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Experimentally fitted biodynamic models for pedestrian–structure interaction in walking situations

Marcelo André Toso [a,*], Herbert Martins Gomes [a], Felipe Tavares da Silva [b], Roberto Leal Pimentel [c]

[a] Mechanical Engineering Department, Federal University of Rio Grande do Sul, Sarmento Leite, 425, 90050-170 Porto Alegre, RS, Brazil
[b] Faculty of Architecture and Urban Studies, Federal University of Bahia, Caetano Moura, 121-Federação, 40210-905 Salvador, BA, Brazil
[c] Civil Engineering Department, Federal University of Paraíba, Campus Universitário, s/n-Castelo Branco, 58051-900 João Pessoa, PB, Brazil

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ABSTRACT

The interaction between moving humans and structures usually occurs in slender structures in which the level of vibration is potentially high. Furthermore, there is the addition of mass to the structural system due to the presence of people and an increase in damping due to the human body´s ability to absorb vibrational energy. In this paper, a test campaign is presented to obtain parameters for a single degree of freedom (SDOF) biodynamic model that represents the action of a walking pedestrian in the vertical direction. The parameters of this model are the mass (m), damping (c) and stiffness (k). The measurements were performed on a force platform, and the inputs were the spectral acceleration amplitudes of the first three harmonics at the waist level of the test subjects and the corresponding amplitudes of the first three harmonics of the vertical ground reaction force. This leads to a system of nonlinear equations that is solved using a gradient-based optimization algorithm. A set of individuals took part in the tests to ensure inter-subject variability, and, regression expressions and an artificial neural network (ANN) were used to relate the biodynamic parameters to the pacing rate and the body mass of the pedestrians. The results showed some scatter in damping and stiffness that could not be precisely correlated with the masses and pacing rates of the subjects. The use of the ANN resulted in significant improvements in the parameter expressions with a low uncertainty. Finally, the measured vertical accelerations on a prototype footbridge show the adequacy of the numerical model for the representation of the effects of walking pedestrians on a structure. The results are consistent for many crowd densities.

1. Introduction

Among human movements, walking is the design condition for footbridges in normal use, because these structures are designed for the conveyance of pedestrians. Recently, Dang and Zivanovic [1] noted that the frequency range from 1.5 to 2.4 Hz of the usual human pacing rate poses a concern for the vibration serviceability of footbridges under pedestrian traffic.

* Corresponding author. Tel.: +55 51 3308 3681; fax: +55 51 3308 3222.
E-mail addresses: marcelo.toso@yahoo.com.br (M.A. Toso), herbert@mecanica.ufrgs.br (H.M. Gomes), felipe.estruturas@gmail.com (F.T. da Silva), r.pimentel@uol.com.br (R.L. Pimentel).

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Walking at a pacing rate close to the frequency of a structure increases the probability of resonance and can therefore result in a high vibration response.

Pedestrian load has been determined from investigations using force platforms, treadmill machines and even prototype footbridges, in which the applied force is the amount produced by a single walking pedestrian. The combined force applied by individuals is considered for groups of pedestrians or crowds. Thus, the design load is a force model. For the characterization of human- induced loads, most standards (for instance, SETRA [2] and ISO 10137 [3]) often consider three to five harmonics of the frequency spectrum of ground reaction forces (GRF). These harmonics appear due to the pattern of walking, featuring an increasing loading from one foot and the simultaneous unloading of the other foot and variations in the force amplitude when the weight is transferred between legs.

There have been reported cases of unstable footbridges in the past, but this problem attracted considerable public and professional attention after lateral vibration problems arose in the Millennium Bridge in London during its opening (Dallard et al. [4]). Attention has been drawn by some recent publications (Barker and Mackenzie [5]; Kim et al. [6]; Miyamori et al. [7]; Zivanovic et al. [8]) to the potential effects of the dynamic interactions between pedestrians and structures when crossing footbridges alone or in crowded situations. According to Zivanovic et al. [9], the pedestrian–structure interaction is an important new topic to consider in the design of day to day slender structures that are liable to be dynamically excited by humans. Barker and Mackenzie [5] called attention to studies that suggest the increase of system damping and, thus, the reduction in the structural response in crowded situations.

It is worth calling attention, to the terminology used for the different pedestrian modelling methods. Herein, a force model considers only the ground reaction forces (GRF) applied by a pedestrian in simulations. A biodynamic model considers not only the GRF but also the mass, stiffness and damping of the pedestrian, all of which can interact with the structure.

Accordingly, Kim et al. [6] investigated the effects of the dynamics of pedestrians walking along a footbridge. Each pedestrian was represented as a biodynamic system, possessing equivalent mass, stiffness and damping. A model with two vertical degrees of freedom was used, in accordance with ISO 5982 [10]. They observed differences in the structural response between the force model and biodynamic model for pedestrian action. The authors concluded that the dynamic responses from the analyses using biodynamic models were larger than those obtained by employing the force model because of the human–structure interaction effects. This is in conflict with what Barker and Mackenzie [5] reported. A similar study, but with different results, was presented by Miyamori et al. [7]. The purpose was to develop a model with three degrees of freedom to represent the dynamics of an individual in the vertical direction. The authors defined the parameters of mass, stiffness and damping of the model based on several measurements of individuals crossing a pedestrian footbridge. They found a small decrease in the response provided by this model relative to that of force models.

Willford [11] asserted that, when pedestrians walk over a vertically oscillating structure, there is evidence that the structural damping will increase. Indeed, Zivanovic et al. [9] explored the strategy of an arbitrary increase in the damping of the system to account for human–structure interaction and noted a strong need for further research into the quantification of human–structure interactions.

To improve the models for vibration serviceability in footbridge structures, a sound understanding of the walking process and the ways in which pedestrians in motion interact with vibrating structures is necessary. Zivanovic et al. [9] affirm that there are, in general, two approaches to analysing human–structure interactions: the first approach investigates changes in dynamic force that occur due to people either consciously or unconsciously changing their behaviour as a reaction to being supported by a perceptibly 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 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. In terms of design, some standards adopt classical pedestrian force models that are applicable to simple structures and do not account for pedestrian–structure interactions, for instance, UK-NA [12] and SETRA [2].

The previously mentioned studies have provided evidence that, in structures subjected to a flow of pedestrians (e.g, footbridges in urban areas), the dynamics of pedestrian body should be considered to define the design load or even to investigate its effects properly. In this paper, a single degree of freedom (SDOF) model, herein called a biodynamic model, is proposed to represent the action in the vertical direction of a pedestrian, aiming to investigate vibration effects on footbridges. This paper is a follow-up to previous investigations (Silva et al. [13] and Toso [14]). In this study, a broad range of experimental data is included to obtain more precise correlations among the parameters of the model that is being proposed.

The investigation is based on simultaneous measurements of body acceleration at waist level and force measurements from test subjects walking on a force platform. The designed platform consists of two force plates placed side by side in the direction of walking. It is possible to separately measure the force signals from each foot. This also allows evaluation of the step positioning. The main assumption is that each individual has his/her own walking characteristics, and thus, model parameters can be obtained by averaging several crossings of the same subject. Regression expressions and artificial neural networks (ANNs) are used to relate the model parameters to the pedestrian's pacing rate and body mass. Finally, experiments are conducted using a prototype footbridge considering three pedestrian densities (0.3, 0.7 and 0.9 ped/m^2) to verify the applicability of the proposed model. The footbridge has a deck consisting of a 10 cm thick and 1.80 m wide slab

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