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Multivariable control of transmitted vibrations to the seat model of the human body

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A B S T R A C T

Advanced control techniques are required for the vibrations suppression of the seated human body in different places like automotive and public transportation lines. In this paper, an active multivariable control strategy is applied to a seated human body model and results are simulated and examined via MATLAB. Dynamic equations of the model are derived using Lagrange method and they are linearized around the equilibrium point of the system. After assessing the deficiencies of the previous models and control strategies proposed for the human body, an active control method is presented based on pole placement analysis. This control strategy is designed for a realistic model of the human body with 5 degrees of freedom (5DOF) and in the presence of road excitations. In the proposed multivariable control system, human body movements in five directions (as the five outputs) are controlled via manipulation of the forces in vertical and horizontal directions and a moment about y-axis (as the three inputs). For the simulation purposes, it is assumed that these control inputs are provided by actuators (e.g., piezoelectrics). Dynamic behavior of the system is evaluated around its natural frequencies and the effectiveness of the proposed active multivariable control is investigated. It is observed that under various resonance conditions, the controller acts efficiently in vibrations suppression.

1. Introduction

Development of new technologies, especially in the transport industry has caused constant exposure of the human body to the induced vibrations. In several researches, the effects of vibration on human health have been studied (Lewis and Griffin, 1978; McLeod and Griffin, 1989; El Falou et al., 2003; Wilkinson and Gray, 1975; Sandover, 1998; Thomas et al., 2004). Results show that vibrations have some adverse effects on human mind; among which the mental fatigue can be cited. Exhaustion during driving the automobile has an important role on driver's performance and the occurrence of accidents (Lewis and Griffin, 1978; McLeod and Griffin, 1989). The results approve that with long-term exposure of the human body, the number of errors are increasing in performance due to impaired perception (El Falou et al., 2003; Wilkinson and Gray, 1975). Also, dynamic stresses are induced in the spine as a result of the whole-body vibrations, producing micro-fractures in the endplates and vertebral body (Sandover, 1998; Thomas et al., 2004). Thus, attenuating unwanted vibrations seems to be crucial to prevent these negative impacts.

The seated human body exposed to the vibrations is a complex dynamic system that its properties are varying from one individual to another. So far, from a fair amount of researches, several biomechanical models have been developed to describe the human body vibrations' motion. These models can be classified in two main categories, lumped and distributed parameter models. In comparison with the distributed parameter model, the lumped-parameter model is an appropriate method for computer simulations because of its relatively simple structure. There are various ways to obtain these parameters including the seat-to-head transmissibility, driving-point impedance and apparent mass (APMS) (Cho and Yoon, 2001). Kitazaki and Griffin developed a two-dimensional distributed parameter model for prediction of the vertical vibration behavior of seated human body using the finite element method (Kitazaki and Griffin, 1997). Boileau and Rakheja derived a four-degrees-of-freedom linear model using driving-point mechanical impedance and seat-to-head transmissibility approaches simultaneously (Boileau and Rakheja, 1998). Kims and Yoon proposed a model of seated human body for assessing the head vibration transmissibility and apparent mass on vertical vibrations (Kim et al., 2005). In fact, values of the APMS of a seated human body alter with the amount and angle of excitation and the number of axes, which the human body is exposed

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to (Rakheja et al., 2010; Mansfield and Maeda, 2006; Hinz et al., 2006; Mansfield and Lundstrom, 1999).

In many researches of the literature, several human body models can be found for evaluation of the vibrations in the vertical direction. Hence, these models are not reliable for prediction of the vibrations in fore-and-aft directions. However, through data analysis, it was found that unweighted root-mean-square value of acceleration in fore-and-aft direction and vertical direction are relatively in correspondence. As a result, dynamic models for the design of a seat system should be extracted by the extension of traditional models in one direction. So, in this paper, a five-degrees-of-freedom model based on APMS method which eliminates the cited defects is used (Rakheja et al., 2006; Stein et al., 2006; Kim et al., 2011).

For attenuating the vehicle vibrations, efficient and reliable control strategies are required. In the last twenty years, many researches have applied some linear and non-linear control methods on the vehicle models. Gulclu and Gulez (Guclu and Gulez, 2008) applied a Neural Network (NN) based controller on a non-linear eight-degrees-of-freedom vehicle model with active suspension. Sakman et al., designed two fuzzy controllers for a nonlinear model of vehicle (Sakman et al., 2005). Choi and Han (Choi and Han, 2007) controlled vibration of a semi-active seat suspension system by realizing the sliding mode controller (SMC). Choi and Park (Choi et al., 2000) proposed a full-car suspension system featuring ER damper. They controlled vibrations via HILS method and presented the control responses in both time and frequency domains. Park and Kim (Park and Kim, 1998) used a full-car model for designing a decentralized variable structure controller (DVSC) using a plant transformation to a regular form. Crolla and Abdel Hady (Crolla and Abdelhady, 1991) applied some active suspension control laws on a full car model and then compared them. They used filtered white noise as the road input.

In another research, three different control techniques were compared for designing the semi-active suspension system of a quarter-car. These three techniques were optimal gain switching, discontinuous variable structure control and explicit model predictive control (Paschedag et al., 2010). Also, an adaptive two-degree-of-freedom controller for active suspensions was proposed (Zin et al., 2008). In addition, the optimal performance comparison of variable component suspension, including the active damping and full-state feedback, for "quartercar" heave models was examined (Redfield and Karnopp, 1988).

So far, various passive vibration control techniques have been utilized to reduce the vibrations. However, the functionality of passive systems cannot be guaranteed against the road inputs which contain different dominant frequencies. Also, in designed control systems, keeping the weight as low as possible is an important issue; while the passive devices are usually bulky. In control system, transforming the electrical energy to the mechanical energy and vice versa is required. Piezoelectricity is a material property which conjoin material's mechanical and electrical behaviors. As a result, piezoelectric material can be used as actuators and sensors simultaneously in smart systems (Ebrahimnejad et al., 2010; Crawley and Anderson, 1990; Bailey. and Hubbard, 1985; Chen and Chen, 2004; St-Amant and Cheng, 2000).

As it is observed, in the majority of the previous works, the control systems were designed for the vehicle models. Unlike the most of the previous researches, the main contribution of this paper is the design of a multivariable active control strategy to suppress the undesirable vibrations transmitted to the human body in seating mode. For this purpose, a realistic five-degrees-of-freedom model of human body seat is considered. Among various control strategies, the pole placement is selected for the vibration suppression; because the complex control laws like the nonlinear, robust and adaptive control are difficult to implement and sometime they are impractical. On the other hand, for the selected multivariable model in the absence of nonlinear dynamics, it is more convenient to use a more straightforward control strategy like the pole placement for simplicity. For the first time, dynamic behavior of the system is evaluated around its natural frequencies and the effectiveness of the assumed actuators (e.g., piezo-electric ones) is investigated. It is observed that the controller acts efficiently in vibrations suppression under various resonance and non-resonance conditions.

2. Multivariable dynamic model of the human body seat

2.1. Model definition and dynamic equations of motion

Fig. 1 shows the geometry of five degrees-of freedom model of a seated human body. Parameters of this model are presented in Table 1. The selected model, unlike other complex theoretical models for human body seat (e.g., with 9 DOFs), is obtained using the theoretical methods in alongside with verification by experiments (Kim et al., 2011).

The parameters of the model may not necessarily represent the physical values of a human body because only the apparent inertia matrix at human body-seat interface was reflected. However, due to its simple structure, this model is considered in this paper for the convenience of application in computer simulations.

Mass and moment of inertia of the rigid body ① in Fig. 1 denotes the femur, pelvis and vertebra; that of the rigid body ② for the head; and the mass element ③ along the rigid body ① stands for the viscera. The rigid body ① is capable of rotating and translating relative to the seat. The springs and dampers, such as those between the rigid body ① and the seat are adopted for the description of translational and rotational resilient forces. Since these elements

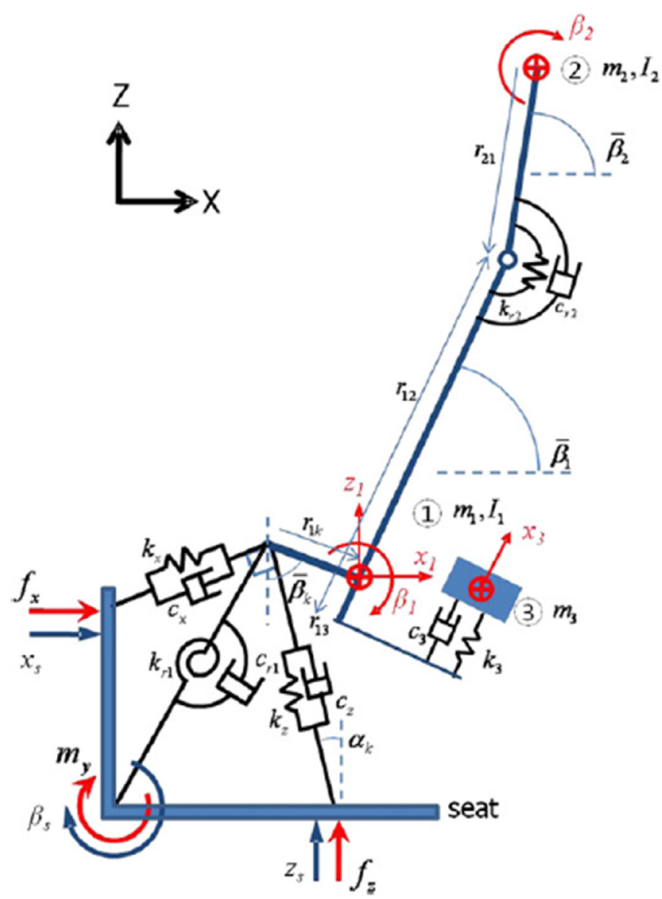

Fig. 1. A schematic view of the five degrees-of-freedom model of the seated human body.