15th Triennial World Congress, Barcelona, Spain

ESTIMATION OF VEHICLE VELOCITY USING BRAKE-BY-WIRE ACTUATORS

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Abstract: This paper describes an approach of how to estimate the vehicle velocity using additional sensors provided by the brake-by-wire actuators. The advantage of brake-by-wire actuators - such as the electro-hydraulic (EHB) and the electro-mechanical brake (EMB) - is that the caliper pressure or the clamping force, respectively, are known. Wheel speed, vehicle acceleration, and caliper pressure or clamping force, respectively, are used to estimate the vehicle velocity using a fuzzy approach. Besides, the mass of the vehicle and the slope of the road are derived from the sensors provided. Finally, it will be shown by measurement results that the velocity of a research vehicle equipped with brake-by-wire actuators and a new ABS approach can be estimated very precisely even at very high wheel slips and different road conditions.

Keywords: antilock braking systems, brakes, fuzzy systems, vehicle, velocity measurements

1. INTRODUCTION

The objective of Antilock Braking Systems (ABS) is to increase the safety of a vehicle in emergency braking situations. This is accomplished by maintaining steerability and stability of the vehicle as well as reducing braking distance by keeping the wheel at an optimum brake slip.

Current ABS controllers are based on a combination of wheel slip and wheel acceleration control in order to prevent wheels from locking. The input signals provided to the system are the wheel speeds, in case of four-wheel driven vehicles maybe also a longitudinal acceleration sensor. Output signals are valve switching pulses which increase, hold or decrease the caliper pressure. Different velocity estimation algorithms were already introduced for these conventional ABS systems, e.g. Würtenberger (1997), Daiss (1996).

An ideal Antilock Braking System (ABS) is able to keep the slip of the wheels at a point of maximum vehicle deceleration which leads to a minimum braking distance. The function which shows the relation between wheel slip λ and road friction coefficient μ is called *m*-*l* curve. The shape of this curve is defined by many factors, e.g. tire, surface, load, temperature etc. The curve itself is divided in stable and unstable areas in respect to the wheel slip control.

Continental Teves and the Institute of Automatic Control are currently developing a new generation of ABS for brake-by-wire actuators (Semmler, *et al*., 2002). This ABS is capable of keeping the wheel at any desired slip with high accuracy - whether in stable or unstable areas of the *m*-*l* curve. In order to control the wheel slip, it is necessary to have a good estimation of the vehicle velocity. In the following, a fuzzy approach is described which is able to provide a good estimation of the vehicle velocity including the clamping force/caliper pressure as additional information in order to increase the accuracy of the velocity estimation.

2. DESCRIPTION OF THE BRAKE BY WIRE SYSTEM

The brake-by-wire systems used for this research were developed by Continental Teves AG & Co. oHG. A detailed description of the systems can be found in Schwarz (1998) and Stölzl (2000).

2.1 Electro-Hydraulic Brake (EHB)

The hydraulic connection between brake pedal and brake calipers is separated in EHB systems. An electronic pedal module with pedal feel simulator and electronic sensor pickup replaces the classic brake actuation. Module signals are transmitted "by wire" to a hydraulic unit with an integrated electronic control unit (ECU). The wheel brakes are still conventional, but, the EHB implements all brake and stability functions. The EHB is quiet, comfortable, and compact (Continental Teves, 2000a).

2.2 Electro-Mechanical Brake (EMB)

EMB represents a step towards the pure x-by-wire technique. Electromechanical wheel brake modules (Fig. 1) generate brake forces directly at the wheels. The brakes are controlled by an ECU and actuated by an electronic pedal module (Fig. 2) that may contain an accelerator and its own ECU. No more brake fluids or hydraulic circuits are required. The EMB implements all brake and stability functions, and is virtually noise-free even in ABS mode. An electrical parking brake can easily be integrated (Continental Teves, 2000a).

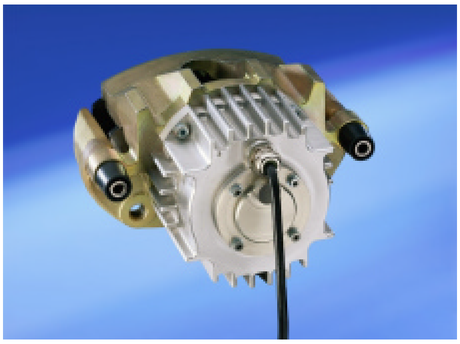

Fig. 1. Electro-mechanical brake (Continental Teves, 2000b)

Fig. 2. Pedal Unit of the EMB (Continental Teves, 2000b)

3. DATA EVALUATION

In order to estimate the vehicle velocity, the research vehicles are equipped with the following sensors:

- four wheel speed sensors
- four brake circuit pressure sensors (EHB), four clamping force sensors (EMB)
- longitudinal and lateral acceleration sensors
- yaw rate sensor
- steering wheel angle

In the following, the processing of the sensor signals is explained.

3.1 Wheel speed sensor

When the longitudinal forces that are acting on the vehicle are very small in comparison to the maximum force which can be applied to the vehicle, the wheel slip is small. In this case, the wheel speed sensors provide reliable information concerning the actual vehicle velocity. Only during cornering, a correction term has to be considered which compensates for the different wheel speeds in curves.

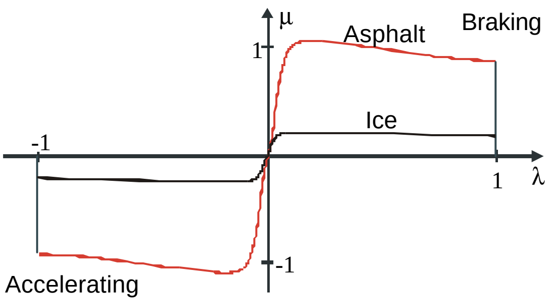

Fig. 3. Two typical μ-λ-curves

Two typical m-l curves are given in Fig. 3 which relates the wheel slip to the road friction coefficient.

The wheel speed during cornering is generally expressed as

$$\underline{v}_F = \underline{v} + \underline{w}\cdot\underline{r} = \underline{v} + \dot{\Psi}\cdot\begin{pmatrix} b \\ l \end{pmatrix} \quad (1)$$

The vehicle velocity $\underline{v}$ at the center of gravity is given by

$$\underline{v} = v(t)\cdot\begin{pmatrix}\cos(b(t))\\ \sin(b(t))\end{pmatrix} \quad (2)$$

Since the side slip angle b is considered to be very small, i.e. $sin(b(t))\approx b$ and $cos(b(t))\approx 1$, Eqn. 1 can be simplified as

$$\begin{aligned} v_{FFL} &= v - \dot{\Psi}\cdot(b_{FL} - l_F\cdot b) \\ v_{FFR} &= v + \dot{\Psi}\cdot(b_{FR} + l_F\cdot b) \\ v_{FHL} &= v - \dot{\Psi}\cdot(b_{RL} + l_R\cdot b) \\ v_{FHR} &= v + \dot{\Psi}\cdot(b_{RR} - l_R\cdot b) \end{aligned} \quad (3)$$

The wheel speed transformed into the center of gravity of the vehicle is hereby defined as

$$v = v_{**} \pm \dot{\Psi}\cdot(b_{**}\cdot\cos b \mp l_*\sin b)) \quad (4)$$

where b stands for the side slip angle. Since the longitudinal wheel speed of the contact area is measured, the tire side slip angle a_{**} has to be taken into account. This leads to

$$v_{R,K,**} = \frac{v_{R,**}}{\cos a_{**}} \pm \dot{\Psi}\cdot(b_{**}\cdot\cos b \mp l_*\sin b)) \quad (5)$$

When the wheel slip increases, the wheel speed is not allowed to be used for a reliable estimation of the vehicle velocity.

3.2 Acceleration sensor

The measurement signal of the acceleration sensors (a_x, a_y) is noisy due to vibrations of the vehicle. For example, the movement of the axes during braking and the movable parts of the internal combustion engine disturb the sensor signal. Especially due to influences of the axes, the sensor signals are filtered as follows

$$H(z) = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{b_0 + b_1 z^{-1} + b_2 z^{-2}} \quad (6)$$

The coefficients a_i and b_i are calculated according to a bessel filter with a cut-off-frequency of 7 Hz.

Also roll and pitch angle have an effect on the acceleration sensor as well as the road slope. These effects have to be compensated for.

$$\begin{pmatrix} a_{x,k} \\ a_{y,k} \end{pmatrix} = \begin{pmatrix} a_{x,F} \\ a_{y,F} \end{pmatrix} - g\cdot\begin{pmatrix} -\sin(c)\cdot\cos(j) \\ \sin(j)\cdot\cos(c) \end{pmatrix} \quad (7)$$

In this case, $a_{*,F}$ stands for the filtered acceleration, influences of roll c and pitch j are compensated for in $a_{*,k}$. The acceleration in longitudinal direction of the vehicle based on the acceleration sensor is given below.

$$\dot{v}_a = a_{x,k}\cdot\cos(b) + a_{y,k}\cdot\sin(b) - a_{Road} \quad (8)$$

Therefore, this part of the system can be described as follows

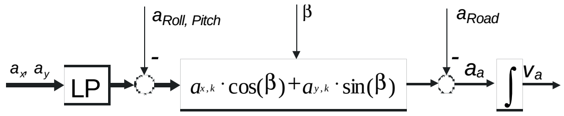

Fig. 4. Evaluation of the acceleration sensor signal including a low-pass filter (LP) and corrections for roll, pitch and road slope

3.3 Clamping force/brake circuit pressure sensor

To calculate the longitudinal force $F_{R,x}$ on a wheel, the torque provided by the engine and the brakes as well as the inertia of the wheel J_R have to be taken into account. Fig. 5 illustrates forces and torques acting on the wheel.

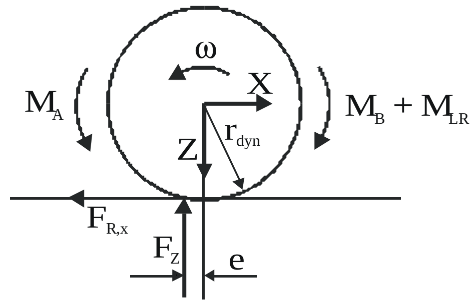

Fig. 5. Forces and torques acting on the wheel

M_A, M_B and M_{LR} stand for torques due to acceleration, braking and bearing friction/stiction, r_{dyn} is the dynamic wheel radius, and e is the lever arm of the normal force F_Z.

The longitudinal force of the wheel $F_{R,x}$ in the inertial system of the wheel is therefore given by

$$F_{R,x} = \frac{M_A - M_B - M_{LR} - J_R\cdot\dot{w}}{r_{dyn}} - F_Z\cdot\frac{e}{r_{dyn}} \quad (9)$$

with

$$M_B = r_B\cdot C^*\cdot F_{Sp} = r_B\cdot C^*\cdot A_{Pist}\cdot p_{Calp} \quad (10)$$

The braking torque M_B is dependent on the radius of the disc brake r_B, friction coefficient C^* between disc brake and brake lining, and clamping force F_{Sp} (EMB) which is the product of brake circuit pressure p_{Calp} and brake piston surface A_{Pist}.

In order to estimate the vehicle velocity based on the clamping force, a series of additional forces acting on the have to be considered.

Therefore, the air and wheel resistances as well as the disturbance due to the slope of the road are examined in the following.

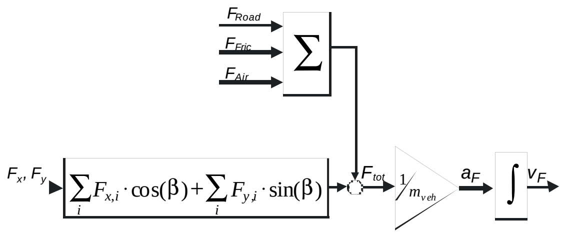

Fig. 6. Evaluation of the clamping force/brake circuit pressure sensor signal

4. DISTURBANCES

Besides the forces transmitted by the wheels, the air and rolling resistances and the slope of the road also have to be taken into account. A detailed explanation can be found in Mitschke (1995).

4.1 Wheel resistance

The rolling resistance occurs due to deformations of the wheel and the road. It is characterized by the rolling resistance value f_R. The value changes depending on the vehicle velocity.

$$f_R = f_{R,0} + f_{R,1} \cdot v + f_{R,4} \cdot v^4 \tag{12}$$

The force due to the wheel resistance is

$$F_{Fric} = F_z \cdot f_R \tag{13}$$

Typical values for f_R are between 0.013 and 0.15.

4.2 Air resistance

The force which is caused by the air resistance is applied in the opposite direction of the driving direction.

$$F_{Air} = \frac{r_L}{2} \cdot c_W \cdot A \cdot v^2 \tag{14}$$

Hereby, $c_W \cdot A$ describes the aerodynamic behavior of the vehicle. A typical value is around 0.5m^2.

4.3 Road slope

Besides the rolling and air resistance, the slope of the road is also relevant. The force can be calculated by using the road slope a_{Road}, the mass m of the vehicle and the gravity constant g. The slope is estimated by comparing the wheel speed and vehicle acceleration in case of non-braking. In case of a braking maneuver, both acceleration and clamping force/brake circuit sensors are compared which is not subject of this paper.

$$F_{Road} = m \cdot g \cdot \sin(a_{Road}) \tag{15}$$

5. FUZZY SYSTEM

Depending on the driving situation, the quality of the velocities provided to the fuzzy system differs enormously. Therefore, a weighted average is used whereby the weights k_R, k_a and k_F are changed depending on the driving situation.

$$v_{Fuz} = \frac{k_R \cdot \frac{1}{4}\sum_{i=1}^{4} v_{R,K,i} + k_a \cdot v_a + k_F \cdot v_F}{\sum_{i=1}^{3} k_i} \tag{16}$$

The fuzzy estimator uses five input signals in order to calculate the vehicle velocity. These inputs are:

- lowest out of four wheel slips l_i (using the estimated vehicle velocity and the wheel speed)
- absolute value of the calculated wheel acceleration $\dot{w}$ of the wheel with the lowest slip
- longitudinal acceleration a_a provided by the acceleration sensor signals a_x and a_y
- calculated acceleration a_F based on the clamping force/caliper pressure sensors
- absolute value of the side slip angle b calculated by a nonlinear observer (not subject of this paper)

The output of the system are the values of the three weights k_R, k_a and k_F. The wheel slip in case of braking is calculated using Eqn. 17.

$$l_B = \frac{v - v_R}{v} \tag{17}$$

The weights are now calculated according to the five fuzzy inputs mentioned above.

E.g. if the driver does not accelerate and brake, the estimated l is very low, $\dot{w}$ is close to zero, the acceleration a_a (provided by acceleration sensor) and a_F (provided by clamping force sensor) are very small. This results in k_a and k_F close or even equal to zero.

In case of maximum braking, l is high, the absolute value of $\dot{w}$ is high, the acceleration a_a (provided by acceleration sensor) and a_F (provided by clamping force sensor) are also high. This results in a high k_a and k_F and a very low k_R.

It is now assumed that the system has a good estimate v_{Fuz} of the vehicle velocity at the time t. The acceleration based on clamping force sensors and acceleration sensors is now used to calculate the vehicle velocity for $t+T_A$ where T_A stands for the sampling rate of the system using an Euler integration.

$$\begin{aligned} v_a(k) &= v_a(k-1) + T_A \cdot v_{Fuz}(k-1) \\ v_F(k) &= v_F(k-1) + T_A \cdot v_{Fuz}(k-1) \end{aligned} \tag{18}$$

After correcting the wheel speeds according to Eqn. 5, the maximum wheel speed v_R is taken as a third estimate of the vehicle velocity.

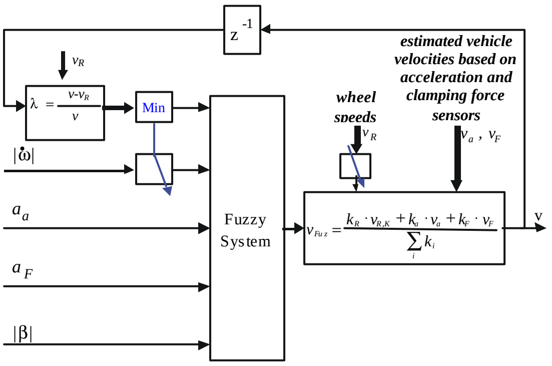

Fig. 7. Inputs and outputs of the fuzzy system

The resulting fuzzy system is given by Fig. 7. The inputs of the fuzzy system can be seen on the left side of the figure. The maximum wheel velocity and the estimated velocities based on the acceleration and clamping force/caliper pressure sensors are denominated as v_R, v_a and v_F.

Table 1. Fuzzy rules (extract)

l	a_F	a_a	k_R	k_F	k_a	explanation
-- -	--	-- -	min	max	max	max. braking
-- -	-	-- -	min	max	max	low braking
+	--	--	med	max	max	free wheel/ABS
0 +	0	0 -	max	min	med	no braking
0 +	0	0	max	min	med	no braking
+	0	+	med	min	med	accelerating
-- -	*0*	*--*	*min*	*min*	*max*	*error occured*

The input membership functions used for this fuzzy system are shown in Fig. 9. The position of the curves are based on a gradient optimization algorithm. The most important fuzzy rules for the inference are given below. Looking at the last rule, the large difference between a_F and a_a can either be caused by a sensor error or by an inaccurate road slope estimation The output membership functions are shown in Fig. 8.

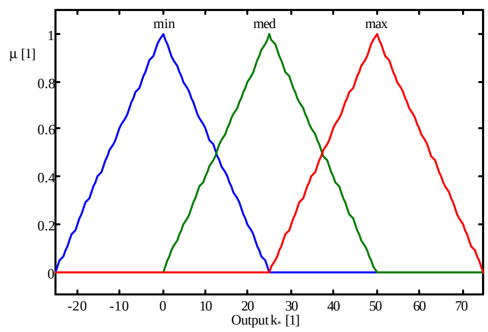

Fig. 8. Output membership functions

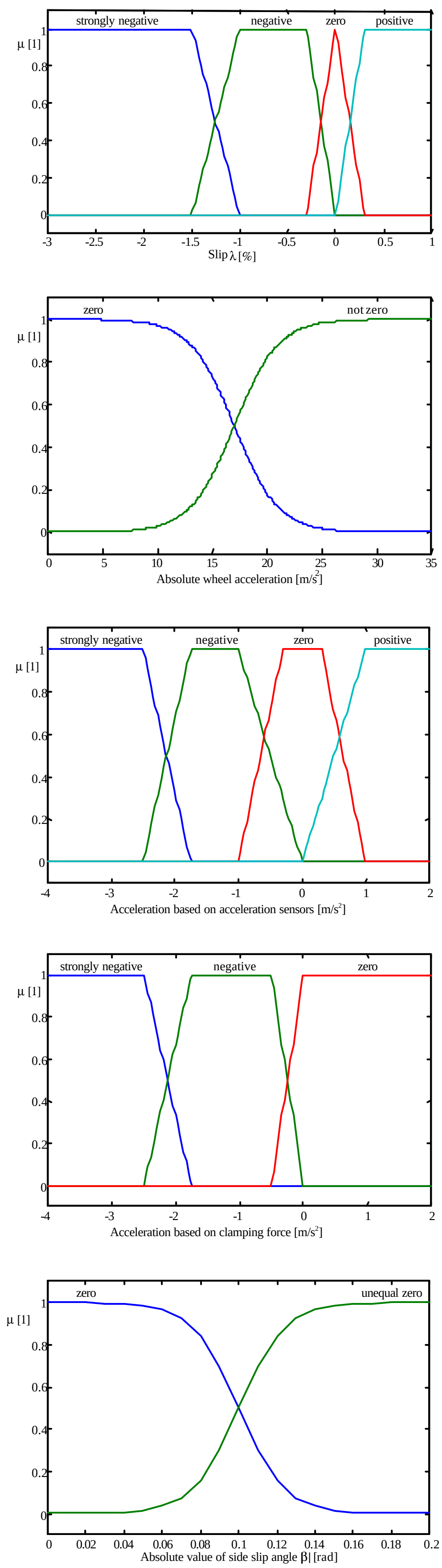

Fig. 9. Input membership functions

6. MEASUREMENT RESULTS

The measurements shown in the following are realized with a BMW E46 research vehicle equipped with electro-mechanical brakes (EMB). All wheels are in ABS mode. The slip controller which was used in this context is explained in (Semmler, *et al*., 2002).

Fig. 10 and 11 show a braking maneuver on ice changing to asphalt conducted at the Continental Teves Test Center Arvidsjaur, Sweden. The control parameters of the ABS were chosen such that the slip increases above 50% (at t=0.25s) in order to evaluate the behavior of the velocity estimation under extreme conditions. At t=1s, the ground surface changes from ice to asphalt.

Fig. 10 shows six different velocities: four wheel speeds, the absolute velocity of the vehicle (black line) measured by a correvit sensor which is based on optical correlation, and the estimated velocity of the fuzzy system (grey line). Due to a very precise estimation, both estimated and true vehicle velocity correlate very well.

As seen before, the weights of the three velocities provided by wheel speed sensors, acceleration sensors and clamping force sensors depend on the estimated wheel slip and wheel acceleration as well as on the acceleration of the vehicle (Fig. 11).

The absolute error is plotted in Fig. 12. The accuracy of the fuzzy velocity estimation algorithm is very high. It should be noted that the accuracy of the velocity estimation in case of braking mainly depends on the duration of braking and not on the road conditions itself since two integrators are used for the velocity estimation.

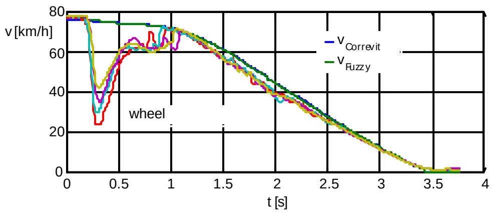

Fig. 10. Wheel speeds, estimated and measured vehicle velocity

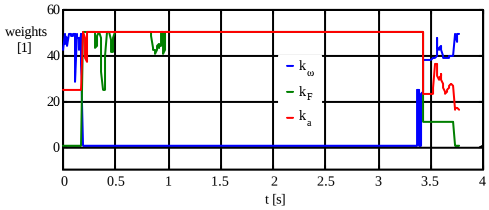

Fig. 11. Weights for inputs (wheel speed sensor, acceleration sensor, clamping force sensor)

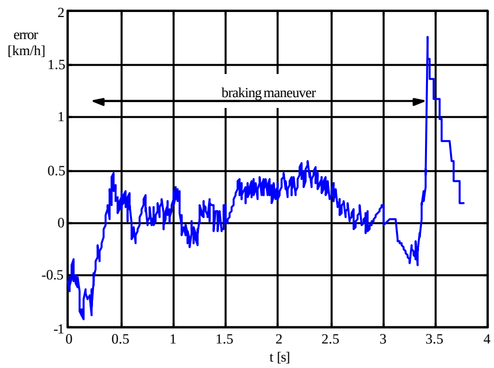

Fig. 12. Absolute error in [km/h]

7. CONCLUSION

This paper describes an approach of how to estimate the vehicle velocity using additional sensors provided by the brake-by-wire actuators. The advantage of brake-by-wire actuators - such as the electro-hydraulic (EHB) and the electro-mechanical brake (EMB) - is that the brake circuit pressure or the clamping force, respectively, is known. Wheel speed, acceleration, and clamping force were used to estimate the vehicle velocity applying a fuzzy approach. It was shown by measurement results that the velocity of the research vehicle equipped with EMB and the new ABS approach can be estimated very precisely even at very high wheel slips and different road conditions.

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