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Time-dependent spectral analysis of interactions within groups of walking pedestrians and vertical structural motion using wavelets

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ABSTRACT

A multi-scale and multi-object interaction phenomena can arise when a group of walking pedestrians crosses a structure capable of exhibiting dynamic response. This is because each pedestrian is an autonomous dynamic system capable of displaying intricate behaviour affected by social, psychological, biomechanical and environmental factors, including adaptations to the structural motion. Despite a wealth of mathematical models attempting to describe and simulate coupled crowd-structure system, their applicability can generally be considered uncertain. This can be assigned to a number of assumptions made in their development and the scarcity or unavailability of data suitable for their validation, in particular those associated with pedestrian-pedestrian and pedestrian-structure interaction. To alleviate this problem, data on behaviour of individual pedestrians within groups of six walkers with different spatial arrangements are gathered simultaneously with data on dynamic structural response of a footbridge, from a series of measurements utilising wireless motion monitors. Unlike in previous studies on coordination of pedestrian behaviour, the collected data can serve as a proxy for pedestrian vertical force, which is of critical importance from the point of view of structural stability. A bivariate analysis framework is proposed and applied to these data, encompassing wavelet transform, synchronisation measures based on Shannon entropy and circular statistics. A topological pedestrian map is contrived showing the strength and directionality of between-subjects interactions. It is found that the coordination in pedestrians' vertical force depends on the spatial collocation within a group, but it is generally weak. The relationship between the bridge and pedestrian behaviour is also analysed, revealing stronger propensity for pedestrians to coordinate their force with the structural motion rather than with each other.

1. Introduction

It is widely recognised that crowd dynamics are determined by local interactions between pedestrians and pedestrians and the environment [1]. For example, adaptations in gait patterns associated with collision avoidance can involve

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intermittent changes in pacing rate, step length and walking velocity. Such behaviour can introduce non-stationary power at different frequency components in the spectra of the signals associated with pedestrian structural loading. Similar effects can occur due to psychological and sociological factors influencing behaviour of walkers. However, the nature of these gait adaptations in the context of structural stability is currently not well understood. As a consequence, a common practice in the development of crowd loading models on structures is to adopt an ansatz relating crowd density and the level of synchronisation of pedestrians' footsteps, or model pedestrian loading within a highly stochastic framework disregarding any deterministic relationships which can govern pedestrian behaviour.

The tendency for widespread synchronisation of pedestrians' walking frequencies and phases, hereafter referred to in a more general term as human-human interaction and abbreviated by HHI, has been one of the most often purported mechanisms affecting the stability of structural modes. The other mechanism is pedestrian-structure interaction, hereafter referred to in a more general term as human-structure interaction and abbreviated by HSI. This mechanism, pertaining to the energy feedback between pedestrian and structural motion, has been given more attention in recent years and indeed a considerable body of work already exists dealing with this problem; see e.g. [2–4] which cover this topic well. It is now generally accepted that walking pedestrians, on average, add damping and mass to the vertical vibration modes. Some uncertainties, however, still remain. While some sources report occurrences of synchronisation of pedestrian footsteps to the vertical ground motion [5,6], other suggest this propensity to be weak [7]. Furthermore, it is not known whether the HHI or HSI is the prevalent mechanism in the case of crowd loading.

Very few dedicated studies have so far been conducted to assess interpersonal gait coordination in the context of walking on flexible structures. Araújo et al. [8] used video recordings to determine the level of synchronisation among pedestrians walking in groups of different densities across 12 m long simply-supported slab, based on lateral motion of pedestrians' heads. No evidence of synchronisation between walkers was found in that study. Ricciardelli & Pansera [9] used pedometers to study gait characteristics and interactions of pedestrians in a crowd. A considerable variability in pedestrian behaviour was observed, pointing towards a need for further studies. To the best of the authors' knowledge, the only study reporting results from a flexible structure in situ, which mentioned the level of pedestrians' interpersonal synchronisation, is that reported in Van Nimmen et al. [10]. A set of wireless 3D motion sensors was used to record body motion of walkers crossing a footbridge. A step model of Li et al. [11] was fitted to these data to determine synchronisation of footsteps, although the rate of synchronisation was not quantified *per se* in that study.

More studies on interpersonal synchronisation in walking have been conducted in the fields of cognitive psychology, physical therapy and, broadly understood, human movement. It has been shown that visual information alone is generally a relatively weak stimulus for gait synchronisation [12,13]. However, tactile coupling, e.g. achieved by holding hands [14] or being connected at the waist level by an elastic link [15], significantly improved interpersonal synchronisation. Since these studies focused exclusively on a pair of test subjects walking either side-by-side or front-to-back, there is a need to expand the field of enquiry to account for more complex scenarios representative of walking in a crowd on real-life full-scale structures.

Considering the scarcity of data on pedestrian interactions while occupying structures capable of dynamic response and the uncertainty of the pedestrian loading and structural response models proposed in recent years, the purpose of this study is to propose a new framework for the assessment of interactions between the components of crowd-structure system. The proposed framework yields results suitable for the application in agent-based crowd models in which each pedestrian is modelled as a discrete particle. Since up to 70% of pedestrians in a crowd belong to a cohesive group [16], the behaviour of six pedestrians walking in groups of different spatial arrangements across a long-span footbridge is investigated together with the resulting structural response. The rest of the paper is organised as follows. Section 2 presents materials used and describes the conducted tests along with the methods applied in the analysis of the collected data. A new method of quantification of synchronisation between components of a system consisting of a structure and walking pedestrians is described in detail in Section 2.5. Although the proposed method is used in this study to analyse a vertical bridge motion due to the presence of a group of walking pedestrians, it is also applicable in the case of crowd loading on this and other types of structures exhibiting dynamic response in any direction. Section 3 presents the results of analysis conducted within the proposed method. Specifically, the strength and directionality of synchronisation between pedestrians is quantified in Section 3.1, while the strength of synchronisation between pedestrian and structural motion is quantified in Section 3.2. Concluding remarks are given in Section 4.

2. Materials and methods

This section gives details of the experimental tests conducted for the purpose of this study and methods of analysis of the collected data. Section 2.1 provides information on the structure chosen for the tests, Section 2.2 provides information on the participants, Section 2.3 provides information on the instrumentation deployed during the tests and Section 2.4 provides information on the applied experimental protocol. Section 2.5 presents a new method for quantification of interactions between components of a dynamical system consisting of a structure and walking pedestrians.

The experimental campaign was approved by the College of Engineering, Mathematics and physical Sciences Ethics of Research Committee at the University of Exeter.