# A NEW CONCEPT FOR YAW RATE SENSOR MONITORING

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Abstract: The electronic stability program (ESP) is a dynamical driving control system that is used to support drivers in critical driving situations. An essential component integrated in the ESP-system is the well-known sensor monitoring system that is mainly applied to detect sensor faults as early as possible so that fail controls can be prevented. Improving the current monitoring system is demanded by automobile industry. In this contribution a new concept, which allows not only a fault detection on banked roads, but also a fault evaluation using statistic method, is presented. The performance of this concept is tested by car tests. *Copyright 2005 IFAC*

Keywords: automobile industry, vehicle dynamics, error analysis, threshold functions and fault detection.

## 1 INTRODUCTION

The electronic stability program (ESP) is a dynamical driving control system and meanwhile widely used in different types of series-produced vehicles. The process “car driving equipped with ESP” is described schematically in Fig. 1.

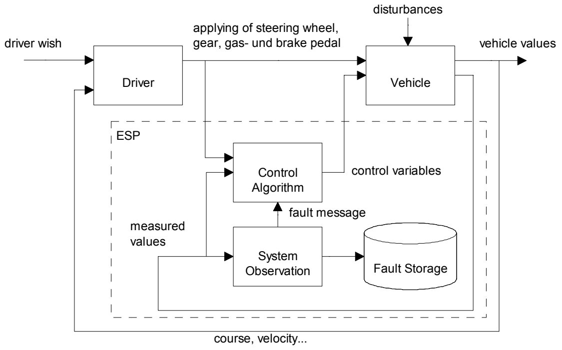

Fig. 1: Car driving equipped with ESP

The core of the dynamical driving control system is the introduction of an internal feedback control loop, which is denoted by ESP in Fig. 1. This control system supports drivers in critical driving situations, especially in case that the driver has no directly interfering possibility. The system helps, for instance, braking if the vehicle is on the road with low or varying friction values and therefore becomes uncontrollable or gets into skidding due to blocked wheels, or accelerating, where the danger of driven wheel spinning exists, it helps also steering in a bend, where the vehicle could get into over or under steering. Generally speaking, the main aim of using the ESP-systems is to improve the convenience and active safety during car driving (Ghoneim *et. al.*, 2000). The ESP-sensors are essential components of the control loop and provide the controllers with necessary information about the actual state of the vehicle dynamic system. A successful vehicle control strongly depends on the performance of the sensors. For this reason, an on-line sensor monitoring and early warning system are an essential component integrated in the ESP-system for detecting sensor faults as early as possible so that fail interventions can be prevented (Fennel and Ding, 2000).

The activation of the lateral dynamic control of ESP relies on two ESP-sensor signals, namely the yaw rate sensor signal and the lateral accelerometer signal. The lateral accelerometer is monitored by using the redundant sensor equipped in modern vehicles for the passive safety system. This lateral accelerometer monitoring delivers satisfying results (Ding and Massel, 2005). Therefore, aim of this contribution is to develop a new concept for monitoring the yaw rate sensor, which allows not only a fault detection on banked roads, but also a fault evaluation with the statistic method.

## 2 DESCRIPTION OF THE ESP-SYSTEM

The ESP-system consists of (Fennel and Ding, 2000):

- the anti-block system (ABS),
- the traction control system (TCS) and
- the yaw torque control (AYC),

where the following sensors are used:

- a yaw rate sensor,
- a lateral accelerometer,
- a steering wheel angle sensor,
- a pressure sensor and
- four wheel speed sensors.

Aiming at early detection of faults in the ESP-sensors, an on-line monitoring concept consisting of a Multi-Level-Check (MLC) is developed (Fennel and Ding, 2000). In this MLC, the following three methods are used:

- *Electrical check*: It checks, whether the sensor signals lie in their allowed working ranges.
- *Monitoring using redundant sensors*: It verifies the sensor signals at every operation point in their whole working areas, if it is allowed in respect of cost.
- *Model-based fault detection*: It verifies also the sensor signals at every operation point in their whole working areas, but on the condition that the model describes the process perfectly.

The MLC concept consists of the following levels:

- *Level I*: Supply voltages and cables of all sensors are checked by using the electrical check;
- *Level II*: A part of mounted sensors are the so-called intelligent sensors (Schneider, 1996). They have self-monitoring functions and, in case of a fault, are able to set the output signals to a value that lies out of the allowed working range. Then, the sensor fault can be detected by the electronic check;
- *Level III*: However, the false mounted or loose sensors cannot be detected by using Level I and II. Such mechanical faults can be detected only by using redundant sensors or the model-based approach.

Since the electrical check and the monitoring using redundant sensors are used as a conventional and already developed method for the sensor monitoring, the engineers working in this area focus their attention just on the development of the model-based fault detection in recent years (Frank and Ding, 1997).

## 3 PROBLEM FORMULATION

The basic idea of the model-based fault detection consists in construction of the so-called analytical redundancy using process models. On this basis one can generate residual signals. Fault detection follows by evaluating the residual signals and a logic decision (Isermann *et. al.*, 2000), (Frank and Ding, 1997). It is well known that the main difficulty of using the model-based fault detection schemes lies in the model uncertainty (Frank and Ding, 1997). This problem becomes much more serious by dealing with the sensor fault detection for the ESP-system, since the process „car driving“ is strongly influenced by many unknown factors and disturbances, which can only be partly modeled or even, in some cases, cannot be mathematically described (Ding *et. al.*, 2004). There are in principle two ways to solve this problem:

- Increasing the robustness of the detection system by using the modern robust Fault Detection and Isolation (FDI) theory (Frank and Ding, 1997), (Gertler, 1998), (Chen and Patton, 1999). Although the robust FDI theory is well established, its application to the processes with dominant model uncertainties is limited.
- Utilization of additional information. This is an active way and can be realized by
  - either improving the model, that means, on the one hand, making use of additional off-line information and on the other hand, additional on-line calculations;
  - or utilizing and processing redundant information and establishing adaptive thresholds (Frank and Ding, 1997). This is the way we follow consequently.

The essential ideas of the fault detection scheme using in series-produced vehicles (Ding *et. al.*, 2004) originated from the following facts:

- Behavior of a sensor can be described by different physical laws and using the available sensor signals from other signal sources. This means, different from the widely used model based FDI technique, where just a single model is used, a sensor behavior can be described by using a multi-model. This redundant modeling improves the performance of the fault detection;
- It is well known that an adaptive threshold is an effective way to solve the problem caused by model uncertainties (Frank and Ding, 1997). Since a number of signals are available in the ESP system, they can be used to define different driving situations (Ding *et. al.*, 2004). Based on this, monitoring thresholds, which adapt to the driving situations can be generated.

Though the monitoring system described above is already used in series-produced vehicles, there exist still some weaknesses, which can be summarized as follows:

- The adaptive thresholds are step-shaped signals. This means, that the thresholds are sometimes undesirably high, so that the monitoring system does not work effectively enough;
- Banked roads are not considered. The monitoring system cannot work there correctly. Therefore, the threshold has to be increased on banked roads, also during steady driving;

- As well-known noise is normally involved in measurement. The sensor signals used here are not excepted and even strongly affected by lots of unknown disturbances during car driving. This can lead to increase of the thresholds by the deterministic fault evaluation used in the current version of ESP. It makes the monitoring less effective, too.

To increase the efficiency and to improve the performance of the monitoring, developing a new concept is necessary. The new concept should be so designed that no limitation of physical values is needed.

## 4 MODELLING

### *4.1 Yaw rate sensor models*

Fig. 2 shows the schematic of the vehicle roll motion on a banked road,

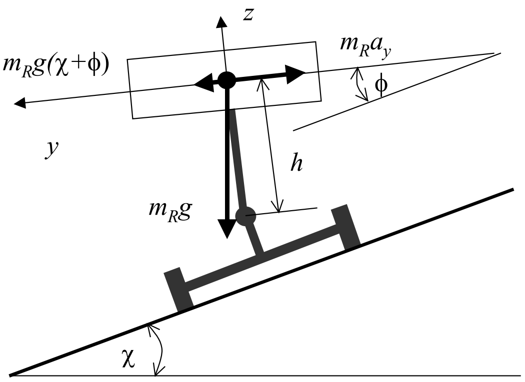

Fig. 2: Schematic of the roll motion

where:

$g$: acceleration of gravity,
$\chi$: road bank angle,
$a_y$: lateral acceleration of the vehicle body center,
$\phi$: vehicle body roll angle in relation to the road,
$m_R$: sprung mass of the vehicle,
$h$: height of the center of gravity of the vehicle body in relation to the roll axis.

Neglecting the vehicle body roll angle in relation to the road, the behavior of yaw rate sensor $\omega_{z,S}$ that measures the yaw rate in relation to the vehicle coordinate system can be reconstructed simply by using the wheel speed sensor signals in the following two ways:

$$\omega_{z,M_1} = (v_{fr} - v_{fl}) / S_f \qquad (1)$$

or

$$\omega_{z,M_2} = (v_{rr} - v_{rl}) / S_r , \qquad (2)$$

where:

$\omega_{z,M}$: yaw rate sensor signal reconstructed,
$v_{fl}$: wheel speed front left,
$v_{fr}$: wheel speed front right,
$v_{rl}$: wheel speed rear left,
$v_{rr}$: wheel speed rear right,
$S_f$: track gage front and
$S_r$: track gage rear.

From Equation ( 1 ) and ( 2 ) one can see that the both sensor models depend on the constant vehicle parameters $S_f$, $S_r$ and the four wheel speeds. These four sensor signals are permanently verified and therefore can be used as reliable signals. However, it cannot be guaranteed yet, that the both models work permanently correctly, since the wheels can get into slip on low-$\mu$ roads. In this case, the threshold for the yaw rate sensor monitoring has to be increased appropriately. This threshold will be generated by using the lateral accelerometer signal $a_{y,S}$ and the lateral accelerometer models.

### *4.2 Lateral accelerometer models*

Since not only the lateral, but also the roll dynamics are involved in the lateral acceleration measurement, the lateral accelerometer behavior $a_{y,S}$ can be formulated by the following equation:

$$a_{y,S} = a_y + g\sin(\chi + \phi) . \qquad (3)$$

In steady driving maneuvers the differentiation of the vehicle sideslip angle $\beta$ (Ryu *et al.*, 2002) can be assumed as zero. Only in this situation the lateral acceleration $a_y$ can be calculated by using the yaw rate sensor signal $\omega_{z,S}$ and the vehicle velocity $v$:

$$a_y = v(\omega_{z,S} + \dot{\beta}) \cong v\omega_{z,S} . \qquad (4)$$

Since both the roll bank angle $\chi$ and the vehicle body roll angle $\phi$ are unknown variables, one cannot use Equation ( 3 ) and ( 4 ) to monitor the lateral accelerometer signal $a_{y,S}$ on banked roads due to the missing information. To solve the modeling problem on banked roads, the relation between the signals of the three ESP-sensors, namely the yaw rate sensor, the lateral accelerometer and the steering wheel angle sensor, has been derived from the physical and mechanical basic principles on the condition that the vehicle sideslip angle should be small (Ding *et. al.*, 2002):

$$v = \frac{l \cdot \omega_{z,S}}{\frac{\delta_{L,S}}{i_L} - \frac{l \cdot a_{y,S}}{v_{ch}^2}} , \qquad (5)$$

where:

$\delta_{L,S}$: steering wheel angle sensor signal,
$i_L$: steering wheel transmission ratio,
$l$: distance between the front and rear axle and
$v_{ch}$: characteristic velocity.

The benefit of Equation ( 5 ) is, that the relation between the three ESP-sensor signals does not depend on the angles $\chi$ and $\phi$. Reforming Equation ( 5 ), the lateral accelerometer signal $a_{y,S}$ can be reconstructed in principle as follows:

$$a_{y,M} = \frac{v_{ch}^2}{l}\left(\frac{\delta_{L,S}}{i_L} - \frac{l \cdot \omega_{z,S}}{v}\right). \qquad (6)$$

Replacing $\omega_{z,S}$ in Equation ( 6 ) with Equation ( 1 ) and ( 2 ) respectively, we obtain:

$$a_{y,M_1} = \frac{v_{ch}^2}{l}\left(\frac{\delta_{L,S}}{i_L} - \frac{l}{v}\left(\frac{v_{fr} - v_{fl}}{S_f}\right)\right) \qquad (7)$$

and

$$a_{y,M_2} = \frac{v_{ch}^2}{l}\left(\frac{\delta_{L,S}}{i_L} - \frac{l}{v}\left(\frac{v_{rr} - v_{rl}}{S_r}\right)\right). \qquad (8)$$

In comparison with Equation ( 1 ) and ( 2 ), Equation ( 7 ) and ( 8 ) need additional signals, namely the steering wheel angle sensor signal and the vehicle velocity, which can be also regarded as reliable signals.

The precision of the lateral accelerometer models depends on the absolute value of the vehicle sideslip angle. To generate the threshold properly, the information on the vehicle sideslip angle should be taken into account. In (Ding *et al.*, 2002) three static models for vehicle sideslip angle estimation are derived on the assumption that driving maneuvers are steady, where banked roads are considered. For the yaw rate sensor monitoring the following static model is used:

$$\beta = \frac{l_r}{l}\frac{\delta_{L,S}}{i_L} - \left(\frac{l_f}{l}\frac{m}{C_{\alpha r}} + \frac{l_r}{v_{ch}^2}\right) a_{y,S}, \qquad (9)$$

where:

$l_f$: distance between the front axle and the center of gravity,
$l_r$: distance between the rear axle and the center of gravity,
$m$ : total mass of the vehicle,
$C_{\alpha r}$: rear cornering stiffness coefficient.

Though the static model cannot describe the vehicle sideslip angle correctly in dynamical maneuvers, the models deliver the sufficient information for adapting the threshold generated by using the lateral accelerometer signal and models.

## 5 RESIDUAL EVALUATION

As mentioned before all of the sensor signals used here are strongly affected by lots of unknown disturbances during car driving. Therefore, it is reasonable to use the statistic method to evaluate the residuals. Forming the differences between the model signals and the sensor signal of the yaw rate and calculating the effective values (root mean square) of these residuals, we obtain:

$$\left(\Delta\omega_{z,1}\right)_{eff} = \left(\omega_{z,S} - \omega_{z,M_1}\right)_{eff} \qquad (10)$$

$$\left(\Delta\omega_{z,2}\right)_{eff} = \left(\omega_{z,S} - \omega_{z,M_2}\right)_{eff} \qquad (11)$$

These effective values of the yaw rate residuals can be used for the fault evaluation described in Chapter 7.

## 6 THRESHOLD GENERATION

For monitoring the effective values of the yaw rate residuals two thresholds are needed, whose dimensions are the same as Equation ( 10 ) and ( 11 ). For this purpose we use the relation between the yaw rate and the lateral acceleration described in Equation ( 4 ):

$$\Delta\omega_z \cong \Delta a_y / v \qquad (12)$$

and calculate the following effective values:

$$\left(\Delta a_{y_1} / v\right)_{eff} = \left(\left(a_{y,S} - a_{y,M_1}\right)/v\right)_{eff}, \qquad (13)$$

$$\left(\Delta a_{y_2} / v\right)_{eff} = \left(\left(a_{y,S} - a_{y,M_2}\right)/v\right)_{eff}. \qquad (14)$$

The lateral accelerometer models do not work correctly, if the vehicle sideslip angle is large, especially on low-$\mu$ roads. Therefore, the results of Equation ( 13 ) and ( 14 ) cannot be directly used as thresholds. They have to be corrected by using the vehicle sideslip angle. From the investigation results of the car tests one can find out, that the lateral acceleration residuals are larger, if the vehicle sideslip angle is larger. So, the thresholds $TH_1$ and $TH_2$ can be generated for the two yaw rate residuals respectively as follows:

$$TH_1 = \left(\Delta a_{y_1} / v\right)_{eff} / F_{corr}, \qquad (15)$$

$$TH_2 = \left(\Delta a_{y_2} / v\right)_{eff} / F_{corr}, \qquad (16)$$

where the non-dimensional correction factor $F_{corr}$ is calculated by using the effective values of the vehicle sideslip angle in the following form:

$$F_{corr} = \max[1.5,\ (\beta/1^\circ)_{eff}]. \qquad (17)$$

## 7 FAULT PROBABILITY

The current version of the ESP-sensor monitoring delivers the controller just the information about the sensor state that means whether the sensor signal is false or not. This demands on the sensor monitoring for absolute correctness. The controller has no chance to deal, if this information is false. In this new concept, we generate a fault probability, so that the controller receives the information not only on the sensor state, but also on the monitoring or on the driving state. Using the two residuals and two thresholds (see Equations ( 10 ), ( 11 ), ( 15 ) and ( 16 )) we calculate the fault probabilities $FP_1$ and $FP_2$ respectively:

$$FP_i = \begin{cases} 0, & \text{if } x_i < 0 \\ x_i, & \text{if } 0 \le x_i \le 1 \\ 1, & \text{if } x_i > 1 \end{cases}, \quad \text{for} \quad i = 1{,}2, \qquad (18)$$

where the non-dimensional value $x_i$ is defined as follows:

$$x_i = 0.5 + \left(\left(\Delta\omega_{z,i}\right)_{eff} - TH_i\right) / \left(\Delta\omega_{z,i}\right)_{eff} .$$

Equation ( 18 ) means:

- the fault probability is about one, if the residual is much larger than the threshold;
- the fault probability is about zero, if the residual is much smaller than the threshold and
- the fault probability is equal to 0.5, if the residual is equal to the threshold;

Forming the arithmetic mean value of the both probabilities, the fault probability *FP* results:

$$FP = (FP_1 + FP_2)/2. \qquad (19)$$

This fault probability will be sent to the ESP-controller as the status information from the fault detection unit.

## 8 CAR TEST RESULTS

This new concept is tested in lots of different driving situations. From the previous experiences we know that the yaw rate sensor models as well as the lateral accelerometer models used here can almost exactly describe the vehicle behavior in steady driving maneuvers. As a matter of course there is no problem for the new concept during the steady driving. But, the challenge for this new concept is to be able to operate correctly also during extremely dynamical driving maneuvers on all road surfaces, especially on low-$\mu$ roads. For the presentation in this paper, just three driving maneuvers are selected. They are:

a) circular driving on a banked asphalt road and a step-shaped yaw rate sensor fault of 5°/s at $t = 50$ sec.,
b) handling curse on a wet asphalt road and a step-shaped yaw rate sensor fault of 40°/s at $t = 30$ sec.,
c) circular driving on ice and a step-shaped yaw rate sensor fault of 40°/s at $t = 50$ sec..

Each figure in the following contains five diagrams. The first diagram shows the vehicle velocity, while the second one contains the yaw rate sensor, the lateral accelerometer and the steer angle signal. They are used to illustrate the dynamical behavior. The third diagram presents the residual and its threshold generated by using the front wheel speeds, while the fourth one shows the results by using the rear wheel speeds. The fifth diagram illustrates the fault probability *FP*.

Fig. 3 shows the result of test a). Since the new concept considers the influence of banked roads, the

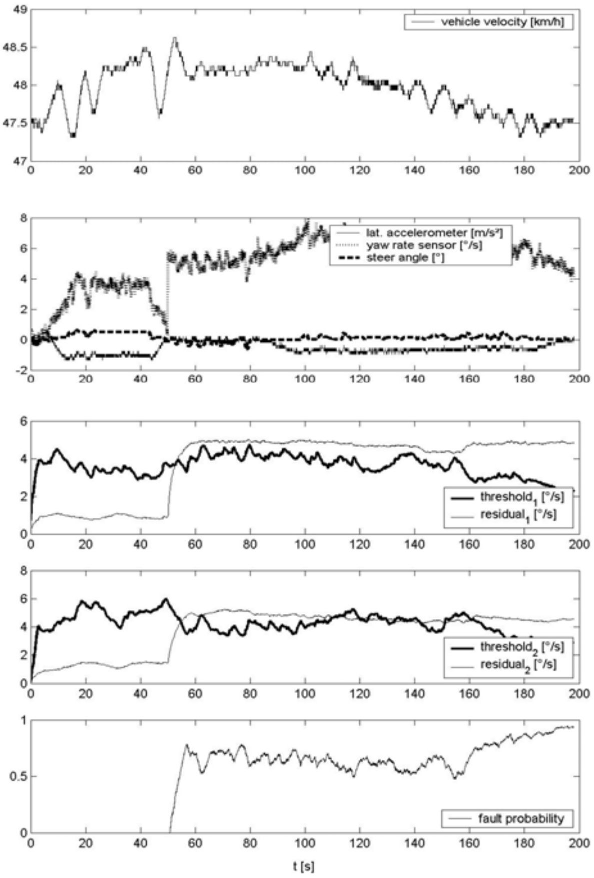

Fig. 3: Circular driving on a banked asphalt road

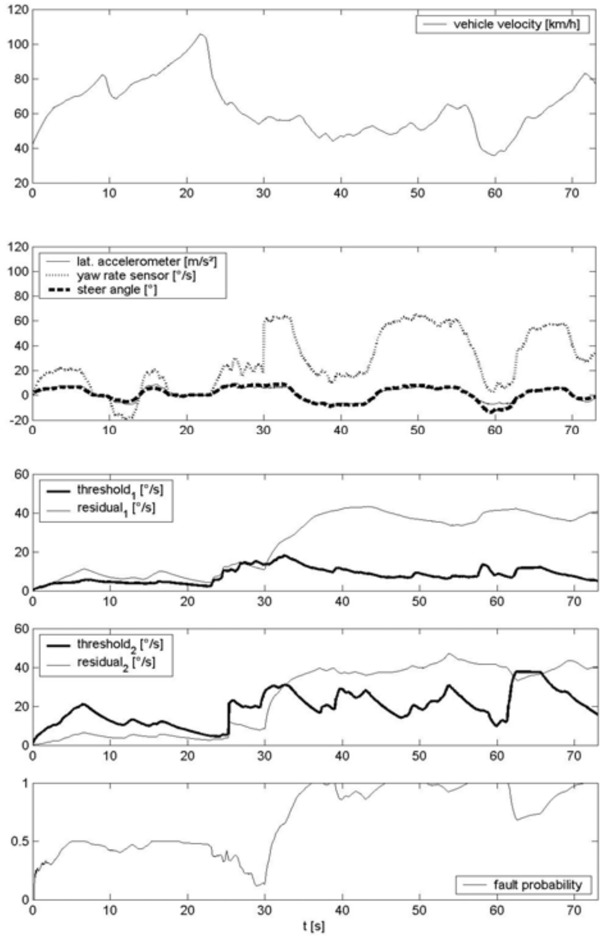

Fig. 4: Handling curse on a wet asphalt road

thresholds are smaller in comparison with the current ESP-version in the same situation. During the car test without sensor faults the residuals are very small, so that the fault probability is equal to zero. The fault probability increases to about 0.7, as soon as the yaw rate sensor fault of 5°/s occurs. One can see that such small yaw rate sensor faults can also be detected on banked roads now. Fig. 4 presents the result of test b). During the extremely dynamical driving both of the residuals lie close to the thresholds. Therefore, without sensor faults the fault probability is about 0.5. Because of the relatively high threshold large yaw rate sensor faults can be detected only. The fault probability increases to about 1.0, if the yaw rate sensor fault of 40°/s occurs. The car test c) is demonstrated in Fig. 5. During the circular driving on ice the wheels, especially the rear wheels in this type of cars, get into slip. Due to the low-$\mu$ the lateral acceleration is very small and the sideslip angle is very large. In this situation the thresholds are also very high and just large yaw rate sensor faults (> 50°/s) can be detected.

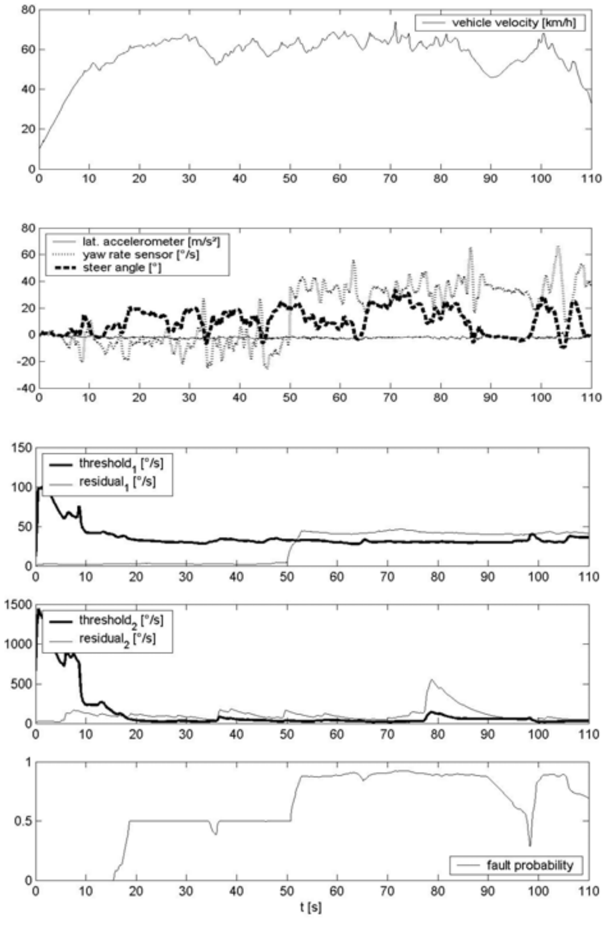

Fig. 5: Circular driving on ice

## 9 CONCLUSION

In this paper a new concept for monitoring the yaw rate sensor on-line is described. The new concept allows an automatic threshold generation by using the other reliable ESP-sensor signals. Both the residual evaluation and the threshold generation are based on statistic calculation. Finally, a fault probability can be delivered that contains the information not only on the sensor state, but also on the monitoring state. Using this additional information on the monitoring state the performance of the controller can be improved concerning the deal with sensor faults. The new concept uses the automatically generated thresholds only and does not need any limits of physical values as desired. However, the described results in this paper can be just regarded as a preliminary investigation. Further investigations are still necessary.

## 10 ACKNOWLEDGEMENT

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