ESTIMATION OF ROAD PROFILE USING SECOND ORDER SLIDING MODE OBSERVER

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Abstract: This paper presents an algorithm to estimate the road profile. This method is based on a robust observer designed with a nominal dynamic model of vehicle. The estimation has been validated experimentally using a trailer equipped with position sensors and acceleration sensors.

1 INTRODUCTION

For the purpose of road serviceability, surveillance and road maintenance, several profilometers have been developed. For instance, (Span) have proposed a method based on direct measurements of the road roughness. However, some drawbacks of this method and some limitations of its capabilities have been pointed out in (Meau1992). A profilometer is an instrument used to produce series of numbers related in a well-defined way to the true profile (Span). However, this instrument produces biased and corrupted measures. The Road and Bridges Central Laboratory in French (LCPC) has developed a Longitudinal Profile Analyzer (LPA) (Legea1994). It is equipped with a laser sensor to measure the elevation of road profile. Other geometrical methods using many sensors (distance sensor, accelerometers...) were also developed (Gillespie1987). However, these methods depend directly on the sensors reliability and cost. It is worthwhile to mention that these methods do not take into consideration the dynamic behavior of the vehicle. In a previous work, M'Sirdi and al (M'Sirdi2005)(Im2003)(Rabhi2004) have presented an observer to estimate the road profile by means of sliding mode observers designed from a dynamic modeling of the vehicle. But in the previous method the vehicle rolling velocity is constant and steering angle is assumed zero. For estimation of the road profile, slope and inclination are also neglected. The main contribution is here to extend this observer.

This paper is organized as follows: section 2 deals with the vehicle description and modelling. The design of the second order sliding mode observer is presented in section 3. Some results about the states observation and road profile estimation by means of proposed method are presented in section 4. Finally, some remarks and perspectives are given in a concluding section.

2 VEHICLE MODELING

In literature, many studies deal with vehicle modelling (Kiencken2000)(Rabhi2004)(Ramirez1997). The objective may be either confort analysis or design or increase of safety and mailability of the car. The system under consideration is a vehicle represented as depicted in figure 1. This vehicle is composed by a car body, four suspensions and four wheels. The dynamic equations of the motion of the vehicle body are obtained by applying the fundamental principle of mechanics. When considering the vertical displacement along the z axis, the dynamic of the system can be written as:

$$M\ddot{q} + C\dot{q} + Kq = AU \tag{1}$$

where $(\dot{q}, \ddot{q})$ represent the velocities and accelerations vector respectively. $M \in \mathbb{R}^{7x7}$ is the inertia matrix, $C \in \mathbb{R}^{7x7}$ is related to the damping effects, $K \in \mathbb{R}^{7x7}$ is the springs stiffness vector (see Figure 1). The car body is assumed rigid. $q \in \mathbb{R}^7$ is the coordinates vector defined by:

$$q = [z_1, z_2, z_3, z_4, z, \theta, \phi] \tag{2}$$

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The matrix M, C, K and A are defined in (Rabhi2004). z_i $i = 1..4$ is the displacement of the wheel i. z, θ and ϕ represent the displacements of the vehicle body, roll angle, and pitch angle respectively.

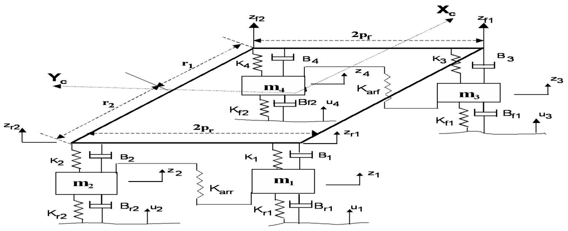

Figure 1: Vehicle Model.

K_i : are the suspension spring stiffness $[N/m]$,
B_i : are the suspension damping $[N/m/s]$,
K_{ri} : are the tire spring stiffness $[N/m]$,
B_{ri} : are the tire spring damping $[N/m/s]$,
$U = [\begin{array}{cccc} u_1 & u_2 & u_3 & u_4 \end{array}]^T$ is the vector of unknown inputs which characterizes the road profile.

The vertical dynamical model 1 can be written in the state form as follows:

$$\left\{ \begin{array}{l} x_1 = q \\ \dot{x}_1 = x_2 \\ \dot{x}_2 = \ddot{x}_1 = \ddot{q} = M^{-1}(-Cx_2 - Kx_1 + AU) \\ y = x_1 \end{array} \right. . \tag{3}$$

where the state vector $x = (x_1, x_2)^T = (q, \dot{q})^T$, and $y = q$ ($y \in \mathbb{R}^7$) is the vector of measured outputs of the system.

$$y = [\begin{array}{ccccccc} z_1 & z_2 & z_3 & z_4 & z & \theta & \phi \end{array}]^T \tag{4}$$

$$\left\{ \begin{array}{l} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1, x_2) + \xi \end{array} \right. . \tag{5}$$

with $f(x_1, x_2) = M^{-1}(-Cx_2 - Kx_1)$. The unknown input component is$\xi = M^{-1}AU$

3 ESTIMATION OF THE ROAD PROFILE

In order to estimate the state vector x and to deduce the unknown inputs vector U, we propose the following second order sliding mode observer (Davila2004):

$$\begin{array}{c} \dot{\hat{x}}_1 = \hat{x}_2 + z_1 \\ \dot{\hat{x}}_2 = f(t, x_1, \hat{x}_2) + z_2 \end{array} \tag{6}$$

where $\hat{x}_1$ and $\hat{x}_2$ are the state estimations, and the correction variables z_1 and z_2 are calculated by the super-twisting algorithm

$$\begin{array}{c} z_1 = \lambda |x_1 - \hat{x}_1|^{1/2} \, sign(x_1 - \hat{x}_1) \\ z_2 = \alpha \, sign(x_1 - \hat{x}_1). \end{array} \tag{7}$$

The initial moment $\hat{x}_1 = x_1$ and $\hat{x}_2 = 0$, are taken to ensures observer convergence. We assume x_1 available for measurement and we propose the following sliding mode observer:

$$\dot{\widehat{x}}_1 = \widehat{x}_2 + \lambda \sqrt{|x_1 - \widehat{x}_1|} sign(x_1 - \widehat{x}_1) \tag{8}$$

$$\dot{\widehat{x}}_2 = f(x_1, \hat{x}_2) + \alpha sign(x_1 - \widehat{x}_1) \tag{9}$$

where $\widehat{x}_i$ represent the observed state vector and α, β and λ are the observer gains.

It i important to note that in a first step, input effects on the dynamic are rejected by the proposed observer like a perturbation. Taking $\tilde{x}_1 = x_1 - \hat{x}_1$ and $\tilde{x}_2 = x_2 - \hat{x}_2$ we obtain the equations for the estimation error dynamics

$$\begin{array}{c} \dot{\tilde{x}}_1 = \tilde{x}_2 - \lambda |\tilde{x}_1|^{1/2} \, sign(\tilde{x}_1) \\ \dot{\tilde{x}}_2 = F(x_1, x_2, \hat{x}_2) - \alpha \, sign(\tilde{x}_1) \end{array} \tag{10}$$

Let us recall that $F(t, x_1, x_2, \hat{x}_2) = f(t, x_1, x_2) - f(t, x_1, \hat{x}_2) + \xi(t, x_1, x_2)$
In our case, the system states are bounded, then the existence of a constant bound f^+ is ensured such that

$$|F(x_1, x_2, \hat{x}_2)| < f^+ \tag{11}$$

holds for any possible t, x_1, x_2 and $|\hat{x}_2| \leq 2v_{\max}$. v_{max} and x_{max} are defined such that $\forall t \in \mathbb{R}^+$ $\forall x_2, x_1$ $|x_2| \leq v_{\max}$ and $x_1 \leq x_{\max}$

The state boundedness is true, because the mechanical system (5) is BIBS stable, and the control input u is bounded. The maximal possible acceleration in the system is a priori known and it coincides with the bound f^+. In order to define the bound f^+ let us consider the system physical properties. We have: - $\underline{m}I \leq M \leq \overline{m}I$ - $\underline{c}I \leq M \leq \overline{c}I$ - $\underline{k}I \leq M \leq \overline{k}I$

where $\underline{m}$, $\underline{c}$ and $\underline{k}$ are the minimal respective eigenvalues and $\overline{m}$, $\overline{c}$ and $\overline{k}$ the maximal ones. Then we obtain $max(M^{-1}) = \frac{1}{\underline{m}} I$ and f^+ can be written as $f^+ = \frac{1}{\underline{m}}(\overline{c} v_{\max} + \overline{k} x_{\max})$ Let α and λ satisfy the following inequalities, where p is some chosen constant, $0 < p < 1$

$$\begin{array}{c} \alpha > f^+, \\ \lambda > \sqrt{\frac{2}{\alpha - f^+} \frac{(\alpha + f^+)(1+p)}{(1-p)}}, \end{array} \tag{12}$$

The previous observers ensures that in finite time we have $\widetilde{x}_2 = 0$ then

$$\dot{\tilde{x}}_2 = f(x_1, x_2) - f(x_1, \hat{x}_2) + \xi - z_2 = 0 \tag{13}$$

Let us take a low pass filtering of z_2 which is defined in equation 6 and 7, then we obtain in the mean average:

$$\xi = z_2 \tag{14}$$

Note that $\overline{z}_2$ is the filtered version of z_2. In order to estimate the elements u_i $i = 1...4$ of the unknown input vector U and according 2 we can write

$$\zeta_1 = A_{11} U_u + B_{11} \dot{U}_u$$

with $\zeta = [\ \zeta_1 \quad 0 \quad 0 \quad 0\ ]^T$, and the matrices A_{11} and B_{11} given in (Rabhi2004). For $i = 1..4$ we have

$$\zeta_{1i} = a_{ii}u_i + b_{ii}\dot{u}_i \tag{15}$$

where a_{ii} and b_{ii} are respectively the elements of A_{11} et B_{11}. To solve this system we can take an approach simpler that the one in (Im2003) which uses a standard observer.

We can write:

$$\begin{cases} \dot{u}_i = g(u_i, \zeta_{1i}) \\ \zeta_{1i} = h(u_i) \end{cases} \tag{16}$$

with:

$$g(u_i, \zeta_{1i}) = \frac{1}{b_{ii}}(-a_{ii}u_i + \zeta_{1i}) \tag{17}$$

The observer proposed here is the:

$$\dot{\widehat{x}}_i = f(\widehat{x}_i, \widetilde{y}_i) + \lambda_i(y_i - \widehat{y}_i) \tag{18}$$

Let us not the the observation error: $\widetilde{u}_i = u_i - \widehat{u}_i$ The observation error dynamics is then obtained from equation (16) and (18).$\dot{\widetilde{u}}_i = g(\widetilde{u}_i, \zeta_{1i}) + \lambda_i(\widetilde{\zeta}_{1i})$ The convergence is proved by the following Lyapunov candidate function:$V_i = \frac{1}{2}\widetilde{u}_i^2$ The time derivative of V is then:$\dot{V}_i = \widetilde{u}_i\dot{\widetilde{u}}_i$ from 17, we obtain:

$$\dot{V}_i = \widetilde{u}_i \left[\frac{1}{b_{ii}}(-a_{ii}\widetilde{u}_i + \widetilde{\zeta}_{1i}) - \lambda_i(\widetilde{\zeta}_{1i}) \right] \tag{19}$$

and then as ζ_{1i} is measured or reconstructured by a observer we choose: λ_i= $\frac{1}{b_{ii}}$, on $\dot{V}_i < 0$,

4 EXPERIMENTAL RESULTS

In this section, we present some experimental results to validate our approach. Several trials have been done with a vehicle (P406 of LCPC) equipped with different sensors. Some tests were carried out at the Road and Bridges Central Laboratory (LCPC) test track with an instrumented car towing two LPA trailers. Measures have been acquired with the vehicle rolling at several speeds. The signal measured by a Longitudinal Profile Analyzer (LPA) constitutes in this experiment our reference profile. The figure 2 shows the vehicle speed variations. The Figure 3 shows clearly that the estimated displacements of the four wheels converge quickly to the measured ones. we present the roll angle and the pitch angle.

A good reconstruction of state enables the estimation of the unknown inputs of the system. Figure 5 presents both the measured road profile (coming from LPA instrument) and the estimated one. We can then observe that the estimated values are quite close the true ones.

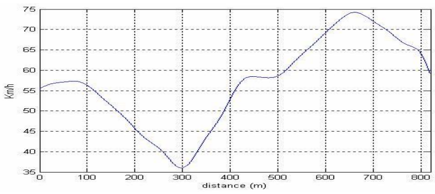

Figure 2: Longitudinal velocity of the vehicle.

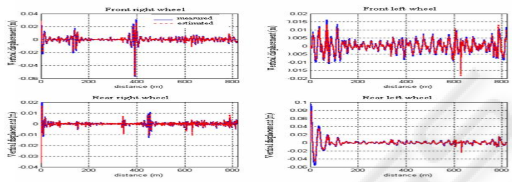

Figure 3: Displacements of wheels: estimated and measured.

5 CONCLUSION

In this paper, we present enhancement of the previously proposed method to estimate the road profile elevation based on second-order sliding-mode. The finite time convergence of the observer is proved. The gains of the proposed observer are chosen very easily ignoring the system parameters. This observer is compared, using experimental data. This observer is better than the previous one in convergence and do not assume the velocity constant. This is due to robustness of the second order observer which allows better rejection of perturbation and then a better reconstruction of the unknown inputs. The latter reconstruction has been also enhanced.

The estimation scheme build up using a Second Order Sliding Mode observers has been tested on experimental data (acquired with a P406 vehicle) and shown to be very efficient. The actual results prove effectiveness and robustness of the proposed method. In our further investigations the estimations produced on line will be used to define a predictive control to enhance the safety.

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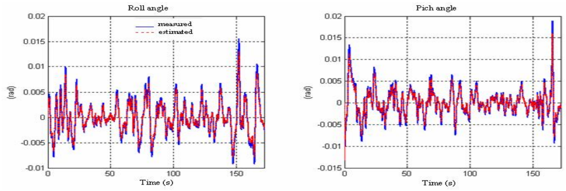

Figure 4: Estimation of the roll angle and the pich angle.

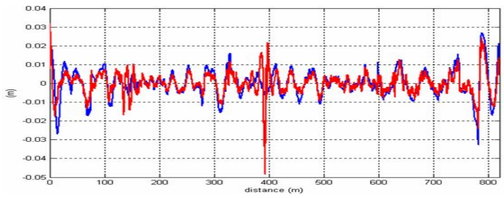

Figure 5: Comparison between observers approach and LPA profile.

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