An Observer-based Fault Detection Approach for Vehicle Lateral Dynamics Control System

Ali Abdo
University of Duisburg-Essen

Jedsada Saijai
Burapha University

Waseem Damlakhi
University of Duisburg-Essen

Steven Ding
University of Duisburg-Essen

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A. Abdo, J. Saijai, W. Damlakhi, S. X. Ding

Institute for Automatic Control and Complex Systems (AKS), University of Duisburg - Essen, Duisburg 47057, Germany. (Tel: +49 203 379 4296; e-mail: ali.abdo, jedsada.saijai, waseem.damlakhi, steven.ding@uni-due.de)

Abstract: In this paper, an FD scheme for detecting sensor faults in Lateral dynamics system is presented. The main contribution is to present an analytical solution to design residual generator using parity space approach in order to handle the time varying parameter in the system. The designed residual generator is realized in an observer structure which provides numerical stability by on-line realization. This proposed scheme can be applied for both continues and discrete systems. The results were implemented in Matlab/Simulink and tested with CarMaker software as realistic vehicle simulator.

Keywords: FD; Sensor fault; Linear Parameter Varying (LPV); Parity space approach; Vehicle lateral dynamic system.

1. INTRODUCTION

A vehicle is a highly complex system, and the challenge of creating more and more accurate models for control and sensor monitoring is increased. In the last decade, there was a large development of the vehicle automatic systems, such as ABS (Antilock Breaking System), ESP (Electronic Stability Program) and ACC (Adaptive Cruise Control). The aim of these systems is to ensure the stability of the vehicle in critical driving situations by using the information provided by the sensors, due to this fact a fault diagnosis system is needed to be integrated in the vehicle automatic systems.

In this paper, a fault detection scheme will be applied to the lateral vehicle dynamic system in order to detect faults in lateral acceleration as well as the yaw rate sensors. This problem has been addressed by many researchers. In Ding [2004] and Fischer [2007], the kinematic model have been used for the purpose of sensor monitoring. In Rehm [2004], the sensor stationary model was extended to include vehicle movement in baked curve with longitudinal inclination. The fault diagnosis scheme has been developed in Unger [2006] using parity space approach, where both bicycle and kinematic model were used for sensor monitoring. Recently, an observer-based FDI has been developed by Ding [2005], where the so called Parity design - observer implementation based residual generator approach was used by Schneider [2005]. This scheme combines the advantage of both approaches. In the both contributions of Ding [2005] and Schneider [2005], the bicycle model used for purpose of FDI was assumed to be Linear Time Invariant (LTI) systems in which the vehicle velocity was considered as constant parameter. The objective of this paper is to design FD scheme for detecting sensor faults in vehicle lateral dynamic system where the velocity is considered as varying parameter.

In the recent years, LPV methods have received a significant attention especially in the field of aerospace and vehicles, see for instance surveys by Rugh [2000], Leith [2000]. The FD problem for LPV has been addressed by for example Balas [2002] in which a fault detection filter was designed using a geometric approach. In Armeni [2008], a residual generator has been designed for class of LPV which enhances the transmission dc gain of the fault.

In the following study, an approach using parity space to handle varying parameter in FD system is presented. In order to meet this objective, a scheme which gives the parity vector as a function of the varying parameter is proposed. Thanks to the one-to-one relation between parity space and observer based approach, the designed residual is then realized in an observer form which provides numerical stability by on-line realization. The proposed scheme can be applied for both continuous and discrete systems.

This paper is organized as follows. Section 2 describes the vehicle model under consideration. In Section 3, an overview of model-based residual generators namely parity space approach and diagnosis observer, together with a new scheme using those approaches for handling the parameter varying is presented. The design procedure for developing the FD scheme will be presented in Section 4.

2. VEHICLE LATERAL DYNAMIC MODEL

For the purpose of designing model-based fault detection scheme for a vehicle lateral dynamic system, a mathematical model which describes the lateral dynamic behavior should be established. In this paper, a well-known bicycle model is used. This model is derived based on the following assumptions:

- Tires of each axles are lumped into single tire. That means only two tires are considered.
- Center of gravity of the vehicle is on the road surface.
- The roll and pitch movement are neglected.
- Tire cornering stiffnesses are constant. That means the lateral forces subject to each tire is proportional to its slip angle.
- Longitudinal acceleration a_x is zero or very low, i.e. $v_x \approx$ constant.
- Lateral acceleration: $a_y \leq 4\ m/s^2$
- Road surface is flat and covered with dry asphalt.

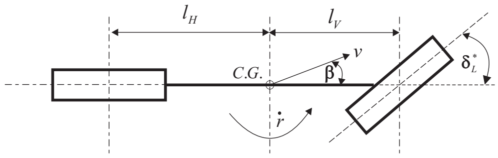

Fig. 1. One-track model

The dynamic behavior of this model is described in the state space model as follows, (Mitschke [1990]):

$$\begin{bmatrix} \dot{\beta}(t) \\ \dot{r}(t) \end{bmatrix} = \begin{bmatrix} \dfrac{Y_\beta}{mv(t)} & \dfrac{Y_r}{mv(t)} - 1 \\ \dfrac{N_\beta}{I_z} & \dfrac{N_r}{I_z} \end{bmatrix} \begin{bmatrix} \beta(t) \\ r(t) \end{bmatrix} + \begin{bmatrix} \dfrac{Y_\delta}{mv(t)} \\ \dfrac{N_\delta}{I_z} \end{bmatrix} \delta_L^*(t) \tag{1}$$

$$\begin{bmatrix} a_y(t) \\ r(t) \end{bmatrix} = \begin{bmatrix} \dfrac{Y_\beta}{m} & \dfrac{Y_r}{m} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \beta(t) \\ r(t) \end{bmatrix} + \begin{bmatrix} \dfrac{Y_\delta}{m} \\ 0 \end{bmatrix} \delta_L^*(t) \tag{2}$$

with

$Y_\beta = -(c'_{\alpha V} + c_{\alpha H})$, $Y_r = \frac{(l_H c_{\alpha H} - l_v c'_{\alpha V})}{v(t)}$, $Y_\delta = c'_{\alpha V}$

$N_\beta = l_H c_{\alpha H} - l_V c'_{\alpha V}$, $N_r = -\left(\frac{l_v^2 c'_{\alpha V} + l_H^2 c_{\alpha H}}{v(t)}\right)$,

$N_\delta = l_V c'_{\alpha V}$

It is clearly seen from (1) and (2) that the dynamic behavior of this model depends on its velocity, $v(t)$, which is unknown priori but on-line measurable. Therefore, this system can be considered as LPV system which can be described in standard state space form as follows,

$$\begin{aligned} \dot{x}(t) &= A(\theta)x(t) + B(\theta)u(t) \\ y(t) &= C(\theta)x(t) + D(\theta)u(t) \end{aligned} \tag{3}$$

where $\theta = v(t)$, $x(t) = [\,\beta(t)\ r(t)\,]^T$, $y(t) = [\,a_y(t)\ r(t)\,]^T$, $u(t) = \delta_L^*(t)$

and $A(\theta)$, $B(\theta)$, $C(\theta)$, $D(\theta)$ are matrices with appropriate dimensions which are the function of the parameter varying θ.

In this study, the problem of designing FD scheme to detect sensor faults in lateral acceleration and yaw rate sensors is reformulated as follows,

- Designing the residual generator for vehicle lateral dynamic system which velocity is taken as a time varying parameter.
- Implementation of the residual generator in an observer form which is suitable for on-line realization.

3. MODEL-BASED RESIDUAL GENERATION APPROACH

There are various model based approaches for designing residual generator in the literature. Between, the well known methods namely parity space and observer based approaches will be briefly presented. For details, reader is referred to Patton [2000],Ding [2008] and Isermann [2006].

3.1 Parity space residual generation method

Suppose that the system is described in state space of linear discrete time form as follows,

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + E_f f(k) \\ y(k) &= Cx(k) + Du(k) + F_f f(k) \end{aligned} \tag{4}$$

with $x(k) \in R^n$ is state vector, $u(k) \in R^{n_u}$ is the input vector, $y(k) \in R^m$ is the output vector and $f(k) \in R^{n_f}$ is the vector of faults to be detected. A, B, C, D, E_f and F_f are the known matrices with appropriate dimension.

The basic idea of designing parity space based residual generator is to find a so called parity vector, v_s, such that

$$v_s H_{o,s} = 0 \tag{5}$$

where $v_s = [\,v_{s,0}\ v_{s,1}\ \dots\ v_{s,s}\,]$, $H_{o,s} = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^s \end{bmatrix}$ and s is the order of parity space.

The residual signal $r(k)$ is realized using the measurements of output and input signals as follows,

$$r(k) = v_s(y_s(k) - H_{u,s}(k)u_s(k)) \tag{6}$$

where

$$y_s(k) = \begin{bmatrix} y(k-s) \\ y(k-s+1) \\ \vdots \\ y(k) \end{bmatrix},\ u_s(k) = \begin{bmatrix} u(k-s) \\ u(k-s+1) \\ \vdots \\ u(k) \end{bmatrix}$$

$$H_{u,s} = \begin{bmatrix} D & 0 & \dots & 0 \\ CB & D & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{s-1}B & CA^{s-2}B & \dots & D \end{bmatrix}$$

3.2 An observer based residual generation method

For the system described in (4), the so called diagnosis observer based residual generation (DO) is constructed as follows,

$$\hat{z}(k+1) = A_z \hat{z}(k) + B_z u(k) + Ly(k) - L_0 r(k) \tag{7}$$

$$r(k) = gy(k) - c_z\hat{z}(k) - d_z u(k) \quad (8)$$

where $\hat{z} = T\hat{x}$, $\hat{z} \in R^s$ represent estimated state,

s is the observer order which can be less or more than system order n,

$L_0 = \begin{bmatrix} l_0 \\ l_1 \\ \vdots \\ l_{s-1} \end{bmatrix} \in R^s$ is the feedback matrix gain, which is arbitrary selected.

Substituting (8) into (7) yields

$$\hat{z}(k+1) = \bar{A}_z\hat{z}(k) + \bar{B}_z u(k) + \bar{L}y(k) \quad (9)$$

with $\bar{A}_z = A_z + L_0 c_z$, $\bar{B}_z = B_z + L_0 d_z$, $\bar{L} = L - L_0 g$

The design parameters A_z, B_z, L, L_0, c_z, d_z and g are selected in order to fulfill the Luenberger conditions

- $\bar{A}_z$ is stable
- $TA - \bar{A}_z T = \bar{L}C$, $\bar{B}_z = TB - \bar{L}D$
- $gC - c_z T = 0$, $d_z = gD$

The relationship between DO and parity space based method has been studied and a one-to-one transformation between both methods has been founded and established as the following theorem:

Theorem 1. (Ding [2008]) *Given the system model (4) and parity vector given by (5) then the observer based residual generator design parameters $\bar{A}_z \in R^{s\times s}$, $T \in R^{s\times n}$, $\bar{L} \in R^{s\times m}$, $\bar{B}_z \in R^{s\times n_u}$, $d_z \in R^{1\times n_u}$, $c_z \in R^{1\times s}$ and $g \in R^{1\times m}$ as follows,*

- $c_z = [\,0\ 0\ \ldots\ 1\,], g = v_{s,s}$
- $\bar{A}_z = A_z + L_0 c_z = \begin{bmatrix} 0 & 0 & \ldots & 0 & l_0 \\ 1 & 0 & \ldots & 0 & l_1 \\ \vdots & \ddots & \ddots & \vdots & \vdots \\ 0 & \ldots & 1 & 0 & l_{s-2} \\ 0 & \ldots & 0 & 1 & l_{s-1} \end{bmatrix}$
- $T = \begin{bmatrix} v_{s,1} & v_{s,2} & \ldots & v_{s,s-1} & v_{s,s} \\ v_{s,2} & \ldots & \ldots & v_{s,s} & 0 \\ \vdots & \ldots & \ldots & \vdots & \vdots \\ v_{s,s} & 0 & \ldots & \ldots & 0 \end{bmatrix} \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{s-2} \\ CA^{s-1} \end{bmatrix}$
- $\bar{L} = L - L_0 g = -\begin{bmatrix} v_{s,0} \\ v_{s,1} \\ \vdots \\ v_{s,s-1} \end{bmatrix} - L_0 g$
- $d_z = gD$
- $\bar{B}_z = B_z + L_0 d_z$

$$= \begin{bmatrix} v_{s,0} & v_{s,1} & \ldots & v_{s,s-1} & v_{s,s} \\ v_{s,1} & v_{s,2} & \ldots & v_{s,s} & 0 \\ \vdots & \vdots & \ldots & \vdots & \vdots \\ v_{s,s-1} & v_{s,s} & \ldots & 0 & 0 \\ v_{s,s} & 0 & \ldots & 0 & 0 \end{bmatrix} \begin{bmatrix} D \\ CB \\ \vdots \\ CA^{s-2}B \\ CA^{s-1}B \end{bmatrix} + L_0 gD$$

fulfill the Luenberger conditions.

Based on the above relation, a design strategy called **parity space design - observer based implementation form** is established, which makes use of the computational advantage of parity space approach for the system design and then realize the solution in the observer form to ensure the numerically stable and less consuming on-line computation. This means the proposed FD scheme combines the advantages from both methods. More precisely, the main idea of this strategy is to find parity vector v_s. Once it is founded, the residual generator can be implemented in the observer form.

It can be seen that this strategy is originally developed for discrete time system. In the following, an approach using this strategy, which can be also applied for the continuous system, is presented. In the following subsection the proposed approach of designing FD scheme for LPV system as an analytical solution is presented.

3.3 Parity space design - observer based implementation residual generator for LPV system

Suppose the system under consideration is given in discrete state space general form

$$\begin{aligned} x(k+1) &= A(\theta(k))x(k) + B(\theta(k))u(k) + E_f(\theta(k))f(k) \\ &\quad + E_d(\theta(k))\xi(k) \\ y(k) &= c(\theta(k))x(k) + d(\theta(k))u(k) + F_f(\theta(k))f(k) \\ &\quad + F_d(\theta(k))\xi(k) \end{aligned} \quad (10)$$

where $f(k)$ is the vector of the faults to be detected, $\xi(k)$ is the vector of the unknown disturbances.

At the sampling time k, the system can be considered as LTI system and the corresponding transfer function between input and output signal can be constructed as follow,

$$y(z) = \frac{b_n(\theta(k))z^n + b_{n-1}(\theta(k))z^{n-1} + \ldots + b_0(\theta(k))}{z^n + a_{n-1}(\theta(k))z^{n-1} + \ldots + a_0(\theta(k))}u(z) \quad (11)$$

Note that when a sampling time is considered small, discrete system can be assumed as continuous system.

Apply the Cayley-Hamilton theorem for the system (11) states that

$$A^n(\theta(k)) + a_{n-1}(\theta(k))A^{n-1}(\theta(k)) + \ldots + a_0(\theta(k)) = 0 \quad (12)$$

or in the matrix form

$$\left[\, a_0(\theta(k))\ a_1(\theta(k))\ \ldots\ a_{n-1}(\theta(k))\ 1 \,\right] \begin{bmatrix} c(\theta(k)) \\ c(\theta(k))A(\theta(k)) \\ \vdots \\ c(\theta(k))A^{n-1}(\theta(k)) \\ c(\theta(k))A^n(\theta(k)) \end{bmatrix} = 0 \quad (13)$$

From (5) and (13) and assume that the varying parameter θ in the observability matrix at a sampling time k-n up to k are considered as a constant, it can be shown that

$$v_s(\theta(k)) = [\, a_0(\theta(k))\ a_1(\theta(k))\ \ldots\ a_{n-1}(\theta(k))\ 1 \,] \quad (14)$$

can be selected as a parity vector of the system defined by (11) with order $s = n$

This assumption is valid either the order s is small or the varying parameter is slowly changing.

From this result, together with (6), the residual signal can be constructed as follows,

$$r(p) = [\, a_0(\theta_i) \;\; a_1(\theta_i) \;\; a_2(\theta_i) \ldots \; a_{n-1}(\theta_i) \;\; 1\,]\, y(p) \\ -v_s(\theta_i) H_{u,s}(\theta_i) u(p) \qquad (15)$$

and from (11), $v_s(\theta_i)H_{u,s}(\theta_i)$ should satisfy

$$v_s(\theta_i)H_{u,s}(\theta_i) = [\, b_0(\theta_i) \;\; b_1(\theta_i) \;\; \ldots \;\; b_{n-1}(\theta_i) \;\; b_n(\theta_i)\,] \qquad (16)$$

By using (14) and theorem in previous section, the DO design parameters can be now established. Comparing (16) and the relation of $\bar{B}_z$ and d_z from the Luenberger condition, it can be shown that

$$\begin{bmatrix} \bar{B}_z(\theta_i) \\ d_z(\theta_i) \end{bmatrix} = \begin{bmatrix} b_0(\theta_i) + l_1 b_n(\theta_i) \\ b_1(\theta_i) + l_2 b_n(\theta_i) \\ \vdots \\ b_{n-1}(\theta_i) + l_n b_n(\theta_i) \\ b_n(\theta_i) \end{bmatrix} \qquad (17)$$

Other parameters of DO are constructed related to system transfer function (11) as follow,

$$g = v_{s,s} = 1 \qquad (18)$$

$$c_z = [\, 0 \;\; 0 \;\; \ldots \;\; 1\,] \qquad (19)$$

$$\bar{L}(\theta_i) = -\begin{bmatrix} a_0(\theta_i) \\ a_1(\theta_i) \\ \vdots \\ a_{n-1}(\theta_i) \end{bmatrix} - \begin{bmatrix} l_0 \\ l_1 \\ \vdots \\ l_{n-1} \end{bmatrix} \qquad (20)$$

which are used to implement DO residual generation according to (8) and (9).

In order to analyze the proposed scheme, the dynamic behavior of the residual generator should be studied.

Consider the state error $e(t) = Tx(t) - \hat{z}(t)$. By straightforward calculation, error dynamics is given as follows,

$$\dot{e}(t) = \bar{A}_z e(t) + \left(T(\theta)A(\theta) - \bar{L}(\theta)c(\theta) - \bar{A}_z T(\theta)\right) x(t) \\ + \left(T(\theta)B(\theta) - \bar{B}_z(\theta) - \bar{L}(\theta)d(\theta)\right) u(t) + \bar{E}_f(\theta)f(t) \\ r(t) = c_z e(t) + (gc(\theta) - c_z T(\theta))\, x(t) + (gd(\theta) - d_z(\theta))\, u(t) \\ + gF_f f(t) \qquad (21)$$

with $\bar{E}_f(\theta) = T(\theta)E_f(\theta) - L(\theta)F_f(\theta)$,

By choosing the parity vector from (14) and apply theorem 1, it turns out

$$\dot{e}(t) = \bar{A}_z e(t) + \bar{E}_f(\theta) f(t) \\ r(t) = c_z e(t) + gF_f f(t) \qquad (22)$$

It is evident by selecting appropriate observer gain L_0 the followings are ensured

$$\lim_{t\to\infty} r(t) = 0 \text{ for } \forall\theta \text{ and } f(t) = 0 \\ \lim_{t\to\infty} r(t) \neq 0 \text{ for } \forall\theta \text{ and } f(t) \neq 0 \qquad (23)$$

From (23), it is clearly seen that the dynamic of residual signal is independent of system parameter θ.

The design procedure of the proposed approach can be given in the following algorithm:

Algorithm 1. Given system (11) the residual generator can be designed and implemented as follows,

- *Obtain the parity vector in the form of (14)*
- *Obtain the coefficients of the numerator of transfer function (11)*
- *Select L_0 such that the stability of $\bar{A}_z$ is ensured. For discrete time system L_0 can be set to 0 which yields dead beat type observer.*
- *Calculate DO parameters follow (17) - (20) and implement residual generator according to (8) and (9)*

4. DESIGN, IMPLEMENTATION AND SIMULATION RESULTS

The model-based FD system consists of two main functions namely residual generation and residual evaluation. In the following study only design the residual generator is considered, whereas the evaluation stage follows the scheme proposed by Andreas [2006].

4.1 Residual generator structure and design concept

As seen from Fig. 2, The FD scheme is structured from two residual generators. Each is driven by input signal and one output signal, whose sensor fault will be detected. This structure is known in the literature as "Generalized observer structure: GOS".

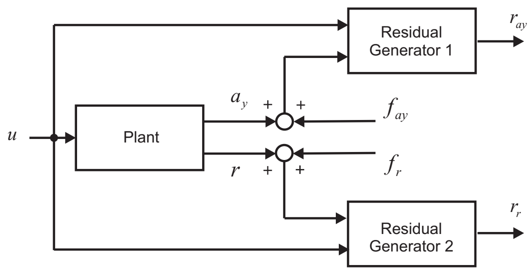

Fig. 2. FD scheme for vehicle lateral system sensor faults

4.2 Design procedure

Consider the system for $v = v_i$, the single-input multiple-output transfer functions are as follows,

$$\frac{a_y(s)}{\delta_L^*(s)} = \frac{b_{2,a_y}s^2 + b_{1,a_y}s + b_{0,a_y}}{s^2 + a_1 s + a_0} \qquad (24)$$

and

$$\frac{r(s)}{\delta_L^*(s)} = \frac{b_{2,r}s^2 + b_{1,r}s + b_{0,r}}{s^2 + a_1 s + a_0} \qquad (25)$$

with

$b_{2,a_y} = \frac{c'_{\alpha V}}{m}$; $b_{1,a_y} = \frac{c'_{\alpha V} c_{\alpha H} l_H l}{I_z m v_i}$; $b_{0,a_y} = \frac{c'_{\alpha V} c_{\alpha H} l}{I_z m}$

$b_{2,r} = 0$; $b_{1,r} = \frac{c'_{\alpha V} l_V}{I_z}$; $b_{0,r} = \frac{c'_{\alpha V} c_{\alpha H} l}{I_z m v_i}$

$a_1 = \left(\frac{c'_{\alpha V} c_{\alpha H}}{m v_i}\right) + \left(\frac{l_V^2 c'_{\alpha V} + l_H^2 c_{\alpha H}}{I_z v_i}\right)$;

$a_0 = \left(\frac{c'_{\alpha V} c_{\alpha H} l^2}{I_z m v_i^2}\right) + \left(\frac{l_H c_{\alpha H} - l_V c'_{\alpha V}}{I_z}\right)$

According to (14), the parity vector is selected from the coefficient of the transfer function's denominator as $v_s(v_i) = [\, a_0 \;\; a_1 \;\; a_2 \,]$, which is a function of vehicle velocity. In this way, we can design the parity vector as a function of velocity.

Follow by constructing observers whose design parameters are calculated as follows,

$$g_{a_y} = g_r = 1,\; \bar{L}_{a_y}(v_i) = \bar{L}_r(v_i) = -\begin{bmatrix} a_0 + l_1 \\ a_1 + l_2 \end{bmatrix},$$

$$c_{z,a_y} = c_{z,r} = [\, 0 \;\; 1 \,]$$

$$\begin{bmatrix} \bar{B}_{a_y}(v_i) \\ d_{z,a_y}(v_i) \end{bmatrix} = \begin{bmatrix} b_{0,a_y} + l_1 b_{2,a_y} \\ b_{1,a_y} + l_2 b_{2,a_y} \\ b_{2,a_y} \end{bmatrix},$$

$$\begin{bmatrix} \bar{B}_r(v_i) \\ d_{z,r}(v_i) \end{bmatrix} = \begin{bmatrix} b_{0,r} + l_1 b_{2,r} \\ b_{1,r} + l_2 b_{2,r} \\ b_{2,r} \end{bmatrix}$$

4.3 Residual evaluation

Normally, model-based FD is affected from the uninteresting signals by means of fault detection purpose such as measurement noises $\xi(t)$, external disturbances $d(t)$ and model uncertainties $\Delta(t)$. These signals bring residual signal from zero level even when $f = 0$ and may cause false alarm. To be able to distinguish faults from these signals, residual evaluation block, which consist of evaluation function and threshold setting, is required.

Firstly, evaluation function proposed by Andreas [2006] is applied as follow,

$$(\mathcal{E}_w r)(t) := \int_0^t w(t-\tau)|r(\tau)|d\tau \qquad (26)$$

The propose of weighting function $w(t)$ is to increase the influence of the most recent data by means of exponential forgetting.

Secondly, threshold is designed in order to distinguish between fault signal and other uninteresting signals. It is set as follow,

$$J_{th} = \sup_{f=0,\xi(t),d(t),\Delta(t)} (\mathcal{E}_w r)(t) \qquad (27)$$

4.4 Implementation and simulation results

The proposed FD scheme is implemented in the environment of MATLAB computational program. Matrix $\bar{A}_z$ is selected such that the observer is stable. By assigning $L_0 = [\, -100 \;\; -20 \,]^T$ gives its eigenvalues at $s = -10, -10$ and ensures system stability.

A number of driving maneuvers, which provided from the simulation program CarMaker, are used as testing data to prove and demonstrate the performance of the proposed FD scheme. This software offers a professional simulation platform for virtual test driving, which simulate the driving dynamic realistically up to the dynamic limits.

To show the performance of the proposed FD scheme during a system parameter, which is velocity, is varied, three test driving maneuvers are selected as examples. The performance of this FD are shown by comparing residual signals with others generated by another FD whose velocity is consider as the constant values.

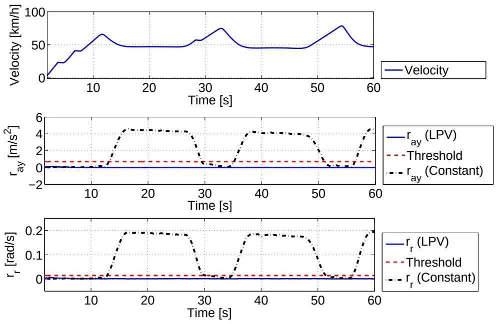

Fig. 3. Driving on eight-shape road in fault free case

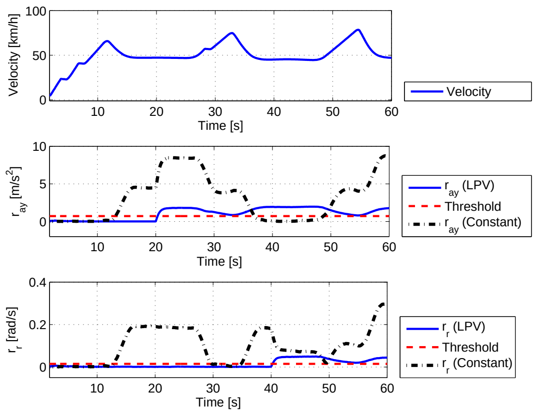

Fig. 4. Driving on eight-shape road with sensor faults

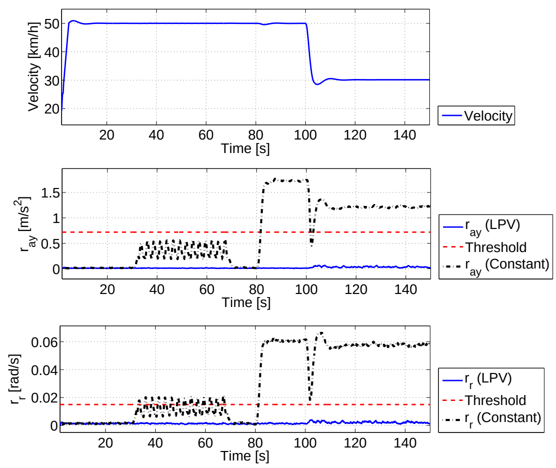

Fig. 5. Slalom follow by circle driving in fault free case

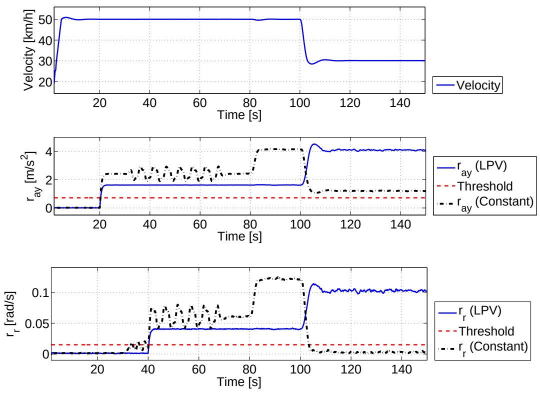

Fig. 6. Slalom follow by circle driving with sensor faults

Fig. 3 and 5 are the results of the proposed FD scheme performance during an absent of faults for each driving maneuver respectively. It can be seen that the proposed FD scheme generates residual signals whose maximum values are under the threshold and imply the fault free situation. In contrast, residual signals generated from FD scheme that consider velocity as a constant value excess this decision level and cause false alarm.

The results of residual signals while offset faults in lateral acceleration sensor, $f_{a_y} = 2m/s^2$ and in yaw rate sensor, $f_r = 0.05rad/s$ affect the system are shown in Fig. 4 and 6 for each driving maneuver respectively. By following these purposed FD scheme, it can be clearly seen that faults in both sensors are detected at $t = 20s$ and $t = 40s$ correctly when compare with constant velocity FD scheme.

5. CONCLUSION

In this study, an FD scheme for vehicle lateral dynamic system has been developed. The main objective was to handle time varying parameter by designing residual generator.

To achieve this objective, a design method using parity space approach, in which parity vector is given as a function of parameter varying, has been presented. The simulation results have shown the effective of this proposed scheme. Future work will be extended to include the robustness against model uncertainties and disturbances such as road bank angle.

REFERENCES

Andreas, J., Baska, M., and Norlanderb, T. Dynamic threshold generators for robust fault detection in linear systems with parameter uncertainty. *Automatica, vol. 42*, pp. 10951106, 2006.

Armeni, S., Casavola, A., and Mosca, E. Robust fault detection and isolation for LPV systems under a sensitivity constraint. *International Journal of Adaptive Control and Signal Processing*, 2008.

Balas, G., Bokor, J., Szabo, Z. Failure detection for lpv systems-a geometric approach. *Proceedings of the American Control Conference, vol. 6*, pp. 4421-4426, 2002.

Ding, E.L., Fennel, H. and Ding, S.X. Model-based diagnosis of sensor faults for ESP systems. *Control Engineering Practice 12*, pp. 847-856, 2004.

Ding, S.X., Schneider, S., Ding, E.L., and Rehm, A. Advanced model-based diagnosis of sensor faults in vehicle dynamic. *IFAC World Congress 2005*, Prague, 2005.

Ding, S.X., Ding, E.L., and Jeinsch, T. An approach to analysis and design of observer and parity relation based FDI systems. In A.F. Round, editor, *IFAC, 14th Triennial World Congress*, Beijing, 1999.

Ding, S.X., Guo, L., and Jeinsch, T. A numerical approach to analysis and design of FDI systems. *Proceedings of the 37th IEEE CDC*, pp. 1137-1142, 1998.

Ding, S.X. *Model-Based Fault Diagnosis Technique: Design schemes, algorithms and tools*. Springer, 2008.

Fischer, D., Borner, M., Schmitt, J. and Isermann, R. Model-based diagnosis of sensor faults for ESP systems. *Control Engineering Practice 15*, pp. 315-324, 2007.

Isermann, R. *Fault Diagnosis Systems*. Springer, 2006.

Leith, DJ., Leithead, WE. Survey of gain-scheduling analysis and design. *International Journal of Control, vol.73*, pp. 10011025, 2000.

Mitschke, M. *Dynamik der Kraftfahrzeuge Band C*. Springer, 1990.

Patton, R.J., Frank, P.M., and R.N.C.(Eds.). *Issues of Fault Diagnosis for Dynamic Systems*. Springer, 2000.

Rehm, A. and Otterbein, S. A unified approach towards fault detection of vehicle lateral dynamics sensors. *Proceedings of the 16th IFAC World Congress*, Prague, 2005.

Rugh, WJ. and Shamma, JS. Research on gain scheduling. *Automatica, vol.36*, pp. 14011425, 2000.

Schneider, S., Weinhold, N., Ding, S.X., and Rehm, A. Parity Space based FDI-Scheme for Vehicle Lateral Dynamics. *Proceedings of 2005 IEEE Conference on Control Applications*, Toronto, 2005.

Unger, I. and Isermann, R. Fault tolerant sensors for vehicle dynamics control. *Proceedings of the 2006 American Control Conference*, Minnesota, 2006.

Appendix A. NOMENCLATURES AND TECHNICAL DATA FOR THE TEST VEHICLE

Variable	Value	Unit	Explanation
g	9.80665	m/s^2	gravity acceleration constant
m	1463	kg	total mass
l_V	1.108	m	distance from CG. to front axle
l_H	1.42	m	distance from CG. to rare axle
l	$l_V + l_H$	m	distance between front and rare axle
I_z	1805.7	kgm^2	moment of inertia about the z-axis
$c_{\alpha V}$	103950	N/rad	front axle tire cornering stiffness
$c_{\alpha H}$	108130	N/rad	rare axle tire cornering stiffness
v_{ref}		m/s	longitudinal velocity
β		rad	vehicle side slip angle
r		rad/s	vehicle yaw rate
a_y		m/s^2	vehicle lateral acceleration
δ_L^*		rad	vehicle steering angle