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On 4-degree-of-freedom biodynamic models of seated occupants: Lumped-parameter modeling

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ABSTRACT

It is useful to develop an effective biodynamic model of seated human occupants to help understand the human vibration exposure to transportation vehicle vibrations and to help design and improve the anti-vibration devices and/or test dummies. This study proposed and demonstrated a methodology for systematically identifying the best configuration or structure of a 4-degree-of-freedom (4DOF) human vibration model and for its parameter identification. First, an equivalent simplification expression for the models was made. Second, all of the possible 23 structural configurations of the models were identified. Third, each of them was calibrated using the frequency response functions recommended in a biodynamic standard. An improved version of non-dominated sorting genetic algorithm (NSGA-II) based on Pareto optimization principle was used to determine the model parameters. Finally, a model evaluation criterion proposed in this study was used to assess the models and to identify the best one, which was based on both the goodness of curve fits and comprehensive goodness of the fits. The identified top configurations were better than those reported in the literature. This methodology may also be extended and used to develop the models with other DOFs.

1. Introduction

Transportation vehicles such as automobiles, ships, and aircrafts generate vibration when in motion. Passengers may feel uncomfortable and even suffer injuries [1] when the vertical vibration frequency falls within 4–8 Hz [2]. A thorough study on dynamic comfort [3] of vehicle occupants is an important approach to improve the riding experience of the passengers. Experiments evaluated by the feelings of the tested occupants are often implemented to study the ride comfort performance of transportation vehicles. As a result, however, experimental methods are not only time-consuming and costly, but also highly subjective. In addition, it's hard to quantify and standardize. Another approach is to use simulation methods to improve engineering design, shorten product development cycles, and reduce cost. Simulations should also make it easy to investigate the dynamic comfort of the occupants (or the test dummies) and to help design and improve the anti-vibration devices, such as vehicle seats, suspension systems of ground vehicles, and anti-vibration gloves. Therefore, in order to achieve the goals of comfortable ride for the passengers and high-efficiency anti-vibration devices, it is important to establish simple-while-effective biodynamic models of seated occupants.

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Human bodies are highly complex multi-body systems. The mechanical properties of each part of the human body are different. Human bodies also vary from person to person. Dynamic responses of seated occupants are an important criterion to evaluate dynamic comfort of passengers and also the effectiveness of anti-vibration devices. Since 1962, quit a few biodynamic models have been proposed to describe the dynamic responses of seated occupants and further to help optimize the anti-vibration devices. According to modeling methods, these models can be categorized as the finite element models, the multi-body models, and the lumped-parameter models.

Finite element models for analyzing the biodynamics of seated human use numerous small units to describe human body parts [4–10]. They are often used to deal with impact issues and local stress-strain issues. Finite element models have the advantages of accurate description and broad application scope, but the modeling procedure is very complicated, time-consuming, and costly. On one hand, finite element models require extremely high computing capability. Although the researches on local structures of human body systems such as neck [4], spine [5–8], pelvic [9], and joints [10] are sound and helpful, accurate finite element analyzing on the entire human body is still not easy to realize, due to the limitation of the computing power. On the other hand, the finite element models require large amount of actual experimental data of human bodies which are hard to collect. Corpses were dissected to obtain the data of human bodies. However, the mechanical properties of the corpses and living human bodies are not the same [1].

Multi-body models deal with issues of multiple directions and motions by simplifying the body into several articulated-rigid body [11–16]. Multi-body models can be used to investigate the mechanical responses of each part when the system is excited in the way of the kinetics. They can also be used to study the kinestate description of each part in the motion state in the way of the kinematics.

Lumped-parameter models describe human body systems by using ordinary difference equations or ordinary differential equations containing mechanical system parameters such as mass, stiffness, and damping. Lumped-parameter models use simple mechanical components, which actually implies that the models could not describe the performances of the human bodies in the way of the human anatomy. In other words, the system parameters of the lumped-parameter models will not be completely consistent with the actual parameters of human anatomy and biodynamics. Lumped-parameter models are designed to describe and predict the human responses when under a variety of excitations. The particular advantages of these models are that the models can be easily established, and the analysis, the parameter identification, and the experimental verification are easy to implement. They are low cost as well. The disadvantage is, due to the necessary simplification for the lumped-parameter models, the lumped-parameter models may not fully reflect the responses of each part of human bodies. The responses of each part of human bodies can be described by increasing the degrees of freedom of the models. But the increase of degrees of freedom will inevitably increase the complexity of the models and the practicability weakens in turn. It is noted that, the lumped-parameter models are often used to describe a uni-directional (vertical or lateral) dynamic responses of the human bodies because of compact expression and effective performance of the models with only parameters of mass, stiffness, and damping. Early lumped-parameter models are not suitable for analysis of multi-directional problems. Researchers studied multi-directional biodynamic responses through analyzing in different directions separately incorporating rotating bushing model or human hand-arm system.

In 1962, Coermann [17] measured the mechanical impedances of eight people with different heights, weights, and ages, and presented a 1-degree-of-freedom (1DOF) linear model. From then on, the lumped-parameter model has become an important and attractive means to investigate the dynamic responses of seated occupants. Stech and Payne [18] proposed a 1DOF nonlinear model and applied it to the analysis of dynamic responses of human bodies during helicopter landing. They considered that the connection between human body and the seat is rigid and the seat was not included in the model.

Using variable damping devices, Muksian and Nash [19] proposed a 2DOF nonlinear model to describe dynamic responses of human bodies under different excitation frequencies. Allen [20] and Wei and Griffin [21] proposed two different 2DOF linear models considering hip-seat rigid body. The seat mass was not taken into account in Allen's model, and Wei and Griffin considered that the model excitation comes from hips and legs.

Suggs et al. [22] proposed a 3DOF linear model and fabricated a dummy based on the model's parameters to simulate the dynamic responses of seated occupants. Based on this model and the dummy, Feng modified the model parameters for Chinese passengers and employed the modified model to improve ride comfort of transportation vehicles [23]. Hou and Gao came up with a 2DOF parallel linear model and a 3DOF series-to-parallel linear model with better performance based on the test of 28 Chinese adults' apparent masses (AMs) [24,25]. To evaluate the effects of the polyurethane seats on human bodies, Kang [26] studied and presented a 3DOF parallel linear model and a 3DOF series-to-parallel linear model.

Considering friction between the back and torso, related muscle contraction and ballistocardiographic, and diaphragm muscle forces, a 6DOF nonlinear model proposed by Muksian and Nash [27]. Patil et al. [28] presented a 7DOF nonlinear model based on Muskian and Nash's 6DOF nonlinear model. The friction was neglected while the elasticity and damping between hip and seat were taken into account. Modifying Patil et al's. model, Qassem et al. presented an 11DOF linear model later, which neglected the nonlinear element in Patil et al's. model. The model divided the torso part in Patil et al's. model into three subparts as the lower limbs, upper limbs, and torso [29]. It also divided the back part into cervical, thoracic, and lumbar vertebras. Later, an 11DOF linear model for pregnant women based on Qassem et al's. model considering fetus mass as a part of abdomen was further presented by Qassem and Othman [30].

In 1995, Wan and Schimmels used a 4DOF series-to-parallel linear model to describe the dynamic responses of seated occupants under vibration excitation [31]. Liu et al. [32] and Abbas et al. [33] implemented nonlinear optimization and model parameters optimization using the weighted genetic algorithm (GA) respectively. Singh and Wereley [34]