Journal of Sound and Vibration 403 (2017) 38–58

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Directional and sectional ride comfort estimation using an integrated human biomechanical-seat foam model

Navid Mohajer *, Hamid Abdi, Saeid Nahavandi, Kyle Nelson

Institute for Intelligent Systems Research and Innovation (IISRI), Deakin University, Australia

A R T I C L E I N F O

Article history:
Received 31 August 2016
Received in revised form
14 April 2017
Accepted 9 May 2017
Handling Editor: J. Macdonald

Keywords:
Human biomechanical model
Multibody system
Foam vibration model
Ride comfort

A B S T R A C T

In the methodology of objective measurement of ride comfort, application of a Human Biomechanical Model (HBM) is valuable for Whole Body Vibration (WBV) analysis. In this study, using a computational Multibody System (MBS) approach, development of a 3D passive HBM for a seated human is considered. For this purpose, the existing MBS-based HBMs of seated human are briefly reviewed first. The Equations of Motion (EoM) for the proposed model are then obtained and the simulation results are shown and compared with idealised ranges of experimental results suggested in the literature. The human-seat interaction is established using a nonlinear vibration model of foam with respect to the sectional behaviour of the seat foam. The developed system is then used for ride comfort estimation offered by a ride dynamic model. The effects of human weight, road class, and vehicle speed on the vibration of the human body segments in different directions are studied. It is shown that the there is a high correlation (more than 99.2%) between the vibration indices of the proposed HBM-foam model and the corresponding ISO 2631 WBV indices. In addition, relevant ISO 2631 indices that show a high correlation with the directional vibration of the head are identified.

1. Introduction

In the current automotive market, customers expect that the vehicles provide an adequate sense of pleasure and support [1] which is referred to the high level of comfort. Ride comfort is related to the feeling of a vehicle occupant during a ride experience and has become more important for many individuals. This is because they drive their cars for long hours in their daily routines which might be due to the dense traffic of large cities or specific requirements of some businesses. Lack of comfort not only affects the ride experience, but it could also have an adverse effect on the passengers' health [2,3]. Hence, it is critical that road vehicles provide the highest possible level of comfort, depending on the class of the vehicles.

Analysis of human comfort is a complex problem as it involves several influential parameters. Ride comfort may be described by the level of discomfort [1,4]. Discomfort is an inherently subjective concept with intra- and inter-subject variability. For a human seated inside a moving car, the discomfort is affected by several factors which are (1) ride quality which is the vibration characteristics of the vehicle's cabin i.e. magnitude, frequency, and direction of vibration, (2) handling performance which includes the higher magnitude of lateral, roll, and yaw accelerations of the vehicle, (3) occupant features which are characterised by weight, body size, age, gender, and psychological effects, (4) seat characteristics, (5) sitting

* Corresponding author.
E-mail address: n.mohajer@research.deakin.edu.au (N. Mohajer).

http://dx.doi.org/10.1016/j.jsv.2017.05.019

posture, and (6) exposure time. Evaluation of discomfort is a complex, time-consuming, laborious task that often needs an expensive test setup.

Simulation-based assessment and sensory measurement are normally used for the objective evaluation of ride comfort [5]. These methods are considered as supplementary methods that could partially replace the subjective rating methods. Among the two objective methods, the simulation-based method does not require hardware implementation, hence it is cost and time effective. Within the literature, objective evaluation has been conducted based on WBV [4], human motion and posture [1,6], Seat Pressure Distribution (SPD) [7,8], and biological activity such as Electromyography (EMG) [9].

Ride comfort is mainly influenced by WBV that causes human fatigue and may result in a prevalence of pain in the organs or serious musculoskeletal difficulties. For instance, it was shown that WBV could increase the risk of lower-back pain and cause spine structural injury [10,11]. Furthermore, WBV raises safety concerns for those individuals who drive their cars for long periods of time. For example, it was shown in [4] that vertical and rotational vibrations of the drivers' head negatively affect their eyesight. To analyse the WBV, magnitude, frequency, and direction of the transmitted vibration, as well as the exposure time are required to be considered.

A Human Biomechanical Model (HBM) has the potential to be used for WBV studies, hence it could be utilised for ride comfort evaluation. Many HBMs have been developed in the literature and the corresponding biomechanical responses have been validated through the definition of various transfer functions. The focus of this study is on the application of a Multibody System (MBS)-based HBM for the estimation of ride comfort. The main contributions of our work are (1) Development of a 3D passive MBS-based HBM, (2) Modification and integration of a nonlinear vibration foam model to the proposed HBM, (3) Estimation of directional and sectional vibration of human subjects with different weights, and (4) correlation analysis between the vibration levels of the proposed HBM and the ISO WBV standard indices.

The remainder of the paper is organised as follows. Section 2 outlines the biomechanical modelling methods and the parameters which are normally used for the evaluation of biomechanical responses. This section also provides a review of the existing HBMs developed based on MBS approach. In Section 3, a 3D passive MBS-based HBM is developed and a few preliminary simulation results are presented. Section 4 is allocated to the modification and application of a nonlinear vibration foam model in order to establish vehicle-human interaction. The overall simulation results of the integrated human-seat model and are shown in Section 5. This section also presents the results of correlation analysis. Finally, the discussion and concluding remarks are given in Section 6 and Section 7, respectively.

2. A review on biomechanical modelling

In this section, a critical review of biomechanical modelling methods, the parameters used for the evaluation of HBM responses, and the existing MBS-based HBM of the human seated inside a car are presented. For each topic, we highlight the efficacy, application, and pros and cons of the methods, parameters, or models.

2.1. Biomechanical modelling methods

The methods of biomechanical modelling are categorised into Lumped-Parameter Model (LPM), Finite Element (FE) model, and MBS model.

LPMs are composed of lumped masses, springs, and dashpots. These models are simple to analyse and easy to validate, and they are generally used for single axis motion which is usually the vertical motion. LPMs do not reflect some properties of the body segments such as the moment of inertia and joint location. Due to this matter, consideration of all vibration inputs to the human body or multi-directional analysis of vibration responses requires a complex LPM. A critical review of thirteen existing LPMs of seated human subjects exposed to vertical excitation has been performed by Liang and Chiang [12]. In their work, several LPMs with different Degrees of Freedom (DoF) have been characterised and evaluated using the classified experimental data provided by Boileau et al. [13]. Liang and Chiang also identified the best models that could accurately emulate the experimental data of a seated human subject.

An accurate FE model requires a sophisticated meshing algorithm and a large amount of input data. FE models are suitable for static analysis of the biomechanical responses, and they are able to model the human-seat interaction [14]. This method has been particularly used for the analysis of vibration effects on different human organs such as spine [15,16]. The output of FE models may include the information about local effects of joints, tissues deformation, vibration modes, human-seat pressure distribution profile, or the other biodynamic responses. It is noted that FE method is not efficient with respect to the computational cost.

MBS models are made of several discrete rigid or flexible bodies interconnected by different types of joints. To address the compliancy of the system, translational and rotational spring-damper elements are utilised. In this method, the Equations of Motion (EoM) are numerically solved to find different parameters of the model including the kinematic parameters of bodies' Centre of Mass (CoM) and joints reaction forces. The MBS method is capable of producing multi-segment models of the human body and it needs lower computational cost. Due to these advantages, 2D and 3D MBS-based HBMs reflect high flexibility and capability for the simulation of biomechanical responses of different body segments in different directions.

The frequency responses of seated human model are relatively simple profiles, for example they have few peaks. The development of LPMs for simulating such simple profiles only needs parameter identification using measured responses. For