ROAD SURFACE ESTIMATION FOR CONTROL SYSTEM OF ACTIVE SUSPENSIONS

Levente BALOGH * - Árpád MÉSZÁROS-KOMÁROMY *- László PALKOVICS+

*Department of Automobiles
Budapest University of Technology and Economics
Sztoczek Str. No.6, Bld. J., Budapest, H-1111 Hungary
Phone: +36-1463-1753, Fax: +36-1463-3978
Email: balogh.levente@auto.bme.hu

+Knorr Bremse Systems for Commercial Vehicles
Robert Bosch Str.5, D-71701 Schwieberdingen, Germany
Phone: +49-7150-307400, Fax: +49-7150-307 120
Email: laszlo.palkovics@knorr-bremse.com

Keywords: suspension, vibration system, X-by-wire, road model

ABSTRACT

The control correction of the active and semi-active suspension systems is mainly based on the difference between the computed and the real, measured accelerations. The calculation of the desired acceleration is executed by a suspension simulating model with the road function as input. Some modifying factors - like the parameters of the steering system, brake system, etc. - can correct the control algorithm, but the main influential element is the structure and the inputs of this model.

Venhovens [1] described the construction of a control system in details, where the inputs are supplied by sensors and stochastic models. It presents the creation method of the road model for a quarter-car and a full-car model. This way we can produce the road disturbances as a coloured noise resulting from a first order AR filter. Thus the suspension model can generate the desired accelerations from one or two uncorrelated random signals. The other solution for the estimation of the road surface is the deduction from the signals of the acceleration sensors. Hereunder we try to present an alternative option to eliminate the use of stochastic models or numerous sensors. We trace the production of the road surface back to the direct or indirect force measuring.

INTRODUCTION

The control of the active and semi-active suspension found in bibliography examples is based on the difference between the calculated and the measured vehicle accelerations. Accelerations are calculated from stochastic road model. One of the disadvantages is that sensors must be installed on the vehicle. On the other hand at the production of the stochastically estimated road function the signals of sensors aren't taken into consideration.
Our object is to estimate the surface of the road passed during a certain time interval and the acceleration of the sprung mass based on the lorry's airspring pressure signals and the wheelspeeds. Hereby the input functions of the active suspension can be refined and the sensors can be used, which are more frequently located on lorries.

THE VALIDATION HARDWARE OF ESTIMATION

For validating the road surface-estimating algorithm, we made reference measurements on a Mercedes Actros truck. We applied acceleration sensors during the comparison, because it's very difficult to measure the road surface directly. Figure 1 shows the assembly of the measurement system.

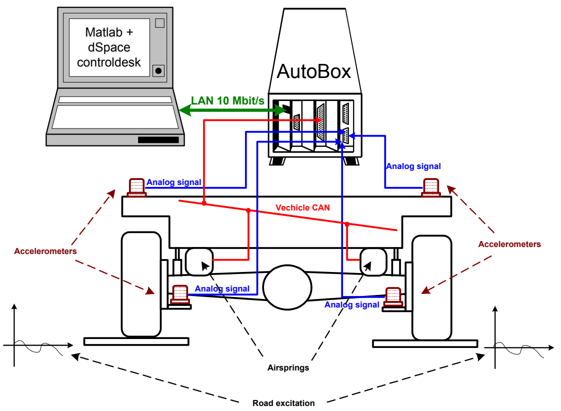

Figure 1: Measuring system

We placed acceleration sensors on the wheels and on the vehicle structure. Signals from airspring pressures sensors can be found on the vehicle CAN network. For the calculations of the algorithm we had to register the wheel speeds too. This information is findable on the vehicle CAN. We used dSpace AutoBox to collect measured data. In the course of measurements we recorded reference data on the following surfaces:

- asphalt,
- concrete,
- dirt road.

With the help of the system it is possible to assign estimated surface numbers calculated from airspring pressures to road function expressed in units. We needed the acceleration sensors to determine these road functions. On the other hand the inputs of active suspension control are also accelerations, so these measurements create the possibility to define coherency between accelerations and airspring pressures. Especially it is important in semi-active suspension, because there is a speed dependant powersource beside the actuator and the airsprings.

ROAD SURFACE ESTIMATION METHOD

On the basis of airspring pressure and wheel speed (vehicle speed) signals we determine with Matlab Simulink a number characteristic to the road.

- the base of calculations are the airspring pressure signals of the system ELC
- we make a statistical model from the measured pressure
- statistical identification for the elements of the model
- a ratio shows the quality of the road, which is derived from coefficients of the polynome

Inputs of the algorithm are potentials from the test vehicle's airspring system. These voltages must be converted to pressure, to get usable data for the algorithm. After conditioning the signals, we make a statistical model, on which we perform a statistical identification (Figure 2).

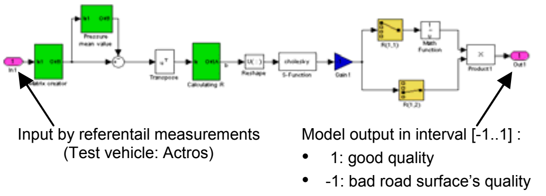

Figure 2: Road surface estimation model

From the coefficients of the output polynomial we compose a ratio which shows the quality of road surface.
Tests have been executed at the airport of Kiskunlacháza (Hungary), where we passed through several different surfaces (plain asphalt, potholed asphalt, concrete, plain dirt road, rugged dirt road). Although our target is the estimation of displacement function of road, without active suspension we can use yet the information of the algorithm for other tasks. For example we can give orientation for the driver about the road quality based on predefined categories listed in the parenthesis.
Measurements were taken on flat road. In the first 5 seconds the vehicle passed through a plain asphalt surface at the rate of 30 km/h, after that it drove through a rugged dirt road keeping its speed.
In Figure 3 we can see the results on this road. The upper diagram shows the airspring pressure plotted against time. The flat pressure level during the first five seconds can be seen very well, and also the oscillation later.

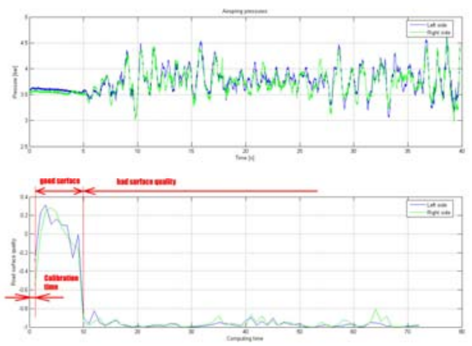

Figure 3: The estimated road surface quality

The lower diagram shows the ratio calculated for the rear wheels. A calibration time is visible in both cases, during which the algorithm calculates imprecisely.
However it tracks rapidly the altering of surface quality. The resulted value shows the class of road surface on a pre-calibrated scale. The calibration of the scale depends on our target. In our case we will assign to displacements in the normal direction of the road surface. Otherwise the scale can be assigned to road classes or speed limits and so on.

IDENTIFICATION OF THE SUSPENSION

The road surfaces used during the tests were almost the same on two sides of the vehicle, that's why we can analyze the left and right side separately to simplify the calculations. As a result we can represent the lorry's suspension as a quarter-car model, as Figure 4 shows.

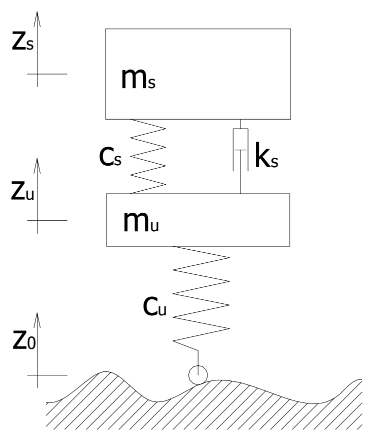

Figure 4: Quarter-car model

Transfer functions are easily definable between road surface, sprung mass and unsprung mass by the equations of motion of the quarter-car model.

$$m_s \cdot \ddot{z}_s = k_s \cdot (\dot{z}_u - \dot{z}_s) + c_s \cdot (z_u - z_s)$$
$$m_u \cdot \ddot{z}_u = c_u \cdot (z_0 - z_u) - k_s \cdot (\dot{z}_u - \dot{z}_s) - c_s \cdot (z_u - z_s)$$

$\mathcal{L}$-transformation:

$$m_s \cdot Z_s \cdot s^2 = k_s \cdot (Z_u - Z_s) \cdot s + c_s \cdot (Z_u - Z_s)$$
$$m_u \cdot Z_u \cdot s^2 = c_u \cdot (Z_0 - Z_u) - k_s \cdot (Z_u - Z_s) \cdot s - c_s \cdot (Z_u - Z_s)$$

Transfer functions:

$$G_{su} = \frac{\frac{k_s}{m_s} \cdot s + \frac{c_s}{m_s}}{s^2 + \frac{k_s}{m_s} \cdot s + \frac{c_s}{m_s}}$$

$$G_{u0} = \frac{\frac{c_u}{m_u} \cdot s^2 + \frac{k_s \cdot c_u}{m_s \cdot m_u} \cdot s + \frac{c_s \cdot c_u}{m_s \cdot m_u}}{s^4 + \left(\frac{1}{m_u} + \frac{1}{m_s}\right) \cdot k_s \cdot s^3 + \left(\frac{c_s}{m_s} + \frac{c_u}{m_u} + \frac{c_s}{m_u}\right) \cdot s^2 + \frac{k_s \cdot c_u}{m_u \cdot m_s} \cdot s + \frac{c_u \cdot c_s}{m_u \cdot m_s}}$$

We can estimate relatively exactly the sprung mass if we know the data of the vehicle. So on the basis of the coefficients of the G_{su} transfer function we can identify the unknown k_s and c_s parameters.

As first step we precondition the measured acceleration signals. With this we perform the correlation and the frequency analysis. Because of the layout of the mechanical model we can see that the structure of the transfer function between the sprung and unsprung masses show an ARMA(2,1) model. We have to take into consideration that some other functions disregarded under the reduction steps can influence the accelerations. So we will use the information won from the correlation functions for the estimation of the model structure. (Figure 5)

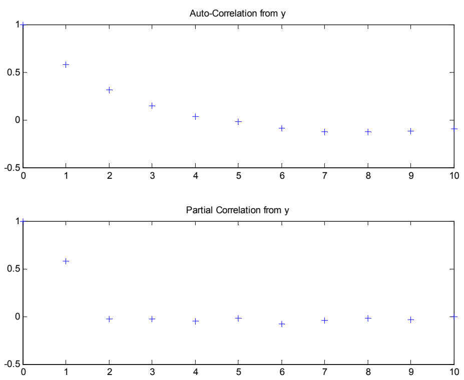

Figure 5: Correlation functions

The measured data registered in discrete steps predicts an AR(2) model. It's because the auto-correlation function calms down in the infinity (the order of the MA member is zero). The other cause is that the partial-correlation function gives significant values to the second member (the order of the AR member is 2).

With the 'identification toolbox' of Matlab we identify a discrete AR(2) model:

$$\tilde{G}_{su} = \frac{1.058}{z^2 + 1.0663 \cdot z + 0.31963}$$

Than we convert to continuous-time:

$$G_{su} = \frac{0.758 \cdot s + 0.21338}{s^2 + 0.766 \cdot s + 0.20245}$$

The Bode-diagrams produced from the estimated continuous transfer function and the measured signals are shown in Figure 6.

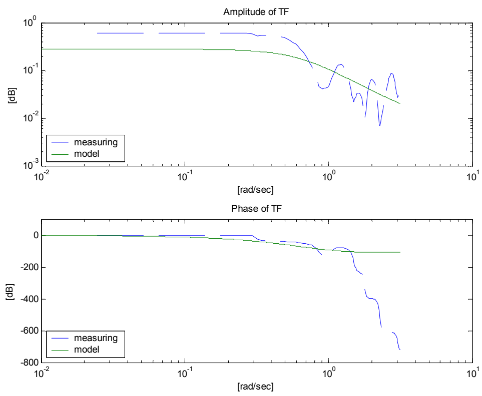

Figure 6: Bode diagrams

This way we get the linearized suspension's parameters that help us to define the coefficients of the G_{u0} transfer function. For realizing this task we need yet two parameters: the stiffness of the tire and the unsprung mass (c_u and m_u). If we know the data of the vehicle and the type of the tire we can determine these unknown values. So the G_{u0} transfer function is:

$$G_{u0} = \frac{0.8435 \cdot s^2 + 0.5472 \cdot s + 0.24352}{s^4 + 1.2564 \cdot s^3 + 0.6345 \cdot s^2 + 0.5472 \cdot s + 0.24352}$$

With this relation the road function is producible by using the accelerations measured on the unsprung mass as inputs. To assign the displacement values to the [-1;1] result interval of the road surface estimator algorithm we have to apply the measurements registered on the different surfaces.

In the course of comparisons we get the relation shown in Figure 7.

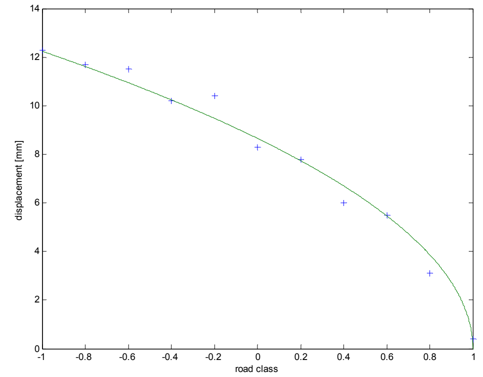

Figure 7: Relation between the displacement and the road class

Certainly we can find numerous and more exact estimations in the literature. The input function of these road function predictors are the accelerations too. For example Gáspár-Szabó-Bokor [2] propose the 'linear parameter varying' method. With their procedure we can calculate with the nonlinearity of the suspension. Generally the precision of the used method depends on the conditions and the actual vehicle, which is determined by the selection.

APPLICATION FOR AN ACTIVE SUSPENSION

Generally the control of the active suspension uses the road functions produced by stochastic models and the signals of some accelerometers. These sensors are installed on the sprung mass (vehicle body) and the unsprung mass (wheel). The control force is generated by the algorithm that works from these inputs. Earlier we have shown how we can use the airspring sensors' pressure values, with the help of the wheel speeds, to estimate the roughness of the road. With this method we get more exact approach relating to the road disturbances. It's because the estimation calculates from measured values and not from values determined by statistic tools.

The other important input function is the acceleration of the sprung mass. The computation of this value is different in the active and the semi-active suspension system.

With the active suspension the situation is simpler because the motion of the sprung mass depends on two elements in this case. These two parts are the actuator and the airspring that are shown in Figure 8.

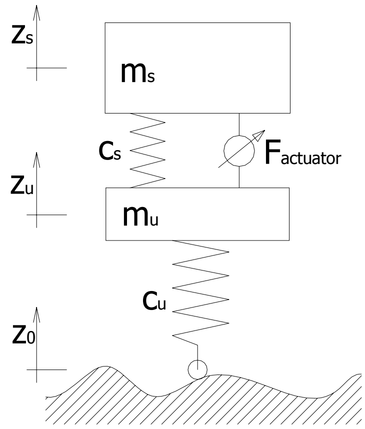

Figure 8: Active suspension

The solution is very simple, the wanted acceleration is:

$$\ddot{z}_s = \frac{F_{actuator}}{m_s} + \frac{F_{airspring}}{m_s} \qquad where \qquad F_{airspring} = f(p_{airspring})$$

In the case of the semi-active suspension the next determinant is the influence of the shock absorber. In a linearized model the damping force is commensurate with the difference of displacement-velocity of the sprung and unsprung mass. At the same time the spring force is commensurate with the difference of the displacements. In the course of measurements we can establish the function $p_{airspring}=f((z_u-z_s))$. Let's instruct the inverse function of 'f ': $g(p_{airspring})=f^{-1}((z_u-z_s))$. We can measure the characteristic of the shock absorber $F_{damper}=h((\dot{z}_u-\dot{z}_s))$. Thus the acceleration of the sprung mass is the following:

$$\ddot{z}_s = \frac{F_{actuator}}{m_s} + \frac{F_{airspring}}{m_s} + \frac{F_{damper}}{m_s}$$

where:

$$F_{airspring} = f(p_{airspring})$$

$$F_{damper} = h((\dot{z}_u - \dot{z}_s)) = h\left(\frac{d}{dt} g(p_{airspring})\right)$$

This way we can realize an optional suspension control. For choosing one we have to look for some examples in the literature. The system amended with the above mentioned parts is represented with the control of Hawley-Zhou-McEnhill-Lin [3]. Figure 9 shows the structure of this system.

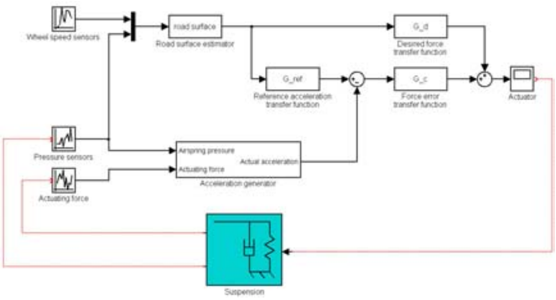

Figure 9: An example for control design

CONCLUSIONS

In this paper we tried to give an alternative chance for controlling active suspensions, with which we can rationalize the tool demands and we can improve its efficiency. The algorithm used to estimate road surface has proved that it is capable to substitute stochastic road models. Several further opportunities are still available to get more exact correspondence between road surface-classes and real movements. By analyzing these possibilities more refinements can be done.

REFERENCES

[1] **P. J. Th. Venhovens** (1993). "Optimal control of vehicle suspensions"

[2] **I. Szaszi, P. Gaspar, J. Bokor** (2002). "Non-linear active suspension modelling using linear parameter varying approach", *Mediterranean Control Conference, Lisabon*

[3] **S. Hawley, J. Zhou, H. McEnhill, T. Lin**. „The Design and Evaluation of a Four-Wheel Vehicle Active Suspension", *ME 461 Course Project report*

[4] **X. Shen, H. Peng** (2003). „Analysis of Active Suspension Systems with Hydraulic Actuators", *IAVSD Conference, Atsugi, Japan*

[5] **Bokor, J., Keresztes, A., Palkovics, L., and Varlaki, P.** (1994) "Design of an Active Suspension System in the Presence of Physical Parameter Uncertainties", *FISITA'94 World Congress, China*