Mechanical Systems and Signal Processing 50-51 (2015) 632–645

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

# Real-time identification of vehicle motion-modes using neural networks

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ARTICLE INFO

*Article history:*
Received 6 November 2012
Received in revised form
8 November 2013
Accepted 30 May 2014
Available online 20 June 2014

*Keywords:*
Vehicle dynamics
Identification
Motion-mode
Neural networks
Motion-mode energy method

ABSTRACT

A four-wheel ground vehicle has three body-dominated motion-modes, that is, bounce, roll, and pitch motion-modes. Real-time identification of these motion-modes can make vehicle suspensions, in particular, active suspensions, target on the dominant motion-mode and apply appropriate control strategies to improve its performance with less power consumption. Recently, a motion-mode energy method (MEM) was developed to identify the vehicle body motion-modes. However, this method requires the measurement of full vehicle states and road inputs, which are not always available in practice. This paper proposes an alternative approach to identify vehicle primary motion-modes with acceptable accuracy by employing neural networks (NNs). The effectiveness of the trained NNs is verified on a 10-DOF full-car model under various types of excitation inputs. The results confirm that the proposed method is effective in determining vehicle primary motion-modes with comparable accuracy to the MEM method. Experimental data is further used to validate the proposed method.


## 1. Introduction

Vehicle suspensions have been extensively adopted by ground vehicles to isolate ground vibrations and to provide passengers' ride comfort and safety. Three kinds of suspensions, that is, passive, semi-active, and active suspensions, have been proposed so far [1–3]. In comparison with passive suspensions, active suspensions are more effective and flexible in achieving the best ride comfort, integrated vehicle handling and safety control. However, active suspensions are associated with issue of their overall cost and power consumption, which so far prevents the wide application of active suspensions for ordinary passenger cars. It is because in order to control objectives in a wide frequency range, active suspensions usually use four individually controlled expensive linear motors or electro-hydraulic actuators. To overcome these problems, an active hydraulically interconnected suspension, which consists of four double direction hydraulic actuators interconnected by hydraulic lines and powered by an electrical pump, was recently developed [4–6]. This suspension can possibly reduce its overall cost and its system power consumption because it only needs to control one pressure valve. The reaction forces, which are generated between the vehicle rigid body and the wheels through closed fluid circuits, can largely reduce the required control effort. In addition, by switching its hydraulic configuration into different modes, the vehicle primary dynamic modes can be effective controlled with less power consumption.

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http://dx.doi.org/10.1016/j.ymssp.2014.05.043

To realise the potential of the abovementioned re-configurable hydraulic active suspension, we need to refine the control objectives and identify the primary control targets. In general, vehicle body-wheel motion-modes are defined by vehicle's relative motions between body and wheels, and can be sub-classified into several distinct modes in terms of their characteristic frequency, phase and damping ratio. For a two-axle four-wheel vehicle, there are seven body-wheel motion-modes [7,8]. The three body-dominated motion-modes are usually referred to as vehicle bounce, roll and pitch in literature. Their frequencies generally range between 1 and 3 Hz, and their mode shapes show that the vehicle body has much larger displacement compared to those of the wheels. The four wheel-dominated motion-modes, of which frequencies generally range between 10 and 15 Hz, are not distinguished in the literature and generally referred to as wheel 'hop' modes, regardless of the relative phases of the wheels. Vehicle body-dominated motions contribute most to vehicle ride comfort and handling, and thus naturally attract more attention from researchers. The research on vehicle dynamics is mostly dedicated to the study and control of these three motion-modes.

One of the most important and interesting properties of the aforementioned motion-modes is their orthogonality, which means the energy contained in one motion-mode cannot transfer to other motion-modes. To this end, motion-mode-based control is expected to be more effective than motion-based control because the control of one motion-mode will not affect other motion-modes due to their orthogonal characteristic. Given that a vehicle's body-wheel relative motions are driven/propelled by the energy contained in its body-wheel motion-modes, tracking the motion-mode energy can provide us a clear image of the dominating energy sources that cause vehicle motions.

The motion-mode-based control is also able to provide a better integrated strategy for controlling vehicle body's dynamics. As shown in [9], the control performance is improved when controlling vehicle body's bounce, roll and pitch motion-modes separately. Motion-mode energy is considered to be more stable, accurate, and comprehensive than one or a few isolated measurements in monitoring vehicle dynamic states, and thus the observation of the motion-mode contribution will provide more justification to switch control strategies than the direct measurement of motion will [10].

To enable the implementation of motion-mode-based control, the motion-modes need to be identified first. Recently, a motion-mode energy method (MEM), which calculates the energy contribution ratio in terms of the energy contained in each body-wheel motion-mode, was developed [8,11]. The motion-mode energy contribution ratio, which is written as mode-ratio for short in the rest of the paper, is a normalised ratio for the energy of all the considered motion-modes and can be used as an indication for the dominant motion-mode at each time instant.

Although the MEM method can provide an accurate solution of mode-ratio in real-time, it is obtained under the assumption that the system's state vector and ground road inputs are known. This, however, is impractical for most vehicles as the ground road inputs and some of the states are not measurable or can only be measured by expensive sensors which are not affordable or reliable for ordinary passenger cars. The estimation of ground road inputs and state vector is normally noise sensitive and can be computationally intensive. Therefore, an alternative method needs to be developed. This motivates the current paper to present a Neural Networks (NNs) based method for the recognition of motion-modes from the measured suspension deflections only.

Neural networks have proven to be effective and efficient in pattern recognition as well as control. Their applications in vibration-based fault detection have been carried out for more than a decade, e.g., fault diagnostics of induction machine stator [12] and rolling element bearings [13,14]. In automotive applications, neural networks have already been applied in driving pattern recognition [15], suspension dynamic control [16], and vehicle dynamic modelling [17]. In dynamic pattern recognition, different feature enhancement methods have been employed for NNs, such as, frequency domain methods [18], the Principal Component Analysis (PCA) method [19] and the Empirical Mode Decomposition(EMD) method [20,21].

In this study, two feed-forward NNs are adopted. These two NNs will be trained by using the training data sets generated by two 4 degree-of-freedom (DOF) half-car models in roll- and pitch-planes. In the training data sets, the target outputs are the mode-ratios calculated by the MEM method and the inputs are the corresponding suspension deflections. In order to effectively use NNs for recognising vehicle primary motion-modes, a new feature extraction algorithm is proposed.

This algorithm is a model-based principal component decomposition method which extracts the main features in relation to the motion-mode energy from the measured suspension deflections. In addition, to simplify the training process, the target outputs will be discretised into 11 sub-classes with equal intervals in the range of [0, 1]. The training inputs will also be appropriately generated to match these sub-classes. To interpret the results obtained from the NNs, which are the continuous values in the range of [0, 1], a probability mapping algorithm will be applied. Finally, the effectiveness of motion-mode recognition of the trained NNs is then verified on a 10-DOF full-car model under various types of excitation inputs. The obtained results confirm that the proposed method is effective in recognising vehicle primary motion-modes with comparable accuracy to the MEM method. Experimental data is also used to validate the proposed method.

The rest of the paper is organised as follows. In Section 2, two simplified 4-DOF half-car models are introduced. These models will be used to generate the training data sets for the NNs. The MEM is provided in Section 3, and the configuration of the NNs, the feature extraction, training, and result interpretation are presented in Section 4. The obtained results are validated in Section 5 for different cases, and the accuracy of the proposed method, practical training data obtaining and future development are discussed in Section 6. The conclusions are summarised in Section 7.