Identification of parameters for complex vehicle models

R. Majjad, M. Hafner

Institute for Industrial Information Systems
University of Karlsruhe
Hertzstr. 16, 76187 Karlsruhe, Germany
Fax: 00 49 721 75 57 88
e_mail: majjad@iiit.etec.uni-karlsruhe.de

Abstract: *In the last years many efforts have been taken to develop simulation models. These models need a large amount of parameters. Many of these parameters are unknown and difficult to measure. A precise knowledge of interior parameters of the car is necessary to be able to make a model which delivers accurate and reliable results. This paper presents the identification of some important parameters concerning the dynamical behaviour of the vehicle. These parameters are the road slope ε and the moments of inertia J_X, J_Y, J_Z for the x-,y- and z-axis and the mass of the chassis. To achieve this goal, a non-linear observer will be used to calculate and to validate the wheel forces which are needed as input values for an estimator. The five parameters are estimated using a RLS method. According to measurements in a test car our method delivers a very good estimation for the behaviour of the vehicle.*

Key Words: Identification, Observer, Vehicle model, Non-linear model.

1. Introduction

Intelligent automotive control systems improve the safety of cars in many fields. For example, a driving stability control by active braking of individual wheels [1] stabilizes the car in critical situations.

These dynamic control systems are always based on more or less complex vehicle models. For accurate vehicle simulations, the vehicle models should be adapted to different cars by adapting several specific vehicle parameters.

Many of these parameters are unknown and difficult to measure. A precise knowledge of interior parameters of the car is necessary to make the model deliver good, accurate and reliable results. Estimating non measurable parameters gives the opportunity to get to know the needed parameters.

In this paper the identification of some important parameters concerning the dynamical behaviour of cars is presented. These parameters are the road slope ε and the moments of inertia J_X, J_Y, J_Z for the x-,y- and z-axis and the mass of the chassis.

After a short description of the vehicle model in part 2, the determination of the wheel forces is dealt with in chapter 3. The wheel forces in x-, y- and z-direction are needed as input values for the estimator. A non-linear observer will be used to validate the calculated wheel forces indirectly.

In chapter 4 the identification of the parameters is presented. After introducing the Recursive Least Squares estimator, the road slope and the moments of inertia are estimated. Together with the moments of inertia a second parameter can be identified, namely the product of vehicle mass and distance between center of gravity and rotation axis.

The measurements are described in chapter 5 and the results are presented in chapter 6.

2. The vehicle model

The described vehicle dynamic model consists of several submodels which are modularly implemented in Matlab/Simulink. An example of such a model is shown in figure 1. The model uses the input values steering angle, wheel velocity, weather conditions and initial speed of the car.

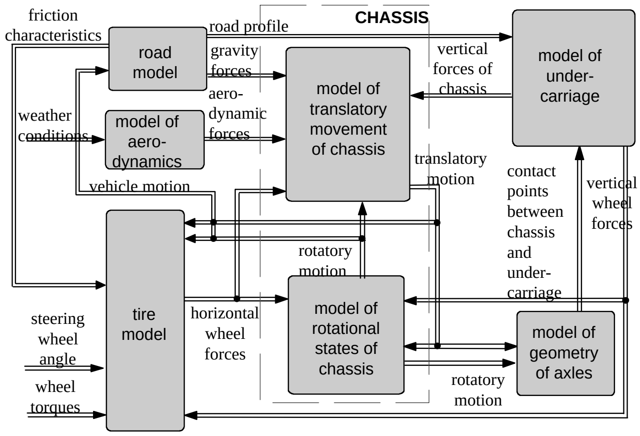


Figure 1: Modular implementation

With this model it is possible to determine non-measurable dynamic parameters of a real driving manoeuvre if the measured steering angle and wheel velocities of the manoeuvre are used as input.

The model itself can be adapted to any car by adapting the physical parameters of the specific car. However, many of these physical parameters are unknown and hardly measurable. The only way to get these parameter is to carry out an identification process.

3. Determination of the wheel forces

The wheel forces are essential as input for the identification task of some parameters. As they are very difficult to measure, they have to be modelled.
The normal forces depend on suspension dynamics and on the driving situation [2].
The normal forces at the front and rear wheels are assumed to be described by the following relations [3]

$$\begin{bmatrix} F_{ZVL} \\ F_{ZVR} \\ F_{ZHL} \\ F_{ZHR} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} m\cdot(\frac{l_H}{l} g - \frac{h}{l} a_X) - m\cdot(\frac{l_H}{l} g - \frac{h}{l} a_X)\cdot\frac{h\cdot a_Y}{b_V\cdot g} \\ \frac{1}{2} m\cdot(\frac{l_H}{l} g - \frac{h}{l} a_X) + m\cdot(\frac{l_H}{l} g - \frac{h}{l} a_X)\cdot\frac{h\cdot a_Y}{b_V\cdot g} \\ \frac{1}{2} m\cdot(\frac{l_V}{l} g + \frac{h}{l} a_X) - m\cdot(\frac{l_V}{l} g + \frac{h}{l} a_X)\cdot\frac{h\cdot a_Y}{b_H\cdot g} \\ \frac{1}{2} m\cdot(\frac{l_V}{l} g + \frac{h}{l} a_X) + m\cdot(\frac{l_V}{l} g + \frac{h}{l} a_X)\cdot\frac{h\cdot a_Y}{b_H\cdot g} \end{bmatrix}$$

where l_V, l_H, b_V, b_H are geometric parameters and a_X, a_Y the acceleration of the chassis in the center of gravity.

The next step is to define that the tire is subject to a longitudinal force and a lateral force as a function of the load F_Z and the friction coefficient :

$$F_L = F_Z\cdot\mu_L$$
$$F_S = F_Z\cdot\mu_S$$

The friction between tire and road is dependent on the road surface as is shown in figure 2.

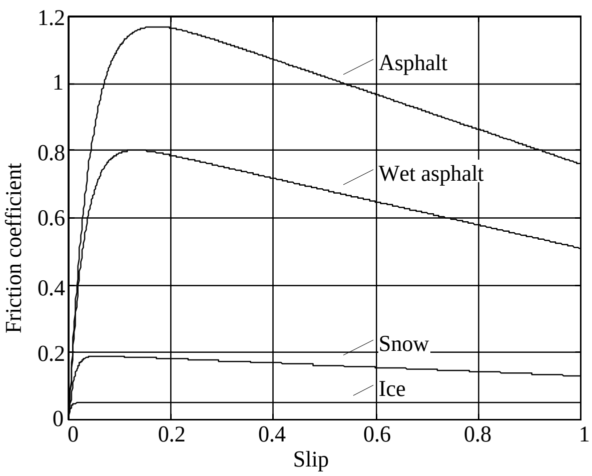


Figure 2 : Friction characteristics for some typical surfaces

Now the wheel forces in x- and y-direction can be found with a wheel model. Burckhardt [4] and Pacejka [5] give some equations to analytically describe the non-linear adhesion curve.

Burckhardt uses exponential functions to approximate the adhesion curve as following

$$\mu_{RES}(s_{RES}) = [c_1\cdot(1-e^{-c_2\cdot s_{RES}}) - c_3 s_{RES}]\cdot e^{-c_4\cdot s_{RES}\cdot v_{Ch}}\cdot(1-c_5\cdot F_Z^{\,2})$$

whereas Pacejka makes use of trigonometric functions

$$F(s) = D\sin[C\arctan\{B\cdot s - E(B\cdot s - \arctan(B\cdot s))\}]$$

in order to describe the wheel force as a function of the wheel slip.

The parameters c_1, c_2, c_3, c_4, c_5 and B, C, D, E, respectively, give us the characteristics of the road surfaces or the tire.

After calculating the wheel forces, we also had to validate our results before using them as input values for the identification. For this purpose a nonlinear observer was used with the wheel forces in x- and y-direction as inputs and the observed velocity v, slip angle β and yaw rate $\dot{\psi}$ as outputs. The observer was built upon the nonlinear two track model [6].

Figure 3 shows the implemented observer to validate the wheel forces:

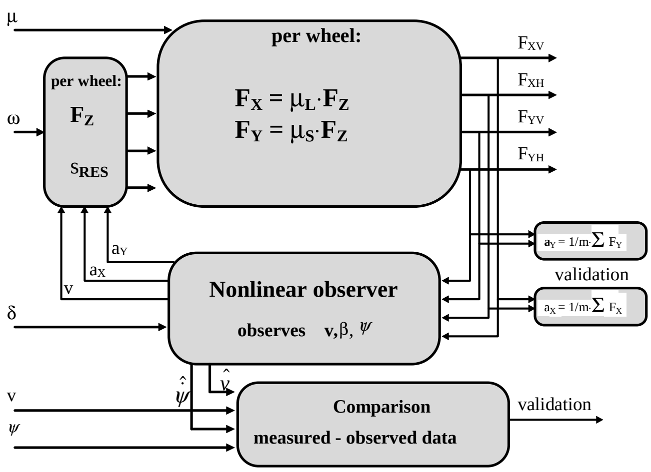


Figure 3 : Validation of wheel forces with non-linear observer

By comparing the observed velocity and yaw rate with their measured values, one can make conclusions on the accuracy of the input values of the wheel forces.

Figure 4 shows the measured and the observed data, namely the velocity, the yaw rate, the acceleration in x- and y-direction and the forces F_{XVL}, F_{YVL} of the front left wheel as an example.

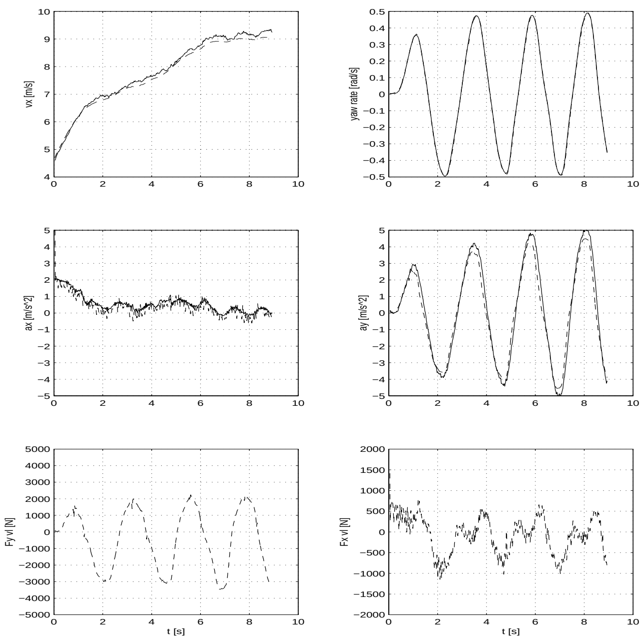


Figure 4 : Validation of the results from the non-linear observer

Another way to get the wheel forces is to use the vehicle model described in chapter 2. Once validated, both methods are capable of determining the wheel forces from the measured steering wheel angle and the wheel velocity.

4. Identification of parameters

4.1. Identification methods

Depending on model structure, a-priori information, disturbances and real-time feasibility, there is a vast variety of different estimation methods. A very common and powerful method is the Recursive Least Squares (RLS) Estimator [7] and some of its derivatives.

The estimation terms of the RLS are

$$\gamma(k) = \frac{P(k)\cdot\psi(k+1)}{\psi^T(k+1)P(k)\cdot\psi(k+1)+\lambda}$$

$$\Theta(k+1) = \Theta(k) + \gamma(k)\cdot[y(k+1) - \psi^T(k+1)\cdot\Theta(k)]$$

$$P(k+1) = [I - \gamma(k)\cdot\psi^T(k+1)]\cdot P(k)\frac{1}{\lambda}$$

In order to avoid numeric problems due to badly conditioned matrices, it is advisable to use some numerically improved identification method, e.g. the discrete square root filter in the covariance form (DSFC) [8].

These equations are:

$$f(k) = S^T(k)\cdot\psi(k+1)$$
$$a(k) = \frac{1}{f^T(k)\cdot f(k)+\lambda}$$
$$\gamma(k) = a(k)\cdot S(k)\cdot f(k)$$
$$S(k+1) = [S(k) - \frac{1}{1+\sqrt{\lambda\cdot a(k)}}\cdot\gamma(k)\cdot f^T(k)]\cdot\frac{1}{\sqrt{\lambda}}$$
$$\Theta(k+1) = \Theta(k) + \gamma(k)\cdot\underbrace{[y(k+1) - \psi^T(k+1)\cdot\Theta(k)]}_{e(k+1)}$$

Before applying the identification equations you have to determine the data-matrix Ψ, the parameter-matrix Θ and the output-matrix y according to the Least Squares equation

$$y(k) = \Psi^t(k)\cdot\Theta(k)$$

4.2. Identification of the moments of inertia

The moments of inertia can be found in the equations of the rotatory motion of the chassis. The three torque equations are described in [2] as follows:

Torque equation for the yaw rate:

$$J_Z\ddot{\psi} = \left(F_{XVR} - F_{XVL}\right)\cdot\frac{1}{2}b_V + \left(F_{XHR} - F_{XHL}\right)\cdot\frac{1}{2}b_H + \left(F_{YVL} + F_{YVR}\right)\cdot l_V - \left(F_{YHL} + F_{YHR}\right)\cdot l_H$$

Torque equation round a longitudinal axis:

$$J_X\ddot{\chi} = \left(F_{ZVL} + F_{ZHL}\right)\cdot\frac{b}{2} - \left(F_{ZVR} + F_{ZHL}\right)\cdot\frac{b}{2} + ma_Y h$$

Torque equation round a lateral axis:

$$J_Y\ddot{\varphi} = \left(F_{ZVL} + F_{ZVR}\right)\cdot l_V - \left(F_{ZHL} + F_{ZHR}\right)\cdot l_H + ma_X h$$

In these equations the roll- and pitch-axis were assumed to be on the road surface. To be more exact, it is better to raise the roll- and pitch-axis on their real level somewhere between the street and the center of gravity of the springed car mass. In the equation for the yaw rate the structural caster offset can be taken into consideration which leads to the following RLS-equations:

Identification of the moment of inertia for the x-axis

$$\underbrace{(F_{ZVL} - F_{ZVR}) \cdot \frac{b_V}{2} + (F_{ZHL} - F_{ZHR}) \cdot \frac{b_H}{2} + (\sum_{i=vl}^{hr} F_{Yi}) \cdot (spz - h')}_{y(k)} = \underbrace{\begin{bmatrix} \ddot{\varphi} & -a_Y \end{bmatrix}}_{\Psi^t(k)} \cdot \underbrace{\begin{bmatrix} J_X \\ m \cdot h' \end{bmatrix}}_{\Theta(k)}$$

Identification of the moment of inertia for the y-axis

$$\underbrace{(F_{ZVL} + F_{ZVR}) \cdot l_V - (F_{ZHL} + F_{ZHR}) \cdot l_H + (\sum_{i=vl}^{hr} F_{Xi}) \cdot (spz - h')}_{y(k)} = \underbrace{\begin{bmatrix} \ddot{\chi} & -a_X \end{bmatrix}}_{\Psi^t(k)} \cdot \underbrace{\begin{bmatrix} J_Y \\ m \cdot h' \end{bmatrix}}_{\Theta(k)}$$

Identification of the moment of inertia for the z-axis

$$\underbrace{F_{YV} \cdot (l_V - n_R) - F_{YH} \cdot (l_H + n_R) + F_{XVR} \cdot (\frac{b_V}{2} - n_R \sin(\delta)) - F_{XVL} \cdot (\frac{b_V}{2} + n_R \sin(\delta))}_{y(k)}$$

$$= \underbrace{\begin{bmatrix} \ddot{\psi} & -\frac{F_{XHR} - F_{XVL}}{2} \end{bmatrix}}_{\Psi^t(k)} \cdot \underbrace{\begin{bmatrix} J_Z \\ b_H \end{bmatrix}}_{\Theta(k)}$$

It is obvious that a second parameter can be identified in addition to the moments of inertia. For the x- and y-axis this second parameter is the product ($m \cdot h'$), the vehicle mass m and the distance between center of gravity and rotation-axis h'. With the knowledge of one of these two parameters it is possible to identify the vehicle mass or the parameter h'.

4.3. Identification of the road slope

The knowledge of the road slope ε is essential for an accurate vehicle dynamics model to work in real time on the car.
The slope can be determined by the offset of the real acceleration and the measured acceleration in x-direction which is due to the orientation of the acceleration sensor. As the sensor is not oriented horizontally when driving upwards, it also measures a part of the gravity-acceleration depending on the road slope.

$$a_X = \ddot{x} + g \cdot \sin\varepsilon$$

The real acceleration of the car can be calculated from the wheel rates

$$\ddot{x} = r_{dyn} \cdot \dot{\omega}$$

In order to avoid errors due to wheel slip it is advisable to use the wheel rates of the not driven wheels.
Solving the above equations for the road slope and neglecting the sin for small angles leads to

$$\varepsilon = \frac{a_X - \ddot{x}}{g}$$

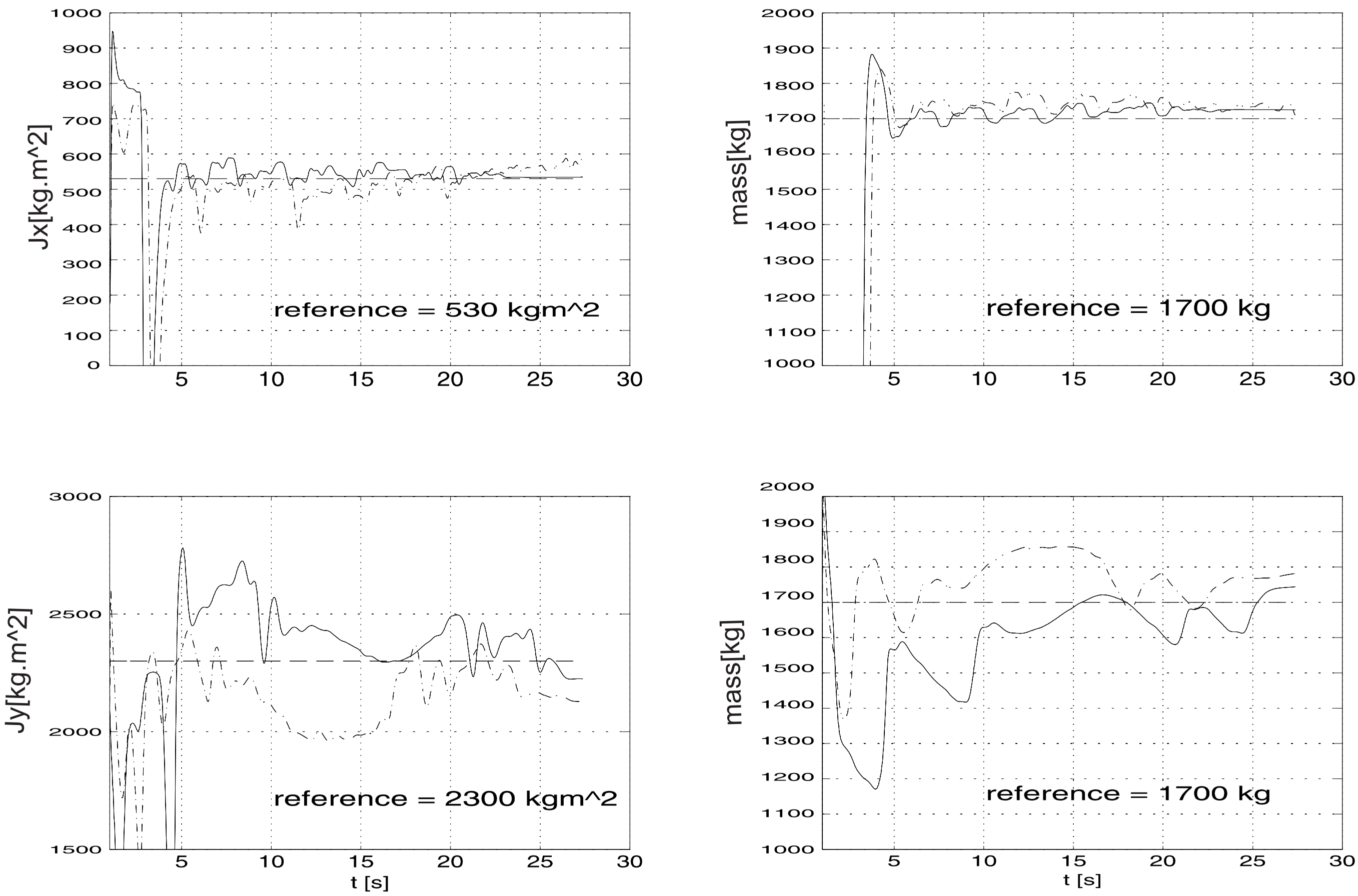
5. Measurements

The test car was equipped with a steering angle sensor and a motion-pak.box in the car's center of gravity to measure the accelerations and the rotation rates of the three axes. The velocity was measured with a correvit-sensor and the wheel rates were taken from the ABS-unit.
In order to stimulate the input of the estimator adequately, special manoeuvres were chosen to get good results. The most important manoeuvres were accelerated and decelerated rides straight forward, slalom rides at constant velocity and rides with steps in the steering angle.
The measured data were filtered and saved in the Matlab format. At this stage the data were then evaluated off-line with Matlab/Simulink on a PC but the used algorithms would all work for real time applications as well.

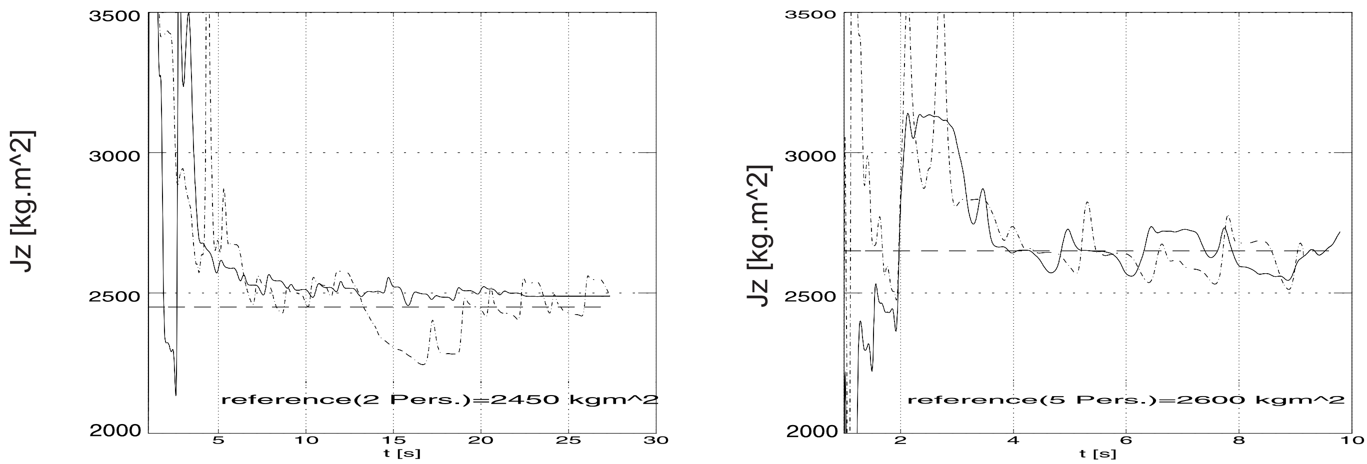
6. Results

The estimated parameters are presented in the following figures. The calculated reference-line in the plots demonstrate the accuracy of the results for the specific manoeuvre. With the moments of inertia for the x- and y-axis the second parameter ($m \cdot h'$) was solved assuming a specific value for h', the distance between center of gravity of the springed vehicle mass and the rotation axis.
For the road slope two plots are presented showing the same valley twice, first driven in one direction and then the same way backwards.

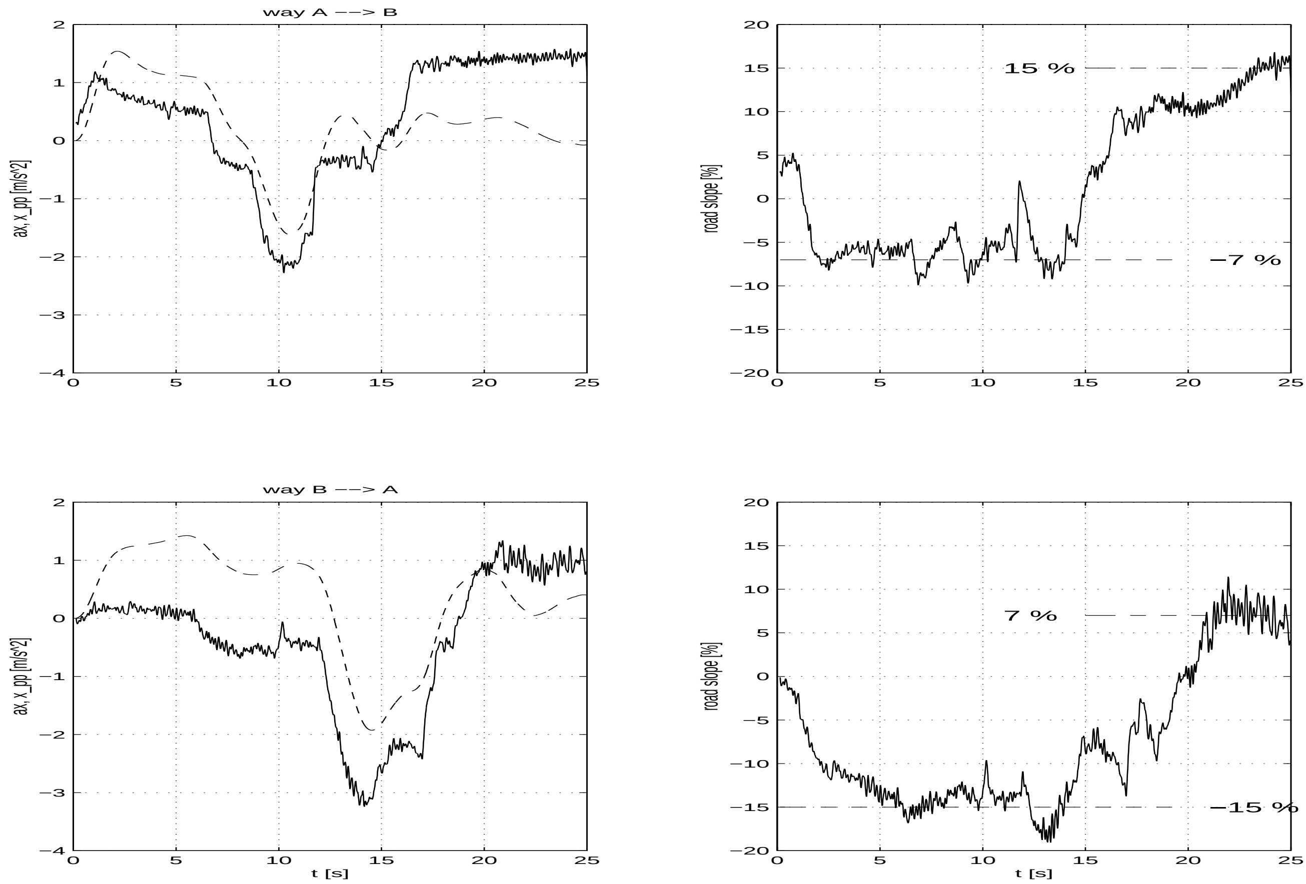
Result 1: The plots on the left side show the results of the moments of inertia for the x- and y-axis, the left plots show the results for the estimated vehicle mass



Result 2 : The second figure shows the estimated moment of inertia for the z-axis



Result 3 : In this figure the detected road slope is presented, driving through the same valley to and fro



7. Conclusions

The identification of the parameters road slope ε, moments of inertia J_X, J_Y, J_Z for the x-,y- and z-axis and the product m·h' of vehicle mass and distance between center of gravity and rotation axis produced good results. The wheel forces which are needed as input values for the identification could be calculated with specific wheel load- and tire-models and could be validated with help of a non-linear observer.

The algorithm to estimate the road slope is numerically easy to implement and gives in its simple form a resolution of less than 5% slope.

Using adequate driving-manoeuvres it was possible to get reliable values for all three moments of inertia.

Additionally, with the knowledge of either *m* or *h'*, one of these parameters could also be determined. In the plots of results1 *h'* was given a fix value to determine the vehicle's mass.

Having estimated the above parameters, the vehicle model described in chapter 2 could be improved by using the current parameters during a driving manoeuvre. In particular the dynamic changes in the road slope make the simulation model more accurate when used for on-line modelling of a driving condition. The simulated dynamics of the car are then more reliable and more accurate then and therefore can be used as inputs for automotive control systems e.g. Bosch FDR [9].

8. References

[1] Alberti,V., 'Fahrstabilitätsregelung durch Aktivbremsung einzelner Räder ', Automatisierungstechnische Zeitschrift at 5/96, 1996, pp 213-218

[2] Majjad, R., 'Simulation of vehicle dynamics ', Intern Report of the Institute, 1996

[3] Kiencke, U., 'Regelung und Signalverarbeitung im Kraftfahrzeug', Intern Report, 1996

[4] Burckhardt, M, ' Fahrwerktechnik : Radschlupfregelsystem ', Vogel Fachbuch, 1993

[5] Pacejka, H.B., 'The Magic Formula Tyre Model', Delft University of Technology, 1993

[6] Mitschke, M, ' Dynamik der Kraftfahrzeuge ', Band A, B, C, Spring Verlag 1988

[7] Ljung, L, 'System Identification, Theory for the user', Prentice Hall, 1987

[8] Isermann,R., 'Identifikation dynamischer Systeme', Band I, II, Springer Verlag, 1991

[9] van Zanten, A., Erhardt, R., Pfaff, G., ' FDR Die Fahrdynamikregelung von Bosch ', Automobil-technische Zeitschrift 96, 1994, p. 674-688