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Design and Experimental Validation of an Extended State Observer for Estimating of Uncertainties and Unknown Road Input in a Quarter-car McPherson Suspension System

Zahra Ahangari Sisi, Mehdi Mirzaei, Sadra Rafatnia

Faculty of Mechanical Engineering, Sahand University of Technology, Tabriz, Iran

ABSTRACT: This paper deals with the design and experimental implementation of an extended state observer for a fabricated quarter-car suspension platform with a McPherson mechanism equipped with different sensors. The algorithm aims to estimate uncertainties and road input, leading to an accurate dynamic model for the vehicle suspension system. In the proposed method, the terms including uncertainties and unknown road input are added to the system equations as new state variables and then estimated along with other state variables using data of sprung mass and un-sprung mass displacements. A nonlinear Kalman filter with unknown input is also designed to be compared with the extended state observer. The comparison results using the experimental data under measurement errors indicate the high accuracy of the extended state observer in constructing a precise dynamic model for the system. Meanwhile, the extended state observer uses fewer sensors and its regulation is easier. Both observers are used within the structure of the active suspension system under an optimal nonlinear controller to provide the objectives of the suspension system. Co-simulation results of Adams/MATLAB show the better performance of the proposed controller using the extended state observer.

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1- Introduction

Active suspension systems (ASS) are designed to enhance ride comfort by isolating vibrations due to road irregularities while ensuring tire contact with the road to improve braking and steering capabilities [1]. Accurately estimating road irregularities and obtaining precise information about the suspension system are essential for the development of a dynamic model used to design model-based controllers. To achieve such a model of a vehicle suspension system in the presence of uncertainties and road irregularities, estimation algorithms based on sensor information can be utilized.

This paper aims to provide an extended state observer (ESO) to simultaneously estimate the road input and model uncertainties of vehicle suspension systems. The proposed method utilizes information about the sprung and un-sprung mass displacements to estimate model uncertainties and disturbances. Given that this information is unavailable via sensors in real-world environments, the necessary outputs of the observer are derived through the double integration of band-pass filtered accelerations. Practical tests for a fabricated suspension system with a MacPherson mechanism are used to verify the presented estimation algorithm in a real environment. For comparison with other common methods, the obtained results are contrasted with the unknown-input Kalman filter developed in references [2, 3]. The results indicate the superior accuracy of the proposed method in estimating the states of the system, road inputs, and uncertainties. In the rest of the paper, an optimal nonlinear controller based on the provided observers is developed. This control method has previously been introduced by the authors in references [4, 5]. The primary objective of the proposed controller is to enhance ride comfort, ensure admissible working space, and maintain tire contact with the road. The efficacy of the controller is verified through ADAMS/Matlab co-simulation studies. Furthermore, the results are compared with those obtained from the controller utilizing the unknown-input Kalman filter. The comparative analysis indicates that the ESO can effectively estimate the state of the system, road input, and uncertainties. Consequently, the resultant controller demonstrates a robust performance in reducing body acceleration despite the physical limitations of the active suspension system.

2- The Overview of the Estimation Algorithm

Figure 1 presents an overview of the proposed estimation method for a quarter-car structure. This method utilizes two Wilcoxon-777B accelerometers to capture vertical accelerations of the sprung and un-sprung masses at 100 Hz. Data is collected and processed using LabVIEW software via a data acquisition card. The estimation algorithm corrects

*Corresponding author's email: mirzaei@sut.ac.ir

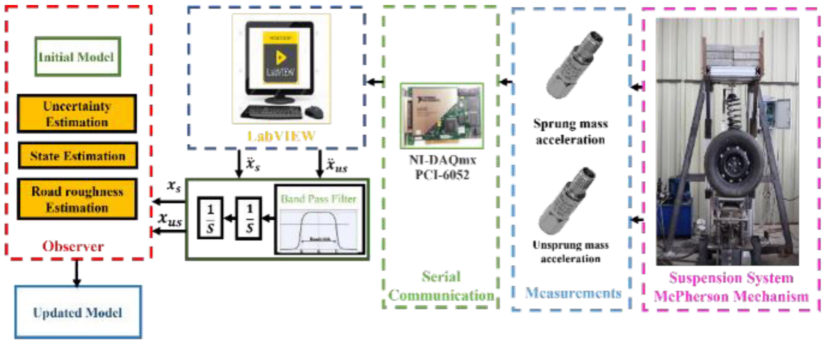


Fig. 1. The overall structure of the proposed algorithm.

mismatches between the theoretical model and the actual platform using displacement data derived from the double integration of filtered accelerometer outputs.

3- State Space Model of Quarter Suspension System

The state space of the model of the system can be derived as

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = f_1 + \dfrac{1}{m_s}u. \end{cases} \tag{1}$$

$$\begin{cases} \dot{x}_3 = x_4, \\ \dot{x}_4 = f_2 + d_1 x_r - \dfrac{1}{m_{us}}u, \end{cases} \tag{2}$$

where $x_{i\,(i=1,\ldots,4)}$ are the states of the system including the displacements and velocities of sprung and un-sprung masses.

4- Extended State Observer

By utilizing Eqs. (1) and (2) and augmenting the terms of uncertainties and unknown inputs as additional state variables, the state space model is effectively expanded as

$$(i=1,2)\begin{cases} \dot{\boldsymbol{\xi}}_i = \mathbf{A}\boldsymbol{\xi}_i + \mathbf{E}H_i + \mathbf{B}_i u, \\ \bar{\mathbf{y}}_i = \mathbf{C}\boldsymbol{\xi}_i, \end{cases} \tag{3}$$

where

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix},\ \mathbf{E} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},\ \mathbf{B}_1 = \begin{bmatrix} 0 \\ \dfrac{1}{m_s} \\ 0 \end{bmatrix},\ \mathbf{B}_2 = \begin{bmatrix} 0 \\ \dfrac{-1}{m_{us}} \\ 0 \end{bmatrix}$$
$$\mathbf{C} = [1 \quad 0 \quad 0],\ \hat{\xi}_1 = [x_1 \quad x_2 \quad F_1]^T$$
$$\hat{\xi}_2 = [x_3 \quad x_4 \quad F_2]^T \tag{4}$$

in which $F_1 = f_1$ and $F_2 = f_2 + d_1 x_r$. With these definitions, the observer state-space is obtained as

$$(i=1,2)\begin{cases} \dot{\mathbf{z}}_i = \mathbf{A}\mathbf{z}_i + \mathbf{B}_i u + \mathbf{L}_i(\bar{\mathbf{y}}_i - \mathbf{y}_i), \\ \mathbf{y}_i = \mathbf{C}\mathbf{z}_i, \end{cases} \tag{5}$$

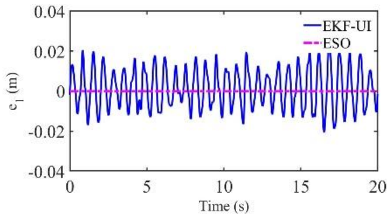
where the observer gains are shown by $\mathbf{L}_1 = [\beta_1 \quad \beta_2 \quad \beta_3]^T$ and $\mathbf{L}_2 = [\beta_4 \quad \beta_5 \quad \beta_6]^T$.

5- Results and Discussion

The comparative results of the proposed observer with the unknown-input Kalman filter are presented in Fig. 2. As illustrated in this figure, the proposed method demonstrates superior performance in estimating the displacements and velocities of both sprung and unsprung masses.

6- Conclusions

In this article, an extended state observer algorithm has been designed for estimating uncertainties and unknown road inputs. The results indicate the efficiency of the proposed extended state observer in reducing estimation error in the presence of various sources of uncertainty and disturbances. Additionally, comparative results with an unknown-input Kalman filter demonstrate the high accuracy of the proposed observer in providing a reliable dynamic model for the



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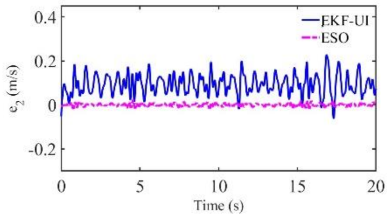

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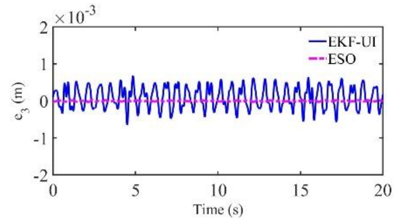

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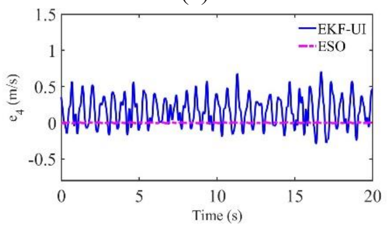

(d)

Fig. 2. The comparative results of the proposed method with unknown-input Kalman filter.

suspension system.

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