ARTICLE IN PRESS

Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Effect of group walking traffic on dynamic properties of pedestrian structures

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A R T I C L E I N F O

Article history:
Received 23 February 2015
Received in revised form
5 October 2016
Accepted 11 October 2016
Handling Editor: Dr. J. Macdonald

Keywords:
Vibration serviceability
Human-structure dynamic interaction
Walking
Crowd
Footbridge
Floor

A B S T R A C T

The increasing number of reported vibration serviceability problems in newly built pedestrian structures, such as footbridges and floors, under walking load has attracted considerable attention in the civil engineering community over the past two decades. The key design challenges are: the inter- and intra-subject variability of walking people, the unknown mechanisms of their interaction with the vibrating walking surfaces and the synchronisation between individuals in a group. Ignoring all or some of these factors makes the current design methods an inconsistent approximation of reality. This often leads to considerable over- or under-estimation of the structural response, yielding an unreliable assessment of vibration performance.

Changes to the dynamic properties of an empty structure due to the presence of *stationary* people have been studied extensively over the past two decades. The understanding of the similar effect of walking people on laterally swaying bridges has improved tremendously in the past decade, due to considerable research prompted by the Millennium Bridge problem. However, there is currently a gap in knowledge about how *moving* pedestrians affect the dynamic properties of vertically vibrating structures. The key reason for this gap is the scarcity of credible experimental data pertinent to moving pedestrians on vertically vibrating structures, especially for multi-pedestrian traffic.

This paper addresses this problem by studying the dynamic properties of the combined human-structure system, i.e. occupied structure damping ratio, natural frequency and modal mass. This was achieved using a comprehensive set of frequency response function records, measured on a full-scale test structure, which was occupied by various numbers of moving pedestrians under different walking scenarios. Contrary to expectations, it was found that the natural frequency of the joint moving human-structure system was *higher* than that of the empty structure, while it was *lower* when the same people were standing still. The damping ratio of the joint human-structure system was considerably higher than that of the empty structure for both the walking and standing people – in agreement with previous reports for stationary people - and was more prominent for larger groups. Interestingly, it was found that the walking human-structure system has more damping compared with the equivalent standing human-structure

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http://dx.doi.org/10.1016/j.jsv.2016.10.017

Please cite this article as: E. Shahabpoor, et al., Effect of group walking traffic on dynamic properties of pedestrian structures, *Journal of Sound and Vibration* (2016), http://dx.doi.org/10.1016/j.jsv.2016.10.017

system. The properties of a single degree of freedom mass-spring-damper system representing a moving crowd needed to replicate these observations have been identified.

1. Introduction

Over the past two decades, there has been a growing interest in vibration serviceability assessments of civil engineering structures, such as footbridges and floors due to people walking on them. The current trend towards more slender design and longer spans has made structures more sensitive to pedestrian-induced dynamic loading and consequently more susceptible to vibration problems, giving a serious cause for concern about the safety and comfort of the occupants. Moreover, such problems emphasise the need for more accurate and inclusive design methods which will take into account all aspects of human-structure dynamic interaction (HSI) [1–6].

Most of the current design guidelines, such as ISO 10137 standard [7] and UK National Annex to Eurocode 1 (BSI) [8], either ignore (ISO) or do not adequately treat (BSI) the main aspects of HSI [9]: (1) the effect of people on the dynamic properties of the structure, and (2) the changing of pedestrians' gait due to structural vibrations. The latter aspect occurs because the human body is a very sensitive vibration receiver, characterised by the innate ability to adapt quickly to almost any type and level of vibration which normally occurs in nature [10]. It has been experimentally observed that people change their pacing frequency and step width to adapt to clearly perceptible lateral vibrations of the supporting ground, which may lead to the so called 'lock-in' effect, as observed on the Millennium Bridge during its opening day in 2000 [11–13]. However, similar studies on the effect of the vertical vibrations on pedestrian gait are very rare and limited to individuals [14].

A number of studies, mostly based on full-scale measurements, have found that a passive human (sitting and standing) has a significant effect on the dynamic properties of a structure and, therefore, cannot be ignored. Typical findings include a considerable reduction in vibration response and slight changes in the natural frequency and damping of the structure [15]. This effect has been successfully modelled analytically by describing a group of passive people as an SDOF mass-spring-damper system attached to the empty structure [16].

Motivated by these findings, the present study was designed to collect a uniquely extensive experimental data,[1] which is needed for the analytical parameter identification of a mass-spring-damper (MSD) model of multiple *walking* people. Section 2 of this paper describes the modal parameters of the empty (unoccupied) structure used as a test bed for the walking people. Sections 3 and 4 study experimentally measured modal parameters of the structure when occupied by different numbers of standing and walking people, respectively. A comparison of the effects of standing and walking people on the modal parameters of the empty structure is presented in Section 5. In Section 6, a simple two-degrees-of-freedom mass-spring-damper model is used to simulate the joint human-structure system for both standing and walking scenarios. The analytical results are then critically evaluated against the corresponding experimental results. Finally, the main findings of this research are highlighted in Section 7.

2. Modal properties of the empty test structure

The test structure used in this study was a simply supported, in-situ cast, post-tensioned concrete slab strip constructed in the Light Structures Laboratory at the University of Sheffield (Fig. 1a). It rested on two knife edge supports along its shorter edges (Fig. 1b) and, with a span-to-depth ratio of 40, could be considered to be a representation of both a footbridge and a long-span slender floor. More specifically, the total length of the slab was 11.2 m, including 200 mm overhangs over the supports. Its rectangular cross section had a width of 2.0 m and a depth of 275 mm, and it weighed just over 14 t. The modal tests carried out by Shahabpoor and Pavic [17] showed natural frequencies of 4.44 Hz and 16.78 Hz for the first two vertical modes of the structure (Fig. 2) with a modal mass of 7128 kg for both modes, which is half of the total mass, assuming unity-scaled sinusoidal mode shapes. These two modes were selected for further analysis.

2.1. Non-linear behaviour of the empty structure

Knowledge about the potential non-linear behaviour of the structure plays an important role when judging whether changes in the modal properties of the occupied structure are related to the presence of people or to some form of structural non-linearity [18]. The amplitude-dependent behaviour of the damping ratio and natural frequency of the first mode were measured by Racic et al. [19] by curve-fitting cycle-by-cycle the free vibration decay of the structure at the midspan. The results are shown in Fig. 3.

[1] The work described in this article is carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans.