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Vertical ground reaction forces on rigid and vibrating surfaces for vibration serviceability assessment of structures

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ABSTRACT

Lightweight structures are sensitive to dynamic force generated by human walking and consequently can exhibit excessive vibration responses. The imparted forces, known as ground reaction forces (GRFs), are a key input in the vibration serviceability assessment of footbridges. Most GRF measurements have been conducted on rigid surfaces such as instrumented treadmills and force plates mounted on strong floors. However, it is thought that the vibrating surface of a footbridge might affect the imparted human force. This paper introduces a unique laboratory experimental setup to investigate vertical GRFs on both rigid surface (strong floor) and a higher-frequency flexible surface (footbridge). 810 walking trials were performed by 18 test subjects walking at different pacing frequencies. For each trial, test subjects travelled a circuit of a vibrating footbridge surface followed by a rigid surface. A novel data collection setup was adopted to record the vertical component of GRFs, and the footbridge vibration response during each trial. Frequency-domain analysis of both single-step and continuous GRFs was then performed. The results show that the footbridge vibration affects GRFs, and changes GRF magnitudes for harmonics in resonance with the footbridge vibration (up to around 30% reduction in the dynamic load factor of the third harmonic). This finding, and the measured GRFs, can be used for more accurate vibration serviceability assessments of existing and new footbridges.

1. Introduction

1.1. Background

Due to their increasingly slender nature, many modern structures are prone to excitation from human activity. Human activities such as walking, running, jumping, and bouncing, can cause uncomfortable vibrations, potentially leading to reduced usage of the facility. Among these activities, walking is a key consideration for footbridge vibration. For low-frequency structures having one or more natural frequencies within range of first harmonic of walking force (1.6–2.4 Hz), walking at a pacing frequency close to the natural frequency of the structure might cause a vibration response that is considered uncomfortable by bridge users. The vibration response of a footbridge is generally largest if the resonance is excited by the first harmonic of walking force. For structures with natural frequencies within range of higher harmonics of walking force (larger than about 3.2 Hz – "higher-frequency"), the resonance by the second or third forcing harmonic might also be significant, even though the force amplitudes are smaller. To investigate higher-frequency vibration effects, extensive walking experiments were conducted on a higher-frequency footbridge for which the first frequency is in resonance with the third harmonic of walking force.

1.2. Ground reaction forces

To have a good prediction of footbridge vibration response, accurate estimation of the input walking force and reliable modelling of the structure are required. The former is the focus of this study. Humans apply an approximately periodic time-dependent force with vertical, lateral, and longitudinal components, referred to as ground reaction force (GRF) [1–3]. The vertical GRF has two distinctive peaks at heel-strike and toe-off phases, and a trough at mid-stance phase for one step during walking, as shown in Fig. 1. The vertical GRF has received much attention by previous researchers [4–19].

In the time domain, continuous walking GRFs are commonly described using a Fourier series [20–23]:

$$G_c(t) = W_p \sum_{k=0}^{r} DLF_k \cos(2\pi k f_p t + \varphi_k) \tag{1}$$

where $W_p = m_p g$ and m_p is the pedestrian mass, g is the acceleration due

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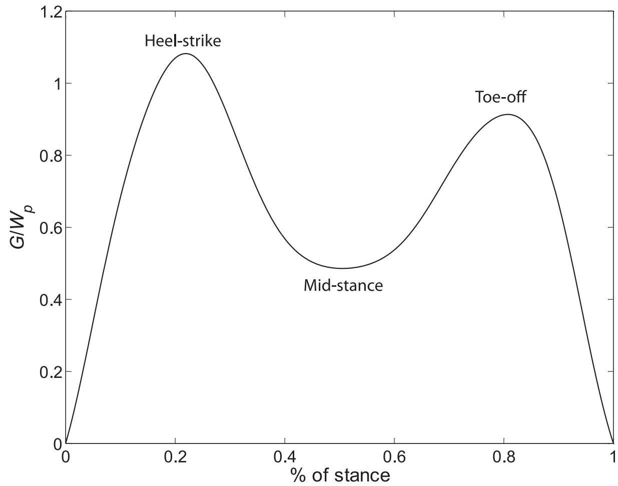

Fig. 1. Typical shape of a vertical GRF for a single step in walking.

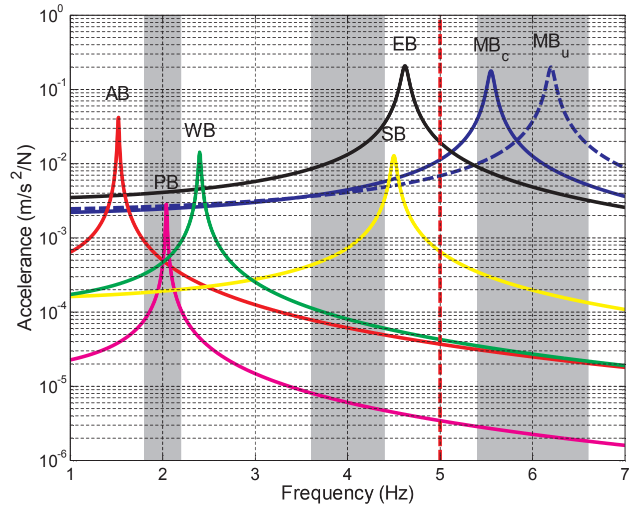

Fig. 2. First mode accelerance frequency response functions (FRFs) of different footbridges, walking harmonics (Shaded grey), and the 5 Hz limit. AB – Aberfeldy Footbridge (GFRP), PB – Podgoricia Bridge (Steel), WB – Warwick Bridge (Steel-Concrete Composite), SB – Sheffield Bridge (Prestressed Concrete), EB – EMPA Bridge (GFRP deck), MB_u – Monash Bridge, uncovered (GFRP), and MB_c – Monash Bridge, covered (some data from [31]).

to gravity; f_p is the walking pacing frequency; and DLF_k is the dynamic load factor (DLF) for the kth harmonic. The phase angle of the kth harmonic is denoted by φ_k, and r represents total number of harmonics considered. In this representation, the harmonic $k = 0$ corresponds to the static pedestrian weight, and so $\varphi_0 = 0$ and $DLF_0 = 1$.

All GRF studies explained so far originate from GRF measurements on rigid surface. These GRFs were measured by force plates and instrumented treadmills placed on rigid floors. This leaves the possibility that the reported vertical GRFs could be different to those that actually occur on lively footbridges, i.e. they could be affected by the vertical movement of the walking surface. Only a few works in the past have considered this. Ohlsson [24] reported that the spectrum of the walking force showed a drop around the natural frequency of the structure where the response was significant. Baumann and Bachmann [25] similarly reported DLFs of walking force, which were around 10% lower on the vibrating surface. However, they measured only single footsteps by a force plate mounted on a 19 m prestressed beam of frequency 2.3 Hz ("low-frequency bridge"). Pimentel [26] also suggested 10% and 40% reductions respectively in the first and second DLFs of the walking force by matching measured vibration responses with those calculated from an updated finite element (FE) model using a moving force model for two test subjects; but DLF models based on rigid surface measurements were used, and no GRFs were measured on the vibrating footbridge. In a unique study, Dang and Živanović [27] studied the influence of vertical vibration on vertical GRFs using an instrumented treadmill on a low-frequency laboratory footbridge. The results show that the footbridge vibration reduces vertical GRFs at the first harmonic of resonant walking. However, only a limited number of test subjects walked on-the-spot for this study, and it is limited to a footbridge with frequency at the first harmonic of the walking force ("low-frequency bridge"). To conclude, the literature lacks measurements of GRFs due to walking on vibrating bridge surfaces, particularly for higher-frequency footbridges for a large range of test subjects. The aim of the paper is to address this gap using a novel experimental set-up.

1.3. Lightweight high-frequency footbridges

Glass fibre reinforced polymer (GFRP) material is increasingly applied in the construction industry for its desirable properties such as high strength-to-weight ratio and good durability in extreme environments. These properties make GFRP well suited to modular structural forms such as floors and footbridges. However, GFRP structures are lighter than equivalent conventional structures, rendering them potentially more susceptible to human-induced vibration due to a higher accelerance amplitude (acceleration response per unit harmonic force) [28]. Therefore, a GFRP footbridge was designed and built to establish the performance of such structures, and the influence of structural vibration on GRFs.

The vibration design rules for FRP footbridges have evolved from experience with steel and concrete structural forms [29,30]. The AASHTO Design Guideline for FRP Footbridges [29] states that bridges with a first natural frequency greater than 5 Hz are deemed acceptable for vibration serviceability. However, this seems to neglect the altered mass-stiffness relationship of FRP when compared with traditional steel and concrete structures. The altered relationship affects the magnitude of the accelerance function. Živanović et al. [31] compared accelerance functions of several FRP footbridges against comparable steel/concrete footbridges. The accelerance functions of Monash University laboratory GFRP footbridge—uncovered and covered (to be described later)—have been added to those presented by Živanović et al. [31], and they are shown in Fig. 2. In addition, the frequency ranges for first three walking harmonics are shown shaded, along with the 5 Hz limit [29]—shown as red dashed line in the same figure.

Fig. 2 shows that the GFRP footbridges (AB, EB, MB_u, MB_c) exhibit higher accelerance compared to other footbridges. Given that vibration response increases when the natural frequencies lie in the harmonic ranges excitable by human normal walking, these footbridges could have vibration serviceability design problems. Interestingly, the 5 Hz frequency limit, developed many decades ago from experience with steel and concrete structures has been adopted in AASHTO [29]. As seen in Fig. 2, the purpose-built Monash Bridge (MB) was designed to meet the 5 Hz limit. The resulting bridge has a natural frequency within the range excitable by the third harmonic of walking force and creates opportunity to critically evaluate the suitability of the 5 Hz limit for lightweight structures.

1.4. Contribution

Although most GRF models are based on data collected on rigid surfaces, it is the GRFs imparted on the actual bridge surfaces, which are typically flexible, that are of most interest for predicting the vibration response of lively structures reliably. Further, higher-frequency lightweight footbridges ought to be studied, as resonance with higher harmonics of the walking force might result in a large vibration response despite the bridge satisfying the 5 Hz limit. To address these two goals, reliable measurement of vertical GRFs on both rigid and a higher-