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A framework for quantification of human-structure interaction in vertical direction

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ABSTRACT

In lightweight structures, there is increasing evidence of the existence of interaction between pedestrians and structures, now commonly termed pedestrian-structure interaction. The presence of a walker can alter the dynamic characteristics of the human-structure system compared with those inherent to the empty structure. Conversely, the response of the structure can influence human behaviour and hence alter the applied loading. In the past, most effort on determining the imparted footfall-induced vertical forces to the walking surface has been conducted using rigid, non-flexible surfaces such as treadmills. However, should the walking surface be vibrating, the characteristics of human walking could change to maximize comfort. Knowledge of pedestrian-structure interaction effects is currently limited, and it is often quoted as a reason for our inability to predict vibration response accurately. This work aims to quantify the magnitude of human-structure interaction through an experimental-numerical programme on a full-scale lively footbridge. An insole pressure measurement system was used to measure the human-imparted force on both rigid and lively surfaces. Test subjects, walking at different pacing frequencies, took part in the test programme to infer the existence of the two forms of human-structure interaction. Parametric statistical hypothesis testing provides evidence on the existence of human-structure interaction. In addition, a non-parametric test (Monte Carlo simulation) is employed to quantify the effects of numerical model error on the identified human-structure interaction forms. It is concluded that human-structure interaction is an important phenomenon that should be considered in the design and assessment of vibration-sensitive structures.

1. Introduction

Many newly built structures have light weight, low damping, and low stiffness, and they may not satisfy vibration serviceability criteria when occupied and dynamically excited by humans [1]. Observed problems have been caused typically by human occupants performing normal activities such as walking, running, jumping, bouncing/bobbing, and dancing. Vibration beyond the human comfort range will influence human comfort and so is a key consideration for designers. Human

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presence can affect the dynamic characteristics of the coupled human-structure system during motion, named here as Human-to-Structure Interaction (H2SI). On the other hand, the vibrating structure may change the human activity force pattern, and this potential phenomenon is named here as a Structure-to-Human Interaction (S2HI) (Fig. 1). These postulated mutual effects between human and structure are collectively referred to as human-structure interaction (HSI). Since for this work we consider only single human loading situations, we do not consider human-to-human interaction which can take place in crowds. The H2SI and S2HI effects are usually considered mutually exclusive [2], meaning that HSI is often modelled through a change in the dynamic properties of the system only or a change in walking force only. In this study, they are assumed to be mutually independent, isolated and examined individually using a novel experimental-numerical programme while both types occur simultaneously.

The focus of this study is on human walking and the resulting vibration. To assess the vibration response of structures susceptible to human walking, accurate estimation of human force, dynamic characteristics of the structure, and human-structure interaction are required (Fig. 1). As a novel aspect of this work, human walking force was measured using TekScan F-scan in-shoe plantar pressure sensors intended for medical applications. The plantar pressure force gives a reliable measurement of the vertical walking force [3], [4]. Further, the mass, damping, and stiffness of the structure were obtained using system identification methods. The most challenging part of the study of human-structure interaction is to identify and quantify the postulated forms of HSI separately. This study proposes an experimental-numerical framework to address this challenge. It relies on acquiring sufficiently accurate measurements of the human force, structure dynamics, and comparison of data recorded on rigid and flexible surfaces. The two postulated forms of HSI will be described in more detail in the next two sections.

The human body is a sensitive vibration receiver characterized by an innate ability to adapt quickly to almost any type and level of vibration which normally occurs in nature [5]. This effective self-adapting mechanism triggers pedestrians to change their walking behaviour [6]. In turn, it leads to walking force patterns that can be different to those measured on non-vibrating rigid surfaces [7].

There have been numerous attempts to measure or model pedestrian-induced forces, referred to as ground reaction forces (GRFs); see for example [8–14]. Past GRF measurement facilities typically comprised equipment for direct force measurements, such as a force plate [15], or an instrumented treadmill usually mounted on rigid laboratory floors [16–18]. However, GRFs could differ when walking on vibrating surface. For example, Ohlsson [19] found that the vertical force measured on a flexible timber floor is different from that measured on a rigid base. Pavic et al. [20] pointed out that the force induced by jumping on a flexible concrete beam was lower than that on a force plate. Van Nimmen et al. [21] and Bocian et al. [22] indirectly reconstructed vertical walking force on bridge surfaces from inertial motion tracking and a single point inertial measurement respectively. To the authors' knowledge, Dang and Zivanovic [23] is the only experimental work on direct measurement of walking GRFs on lively structures in the vertical direction. The results showed a drop in the first dynamic load factor of the walking force due to the bridge vibration at the resonance. However, test subjects walked on-the-spot on a treadmill for this study.

Humans add mass, stiffness, and damping to the coupled human-structure system. The influence of passive humans on the dynamic properties of the structure they occupy (i.e. modal mass, damping, and stiffness) have been well-documented in the literature [24,2,25,26]. For example, Ohlsson [19] found that a walking pedestrian can increase the HSI system's frequency and damping, while Willford [27] also reported a change in the system's damping due to moving crowd in the vertical direction. Zivanovic et al. [28] and Van Nimmen et al. [29] identified modal properties of the HSI system and showed that the presence of humans on the structure, either in standing or walking form, will increase the damping of the system compared to the empty structure. Zivanovic et al. [30] revealed that crowd effects can be also modelled as an increase in the damping of the

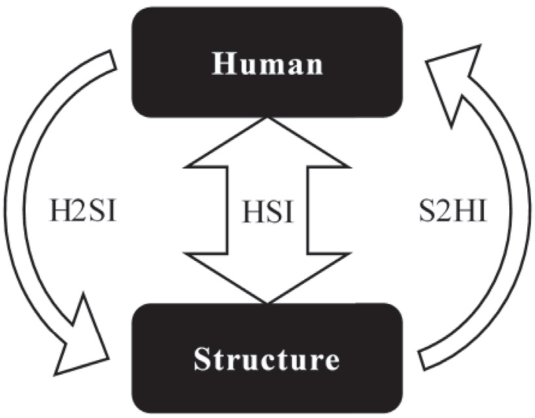

Fig. 1. Interactions between humans and the structure in the human-structure system are collectively called Human-Structure Interaction (HSI), but are considered separately here as Human-to-Structure Interaction (H2SI) and Structure-to-Human Interaction (S2HI).