Engineering Structures 115 (2016) 165–178

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Evaluation of the dynamic behaviour of steel staircases damped by the presence of people

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ARTICLE INFO

Article history:
Received 3 March 2015
Revised 25 November 2015
Accepted 22 February 2016
Available online 5 March 2016

Keywords:
Human–structure interaction
Slender structure
Structure vibration
Damping
Staircase

ABSTRACT

People acting on a slender structure can affect the dynamic behaviour of the structure they occupy, in addition to being a source of forcing. In such cases, the use of the dynamic properties of the empty structure to estimate the structural response can lead to an erroneous estimation of the amplitudes of vibration. This work proposes an approach to improve the prediction of the structural response due to the presence of people. The method is based on the identification of an equivalent set of frequency response functions to represent the dynamic behaviour of the joint structure-moving people system. The method starts from the modal model of the empty structure, i.e., natural frequencies, damping ratios and mode shapes. No restriction on the number of degrees of freedom of the structure is required. Each subject is modelled through an equivalent apparent mass and is introduced on the model of the empty structure to obtain a model of the joint structure-moving people system. An active force is then applied to the equivalent model to obtain a prediction of vibration levels. The effectiveness of the approach was verified through experimental tests performed in controlled conditions. Two lightly damped steel staircases were used as test cases. A comparison between the amplitudes of the measured vibration and those predicted using the proposed methodology is presented. The results show that the use of the empty structure model can lead to a high overestimation of the vibration amplitudes. Conversely, the results obtained with the proposed approach are in agreement with the experimental data.

1. Introduction

In recent years, problems related to in-service vibrations have gained growing attention [1]. Since brand new structures have become more and more slender, an increasing number of problems related to the unexpected high vibration amplitudes have been recorded. Reported problems have occurred in various types of structures, such as footbridges [2,3], football stadia [4,5] and long-cantilevered structures [6]. Indeed, the prediction of in-service vibration amplitudes of structures occupied by people is a complex task. In particular, at least two main critical challenges can be identified.

The first aspect regards the correct characterisation of the active forces induced by people on the structure. The majority of standards and codes suggests modelling human-induced forces as deterministic harmonic forces [7,8]. However, this assumption is too simplistic and does not reflect the real trend of human-induced forces. This problem was addressed in many works, such as Refs. [9,10], and approaches to correctly identify such forces were proposed [11–16].

The second aspect regards the influence of people on the dynamic properties of the structure. Indeed, it is well known that people acting on a pedestrian structure behave as dynamical systems capable of modifying the dynamics of the structure itself [16]. In the literature, few attempts have been made to include the effects of people. Particularly, a paper by Qin et al. [17] faced the problem of a pedestrian-bridge interaction using a bipedal walking model. The proposed method consisted of a feedback control force applied by the pedestrian. The results of the numerical study showed that the effect of people increased with the amplitude of vibration. However, despite an increase of damping ratios due to the presence of people, the results showed an increase of predicted amplitudes of vibration using the model of Human–Structure Interaction (HSI), in contrast to experimental evidence. A work by Pavic and Reynolds [18] proposed the use of a three degrees-of-freedom (DOF) model to represent the dynamics of a structure occupied by passive and active subjects. In the proposed model, the three DOF represented the structure, the passive crowd and the active crowd. The model was used to predict the response

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http://dx.doi.org/10.1016/j.engstruct.2016.02.028
0141-0296/

of a stadium grandstand with good results. Another work by Shahabpoor et al. [19] proposed the use of a mass-spring-damper (MSD) model of the human body to predict the effect of walking pedestrians on the dynamic properties of a structure. In their work, the authors reported a theoretical analysis of the proposed approach. However, as evidenced by the authors, experimental data were required to validate the methodology. A common assumption and limitation of the last two above-mentioned approaches is the modelling of the structure and the people as single DOF (SDOF) systems.

Although experimental evidence suggests that appropriate dynamic models of human occupants should be used to obtain an accurate description of HSI, at the design stage, it is common practice to consider people interacting with a structure as only a source of force [20–22]. However, this approach may lead to an erroneous estimation of the vibration levels at the design stage for cases where the influence of people is not negligible. To overcome this issue, a recent guidance [23] (Joint Working Group, 2008), regarding the dynamic performance requirements for permanent grandstands subjected to crowd action, recommends the consideration of HSI at the design stage. Indeed, the guidance underlines that if the effects due to HSI are ignored in calculations, the response of the structure will be incorrectly represented in the analysis. In Ref. [23], an analytical method for treating human structure interactions is proposed. This approach was developed using the most recent research and available experimental data, with the aim of reproducing the patterns of behaviour observed in actual structures subjected to dynamic crowd loading. However, as evidenced in the guidance, the method is not able to address all the variations in human behaviour and physical characteristics that affect the structural dynamics. When brand new structures fail the vibration serviceability check, an a-posteriori mitigation of the vibration amplitudes is often required [24,25]. Thus, many types of solutions have been proposed in the past years [26,27]. However, such solutions imply additional costs. A better knowledge of the effect of people on the dynamic behaviour of structures would allow a more accurate evaluation of the vibration amplitudes at the design stage [28]. As a consequence, the cost and effort to mitigate vibration amplitudes a-posteriori could be avoided or at least reduced. In this context, there are still grounds for general methods to account for the presence of people.

This work focuses on the analysis of vertical vibrations of a slender structure and proposes an approach to predict such vibrations. Regarding vertical vibrations, experimental evidence suggests that people interacting on a structure is a source of added damping [29–32]. If the damping ratios change significantly, considering the dynamic properties of the empty structure for estimating the structural response can lead to a high overestimation of the amplitudes of vibration [32]. Therefore, this work validates an approach to include the effect of people on the dynamic behaviour of a structure in terms of changes in the modal parameters. In the proposed method, no restriction on the number of DOFs of the structure and of people's model is required. This would allow for obtaining a reliable prediction of the structural response even in the case of a high modal density. The proposed method is a generalisation of a recent work [33] proposing an approach to evaluate the influence of passive people on the dynamic behaviour of a structure. The present work proposes an extension of this approach to the case of moving people. The idea behind such an extension is the identification of an equivalent model to represent the dynamic behaviour of the joint structure-moving people system. An appropriate active force is then applied to this equivalent model to obtain a prediction of vibration levels.

The key aspects of the methodology proposed in [33] are revised in Section 2, and its extension to the case of moving people is proposed. Sections 3 and 4 explain the calculations of passive ground reaction forces and active ground reaction forces, respectively. The ground reaction forces are treated in the literature as the total forces exchanged between the structure and the people, and in these two sections the split into passive and active forces is explained. Section 5 details the whole procedure used to predict the vibration of the structure with the theoretical approach described in Section 2. Finally, Section 6 discusses the experiments carried out to validate the method proposed herein.

All the performed tests were carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans.

2. An approach to evaluate structural responses due to the presence of people

A recent work [33] proposed a model to evaluate the effect of passive people on the dynamic behaviour of a slender structure.

The method suggested in Ref. [33] requires the knowledge of the dynamic behaviour of the empty structure. This is represented by the matrix of Frequency Response Functions (FRFs), $\mathbf{G}(\omega)$ (Eq. (1)):

$$\mathbf{G}(\omega) = \sum_{k=1}^{n} \frac{\boldsymbol{\phi}_k \boldsymbol{\phi}_k^T}{\omega_k^2 - \omega^2 + 2j\zeta_k \omega \omega_k} \tag{1}$$

where $\boldsymbol{\phi}_k$ is the jth mode shape vector (scaled to the unit modal mass) measured/evaluated at discrete points, ω_k is the natural frequency of the kth mode, ζ_k is the kth non-dimensional damping ratio and n is the (arbitrary) number of considered modes; T indicates the transpose, j is the imaginary unit and ω is the circular frequency. Because the eigenvectors are known at discrete (m) points, the matrix $\mathbf{G}(\omega)$ is the $m \times m$ matrix containing the Frequency Response Functions (FRFs) for these points.

If $\mathbf{x}(\omega) = [x_1(\omega), \ldots, x_m(\omega)]^T$ is a vector which contains the responses of the structure in the considered points, and $\mathbf{f}(\omega) = [f_1(\omega), \ldots, f_m(\omega)]^T$ is a vector containing all the external forces applied to the structure, the structural response can be expressed in Eq. (2) as:

$$\mathbf{x}(\omega) = \mathbf{G}(\omega)\mathbf{f}(\omega) \tag{2}$$

When a person is in contact with a point of a structure, he/she produces a Ground Reaction Force (GRF). The GRF is the total force exchanged between the person and the structure. If we consider a passive person, the GRF is just due to the dynamic characteristics of the person and the structure. This force is termed as the Passive Ground Reaction Force (PGRF) and will be indicated by the symbol f^{GR}. The PGRF is a force which is generated by structural movement; when an external force f acts on the structure, this vibrates and excites the person. If we consider a person to be a dynamic system, it starts to vibrate as well. The consequence is that a force (i.e., PGRF) is exerted by the person on the structure. Fig. 1a shows the situation related to the case mentioned above; the structure and the person are described as SDOF systems to simplify the sketch, and both can be described by multi-DOF systems. Fig. 1b shows the GRF, which is a PGRF in this case. On the other hand, if we consider a moving person (active people), the GRF can be split into two components, i.e., GRF = PGRF + AGRF (where AGRF is the Active Ground Reaction Force). The PGRF is due to the dynamic characteristics of the person and the structure, while the AGRF is due to the active force generated by the person's active movement. The AGRFs do not depend on (and are not generated by) the vibration of the structure behind the person and are only due to the active movement of the person. We can see AGRF as the force exerted by a moving person on a structure with an infinite stiffness (i.e., $\mathbf{x} = 0$, which corresponds to a null PGRF). Fig. 1c shows an example scheme of