Mechanical Systems and Signal Processing 103 (2018) 352–367

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Identification of walking human model using agent-based modelling

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

[a] Department of Architecture and Civil Engineering, University of Bath, Claverton Down, Bath BA2 7AY, UK
[b] INSIGNEO Institute for In-Silico Medicine, Department of Civil & Structural Engineering, University of Sheffield, Sheffield S1 3JD, UK
[c] Vibration Engineering Section, College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK
[d] Department of Civil and Environmental Engineering, Politecnico di Milano, Italy
[e] Department of Civil & Structural Engineering, University of Sheffield, UK

ARTICLE INFO

Article history:
Received 29 August 2016
Received in revised form 12 September 2017
Accepted 20 October 2017

Keywords:
Human-structure interaction
Vibration serviceability
Discrete traffic model
SDOF moving human model
FRF-based modal testing

ABSTRACT

The interaction of walking people with large vibrating structures, such as footbridges and floors, in the vertical direction is an important yet challenging phenomenon to describe mathematically. Several different models have been proposed in the literature to simulate interaction of *stationary* people with vibrating structures. However, the research on *moving* (walking) human models, explicitly identified for vibration serviceability assessment of civil structures, is still sparse. In this study, the results of a comprehensive set of FRF-based modal tests were used, in which, over a hundred test subjects walked in different group sizes and walking patterns on a test structure. An agent-based model was used to simulate discrete traffic-structure interactions. The occupied structure modal parameters found in tests were used to identify the parameters of the walking individual's single-degree-of-freedom (SDOF) mass-spring-damper model using 'reverse engineering' methodology. The analysis of the results suggested that the normal distribution with the average of $\mu = 2.85\text{Hz}$ and standard deviation of $\sigma = 0.34\text{Hz}$ can describe human SDOF model natural frequency. Similarly, the normal distribution with $\mu = 0.295$ and $\sigma = 0.047$ can describe the human model damping ratio. Compared to the previous studies, the agent-based modelling methodology proposed in this paper offers significant flexibility in simulating multi-pedestrian walking traffics, external forces and simulating different mechanisms of human-structure and human-environment interaction at the same time.

1. Introduction

Over the past three decades, investigations into a considerable number of vibration serviceability problems of structures [1,2], both in the vertical and horizontal directions, have highlighted the inability of the current design methods to reliably estimate the vibration response of structures to walking pedestrians. This is mainly due to the methods ignoring the natural *inter-* and *intra- subject variability* of people and their *interaction* with vibrating structures [2–5]. This is despite such interactions have been an integral part of the design process relating to vehicle-structure interaction for a long time [6,7]. The excessive lateral vibration of the London Millennium Bridge in 2000 caused a wave of research on the interaction of walking people with pedestrian structures in the lateral direction [8]. However, human-structure interaction (HSI) in the vertical

---

[*] Corresponding author at: Department of Architecture and Civil Engineering, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom.
E-mail address: e.shahabpoor@bath.ac.uk (E. Shahabpoor).

https://doi.org/10.1016/j.ymssp.2017.10.028
0888-3270/© 2017 The Authors. Published by Elsevier Ltd.

direction during walking has been explored much less, is not understood well and consequently does not feature in key design guidelines [9–11]. However, the importance of HSI in the vertical direction is most recently demonstrated by Zivanovic et al. [11], Shahabpoor et al. [10] and Kasperski [12] based on experimental data collected from full-scale structures.

One of the key mechanisms of the HSI in the vertical direction is the effect of the human body on the dynamics of the structure over which the body moves. It is well known that the mass of a stationary human body accelerates when exposed to structural vibration and applies interaction force to the structure [13]. The same applies to the moving body, in which case *additional* ground reaction force (GRF) is created due to the base vibration. This force is super-imposed on the normal GRF, caused by acceleration and deceleration of the internally propelled human body and manifests itself as changes in the modal frequency (i.e. mass and/or stiffness) and damping of the empty structure. This is because such force has components proportional to the acceleration, velocity and displacement of the structure, as well as independent components [14].

In the past, several biodynamic models, such as a single degree of freedom (SDOF) mass-spring-damper model, were suggested to simulate the effects of walking humans on the structural vibrations in the vertical direction [15–21]. In most of these models, however, the human model parameters were adopted from the biomechanics literature and were not validated for the vibration serviceability assessment of civil structures. The works of Silva and Pimentel [16], Toso et al. [21] and Shahabpoor et al. [22] are the only examples to date known to the authors that propose a range of parameters for the SDOF walking human model in the context of the vibration serviceability of civil structures. Silva and Pimentel [16] suggested three empirical equations for mass (m), damping (c) and stiffness (k) of the SDOF human model by analysing the vertical walking force and measured vertical acceleration of the human trunk recorded at the pelvis (i.e. waist):

$$m = 97.082 + 0.275 \times M - 37.518 \times f_p \tag{1}$$

$$c = 29.041 \times m^{0.883} \tag{2}$$

$$k = 30351.744 - 50.261 \times c + 0.035 \times c^2 \tag{3}$$

In Eqs. (1)–(3), M [kg] is the total mass of the human body, f_p [Hz] is the pacing frequency and m [kg], c [Ns/m] and k [N/m] are the human SDOF model mass, damping and stiffness, respectively.

Toso et al. [21] used a similar methodology to calculate the spectral amplitudes of the first three harmonics of the vertical acceleration measured at the waist level of 35 test subjects. In addition, they calculated spectral amplitudes of the first three harmonics of the corresponding vertical GRF, which was also measured simultaneously with the acceleration of the pelvis. They used artificial neural network (ANN) to relate the biodynamic parameters to the pedestrians pacing rate and body mass:

$$m(f_p, M) = -231.34 + 3.69M + 154.06f_p - 1.97Mf_p + 0.005M^2 - 15.25f_p^2 \tag{4}$$

$$c(M, m) = -1115.69 + 92.56M - 108.94m + 2.91Mm - 1.33M^2 - 1.30m^2 \tag{5}$$

$$k(M,f_p) = 75601.45 - 1295.32M - 33786.75f_p + 506.44Mf_p + 3.59M^2 + 539.39f_p^2 \tag{6}$$

Both studies provided invaluable insights into the ranges of SDOF walking human parameters. However, they lack convincing experimental verification on real-world structures. The recorded acceleration of the pelvis was not transformed from the internal (i.e. local) coordinate frame of the measuring sensor to the Earth global frame, where the vertical axis is parallel to the gravity. Therefore, the recorded 'vertical' accelerations most likely contain some levels of error due to the rotation of the pelvis during walking [4,14]. Finally, common to all 'black box' approaches, the ANN used in Toso et al. study does not provide any physical insight on the obtained SDOF m, c and k parameters.

Shahabpoor et al. [22] used a comprehensive set of experimental data, measured on a full-scale post-tensioned concrete footbridge for different sizes of walking pedestrian traffics to identify parameters of a SDOF walking human model. A discrete multi-degree-of-freedom model of human–structure system was used to simulate the interaction of multi-pedestrian walking traffic with the vibrating structure. Each walking human was modelled using an SDOF MSD model. The structure was also modelled with an SDOF model representing a mode of its vibration. 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 SDOF model of a walking human, having a constant mass of 70 kg. The identification procedures used in this study modelled the time-varying location of walking pedestrians on the structure with an increasing level of detail and complexity. However, in all of these procedures the location of the walking human body on the structure was assumed to be 'stationary' during each time-step of the simulation selected to be sufficiently small. The effects of walking forces and shaker force (during forced FRF tests) were also assumed negligible.

To address these limitations, this paper utilises a very comprehensive set of multi-pedestrian walking traffic tests over a laboratory-based but realistic 15-tonne prototype footbridge structure. An *agent-based* traffic-structure model (ABM) was then used for simulation, where each individual and the relevant mode of the structure were both modelled using a SDOF mass-spring-damper model. The natural frequency and damping ratio of the walking human SDOF model were identified for each test in a way that the analytical frequency response function (FRF) of the occupied structure (OS) matched its experimental counterpart. Compared to the Shahabpoor et al. [22], the identification methodology proposed in this paper