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Formulation of human–structure interaction system models for vertical vibration

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ABSTRACT

In this paper, human–structure interaction system models for vibration in the vertical direction are considered. This work assembles various moving load models from the literature and proposes extension of the single pedestrian to a crowd of pedestrians for the FE formulation for crowd–structure interaction systems. The walking pedestrian vertical force is represented as a general time-dependent force, and the pedestrian is in turn modelled as moving force, moving mass, and moving spring–mass–damper. The arbitrary beam structure is modelled using either a formulation in modal coordinates or finite elements. In each case, the human–structure interaction (HSI) system is first formulated for a single walking pedestrian and then extended to consider a crowd of pedestrians. Finally, example applications for single pedestrian and crowd loading scenarios are examined. It is shown how the models can be used to quantify the interaction between the crowd and bridge structure. This work should find use for the evaluation of existing and new footbridges.

1. Introduction

The vibration analysis of pedestrians on bridges has been a topic of interest for many researchers in the last decade or so. Human-induced vibrations are increasingly important for serviceability and safety considerations in the design of new structures, particularly footbridges. Contemporary challenges in footbridge design lie in the satisfaction of architectural demands for long, light, and slender structures. With such aesthetic criteria, many new footbridges are experiencing excessive vibrations which can lead to discomfort for pedestrians. The temporary closures of both the Pont de Solferino bridge in Paris in 1999 (Sétra [1]) and then the London Millennium Bridge in 2000 (Dallard et al. [2]), following excessive pedestrian-induced vibrations during their inaugurations, are probably the most prominent cases. In recent years, many studies have been carried out within the area of human-induced vibrations; literature reviews by Živanović et al. [3], Racic et al. [4], Venuti and Bruno [5], and Ingolfsson et al. [6] cover the topic well.

In order to simulate human-induced vibration, there exist different approaches in the literature for modelling both the structure and the human. The bridge can be modelled using either a formulation in modal coordinates, hereafter referred to as modal analysis (MA), or Finite Element (FE) methods. The pedestrian effects on the bridge can be considered in different ways. The simplest model considers the pedestrian as a moving force (MF), that is, a concentrated load travelling at a constant walking velocity. However, a MF model may overestimate bridge response since it does not take into account

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interaction between the pedestrians and the vibrating bridge [7]. Going a step further, a more realistic model can be reached using a moving mass which can account for mass-interaction of pedestrians. This is referred to as moving mass (MM) model, originally developed by Biggs [8]. However, considering the separation between the human centre of mass and the bridge surface, it would be even more realistic to model the human as a moving spring–mass–damper (SMD) system [9], and consequently this approach has begun to emerge recently in the literature [10]. Thus, the challenge is to identify and calibrate suitable human and bridge models to simulate crowd–structure interaction to better predict the vibration response.

Pedestrians apply a reasonably periodic time-dependent force which has components in the vertical, horizontal–lateral, and horizontal–longitudinal directions (Fujino et al. [11]). In this paper, only the vibrations in the vertical direction are considered. For vibration response in the vertical direction, the accurate evaluation of the force produced by a moving pedestrian is vital. The temporal shape of the vertical force with two peaks was shown by many researchers (Galbaith [12], Andriachi [13], Blanchard et al. [14], Bachmann and Ammann [15], Ohlsson [16]). By combining single foot forces, often assumed to be the same, a continuous walking force can be obtained. For example, Ebrahimpour et al. [17] and Sahnaci and Kasperski [18] used instrumented platforms to measure continuous walking time histories comprising several steps. In order to use the measured forces for vibration response prediction, an analytical model is required. The force models can be divided into time-domain and frequency-domain categories. Among force models in the time domain, harmonic functions are often used (Rainer et al. [19], Yao et al. [20], Wheeler [21]). Some probabilistic time-domain models can be found in Tuan and Saul [22], Ebrahimpour and Sack [23], Ebrahimpour et al. [24], and Živanović et al. [25] as well. For frequency-domain force models, Ohlsson [16], Brownjohn et al. [26], Piccardo and Tubino [27], and Caprani [28] made attempts to describe

Table 1
Models found in the literature for bridge and pedestrian subjected to either single pedestrian or crowd load.

Study (date order)	**Ref.**	**Bridge model**		**Pedestrian model**					**Load type**	
		MA	**FE**	**MF**	**MM**	**SMD**	**Bipedal**	**Other**	**Single**	**Crowd**
BS 5400 (1978)	[30]	•		•					•	
Wheeler (1982)	[21]	•		•					•	
OHBDC (1983)	[29]	•		•					•	
Rainer et al. (1988)	[19]	•		•					•	
ISO-10137 (1992)	[31]	•		•					•	
Eurocode 5 (1997)	[32]	•		•						•
Young (2001)	[55]	•		•					•	
Archbold (2004)	[46]	•	•			•			•	
Fanning et al. (2005)	[7]	•				•			•	
Dougill et al. (2006)	[56]	•						•	•	
Setra (2006)	[1]	•	•	•						•
Zhou and Ji (2006)	[79]		•					•		•
Zhoua and Ji (2007)	[80]	•						•	•	•
Venuti et al. (2007)	[81]	•						•		•
Archbold (2008)	[47]		•			•				•
Brownjohn et al. (2008)	[26]	•		•						•
Figueiredo et al. (2008)	[82]		•	•					•	•
HIVOSS (2008)	[33]	•		•						•
Kim et al.(2008)	[48]		•			•				•
Li et al. (2010)	[83]	•		•						•
Pedersen and Frier (2010)	[84]	•		•					•	
Archbold et al. (2011)	[10]		•			•			•	
Caprani et al. (2011)	[51]	•	•			•			•	•
Ingólfsson and Georgakis (2011)	[85]	•		•						•
Živanović (2011)	[86]	•		•					•	
Bocian et al. (2012)	[87]	•						•		•
Caprani et al. (2012)	[71]		•	•						•
Piccard and Tubino (2012)	[88]	•		•						•
O'Sullivan et al. (2012)	[73]	•		•	•	•			•	
Zuo et al. (2012)	[89]	•						•		•
Caprani (2013)	[28]	•		•					•	
Mashaly et al. (2013)	[90]		•	•					•	
Qin et al. (2013)	[74]	•					•		•	
Qin et al. (2013)	[91]		•				•		•	
Shahabpoor et al. (2013)	[92]	•				•			•	
Tavares da Silva et al. (2013)	[49]		•			•				•
Caprani (2014)	[93]	•		•					•	
Pfeil et al. (2014)	[94]	•				•			•	
Venuti et al. (2014)	[50]	•				•				•
Van Nimmen et al. (2015)	[52]	•				•				•
Zhang et al. (2015)	[63]	•				•			•	