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Parameter identification of pedestrian's spring-mass-damper model by ground reaction force records through a particle filter approach

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A B S T R A C T

The spring-mass-damper (SMD) model with a pair of internal biomechanical forces is the simplest model for a walking pedestrian to represent his/her mechanical properties, and thus can be used in human-structure-interaction analysis in the vertical direction. However, the values of SMD stiffness and damping, though very important, are typically taken as those measured from stationary people due to lack of a parameter identification methods for a walking pedestrian. This study adopts a step-by-step system identification approach known as particle filter to simultaneously identify the stiffness, damping coefficient, and coefficients of the SMD model's biomechanical forces by ground reaction force (GRF) records.

After a brief introduction of the SMD model, the proposed identification approach is explained in detail, with a focus on the theory of particle filter and its integration with the SMD model. A numerical example is first provided to verify the feasibility of the proposed approach which is then applied to several experimental GRF records. Identification results demonstrate that natural frequency and the damping ratio of a walking pedestrian are not constant but have a dependence of mean value and distribution on pacing frequency. The mean value first-order coefficient of the biomechanical force, which is expressed by the Fourier series function, also has a linear relationship with pacing frequency. Higher order coefficients do not show a clear relationship with pacing frequency but follow a logarithmic normal distribution.

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1. Introduction

Long-span civil engineering structures, such as cantilever stands, pedestrian bridges and floors, may experience vibrations when subjected to human-induced dynamic loads due to walking, jumping, etc. When the load's dominant frequency is equal or close to the natural frequency of the structure, resonant or near-resonant vibrations will occur and can be perceptible to occupants. These vibrations can cause occupants to be distracted, dizzy or even terrified if excessive, leading to vibration serviceability problems [1,2], which need to be addressed at the design stage of a vibration-prone structure. An accurate and

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reliable load model is a prerequisite for predicting and controlling this vibration. Walking loads are the most common type of human-induced loads. Extensive research has been carried out to develop a mathematical model, either deterministic or stochastic, for walking loads based on experimental records of human walking loads. A small sample includes [3–9] among many others. A comprehensive review of walking load models has been given in Ref. [10].

All the above models generally treat 'a walking pedestrian' as 'a moving load', implying it does not change the dynamic properties of the structure. However, researchers found that human beings do change the dynamic properties including the damping and natural frequency of the structure they occupy [11–14]. This phenomenon is explained by the fact that human beings have their own mass, damping and stiffness, which increases the number of degrees of freedom applicable to the structure through the coupled human-structure interaction (HSI). Clearly, any changes to the properties of the human-structure system are highly related to the properties of the human beings occupying the structure. To investigate this influence, the SMD model and bipedal model are utilized by researchers to model human beings as a mechanical system. Although the bipedal model is able to mirror or duplicate the leg-switching behavior in human walking, and thus can better reflect the strong interaction between the structure and pedestrian [15], it is more complicated and cannot be easily implemented for practical use, while an SMD model can be used for both static and walking people, which gives it the advantage of simplicity.

From the HSI point of view, it is essential to know the model parameters, i.e., natural frequency (or stiffness) and damping ratio, when using the SMD model. Many researchers focused on human SMD parameters for sitting [16–18] and standing [19–21], giving results ranging from 5 Hz to 10.43 Hz and 0.2–0.5, for natural frequency and damping ratio, respectively. For SMD parameters of walking pedestrian, Shahabpoor [22] adopted the SMD model for walking people from tests of the frequency response function (FRF) on a structure with and without occupants. The natural frequency was given to be 2.75–3 Hz and damping ratio is 0.275–0.3. Nimmen [23] performed tests on a footbridge with people standing on the bridge but in a posture pretending to be walking. The natural frequency of 3.34 Hz and a damping ratio of 0.26 were found. Zhang [24] included the biomechanical forces within the legs to provide input force for the human-structure coupling system, and laboratory experiments were undertaken using force plates and a 3D motion capture system. Natural frequency and biomechanical load factors (BLFs) were found to be related with the walking frequency based on the assumption of a constant damping ratio of 0.3. Note that most SMD model parameters mentioned above are for people in a static status [16–21]. For limited research on effect of walking people on buildings [22–24], some parameters or conditions, i.e., constant damping ratio or walking-like gesture, need to be assumed, which may not be realistic. Moreover, the biomechanical forces are often ignored when identifying the SMD parameters. Therefore, this paper introduces a new method to obtain SMD parameters, together with coefficients for biomechanical forces.

Estimating human model parameters is an output-only inverse dynamic problem, since the inputs are unknown. In recent years, many methods have been proposed to identify input and structural parameters simultaneously from structural responses [25–27]. One popular method is the Kalman filter (KF) method [28], which includes the extended Kalman filter (EKF) and the unscented Kalman filter (UKF). A development of KF method is the particle filter method [29], where the Gaussian assumption in the traditional Kalman filter is relaxed so that more accurate results can be obtained [30,31]. In this paper, the particle filter method is adopted to identify human model parameters and the unknown biomechanical force input from the ground reaction force obtained experimentally.

2. Spring-mass-damper model of walking pedestrian

The SMD model is the simplest model for a pedestrian. It concentrates all the pedestrian mass at the body center-of-mass (COM), resulting in a single-degree-of-freedom system including mass, spring and damper, as shown in Fig. 1. A force couple of equal and opposite biomechanical forces generated by the movement of human muscles is assumed to exist inside the

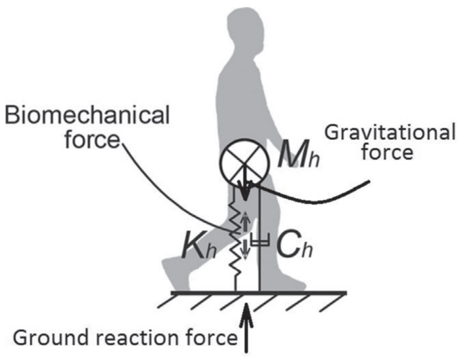

Fig. 1. SMD model of a pedestrian with a pair of biomechanical forces.

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