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A framework for experimental determination of localised vertical pedestrian forces on full-scale structures using wireless attitude and heading reference systems

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ABSTRACT

A major weakness among loading models for pedestrians walking on flexible structures proposed in recent years is the various uncorroborated assumptions made in their development. This applies to spatio-temporal characteristics of pedestrian loading and the nature of multi-object interactions. To alleviate this problem, a framework for the determination of localised pedestrian forces on full-scale structures is presented using a wireless attitude and heading reference systems (AHRS). An AHRS comprises a triad of tri-axial accelerometers, gyroscopes and magnetometers managed by a dedicated data processing unit, allowing motion in three-dimensional space to be reconstructed. A pedestrian loading model based on a single point inertial measurement from an AHRS is derived and shown to perform well against benchmark data collected on an instrumented treadmill. Unlike other models, the current model does not take any predefined form nor does it require any extrapolations as to the timing and amplitude of pedestrian loading. In order to assess correctly the influence of the moving pedestrian on behaviour of a structure, an algorithm for tracking the point of application of pedestrian force is developed based on data from a single AHRS attached to a foot. A set of controlled walking tests with a single pedestrian is conducted on a real footbridge for validation purposes. A remarkably good match between the measured and simulated bridge response is found, indeed confirming applicability of the proposed framework.

1. Introduction

Modelling the behaviour of lightweight structures due to the presence of active human occupants is a major challenge in the structural engineering community. The complexity arises owing to the highly adaptive nature of human behaviour and the potential of lightweight structures for dynamic response due to footfall loads, known as ground reaction forces (GRFs).

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Nomenclature

AHRS	altitude and heading reference system
BB	Baker Bridge
C7	seventh cervical vertebra
FEM	finite element model
GRF	ground reaction force
LB	lower back
LCS	local coordinate system
MCS	motion capture system
N	navel
oGRF	origin of the ground reaction force vector
PDR	pedestrian dead reckoning
QA	Honeywell accelerometer
S	sternum
TD	touch-down of the foot with the ground
TO	take-off of the foot from the ground
WCS	world coordinate system
ZUPT	zero velocity update

Both of these conditions can lead to human–structure interaction phenomena and emergent crowd behaviour, which might influence dynamic structural stability. Human–structure interaction refers to a feedback loop in which the energy is transferred between two dynamical systems – a human and a structure. Emergent crowd behaviour refers to the ability of a crowd to exhibit complex behaviours, resulting from simple local interactions between crowd members. Because of this complexity, the behaviour of an individual pedestrian must be first understood in order to build a reliable crowd–structure system model, including any relationships between the components of the system.

1.1. Background

Significant progress on this topic has been made in recent years by looking for inspiration in other fields of science, traditionally seen as unrelated to structural engineering. Physics-based, biomechanically-inspired modelling of pedestrian loading has revealed plausible mechanisms of pedestrian–structure interaction [1–5], some already supported by direct empirical evidence from laboratory investigations [6–8] and indirect evidence from measurements and modelling studies on full-scale structures [2]. Further progress is being made by turning attention to and drawing from achievements in the field of cognitive science. It is becoming evident that, in order to capture natural pedestrian behaviour, the experimental conditions during laboratory trials must closely resemble real life experience [8,9]. However, while this approach can help to understand adaptations in pedestrian gait invoked by the presence of structural motion, it does not provide any information about the behaviour of a pedestrian in a crowd. Resolution of this issue has been long overdue in the field of research concerned with the dynamic stability of structures.

Although increasingly sophisticated mathematical models of pedestrian–structure interaction and crowd dynamics appear regularly in scientific literature [10–12], most of them suffer from lack of hard evidence to support their main assumptions. This is particularly true for numerous models of synchronisation of walking pedestrians to structural motion or to each other, which are the most often purported mechanisms responsible for the build-up of large amplitude structural vibrations. This problem has persisted due to lack of suitable technology allowing pedestrians' and structural behaviour to be measured simultaneously in situ [13]. As a result, loading models are usually derived and extrapolated to real life structures based on laboratory test data, most often collected while walking on a rigid surface in an environment offering incongruent sensory information and preventing a test subject to freely adjust their gait. These limitations can be argued to be the root cause of instability of the London Millennium Footbridge [14].

To address the abovementioned limitations of current modelling approaches a few attempts have been made in recent years to develop a suitable framework for capturing pedestrian behaviour in situ. Two main technology trajectories are being explored – optical motion capture systems (MCS) and wireless inertial measurement units or monitors. These monitors, when using a fusion algorithm to compute global orientation (i.e. relative to the direction of gravity and Earth's magnetic field) from a triad of accelerometers, gyroscopes and magnetometers along with motion data, are referred to as Attitude and Heading Reference Systems (AHRS), and a single monitor is *an* AHRS. An optical MCS, managed by a dedicated data processing unit, consists of cameras tracking coordinates of markers.

1.2. Recent advances in in-situ measurement of pedestrian forces

The applicability of wireless AHRS for characterisating pedestrian walking forces was studied by Van Nimmen et al. [15]. In their modelling framework acceleration data from an inertial monitor attached at pedestrian waist level were used to obtain information on timing of footsteps. Subsequently, the loading model proposed by Li et al. [16] was fitted for the duration of each single step. This model relies on summing five Fourier components representative of mean pacing frequency and its higher harmonics, with amplitudes scaled in proportion to the walker body mass. Although the approach (i.e. attempting in-situ measurement of pedestrian forces on a real structure) is an advance on earlier work in the area, some limitations remain. For example, assigning a simple load shape function based on Fourier decomposition, even if implemented when footstep onset is not periodic, introduces certain artificial repeatability and neglects genuine time and amplitude variability present in force patterns, some of which can be associated with human–structure interaction. Some