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

From phase drift to synchronisation – pedestrian stepping behaviour on laterally oscillating structures and consequences for dynamic stability

Mateusz Bocian [a,*], Jeremy F. Burn [b], John H.G. Macdonald [c], James M.W. Brownjohn [d]

[a] *Department of Engineering, University of Leicester, University Road, Leicester LE1 7RH, UK*
[b] *Department of Mechanical Engineering, University of Bristol, University Walk, Bristol BS8 1TR, UK*
[c] *Department of Civil Engineering, University of Bristol, University Walk, Bristol BS8 1TR, UK*
[d] *Vibration Engineering Section, University of Exeter, North Park Road, Exeter EX4 4QF, UK*

ARTICLE INFO

Article history:
Received 6 April 2016
Received in revised form
26 November 2016
Accepted 13 December 2016

Keywords:
Human-structure interaction
Synchronous lateral excitation
Self-excited forces
Instrumented treadmill
Human loading
Structural stability

ABSTRACT

The subject of this paper pertains to the contentious issue of synchronisation of walking pedestrians to lateral structural motion, which is the mechanism most commonly purported to cause lateral dynamic instability. Tests have been conducted on a custom-built experimental setup consisting of an instrumented treadmill laterally driven by a hydraulic shaking table. The experimental setup can accommodate adaptive pedestrian behaviour via a bespoke speed feedback control mechanism that allows automatic adjustment of the treadmill belt speed to that of the walker. 15 people participated in a total of 137 walking tests during which the treadmill underwent lateral sinusoidal motion. The amplitude of this motion was set from 5 to 15 mm and the frequency was set from 0.54 to 1.1 Hz. A variety of stepping behaviours are identified in the kinematic data obtained using a motion capture system. The most common behaviour is for the timing of footsteps to be essentially unaffected by the structural motion, but a few instances of synchronisation are found. A plausible mechanism comprising an intermediate state between unsynchronised and synchronised pedestrian and structural motion is observed. This mechanism, characterised by a weak form of modulation of the timing of footsteps, could possibly explain the under-estimation of negative damping coefficients in models and laboratory trials compared with previously reported site measurements. The results from tests conducted on the setup for which synchronisation is identified are evaluated in the context of structural stability and related to the predictions of the inverted pendulum model, providing insight into fundamental relations governing pedestrian behaviour on laterally oscillating structures.

1. Introduction

It is now well known that walking pedestrians have a capacity to cause lateral dynamic instability of structures [1]. Whether divergent-amplitude lateral structural vibrations will develop under the action of walking pedestrians depends on

---

[*] Corresponding author.
E-mail address: m.bocian@leicester.ac.uk (M. Bocian).

http://dx.doi.org/10.1016/j.jsv.2016.12.022

Please cite this article as: M. Bocian, et al., From phase drift to synchronisation – pedestrian stepping behaviour on laterally oscillating structures and consequences for dynamic stability, *Journal of Sound and Vibration* (2016), http://dx.doi.org/10.1016/j.jsv.2016.12.022

the net damping of the crowd-structure system. The initiation of dynamic instability for a given vibration mode will occur when the total negative damping of the mode from the pedestrians is greater in magnitude than the structural damping. The most widely publicised occurrence of pedestrian-induced instability is the case of the London Millennium Footbridge which suffered from excessive vibrations on the day of its opening. Subsequently, a series of controlled crowd loading tests was conducted on that bridge of which results showed that pedestrian lateral force is approximately proportional to the lateral velocity of the deck. It was proposed to model this force as a damping coefficient per pedestrian, having an empirical numerical value of -300 N s m^{-1} for structural vibration modes within the frequency range 0.5–1 Hz [2]. This modelling framework was later extended to account for the component of pedestrian lateral force at the frequency of the excited vibration mode orthogonal to the one in phase with structural velocity [3]. Similar to the approach adopted in wind engineering for modelling flutter [4], after appropriate scaling, the components in phase with velocity and acceleration can be expressed as equivalent added damping and mass to the structure [e.g. 5–7], denoted herein as ΔC and ΔM, respectively, and expressed per pedestrian. This framework implies that ΔC and ΔM, which are often termed as self-excited (or motion-dependent) forces, are in fact independent of bridge motion amplitude, which might not always be the case. Nevertheless, it has become a convention to express self-excited pedestrian forces in this concise form. The effect of ΔM is effectively to change the vibration frequency, which should be accounted for in analyses of dynamic structural stability as, at least in theory, this could in turn have an effect of modifying ΔC [7]. ΔC itself is more important as it can become negative hence effectively reduce the total damping. However, what value of ΔC should be used for the assessment of structural stability remains an open issue. This is because a discrepancy exists between the measurements of ΔC obtained from tests on full-scale structures, representing a top-down approach to the derivation of self-excited forces, and results of laboratory investigations on the behaviour of a single walker, representing a bottom-up approach.

The values obtained using a top-down approach, relying on back-calculation of ΔC from the measured structural response, are summarised in Table 1.

It can be seen that, with the exception of ΔC derived from the behaviour of the Clifton Suspension Bridge, all the values fall at or below -300 N s m^{-1}. This is considerably lower than the average values reported from an extensive experimental campaign of Ingólfsson et al. [5], which reached a minimum of approximately -200 N s m^{-1} for a vibration amplitude of 4.5 mm, but increased to above half that value (hence became less detrimental in the context of structural stability) for vibration amplitudes above 20 mm. This seems inconsistent with the measurements on the London Millennium Footbridge, for which ΔC was found to be fairly constant up to the maximum vibration amplitude of 48 mm experienced in the tests [2]. The recent laboratory results reported by Bocian et al. [11] concur in that respect, suggesting that the expected ΔC for a mode at 0.9 Hz vibrating with an amplitude of 10 mm would be just -150 N s m^{-1}, accounting only for pedestrians unsynchronised to the lateral motion, walking at their preferred unimpeded speed.

It is noteworthy that during the tests on instrumented treadmills aiming at quantification of self-excited forces the speed of the walker was either imposed (equal to the preferred walking speed on an unactuated treadmill) [2], or self-selected (i.e. unconstrained) due to the application of a treadmill belt speed feedback control mechanism [11]. All these speeds might not correspond to the speed of a pedestrian walking in a dense crowd, which can be expected to reduce with increasing crowd density. The predictions of the inverted pendulum pedestrian model (IPM) proposed by Macdonald [6] suggest that ΔC can then become more detrimental, for the range of natural frequencies coinciding with the frequencies of the excited modes listed in Table 1 [7]. This might explain the large negative values of $.5823mm,lt)=''graphic:mml:print:m440856860_{2}8010''$ observed on most of the bridges identified in Table 1 [12]. However experimental evidence is currently lacking to validate this prediction.

Another suggested explanation of the discrepancy in ΔC derived using bottom-up and top-down approach is preferential phase frequency entrainment [13]. This is a state in which the pedestrians synchronise their motion to the motion of the vibrating structure, adjusting their relative phase such as to input more energy into the excited structural mode than the average expected ΔC for unsynchronised walking. It has been suggested that this behaviour might be driven by a desire to avoid less comfortable gait patterns in which the step width becomes narrow or the position of the foot during a step crosses to the contralateral side of the body [14]. However, no experimental evidence has been presented supporting the prevalence of preferential phase frequency entrainment or even its very existence.

To address the uncertainty as to the discrepancy between self-excited forces obtained using top-down and bottom-up approaches, the aim of this study is to evaluate temporal pedestrian stepping behaviour on laterally oscillating structures and its consequences for structural stability. To this end a series of tests was performed on a laterally oscillating instrumented treadmill in which kinematic data of the behaviour of walkers were collected with a motion capture system. Critical for realising the aim of this study is the capacity of the experimental setup to accommodate adaptive pedestrian behaviour via a bespoke speed feedback control mechanism that allows automatic adjustment of the treadmill belt speed to

Table 1
Pedestrian damping coefficient identified from tests on full scale structures. The values in brackets denote the natural frequencies of the relevant modes.

	London Millennium Footbridge [2]	**Changi Mezzanine Bridge** [8]	**Clifton Suspension Bridge** [9]	**Pedro and Inês Footbridge** [10]
ΔC [N s m^{-1}]	-300 (0.5 & 1 Hz)	-376 (0.9 Hz)	-160 (0.52 Hz) & -210 (0.74 Hz)	-300 (0.91 Hz)

Please cite this article as: M. Bocian, et al., From phase drift to synchronisation – pedestrian stepping behaviour on laterally oscillating structures and consequences for dynamic stability, *Journal of Sound and Vibration* (2016), http://dx.doi.org/10.1016/j.jsv.2016.12.022