamental frequency of a floor is close to the cut-off frequency between the low-frequency and high-frequency floors (Figure 1b), which clearly indicates the need for a uniform model capable of taking into account the complete frequency content of walking forces [6, 11]. In an attempt to overcome this problem, Zivanovic and Pavic [26] merged together the Appendix G impulses and their previously published low-frequency force model based on the Fourier approach [27]. The new model takes into account the differences in the walking force induced by different people and, as a result, can estimate the probability distribution of vibration responses generated by a pedestrian population. However, Middleton [28] showed that inter-subject variations do not affect the dynamic response as much as variations in an individual's pace rate for successive steps. This randomness is called "intra-subject variability", which essentially means that people do not walk regularly like robots. In the case of high-frequency floors, a lack of these variations can overestimate response by up to 40%. Various authors [23, 29-31] showed that the actual narrow-band nature of the forces could be described in the frequency domain via auto-spectral density (ASD). However, predicted acceleration provides no information about the expected performance of the structure in real time. For instance, when and where do the peak responses happen? Therefore, a reliable time-domain model of walking forces is clearly the way forward.

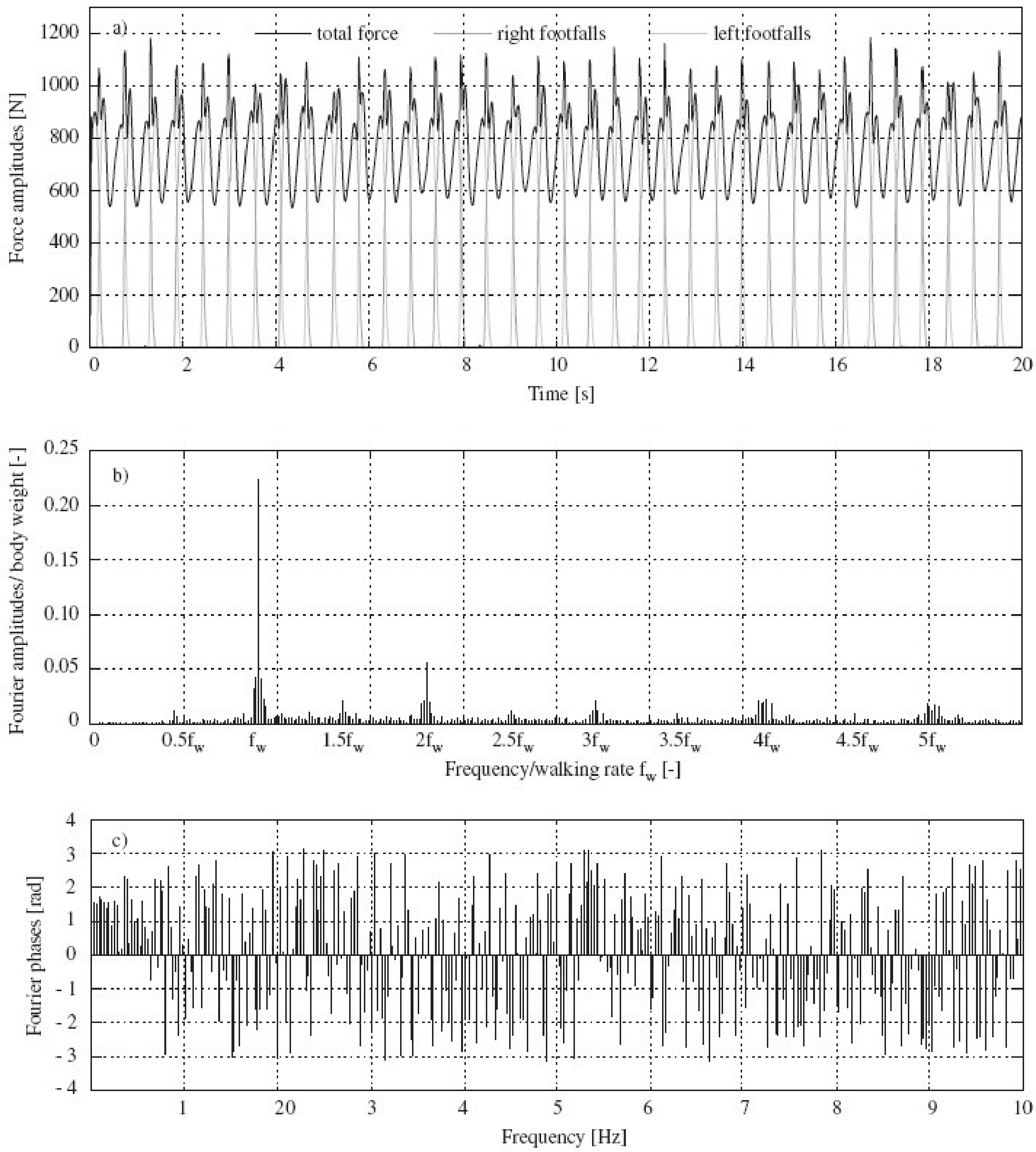

Figure 2. Vertical walking force record. After Racic and Brownjohn [11]

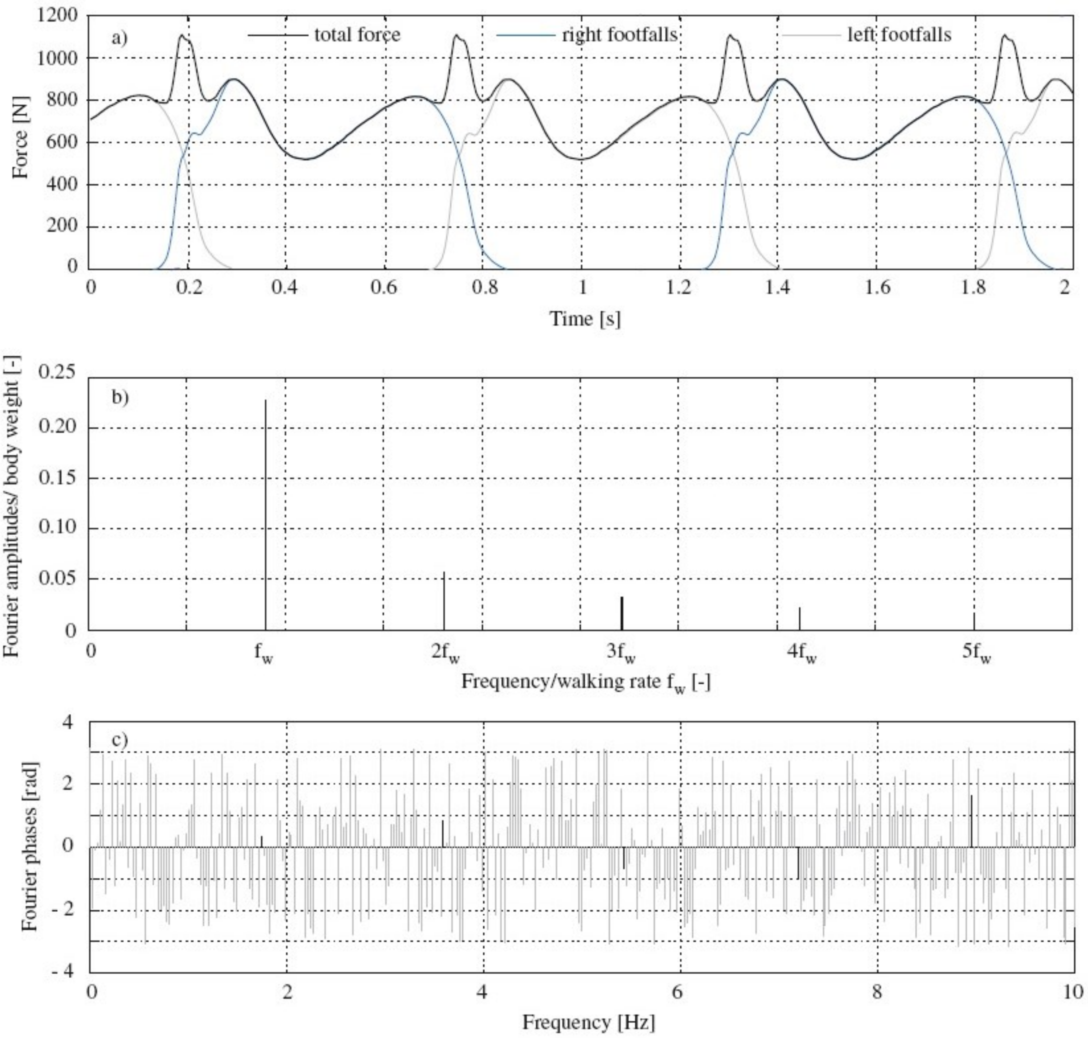

Figure 3. Periodic approximation of the force record shown in Figure 1. After Racic and Brownjohn [11]

A significant move toward a more realistic description of individual walking loads was made recently by taking into account the inter- and intra-subject variability of the pedestrians as a stochastic process. While the models of Racic et al. [11, 12] , Zivanovic et al. [27] , García-Diéguez et al. [32], and Muhammad et al.[33] all provide the best-to-date estimations of vibration levels, they require extensive and time consuming coding. The luxury of time is not often given to structural engineers in everyday design practice. Van Nimmen et al. [34] studied the vibration response records of real footbridges to prove that the variation in the individual footfall rate is the key force parameter needed for simulating accurately the shape of the vibration response (Figure 4). Moreover, they speculated that the apparent differences between measured and simulated vibration amplitudes could be attributed to the HSI phenomenon, which will be discussed in the next section.

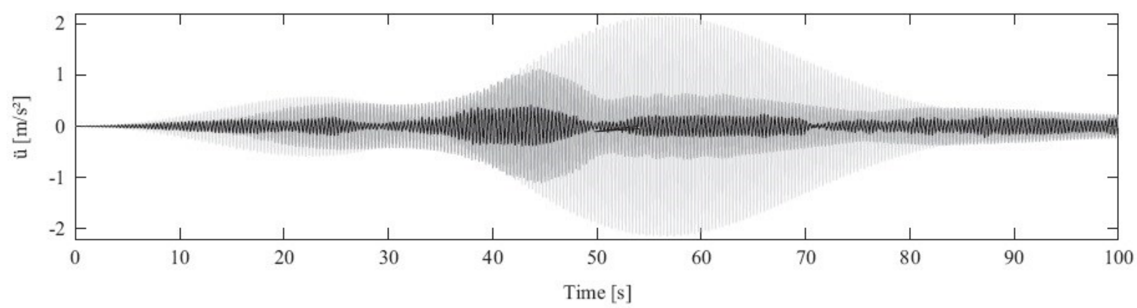

Figure 4. Vertical acceleration at the mid-span of a bridge: measured (black), simulated using perfectly periodic force of a kind shown in Figure 2 (light grey) and simulated using identical footfall shapes but different footfall rates (dark grey). After van Nimmen et al. [34]

3 Human-structure interaction

The HSI has been intensively studied in the lateral direction [35-37] since the infamous vibration problem of the London Millennium Bridge in 2000 [7]. It is now widely accepted that pedestrians are complex, vibration-sensitive dynamic systems whose lateral motion and corresponding contact forces are likely to be influenced by the lateral sway of the supporting structure. Moreover, they often synchronise their footfalls with the lateral structural motion (the so-called "lateral lock-in" effect), and thereby supply energy within the coupled pedestrian-structure dynamic system while acting as negative dampers [8]. On the other hand, very little is known about HSI in the vertical direction. Rare studies indicate that the individuals mainly add damping to vertical vibrations without necessarily involving the vertical lock-in effect [36].

Two types of coupled pedestrian-structure models have been proposed so far to describe HSI in the vertical direction (Figure 5). Transferred and adopted from the biomechanics of human gait, the first modelling approach represents a pedestrian as a simple inverted pendulum that oscillates in the vertical plane while moving along a bridge (Figure 5a). This modelling concept was first used by Macdonald [35] to simulate HSI on laterally swaying bridges, then adapted by Bocian et al. [36] to describe the vertical vibration. Apart from the lack of adequate experimental validation, the non-linear interaction mechanism, which is an essential part of these models, is not straightforward for implementation in design practice. Moreover, the credibility of the results of IP models is usually compromised by the large number of assumptions.

The other type of HSI model couples a single-degree-of-freedom (SDOF) model of a structure with a moving (usually) SDOF mass-spring-damper (MSD) oscillator representing a pedestrian walking (Figure 5b). Zivanović et al. [38] did a series of frequency response function (FRF) measurements on a test footbridge and studied the changes in the dynamic properties of the structure in the vertical direction due to the presence of either all standing or all walking groups of people (Figure 6). They reported a slight increase in the natural frequency and a three-fold increase in the damping of the occupied structure relative to the empty structure. Moreover, the authors observed that the walking people added less damping to the structure than the stationary people. Shahabpoor et al. [10] carried out more elaborate tests on the same structure and showed that the natural frequency of a vertical mode of the occupied structure can either increase or decrease depending on the frequency of the human SDOF system , while damping of the structure always increases. These changes appeared prominent especially when the natural frequency of the human SDOF system was close to the modal frequency of the empty structure. Note that all the available studies focus on a single structure and have very limited group sizes. There is no fully developed and experimentally verified universal model to reliably simulate the changes in the modal properties of an empty structure for a diverse range of loading scenarios and structural designs. This is because collecting the key experimental data for walking people still remains a challenge, mainly due to the lack of adequate technology.

4 Crowd loading

In the case of multi-pedestrian traffic, the net force is most commonly modelled by multiplying the individual walking force described by Equation (1) by factor(s) which often depend on the pedestrian density on the structure [5]. On the other hand, crowds are portrayed as the equivalent of uniformly distributed loading in the French guideline Setrà [2]. The most notable drawback specific to these models is their deterministic nature.

Moving from a stochastic models of a single walking person [] to multi-pedestrian walking traffic, the random nature of relevant modelling parameters needs to be considered. Variability of the human mass, stiffness, and damping between different people and even for the same person under different walking scenarios, interaction of people with each other and time-varying location of people on the structure (Figure 7), all make the pedestrian traffic-structure system highly complex. Modelling the scale and character of the net crowd dynamic load on the structure remains a challenge, mainly due to the shortage of knowledge on the proportion of individuals who interact with each other, and the effect of the surrounding environment on the pedestrian gait and walking trajectories. Pedestrians are "intelligent" agents who react to what they perceive around

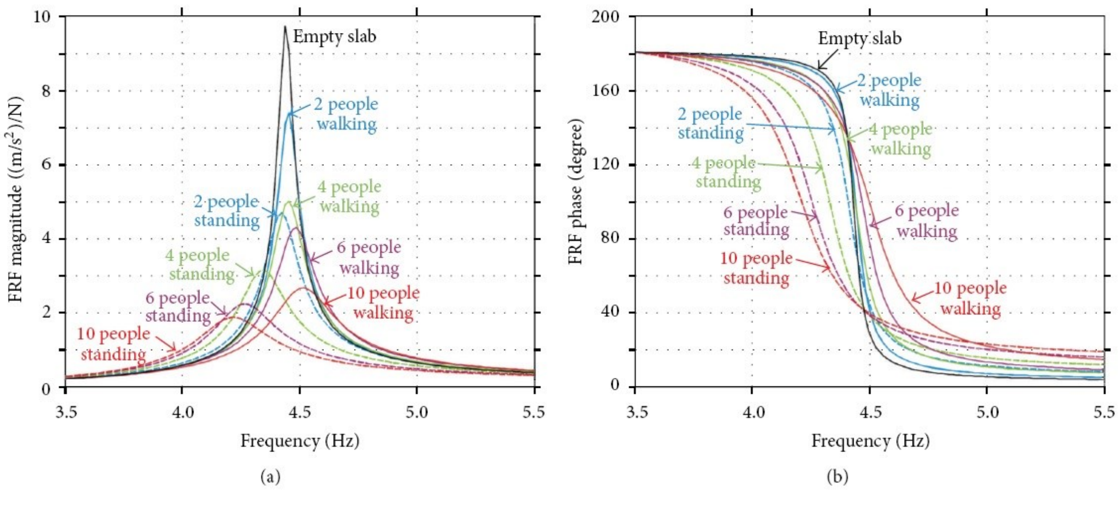

Figure 5. FRF magnitude and phase graphs of a footbridge when occupied by different number of standing/walking groups of people. After Zivanovic et al. [38]

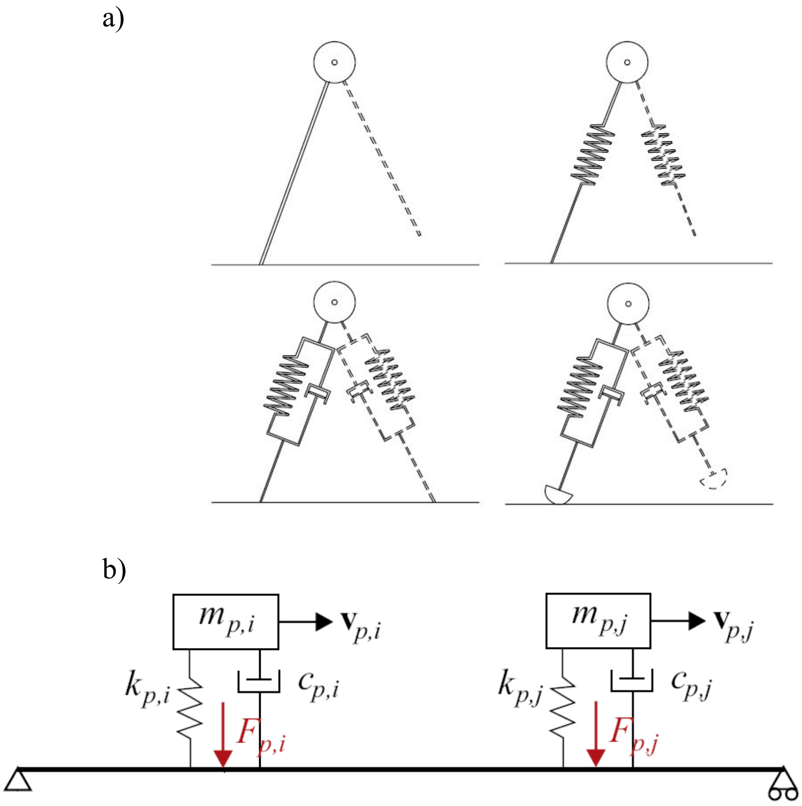

Figure 6. Examples of models suggested in the literature for modelling pedestrian-structure interaction in the vertical direction (a) IPM models and (b) a moving MSD model (i and j represent different individuals)

them. There is strong evidence that peripheral stimuli, such as visual, auditory and tactile, have an equal impact on pedestrian gait [5]. Since the early sixties, applied mathematicians and transportation engineers have proposed several mathematical models of pedestrian behaviour in crowds to address issues relevant to urbanism, evacuation of public buildings, and public safety. They can be divided into two main categories: macroscopic models based on the analogy between a pedestrian flow and the flow of a continuous fluid, and microscopic models, which describe the time-varying position and velocity of each individual in a crowd. Macroscopic models imply a coarse approximation of reality due to the "granular" nature of the crowd, so they can be appropriate (only) in cases of high pedestrian density. Moreover, their modelling parameters do not target individuals but the whole crowd, such as the mean crowd density and velocity of the pedestrian traffic, thus they are not able to explicitly describe the inter-subject variability. Caroll et al. [20] and Venuti et al. [21] used successfully a microscopic approach to simulate lateral and vertical pedestrian loading, respectively. Figure 7:

Using the microscopic approach, Venutti et al. [40] proposed a modelling framework for simulating crowd excitation on footbridges, including the inter- and intra-variability as well as the HSI. Although the framework was demonstrated on the vertical vibrations, it can be applied to the lateral vibrations without losing generality. Each of its sub-models describing crowd dynamics, pedestrian moving bodies and walking forces is adapted or derived from the most reliable models and data available in the literature. The sub-models can be updated independently as soon as their better models have been published or the relevant experimental data have been made available for calibration and verification.

Figure 7. An example of simulated pedestrian traffic on a footbridge at an instant in time. Dots represent different individuals. After Venutti et al. [40]

5 Conclusions

The key impression at the end of this survey is that there is a colossal disconnect between academia and industry. The dissemination of research outcomes to industry is almost nonexistent, resulting in structural designers using outdated information. Academia needs to be engaged with industry and relevant professional institutes to provide up-to-date design guidance based on research best practices.

Future research in this area should be based on simultaneously collecting vibration data and pedestrian-structure and pedestrian-pedestrian interaction data on real structures under different walking traffic scenarios. Such datasets are needed for different types of footbridges and floor structures to identify and validate walking human models and analyse their robustness and versatility. The research findings need to be codified so the next generation of design guidelines can incorporate a realistic model of walking loading, crowd dynamics, and a comprehensive HSI model into a practical and inclusive modelling approach that can be used in everyday design practice.

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