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A coupled biodynamic model for crowd-footbridge interaction

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ABSTRACT

Nowadays, there are growing interests in vibration serviceability assessments of high buildings, slabs, metallic and timber structures, and composite footbridges. Indeed, new design trends of composite footbridges make them slender civil structures that may be affected by the load action of walking pedestrians resulting in large deflections or even uncomfortable vibrations. Furthermore, the presence of people on the footbridges cause the addition of mass to the structural system and due to the human bodýs ability to absorb vibrational energy, an increase in structural damping. In this paper, the interaction between pedestrian and structure is modelled using data from pedestrian characteristics and vibration data from a measured footbridge as a comparison basis. The novelty of the papers relies on the proposed new Biodynamic Synchronized Coupled Model (BSCM). It consists in a fully synchronized force model in the longitudinal and lateral direction of pedestrian's movement and a biodynamic model (with parameters mass, damping and stiffness). This model is coupled to the structural FEM at the feet's contact points. Pedestrians are treated as individuals with intrinsic kinetic and kinematic parameters following a measured correlation matrix obtained by the use of an especially designed force platform. Finally, the adequacy of the proposed model to represent the pedestrians as BSCM for the walking effects on the structure is investigated by experimentally measured vertical accelerations on a footbridge where two crowd densities, freely walking and synchronism of the pacing rate with continuous crossing are also investigated.

1. Introduction

Several cases of excessive vibrations have been studied in the past. But, cases of unstable footbridges such as the Millennium Bridge in London and the Solferino Footbridge in Paris have attracted considerable public and professional attention. These footbridges presented large vibrations on their opening days (Dallard et al. [1]). This occurs because many footbridges have natural frequencies that are coincident with the dominant frequencies of the pedestrian induced load and therefore they have a potential to undergo excessive vibrations. Humans are quite sensitive to vibration in a low-frequency range of whole-body vibrations where natural frequencies of the human body limbs and systems can be observed. Normally, there are physiological changes that are less sensitive than psychological reactions (e.g., discomfort) as the walking behaviour tends to change for perceived acceleration in vertical and horizontal direction. The first published international recommendation concerned with human body vibration was the ISO 2631 [2] which sets out limitation curves for exposure times from 1 min to 12 h over the frequency range in which the human body has been found to be most sensitive, 1 Hz to 80 Hz. Zivanovic et al. [3] state that the pedestrian-structure interaction is a relatively new and important topic in footbridge design. The interaction definition is still subject of controversy in the literature since the interaction refers to force interaction and changes in overall dynamic structure parameters (mainly mass, energy absorption and modal frequency) when compared to the "empty" one. There is a concern with the design of slender structures that are excited by humans walking. Common physical activities such as jumping, running and walking on footbridges produce dynamic efforts and as consequence, generating appreciable vibrations. These vibrations may cause discomfort to pedestrians and potential deterioration of the footbridge's structural integrity as well. Dang and Zivanovic [4] reported that if modern structures like footbridges under pedestrian traffic have one of the vibration modes in the frequency range of the human pacing rate (i.e. 1.5–2.4 Hz), serviceability vibration problems are usually of concern. People walking at a pacing rate close to one of the structural frequencies increases the probability of resonance onset and therefore, it can result in high levels of vibration response.

There are some groups of light and flexible structures which are prone to have vibration serviceability problems, like timber floors, ribbed and flat slabs, hybrid structures and steel decks floors, just to name a few. Some engineering projects like footbridges sometimes have large spans and as a result, these structures have low natural

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frequencies that may generate large amplitudes of vibration when subjected to pedestrian's loads. Gao et al. [5], provided evidence that structures subjected to a flow of pedestrians (e.g. footbridges in urban areas), the pedestrian body dynamics should be considered in order to define the design load or even to investigate its effects properly. The researcher's results show the need to evaluate pedestrians as biodynamic models (considering mass, damping and stiffness) because the large crowd size can reduce structural frequencies and increase the structural damping. Following the same idea, Kim et al. [6] evaluated the possible effects of the dynamic properties of pedestrians walking on the footbridge. Pedestrians were represented as a biodynamic system (keeping equivalent mass, damping and stiffness). A human body model for generating pedestrian excitation was developed considering two vertical degrees of freedom according to ISO 5982 [7]. The results showed differences in the structural response considering four pedestrians densities: 0.3, 0.6, 1.0 and 1.5 pedestrians/m^2. Dynamic analysis results using biodynamic models were larger than those obtained by employing the force model because of the human-structure interaction effects. According to Willford [8], when pedestrians walk over a vertically oscillating structure, there is evidence that the structural damping will increase. Besides, Zivanovic et al. [9] analyzed an alternative way to account human/structure interaction by setting an arbitrary increase in the damping of the system. The authors pointed the need for further research into the quantification of human–structure interactions.

Regarding coupled systems (pedestrians and structure) Van Nimmen et al. [10] proposed a numerical study and full-scale experimental involving a realistic crowd model considering the inter-person variability to assess the influence of human structure interaction on the dynamic properties of the coupled crowd-structure system. In this study, the mean value of the pedestrians pacing rate are chosen to coincide with the natural frequency of the footbridge. The pedestrians and the footbridge are considered as two linear subsystems coupled at a single contact point. But, in this analysis, the pedestrian contact force is reduced to a single point representing at the same time the left and the right foot (pedestrian step width was not considered). The mains dynamic load factors were used according to Kerr [11] and Zivanovic et al. [12]. The researcher's results show that the moving force model leads to a reduction of the structural response (about 30%). This reduction is most important for structural modes with natural frequencies between 2.5 Hz and 4.5 Hz and for low values of the associated modal damping ratio and modal mass.

Recently, Tubino [13] presented a numerical model that accounts for pedestrian structure coupling in the vertical direction. The bridge is modelled as a continuous unidimensional beam dynamic system, while pedestrians are schematized as moving single-degree-of-freedom systems with random dynamic properties. Assuming there is no reliable information for the crowd, the paper results show possible variations of damping ratio and natural frequency in the coupled system based on the random pedestrians' parameters.

Pfeil et al. [14] proposed an analytic numerical model considering the coupling of a biodynamic model (only vertical direction and a single walking person) to one degree of freedom system representing the structure. The walking person is simulated by the single degree of freedom model whose mass is set into vertical motion by heeĺs elevations in the forward steps. The proposed model was applied to the Aberfeldy cable-stayed composite footbridge (Harvey [15]). The results show that the interaction considering the coupling of a biodynamic model to the structure is an appropriate methodology to simulate the footbridge response under the passage of a pedestrian in a resonance condition. The authors conclude that the proposed model isn't too conservative as the traditional moving load model to predict the maximum structural acceleration response.

Additionally, Venuti et al. [16] affirm that deterministic models of ground reaction forces, usually periodic forces based on Fourier series, are not suitable to describe and represent the walking excitation phenomenon, mainly due to lack of consideration for inter and intra-subject variability in walking load, most of time leading to under- or over-estimation of the vibration response.

This paper proposes to assess the interaction between pedestrian/structure using data from an experimentally measured footbridge as a basis for comparisons. In the longitudinal and transversal direction of movement a fully synchronized force model is used and in the vertical direction, it is combined with a biodynamic model (mass-spring-damper parameters) that is coupled to the structure (herein called, BSCM, Biodynamic Synchronized Coupled Model). A fully synchronized force model, as described in Toso et al. [17], is used in the longitudinal and lateral directions. This brings a more representative model that allows assessing the structural behaviour in all directions. This new model access important features of walking situations, like spatiality and the forces components synchronization. In this model, the term "synchronization" refers to a spatial and temporal adjustment of the three forces components. Following the use of the BSCM, the mid-span RMS (root-mean-square) acceleration of a footbridge structure is evaluated to check its serviceability. For the applied BSCM, kinetic (forces) and kinematic (speeds, pacing rate, step length and step width) parameters are used. As mentioned previously, a force platform specially designed to capture such kinetic and kinematic parameters for the human gait is used in this paper.

Another widely model used to represent the pedestrian loading, herein called, Simple Force Model (SFM) is also used in this paper for sake of comparison. This force model has been widely used by engineers to analyze the pedestrian loading on footbridges. Briefly, it assumes that the force from successive footfalls is represented by the Fourier series and that the pedestrian travels at a constant speed. Additionally, it assumes applied loads acting in a straight line along the walking direction, thus neglecting the natural lateral bouncing. Finally, the numerical models are tested with two pedestrian crowd densities (0.25 and 0.15 pedestrians/m^2) and compared to experimental results.

2. Force models

Regarding to force models, Zivanovic et al. [3] state that assessing the human-induced dynamic forces is a complicated task, due to a number of reasons: (*i*) there are different types of human-induced forces and some of them change not only in time but also in space; (*ii*) forces are dependent on many parameters (pacing rate, walking speed, contact time, step length, step width among others); (*iii*) the dynamic force generated by a single person is essentially a process which is not well understood and therefore difficult to model; (*iv*) the influence of the number of persons as well as their degree of synchronization/correlation is difficult to generalize, in this context, synchronization refers to an inter-pedestrian synchronization; and (*v*) there is strong evidence that the forces are different in cases of noticeable and not so noticeable moving footbridges because of the distinct behaviour of people in these situations.

In this paper, a Simple Force Model (SFM) will designate a model that represents the force magnitude from successive footfalls by a Fourier series. Besides, this model also assumes forces acting in a straight line along the direction of walking at a constant speed as defined in some Design Codes (SETRA Guideline [18] and ISO 10137 [19]). This is a very common assumption for analysis and design of footbridges. The SFM can be subdivided into vertical, lateral and longitudinal force models. SETRA Guideline [18], states that while walking, the vertical force induced by each foot has the same magnitude and the overall force is periodic, represented by Eq. (1).

$$F(t) = G + \sum_{i=1}^{n} G\alpha_i \sin(2\pi i f_p t - \varphi_i) \tag{1}$$

where $F(t)$ is the time varying vertical force, G it is the pedestrian weight, $\alpha_i$is the Fourier's coefficient of the i^{th} harmonic defined as