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Experimental identification of the behaviour of and lateral forces from freely-walking pedestrians on laterally oscillating structures in a virtual reality environment

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ABSTRACT

Modelling pedestrian loading on lively structures such as bridges remains a challenge. This is because pedestrians have the capacity to interact with vibrating structures which can lead to amplification of the structural response. Current design guidelines are often inaccurate and limiting as they do not sufficiently acknowledge this effect. This originates in scarcity of data on pedestrian behaviour on vibrating ground and uncertainty as to the accuracy of results from previous experimental campaigns aiming to quantify pedestrian behaviour in this case. To this end, this paper presents a novel experimental setup developed to evaluate pedestrian actions on laterally oscillating ground in the laboratory environment while avoiding the implications of artificiality and allowing for unconstrained gait. A biologically-inspired approach was adopted in its development, relying on appreciation of operational complexities of biological systems, in particular their adaptability and control requirements. In determination of pedestrian forces to the structure consideration was given to signal processing issues which have been neglected in past studies. The results from tests conducted on the setup are related to results from previous experimental investigations and outputs of the inverted pendulum pedestrian model for walking on laterally oscillating ground, which is capable of generating self-excited forces.

1. Introduction

A number of attempts to determine pedestrian loading on laterally oscillating bridges in which pedestrian forces are inferred through inverse dynamics, i.e. from analysis of the time histories of the behaviour of full scale bridges during pedestrian occupancy, can be classified as *top-down* modelling approaches. This type of identification process is essentially achieved through decomposition of the coupled crowd-structure system into its more basic components and analysis of their contributions to the system dynamic behaviour. The obtained pedestrian forces come from empirical data hence have an advantage of being based on direct evidence. However, loading models constructed in this manner do not generally have the capability of explaining mechanisms causing lateral instability nor can they be generalised to other structures. The reason for this is the inherent bias of *top-down* modelling approaches towards higher organisational rank, i.e. fitting unknown behaviour of the input drivers to the known performance of the whole system. This favouritism can lead to misinterpretation of the system, in this case the oversimplification of pedestrian behaviour, which is often assumed rather than evidential, and as an effect can obstruct rather than facilitate understanding. This problem is the most relevant to a number of modelling approaches in which synchronisation of a group of pedestrians was proposed as the sole mechanism causing structural instability [1].

Alternative approaches to the pedestrian–structure interaction problem utilise *bottom-up* modelling. *Bottom-up* modelling relies on pre-existing knowledge of elementary components of the system and their behaviour in building of the system model.

Abbreviations: CoM, centre of mass; CoP, centre of pressure; FFT, fast Fourier transform; GRF, ground reaction force; HMD, head-mounted display; IPM, inverted pendulum model; MCS, motion capture system; MIV, manipulated independent variable; NTLM, no treadmill lateral motion; NVR, no virtual reality; TLM, treadmill lateral motion; VR, virtual reality.

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It therefore fundamentally differs from the *top-down* modelling in that it involves synthesis rather than decomposition. In the context of pedestrian–structure interaction on bridges the constituent components for synthesis are the bridge and the pedestrians. With the modal properties of the bridge usually well defined, either through analytical or experimental methods (i.e. finite element modelling and modal testing, respectively), the veracity of the model depends on accurate characterisation of the ground reaction forces occurring at the interface of these two dynamic subsystems. This critical task, in turn, demands good understanding of pedestrian behaviour and requires separate, purpose-oriented investigations.

Today, the prevailing concept in modelling pedestrian lateral loading is that proposed by Arup [2], derived from analysis of measurements from the dynamic behaviour of the London Millennium Footbridge under the action of crowds, thereby representing the *top-down* modelling approach. It relies on an observation that walking pedestrians, within certain conditions, can be treated as a source of negative damping to the structure. In fact many other models, which are most often based on the notion of synchronisation, are at their culmination simply calibrated to match the results obtained by Arup over a decade ago. Therefore their applicability in predicting structural dynamic behaviour, especially for cases when the structural and crowd characteristics are different than those experienced on the London Millennium Footbridge, can be considered questionable. A better solution to the problem is to develop a fundamental pedestrian model, applicable to walking on vibrating ground, while avoiding any preconceptions of pedestrian behaviour.

1.1. A fundamental model of pedestrian behaviour while walking on laterally oscillating ground

Based on a framework introduced by Barker [3], a fundamental pedestrian model for walking on laterally oscillating ground was proposed by Macdonald [4]. He conceived an inverted pendulum pedestrian model (IPM) rooted in the field of biomechanics, representing dynamics of walking in the frontal plane (i.e. vertical plane perpendicular to the direction of progression). As in Barker's model, the self-excited forces were generated based on an assumption of the pedestrian walking frequency being unaffected by the bridge motion. Unlike in Barker's model, Macdonald's model included allowance for the effect of the forces from bridge motion on the pedestrian mass hence accounted for the full bi-directional pedestrian–structure interaction. Because step width modulation is known to be the most important balance control strategy in the presence of lateral gait perturbation while walking on stationary ground [5], a stepping control law was adopted in the model based on findings by Hof et al. [6]. According to that control law a pedestrian will respond to lateral perturbation by augmenting the step width proportionally to the lateral velocity of the CoM and a constant offset, at the instance of foot placement.

Fourier decomposition of the pedestrian lateral force in the presence of lateral bridge motion with frequency f_b obtained from the IPM revealed that in addition to components of the force characteristic for walking on stationary ground, at stride frequency f_p and its odd harmonics, other self-excited (or motion-dependent) force components which lay symmetrically around these harmonics at $jf_p \pm \delta f$, where j is an odd integer and $\delta f = |f_p - f_b|$ is the beating frequency, are present in the frequency spectrum [4]. The component of the self-excited forces at the bridge vibration frequency, F_{Lf_b}, is of upmost importance as it can input energy into (or extract energy from) the relevant vibration mode.

The premise of the bridge motion not affecting pedestrian walking frequency, underlying Barker's [3] and Macdonald's [4] models, and the observation that unsynchronised pedestrians' loading is able to lead to structural instability are corroborated by the results of measurements of dynamic behaviour of the Changi Mezzanine Bridge (CMB) at the Singapore's Airport by Brownjohn et al. [7] and on the Clifton Suspension Bridge by Macdonald [8]. No evidence of synchronisation was observed on these bridges during divergent amplitude vibration periods. In agreement with the observation made by Arup on the London Millennium Footbridge [2], the amplitude of the effective pedestrian lateral force on each mode was found to be proportional to the amplitude of the local lateral velocity of the deck. As with any tests on full-scale structures, only certain parameter ranges could be investigated, determined by the intrinsic dynamic characteristics of the structures.

Further theoretical analyses of the model were conducted by Bocian et al. [9,10], McRobie [11] and McRobie et al. [12]. A few experimental studies have also been conducted which give some support to the applicability of the IPM proposed by Macdonald [4].

1.2. Experimental identification of self-excited forces on laterally oscillating structures

To date, the most valuable effort of measuring lateral pedestrian forces in the presence of lateral bridge motion in a laboratory environment has been made by Ingólfsson et al. [13] who conducted an extensive experimental campaign on a slightly modified setup of Pizzimenti and Ricciardelli [14]. Adopting the framework of Pizzimenti and Ricciardelli [14], the self-excited component of the force at the bridge vibration frequency was quantified in terms of additional damping and mass (rather than stiffness as in [14]) to the structure for combinations of vibration frequency and amplitude in the ranges of 0.33–1.07 Hz and 4.5–48 mm, respectively. Large scatter of the results was observed, particularly at low vibration amplitudes, while F_{Lf_b} was found to depend on the vibration frequency and amplitude. Subsequently, a stochastic model of pedestrian loading was proposed based on the experimental findings [15]. Although significant insight into the interaction between pedestrians and laterally oscillating bridges was gained, many issues remained unresolved, mainly due to the shortcomings of the experimental setup and the experimental protocol, thus questioning the accuracy of the derived loading model and its predicted structural response. Specifically, the following main points (hereafter referred to as Points 1–3) were not addressed:

1. The tests were conducted in a laboratory environment with an abundance of stationary visual reference cues (as the walker on a treadmill is generally stationary relative to the environment). However, normal overground walking causes a specific optic flow, i.e. a pattern of apparent motion of the physical world perceived by an observer through their visual system due to self-motion, with a focus of radial expansion fixed at the point towards which the observer is moving [16]. Additional information to the locomotor system (i.e. organ system allowing movement to be generated using muscular and skeletal systems) is provided by motion parallax, i.e. apparent relative motion of objects away from the observer against the rest of the visual field caused by self-motion of the observer [17]. Both of these mechanisms through which visual perception is realised have been found to contribute to postural sway during walking and to influence stability [18]. As observed in the context of walking by Guerin and Bardy [19], dynamic systems theory dictates that, considering this adaptive nature of human gait, lack of congruence between visual and non-visual information can have an effect in that the locus of attracting and repelling states of the system can be changed. In other words, pedestrian behaviour (hence loading) can depend on the quality of visual information available to the walker. A lack of compatibility