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Improved model for human induced vibrations of high-frequency floors

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ABSTRACT

The key UK design guidelines published by the Concrete Society and Concrete Centre for single human walking excitation of high-frequency floors were introduced more than 10 years ago. The corresponding walking force model is derived using a set of single footfalls recorded on a force plate and it features a deterministic approach which contradicts the stochastic nature of human-induced loading, including intra- and inter- subject variability. This paper presents an improved version of this force model for high-frequency floors with statistically defined parameters derived using a comprehensive database of walking force time histories, comprising multiple successive footfalls that are continuously measured on an instrumented treadmill. The improved model enables probability-based prediction of vibration levels for any probability of non-exceedance, while the existing model allows for vibration prediction related to 75% probability of non-exceedance for design purposes. Moreover, the improved model shifts the suggested cut-off frequency between low- and high-frequency floors from 10 Hz to 14 Hz. This is to account for higher force harmonics that can still induce the resonant vibration response and to avoid possible significant amplification of the vibration response due to the near-resonance effect. Minor effects of near-resonance are taken into account by a damping factor. The performance of the existing and the improved models is compared against numerical simulations carried out using a finite element model of a structure and the treadmill forces. The results show that while the existing model tends to overestimate or underestimate the vibration levels depending on the pacing rate, the new model provides statistically reliable estimations of the vibration responses. Hence, it can be adopted in a new generation of the design guidelines featuring a probabilistic approach to vibration serviceability assessment of high-frequency floors.

1. Introduction

The advancements in construction materials and design software have boosted the current architectural trend of building lighter structures than ever with increasingly longer spans and reduced carbon footprint. While the Ultimate Limit State (ULS) requirements for these modern structures are normally met, Serviceability Limit State (SLS) criteria increasingly govern design. This is particularly the case with vibration serviceability of structures due to human activities, such as walking, running and jumping [1,2].

Building floors have traditionally been designed mainly to accommodate people, who are by their nature very sensitive vibration receivers [3]. Nowadays there is a growing need for floors accommodating vibration sensitive equipment, such as microscopes and lasers in hospitals and hi-tech laboratories. Their optimal functioning commonly permits extremely low vibration levels (often micro-levels) of the supporting structure which are far below human perception. Vibration criteria (VC) for sensitive equipment is normally provided by the manufacturer, leaving the provision of the adequate floor to clients and structural designers [2].

Early studies made vibration assessment based on static deflection of a floor and suggested increasing the stiffness and therefore the fundamental frequency to reduce the vibration response. The same concept features the work by Ungar and White [4] who were the first to use an “idealised footfall force” [5] in a method to calculate the maximum velocity response. This method has been further developed by Amick [6] and adopted in a number of design guidelines [7,8].

A more sophisticated approach was based on the nature of the vibration response [9,10]. If the response is dominated by a resonant build-up they are known as *low-frequency floors*, while those that show a sequence of transient responses due to each successive footfall are called *high-frequency floors*. The division between low- and high-frequency floors depends on whether the fundamental frequency of the floor is relatively low or high, respectively. The threshold frequency (known as *cut-off frequency)* varies significantly for different authors and design guidelines, as shown in Table 1.

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Table 1
Cut-off frequency between low- and high-frequency floors adopted by different authors and design guidelines.

Author	Cut-off frequency
Ohlsson [36]	8 Hz
Wyatt and Dier [9]	7 Hz
Allen and Murray [37]	9 Hz
The concrete society [27]	10 Hz
The concrete centre [38]	10 Hz
The Steel Construction Institute P354 [39]	10 Hz for general floors, open plan offices, etc. 8 Hz for enclosed spaces, e.g. operating theatre, residential
American institute of steel construction [26]	9 Hz

Floors supporting sensitive equipment are required to have low-level transient vibration responses due to human walking excitation [11,12], thus they should be high-frequency floors. A number of studies [13,14] reported that the cut-off frequencies given in Table 1 are too conservative, which has a major effect on the design and cost of ultra-sensitive facilities. They showed that the resonant build-up response can occur even for floors with a fundamental frequency of above 15 Hz [14]. This is because there are higher dominant harmonics of walking loading at frequencies above 10 Hz, which contain a significant amount of energy. For example, according to the design guidelines, a floor with a fundamental frequency of 11.5 Hz is a high-frequency floor. However, a person walking at a pacing rate 2.3 Hz, whose corresponding walking force has Fourier amplitudes shown in Fig. 1, still can induce the resonant vibrations by the harmonic corresponding to the fifth integer multiple of walking loading. This error in the floor type yields an underestimated vibration response, hence a floor may not be fit for purpose.

The uncertainty linked to the cut-off frequency could be explained by the lack of knowledge and/or reliable experimental data pertinent to human walking excitation. This study addresses this issue by determining a cut-off frequency based on detailed numerical analysis featuring a large number of continuously measured walking forces generated by many people walking on an instrumented treadmill [15,16]. Another major drawback of the available design guidelines is the deterministic mathematical description of human-induced loading, while a probabilistic approach is arguably more suitable due to the inherent stochastic nature of human walking forces [16–19]. This study proposes an improved and probability-based version of the widely used Arup's force model for high-frequency floors [20]. This model was chosen as it provides closest and least conservative predictions of floor vibrations compared with experimental results [12,14,21,22]. The parameter estimation of the proposed model and the model implementation take statistical approaches. Moreover, the effect of structural damping is introduced in this model to take into account any "near-resonance" effects.

For high-frequency floors, the time domain modelling approach used here is more appropriate than the frequency domain approach used elsewhere [17,23,24] due to its capability to describe the peak responses corresponding to footfall strikes. The performance of the new model has been verified via numerical simulations utilising the treadmill forces and a finite element model of a high-frequency floor.

Section 2 of this paper describes the nature of the human-induced vibration responses and the procedure followed to derive a more reliable cut-off frequency between low- and high-frequency floors. The new model and its implementation procedure are elaborated in Section 3, while its verification is demonstrated in Section 4. Finally, a discussion of the results and the main conclusions are presented in Section 5.

2. Resonant and transient vibration responses due to human walking excitation

This section demonstrates the nature of the resonant and transient vibration responses due to human walking excitation based on numerical simulations using measured walking forces (Section 2.1) applied to different Single Degree of Freedom (SDOF) oscillators (Section 2.2). Moreover, it aims to derive a reliable value of the cut-off frequency (Section 2.3) relevant to the model development presented in Section 4.

2.1. Walking forces

The authors have at their disposal a comprehensive database of 715 continuously measured vertical force time histories, generated by more than 70 test subjects walking individually on an instrumented treadmill [15,16]. Each test subject followed the same test protocol designed to record a force signal at a constant speed of rotation of the treadmill belts per each test. The speed was varied randomly from slow to fast across successive tests, so the database comprises forces for a wide range of pacing rates. Each force time history contains at least 60 successive footfalls, rather than a single footfall only used in development of Arup's model. This makes it possible to study the intra-subject variability of the walking loads, i.e. the inability of a person to generate two identical footfalls during a walking test. The large number of test

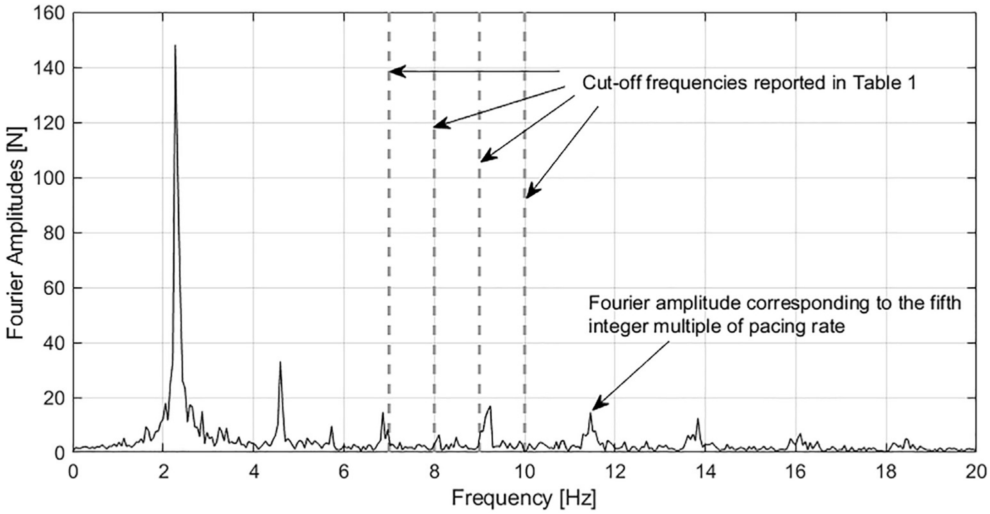

Fig. 1. Fourier amplitudes of a walking force signal measured using an instrumented treadmill corresponding to a pacing rate of 2.3 Hz.