Structures 5 (2016) 233–246

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

Identification of mass–spring–damper model of walking humans

Erfan Shahabpoor [a,*], Aleksandar Pavic [b], Vitomir Racic [c,d]

[a] INSIGNEO Institute for In-Silico Medicine, Department of Civil & Structural Engineering, University of Sheffield, UK
[b] Vibration Engineering, College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK
[c] Department of Civil and Environmental Engineering, Politecnico di Milano, Italy
[d] Department of Civil & Structural Engineering, University of Sheffield, UK

ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form 27 October 2015
Accepted 14 December 2015
Available online 23 December 2015

Keywords:
Vertical human–structure interaction
Multi-pedestrian traffic
Vibration serviceability
Bridges
Floors
Moving body parameters

ABSTRACT

Interaction of walking people with vibrating structures is known to be an important yet challenging phenomenon to simulate. Despite of its considerable effects on the structural response, no properly formulated and experimentally verified model currently exists to simulate this interaction in the vertical direction.

This work uses a single-degree-of-freedom mass–spring–damper model of a walking human to simulate its interaction with a vibrating structure. Extensive frequency response function measurements were performed on a test structure that was occupied by more than a hundred test subjects walking in various group sizes and at different times in 23 tests. The identified modal properties of the occupied structure were used in three different identification procedures to estimate the parameters of the walking human model.

A discrete model of human–structure system was used to simulate interaction of each walking person with the structure. The analysis identified the range of 2.75–3.00 Hz for the natural frequency and 27.5%–30% for the damping ratio of the model of a walking human, having constant mass of 70 kg. The extent of the experimental data and the measurement details, diversity of loading scenarios and consistency of the results of the different identification procedures, provided high level of confidence on the suggested parameters for the single-degree-of-freedom walking human model.

1. Introduction

Vibration serviceability of structures under a range of different human activities has been a growing concern to civil structural engineers since the 19th century [1,2]. The current design trends towards more slender and longer span structures have made them more susceptible than ever before to vibration serviceability problems [3–6]. Investigations of several recent incidences due to walking pedestrians, both in the vertical and lateral directions, have highlighted the inability of the contemporary design guidelines to estimate reliably the vibration response [7,8]. The key reason for this unsatisfactory situation is a widespread, yet utterly wrong, assumption that walking people affect structural dynamics only through the inertia of their moving bodies, thereby acting only as the main source of the vibration [4]. In reality, the human bodies have equally powerful effect on the modal properties of the occupied structure which, as this paper will demonstrate, should not be ignored [8–11].

The simplest walking load models, such as those suggested by FIB [12], ISO 10137 [13], French design guideline [14] and UK National Annex to Eurocode 1 [15], approximate the walking force of an individual with a periodic function presentable via up to four dominant Fourier harmonics. Typically, one of these harmonics is tuned to match the frequency of a target mode of the structure to create resonance. In case of a multi-pedestrian traffic, the net force is most commonly calculated by multiplying the individual walking force by factor(s) which often depend on the pedestrian density on the structure [4,16].

A significant move towards more realistic estimation of the structural response was made only recently by taking into account inter- and intra-subject variability of the pedestrians in the form of statistical models of their walking force [6,17–22]. This has increased considerably the fidelity of the walking force models, but they still cannot account fully for the human–structure interaction (HSI) [8,11].

Mass of a stationary human body accelerates when exposed to vertical structural vibration, thereby creating an interaction force at the contact point with the structure [23]. The same applies to the moving people, in which case additional ground reaction force is created due to the self-propelling body motion. These interaction forces manifest as changes in the modal frequency of the empty structure (i.e. through the alteration of modal mass and/or stiffness) and damping. This is because such forces have components proportional to acceleration, velocity and displacement as well as independent components [24]. There have been several successful studies designed to quantify changes of the modal properties of structures when occupied

* Coresponding author at: Department of Civil & Structural Engineering, University of Sheffield, Sir Frederick Mappin Building, Sheffield S1 3JD, UK. Tel.: +1 114 2225745; fax: +1 114 2225700.
E-mail address: e.shahabpoor@sheffield.ac.uk (E. Shahabpoor).

http://dx.doi.org/10.1016/j.istruc.2015.12.001

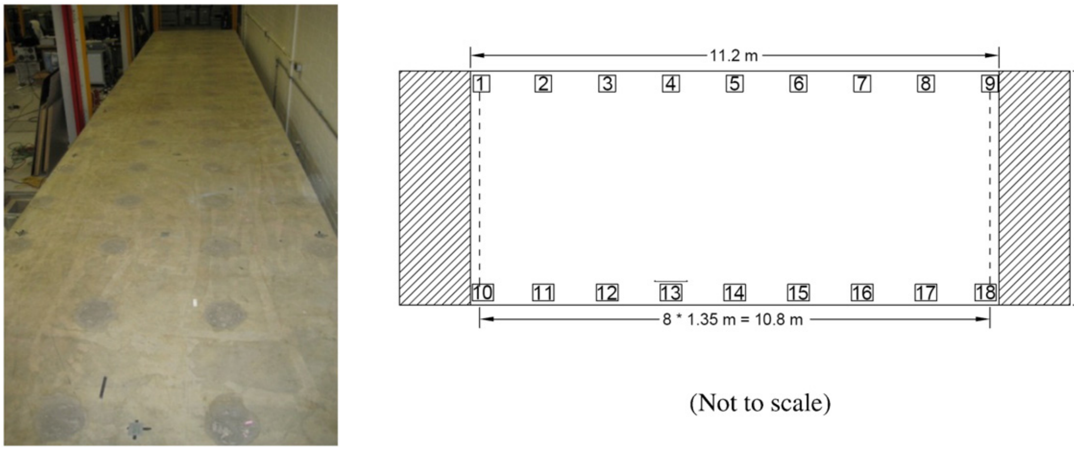

Fig. 1. Photo, plan and modal test grid of the Sheffield footbridge. Two side platforms are shown with hatched rectangles.

by stationary (e.g. standing or sitting) people [25–29]. The results consistently suggested a more or less significant increase in structural damping and shifting of the natural frequency in, surprisingly, either direction. Experimental and analytical studies prompted by the Millennium Bridge problem [30] reported that walking people also add considerable damping when they excite lateral vibration modes of a structure [31]. However, similar studies on the effect of walking people on the vertical structural modes are very rare and limited [32,33].

Živanović et al. [33] did a series of 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. They reported a slight increase in the natural frequency and a three-fold increase of 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. Based on an analytical study featuring a walking human as a single-degree-of-freedom (SDOF) mass–spring–damper (MSD) oscillator, Shahabpoor et al. [34,35] 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.

Miyamori et al. [36] reported similar results using a more complex 3DOF biodynamic model of a walking individual, but also without experimental verification. Kim et al. [37] used a simpler 2DOF MSD model with little success because the majority of the human model parameters were adapted from ISO 5982:1981 [38], which refers to stationary standing (rather than walking) people. Favored for its simplicity, the elementary SDOF MSD model was used in a number of studies to simulate pedestrian–structure interaction in the vertical direction [17,39–44]. However, due to the lack of knowledge about the true values of the parameters of a walking human SDOF system, the values were either assumed or adapted from sparse biomechanical studies relevant to other activities, such as bouncing and jumping. The work of Silva and Pimentel [41] and Jiménez-Alonso and Sáez [44] are the only examples to date known to the authors that proposed a

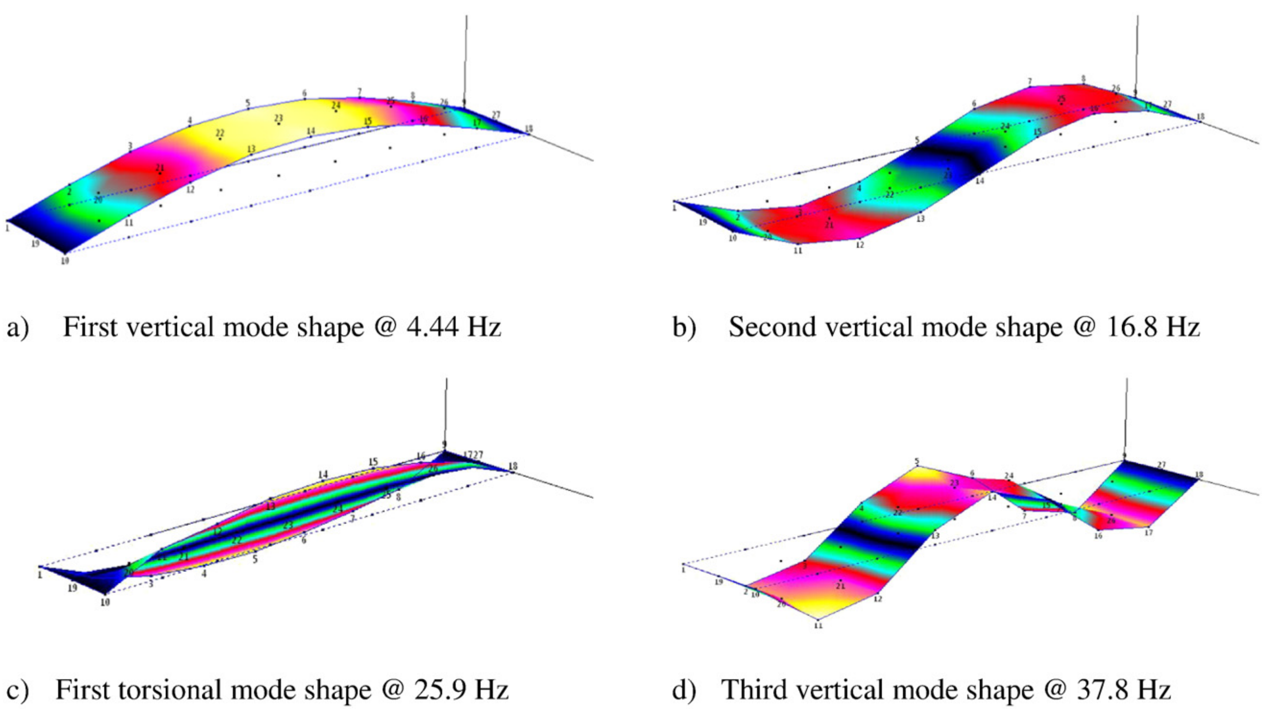

Fig. 2. Experimentally acquired mode shapes of PT slab.