An IMC Controller Design for a Steer-By-Wire Vehicle

Xiong LI[1], Mengqi LIN[1], Xiaoxuan CHENG[2], Li CHEN[2], Fan YU[1]
1.School of Mechanical Engineering, Shanghai Jiao Tong University
2. State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University
NO.800 Dongchuan Road 200240 shanghai. China
Email: corresponding. fanyu@sjtu.edu.cn

The purpose of this study is to build a novel control scheme for a Steer-by-Wire system. Corresponding steer execution system model and environment are developed respectively. An Internal Model Control(IMC) strategy for steering execution system control of SBW is applied to track reference vehicle states. Then co-simulation is carried out via MATLAB/Simulink and CarSim, to validate controller with double lane change(DLC) test and other driving condition tests. The simulation test show the satisfactory angle tracking capability on the premise of vehicle stability, which indicates that the proposed control structure exploits the features of IMC strategies that allow to guarantee stability and to enhance performances.

Topic / Vehicle Dynamics and Chassis Control

1. INTRODUCTION

Recent development of automobile receives a lot of attention. In the further development of automatic driving progress, Steer-By-Wire (SBW) system will be a key element for highly automatic driving[1] , and has become the key technology for path tracking and obstacle avoidance of automatic driving. Thus it can improve the safety of steering maneuver in emergency due to decoupling of driver steering and vehicle lateral motion[2] .

SBW system removes the intermediate steering shaft, and directly uses the motor to realize the road sense feedback control and the wheel steering control. In order to keep steering tracking ability, more and more control systems are being applied to SBW system. Such as Fractional order PID[3], linear quadratic regulator (LQR)[4], H∞ robust control[5] and so on. However, the robust steering performance cannot be guaranteed because of the nonlinearity of vehicle model and complex driving conditions. Do, Manh Tuan, et al[6] applying slid mode control (SMC) to SBW system, the results show that designed SMC controller drive both the sliding variable and the tracking error converge to zero. Hai Wang et al.[7] employs an adaptive terminal sliding-mode control (ATSMC) to assure the finite-time error convergence without to know the prior knowledge of the system parameters and road information. Internal mode control (IMC) which was first proposed by Horowits[8], has been widely used in industrial process for its great robustness. Canale, Massimo, et al.[9-10] used IMC to finished the stability control of 4WS vehicle , and also compared the IMC and SMC control for vehicle yaw control, it is shown that chattering of the control input is absent with the designed IMC controller, whereas it could be a serious issue in SMC control. Men, Jinlai, et al.[11] used IMC to do the 4WS control , the results showed that IMC controller can be applied to most driving maneuvers and road surface conditions by applied linear internal vehicle model. Wu, Jian, et al.[12] put forward a 2-dof IMC controller to reach high performance of yaw rate tracking with certain robustness.

Above all, this paper is organized as follows. In section 2, the math model of SBW execution system is derived and a vehicle dynamics model is built in CarSim, while the SBW model is developed in MATLAB/Simulink. In section 3, an IMC controller is designed to track the vehicle state variables. In section 4, simulation under certain conditions and some comparison are developed and discussed. The final conclusions are given in section 5.

2. MODELING

This section first uses CarSim to provide the vehicle dynamic environment and operating conditions. Then MATLAB/Simulink is used to build the SBW dynamics model and the actuator internal model controller. The physical execution system framework and built test bench studied in this paper is shown below.

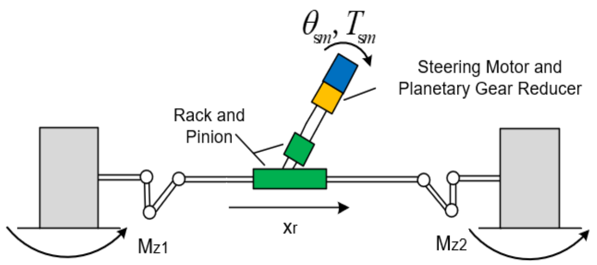

Fig. 1 SBW system physical framework

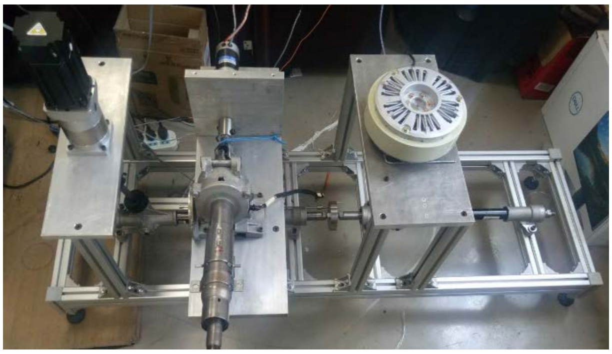

Fig. 2 SBW system test bench

Based on the B-Class Hatchback, the vehicle parameters are modified according to the real vehicle parameters, after which it is necessary to shield the steering system of the original vehicle, as CarSim doesn't contain SBW configuration. Other vehicle parameters such as brakes, suspensions, and tire models stay with the original parameters.

The steering execution system mainly includes a steering motor, a planetary gear reducer, a rack and pinion, and related couplings. Corresponding formulas are derived and with simplified motor model and Laplace Transformation, the SBW execution model equations are as follows.

$$(M_r s^2 + B_r s + \frac{K_{md}\, g_{sm}^2}{r_p^2}) \bullet x_r(\mathrm{s}) + F(\mathrm{s}) = \frac{K_{md}\, g_{sm}}{r_p}\theta_{sm}(\mathrm{s}) \quad (1)$$

$$T_{sm}(\mathrm{s}) = \left(J_{sm}s^2 + B_{sm}s + K_{md}\right) \bullet \theta_{sm}(\mathrm{s}) - \frac{K_{md}\, g_{sm}}{r_p} x_r(\mathrm{s}) \quad (2)$$

$$U_{sm}(\mathrm{s}) = \frac{R_{sm} + L_{sm}s}{K_2} T_{sm}(\mathrm{s}) + K_{sm}s\theta_{sm}(\mathrm{s}) \quad (3)$$

Where M_r is the steering rack mass, B_r is the steering rack damping coefficient, x_r is the steering rack displacement, F is the steering resistance applied to both ends of the rack by front wheels, K_{sm} is the pinion gear torsional stiffness, g is the steering motor reduction ratio, θ_{sm} is the steering motor rotation angle, r_p is the steering pinion radius, T_{sm} is motor torque, J_{sm} is motor moment of inertia, B_{sm} is motor damping coefficient, U_{sm} is motor voltage, R_{sm} is motor resistance, L_{sm} is motor inductance.

3. CONTROLLER DESIGN

The designed controller is an IMC controller to track the vehicle state variables. A typical internal mode controller block diagram is shown in Fig.2.

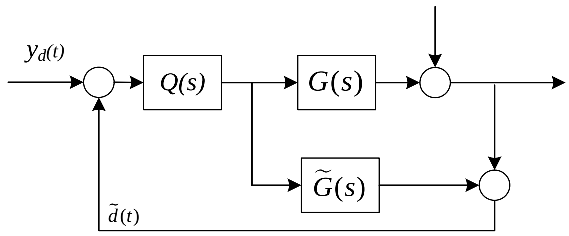

Fig. 3 Typical internal model control block diagram

According to the dynamic model of SBW system established above, choosing the rack and the steering motor as controlled object, the system input can be the steering resistance at both ends of the rack and the motor input at the motor end. The overall system input is the reference front wheel angle calculated by the upper controller, which is calculated by driver model in this study. The output is the actual front wheel angle, as the input of CarSim model. The control block diagram shown in Fig.4.

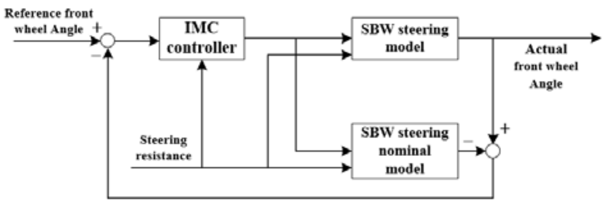

Fig. 4 IMC of the steering actuator system

Formulas (1) to (3) can be rewritten as below and controlled actuator system can be represented in Fig.4.

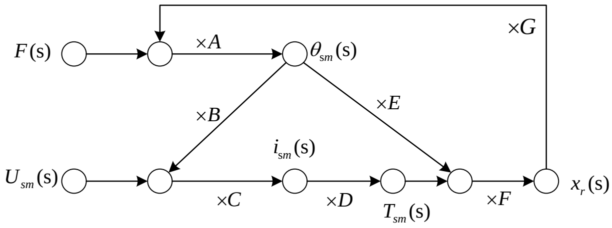

Fig. 5 Transfer function diagram of SBW actuator system

The variables above in can be represented as below and rewritten in matrix:

$$\begin{cases} \mathrm{A} = \dfrac{r_p}{K_{md}g_{sm}},\ \mathrm{B}{=}{-}K_{sm}s,\ \mathrm{C}{=}\dfrac{1}{R_{sm}+L_{sm}s},\ D = K_2 \\ E = -\left(J_{sm}s^2 + B_{sm}s + K_{md}\right),\ \mathrm{F}{=}{-}\dfrac{r_p}{K_{md}g_{sm}} \\ \mathrm{G} = (M_r s^2 + B_r s + \dfrac{K_{md}\,g_{sm}^2}{r_p^2}) \end{cases} \tag{4}$$

$$\begin{cases} x_r(\mathrm{s}){=}\left(H_1(\mathrm{s}) \quad H_2(\mathrm{s})\right)\bullet\begin{pmatrix} F(\mathrm{s}) \\ U_{sm}(\mathrm{s}) \end{pmatrix} \\ H_1(\mathrm{s}){=}\dfrac{ABCDF + AEF}{1-(\mathrm{ABCDFG+AEFG})} \\ H_2(\mathrm{s}){=}\dfrac{CDF}{1-(\mathrm{ABCDFG+AEFG})} \end{cases} \tag{5}$$

$$U_{sm}(\mathrm{s}){=}\left(x_r(\mathrm{s}) - H_1(\mathrm{s})\bullet F(\mathrm{s})\right)\bullet\frac{1}{H_2(\mathrm{s})} \tag{6}$$

And IMC controller can be designed as :

$$C(\mathrm{s}){=}\left(e_{xr} - H_1(\mathrm{s})\bullet F(\mathrm{s})\right)\bullet\frac{1}{H_2(\mathrm{s})} \tag{7}$$

Where e_{xr} represents the angle difference of actual model and nominal model.

As lack of specific value of parameters, the model identification is carried out with ARX algorithm to establish the nominal model of actuator system, which can be described as discrete transfer function:

$$A(z)\delta\left(t\right) = B_1(z)U(t-d) + B_2(z)F(t-d) \tag{8}$$

and the identification result is:

$A(z)$=1-0.9721z^{-1}-0.1091 z^{-2}-0.00907 z^{-3}+0.1009z^{-4} -0.01069z^{-5}

$B_1(z)$=-0.009372+0.02649z^{-1}- 0.00885 z^{-2}-0.009274z^{-3}

$B_2(z)$=-0.000129-0.0003104 z^{-1}+0.0004192 z^{-2} -0.0001281z^{-3}

Based on Laplace and Z Transform, combined equations (4) and (5) with identification result, corresponding parameters of steering actuator system can be specified.

4. SIMULATION RESULTS AND DISCUSSION

According to previous section, MATLAB/Simulink is used to model the SBW system controller and dynamics model, and CarSim is used to set up the simulation test conditions. In order to verify the control precision of the designed steering system internal model controller, this study designs the sine sweep steer input condition as the driver's open-loop input conditions. For the driver's closed-loop input conditions, double lane change condition and collision avoidance condition are designed. The parameters of the SBW system are shown in Table 1.

Table 1 Steering actuator parameters

Parameter	**Symbol / Unit**	**Value**
Steering motor moment of inertia	J_{sm} / $kg\cdot m^2$	0.00078
Steering motor damping coefficient	B_{sm} / $kg\cdot m^2\cdot s^{-1}$	0.00023
Steering motor reduction ratio	g_{sm}	20
Steering motor resistance	R_{sm} / Ω	0.51
Steering motor inductance	L_{sm} / H	0.00033
Steering motor electromagnetic torque coefficient	K_2 / $V\cdot s\cdot rad^{-1}$	0.056
Steering motor counter electromotive force coefficient	K_{sm} / $N\cdot m^{-1}$	0.056
Pinion gear torsional stiffness	K_{md} / $M\cdot m\cdot rad^{-1}$	180

Steering pinion radius	r_p / m	0.008
Steering rack mass	M_r / kg	2.31
Steering rack damping coefficient	$B_r / N \cdot m \cdot s \cdot rad^{-1}$	642

4.1 Sine sweep steer input condition

The simulation speed is set to 60km/h and the simulation step length is 0.001. The front wheel angle signal tracking and error are shown in Fig.6 and Fig.7.

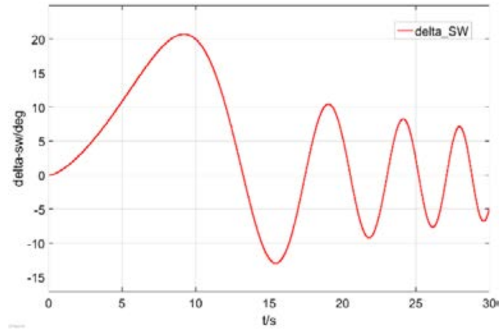

Fig. 6 Sine Sweep Steer Input

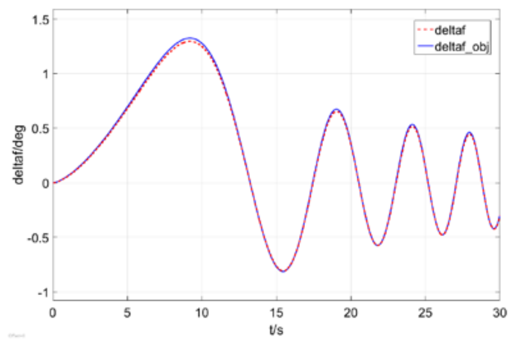

Fig. 7(a) Front Wheel Angle

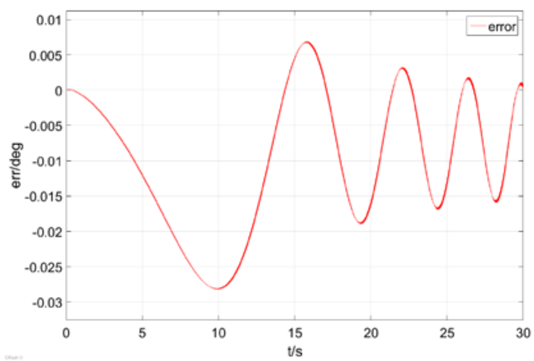

Fig. 7(b) Error of Front Wheel Angle

The figures show that when the driver changes the steering wheel angle frequency and amplitude, the internal model controller can track and control the front wheel angle very well. Max front wheel angle is 1.35°, while the max absolute tracking error is about 0.027° and the relative error is 2%, which indicates that the internal model controller has a good tracking ability of the front wheel angle.

4.2 Double lane change condition

Double lane change(DLC) condition is a typical test condition in the vehicle handling stability test. In this study, driver's preview time is set to 0.5s and vehicle speed is 60km/h. The test results are shown in Fig.8 and Fig.9.

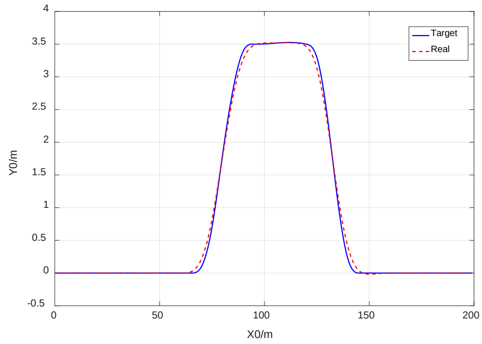

Fig. 8 DLC Vehicle Trajectory

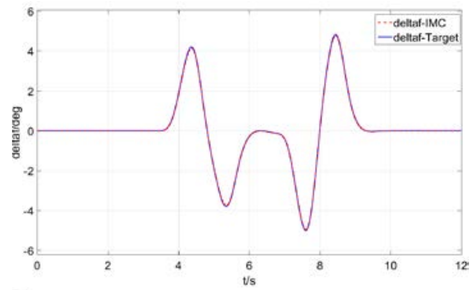

Fig. 9(a) Front Wheel Angle

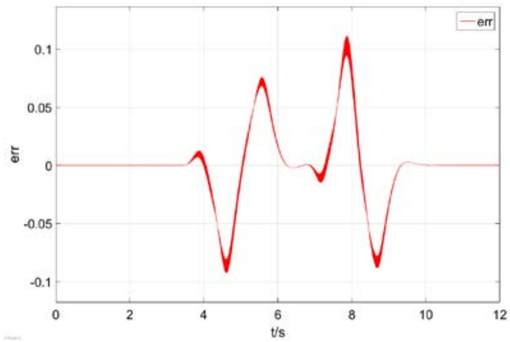

Fig. 9(b) Error of Front Wheel Angle

From Fig.8 and Fig.9, in the closed-loop double lane change trajectory tracking process, the designed controller can track and the previewed ideal trajectory well, with front wheel angle error within ±0.1°. To verify the SBW steering system tracking capability under different speeds, the vehicle speeds are set respectively to low speed (30km/h), medium speed (60km/h), and high speed (90km/h). The simulation results are shown in

Fig.10. As the speed increases, the tracking error increases, but the overall effect shows good response and the tracking condition also meets expectation.

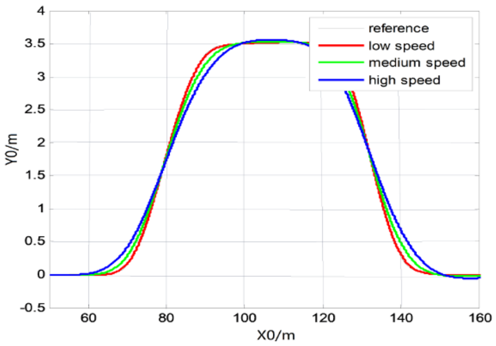

Fig. 10 DLC Trajectory in Different Vehicle Speed

Furthermore, to illustrate advanced anti-interference ability of designed controller, a PID controller, with motor voltage U_{sm} as control input, is designed and applied to the same working condition. The simulation parameters are set to 0.5s for the driver's preview time and the vehicle speed is 30km/h, with white noise interference directly applied to front wheel to simulate the impact of the road surface on the tires in driving, and the simulation results are shown in Fig.11 and Fig.12.

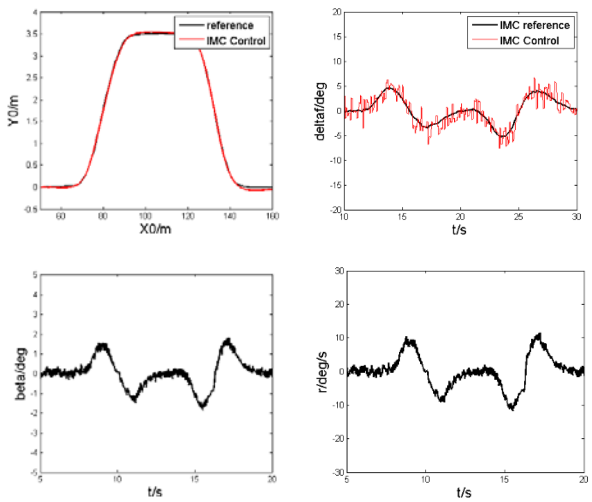

Fig. 11 Vehicle States with IMC Controller

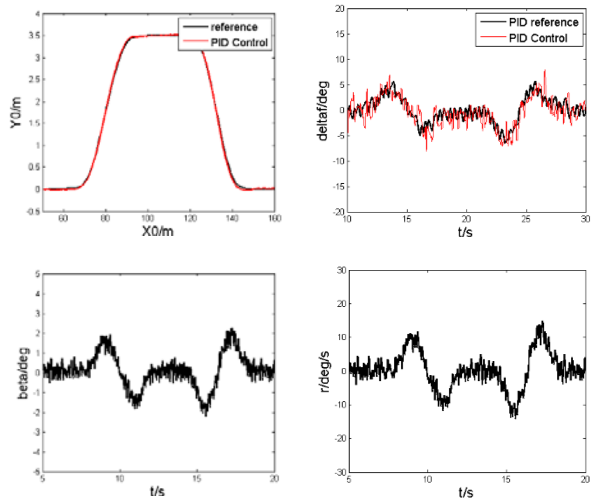

Fig. 12 Vehicle States with PID Controller

The results reported in Fig.11 and Fig.12 related to the DLC test with white noise, show the IMC system's capability to reject disturbances and keep stability. Although trajectory tracking effect with PID is satisfactory, fluctuations of other relative vehicle states are significantly higher. Moreover, the reference front wheel angle, indicating the driver's input to correct the angle deviation, with PID changes more frequently than IMC, which is considered as more consumption of driver's effort to eliminate the impact of interference.

4.3 Collision avoidance condition

The SBW system is one of the key systems for automobile collision avoidance, since the system has faster response characteristics with motor control. A CarSim built-in collision avoidance test for the actuator is carried out. The simulation parameters are set to 0.75s for the driver's preview time and the vehicle speed is 60km/h. The simulation results are shown in Fig.12 and Fig.13.

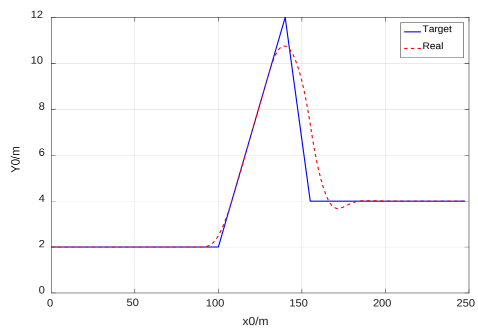

Fig. 12 Trajectory of Collision Avoidance

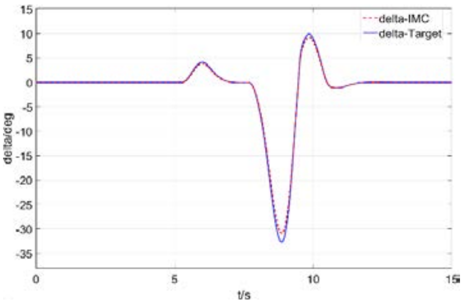

Fig. 13 Front Wheel Angle

According to the figure, under collision avoidance conditions with SBW system, driver can quickly achieve emergency collision avoidance, and the front wheel angle is well tracked with little error.

5. CONCLUSION

Based on the design principle of the internal model controller, this study designs a SBW steering actuator internal model controller with parameter identification of test bench. Then the driver's open-loop and closed-loop input simulation tests are performed. The simulation experiment results show that the designed assembly controller can ensure the achieved performances close to the targets, leading to stability increasement and less consumption of driver's effort.

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