

# THE MECHATRONIC VEHICLE CORNER OF DARMSTADT UNIVERSITY OF TECHNOLOGY–INTERACTION AND COOPERATION OF A SENSOR TIRE, NEW LOW-ENERGY DISC BRAKE AND SMART WHEEL SUSPENSION

Bert Breuer<sup>1)</sup>, Michael Barz<sup>1,2)</sup>, Karlheinz Bill<sup>1,3)</sup>, Steffen Gruber<sup>1)\*</sup>,  
Martin Semsch<sup>1)</sup>, Thomas Strothjohann<sup>1)</sup> and Chunyang Xie<sup>1)</sup>

<sup>1)</sup>Darmstadt University of Technology, Petersenstrasse 30, D-64287 Darmstadt, Germany

<sup>2)</sup>Scientific assistant at fzd until October 1999

<sup>3)</sup>Senior engineer at fzd until September 1999

(Received 26 March 2001; Revised 8 February 2002)

**ABSTRACT**–Future on-board vehicle control systems can be further improved through new types of mechatronic systems. In particular, these systems' capacities for interaction enhance safety, comfort and economic viability. The Automotive Engineering Department (fzd) of Darmstadt University of Technology is engaged in research of the mechatronic vehicle corner, which consists of three subsystems: sensor tire, electrically actuated wheel brake and smart suspension. By intercommunication of these three systems, the brake controller receives direct, fast and permanent information about dynamic events in the tire contact area provided by the tire sensor as valuable control input. This allows to control operation conditions of each wheel brake. The information provided by the tire sensor for example helps to distinguish between straightline driving and cornering as well as to determine  $\mu$ -split conditions. In conjunction with current information of dynamic wheel loads, tire pressures and friction tyre/road, the ideal brake force distribution can be achieved. Alike through integration of adaptive suspension bushings, elastokinematic behaviour and wheel positions can be adapted to manoeuver-oriented requirements.

**KEY WORDS** : Mechatronics, Tire sensor, Brake-by-wire, Active suspension

## 1. INTRODUCTION

Development of today's and future generations of vehicles is focused on improvement of active safety, riding comfort and running characteristics of the vehicle. Mechatronic subsystems ("X"-by-wire systems) and their intelligent control will contribute considerably to finding technical solutions for such conflicts of aim. The electrical interface of the individual subsystems is of special importance in this case.

For this reason, research for a mechatronic vehicle corner is done by the Automotive Engineering Department (fzd) at Darmstadt University Of Technology and is divided into projects A3 (tire sensor), A7 (active suspension) and B6 (mechatronic wheel brake) of special research area 241 IMES, sponsored by Deutsche Forschungsgemeinschaft. After the completion of basic research work for the individual components, the focus is on

interaction between the three subsystems, *i.e.* tire, suspension and brake.

## 2. DARMSTADT TIRE SENSOR

All forces required for acceleration, deceleration, change of direction and course holding of a vehicle must be transmitted by the adhesion between tire and road. The achievable frictional force mainly depends on friction-coefficient  $\mu$  which, together with current wheel load, is a decisive factor for the running characteristics and safety.

Since 1988 research in this area is done by fzd and with the "Darmstadt tire sensor" which is now in the 4<sup>th</sup> generation (Figure 1).

Research is aimed at defining global forces transmitted by the tire as an integral of local individual forces, which are transmitted by the tread element in the tire contact area, on the basis of the tire rotating at the vehicle by measuring the deformation of the tread element in x, y and z-direction without affecting the running characteristics.

---

\*Corresponding author: e-mail: sgruber@fzd.tu-darmstadt.de

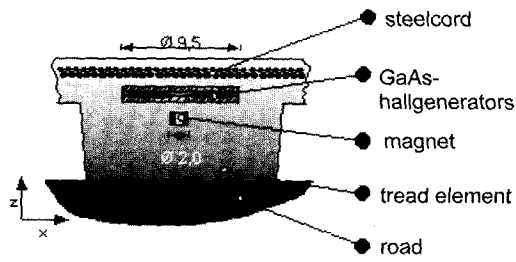


Figure 1. 4<sup>th</sup> generation of the tire sensor.

The sensor measures the tread element deformation as position change of a magnet relative to four Hall sensors with crosswise arrangement. The four elements are interconnected to enable resolution of movements in x, y and z-direction.

The characteristic signal patterns of tread element deformation achieved during tire rotation can be evaluated and assessed on-line to deliver information about

- Coefficient of friction/utilization of friction coefficient,
- Tire pressure/tire pressure OK ?,
- Wheel load,
- Braking and driving forces,
- Side forces,
- Risk of aquaplaning,
- Tire temperature (temperature measuring element at sensor).

Definition of the friction-coefficient is described here as an example (Figure 2): The gradient change of the signal between the curves of high and low coefficient of friction can be clearly identified as a result of beginning local slip. Indexes defining the available coefficient of friction can be calculated from the curves on-line.

Rising internal pressure of the tire reduces the contact

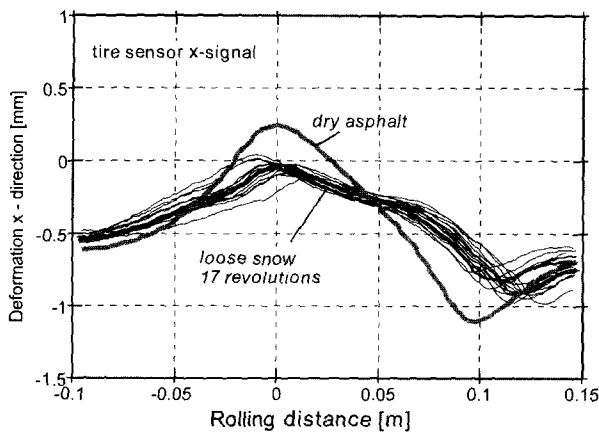


Figure 2. Tire sensor signals of a free-running wheel, variation of the road surface (Bachmann, 1999).

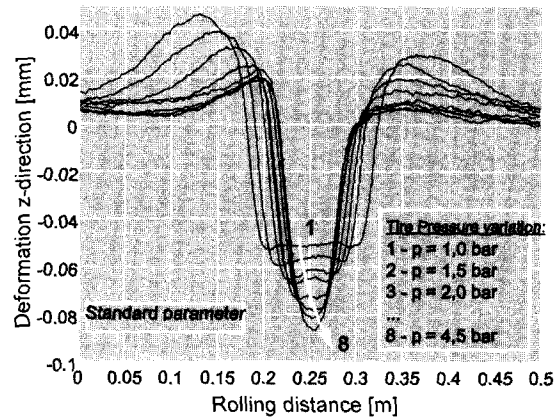


Figure 3. Tire sensor signals of a free-running wheel, variation of the tire pressure.

area and increases surface pressing. This factor not only enables definition of the tire pressure at known load but also checking of the correct pressure for actual wheel load at any time. Figure 3 illustrates definition of internal tire pressure on the basis of z-signals.

Indexes for the remaining parameters are calculated in the same way. These values may be used for immediate warning of the driver and be transmitted to host systems for intervention into the vehicle which helps to increase driving safety and economic viability.

### 3. INTERACTION BETWEEN TIRE AND ROAD DURING BRAKING

The interaction between tire and road is decisive for the forces available to the vehicle. Interaction is influenced by many factors such as, for instance, road surface, characteristics of rubber, wheel position, driving operation, environment (temperature, wetness) etc. The tread elements are deformed by the effects of road surface and flat spotting of the tire to produce the friction-coefficient on braking. Deformation of the tread element exactly describes the results of such interaction. The road surface is stochastic and therefore interaction is highly dynamic and complex. Until today, the dynamical process between tire and road can be simulated only approximately which is due to a lack of experiments and measuring tools. The Darmstadt tire sensor is the first one to enable the measurement of tread element deformation in the rotating tire on real roads by installation of the signal-producing magnet in the tread element. The diameter of the magnet is only 2 mm which allows for the acquisition of interaction between tire and road by a sensor.

Figure 4 shows the tread element deformation in x-direction during the change of brake slip on the LINUS test stand in Darmstadt. Coarse sand paper was pasted on

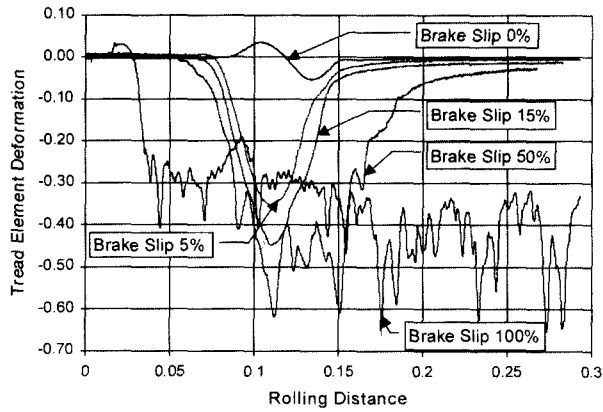


Figure 4. Tread element deformation at varied brake slip.

the track in this case. With free-running tire the tread segment is deformed opposed to the direction of rotation of the wheel in the run-in range whereas it is deformed in the direction of rotation in the coast-down range. Figure 4 shows that the tread element deformation increases with rising brake slip, *i.e.*, deformation of the tread element may be considered as a dimension of potential adhesion between tire and track. The tread segment slides with the magnet at a 100% brake slip and represents the tread element deformation in x-direction.

State-of-the-art control of ABS uses the wheel speed as input parameter to optimize the adhesion between tire and road. This information can, however, not be provided optimally by wheel speed alone because adhesion between tire and track is a complex process as already

described above. Today's ABS systems do not make optimal use of adhesion between tire and road which is due to significant braking force fluctuations. The tire sensor is directly attached to the contact point and delivers raw data of the interaction between tire and track. It may be used as a control input in the case of ABS brakes.

#### 4. ELECTRIC DISC BRAKE

Brake-by-Wire systems ease wheel-selective brake intervention and therefore will be increasingly important with regard to future vehicle concepts. Electrically operated brake systems are independent from vacuum and therefore are specially suited for use in modern vehicles with optimized combustion engines or electric drives. Increased dynamic response is another feature resulting from the fact that the specific response of the vacuum booster used as a transmission member in the energy chain has a negative effect on overall control response. Connection by wire makes the man-machine interface independent from mechanical components, it enables better adjustment to man and increases active and passive safety.

Figure 5 shows a general block diagram of an electro-mechanic brake system. This modern design of brake system with maximum function potential can be realized with a strictly modular structure on uniform hardware. Doing away with hydraulic brake fluid makes the system except brake linings free from maintenance and thus environmentally friendly.

Contrary to conventional brakes with which auxiliary force is converted into hydraulic energy by additional

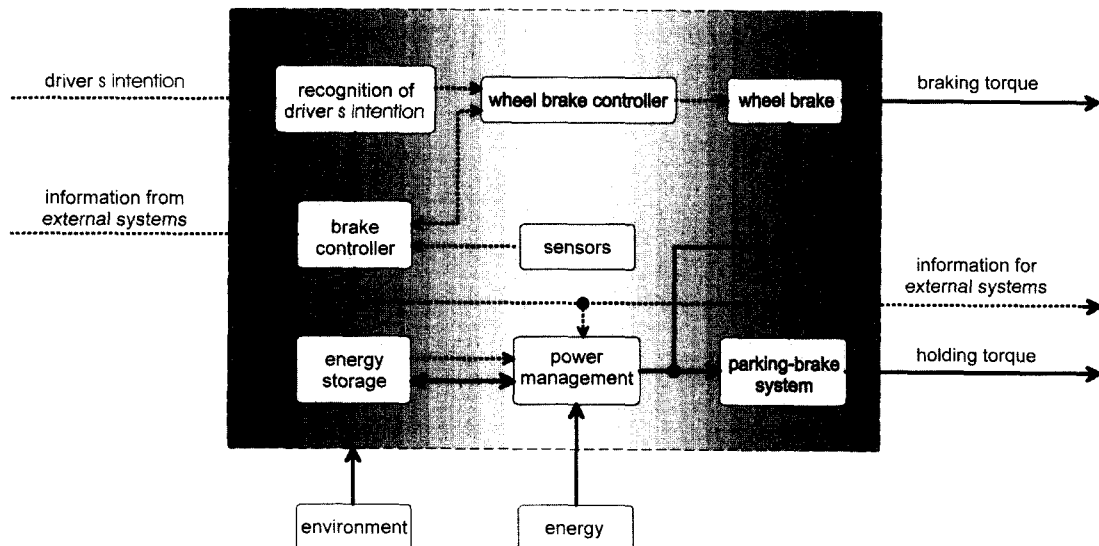


Figure 5. Electromechanic brake system.

components (vacuum brake booster) in the engine compartment, the electro-mechanical wheel brake must convert auxiliary or external energy into mechanical clamping energy at the place of installation, *i.e.* the wheel. The energy and power density of hydraulics is higher than that of electro-mechanics as a matter of principle and therefore the space requirement and weight of previous prototypes still exceed conventional hydraulic wheel brakes by far.

The efficiency of electro-mechanical converters and gearboxes of such wheel brakes is low as compared with hydraulic systems and results in a high absorption of power and energy exceeding the capability of today's vehicle electric systems. The costs of known technical solutions based on high-quality components are unacceptable for future use in serial production. Further investigation is also required with regard to a change from auxiliary brake systems to external power braking systems and their integration into the vehicle together with other subsystems and failsafeness.

The technical approach made by the Automotive Engineering Department (fzd) in sectional project B6 is based upon the use of kinetic energy for clamping the wheel brake similar to drum brakes. Brake factor  $C^*$  is increased by means of a self-reinforcing key mechanism. This principle used in connection with today's possibilities of mechatronics has encouraged us to further investigate such a system and to set up a prototype brake. Modern micro controllers with loop times of a few ms enable to control either the brake clamping force or braking torque. This feature together with possible releasing the self-reinforcing lining by means of an actuator opens up new ways of using kinetic energy available in the vehicle for actuation of the brake.

The main assemblies of engine, gearbox and friction brake have a modular design. A first rotatory/rotatory conversion stage is connected at the output of the electric motor and acts on a spindle drive. The spindle transmits a

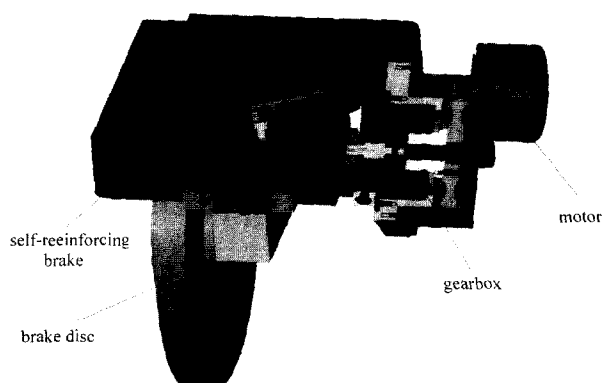


Figure 6. The brake prototype at a glance.

translatory movement and actuating force into the frictional area of the self-reinforcing disk brake with partial lining.

Figure 6 shows 3D-graphics of the realized friction brake. A floating-frame brake was realized with a self-reinforcing lining and a standard lining. The modular design of the friction brake allows to easily change the wedge of the self-reinforcing unit to vary the self-strengthening within reasonable limits. The wheel brake also includes sensors for the verification of calculated and simulated results by experiment.

## 5. SMART WHEEL SUSPENSION

Conflicts of aim with regard to safety, comfort and economic viability of suspensions can only be solved incompletely by using elastokinematics amongst others. In this case different forces acting on the wheels are used to alter the wheel position. It must be said, however, that elastokinematic measures improving the brake stability have a negative effect on comfort and running characteristics during the load changes caused by cornering. Vibrations in the area of suspension are also a problem in modern vehicles. Lowered levels accepted for vibration and noise brings this problem into the foreground on one hand but measures taken for weight reduction result in higher susceptibility to vibrations on the other hand.

The Automotive Engineering Department of Darmstadt University Of Technology therefore developed an actuator to be used as a substitute of common rubber-metal elements for connection of wheel suspensions to the chassis. The properties of the actuator with regard to stiffness, damping capacity and kinematics are variable in a wide range, *i.e.* they may be adjusted to the current driving situation. However, safety has priority over riding comfort.

Experimental investigations were made on a Hydropuls

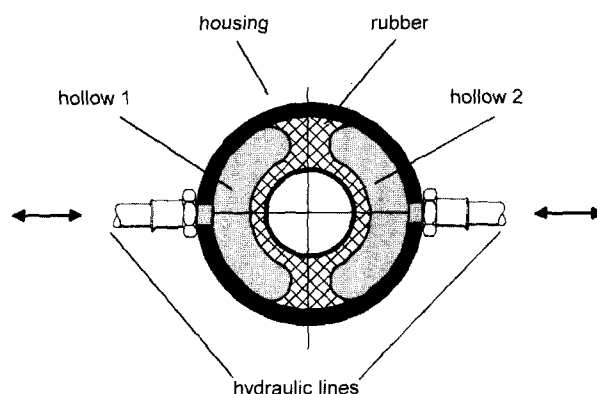


Figure 7. The adaptive bushing (schematic).

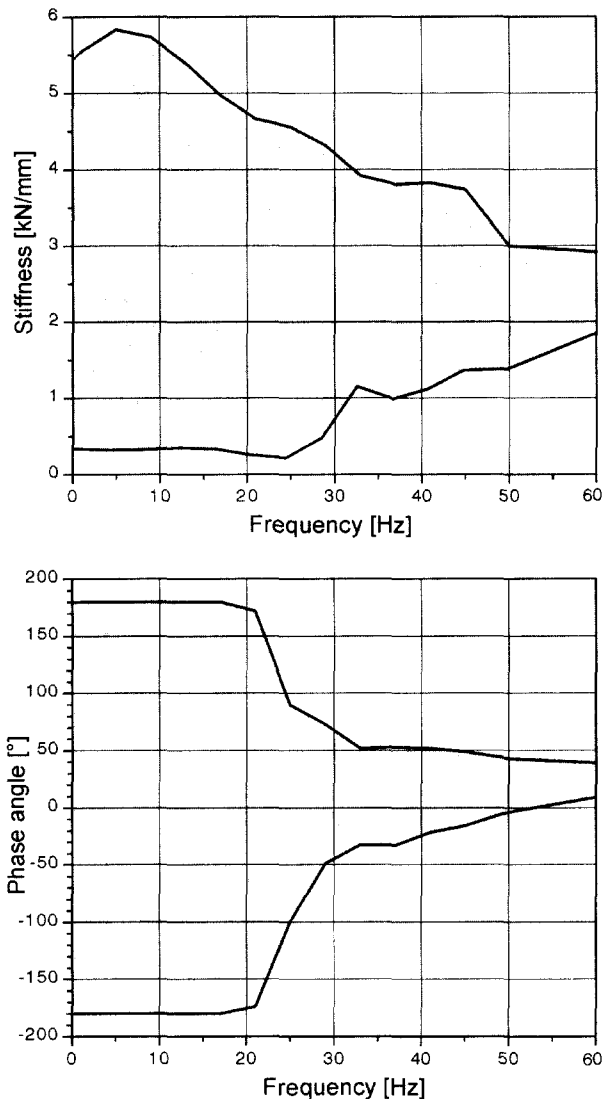


Figure 8. Operational domains of the adaptive bushing.

test stand. The actuator itself consists of a modified rubber-metal element housing two separate hydraulic chambers that can be individually loaded with a pressure medium via hydraulic connection (Figure 7). The adaptive bushing also contains connections to measure pressures inside the chambers that are transmitted as control parameters to individual pressure controllers.

The force resulting from deformation of the rubber is superposed by additional force from pressures inside the chambers if these are loaded by external pressure. The force produced by the pressure medium is calculated from chamber pressures  $p_{k1}$  and  $p_{k2}$  and the effective cross sectional area. The vector of forces created by pressurization of the chambers in addition to rubber-elastic force resulting from external sinusoidal excitation (e.g. unbalance

of wheel, brake judder) superimpose one another. Amplitude and phase relation of the resulting total force and thus dynamic stiffness and loss angle or damping characteristics of the bearing can be modified in wide ranges in case of a sinusoidal differential pressure curve with equal frequency. Uneven filling of the chambers may be used to create kinematic effects in the form of wheel position changes for direct, comfortable and adequate modification of running characteristics.

Rubber-elastic force is very low at low excitation amplitudes that are predominant during normal driving operation. The force that can be produced by different pressures between the two chambers is higher by many times over. Bearing properties at small excitation amplitudes are therefore mainly defined by internal chamber pressures. Shifting of the phase relation between path and differential pressure has immediate effect on the phase of resulting overall force and thus to the phase angle defining the damping which is due to the predominance of pressure. The phase angle can therefore be set within wide limits (Figure 8 below).

The max. dynamical stiffness achievable by the actuator is reduced versus frequency as the amplitudes of differential pressure reachable in the chambers diminish at higher frequencies which is due to the applied hydraulic power pack. In case of frequencies up to approx. 20 Hz the differential pressure inside the chambers is high enough to enable setting of the phase angle over the entire range of  $-180^\circ$  up to  $+180^\circ$ . The ratio of differential pressure force and rubber-elastic force decreases with rising frequency and thus the setting range of the loss angle is reduced accordingly. There is, however, a certain interdependence of dynamic stiffness and set phase angle.

## 6. MECHATRONIC VEHICLE CORNER

The three subsystems introduced before work autonomously at first. Networking to enable exchange of data, communication and interaction between these components results in benefits unreached by conventional systems (Figure 9).

Measuring data includes, amongst others, the tire sensor signals, hydraulic pressure inside the rubber bearing chambers, bearing deflection and acceleration, braking torque, brake lining path, wheel speed, brake tightening force, brake disk temperature and power absorption of the brake. These parameters are first processed and prepared in each individual subsystem, *i.e.*, indexes are calculated for data exchange. The indexes are then transmitted to the master controller via a suitable communication interface. The master controller recognizes the current driving situation and the driver's intention from the data delivered and acts according to the

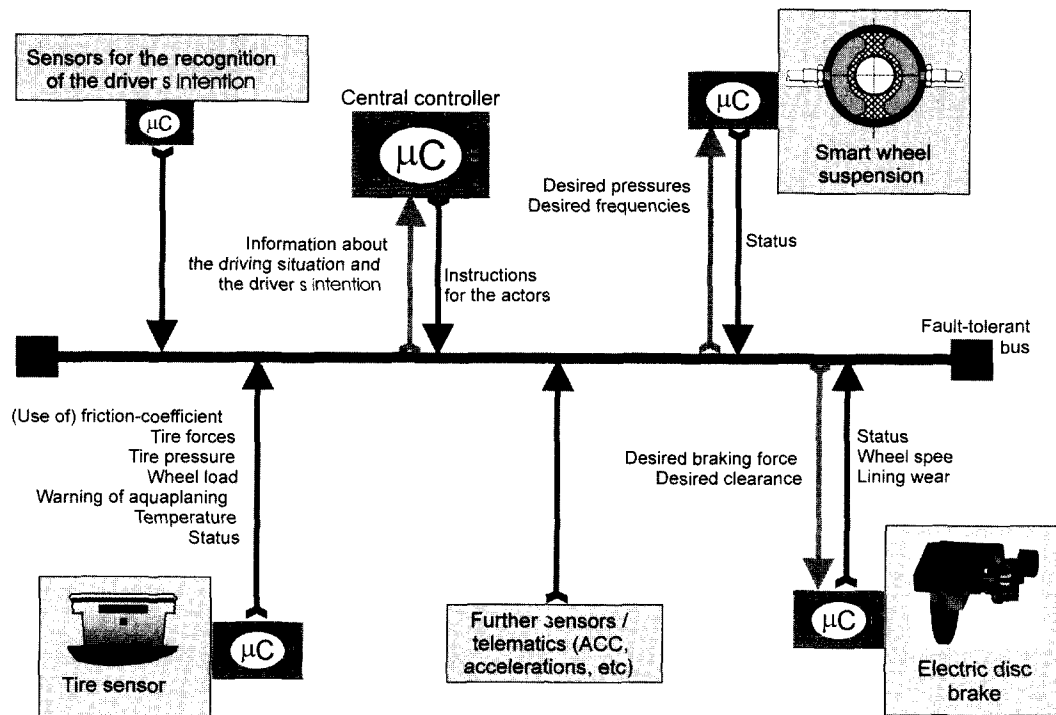


Figure 9. Integration of several vehicle components.

programmed strategies and priorities. Control commands in the form of demand values are then transmitted via the interface to autonomous subsystems for execution.

The Automotive Engineering Department (fzd) has chosen the CAN bus as a communication interface between the subsystems to enable access to information provided by other systems in the vehicle such as yaw rate, longitudinal and transversal acceleration etc. The driver's intention is recognized by means of additional sensors. Prior consideration of trends of measured data enables judgement of the operator's driving style, *i.e.* sporty or comfortable and corresponding setting of the controller.

The majority of indexes made available to the controller is calculated by the tire sensor subsystem. Input information includes statements about the current adhesion between tire and road and use of potential adhesion in addition to tread forces as well as information about wetness of the road, respectively risk of aquaplaning and internal tire pressure. Parameters of the running gear are bearing stiffness, required kinematic effect at the wheel suspension or compensation of miscomforts such as steering wheel vibrations

Example 1: "Full braking on a straightline road"

Elastokinematics as mentioned above is mostly realized by passive rubber-metal elements at present. The driver

who recognizes a dangerous situation requiring full braking, will move his foot from the accelerator to the brake pedal and press it down vigorously. Optical acquisition of this motion or measurement of the pedal path or acceleration initiates an approach of the brake lining to the brake disk and setting of reduced clearance so that the braking effect will be reached faster when actuating the brake later on. The effect of braking effort on the vehicle is also delayed by the resulting elasto-kinematic deformations. Braking is faster if the rubber bearings are hydraulically pretensioned by external hydraulic pressure in parallel with a reduction of the clearance. This also helps reduction of undesired elasto-kinematic effects by increased bearing stiffness and improvement of toe stability. It is even possible to create desired elastokinematic effects such as toe-out on the left-hand and toe-in on the right-hand side. This effect is therefore much higher than with passive elastokinematics which excludes a waste of adhesion potential. Finally it is possible to measure the current max. admissible braking force by the brake system as the tire sensor supplies information about active adhesion and available adhesion potential. An iteration loop used by today's ABS systems to prevent wheel lock is therefore not necessary. Brake judder can be actively damped during the braking procedure. It is possible in addition to shift natural frequencies into currently unexcited ranges just by altering

the stiffness.

#### Example 2: "Braking during cornering"

Load changes during cornering cause a transfer of weight especially to the outer wheel of the front axle related to occurring engine braking torque or forces which finally results in a change of wheel loads and tread forces. The cornering force applied to the wheel must be kept which changes the slip angle and leads to oversteering. Loading of the vehicle adds to this effect. Adhesion potential may also be affected by cornering forces resulting from tensioning as experienced in the case of conventional elastokinematics. This effect can be remedied by active rubber bearings helping to optimize the natural steering characteristics of the vehicle by improved kinematic compensation also with respect to best possible exploitation of the adhesion on all wheels.

#### Example 3: "Side wind"

Sudden side wind acting on the vehicle resulting in deviation from the course intended by the driver normally requires compensation by steering action. Recognition of these additional side forces by means of the tire sensor can be used for minor changes of the toe angle through active bearing control and thus for the correction of steering without driver intervention.

## 7. CONCLUSION AND OUTLOOK

The hardware installation of the mechatronic vehicle corner destined for combined research and demonstration of the interaction of the three subsystems is scheduled for the middle of year 2001 and such cooperation is sponsored by project SFB 241 of Deutsche Forschungs-Gemeinschaft.

An integrated control strategy based on known operating parameters of the involved subsystems will result in the following benefits:

- Reduction of braking path in case of emergency braking achieved through more dynamic gripping of the brakes with already stiffened running gear to a known coefficient of friction at known wheel loads and optimal exploitation of friction on all four wheels,
- Stability of toe at braking especially during cornering through knowledge about braking forces, cornering forces and wheel loads,
- Driver alarm at low coefficient of friction and risk of aquaplaning,
- Countersteering by active bearing kinematics in case of  $\mu$ -split conditions,
- Communication with traffic routing systems: Warning to others/information about bad conditions on the travelled route,
- Improvement of vehicle controls on the basis of known



Figure 10. The test bench for the Darmstadt mechatronic vehicle corner.

- active forces (wheel load, braking and side forces),
  - Improvement of safety by pressure control/adjustment to current load on the vehicle,
  - Correction of faults (load, side wind, crossfall of road),
  - Increase of comfort during "normal operation" owing to "softer" adjustment of the vehicle than was allowed by previous compromise,
  - Recognition of brake squeal and judder and prevention by control of the electric wheel brake and adaptive chassis bearing,
  - Increase of economic viability by adjustment of even wear of all linings in case of smooth braking action.
- Adjustment of the chassis for favourable rolling resistance and little tire wear during straight driving.

**ACKNOWLEDGEMENTS**—We would like to thank Deutsche Forschungs-Gemeinschaft for sponsoring the three sectional projects in SFB 241 and many German companies who made material contributions to our work.

## REFERENCES

- Bachmann, V. (1998). Untersuchungen zum Einsatz von Reifensensoren im PKW-Reifen. *Fortschritt-Berichte VDI*, **12**, **381**, VDI Verlag Düsseldorf.
- Bachmann, V., Fach, M. and Breuer, B. (1998). Future car-tires as provider of information for vehicle systems to enhance primary safety. *SAE Paper No. 981944*, Future Transportation Technology Conference, Costa Mesa, USA.
- Bill, K. H. (1992). Grundsatzuntersuchungen zum Einsatz elektrischer Radbremsen in Personenkraftfahrzeugen. *Fortschritt-Berichte VDI*, **12**, **166**, VDI Verlag Düsseldorf.
- Bill, K. H. (1998). Neue Ansätze zur Untersuchung der Schnittstelle Fahrer/Bremspedal unter realen Fahrbedingungen. *GfA-Herbstkonferenz*, 7.-9.10.1998, in Mensch-

- Maschine-Schnittstellen. Methoden, Ergebnisse und Weiterentwicklungen arbeitswissenschaftlicher Forschungen, Kurt Landau (Hrsg.).* IfAO Institut für Arbeitsorganisation, Stuttgart.
- Bill, K. H., Leber, M., Becker, H. and Breuer, B. (1992). Forschungswerkzeug zur Untersuchung der Schnittstelle Fahrer/Bremspedal, **101, 2**.
- Huinink, H. and Schröder, C. (1999). Dynamische interaktion bremse – reifen – straße. XVIII. Internationales  $\mu$ -Symposium. *Fortschritt-Berichte VDI* **12, 373**, VDI Verlag Düsseldorf.
- Nikitsch, F. (1992). Bremswege bei verschiedenen kombinationen reifen/fahrbahn mit und ohne automatischen blockierverhinderer. *Zeitschrift für Verkehrssicherheit* **38**.
- Roth, J. (1993). Untersuchungen zur kraftübertragung zwischen pkw-reifen und fahrbahn unter besonderer berücksichtigung der kraftschlußerkennung am rotierenden rad. *Fortschritt-Berichte VDI*, **12, 195**, VDI Verlag Düsseldorf.
- Semsch, M. (1999). Neuartige mechatronische teilbelagscheibenbremse. *XIX. Internationales  $\mu$ -Symposium, Bremsen-Fachtagung Bad Neuenahr*.
- Stöcker, J., Kirschbaum, A., Aller, K., Breuer, B., Glesner, M. and Hartnagel, H.-L. (1995). Der “Intelligente Reifen” – erste ergebnisse einer interdisziplinären forschungs-kooperation. **97, 12**.
- Wick, A. (1986). Ermittlung dynamischer kennwerte an Gummi-Metall-Elementen. **88, 4**.