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Influence of visual information on pedestrian actions on laterally oscillating structures – experimental study using virtual reality environments

Mateusz Bocian[a,*], John H.G. Macdonald[b], Jeremy F. Burn[c]

[a]*Department of Engineering, University of Leicester, University Road, Leicester, LE1 7RH, UK*
[b]*Department of Civil Engineering, University of Bristol, University Walk, Bristol, BS8 1TR, UK*
[c]*Department of Mechanical Engineering, University of Bristol, University Walk, Bristol, BS8 1TR, UK*

Abstract

A new line of inquiry into the causes of lateral instability of structures due to actions of walking pedestrians has been opened recently thanks to the fusion of structural dynamics, biomechanics and experimental psychology. This has been achieved by means of a novel experimental setup. The setup consists of an instrumented treadmill, supported by a shaking table providing lateral motion, a motion capture system for monitoring kinematics of walkers, a treadmill speed feedback control mechanism for automatic adjustment of the treadmill speed to that of the walker and immersive virtual reality implemented to provide similarity of the visual environment with real life experience. It has been previously observed that the visual environment can influence pedestrian behaviour and the resulting ground reaction forces. Statistically significant differences between gait parameters and self-excited forces, critical for structural stability, have been measured during tests in which the visual environment was either that of a laboratory, containing an abundance of stationary visual reference cues, or virtual reality representative of walking on a footbridge. This highlighted the importance of providing visual information representative of real life experience. Another opportunity presented by the experimental setup is explored in this study in that it allows the influence of differently structured visual environments to be tested. To this end, two types of visual scenarios are implemented in virtual reality, differentiated by the amount of visual information available to the walker. It is shown that the visual information can indeed alter pedestrian behaviour and that reducing the amount of visual information can have a detrimental effect for structural stability. This raises a question whether a number of design recommendations proposed in recent years, calibrated based on data from laboratory-based investigations neglecting the influence of visual information on pedestrian behaviour, should be reconsidered and updated.

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Keywords: Bridges; lateral vibrations; human-structure interaction; pedestrian loading; self-excited forces; virtual reality; gait biomechanics

* Corresponding author. Tel.: +44-161-252-2539; fax: +44-116-252-2619.
E-mail address: m.bocian@leicester.ac.uk

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1. Introduction

A considerable effort has been made in the quantification of self-excited (or motion-dependent) pedestrian lateral forces since lateral instability was identified on two high-profile footbridges built near the beginning of this century – the Solférino Footbridge in Paris [1] and the London Millennium Footbridge (LMF) [2]. It has since become a convention to express these forces as equivalent added damping and mass per pedestrian, and a database of these measured forces and information on pedestrian behaviour on laterally oscillating structures is currently being populated. Experimental data come from tests conducted on real full-scale structures [3-5], footbridge section models [6] and instrumented treadmills [7, 8]. However, little effort has been made so far on trying to understand the influence of visual information on pedestrian behaviour in the context of structural stability. This is worrying since visual information is known to affect the stability of gait, of which control is the underlying driving mechanism responsible for pedestrian induced lateral structural vibrations. To this end, this paper addresses the uncertainty associated with the influence of visual information on pedestrian actions on laterally oscillating structures. Immersive and interactive virtual reality (VR) technology was employed for this purpose, enabling experimental test subjects walking on a laterally-oscillating instrumented treadmill to be exposed to different visual conditions in the confines of the laboratory environment. The results from the experimental study are considered in the context of structural stability and related to the results previously reported.

2. Materials and methods

2.1. Experimental setup

The experimental setup utilized in this study (see Fig. 1) consists of an instrumented treadmill with a 2 m long by 1.5 m wide walking area, a hydraulic shaking table providing lateral treadmill motion, a motion capture system based on infrared cameras (Qualisys), allowing kinematic data on pedestrian behaviour to be collected, and a fall arrest system ensuring safety of walkers. To allow adaptive pedestrian behaviour via modification of the walking speed, a feedback control mechanism is implemented in the setup enabling automatic adjustment of the treadmill belt speed to that of the walker. To ensure congruence of visual information with that representative of overground walking, hence providing optic flow and motion parallax, immersive and interactive virtual reality is implemented in the setup via a stereoscopic head mounted display (nVisor SX111). Further details on the setup and its validation are available in [9, 10].

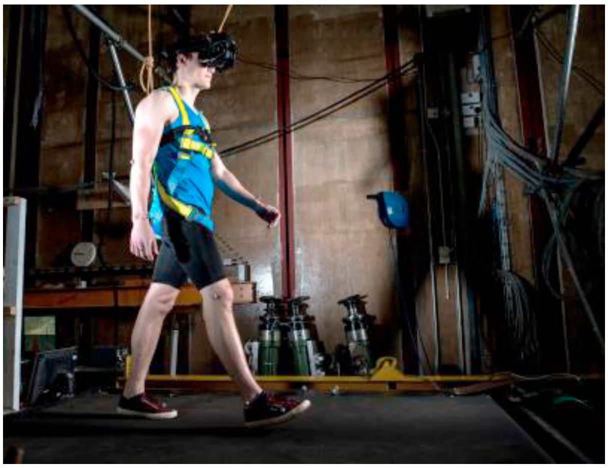

Fig. 1. A test subject walking on the instrumented treadmill undergoing lateral oscillation.

2.2. Participants

Two volunteers participated in the tests and are hereafter denoted S1 and S2. Their basic data are shown in Table 1. Both participants were unaware of the purpose of the experimental protocols, has no known deficiencies in their locomotor system which could impair their performance, and signed an informed consent form prior to participating in the experiments.

Table 1. Basic data for participants of the tests.

ID	Gender	Age (years)	Height (m)	Mass, m_p (kg)
S1	Female	20	1.82	68
S2	Male	21	1.80	67

2.3. Experimental protocols

Both test subject (S1 and S2) wore gym-type clothing and shoes allowing motion capture system markers to be placed close to or on their body. A safety harness was fitted and their height and weight were measured. After habituation to walking on the treadmill, both with it stationary and oscillating in the lateral direction and with and without VR, each participant conducted a number of tests in different visual conditions. The tests in two of these conditions, presented in Fig. 2 and denoted hereafter as VR1 and VR2, are reported herein. In all tests the treadmill was oscillating laterally in sinusoidal motion with 0.01 m amplitude at 0.9 Hz

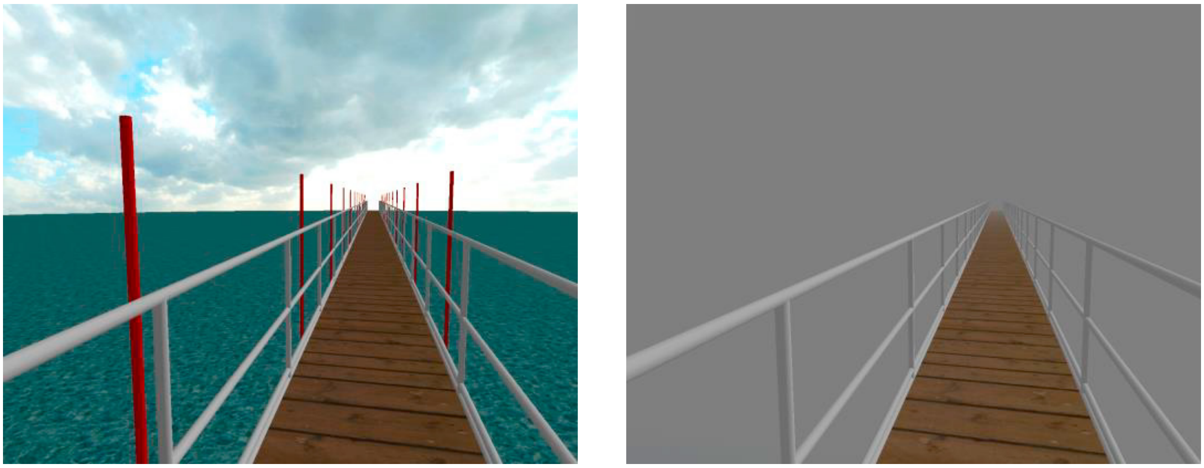

Fig. 2. Virtual reality environments applied during the tests: VR1 (left) and VR2 (right).

- VR1 is representative of conditions whereby an abundance of visual reference cues is available. It consists of a 1.4 m wide virtual bridge with the deck rendered as wooden planks, corresponding to the experience of walking on top of the medium density fiberboards supporting the treadmill belt. The railings of the bridge are built of horizontal and vertical tubes. The bridge is located 4 m above a water-like substratum. Red poles positioned symmetrically along the bridge every 4 m represent stationary (in the global reference frame) features of the environment (e.g. lamp posts). The sky emulates typical British conditions, i.e. some cloud coverage is present. Visual information about forward progression is available from translational motion of the virtual deck, posts and the vertical railing sections and from translational motion with regard to the substratum and red poles. The visual information on treadmill lateral motion comes from movement of the bridge relative to the substratum and red poles.

- VR2 is representative of conditions when a limited number of visual reference cues is available. These conditions can arise when walking in dense fog or in a relatively dense crowd. In the latter case, the information of self-motion is often relative to the motion of other pedestrians, which might be ambiguous. Bering in mind the important role of visual perception on stability of gait, of which maintenance is an underlying cause of structural stability, it can be hypothesized that these visual conditions can influence the magnitudes of pedestrian loading. In VR2 the only visual cues about the treadmill lateral motion are available from the effect of it causing relative motion of the subject's head, which is perceived relative to the deck and railings. Visual information about forward progression is available from translational motion of the virtual deck and vertical railing sections.

Each test lasted approximately three minutes which, after discarding periods associated with gait and experimental setup initiation and termination stages, gave approximately two minutes of data for further processing. The experimental campaign, using human subjects, was approved by the University of Bristol Ethics of Research Committee.

2.4. Data processing

Data processing methods are those previously reported in [9, 11]. In short, in the determination of the magnitudes of self-excited forces in terms of equivalent added damping and mass, care was taken to include, as closely as possible, an integer number of treadmill oscillation and pedestrian gait cycles while taking the longest possible record. This was implemented based on identifying the timing of heel strikes of the foot with the ground, using the motion capture system (MCS) markers, relative to the bridge motion cycle. Pedestrian-induced self-excited forces at the treadmill lateral oscillation frequency, representative of the average pedestrian behaviour during a test, were quantified according to:

$$\Delta M = -\mathrm{Re}\left[H_{\ddot{x}_b F_L}(f_b) - H^*_{\ddot{x}_b F_L}(f_b)\right] \tag{1}$$

$$\Delta C = \mathrm{Im}\left[H_{\ddot{x}_b F_L}(f_b) - H^*_{\ddot{x}_b F_L}(f_b)\right]\omega_b \tag{2}$$

where ΔM and ΔC are the equivalent added mass and damping, respectively, $\mathrm{Re}[\bullet]$ and $\mathrm{Im}[\bullet]$ denote the real and imaginary part of the complex number $\bullet$, respectively, ω_b is the angular treadmill oscillation frequency and $H_{\ddot{x}_b F_L}(f_b)$ and $H^*_{\ddot{x}_b F_L}(f_b)$ are the transfer functions between the measured treadmill acceleration and lateral force, evaluated at the treadmill lateral oscillation frequency f_b. $H_{\ddot{x}_b F_L}(f_b)$ and $H^*_{\ddot{x}_b F_L}(f_b)$ were found from the ratio of the FFTs of the force and acceleration, where $H_{\ddot{x}_b F_L}(f_b)$ was obtained from data from a test with a pedestrian walking on the treadmill, and $H^*_{\ddot{x}_b F_L}(f_b)$ from data collected with the same treadmill vibratory conditions and treadmill belt speed, but without a pedestrian.

Stride time was identified as the time between the instances of two consecutive heel strikes for the same leg. Stride frequency was taken as a reciprocal of the stride time. Stride length was taken as the anterior–posterior distance between the locations of the ankle markers at the instances of two consecutive heel strikes for the same leg, accounting for the motion of the treadmill belt as measured by the MCS. Step width was taken as the medio-lateral distance between the ankle marker and the position of the centre of mass, identified via an inverse dynamics procedure (see [9]), at the instance of heel strike. All data were sampled at 128 Hz.

3. Results and discussion

The results from the tests are presented in Table 2. It can be seen that both subjects (see Table 1) walked with stride frequencies above the treadmill lateral oscillation frequency. Examination of the data suggests that the timing of pedestrian footsteps was essentially unaffected by the treadmill lateral motion during all tests (cf. phase drift in [9, 11]), and indeed the small values of the standard deviation of stride time seem to confirm this assertion. The equivalent added damping was always negative (detrimental) and was more detrimental for structural stability in

VR2 relative to VR1, changing by 25% and 6% for S1 and S2, respectively. The equivalent added mass was always positive and was higher in VR2 relative to VR1, changing by 21% and 20% for S1 and S2, respectively. Considering changes to the average gait parameters in VR2 relative to VR1 for S1, the stride time increased by 6%, the stride length decreased by 10% and the step width decreased by 6%. Little difference in standard deviations for all these parameters are noted for S1. Considering the same for S2, the stride time decreased by 2%, the stride length increased by 4% and the step width increased by 2%. More variability in the standard deviations of all parameters occurred for S2, most notably for the stride length for which the standard deviation decreased by 29%.

Table 2. Results from the tests. The values in brackets, where applicable, are standard deviations.

		VR1	VR2
S1	Body-mass normalized equivalent added damping, $\Delta C/m_p$ [s^{-1}]	-1.43	-1.78
	Body-mass normalized equivalent added mass, $\Delta M/m_p$ [-]	0.34	0.41
	Stride time [s]	1.0023 (0.0093)	1.0628 (0.0092)
	Stride length [m]	1.7652 (0.0295)	1.5921 (0.0305)
	Step width [m]	0.1063 (0.0159)	0.1000 (0.0158)
S2	Body-mass normalized equivalent added damping, $\Delta C/m_p$ [s^{-1}]	-2.55	-2.70
	Body-mass normalized equivalent added mass, $\Delta M/m_p$ [-]	0.40	0.48
	Stride time [s]	0.9721 (0.0095)	0.9494 (0.0089)
	Stride length [m]	1.5622 (0.0398)	1.6298 (0.0282)
	Step width [m]	0.0819 (0.0201)	0.0833 (0.0218)

The results from the tests suggest that the reduction of visual reference cues causes the negative damping effect from pedestrians to be more detrimental for structural stability. Considering the results for both subjects, the negative equivalent added damping decreased on average by 15%, indicating this effect might have to be taken into account in the assessment of lateral stability of structures under the action of walking pedestrians.

The measured positive equivalent added mass agrees with the observation from the Changi Mezzanine Bridge on which pedestrian actions caused instability of the lateral vibration mode at 0.9 Hz [5], corresponding to the frequency of treadmill lateral oscillation applied during the tests. This is different than the results of previous treadmill tests [12] suggesting equivalent added mass in these treadmill vibratory conditions should be close to zero.

Less consistency is evidenced in the gait parameters. While the stride frequency and walking speed decreased for S1 (from 1 to 0.94 Hz and 1.76 to 1.50 ms^{-1}, respectively), the opposite is true for S2 (from 1.03 to 1.05 Hz and 1.61 to 1.72 ms^{-1}, respectively). This might be a reflection of individual preferences or a difference in the adaptive pedestrian behaviour characteristic of many human activities.

The existing design guidelines are currently lacking provisions accounting for different scenarios which might govern stability criteria against lateral instability of structures under pedestrian actions. In the light of the presented results, it seems such provisions should be incorporated. Bearing in mind that the presented results come from two subjects only, more research on this topic is required.

4. Conclusions

This paper addresses the uncertainty pertaining to pedestrian behaviour on laterally oscillating structures and the resulting structural response. Specifically, the influence of the visual environment on pedestrian actions is investigated by means of immersive and interactive virtual reality technology incorporated into a novel experimental setup capable of directly measuring ground reaction forces. Two subjects participated in two sets of tests during which the visual environment delivered via a head mounted display was either that of a bridge, set within a simple virtual world preserving the type of visual information available in normal walking conditions, i.e. an abundance of stationary visual reference cues, or a bridge set within an environment offering reduced visual reference information. The second scenario is relevant to conditions in which reliable visual information on self-motion is scarce or unreliable.

It has been found that the visual environment can indeed influence the magnitudes of self-excited forces, causing the negative damping effect from pedestrians to become more detrimental for structural stability in the case when visual reference cues are limited. This effect was relatively strong during the tests, with negative equivalent added damping reducing on average by 15%. The visual conditions also affected the magnitude of equivalent added mass which increased, on average, by 20% in the case when visual reference cues are limited. This should be taken into account when assessing the susceptibility of structures to pedestrian induced excitation, since the equivalent added mass can shift the natural frequency of the crowd-structure system. The pedestrian equivalent added damping was previously found to be frequency dependent [13-15], and the combined effect of self-excited forces can cause instability boundaries to be extended [16].

To the best of the authors' knowledge, this is the first study delving into the influence of visual environment on pedestrian and structural stability. It is hoped that the adopted methodology will find more use in research on vibration serviceability.

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