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Robust H_∞ fuzzy networked control for vehicle lateral dynamics

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***Abstract*— Networked control system for vehicle lateral dynamics is developed in this study to improve the cornering stability. By considering the packet dropouts, network-induced delay, road adhesion variations, driver effect and only yaw rate sensor for measuring, a robust H_∞ fuzzy static output feedback controller operating through a communication network is designed. After giving the nonlinear model of the vehicle, its Takagi-Sugeno (T-S) incertain fuzzy model representation is first presented. Next, based on the Lyapunov krasovskii functional approach and a parallel distributed compensation scheme, the gains of the fuzzy controller are determined by solving a set of Linear Matrix Inequalities (LMI). Simulations have been conducted to evaluate the performance of the active cornering stability control system under limitation of the network resources caused by data transmission.**

Keywords: vehicle dynamics, Networked control system (NCS), (T-S) incertain fuzzy model, robust H_∞ control, Linear Matrix Inequality (LMI) .

I. INTRODUCTION

In the past few years, to help the driver cope with critical driving situations, the general tendency in automotive vehicle field is to increase the safety of passengers by introducing many active safety systems (ABS, ESP, TCS, ASR, DYC ...) [3], [4], [11]. These systems are generally based on the distributed assistant systems which work through the communication networks such as Controller Area Network (CAN) [8]. Cars accidents occur for several reasons which may involve the driver, the vehicle components or environments. Such situations appear when the vehicle is driven beyond the adherence or stability limits. There are an increasing interests to these embedded distributed control systems in the vehicle electronic control systems because to their low cost, reduced weight and power needs, simple installation and maintenance and high reliability. The characteristic of a Networked control system (NCS) is that its components (sensors, controller , and actuators) are not connected directly by normal wires but through a network. However, when the control signals are transmitted through the communication network, several challenging issues will appear such as network-induced delay and packet dropouts caused by data transmission, will inevitably degrade the performance of the NCSs and even cause system instability [14].

In this work, a networked active safety system (NASS) for vehicle lateral dynamics stability is developed. The NCSS consists of a robust fuzzy static output feedback controller which uses a transmission network for vehicle sensor and actuator data. As design methodology is based on fuzzy H_∞ control technique, a representation of the nonlinear model of lateral vehicle dynamics by an uncertain Takagi-Sugeno (T-S) fuzzy model is considered [10]. This representation largely used these last years to describe the vehicle nonlinear dynamics behavior (see for example [2], [5], [12], [13], [15] and references therein), allows to provide a systematic and effective design strategy to complement other nonlinear control techniques. The typical approach for controller design is carried out via the so-called parallel distributed compensation (PDC) method [7].

Our main objective is to develop a robust fuzzy static output control scheme that uses a communication network to exchange sensor and actuator data transmission between the vehicle and its stability control system. This Networked control system not only takes into account the network effect but also the driving conditions related to the road and the driver.

The structure of this paper is organized as follows : the second section describes the uncertain T-S fuzzy model of vehicle nonlinear dynamics. In section 3, the proposed vehicle networked control structure is introduced and its design method is described. In section 4, simulation results are carried out to demonstrate the effectiveness of the proposed networked active safety system in terms of improving the vehicle stability. Finally, concluding remarks are made in section 5.

The numerical simulation of the vehicle handling with and without the developed controller has been carried out to demonstrate the effectiveness of the proposed algorithm in terms of improving the vehicle stability using active safety system.

Notations:$W + W^T$ is denoted as $Sym(W)$.

The symbol (*) within a matrix represents the symmetric entries.

L_2 is the space of square integrable functions over $[0, \infty)$, and $||.||_2$ denotes the L_2-norm.

II. VEHICLE MODEL DESCRIPTION

The two-dimensional model with nonlinear tire characteristics of the four wheel vehicle behavior can be described by

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differential equations (cf.fig. 2)

$$\begin{cases} \dot{\beta} = \dfrac{2F_f + 2F_r}{mU} - r \\ \dot{r} = \dfrac{2a_f F_f - 2a_r F_r + M_z}{I_z}. \end{cases} \tag{1}$$

Where β denotes the side slip angle, r is the yaw rate, F_f is the cornering force of the two front tires, F_r is the cornering force of the two rear tires. W is the vehicle velocity, I_z is the yaw moment of inertia, m is the vehicle mass. The parameters of the vehicle are given in the following table :

TABLE I
VEHICLE PARAMETERS

Parameters	$I_z(Kg^2m$	m(Kg)	$a_f(m)$	$a_r(m)$	W(m/s)
Values	3000	1500	1.3	1.2	20

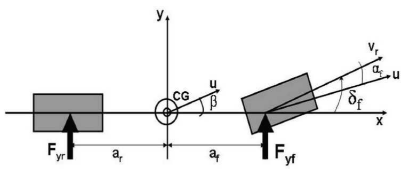

Fig. 1. Bicycle model

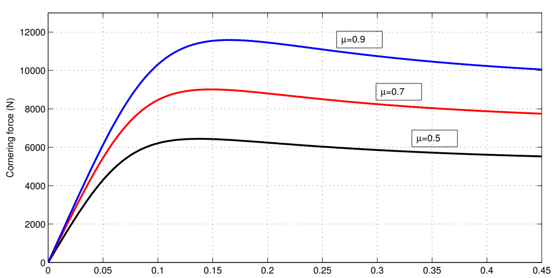

Fig. 2. Cornering forces

Figure 2 shows the cornering force characteristics for some road adhesion coefficients (μ).

To obtain the TS fuzzy model, we propose to approximate front and rear lateral forces [10] by the following rules:

$$\text{IF } |\alpha_f| \text{ is } M_1 \text{ THEN} \begin{cases} F_f = C_{f1}(\mu)\alpha_f \\ F_r = C_{r1}(\mu)\alpha_r \end{cases} \tag{2}$$

$$\text{IF } |\alpha_f| \text{ is } M_2 \text{ THEN} \begin{cases} F_f = C_{f2}(\mu)\alpha_f \\ F_r = C_{r2}(\mu)\alpha_r \end{cases} \tag{3}$$

With :

$$\begin{cases} F_f = h_1(|\alpha_f|)C_{f1}(\mu)\alpha_f + h_2(|\alpha_f|)C_{f2}(\mu)\alpha_f \\ F_r = h_1(|\alpha_r|)C_{r1}(\mu)\alpha_r + h_2(|\alpha_r|)C_{r2}(\mu)\alpha_r \end{cases} \tag{4}$$

Where α_f is the front steer angle, α_r is the rear steer angle $h_j(j=1,2)$ is the j^{th} bell curve membership function of fuzzy set M_j. The membership function parameters and consequence parameters of rules can easily be obtained using an identification method based on the Levenberg-Marquadt algorithm [16].

For road friction coefficient $\mu = 0.7$, membership functions h_1 and h_2 are given in figure 3.

Front and rear Pacejka forces [10] compared to estimated front and rear forces described by equation (4) are shown in figure 4.

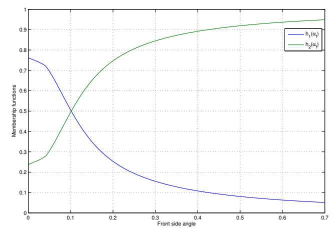

Fig. 3. Membership functions

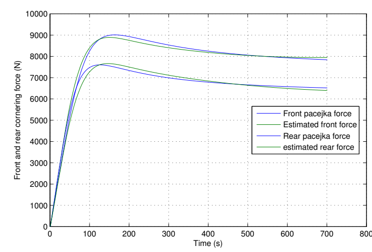

Fig. 4. Comparison of the estimated force and Pacejka force

We note that the stiffness coefficients C_{fi}, C_{ri} are not constant and vary according to the road adhesion. To take into account these variations, we assume that these coefficients vary as follows:

$$\begin{cases} C_{fi} = C_{fi0}(1 + d_i f_i) \quad ,||f_i|| \leq 1 \\ C_{ri} = C_{ri0}(1 + d_i f_i) \end{cases} \tag{5}$$

Where d_i indicates the deviation magnitude of the stiffness coefficient from its nominal value.

Using the above approximation idea of nonlinear lateral forces by TS rules and by considering that $\alpha_f \cong \beta + \frac{a_f r}{W} - \delta_f$, $\alpha_r \cong \beta + \frac{a_r r}{W}$, nonlinear model (1) can be represented by the following TS fuzzy model:

$$\text{IF } |\alpha_f| \text{ is } M_1 \text{ THEN} \tag{6}$$

$$\begin{cases} \dot{x}(t) = (A_{10} + \Delta A_1)x(t) + (B_{f10} + \Delta B_{f1})\delta_f \\ \quad + (B_{10} + \Delta B_1)M_Z \\ y(t) = C_2 x(t) \\ z(t) = C_1 x(t) \end{cases}$$

IF $|\alpha_f|$ is M_2 THEN (7)

$$\begin{cases} \dot{x}(t) = (A_{20} + \Delta A_2)x(t) + (B_{f20} + \Delta B_{f2})\delta_f \\ + (B_{20} + \Delta B_2)M_Z \\ y(t) = C_2 x(t) \\ z(t) = C_1 x(t) \end{cases}$$

Where

$$A_{i0} = \begin{bmatrix} -2\frac{C_{fi0}+C_{ri0}}{mW} & -2\frac{C_{fi0}a_f - C_{ri0}a_r}{mW^2} - 1 \\ -2\frac{C_{fi0}a_f - C_{ri0}a_r}{I_z} & -2\frac{C_{fi0}a_f^2 + C_{ri0}a_r^2}{I_z W} \end{bmatrix},$$

$$B_{fi0} = \begin{bmatrix} -2C_{fi0}mW \\ \frac{2a_f C_{fi0}}{I_z} \end{bmatrix}, B_{i0} = \begin{bmatrix} 0 \\ \frac{1}{I_z} \end{bmatrix}, \tag{8}$$

$$\Delta A_i = D_{Ai}F(t)E_{Ai}, \Delta B_{fi} = D_{Bfi}F(t)E_{Bfi},$$
$$\Delta B_i = D_{Bi}F(t)E_{Bi}$$

$,E_{Ai} = \begin{bmatrix} -2\frac{C_{fi0}+C_{ri0}}{mW} & -2\frac{C_{fi0}a_f - C_{ri0}a_r}{mW^2} \\ -2\frac{C_{fi0}a_f - C_{ri0}a_r}{Iz} & -2\frac{C_{fi0}a_f^2 + C_{ri0}a_r^2}{IzW} \end{bmatrix},$
and $D_{Ai} = D_{Bi} = D_{Bfi} = \begin{bmatrix} 0.01 & 0 \\ 0 & 0.01 \end{bmatrix}$
$,E_{Bfi} = \begin{bmatrix} -2C_{fi0}mW \\ \frac{2a_f C_{fi0}}{Iz} \end{bmatrix}$ and $E_{Bi} = 0$, and $F(t) = \begin{bmatrix} sin(6t) & 0 \\ 0 & sin(6t) \end{bmatrix}$, $C_1 = C_2 = \begin{bmatrix} 0 & 1 \end{bmatrix}$.

Where

$$x(t) = \begin{bmatrix} \beta \\ r \end{bmatrix} \tag{9}$$

where $x(t)$ is the state vector, M_Z is the control input, δ_f is the external disturbance input, $z(t)$ is the controlled output, and $y(t)$ is the measured output.

The defuzzified output of this TS fuzzy system is :

$$\dot{x}(t) = \sum_{i=1}^{r} h_i(|\alpha_f|)[(A_{i0} + \Delta A_i)x(t) + (B_{fi0} + \Delta B_{fi})\delta_f \tag{10}$$
$$+ (B_{i0} + \Delta B_{i0})M_Z]$$
$$y(t) = C_2 x(t)$$
$$z(t) = C_1 x(t)$$

The membership functions are defined as

$$h_1(|\alpha_f|) = \frac{1}{(1 + abs(\frac{|\alpha_f| - c_1}{a_1}))^{2b_1}} \tag{11}$$

$$, h_2(|\alpha_f|) = \frac{1}{(1 + abs(\frac{|\alpha_f| - c_2}{a_2}))^{2b_2}}. \tag{12}$$

With $a_1 = 0.5077$, $b_1 = 0.4748$, $c_1 = 3.1893$, $a_2 = 5.3907$, $b_2 = 0.4356$, $c_2 = 0.5633$.

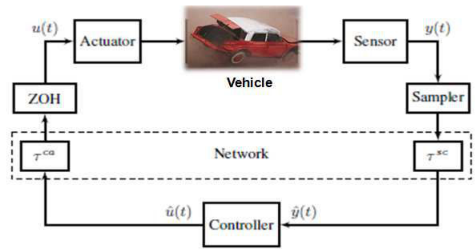

Fig. 5. Framework of networked control system

A typical NCS model with network-induced delays is shown in Fig. 3, where τ_{sc} is the sensor-to-controller delay and τ_{ca} is the controller-to-actuator delay. It is assumed that the controller computational delay can be absorbed into either τ_{sc} or τ_{ca}.
The following assumptions, which are common for NCSs research in the open literature , are also made in this work:

1) The sensors are clock driven, the controller and the actuators are event driven.
2) Data, either from measurement or for control, are transmitted with a single packet.
3) The effect of signal quantization and wrong code in communication are not considered.
4) The real input M_Z, realized through a zero-order hold, is a piecewise constant function.

It is worth mentioning that the sampling period of a sensor is pre-determined for control algorithm design, and thus the sensor can be assumed to be clock driven. However, an actuator does not change its output to the plant under control until an updated control signal is received, implying that the actuator is event driven.

III. H_∞ FUZZY STATIC OUTPUT FEEDBACK DESIGN

To control the stability of vehicle through a communication network, we consider the networked PDC fuzzy controller described by the following rules :

Control rules :
IF $|\alpha_f|$ is M_1 THEN $M_Z(t) = K_1 y(t_k - \tau_k)$

IF $|\alpha_f|$ is M_2 THEN $M_Z(t) = K_2 y(t_k - \tau_k)$
Hence, the inferred fuzzy controller is given by

$$M_Z(t_k) = \sum_{i=1}^{2} h_i(|\alpha_f|)K_i y(t_k - \tau_k).$$

From the ZOH, the input signal is

$$M_Z(t) = \sum_{i=1}^{2} h_i(|\alpha_f|)K_i x(t_k - \tau_k), \quad t_k \leq t \leq t_{k+1} \tag{13}$$

- Network-induced delay (τ_k): Network-induced delays always exist when the data transmits through a network, and obviously, it has both lower and upper bounds. Therefore, a plausible representation of delay would be non-differentiable interval time-varying function. A natural assumption on τ_k can be made as

$$0 < \tau_m \leq \tau_k \leq \tau_M \tag{14}$$

- Packet dropouts : The effect of data packet dropouts in the communication channel can be described as the ZOH is not updating during the time interval of this event, which is referred as vacant sampling. Hence, the effect of one packet dropout in the transmission is just a case that one sampling period delay is induced in the updating interval of ZOH.

$$t_{k+1} - t_k = (\sigma_{k+1} + 1)h + \tau_{k+1} - \tau_k \tag{15}$$

where h denotes the sampling period and σ_{k+1} is the number of accumulated packet dropouts in this period. In the sequel, we note

$$\begin{aligned} &h_i = h_i(|\alpha_f|),\ A(t) = \sum_{i=1}^{r} h_i(A_{i0} + \Delta A_i), \\ &B_f(t) = \sum_{i=1}^{r} h_i(B_{fi0} + \Delta B_{fi}), H(t) = \sum_{i=1}^{r} h_i \sum_{j=1}^{r} h_j H_{ij}, \\ &H_{ij} = (B_{i0} + \Delta B_i)K_j C_2. \end{aligned} \tag{16}$$

Using equations (10) and (13), the closed-loop vehicle networked control system can be written as

$$\begin{cases} \dot{x}(t) = A(t)x(t) + H(t)x(t_k - \tau_k) + B_f(t)\delta_f, \\ t_k \le t \le t_{k+1} \\ y(t) = C_2 x(t) \\ z(t) = C_1 x(t) \end{cases}$$

Let consider $\eta(t) = t - t_k + \tau_k, \quad t_k \le t \le t_{k+1}$, then

$$\tau_m \le \tau_k \le \eta(t) \le (\bar{\sigma} + 1)h + \tau_{k+1} \tag{17}$$

where $\bar{\sigma}$ denotes the maximum number of packet dropouts in the updating periods, $\eta_1 = \tau_m$ and $\eta_2 = (\bar{\sigma} + 1)h + \tau_M$. Thus we get

$$\eta_1 \le \eta(t) \le \eta_2 \text{ and } \dot{\eta}(t) \le h_d \tag{18}$$

Since $\sum_{k=0}^{\infty}[t_k, t_{k+1}) = [0, \infty)$, we have

$$\begin{cases} \dot{x}(t) = A(t)x(t) + H(t)x(t - \eta(t)) + B_f(t)\delta_f, \\ t_k \le t \le t_{k+1} \\ x(t) = \phi(t), t \in [t_0 - \eta_2, t_0] \\ y(t) = C_2 x(t) \\ z(t) = C_1 x(t) \end{cases} \tag{19}$$

Where $\phi(t)$ can be viewed as the initial condition of the closed-loop control system. Then based on (18), it is noted that the NCS (19) is equivalent to a system with an interval time-varying delay.

Our main objective is to develop a robust fuzzy static output control scheme that uses a communication network to exchange sensor and actuator data transmission between the vehicle and its stability control system and that also takes into account the road condition variations and the driver actions. The NCS must ensure the global stability in presence the parametric uncertainties due to road adhesion variations and also the H_∞ performance against the driver actions ($\|y\| \le \gamma\|\delta_f\|$), with γ is attenuation level).

To obtain the main results in this paper, the following lemmas are needed:

Lemma 3.1: [9] For any scalars $M > 0$, $N > 0$, $h(t)$ is a continuous function and satisfies $h_m < h(t) < h_M$, then

$$\begin{aligned} &-\frac{h_M - h_m}{h(t) - h_m}M - \frac{h_M - h_m}{h_M - h(t)}N \\ &\le max(-(M + 3N), -(3M + N)) \end{aligned} \tag{20}$$

Lemma 3.2: [1] Given matrices $D, E, F(t)$ with compatible dimensions and F(t) satisfying $F(t)^T F(t) \le I$. Then, the following inequality holds for any $\epsilon > 0$:
$DF(t)E + E^T F(t)^T D^T \le \epsilon D D^T + \epsilon^{-1} E^T E$

Based on Lyapunov-Krasovskii functional, we establish a practical computable criterion for asymptotic stability of closed-loop vehicle NCS in the following theorem. (19).

Theorem 3.1: For given scalars $\eta_1 > 0$, $\eta_2 > 0$ and $\gamma > 0$, ϵ_i and μ_1, μ_2, and μ_3, the closed-loop system (19) is asymptotically stable with H_∞ norm bounded γ, if there exist positive matrices $\bar{P}$, $\bar{Q}_1$, $\bar{Q}_2$, $\bar{Q}_3$, $\bar{Z}_1$, $\bar{Z}_2$ and , matrices $\hat{G}_1 > 0$, $\hat{G}_2 > 0$ and Y_i with appropriate dimensions, such that the following conditions hold

$$\begin{bmatrix} \bar{\Phi}_{ii} + \bar{\Phi}_1(\bar{Z}_2) & \epsilon_i \bar{\mathcal{D}}_i & \bar{\mathcal{E}}_{ij} \\ * & -\epsilon_i I & 0 \\ * & * & -\epsilon_i \end{bmatrix} < 0 \tag{21}$$

$$\begin{bmatrix} \bar{\Phi}_{ii} + \bar{\Phi}_2(\bar{Z}_2) & \epsilon_i \bar{\mathcal{D}}_i & \bar{\mathcal{E}}_{ij} \\ * & -\epsilon_i I & 0 \\ * & * & -\epsilon_i \end{bmatrix} < 0 \tag{22}$$

$$\begin{bmatrix} \bar{\Phi}_{ij} + \bar{\Phi}_{ji} + 2\bar{\Phi}_1(\bar{Z}_2) & \epsilon_i \bar{\mathcal{D}}_i & \bar{\mathcal{E}}_{ij} \\ * & -\epsilon_i I & 0 \\ * & * & -\epsilon_i \end{bmatrix} < 0 \tag{23}$$

$$\begin{bmatrix} \bar{\Phi}_{ij} + \bar{\Phi}_{ji} + 2\bar{\Phi}_2(\bar{Z}_2) & \epsilon_i \bar{\mathcal{D}}_i & \bar{\mathcal{E}}_{ij} \\ * & -\epsilon_i I & 0 \\ * & * & -\epsilon_i \end{bmatrix} < 0 \tag{24}$$

$$\bar{\Phi}_{ij} = \begin{bmatrix} \bar{\Phi}_{11i} & \bar{\Phi}_{12ij} & \bar{Z}_1 & 0 & \bar{\Phi}_{15i} & -\mu_1 B_{fi} & \bar{\Phi}_{17} \\ * & \bar{\Phi}_{22ij} & 0 & 0 & \bar{\Phi}_{25ij} & -\mu_2 B_{fi} & 0 \\ * & * & -\bar{Q}_2 - \bar{Z}_1 & 0 & 0 & 0 & 0 \\ * & * & * & \bar{Q}_3 & 0 & 0 & 0 \\ * & * & * & * & \bar{\Phi}_{55} & -\mu_3 B_{fi} & 0 \\ * & * & * & * & * & -\gamma^2 I & 0 \\ * & * & * & * & * & * & -I \end{bmatrix} \tag{25}$$

$$\bar{\Phi}_1(\bar{Z}_2) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & -4\bar{Z}_2 & 3\bar{Z}_2 & \bar{Z}_2 & 0 & 0 & 0 \\ * & * & -3\bar{Z}_2 & 0 & 0 & 0 & 0 \\ * & * & * & -\bar{Z}_2 & 0 & 0 & 0 \\ * & * & * & * & 0 & 0 & 0 \\ * & * & * & * & * & 0 & 0 \\ * & * & * & * & * & * & 0 \end{bmatrix} \quad (26)$$

$$\bar{\Phi}_2(\bar{Z}_2) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & -4\bar{Z}_2 & \bar{Z}_2 & 3\bar{Z}_2 & 0 & 0 & 0 \\ * & * & -\bar{Z}_2 & 0 & 0 & 0 & 0 \\ * & * & * & -3\bar{Z}_2 & 0 & 0 & 0 \\ * & * & * & * & 0 & 0 & 0 \\ * & * & * & * & * & 0 & 0 \\ * & * & * & * & * & * & 0 \end{bmatrix} \quad (27)$$

$$\begin{aligned} \bar{\Phi}_{11i} &= \bar{Q}_1 + \bar{Q}_2 + \bar{Q}_3 - \mu_1 sym(A_{i0}\bar{G}) - \bar{Z}_1, \\ \bar{\Phi}_{12ij} &= -\mu_2 \bar{G}^T A_{i0}^T - \mu_1 B_{i0} Y_j C_2, \\ \bar{\Phi}_{22ij} &= -\mu_2 sym(B_{i0} Y_j C_2) - (1 - h_d)\bar{Q}_1, \\ \bar{\Phi}_{15i} &= \bar{P} + \mu_1 \bar{G} - \mu_3 \bar{G}^T A_{i0}^T, \\ \bar{\Phi}_{25ij} &= \mu_2 \bar{G} - \mu_3 C_2^T Y_j^T B_{i0}^T, \\ \bar{\Phi}_{55} &= d_m^2 \bar{Z}_1 + d_r^2 \bar{Z}_2 + \mu_3 sym(\bar{G}), \\ \bar{\Phi}_{17} &= \bar{G}^T C_1^T, \quad d_r = \eta_2 - \eta_1, \quad \bar{G} = V \begin{bmatrix} \hat{G}_1 & 0 \\ 0 & \hat{G}_2 \end{bmatrix} V^T \end{aligned}$$

and

$$\bar{\mathcal{D}}_i = \begin{bmatrix} -\mu_1 D_{Ai}^T & -\mu_2 D_{Ai}^T & 0 & 0 & -\mu_3 D_{Ai}^T & 0 & 0 \\ -\mu_1 D_{Bi}^T & -\mu_2 D_{Bi}^T & 0 & 0 & -\mu_3 D_{Bi}^T & 0 & 0 \\ -\mu_1 D_{Bfi}^T & -\mu_2 D_{Bfi}^T & 0 & 0 & -\mu_3 D_{Bfi}^T & 0 & 0 \end{bmatrix}^T,$$

$$\bar{\mathcal{E}}_{ij} = \begin{bmatrix} E_{Ai}\bar{G} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & E_{Bi} Y_j C_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & E_{Bfi} & 0 \end{bmatrix}.$$

Where $K_i = Y_i W S \hat{G}_1^{-1} S^{-1} W^T$
The proof is omitted due to lack of space

IV. Vehicle simulation results

To show the effectiveness of the proposed robust controller, we have carried the following series of simulations of vehicle controlled through a network. In the design, the nominal stiffness coefficients considered are [6]:

Nominal stiffness coefficients	Cf1	Cf2	Cr1	Cr2
Values	60712	4812	60088	3455

The network-related parameters are assumed: $h = 5ms$, the maximum delay $\eta_1 = 6ms$, $\eta_2 = 10ms$, the maximum number of data packet dropouts $\bar{\sigma} = 3$.The time varying delays between the sensors and controller as well as between controller and actuator are generated randomly such as $\min(\tau^{sc} + \tau^{ca}) \geq \eta_1$, and $\max(\tau^{sc} + \tau^{ca} + (\bar{\sigma} + 1)h) \leq \eta_2$ and packet dropouts are also generated randomly such as $max(Ne) \leq 3$, where Ne is the number of packet dropouts. The minimum allowable γ is 4, $h_d = 0.1$, $\mu_1 = 1$, $\mu_2 = 0.9$ and $\mu_3 = 0.2$ and $\epsilon_i = 60$, by Theorem 3.1 we find a feasible solution as follows

$$K_1 = -2.0397 \quad 10^4, \qquad K_2 = -2.2756 \quad 10^4 \qquad (28)$$

Let consider the steering angle given in figure (6). Firstly, we considered the case where the control system not takes into account the network effect in terms of delay and packet dropout, As shown in figure (7) and figure (8), the behavior of the vehicle becomes unstable .

To overcome this problems, we have tested our proposed method which consider both the delay and packet dropout in data transmission network, figure (7) and figure (8) show state variable evolutions and figure (9) shows the input control in this case. We remark that our proposed active cornering stability control system that uses a data transmission network is efficient and maintains the vehicle stable for the maneuver given in figure (6).

For simulation, the initial condition is assumed to be $x_0 = \begin{bmatrix} 0.1 \\ 0.1 \end{bmatrix}$. The state responses of the NCS with control input are depicted in figures (7) and (8) which we can see that all the states component converge to zero. The simulation results are in accordance with the analysis and support the effectiveness of the developed design strategy.

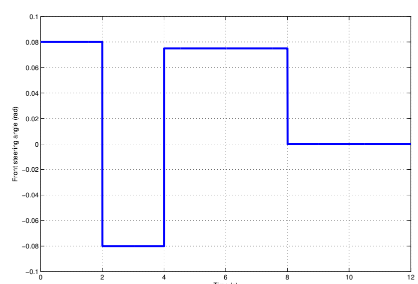

Fig. 6. Front steering angle δ_f

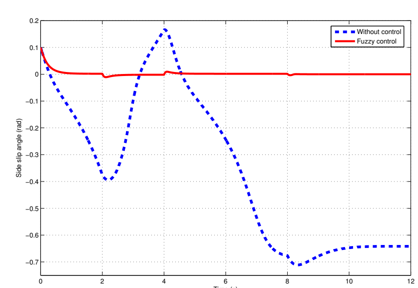

Fig. 7. Response of the sideslip angle β.

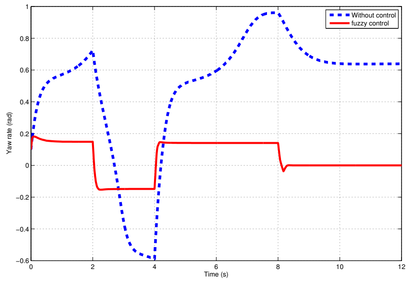

Fig. 8. Response of the yaw rate r.

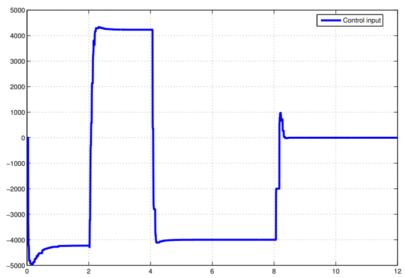

Fig. 9. Curve of moment M_Z.

V. Conclusion

In this paper, we have presented new conditions for Network based robust H_∞ fuzzy static output feedback controller design for vehicle dynamics by taken into account the network induced delay data packet dropout in the network. By considering the nonlinearities of the cornering forces, road adhesion variations and the driver actions, the optimal allowable delay bound and the static feedback gains of a memoryless controller are derived by solving a set of LMI constraints. By simulations, we have shown that the proposed robust controller based on the LMI approach for vehicle cornering stability improvement is very efficient and practical.

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