Road profile estimation in heavy vehicle dynamics simulation

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Abstract: In this paper, a new method is developed in order to estimate the road profile inputs of heavy vehicle. These inputs are very important to evaluate on-board the vertical forces acting on the wheels. The proposed method is based on the use of second and third order sliding mode observers to estimate all the vehicle states (positions, speeds and accelerations) in finite time. Simulations results are given to compare the two observers and to show the robustness of the proposed method.

Keywords: road profile; loads; sliding mode observers; estimation.


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1 Introduction

Recently, the responses of the road profile to the dynamics of vehicle forces have been investigated. However, these inputs are not well known and there are some difficulties to have them in real time. Then it’s not easy to estimate the vertical forces on board.

A variety of sensors and instruments can be used for measuring these inputs (LPA, inertial method, profilometers …) (Karunasena, 1984; Harrison, 1983; Hitti, 1995). But, the sensors are expensive and the measures are not done on board.

In this paper, a new method to evaluate the road profile responses is proposed. These profile are considered as inputs of the developed heavy vehicle model (Imine, 2003).

First, these inputs are measured by the Longitudinal Profile Analyser (LPA) instrument, APL in French which have been developed at Roads and Bridges Central Laboratory (LCPC in French) and applied to a heavy vehicle model (Legeay, 1994). This model has been validated by the comparison between estimated and dynamics responses of the PROSPER simulator developed by Sera-Cd (1988) and validated by a lot of experimental tests (Delanne et al., 2003).

Then a second order sliding mode observer is developed and some estimation results are given. Finally a higher order sliding mode observers is introduced in order to estimate both positions, velocities and accelerations in finite time. This estimation allows to reconstruct the unknown inputs and then the vertical forces, which are very important to calculate the road damage or to evaluate the risk of rollover of the heavy vehicle using the Load Transfer Ratio (Imine, 2006; Imine and Dolcemascolo, 2006).

In a validation procedure, several simulations are made in order to assess the accuracy of the method and the efficiency and reliability of the whole system, by comparing the LPA measures with the estimated road profiles. Simulations are carried out by the PROSPER’s simulator.

This paper is organised as follows: Section 2 deals with the heavy vehicle model description, the design of second and third observers is presented in Section 3 to identify the unknown inputs. Some results about the states observation and the unknown inputs estimation are shown. Finally, some remarks and perspectives are given in a conclusion section.

2 Heavy vehicle model description

Many studies deal with heavy vehicle modelling which represents a complex mechanical system with nonlinear features (Chen and Peng, 1999; Ibrahim, 2004). The models used for heavy vehicles are very complicated. Consequently, it is relatively difficult to define the different parameters of these models.

In this paper, the half tractor model with four degrees of freedom (dof) is considered. It’s composed by two principal bodies: the body $C_1$ which is the unsprung part of the vehicle (unsprung mass, four wheels and front axles), and the body $C_2$ which represents the sprung mass.

This model is derived using Lagrangian equations:

$$M(q) \ddot{q} + C(q, \dot{q}) \dot{q} + K(q) = F_g$$  \hspace{1cm} (1)
where $M \in \mathbb{R}^{3 \times 3}$ is the inertia matrix (mass matrix), $C \in \mathbb{R}^{3 \times 3}$ is related to the damping effects, $K \in \mathbb{R}^{3}$ is the springs stiffness vector and $F_g \in \mathbb{R}^{3}$ is a vector of generalised forces.

$q \in \mathbb{R}^{3}$ is the coordinates vector defined by:

$$q = [q_1, q_2, \theta]^T$$  \hspace{1cm} (2)

The vertical acceleration of the chassis (tractor’s body) is obtained as following:

$$\ddot{z} = \left( k_1q_1 + k_2q_2 + \frac{Tw}{2}\sin(\theta) \right)/M + \left( B_1\dot{q}_1 + B_2\dot{q}_2 - \frac{Tw}{2}\cos(\theta)\dot{\theta} \right)/M$$ \hspace{1cm} (3)

where $\theta$ is the tractor roll angle and $Tw$ is the tractor track width, $q_1$, $q_2$ are respectively the left and right front suspension deflection of the tractor, $z$ is the vertical displacement of the tractor sprung mass (centre of gravity height), $\ddot{z}$ is the vertical acceleration of the sprung mass.

The suspension is modelled as the combination of a spring and damper elements as shown in the Figure 1.

Figure 1  Suspension model (see online version for colours)

The tractor chassis (with the mass $M$) is suspended on its axles through two suspension systems. The tyre is modelled by springs (represented by $k_i$ in the figure) and damper elements (represented by $B_i$ in the figure). The wheels masses are $m_1$ and $m_2$. At the tyre contact, the road profile is represented by $u_1$ and $u_2$, which are considered as heavy vehicle inputs. The variables $z_{r1}$ and $z_{r2}$ are respectively the vertical displacement of the left and right wheel of the tractor front axle. These can be calculated by means of using the following equations:

$$\begin{cases} z_{r1} = z - q_1 - \frac{Tw}{2}\sin(\theta) - r \\ z_{r2} = z - q_2 - \frac{Tw}{2}\sin(\theta) - r \end{cases}$$ \hspace{1cm} (4)

where $r$ is the wheel radius.
The vertical acceleration of the wheels are given by:

\[
\begin{align*}
\ddot{z}_{r1} &= (B_1 \dot{q}_1 - k_1 \frac{T}{2} \sin(\theta) - B_1 \frac{T}{2} \cos(\theta) \dot{\theta} \\
&\quad + k_1 q_1 - k_3 z_{r1} + k_3 u_1) / m_1 \\
\ddot{z}_{r2} &= (B_2 \dot{q}_2 + k_2 \frac{T}{2} \sin(\theta) + B_2 \frac{T}{2} \cos(\theta) \dot{\theta} \\
&\quad + k_2 q_2 - k_4 z_{r2} + k_4 u_2) / m_2
\end{align*}
\]

Then, these last equations allow to write the unknown inputs as follows:

\[
\begin{align*}
u_1 &= (m_1 \ddot{z}_{r1} - B_1 \dot{q}_1 + k_1 \frac{T}{2} \sin(\theta) \\
&\quad + B_1 \frac{T}{2} \cos(\theta) \dot{\theta} - k_1 q_1 + k_3 z_{r1}) / k_3 \\
u_2 &= (m_2 \ddot{z}_{r2} - B_2 \dot{q}_2 - k_2 \frac{T}{2} \sin(\theta) \\
&\quad - B_2 \frac{T}{2} \cos(\theta) \dot{\theta} - k_2 q_2 + k_4 z_{r2}) / k_4
\end{align*}
\]

In the next section, the road profile will be estimated by the second and third order sliding mode observer.

### 3 Estimation of the road profile

In order to develop the observers, the dynamic model defined in equation (1) is rewritten, in the state form as follows:

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= \ddot{q} = M^{-1} (F_g - C(x_1, x_2) x_2 - K(x_1)) \\
y &= x_1
\end{align*}
\]

where \( x = (x_1, x_2)^T \in \mathbb{R}^2 \) is the state vector and \( y = q \in \mathbb{R} \) is the measured outputs vector of the system.

Before developing the sliding mode observer, let us consider the following assumptions:

- The state is bounded (\( ||x(t)|| < \infty, \forall \ t \geq 0 \)).
- The system is inputs bounded (\( \exists \) a constant \( \mu \in \mathbb{R} \) such as: \( |u_i| < \mu, i = 1..2 \)).
- The generalised forces \( F_g \) are bounded (\( \exists \) a constant \( \zeta \in \mathbb{R} \) such as: \( F_{gi} < \zeta, i = 1..3 \)).
- In the vector \( C(x_1, x_2) x_2 \), there are quadratics elements in \( x_2 \). Then, this vector can bounded by:

\[
|| C(x_1, x_2) x_2 || \leq c_1 || x_2 ||^2 \tag{8}
\]

This last hypothesis is coming from mechanical and physical properties of the studied system and because of boundness of the real signals (position, velocity, acceleration).
3.1 Strong observability test

Before developing the observers, a verification of the strong observability of the system is needed. Let us rewrite the dynamic model (1) as:

\[
\begin{align*}
\dot{x} &= Ax + D \\
y &= q = Cx_1
\end{align*}
\]

\[(9)\]

where \(x \in \mathbb{R}^6\) is the state vector, \(y \in \mathbb{R}^6\) is the measured outputs vector. \(A\) is the \((6 \times 6)\) matrix, \(C\) is a matrix in \(\mathbb{R}^{3 \times 3}\) and \(D\) is a vector in \(\mathbb{R}^3\) composed by the nonlinear terms of the system.

**Definition 1:** \(s_0 \in C\) is called an invariant zero of the triple \(\{A; C; D\}\) if \(\text{rank } R(s_0) < n + \text{rank}(D)\), where \(R\) is the Rosenbrock matrix of system (9):

\[
R = \begin{bmatrix}
SI - A & -D \\
C & 0
\end{bmatrix}
\]

**Definition 2:** System (9) is called (strongly) observable if for any initial state \(x(0)\), \(y(t) \equiv 0(\forall t \geq 0)\) implies \(x(t) \equiv 0(\forall t \geq 0)\).

The following statements are equivalent.

i. The system (9) is strongly observable.

ii. The triple \(\{A; C; D\}\) has no invariant zeros.

By means of Definitions 1 and 2, it is easily shown that the system is strongly observable.

3.2 Second order sliding mode observer design

In order to estimate the state vector and to deduce the vertical forces vector \(F_{\text{ni}}\), the following second order sliding mode observer (Emelyanov et al., 1986; Fridman et al., 2006) is proposed:

\[
\begin{align*}
\dot{\hat{x}}_1 &= \dot{\hat{x}}_2 + z_1 \\
\dot{\hat{x}}_2 &= M^{-1}(F_y - C(\hat{x}_1, \hat{x}_2)\hat{x}_2 - K(\hat{x}_1)) + z_2
\end{align*}
\]

\[(10)\]

where \(\hat{x}_1\) and \(\hat{x}_2\) are the state estimations.

The correction variables \(z_1\) and \(z_2\) are output injections of the form:

\[
\begin{align*}
  z_1 &= \lambda \nabla(\hat{x}_1) \text{ sign}(\hat{x}_1) \\
  z_2 &= \alpha \text{ sign}(\hat{x}_1)
\end{align*}
\]

\[(11)\]

where \(\hat{x}_1 = x_1 - \hat{x}_1 \in \mathbb{R}^3\) is a vector of the state estimation error. The gains matrices \((\lambda\) and \(\alpha) \in \mathbb{R}^{3 \times 3}\) and \(\nabla \hat{x}_1\) are defined as:
3.2.1 Convergence analysis

The dynamics estimation errors are calculated as follows:

\[
\begin{align*}
\dot{\hat{x}}_1 &= \hat{x}_2 - \lambda \nabla(\hat{x}_1) \text{sign}(\hat{x}_1) \\
\dot{\hat{x}}_2 &= M^{-1} \hat{F}_g - M^{-1}(C(x_1, x_2)x_2 - C(\hat{x}_1, \hat{x}_2)\hat{x}_2) \\
&\quad - M^{-1}(K(x_1) - K(\hat{x}_1)) - \alpha \text{sign}(\hat{x}_1)
\end{align*}
\]  \tag{13}

Since the accelerations of the system are bounded, the elements of the matrix \( \alpha \) can be minorized, satisfying the inequality:

\[
\alpha_i > 2 \left| \frac{2}{\alpha_i - 2} \frac{\hat{x}_2}{\hat{x}_2} \right| (1 + p_i)^{-1}, \quad i = 1, 3  \tag{14}
\]

On the other hand, from Fridman et al. (2006), the gains of the matrix \( \lambda \) satisfying the inequality, can be selected as:

\[
\lambda_i > \sqrt{\frac{2}{\alpha_i - 2} \left| \frac{\hat{x}_2}{\hat{x}_2} \right| (1 + p_i)} / (1 - p_i), \quad i = 1, 3  \tag{15}
\]

where \( p_i \in [0, 1] \) are some constants to be chosen (proof in Davila et al., 2005).

In order to study the observer stability, first, the convergence of \( \hat{x}_1 \) and \( \hat{x}_i \) to 0, in finite time \( t_0 \) is proved. Then, some conditions about \( \hat{x}_2 \) to ensure its convergence to 0 are deduced. Therefore, for \( t \geq t_0 \), the surface \( \hat{x}_z = 0 \) is attractive, leading \( \hat{x}_z \) to converge towards \( \hat{x}_z \) satisfying the inequalities equations (14) and (15). The proof of the convergence of the second order observer can be found in Davila et al. (2005).

To identify the unknown vector \( U = (u_1, u_2)^T \), the equation (6) are used. First, the vertical accelerations of the wheels \( \hat{\dot{z}}_r \) and \( \hat{\dot{z}}_z \) are estimated by means of double derivation of the systems equation defined in equation (4) and by assuming that \( \sin(\theta) = \theta \) and \( \cos(\theta) = 1 \), we obtain:

\[
\begin{align*}
\ddot{\hat{z}}_r &= \ddot{z} - \hat{q}_1 - \frac{\hat{T}_f}{M} \hat{\dot{\theta}} \\
\ddot{\hat{z}}_z &= \ddot{z} + \hat{q}_2 - \frac{\hat{T}_f}{M} \hat{\dot{\theta}}
\end{align*}
\]  \tag{16}

At the time \( t > t_0 \), the convergence of the vertical acceleration of the body \( \ddot{z} \) is ensured by using the following equation:

\[
\ddot{z} = \left( (k_1\dot{q}_1 + k_2\dot{q}_2 + (k_1 - k_2)\frac{\hat{T}_f}{M} \sin(\hat{\theta})) / M + B_1\dot{q}_1 + B_2\dot{q}_2 - (B_1 - B_2)\frac{\hat{T}_f}{M} \cos(\hat{\theta}) \right) / M
\]  \tag{17}
The vertical accelerations of suspension $\ddot{q}_1$ and $\ddot{q}_2$ are obtained from the equation (10). However, this estimation can give some noises (chattering). That is why, a low pass filter is applied. In this case and according to equations (6) and (16), the unknown inputs of the system can be estimated.

In the next section, some simulation results are presented.

### 3.2.2 Estimation results

In this section some results related to the estimations of the states, the road profile and the vertical forces, in order to verify the robustness of the proposed approach are given. Then several road profile with different amplitudes and frequencies are measured by the LPA to excite the system.

The LPA instrument is represented in the Figure 2.

**Figure 2** Longitudinal Profile Analyser (APL in French) (see online version for colours)

In Figure 3, we have an example of the left and right road profile measured by this instrument.

**Figure 3** Measured road profile (see online version for colours)

Figure 4 shows that the suspension deflection, the vertical displacement of the body (centre of gravity height) and respectively its velocities are correctly observed.
The same remark can be given for the estimation of the vertical acceleration of the body shown in the Figure 5.

This well estimation of all the states of the heavy vehicle allows to identify correctly the road profile.
In the Figure 6, we show the estimation results of the road profile before filtering.

**Figure 6** Estimated road profile before filtering (see online version for colours)

We remark that the result is bad and needs filtration. That is why, a low pass filter is applied.

The result is shown in the Figure 7.

**Figure 7** Estimated road profile after filtering (see online version for colours)

In this case, the filtered road profile is similar compared to the road profile measured by LPA instrument.

However, it’s important to note that the estimation’s error can be corrected with a best choose of the observer gains $\alpha$ and $\lambda$.

In the next section, a third order sliding mode observer is developed.

### 3.3 Third order sliding mode observer design

In this section, the third order sliding mode observer is developed in order to estimate the heavy vehicle dynamic states and the road profile which allow us to reconstruct the
vertical forces (Fridman et al., 2006). A third order sliding mode observer is able to reconstruct the unknown inputs without filtering a signal (Levant, 1997).

The following third order sliding mode observer is proposed (Fridman et al., 2006):

\[
\begin{align*}
\dot{v}_0 &= -\lambda_0 \Sigma_1(v_0, y) \text{sign}(v_0 - y) + v_1 \\
\dot{v}_1 &= -\lambda_1 \Sigma_2(v_1, \dot{v}_0) \text{sign}(v_1 - \dot{v}_0) + v_2 \\
\dot{v}_2 &= -\lambda_2 \text{sign}(v_2 - \dot{v}_1)
\end{align*}
\]  
(18)

where \( v_0, v_1 \) and \( v_2 \) are respectively the estimate of \( x_1, x_2 \) and \( \dot{x}_2 \). The matrices \( \Sigma_1(v_0, y) \) and \( \Sigma_2(v_1, \dot{v}_0) \) are defined as:

\[
\begin{align*}
\Sigma_1(v_0, y) &= \text{diag}\{[|v_{01} - y_1|^{2/3}, |v_{02} - y_2|^{2/3}, |v_{03} - y_3|^{2/3}]\} \\
\Sigma_2(v_1, \dot{v}_0) &= \text{diag}\{[|v_{11} - \dot{v}_{01}|^{1/2}, |v_{12} - \dot{v}_{02}|^{1/2}, |v_{13} - \dot{v}_{03}|^{1/2}]\}
\end{align*}
\]  
(19)

This observer permit to estimate positions, velocities and accelerations of the system. The jerk of the system is bounded and it satisfies the inequality:

\[
f^+ \geq 2 |\ddot{y}|
\]  
(20)

where \( f^+ \) is a some known positive scalar.

Chosen the \( i \)th components of \( \lambda_0, \lambda_1 \) and \( \lambda_2 \) as: \( \lambda_0^i = 3.0 \sqrt{f^+} \), \( \lambda_1^i = 1.5 \sqrt{f^+} \), \( \lambda_2^i = 1.1 f^+ \), \( i = 1..3 \), the convergence of the positions, velocities and accelerations \( v_0, v_1 \) and \( v_2 \) are obtained in finite time \( t_0 \).

Let us consider the convergence of the acceleration of the body for \( t > t_0 \). According to the equation (3), this acceleration is estimated as follows:

\[
\dot{\ddot{z}} = (k_1 \ddot{q}_1 + k_2 \ddot{q}_2 + (k_1 - k_2) \frac{T_p}{2} \sin(\theta)) / M + \\
(B_1 \ddot{q}_1 + B_2 \ddot{q}_2 - (B_1 - B_2) \frac{T_p}{2} \cos(\theta) \dot{\theta}) / M
\]  
(21)

where (\( \dot{\cdot} \)) represents the estimated symbol.

The estimation error is obtained from equations (3) and (21) as follows:

\[
\ddot{z} = (k_1 \ddot{q}_1 + k_2 \ddot{q}_2 + (k_1 - k_2) \frac{T_p}{2} \sin(\theta)) / M + \\
(B_1 \ddot{q}_1 + B_2 \ddot{q}_2 - (B_1 - B_2) \frac{T_p}{2} \cos(\theta) \dot{\theta} - \cos(\theta) \dot{\theta}) / M
\]  
(22)

where (\( \ddot{\cdot} \)) represents the estimated error symbol.

By means of the equation (22), we can easily remark that the estimation error \( \ddot{z} \) converges toward 0 in finite time \( t > t_0 \).

Assuming that the initial conditions of velocities and positions are known, we are able to make a double integration of the acceleration. \( \ddot{z} \) in order to obtain the vertical displacement \( \ddot{z} \) of the chassis. On the another hand, from the equation (4), we estimate the vertical displacements of the wheels by using the following equations:

\[
\begin{align*}
\dot{z}_{r1} &= \ddot{z} - \dot{q}_1 - \frac{T_p}{2} \sin(\theta) - r \\
\dot{z}_{r2} &= \ddot{z} - \dot{q}_2 - \frac{T_p}{2} \sin(\theta) - r
\end{align*}
\]  
(23)
At time $t > t_0$, all positions including the vertical displacement $\hat{z}$ of the chassis are estimated. In such case, by means of the equations (23), these displacements are reconstructed in finite time.

In order to estimate the road profile, it’s necessary to estimate in finite time the vertical acceleration of the wheels. We can note that it’s possible by a double derivation of the equation (23) because all others states are observed for $t > t_0$.

Now, let us consider, the equation (6). We remark that, since all states and vertical accelerations of the wheels are known, the convergence of the road profiles $\hat{u}_1$ and $\hat{u}_2$ in finite time can be proven.

In the next section, some simulation results are given in order to test and validate the approach.

### 3.3.1 Estimation results

Choosing the observer parameters as $f^+ = 2$, $\lambda_0 = 1.33$, $\lambda_1 = 1.5$ and $\lambda_2 = 2.2$, let us verify if the states are well estimated. In the top of the Figure 8, the estimation of the suspension deflection and the roll angle are shown. We remark that these positions are well and fast observed with respect to those given by PROSPER’s simulator. The estimations of its velocities are shown in the bottom of the same Figure 8.

Figure 8  Estimation of the states (see online version for colours)

We note that the velocities are also correctly estimated with small errors. Generally and as we announced previously, a good estimation of the states allow us to reconstruct the vertical acceleration of the body.
In the Figure 9, we show the result of this reconstruction.

**Figure 9** Estimation of the vertical acceleration of the body (see online version for colours)

We can see that this acceleration converges in finite time to the true one given by PROSPER’s Simulator.

Since the vertical acceleration is well estimated, the double integration gives an accurate estimation of the centre of gravity height of the body compared to the true one as shown in the Figure 10.

**Figure 10** Estimation of the centre of gravity height of the body (see online version for colours)

As we said in the previous section, by using the equation (4), and if the positions vector $q$ and the centre of gravity height of the body $z$ are estimated, the vertical displacements of the wheels $z_{r1}$ and $z_{r2}$ can be deduced.
This estimation is then shown in the Figure 11.

**Figure 11** Estimation of the vertical displacements of the wheels (see online version for colours)

![Figure 11: Estimation of the vertical displacements of the wheels](image)

We remark that these displacements are well and in finite time reconstructed with respect to those given by PROSPER’s simulator.

The result about the estimation of the road profile is shown in the Figure 12.

**Figure 12** Estimation of the road profile (see online version for colours)

![Figure 12: Estimation of the road profile](image)

We notice that these signals are estimated with small errors with respect to those measured by the LPA instrument.

The Figure 13 shows the power spectral density of the estimated road profile and the measured one (by LPA instrument).
We note that the short and medium waves of the road (that mean long and medium frequencies) are well reconstructed. However there are limitations of the observer’s method to estimate the long waves of the road.

4 Conclusions and future works

4.1 Conclusions

This paper proposes a method to estimate road profile which is considered as unknown inputs of the heavy vehicle. The knowledge of these inputs is very important in the vehicle dynamics analysis and allows to calculate the vertical forces under each wheel. The first step of the work consists in developing a heavy vehicle model which is validated using PROSPER’s simulator. Then, a second and third order sliding mode observers is developed in order to estimate the vehicle states and the road profile inputs.

The particularity of the third order observer consists in estimating all states of the system including accelerations in finite time. The setting of an estimator needs a model. In this work, a half tractor’s model with four degrees of freedom is then developed and validated. It is simple but sufficiently specified for the concerned application. This model is validated by PROSPER’s simulator. In the second step of the work, and in order to be able to use observers, the strong observability of the system is verified. Since this property is verified, the observers are constructed in the following step. Different simulations are done to compare the two observers.

We show that the suspension deflections, the roll angle and its velocities and accelerations converge quickly and in finite time. This well estimation allows us to reconstruct the acceleration of the centre of gravity height of the body and the acceleration of the wheels. This allows also to estimate well and fastly the vertical displacements of the wheels. The simulation results show an accurate reconstruction of the road profile with respect to the PROSPER’s simulator results.
However, in the case of second order sliding mode, we need to filter the signal with a low pass filter because the observer is not able to estimate the necessary vertical accelerations of the wheels.

4.2 Future works

We plan in the future work, to apply this method to an instrumented heavy vehicle (tractor+semi-trailer) to estimate on board the road profile and the vertical forces under each wheel.

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