Adaptive On-Line Estimation of Road Profile in Semi-active Suspension

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Abstract. An on-line algebraic estimator for parameter identification is integrated a recent road profile estimator. The classical version of a road profile estimator that is based transmission characteristics suffered from parametric variation. Sprung mass is variable by changing the weight of passengers and baggage's. Furthermore, the damping of semi-active suspension does change rapidly during vehicle driving. The challenge is to identify all imperceptible modifications that can threaten the vehicle performances and to keep the credibility of road profile estimator online. A Differential algebra and operational calculus rules can be helpful to overcome the impact of variation in real time. The algebraic estimator has the fastest detection time and non-asymptotic behavior. In literature, the algebraic observers shown a good estimation of vehicle mass uncertainties. Additionally, this estimator requires a lower number of sensors and has a lower computational overhead. Measurements of vertical accelerations are only required to algebraically identify the sprung mass and damping coefficient of a quarter car model. Some numerical simulation results in time domain and frequency domain are provided. This new version of adaptive estimator can be integrated with the active controller in the future with easy implementation.

Keywords: Road profile · Algebraic estimator · Parametric identification · Sprung mass · Damping coefficient

1 Introduction

Several research methods have been proposed to identify road profiles and to get precise information about road service ability. Indeed, road profile excitation is classified as one of the main exogenous perturbation that acts on road vehicles' ride dynamics.

This chapter is focused on the proposed scheme based on the principle transmission characteristics of the system proposed by (Liu et al. 2020). The basic idea is to use vehicle dynamic responses in order to reconstruct the road profile with one sensor. The algorithm requires only the unspring mass, hence the whole process straightforward to tune and is not expensive to implement. This technique is can replace traditional methods

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of estimations. However, for getting a good estimation, a new concept of algebraic parametric estimators will be integrated to previous road profile estimators. The main advantage of this technique, only one setting parameter can be manually adjusted to improve the quality of the estimated road profile. The identification method based on the algebraic parametrical technique was first introduced by (Fliess and Sira-Ramirez 2003).

Actually, the use of operational calculus rules in combination with differential algebra creates an effective methodology for the estimation of dynamic system parameters. Major contributions of the proposed technique have been made in fields such as intelligent controller design (Haddar et al. 2019). The choice of the differential-algebraic theory for estimation is based on characteristic features of finite-time algebraic estimators (non-asymptotic state estimation).In fact, the influence of the initial conditions is indeed removed as claimed by (Beltrán-Carbajal and Silva-Navarro 2013). This truly is an improvement over the classical observers, which need the right initial conditions. Unknown or incorrect initial conditions invariably entail slow convergence of recursive type of observers. In addition, the presence of integrals in the estimation procedure acts like a low pass filter, which naturally reduces the influence of noise and external perturbation and hence is good at estimating vehicle parameters from a noisy signal.

The organization of the paper is as follows: a simple car model and the description of the proposed scheme of road profile estimator are presented in Sect. 2. Section 3 describes the algebraic parametric estimator and its principle rules for implementation process. The effectiveness of the proposed algebraic estimator in enhancing the credibility of road profile estimator is illustrated in Sect. 4. Finally, the conclusion is given in Sect. 5.

2 Scheme of Road Profile Estimation

A model of a vehicle with two degrees of freedom is considered as the most basic model that could describe the automotive suspension (Fig. 1). It consists of an assumption based on considering that the total mass of vehicle is equally distributed among the four wheels. Only vertical movements are considered. Dampers or springs prevent the amplification of disturbances caused by the road profile while maintaining good road contact. The selected simplified model is helpful, for a first study, to validate the proposed estimator. The dynamic behavior of a quarter-car model with a semi-active suspension is described by:

$$m_s \ddot{x}_s = -d_s(\dot{x}_s - \dot{x}_u) - k_s(x_s - x_u) \tag{1}$$

$$m_u \ddot{x}_u = k_s(x_s - x_u) + d_s(\dot{x}_s - \dot{x}_u) - k_t(x_u - x_r) \tag{2}$$

where, x_s, x_u and x_r are the sprung mass displacement, unsprung mass displacement and road profile excitation, respectively. The chassis is represented by m_s, the wheel and the tire are represented by m_u. k_s is the suspension stiffness and k_t is the tire stiffness. The damper d_s in this case, called "controllable damper" and is variable.

The road excitation will be estimated from information's given by the un-sprung mass acceleration and the transmission characteristics of the quarter car model:

$$T(s) = \ddot{x}_u(t) \tag{3}$$

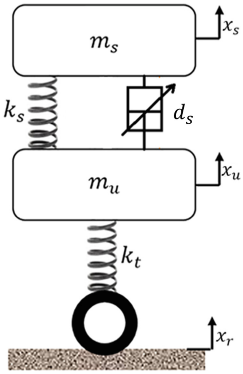

Fig. 1. Semi-active quarter car model

After a Laplace transformation of equation of motion and get rid of the sprung mass expression, we can get the following equation:

$$\left(m_s s^2 + d_s s + k_s + k_t\right) x_u(s) - \frac{(k_s + d_s s)^2}{m_s s^2 + d_s s + k_s} x_u(s) = k_t x_r(s) \tag{4}$$

The relationship between input signal and output signal of Eq. (4), allow us to write a transfer function between road excitation and un-sprung mass acceleration can be created:

$$\frac{x_r(s)}{T(s)} = \frac{m_s m_u s^4 + (m_s d_s + m_u d_s)s^3 + (m_s k_s + m_u k_s + m_s k_t)s^2 + k_t d_s s + k_t k_s}{m_s k_t s^4 + k_t d_s s^3 + k_t k_s s^2} \tag{5}$$

It is observable that the road excitation can be estimated directly by measuring only the vertical wheel acceleration.

3 Estimator of Vehicle Parameters

As we know, the sprung mass is variable and can affects the vehicle dynamics. Furthermore, the damping of semi-active suspension can change rapidly during vehicle driving. In order to estimate failures, we try to incorporate on-line the coefficient of the transfer function for reducing the sensitivity of proposed estimator.

A parametric algebraic estimator is proposed for obtaining the sprung mass and damping coefficient values. Starting by Laplace transformation of the first equation of motion (1):

$$m_s\left[s^2 X_s(s) - s x_s(0) - \dot{x}_s(0)\right] + d_s[s X_s(s) - x_s(0) - s X_u(s) + x_u(0)] = -k_s[X_s(s) - X_u(s)] \tag{6}$$

A double differentiation with respect to s is required for get rid of initial conditions:

$$m_s\left[2X_s + 4s\frac{dX_s}{ds} + s^2\frac{d^2X_s}{ds^2}\right] + d_s\left[2\frac{dX_s}{ds} + \frac{d^2X_s}{ds^2} - 2\frac{dX_u}{ds} - \frac{d^2X_u}{ds^2}\right] = -k_s\left[\frac{d^2X_s}{ds^2} - \frac{d^2X_u}{ds^2}\right] \tag{7}$$

No high power is allowed in order to attenuate the impact of noise:

$$m_s\left[2s^{-2}X_s + 4s^{-1}\frac{dX_s}{ds} + \frac{d^2X_s}{ds^2}\right] + d_s\left[2s^{-2}\frac{dX_s}{ds} + s^{-1}\frac{d^2X_s}{ds^2} - 2s^{-2}\frac{dX_u}{ds} - s^{-1}\frac{d^2X_u}{ds^2}\right] = -k_s\left[s^{-2}\frac{d^2X_s}{ds^2} - s^{-2}\frac{d^2X_u}{ds^2}\right] \quad (8)$$

From Laplace domain to time domain, we can get the following relation based on iterated integrals and required only verticals displacements x_s and x_u:

$$m_s\left[2\iint x_s\,dt + 4\int t\,x_s\,dt + t\,x_s^2\right] + d_s\left[2\iint t\,x_s\,dt + \int t^2\,x_s\,dt - 2\iint t\,x_u\,dt - \int t^2\,x_u\,dt\right] = -k_s\left[\iint t^2\,x_s\,dt - \iint t^2\,x_u\,dt\right] \quad (9)$$

The last Eq. (9), after some more integrations, leads to the linear system of equations:

$$A(t)\theta = B(t) \quad (10)$$

where $\theta = [m_s, d_s]^T$ denotes the parameter that should be identified online, $A(t)$ and $B(t)$ are 2×2 and 2×1 matrices respectively;
$A(t) = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$ and $B(t) = \begin{bmatrix} b_{11} \\ b_{12} \end{bmatrix}$.
whose components are time functions defined as

$$a_{11} = 2\iint x_s\,dt + 4\int t\,x_s\,dt + tx_s^2,\ a_{12} = 2\iint t\,x_s\,dt + \int t^2\,x_s\,dt - 2\iint t\,x_u\,dt - \int t^2\,x_u\,dt,$$

$$b_{11} = -k_s\left[\iint t^2\,x_s\,dt - \iint t^2\,x_u\,dt\right],\ a_{21} = \int a_{11},\ a_{22} = \int a_{12},\ b_{12} = \int b_{11}$$

By solving system (10) one obtains the parameter vector θ as

$$\theta = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}^{-1} \begin{bmatrix} b_{11} \\ b_{21} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} \Delta_1 \\ \Delta_2 \end{bmatrix} \quad (11)$$

with

$$\Delta = a_{11}a_{22} - a_{12}a_{21} \quad (12)$$

$$\Delta_1 = a_{22}b_{11} - a_{12}b_{21} \quad (13)$$

$$\Delta_2 = a_{11}b_{21} - a_{21}b_{11} \quad (14)$$

For avoiding singularities, we propose the following algebraic identifier (Beltrán-Carbajal and Silva-Navarro 2013)

$$\widehat{m}_s = \frac{\iint \Delta_1}{\iint \Delta},\ \widehat{d}_s = \frac{\iint \Delta_2}{\iint \Delta} \quad (15)$$

4 Numerical Simulation

To check the performance of the road profile estimator in the presence of algebraic parametric identifier, some numerical simulations were performed on a 2-DOF quarter car model characterized by the parameters given in Table 1.

The verticle road exciataion is selected according to model presented by Múčka et al. (2020).

Table 1. Parameters of suspension model.

Parameters	Value
Body mass m_s	317.5–635 kg
Wheel mass m_u	45.5 kg
Damping coefficient d_s	1000–7000 N.s/m
Spring stiffness k_s	20000 N/m
Tire stiffness k_t	192000 N/m

Figure 2 and Fig. 3 show the comparison between the real road disturbance and estimated profile in the time domain and frequency domain, respectively. It is perceivable from the Fig. 2 that the road information obtained from transfer function of Eq. (5) gives a good tracking of the original input road (The relative error is equal to 2%). Furthermore the power spectra density (PSD) verifies the effectiveness of the proposed road disturbance estimator Fig. 3.

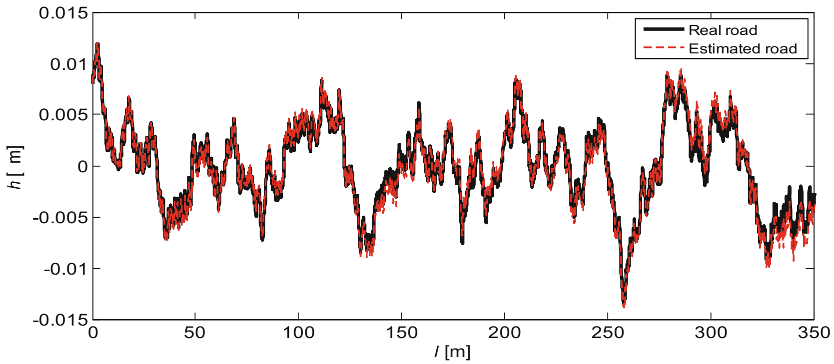

Fig. 2. Estimated road profile

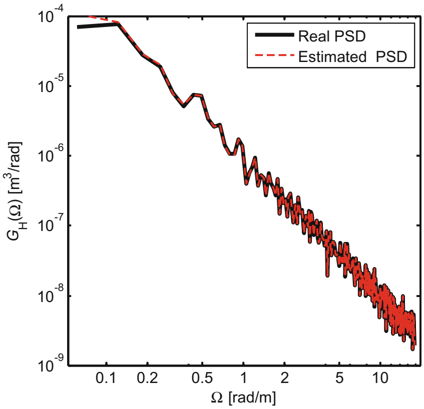

Fig. 3. PSD of estimated road profile

However, the vehicle parameters are able to be changed. The influence of variation is depicted in Fig. 4 and Fig. 5 under different cases:

Estimated 1: $m_s = 317.5\,kg,\ d_s = 7000\,N.s/m.$
Estimated 2: $m_s = 338\,kg,\ d_s = 1000\,N.s/m.$
Estimated 3: $m_s = 635\,kg,\ d_s = 7000\,N.s/m.$

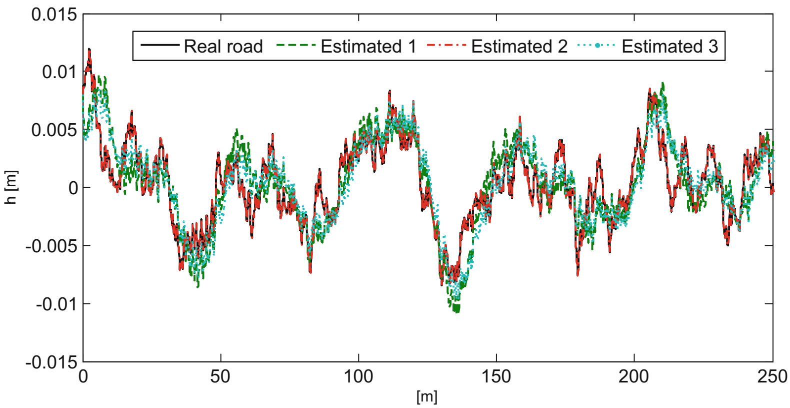

Fig. 4. Estimated road profile with parametric variation

Figure 4 and Fig. 5 shown the sensitivity of transfer function to quarter car model and specially to damping coefficient. The damping is varying in semi active suspension implementation. Sometimes, this change is very rapid. Therefore, it will be with a significant impact of damping variation on the estimate.

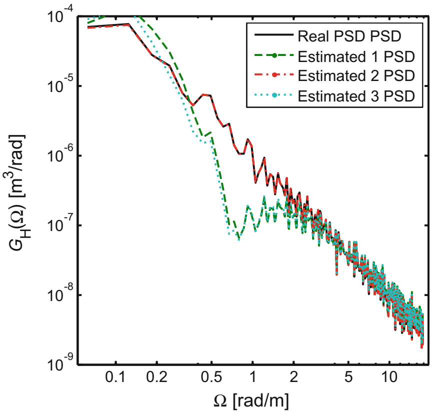

Fig. 5. PSD of estimated road profile with parametric variation

Then, the road disturbance estimator should be adjust the transfer function in real-time according to the variation of sprung mass and the damping coefficient, so as to obtain accurate estimation results.

Figure 5 shows the sprung mass and damping coefficient variations using the algebraic identifiers (15). Runge Kutta method with fixed small step time of 0.001s were used in the simulation implementation with Simulink (Haddar et al. 2017). Fast parameter estimation before t = 0.1 s.

In Fig. 6 the values of the estimated parameters were inserted in the transfer function online after 2 s in the case 3 (where $m_s = 635\,kg,\ \ d_s = 7000\,N.s/m$). Before 2 s, it is shown that the estimation results of the road disturbance in time-domain is deteriorated by the variation of vehicle parameters. However, the estimation results can still well follow the road input in the presence of algebraic identifier (Fig. 7).

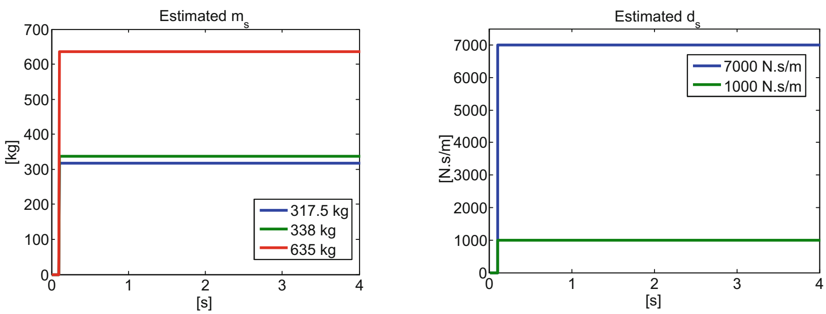

Fig. 6. Estimated vehicle parameters with algebraic estimator

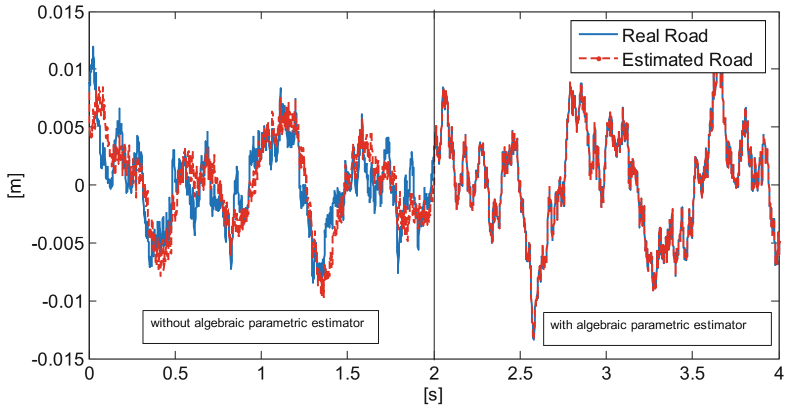

Fig. 7. Estimated road profile with and without algebraic estimator

5 Conclusion

In this chapter, the credibility of modified on-line estimation technique of road profile were tested by changing the sprung mass and damping coefficient The numerical results show that the algebraic estimator can well adjust the transfer function to the variation of model parameters. The proposed scheme can be useful in the case of all process with damping varying, the algebraic estimator always transmits the damping coefficient to the road profile estimator in real-time. In previous work, it is noted that in fact, the damping of the shock absorber cannot be obtained directly during vehicle driving. For exemple, in the case of magnetorheological (MR), only the control current of MR damper can be directly obtained. The corresponding calculation is required to obtain the damping coefficient. However, the proposed scheme is able to avoid this kind of problem and estimate directly the damping coefficient.

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