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Crowd-structure interaction: Investigating the spatiality and synchronization of a pedestrian force model

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ABSTRACT

Composite footbridges are slender civil structures that may be affected by the load action of walking pedestrians resulting in large deflections or even uncomfortable vibrations. There are several ways to model the load action of walking pedestrians on footbridges, but force-only models have been preferred by researchers and standards due to simplicity and good agreement with some measure data in real situations. However, there are some concerns relating to force only models as they do not capture important interaction effects between structure and pedestrians. Important features for force-only model implementation are often neglected by engineers such as the spatiality of the load application and the right synchronization among load components. These features bring more relevance for the simulated data and explain some structural behavior and discrepancies present in analysis using simple force-only models. In this paper, a fully synchronized force model for walking pedestrians is proposed and the effect of such model is compared with a simple force-only model and experimental vibration data obtained in a real composite footbridge. Pedestrians are treated as individuals with intrinsic kinetic and kinematic parameters that are correlated by a measured correlation matrix obtained by the use of a force platform for several pedestrians in laboratory conditions. Pedestrian parameters also follow defined Gaussian probability distribution functions with measured mean and standard deviation. A crowd situation is analyzed and the effect of the fully synchronized force model is assessed. The proposed force model provides a more accurate description of the walking forces applied by the pedestrians.

1. Introduction

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. The interaction between people and structures occurs because humans are quite sensitive to vibration in a low frequency range for whole-body vibrations, in which natural frequencies of the human body limbs and systems can be observed. As such, they tend to change their behavior when they perceive structural vibrations in both vertical and horizontal directions. The latter can be classified as horizontal-lateral and horizontal-longitudinal. According to Zivanovic et al. [1] the pedestrian-structure interaction is a relatively new and important topic in footbridge design, which has also fundamental importance in the design of day-to-day slender structures that are dynamically excited by humans. This occurs because walking, running and jumping on footbridges produce dynamic forces which can generate appreciable vibrations. These vibrations may cause discomfort to pedestrians and potential deterioration of the footbridge's structural integrity as well. Kala et al. [2] affirm that footbridges which exhibit vibration serviceability problems are low-frequency structures with natural frequencies within the normal walking frequency range. Fujino et al. [3] state that it is recognized that the average human walking force has a main natural frequency of about 2.0 Hz in vertical and 1.0 Hz in the lateral direction. In this case, resonance may occur when a natural frequency of the structure is within the range of pedestrian step frequencies or their harmonics. For human gait characterization, most standards often consider the first three or four harmonics of the Ground Reaction Forces (GRF) frequency spectrum. These harmonics appear due to interaction between the increasing loading due to 1 ft and the simultaneous unloading of the other foot, and variations on force amplitude between legs. Recently, Dang and Zivanovic [4] reported that vibration serviceability of modern footbridges under pedestrian traffic is usually of concern if the structure has one of the vibration modes in the frequency range typical of the normal human pacing rate (i.e. 1.5–2.4 Hz). Walking at a pacing rate close to the frequency of the structure increases the incidence of resonance and therefore, it can result in high levels of vibration response.

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Several cases of excessive vibration in vertical direction on footbridges due to human-induced loads have been reported, being usually related to crowd conditions. Until recently, the load due to a pedestrian acting on the structure has been obtained from investigations in load platforms, gait treadmill machines or even prototype footbridges, where the applied force is that produced by a walking pedestrian. A combination of those individual applied forces is considered for groups of pedestrians or crowds. Thus, the design load comes from a force model. To improve the models for vibration serviceability in footbridge structures, a sound understanding of the walking process and the ways pedestrians in motion interact with vibrating structures is necessary. Zivanovic et al. [5] affirm that there are, in general, two approaches to analyse human-structure interactions: the first approach investigates changes in dynamic forces that occur due to people either consciously or unconsciously changing their behavior as a reaction of being supported by a noticeable oscillating structure. For example, when people perceive a strong vertical vibration while crossing a footbridge, they could 'lose' their natural step, which leads to a reduction in the magnitude of the walking applied force. The second approach assesses the influence of people on the dynamic properties of the human-structure system and, consequently, on the structural response, such as an increase in damping or changes in the natural frequency.

Related to design aspects, Zuo et al. [6] affirm that engineering projects like footbridges sometimes have large spans and as a result, these structures have low natural frequencies, that may generate large amplitudes of vibration when subjected to pedestrian's loads. The authors concluded that the studied footbridge was susceptible to vibration due to synchronization (in this context, "synchronization" is when the crowd's pedestrian footfalls are synchronized with the footbridge vibration which can lead to significant vibrations). The results also suggested that the pedestrians walking on the structure have an effect of added mass that may affect the vibration frequency of the footbridge. The increase in the footbridge vibration frequency may be an indication of the level of synchronization of the pedestrian footfalls.

The aforementioned studies provided evidence that in 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. In this paper the interaction between pedestrian/structure is investigated using data from an experimentally measured footbridge with 34.08 m in length and 2.4 m in width as a basis for comparisons. A fully synchronized force model is proposed to account for important features of walking situations like spatiality and the synchronization of forces components. In this proposed force model, the term "synchronization" refers to a spatial and temporal adjustment of the three forces components. Peak and valley values from each force component should be placed accordingly in the right position of the contact surface and the model's reference time adjusted to the correct phase. Thus, there is a spatial and temporal synchronization. In this way, it is possible to obtain a more realistic model and applied forces that are closer to the measured ones. Firstly, an investigation in the footbridge finite element numerical model is carried out in order to perform a model update. The paper presents a comparison of two optimization methods that are used in model updating: Sensitivity Method (SM) and the Particle Swarm Optimization (PSO). Following this, the mid-span RMS (root-mean-square) acceleration of the structure is evaluated to check its serviceability. For the applied force model, kinetic (forces) and kinematic (speeds, pacing rate, step length and step width) parameters are used. Kinetic parameters are used based on the design standard (SETRA Guideline, [7]). Kinematic parameters of the human gait are experimentally obtained using a specially designed force platform. The designed platform consists of two force plates placed side by side in the direction of walking. It is possible to measure separately the force signals applied by each foot. This also allows the evaluation of the step positioning. The main assumption is that each individual has his/her own walking characteristics, and thus, model parameters are obtained by averaging several crossings of the same subject. Time histories for ground forces and waist acceleration as the corresponding FFT spectra are numerically obtained and used a basis for comparisons of the load models.

Two models were used to represent the pedestrian loading: *i)* a simple force model (SFM) where the force from successive footfalls is represented by the Fourier series that comes from a constant speed pedestrian and it is assumed acting in a straight line along the walking direction, this force model has been widely used to analyse the pedestrian loading on footbridges; *ii)* a fully synchronized force model (FSFM) where the load components are represented considering kinetic and kinematic parameters of regular walking that are synchronized both in time and space. The term "synchronization" refers to a spatial and temporal adjustment of the three forces components. Peak and valley values from each force component should be placed accordingly in the right position of the contact surface and the model's reference time adjusted to the correct phase.

2. Design standards

Some design standards define the pedestrian load models applicable for simple structures (for instance UK-NA [8] and SETRA [7]). The load modelling for more complex structures, on the other hand, are not well understood, becoming threads for future studies and often left to the designer. Figueiredo et al. [9] concluded that the design standards can produce unsafe values due to the fact that they are based on excessively simplified load models. Hence, it was detected that footbridges can reach high vibration levels that can compromise user's comfort and especially his or her safety. Alam and Amin [10] performed a study related to this problem in some guidelines (British Standard BS 5400 [11], Eurocode [12], ISO 10137 [13]). They concluded that different internationally accepted codes and provisions do not fulfill the design constraints for footbridge vibrations. For example, in the British standard BS 5400, the load modelling and the evaluation of a design criterion for horizontal vibrations are left to the designer. Eurocode proposes load models for both vertical and horizontal loads, but only for simplified structures (like simply supported beams). The authors affirm that these codes do not provide sufficient guidelines and information to address such vibration problems and to ensure safety and serviceability due to the lack of knowledge on the dynamic performance of footbridge structures. The authors conclude that current codes and standards should be carefully used. In this context, Pimentel [14] suggested guidelines for vibration performance, focusing on the definition of the pedestrian load and frequency ranges of interest, acceptability limits to vibration, treatment of multi-frequency component vibrations and vandal loading. The author investigated the vibrations of two full-scale footbridges under pedestrian activities both analytically and experimentally and found that the dynamic load factors (DLFs) for the first two resonant vertical harmonics were far lower than those reported in the literature on the subject. They suggested that the human induced forces on low frequency structures, such as slender footbridges, differs from the forces measured on rigid structures and that this difference is assumed to be due to human-structure interaction. In fact there is not a single example of design guidance which comprehensively covers all aspects of the problem and this makes the subject an interesting topic for future research.

2.1. Force models

Zivanovic et al. [1] 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 (e.g. walking and running); *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