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ROBUST H∞ HANDLING STABILITY CONTROL FOR ALL-WHEEL INDEPENDENT STEERING VEHICLE WITH TIME DELAY

Naisi Zhang
National Key Lab of Vehicular Transmission
Beijing Institute of Technology
Beijing, China

Jibin Hu, Jun Ni*
National Key Lab of Vehicular Transmission
Beijing Institute of Technology
Beijing, China

***Abstract*—A robust control method considering the pole placement for handling stability of the ground vehicles is studied in this paper. For anglicizing the lateral dynamics problem, the bike vehicle model is introduced firstly. Since saturation and non-linear phenomenon may happen on tires during the time when the vehicle is steering, parameters like cornering stiffness would change during that procedure and hence there're parameter uncertainties in the system. Moreover, the modelling uncertainties and disturbance also exist. Robust control is applied for dealing the problem above. A H∞ controller is designed to guarantee performance of the handling stability. Pole placement method is used for the consideration of the transient response. State feedback controller is derived according to the model with uncertainties and the method. Linear matrix inequality (LMI) method is used for solving the gain of the feedback matrix. Simulations are done for analyzing the effectiveness of the controller. The controller can improve the safety and helping the vehicle track the trajectory.**

Keywords—Robust control; all-wheel independent steering; NCS

I. INTRODUCTION

In the past decade, effort has been done for increasing the vehicle advanced technology. Traditional vehicles are usually controlled singly by drivers. However, the modern vehicles are different. Active control technologies, mainly including AFS, DYC, and ABS [1-3] are widely applied for helping improve fuel economy, driving stability and safety these years. DYC is one of the most concerned issues for improving the handling stability. The method is aiming at calculating proper yaw moment and affecting the vehicle's lateral motion. Different methods including MPC, sliding mode control, fuzzy control and others, have been proposed [4-7] for generating the extra yaw moment. In the past decades, four-wheel-driving electric vehicles with all-wheel independent steering has attracted scientists' attention. Motors on the vehicle can generate the yaw moment flexibly.

For realizing the technologies above, the control unit for vehicle is becoming more and more complex. Numerous units are used including sensors, controllers and actuators with complex wiring connecting. Since the system may be influenced by many factors, time delay exists in the controlling system. The vehicle dynamics controlling system through the field network usually be considered as a networked control system (NCS) [8-9], moreover, data transmission would cause the delay in the system will influence the controlling effect, even the handling stability [10]. Kinds of ways, including Taylor series expansion, modeling Markov chains, predictive control, etc. are used for solving the problem [11-13].

In the other hand, the road and environment changes nearly all the time. The changes influence the value of some parameters such as the cornering stiffness. In a result, time-varying uncertainties and disturbances exist in the system and they are sensitive to the stability of the system. Polytypic methodology with finite vertices, and norm-bounded uncertainty are the two main methods describing the uncertainty in the system [14-15]. The former method should be chosen depends on whether each of the vertex can be calculated by different weighting parameter, and the later method usually depends on whether the number of the vertices is large [16-20]. Usually, the tire model is nonlinear with the saturation property, and its uncertainty can be considered as a norm-bounded variation.

Ackerman steering is a normal steering mode used on traditional vehicles, scholars have discussed much about the handling stability based on the that mode. Controlling strategy for minimizing the sideslip angle based on the reference model are proposed. However, for the all-wheel independent steering vehicle, reference model aiming at minimizing the yaw rate may be put forward.

A robust H∞ state feedback controller aiming at controlling all-wheel independent steer vehicle is proposed, considering the uncertainties in the parameter. The tire cornering stiffness, the change of the vehicle's mass and the moment of the inertia are considered as influence factors. The goal is to improve the vehicle's handling stability. Magic formula is used for modeling the tires, generating the uncertainties. Moreover, the model considers about the uncertainties caused by the change of the mass and moment of inertia, verifying the controller's effectiveness. In the other hand, pole placing is one of the effective methods improving the system's flexibility. It can be used for improving the system's performance by designing a feedback controller. Considering about the uncertainties existing in the system, the poles can be placed in a given region instead of the exactly given points. Linear matrix inequality (LMI) is usually used for describing the problem.

This paper's main contribution can be summarized as following: 1) Improve the controller with considering the maximum time delay during the data transmitting; 2) Proposing a new reference model different from the model in traditional DYC method, helping vehicle improve handling stability and simulate the performance on the simulation platform; 3) Proposing a robust controller help correct the vehicle's tracking trajectory in special occasions.

The structure of this paper is arranging as following. The 2 DoF vehicle model, using the norm-bounded method describing the uncertainty existing in the system and the time delay is introduced in the second part. In the third section, linear matrix inequality (LMI) description is listed for solving the problem, and at last, in section four, simulations results are shown, and then the conclusion is represented.

II. DESCRIPTI ON OF VEHICLE'S UNCERTAIN SYSTEM

A. Vehicle Dynamic Model

For designing the controller, uncertainties are described in this section. Here the traditional bicycle model of vehicle dynamics is used, and the structure of the model is shown in Fig.1. The distances from the front and rear axles to the CG are a and b respectively [21-24]. The front tires' lateral forces are described as F_{y1} and F_{y2}, and δ represents the steering angle.

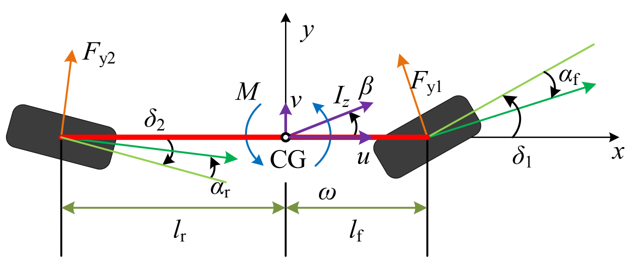

Fig.1 2-DOF vehicle bicycle model

Since there are a lot of uncertainties generated when the vehicle is working, and modeling uncertainties should be considered. The dynamic model of the vehicle can be rewritten as:

$$\dot{x}(t) = (A + \Delta A)x(t) + (B + \Delta B)u(t) + w(t) \qquad (1)$$

with

$$A = \begin{bmatrix} \dfrac{k_1 + k_2}{mu} & \dfrac{ak_1 - bk_2}{mu^2} - 1 \\ \dfrac{ak_1 - bk_2}{I_z} & \dfrac{a^2k_1 + b^2k_2}{I_z u} \end{bmatrix} \quad B = \begin{bmatrix} 0 & \dfrac{1}{I_z} \end{bmatrix}^T$$

The state variable $x(t)=[\beta(t)\ \omega(t)]^T$ stands for the system state, and $u(t)=M(t)$ is the control input, k_1, k_2 are the cornering stiffness for the front and the rear wheels, u is the longitudinal speed, I_z is the inertia. Moreover, the external input signal can be shown according to a linear combination as:

$$w = \begin{bmatrix} -\dfrac{k_1}{mu} & -\dfrac{k_2}{mu} \\ -\dfrac{ak_1}{I_z} & \dfrac{bk_2}{I_z} \end{bmatrix} \begin{bmatrix} \delta_1(t) \\ \delta_2(t) \end{bmatrix}$$

For considering about the uncertainties in the system, including the uncertainties in the parameter such as the cornering stiffness and the changing of the mass and moment of inertia, Δ in the matrix is used for expressing the uncertainties. With a norm-bounded approach describing the indeterminacies, ΔA and ΔB can be expressed as $\Delta A=DFE_1$ and $\Delta B=DFE_2$, where D, E_1 and E_2 are known constant matrix function, which satisfies $FF^T \leq I$.

B. Reference State model

In terms of the common two states in the model for controlling the stability of the vehicle, the slip angle and the raw rate stand for the stability and the handling performance respectively in the traditional Ackerman steering vehicle, so the reference sideslip angle is desired as small as possible to guarantee stability, while in the other hand, the reference yaw rate is related with parameters like the speed, steering angle and so on [25-26].

In this paper, considering the characteristic of the all-wheel steering vehicle, a new reference state is introduced. For making the vehicle keeping stable during the process of the maneuver, the reference state is defined as:

$$x_d = \begin{bmatrix} \beta_{ref} \\ \omega_{ref} \end{bmatrix} = \begin{bmatrix} k_{df} & k_{dr} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} \qquad (2)$$

C. Analysis of model with time-caring delays

For measuring the vehicle states, electric sensors, are usually applied on the vehicle communicating and exchanging data [27-28]. However, since the property of the transmission, delays are existing in the network. Sensor-to-controller delay and controller-to-actuator delay, are as often-considered delay in control system and vary by time [29].

Assuming the time delay $\tau(t)$ satisfying (4) with the upper bound of the time delay t_d:

$$0 < \tau(t) < t_d \qquad (3)$$

Then consider about the time delay, the state feedback controller can be expressed as (5) with the designing gain K:

$$u = u(t - \tau(t)) = Kx(t - \tau(t)) \qquad (4)$$

Submitting (5) into (1), the state-space can be changed as:

$$\dot{x}(t) = (A + \Delta A)x(t) + (B + \Delta B)u(t - \tau(t)) + w(t) \qquad (5)$$

D. Poles placement problem

The transit response of a linear controlling system is related to the location of the system's poles, for a second-order controlling system, the poles $\lambda= -\zeta\omega_n \pm j\omega_d$ can influence the system's performance. Constraining λ into a given region, can help ensure a satisfactory transient response.

For better effect of controlling, the region can be constraint as:

$$S=\left\{x+jy\in C \mid x<-\alpha,\left|x+jy\right|<R,x\tan\theta<-\left|y\right|\right\} \quad (6)$$

In this region, the system can usually obtain the least dumping ratio $\zeta=\cos\theta$ and the largest dumping natural frequency ω_d so that the parameters, such as max overshoot, the rising time and the settling time, would not exceed the bounds determined by them. However, it is not easy to describe the specific zone in direct since there are three equations describing this region. So many people pay attention to a special pole constraint region, that is the circular region. It has the simplest equation constraint; hence the goal pole region can be described via using the circle circular region in a lot of practical designing.

E. Problem statement

Aiming at ensuring the handling stability and adjust the all-wheel independent steering maneuver, define the control output as $z_1(t)=\beta(t)$, $z_2(t)=\omega(t)$, we can get $z_1(t)=C_1x(t)$ and $z_2(t)=C_2x(t)$,
where

$$\begin{aligned} C_1&=\begin{bmatrix}1 & 0\end{bmatrix}x \\ C_2&=\begin{bmatrix}0 & 1\end{bmatrix}x \end{aligned} \quad (7)$$

And then the controlling object is proposed, that is to propose a robust controller satisfying:
1). The system (6) is asymptotically stable with $w(t)=0$;
2). The system (6) has the following H_∞ performance:

$$\left\|T_{z2w}\right\|_\infty=\sup_{\left\|w(t)\right\|_2\neq 0}\frac{\left\|z_2(t)\right\|_2}{\left\|w(t)\right\|_2}<\gamma_1 \quad (8)$$

and the energy-to-peak performance:

$$\left\|z_1(t)\right\|_\infty<\gamma_2\left\|w(t)\right\|_2 \quad (9)$$

where γ_1, $\gamma_2>0$ are given small numbers.

3). The $\mathcal{D}$-stability at a circle region with the center q and the radius r can be guaranteed.

III. Controller Design

In this section, a robust H_∞ controller for all-wheel steering vehicle is designed. For the system description as (1), design controller like (5), satisfying the performance (8) and (9).

For deducting the necessary LMIs, lemmas are introduced firstly:

Lemma 1[16]: In terms of any positive definite matrix $Q\in\mathbf{R}^{n\times n}$, the following inequality holds:

$$-2x^Ty\leq x^TQ^{-1}x+y^TQy \quad (10)$$

Lemma 2[17]: Let $Y=Y^{\mathrm{T}}$, and D and E are the real matrices with proper dimensions, matrix F satisfies $F(t)^{\mathrm{T}}F(t)<I$, then the following LMI:

$$Y+DFE+\left(DFE\right)^T<0 \quad (11)$$

holds if and only if there exists a positive scalar $\varepsilon>0$ such that

$$Y+\varepsilon^{-1}DD^T+\varepsilon E^TE<0 \quad (12)$$

Lemma 3[18]: Consider system as (13):

$$\begin{cases}\dot{x}=Ax+BKx\left(t-\tau\left(t\right)\right)+w\\ z=Cx\end{cases} \quad (13)$$

Lemma 4[19]: The system (13) is $\mathcal{D}$-stabilizable when and only when a positive matrix $X>0$ existing, satisfying the LMI below:

$$\begin{bmatrix}-rX & qX+\left(A+B_2K\right)X\\ * & -rX\end{bmatrix}<0 \quad (14)$$

where r is the radius of the zone and q is the center of the circle zone.

The closed-loop system above can be stable and satisfies the performance $||z||_\infty<\gamma||w||_2$ when and only when there are positive matrix P R with proper dimensions existing, t_d being the max time delay, satisfying LMI (14):

$$\begin{cases}\begin{bmatrix}A^TP+PA+R & PBK\\ * & -\left(1-t_d\right)R\end{bmatrix}<0\\ CPC^T<\gamma^2I\end{cases} \quad (15)$$

The controller is designed as following:

Theorem: For the given scalars $\gamma_1>0$, $\gamma_2>0$, and the maximum of the time delay t_d in the transmission, the feedback controller in (5) is quadratically stable with $w(t)=0$, and satisfying the performance (8) and (9) for $w(t)\in[0,\infty)$, if there exist positive definite matrices X, Q_1, Q_2, Q_3, Y and matrix Z with appreciate dimension satisfying the LMIs below:

$$\begin{cases}\begin{bmatrix}X_1 & X_2\\ * & X_3\end{bmatrix}<0\\ \begin{bmatrix}AX+XA^T+Y & BZ & \varepsilon_3D & XE_1^T\\ * & -\left(1-t_d\right)Y & & ZE_2^T\\ * & * & -\varepsilon_3I & \\ * & * & * & -\varepsilon_3I\end{bmatrix}<0\\ \begin{bmatrix}-Z & C_1^T\\ * & -\gamma_2^2I\end{bmatrix}<0\\ \begin{bmatrix}-rZ & D & qZ+\left(AZ+B_2Q\right) & \left(E_1Z+E_2Q\right)^T\\ * & -I & 0 & 0\\ * & * & -rZ & 0\\ * & * & * & -I\end{bmatrix}<0\end{cases} \quad (16)$$

where

$$X_1=\begin{bmatrix}\Gamma_0 & BZ & 0 & I & XA^T & C_2^T\\ * & -t_d^{-1}Q_1 & 0 & 0 & Z^TB^T & 0\\ * & * & -R & 0 & 0 & 0\\ * & * & * & -\gamma^2 I & 0 & 0\\ * & * & * & * & -t_d^{-1}Q_2 & 0\\ * & * & * & * & * & -I\end{bmatrix}$$

with $\Gamma_0=sys\left(XA^T+BZ\right)+Q_0$

$$X_2=\begin{bmatrix}\varepsilon_1 D & 0 & \left(E_1X+E_2Z\right)^T & XE_1^T\\ 0 & 0 & \left(E_2Z\right)^T & \left(E_2Z\right)^T\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & \varepsilon_2 D & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$$

$X_3=\mathrm{diag}\left(-\varepsilon_1 I,-\varepsilon_2 I,-\varepsilon_1 I,-\varepsilon_2 I\right)$

The required controller can be written as $K=ZX^{-1}$.

Proof:

First, define $\overline{A}=A+DFE_1$, $\overline{B}=B+DFE_2$, then the vehicle's model can be written as following:

$$\dot{x}(t)=\overline{A}x(t)+\overline{B}u(t-\tau)+w(t) \tag{17}$$

Since:

$$\int_{t-\tau}^{t}\dot{x}(s)ds=x(t)-x(t-\tau) \tag{18}$$

we have the equation as following:

$$\dot{x}(t)=\left(\overline{A}+\overline{B}K\right)x(t)-\overline{B}K\int_{t-\tau(t)}^{t}\dot{x}(s)ds+w(t) \tag{19}$$

For analyzing the stability of the system, here Lyapunov stability theorem is used, and the system's Lyapunov function is defined as:

$$\begin{aligned}V\left(x(t)\right)&=x^T(t)Px(t)+\int_{t-t_d}^{t}x^T(s)Rx(s)ds\\&+\int_{-t_d}^{0}\int_{t+\beta}^{t}x^T(\alpha)Qx(\alpha)d\alpha d\beta\end{aligned} \tag{20}$$

where P, Q, R are symmetric positive definite matrices with suitable dimensions. By deriving the derivative of $V(t)$ using the lemma above, we can get the following:

$$\begin{aligned}\dot{V}\left(x(t)\right)&\le x^T(t)\Psi x(t)+w^T(t)Px^T(t)\\&+x^T(t)Pw(t)+t_d\dot{x}^T(t)Q\dot{x}(t)\\&-x^T(t-t_d)Rx(t-t_d)\end{aligned} \tag{21}$$

where

$$\Psi=sys\left[P\left(\overline{A}+\overline{B}K\right)\right]+R+t_dP\overline{B}KQ^{-1}K^T\overline{B}^TP$$

Let $\xi_0^T(t)=[x^T(t), x^T(t-t_d), x^T(t-\tau), w^T(t)]$, the left side of (20) can be written as:

$$\dot{V}\left(x(t)\right)\le\xi^T(t)\Lambda\xi(t)+t_d\dot{x}^T(t)Q\dot{x}(t) \tag{22}$$

where

$$\Lambda=\mathrm{diag}\left(\Phi,-R,0,0\right)$$

with

$$\Phi=sys\left[P\left(\overline{A}+\overline{B}K\right)\right]+R+t_dP\overline{B}KQ^{-1}K^T\overline{B}^TP$$

Then consider the performance of the system, add $z_2^T(t)z_2(t)$-$\gamma^2w^T(t)w(t)$ to both sides of the inequality above, with $z_2(t)=C_2x(t)$, we can get:

$$\dot{V}\left(x(t)\right)+z_2^T(t)z_2(t)-\gamma^2w^T(t)w(t)\le\vartheta^T(t)\Pi\vartheta(t) \tag{23}$$

where

$$\Pi=\begin{bmatrix}\Theta & P\overline{B}K & 0 & P & \overline{A}^T & C_2^T\\ * & -t_d^{-1}Q & 0 & 0 & \left(\overline{B}K\right)^T & 0\\ * & * & -R & 0 & 0 & 0\\ * & * & * & -\gamma^2 I & 0 & 0\\ * & * & * & * & -t_d^{-1}Q^{-1} & 0\\ * & * & * & * & * & -I\end{bmatrix}$$

with

$$\Theta=sys\left[P\left(\overline{A}+\overline{B}K\right)^T\right]+R$$

According to the Lyapunov stable theorem, the closed-loop system can be stable if $\Pi<0$. Consider the uncertainty in matrix A and B, the Π can be written as:

$$\begin{aligned}\Pi=&\begin{bmatrix}\Gamma & PBK & 0 & P & A^T & C_2^T\\ * & -t_d^{-1}Q & 0 & 0 & \left(BK\right)^T & 0\\ * & * & -R & 0 & 0 & 0\\ * & * & * & -\gamma^2 I & 0 & 0\\ * & * & * & * & -t_d^{-1}Q^{-1} & 0\\ * & * & * & * & * & -I\end{bmatrix}+\\ &sys\left(\begin{bmatrix}PD & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & D\\ 0 & 0\end{bmatrix}\begin{bmatrix}F_1 & \\ & F_2\end{bmatrix}\begin{bmatrix}\left(E_1+E_2K\right)^T & E_1^T\\ \left(E_2K\right)^T & \left(E_2K\right)^T\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\end{bmatrix}^T\right)\end{aligned} \tag{24}$$

with

$$\Gamma=sys\left[P\left(A+BK\right)^T\right]+R$$

Then according to the lemma 2 and Schur Complement, and $\Pi<0$ is equal to $\Pi_1<0$, where

$$\Pi_1=\begin{bmatrix}\Pi_{11} & \Pi_{12}\\ * & \Pi_{22}\end{bmatrix} \tag{25}$$

$$\Pi_{11}=\begin{bmatrix} \Gamma & PBK & 0 & P & A^T & C_2^T \\ * & -t_d^{-1}Q & 0 & 0 & (BK)^T & 0 \\ * & * & -R & 0 & 0 & 0 \\ * & * & * & -\gamma^2 I & 0 & 0 \\ * & * & * & * & -t_d^{-1}Q^{-1} & 0 \\ * & * & * & * & * & -I \end{bmatrix}$$

$$\Pi_{12}=\begin{bmatrix} \varepsilon_1 PD & 0 & (E_1+E_2K)^T & E_1^T \\ 0 & 0 & (E_2K)^T & (E_2K)^T \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \varepsilon_2 D & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$\Pi_{22}=\mathrm{diag}(-\varepsilon_1 I, -\varepsilon_2 I, -\varepsilon_1 I, -\varepsilon_2 I)$

By premultiplying and postmultiplying Π_1 by diag (P^{-1}, P^{-1}, I, I, I, I, I, I, I), we can get the congruent transformation of the matrix, and then by defining $X=P^{-1}$, $Z=KP^{-1}$, $Q_0=P^{-1}RP^{-1}$, $Q_1=P^{-1}QP^{-1}$, $Q_2=Q^{-1}$, it can be seen that the inequality (26) is equivalent to the first LMI in (17).

By a similar proof, the other LMIs in (17) can be obtained, then the proof completes.

IV. SIMULATION

In the section, simulation case for different maneuvers are mentioned to validate the proposed method. Both the front and the rear steering angles are set the same for convenience. The reference sideslip angle should be the same with the steering angle. Simulation is based on the Simulink platform. A whole vehicle mode is used. Magic Formula tire model is used, and road roughness exists in simulation. The vehicle parameters are as following: m_0=800kg, I_z=4400kg·m^2, a=1m, b=1m, k_1=-45813N/rad, k_2=-45813N/rad. Consider the max time delay in the system caused by data transmission is 100ms, maneuvers with controller and without controller are simulated. In the simulation cases, steering angle is input when the longitudinal speed is almost keeping as a constant. Simulations are done in a high speed (80km/h). Simulation results for different cases are shown below.

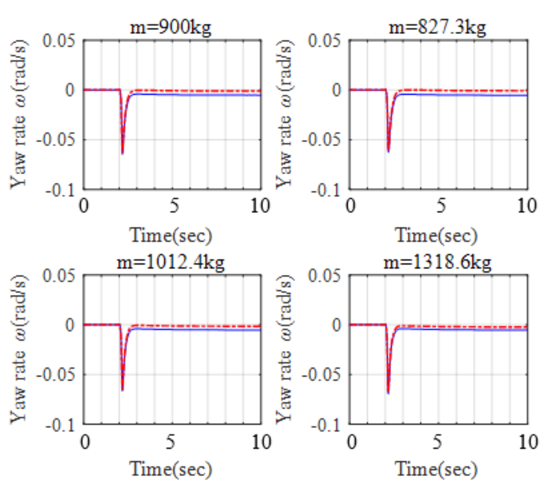

Fig. 2 Yaw rate under different vehicle mass

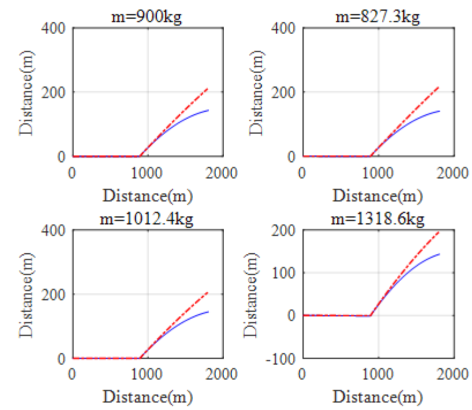

Fig. 3 Trajectory under different vehicle mass

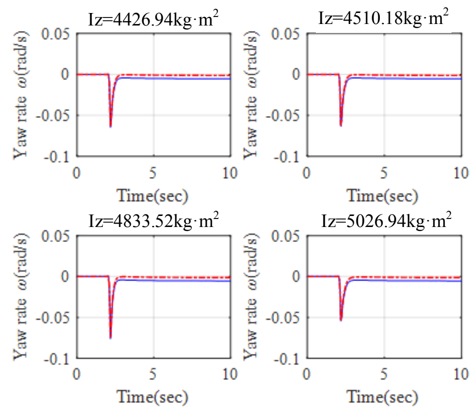

Fig. 4 Yaw rate under different moments of inertia

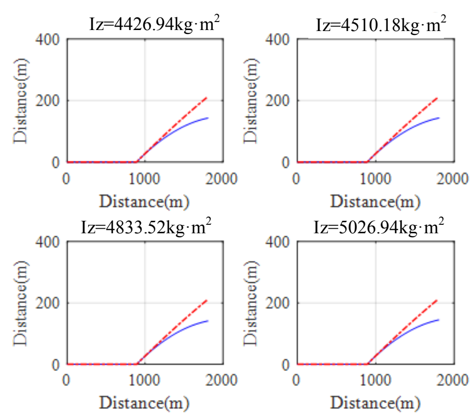

Fig. 5 Trajectory under different moments of inertia

Fig. 2 is the yaw rate response and Fig. 3 is the vehicle's trajectory as the change of the vehicle's mass. The system is robust with the effect of the proposed controller. Fig. 4 and Fig. 5 is the yaw rate response and the trajectory as the change of the moment of inertia respectively. The proposed controller improves the system's performance with better robustness and it can correct the direction of the vehicle, helping vehicle following the correct direction.

V. CONCLUSION

A robust yaw-moment feedback controller by considering the time delay and uncertainties mainly including modeling uncertainties and parameter uncertainties is designed especially for the all-wheel steering vehicles. A reference model aiming at minimizing the yaw rate and making the body sideslip angle linear with the steering angle is mentioned. By analyzing the system's performance and a series of mathematical deduction, the controller with the performance of robustness is obtained. Simulation results under some different cases, mainly including the different mass and the moment of inertia caused by the changing of the vehicle's loading, verify the effectiveness of the proposed control method respectively. The proposed controller can correct the vehicle's direction, especially on the high-speed maneuver. More advanced controlling strategies can be applied in the further study.

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