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Frequency response function-based explicit framework for dynamic identification in human-structure systems

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A B S T R A C T

The aim of this paper is to propose a novel theoretical framework for dynamic identification in a structure occupied by a single human. The framework enables the prediction of the dynamics of the human-structure system from the known properties of the individual system components, the identification of human body dynamics from the known dynamics of the empty structure and the human-structure system and the identification of the properties of the structure from the known dynamics of the human and the human-structure system. The novelty of the proposed framework is the provision of closed-form solutions in terms of frequency response functions obtained by curve fitting measured data. The advantages of the framework over existing methods are that there is neither need for nonlinear optimisation nor need for spatial/modal models of the empty structure and the human-structure system. In addition, the second-order perturbation method is employed to quantify the effect of uncertainties in human body dynamics on the dynamic identification of the empty structure and the human-structure system. The explicit formulation makes the method computationally efficient and straightforward to use. A series of numerical examples and experiments are provided to illustrate the working of the method.

1. Introduction

Dynamic interaction between a human and a low-frequency structure supporting the human is a well-recognised phenomenon that has become increasingly prominent over the last two decades due to the increase in slenderness of modern structures [1–4]. Naturally, the dynamic properties of the human-structure system are influenced by the interplay of dynamics of the two subsystems and they differ from those of the structure itself [1–7]. When considering the vertical flexural vibration modes of a structure, the human occupancy is known to cause a shift in the natural frequency and an increase in the damping ratio [3,8–10]. Knowledge of the dynamic properties of both the occupant(s) and the structure is crucial for developing better understanding of the extent of the human-structure interaction and its influence on the dynamic response analysis and vibration control design for structures accommodating humans.

In structural engineering applications, the dynamics of a human are usually described using a single-degree-of-freedom (SDOF) mass-spring-damper model [3,6,9–14]. The dynamics of a structure are often described utilising a spatial model or a modal model (having, say, n DOFs) that can be established using either finite element method or modal analysis [15]. The

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human-structure system can then be represented by a $n+1$ DOFs model whose modal properties are determined from an eigenvalue analysis, either numerically or analytically [9,15,16].

Key challenge in studying human-structure systems is the identification of the properties of the human model. Several approaches have been proposed for this purpose. For example, Griffin and his colleagues [17,18] estimated the dynamic properties of a human in a standing or sitting posture by curve fitting measured driving-point apparent masses. On the other hand, Foschi et al. [19] estimated the frequency and damping ratio of a human in a standing posture by minimising differences between the computed and measured displacement responses of the human-floor system exposed to a heel-drop impact. Zheng and Brownjohn [6] measured frequency response functions (FRFs) of both the empty structure and the human-structure system. After identifying a SDOF modal model for a vibration mode of interest from the measured FRFs of the empty structure, they combined this model with assumed properties of the human to derive the eigenvalues of the human-structure system. They used a nonlinear optimisation method to identify the properties of the human that result in the best match between the eigenvalues of the human-structure system and the measured counterparts. This procedure was also employed by Shahabpoor et al. [13] to identify a SDOF model for a walking human. Sachse [2] used a similar procedure for identifying the human's dynamic properties, the only difference being that she compared the measured and calculated FRFs of the human-structure system rather than the eigenvalues. This method was also used by Van Nimmen et al. [14] to identify a SDOF model for a stationary crowd. Jones et al. [20] summarised the dynamic properties of the human in a standing posture reported in the literature. The properties vary significantly between individuals: natural frequency was in the range from 3.3 Hz to 10.4 Hz while damping ratio was between 33% and 69%. Human body dynamics are also found to vary with postures [14,18,21].

Most research is devoted to identifying the dynamics of the human body and predicting the dynamics of human-structure systems. These studies were performed with a sole purpose in mind: to develop dynamic models of humans, either standing or sitting, and then to add them to the dynamic model of an empty structure, usually a grandstand, to predict the dynamic response of the human-structure system in sports or music events [10,20,22]. Little attention has been paid to identifying the dynamics of the empty structure provided the dynamics of the human-structure system are known. This scenario is relevant in manually operated impact hammer modal testing in which a hammer operator is present on the structure during data collection. The identification of dynamic properties of the structure routinely neglects the presence of the hammer operator and it assumes that the dynamics of the empty structure are the same as those of the hammer operator-structure system. This assumption might be erroneous since the interaction between a single human and a structure is important in some cases, such as for ultra-lightweight fibre reinforced polymer (FRP) footbridges. Although some existing methods for identifying human body dynamics [2,6,13,14] can also be used, at least in some cases, for the dynamic identification of the empty structure, they are not necessarily convenient to apply.

To the best knowledge of the authors, there does not exist a single theoretical framework which offers both closed-form solutions and flexibility of being used for any of the three applications as and when needed, i.e. the prediction of the dynamics of the human-structure system when the dynamics of individual systems are known, the identification of human body dynamics when the empty structure and human-structure system dynamics are known and the identification of the empty structure when the human and human-structure dynamics are known. This paper proposes a unifying and simple to implement framework for determining the dynamics of any one of the three systems in terms of the dynamics of the other two. The framework provides closed-form solutions for identifying the dynamics of the system under study and therefore does not require utilisation of nonlinear optimisation techniques inherent to some other studies [2,6,13,14]. The framework utilises curve-fitted FRFs (i.e. receptances, mobilities or accelerances) directly as opposed to using FRFs to derive spatial or modal models of the empty structure and the human-structure system required in some other studies [2,6,13,14]. In addition, the second-order perturbation method is utilised to quantify the effect of uncertainties in human body dynamics on the dynamic identification of the empty structure and the human-structure system. The paper focuses on low-frequency structures (i.e. vibration modes with natural frequencies up to about 8 Hz) on which the human-structure interaction is expected to be strongest. In this frequency region, the human is modelled as a SDOF system since only their first vibration mode is likely to interact with the structure. The proposed method is applicable for problems involving humans in any stationary posture (e.g. standing, sitting and crouching to perform the impact hammer test). Future work will be dedicated to generalise the framework for the crowd-structure interaction.

Following this introductory section, Section 2 introduces the novel method in the context of identifying properties of a human-structure system. Use of the proposed method for identifying human body dynamics is presented in Section 3, whilst its use for estimating dynamics of the empty structure is presented in Section 4. Each section is supported by numerical examples and/or experiments. Conclusions are drawn in Section 5.

2. Identification of the dynamics of a human-structure system

This section presents the theoretical framework followed by a numerical example. The proposed framework was inspired by the studies in the research fields of vibration control [23–25] and nonlinear dynamics [26].

2.1. Theoretical framework

The equation of forced vibration of a linear structure having n DOFs may be cast in second order form as