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Structural vibration serviceability: New design framework featuring human-structure interaction

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ABSTRACT

Predicting the effect of walking traffic on structural vibrations is a great challenge to designers of pedestrian structures, such as footbridges and floors. This is mainly due to the lack of adequate design guidelines, which in turn can be blamed on poor research findings. Even the fundamental data are very rare and limited. This study proposes a new and more reliable method for serviceability assessment of the vertical vibrations induced by multi-pedestrian walking traffic. Key novelties include modelling the natural *variability* of the walking forces and the human bodies, as well as their individual *interaction* with the supporting structure at their *moving location*. Moreover, a novel approach to vibration serviceability assessment (VSA) is proposed based on the actual level of vibration experienced by each pedestrian, rather than the typical maximum vibration response at a fixed point. Application of this method on two full-scale footbridge structures have shown that, with a suitable calibration of human model parameters, the proposed method can predict the occupied structure modal frequency with less than 0.1% error and - more importantly - modal damping ratio with less than 1% error. The new method also estimated the structural responses with considerably less error (5–10%) compared to a selection of current design guidelines (200–500%). The proposed VSA method is not suitable for hand-based calculations. However, if coded and materialised as a user-friendly software, it can be incorporated into design guidelines and used by consultants in everyday engineering practice.

1. Introduction

Models of pedestrian dynamic loading used in contemporary vibration serviceability assessment typically describe the vertical walking excitation as a vertical force that does not depend on structural vibrations [1]. The simplest models, such as those presented by FIB [2], ISO 10137 [3], French design guideline [4] and UK National Annex to Eurocode 1 [5], also assume that an individual walking force is periodic and presentable by a Fourier series. The frequency content of such a simple force model typically contains up to the first four dominant harmonics [1]. The design procedures usually require that one of the harmonics matches the frequency of a target vibration mode of the structure to create resonance, i.e. the worst case scenario yielding the maximum vibration response. To account for the imperfect synchronisation between individuals in a group or crowd, the walking force of a multi-pedestrian traffic is calculated by multiplying a sum of the individual forces with factor(s) which commonly depend only on the number of pedestrians on the structure [1].

A significant move towards a more realistic estimation of the vibration response was made only recently, by taking into account inter- and intra- subject variability of the pedestrians in statistical models of their walking force [6–12]. This has increased considerably the fidelity of the walking force models. Yet, these still do not account for human-structure interaction (HSI), despite its widely recognised importance to reliable prediction of the vibration response [13–15]. In the context of the present study, HSI refers to the effect of walking bodies on the dynamic properties of the occupied structure (i.e. modal mass, stiffness and damping).

The UK recommendations for the design of permanent grandstands [16] are the only guidelines that explicitly require taking

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into account the interaction of both passive and active people with the grandstand they occupy and excite by jumping or bouncing in the vertical direction. Based on the model proposed by Dougill et al. [17], this guideline suggests two single-degree-of-freedom (SDOF) systems attached to a SDOF model of the empty structure to simulate the aggregated effect of passive (mostly *sitting*) and active (mostly *jumping/bouncing*) people. Despite the satisfactory performance of this explicit modelling approach [18,19], no other vibration serviceability design guideline has yet adopted a similar modelling concept to account for the HSI due to people *walking*.

The vibration serviceability assessment (VSA) method proposed in this paper (from now on referred to as *interaction-based VSA method*) has been developed to account for the following five main challenges when assessing the effects of walking people on structures:

(1) The human-structure interaction;
(2) Variability of the mass, stiffness and damping of the moving human body and the walking force due to inter- and intra-subject variability;
(3) Variability of pedestrian traffic characteristics, such as traffic *volume* and *regime* (spatially unconstraint/constraint, group, etc.)
(4) Varying *location* of each walking pedestrian on the structure, and
(5) The actual level of vibration experienced by each pedestrian at their continuously moving location on the structure rather than the vibration response of the structure at a fixed point.

The detailed description of the proposed method is presented in Section 2. In Section 3, the sensitivity of the outputs of this method to uncertainties of its inputs is studied. Applications of the proposed *interaction-based VSA method* on two full-scale footbridge structures are described in Section 4, and the relevant response calculations are compared to a selection of current design guidelines. Finally, conclusions are presented in Section 5.

2. Description of assessment method

The proposed interaction-based VSA method involves four steps. In the first step, the effects of HSI are analysed by estimating the *occupied* structure modal properties: natural frequency f_{os} [Hz], modal damping ratio ζ_{os} [–] and modal mass m_{os} [kg]. In the second step, for each relevant mode of the occupied structure, the total modal force due to pedestrian traffic is calculated. This is done by scaling each individual's walking force by the amplitude of the corresponding mode shape, and superimposing such scaled walking forces of all pedestrians according to their arrival time on the structure. In the third step, the modal response of the structure is computed for each relevant mode of vibration, using the calculated modal walking force/s and the *occupied* structure modal properties. Finally, these modal vibration responses are used to calculate the physical vibration levels perceived by each pedestrian at their *continuously changing location* as they walk along the structure. This is deemed to be more appropriate and realistic than using the percentage of time that bridge response is within an acceptable range at a particular fixed location, which may or may not have a pedestrian on it.

It should be noted that the description of the interaction-based VSA method in this study is based on a uniformly distributed unconstrained traffic scenario. However, any traffic pattern/scenario can be simulated using this method by modifying the steps to reflect that pattern. For instance, a constrained walking due to heavy traffic can be simulated by reducing the average walking speed of the crowd, increasing the arrival rate and applying corresponding changes on the walking force and parameters of the SDOF walking human model.

2.1. Input parameters

The input parameters used in the interaction-based VSA method can be divided into four categories. The first category comprises the properties of mode 'j' of the *empty* structure: modal mass $m_{es,j}$, frequency $f_{es,j}$ and damping ratio $\zeta_{es,j}$. In the second category are the parameters of the walking human SDOF model: mass m_h, natural frequency f_h and damping ratio ζ_h. The SDOF mass-spring-damper model of walking humans proposed by Shahabpoor et al. [20] was used in this study (Fig. 1). The authors proposed normal distributions with mean and standard deviations of $\mu = 2.85$ Hz and $\sigma = 0.34$ Hz for natural frequency f_h, and $\mu = 0.295$ and $\sigma = 0.047$ for damping ratio ζ_h of the SDOF human model. Mass m_h can either be generated using a statistical distribution for a certain human population, or assumed to be equal to the average mass of the occupants. Stiffness k_h can be calculated using Eq. (1):

$$k_h = m_h(2 \times \pi \times f_h)^2 \tag{1}$$

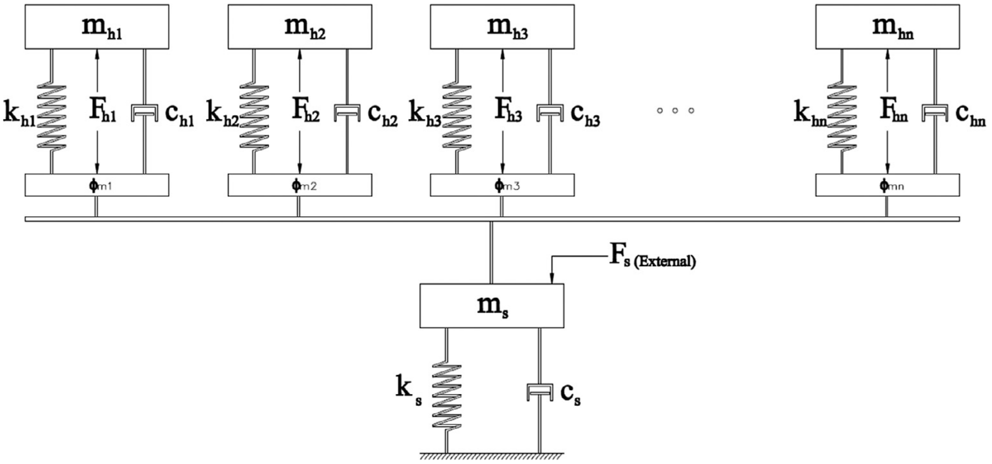

Fig. 1. Mass-spring-damper model of stationary walking traffic-structure system.