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Research on the Control Strategy of Active Front Steering System

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Abstract: The control strategy of Active Front Steering (AFS) which equips vehicle is presented in this study. The proposed control strategy of AFS is designed to meet the demand of the steering characters and control stability of the vehicle. This strategy contains the controller of the variable transmission ratio and the controller of vehicle stability. The first controller applies the fuzzy sliding-mode control method to controlling the angle of the electromotor in order to realize the variable transmission ratio. The second controller put the fuzzy PID control method into use to keep the vehicle stable. According to the two degrees of freedom vehicle model, based on controlling of variable transmission ratio and the yaw velocity, the model of AFS controller is established. The performance of the AFS controller is evaluated by computer simulation. The simulation results demonstrate that: the strategy of AFS makes the vehicle has a good performance of steering characteristics and effectively enhances the control stability, especially in aspect of the surrounding adaptive capacity and driving safety of the vehicle.

Key word: Variable transmission ratio, fuzzy sliding-mode control, fuzzy PI control, control stability

INTRODUCTION

The Active Front Steering (AFS) is a new technology of vehicle steering system. The basic function of AFS is to improve the steering characteristics through variable transmission ratio of steering system which is changed with electronically controlled superposition angle of the steering axle. This technology works out the contradiction of steering portability and steering sensitivity and improves the control stability (Li *et al*., 2009) and driving safety. In addition, AFS enable the driver to obtain the true information of road feeling during driving. Therefore, lots of researches on AFS are carried out in the area of vehicle active control extensively.

Currently, AFS research mainly focused on the variable ratio and its influence on vehicle control stability. Zhao, Yu and Sun respectively designed and synthesized the feed forward and feedback H_8 control parts of active front wheel steering controller, with the consideration of uncertainty of some param eters and disturbance of strong side wind (Zhao *et al*., 2005), While no mention of steering characteristics of active steering system. Zhang and Shang bringed a yaw velocity sensor in active front steering system as feedback information, achieved the feedback control by applying PID control to modify the front steering angle in order to control yaw velocity and side slip angle (Zhang and Shang, 2009). But their study only used the step response and sine response of yaw velocity with the input of steering wheel angle. And always there is poor adaptability on running condition when use the conventional PID control. Zheng and Anwar presented an innovative yaw stability control algorithm via active front wheel steering system. This algorithm robustly decouple the lateral motions and yaw motions and achieved yaw d amping according to the yaw rate and front steering angle of vehicle (Zheng and Anwar, 2009). However they didn't consider that the influence of coefficient of road adhesion and the steering resisting force on the system. For bisectional roads with large difference between road adhesion coefficients of two sides of the road, according to the principle of active steering system working on steering performance with feedback of yaw velocity and deviating distance from the expected track, Zhao, Wei, Zhou and Zhang realized applying active steering to keep brake stability (Zhao *et al*., 2008).

Considering real-time state variety in the process of vehicle running, according to the two degrees of freedom vehicle model, this study proposes the AFS control strategy which employs the fuzzy sliding-mode control (FSMC) method and fuzzy PI control method to control the electromotor to optimize the variable transmission ratio and the yaw velocity respectively. The feasibility of the control strategy is tested and verified through the simulation experiment.

This study mainly researches the AFS control strategy. Through analyzing the principle of the two degrees of freedom vehicle model and the steering system, the study firstly proposes the method that schedules the ideal variable transmission ratio and the

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additional angle. Then, designs the fuzzy sliding-mode control method to realize the additional angle and put the fuzzy PID control method into use to keep the vehicle stable. Finally, the performance of the AFS strategy is researched by simulation test. The simulation results show this strategy has a good performance of steering characteristics and effectively enhances the control stability.

CONTROL STRATEGY OF AFS

Strategy of AFS controller includes two parts: The controller of variable transmission ratio and the controller of vehicle stability. The AFS controller gets the conditions information of vehicle running and driver operation through vehicle speed sensor, steering wheel Angle sensor, electromotor angle sensor and yaw-velocity sensor. According to these kinds of information, the AFS controller adjusts the transmission ratio of the steering system to realize different steering characteristics as designed (Shang *et al.*, 2010) and controls over the conditions of vehicle running to restrain influences of the surroundings interference and asymmetric brake force. The flow-process diagram of the control strategy of AFS is shown as Fig. 1.

Controller of the variable transmission ratio: The ideal variable transmission ratio of the steering system changes with vehicle speed. It can meet the requirement of steering characteristics in high speed and low speed. Through this variable transmission ratio, the vehicle can present steering characteristics that are independent of the driver's manipulation. This study designs the variable transmission ratio according to the vehicle model of two degrees of freedom:

- **Confirming the variable transmission ratio:** It can be known from the two degrees of freedom vehicle model (Yu, 2006) that assuming the vehicle is characteristic of steady state response, the yaw velocity gain λ corresponding to the front wheel angle is obtained from Eq. 1:

$$\lambda = \frac{v/L}{1+Kv^2} \tag{1}$$

where, L stands for the wheelbase, stands for the vehicle speed, K is $m/L^2\ (a/k_2-b/k_1)$, a and b, respectively stand for the di stances from the center of mass to the front axle and to the rear axle k_1 and k_2, respectively stand for the tire stiffness of front and rear wheel, m stands for the mass

The relationship between the front wheel angle and the steering wheel angle is shown as the formula: $\theta_f = \theta_s/i$. In the formula, θ_s stands for the steering wheel angle, θ_f stands for the front wheel angle, i stands for the transmission ratio in steering system. The yaw velocity gain corresponding to the steering wheel angle is described as λ_s which is called yaw velocity gain of steering system and shown as follow (Chen, 2008).

$$\lambda_s = \frac{\lambda}{i} \tag{2}$$

The variable transmission ratio is designed through the fixed yaw velocity gain of steering system. Assuming λ_s = A, the variable transmission ratio is expressed as Eq. 3. It is known from Eq. 3 that i_s is only relative to the vehicle speed:

$$i_s = \frac{1}{A}\frac{v/L}{1+Kv^2} \tag{3}$$

- **Confirming the additional angle of the steering axle:** In AFS system, the steering wheel angle and the electromotor angle act on the steering axle together. Then the synthetic angle passed on from the steering axle to the front wheels through the redirector. Finally AFS presents that the total transmission ratio is i_s from the steering wheel to the front wheels. The electromotor provides steering axle with the angle θ which is called the additional angle of steering axle. When i_s and the original mechanical transmission ratio i_0 are known, the additional angle of steering axle is obtained from Eq. 4:

$$\theta = \theta_s\left(\frac{i_0}{i_s} - 1\right) \tag{4}$$

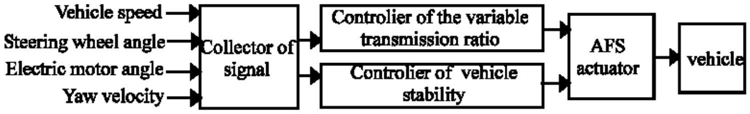

Fig. 1: Flow-process diagram of AFS control strategy

For the front wheel angle varies in a considerable wide rage when car is in low speed or in the process of parking, the transmission ratio which is too small will cause steering angle too much or even exceeding the limit. Those conditions can be avoided by setting up the minimum transmission ratio i_{smin} at low speed ($v \le v_0$, $v_0 = 30$ km h, =30 km h^{-1}). Substituting i_{smin} into Eq. 4, the additional angle of steering axle is presented as the Eq. 5:

$$\theta = \begin{cases} \theta_s\left(\dfrac{i_0}{i_{s\min}} - 1\right) & v \le v_0 \\ \theta_s\left(\dfrac{i_0}{\dfrac{1}{A}\dfrac{v/L}{1+Kv^2}} - 1\right) & v > v_0 \end{cases} \tag{5}$$

- **Design the Controller of the variable transmission ratio:** Sliding-Mode Control (SMC) can overcome the system instability. It has strong robustness in the conditions of external disturbance and un modeled dynamics, especially for the nonlinear system which has good control effects with SMC. For the sample arithmetic and rapid response of variable structure control system, it was widely used in the engineering control region. Its only defect is the chattering during the control process. In order to reduce the extent of chattering and give full play to the advantages of SMC, fuzzy control is applied to optimizing the control value of SMC, which method calls fuzzy sliding-mode control (FSMC) (Hsiao and Chiang, 2012). This study applies FSMC to build the controller of the Variable Transmission Ratio (VTRC)

The controller of the variable transmission ratio by SMC method regards the actual additional angle θ_m which is provided the steering axle with by electromotor as the control object, sets designed additional angle θ of steering axle as the control target value and sets these angles position error e and error rate $\bar{e}$ as the variables, which are shown as the Eq. 6 and the Eq. 7:

$$e = \theta\text{-}\theta_m \tag{6}$$

$$\bar{e} = \bar{\theta}\text{-}\bar{\theta}_m \tag{7}$$

The switching function of SMC (Meng *et al*., 2011) is designed as the following Eq. 8:

$$s = ce+\bar{e} \tag{8}$$

This study applies exponential approach law to design SMC. The law is shown as the Eq. 9:

$$\bar{s} = \varepsilon \text{sgn}(s)\text{-}ks \; (\varepsilon>0,\ k>0) \tag{9}$$

In the Eq. 9, constant expresses the rate that the moving point of system approaches to switching surface (s = 0). On the same condition, the chattering extent of SMC which has designed is depended on ε. For reducing the extent of chattering, the value of ε is adjusted by fuzzy control method

The fuzzy control regards ε as the output variable and sets es (stands for s) and its change rate des as the input variables. The fuzzy subset ε, es, des = {PB, ZO, NB}. The subset elements represent Positive Big, Zero and Negative Big of the discourse domains of theseparameters, respectively. According to the control engineering experience, the fuzzy control rules (Liu, 2005) are built which is expressed as Table 1.

For ε of the exponential approach law should meet the requirement that ε>0, ε chooses the absolute value of the output of the Fuzzy controller. According to the above-mentioned control method, the model of VTRC by FSMC method is established with position error e as controller input and with control angle of the electromotor as controller output.

Vehicle stability controller: Yaw velocity is the significant index which is used to evaluate the vehicle stability. This study applies fuzzy PI control method to build the Vehicle Stability Controller (VSC), which online adjusts the additional angle of steering axle to track the target value of yaw velocity through fuzzy PI control method.

The target value of yaw velocity is calculated according to the two degrees of freedom vehicle model. The vehicle stability controller sets error e between the target value and actual value of yaw velocity and error rate de as the input variables, sets Δk_p and Δk_i as the output variables which are used to adjust the parameters of P and I of PI control method. The fuzzy subset Δk_p, Δk_i, e, de = {NB, NM, NS, ZO, PS, PM, PB}. The subset elements represent Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium and Positive Big of the discourse domains of these parameters, respectively. Then builds the fuzzy PI control rules (Zhang, 2007) which are shown as the Table 2 and 3.

According to the above-mentioned control method, the model of VSC is established to control the yaw velocity in order to realize the vehicle stability.

AFS controller: According to the vehicle model of two degrees of freedom and the AFS principle, combining the controller of the variable transmission ratio and the vehicle stability controller, the model of the AFS

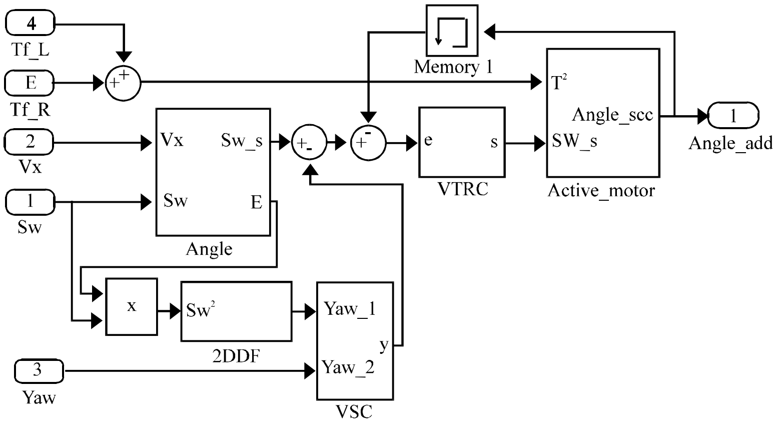

Fig. 2: Simulation model of the AFS controller

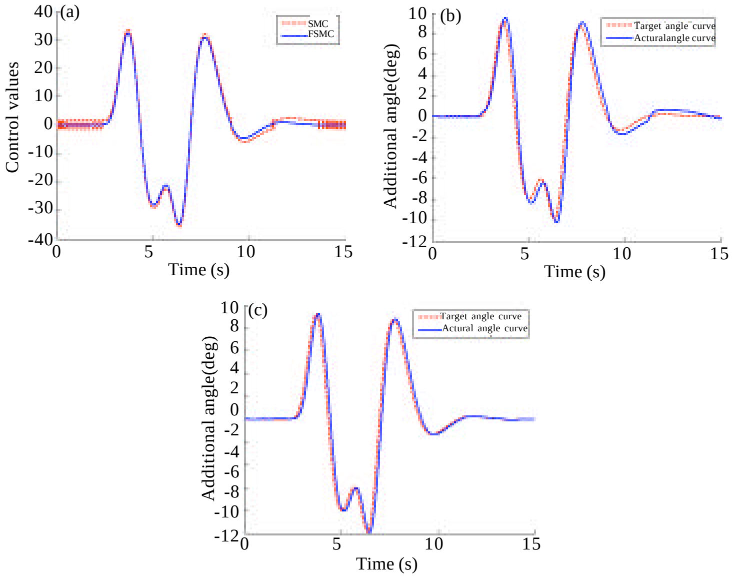

Fig. 3: Control effect of the controller of the variable transmission ratio

controller is established with the steering resisting torque, steering wheel angle and yaw velocity as input variables and the additional angle of steering axle as output variables. The model of the AFS controller is shown as Fig. 2.

Simulation experiment: The performance of the AFS controller is evaluated by computer simulations test. The study carries out the double lane-change test (ISO 3888-1, 1999) and the straight path test with uneven friction coefficient.

Simulation of the controller of the variable transmission ratio: The performance of VTRC is investigated by the double lane-change test at 70 km h^{-1}. Sliding-mode control method sets $\varepsilon = 3$ and the fuzzy sliding-mode control method set that ε is the absolute value of fuzzy controller output which rage is [0, 5]. The simulation results of the controller of the variable transmission ratio show as Fig. 3.

Figure 3a expresses the control value curves of sliding-mode control method and fuzzy sliding-mode control method. In Fig. 3a, the control value of sliding-mode control method is high-amplitude chattering, but the amplitude of chattering is reduced or eliminate after softening by fuzzy control method as shown as the curve of FSMC.

Figure 3b and 3c demonstrate the control effect curves of sliding-mode control method and fuzzy sliding-mode control method, respectively. Figure 3b shows that the chattering of sliding-mode control method has a strong impact on the effect of tracking target value.

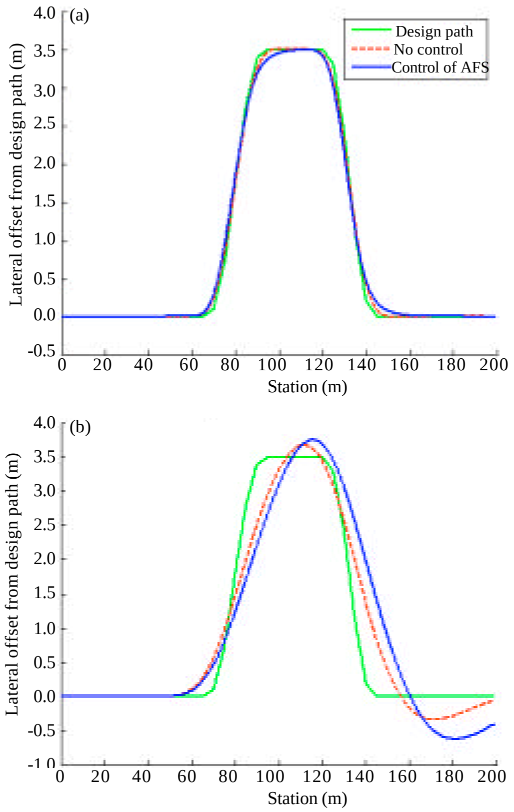

Fig. 4: Running trajectories of vehicle at 30 and 100 km h^{-1}

The aim curve can be followed better by the fuzzy sliding-mode control method as shown in Fig. 3c. So, VTRC which adopts the fuzzy sliding-mode control method has better performance than the other.

Simulation of afs control strategy

Steering characteristics: The steering characteristics can be changed with changing transmission ratio of steering system through AFS. This study tests the steering characteristics through the test of tracking double lane-change line.

Figure 4a shows the running trajectories of vehicle at 30 km h^{-1} that vehicle presents oversteer characteristic at low speed after adding AFS controller. Figure 4b shows the running trajectories of vehicle at 100 km h^{-1} that vehicle presents understeer characteristic at high speed during vehicle running with the same driver model. Figure 4 displays variable steering characteristics according the varied speed.

Control stability

Double lane-change test: The performance of AFS controller is evaluated by the double lane-change test (Zhang and Tang, 2012) at 70 km h^{-1}. The curves of front wheel angle and the yawing rate controlled by the AFS control strategy is shown in Fig. 5.

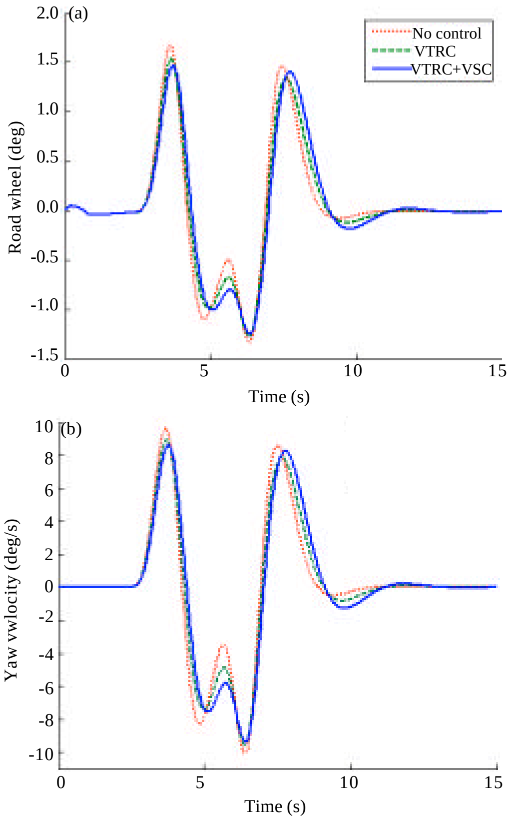

Fig. 5: Curves of the front wheel angle and the curve of yaw velocity

Figure 5a expresses the curves of front wheel angle under control of VTRC and VTRC and VSC, respectively. Figure 5b expresses the curves of yaw velocity under control of VTRC and VTRC and VSC respectively. As shown in Fig. 5a and 5(b), the controller of the variable transmission ratio adjusts the value of yaw velocity through the front wheel angle which is changed according to variable transmission ratio. And adding the vehicle stability controller, the front wheel angle obtains the more suitable adjust and the vehicle stability are improved well further.

Straight path test with uneven friction coefficient: For researching the effect of asymmetric surroundings factors on the vehicle stability, this study set the simulation environment: The straight-line road that contains a road section which left side is set to low friction coefficient surface and the vehicle run on this road.

Figure 6a shows the yaw velocity curves on this straight path test under control of VTRC and VTRC and VSC, respectively. As shown in Fig. 6a vehicle be under steer

Table 1: Fuzzy control rules parameters of

		des		
	ε	PB	ZO	NB
es	PB	PB	ZO	ZO
	ZO	ZO	ZO	NB
	NB	ZO	NB	NB

Table 2: Fuzzy control rules parameters of Δk_p

		de						
	Δk_p	NB	NM	NS	ZO	PS	PM	PB
e	NB	PB	PB	PM	PM	PS	ZO	ZO
	NM	PB	PB	PM	PS	PS	ZO	NS
	NS	PM	PM	PS	PS	ZO	NS	NS
	Z	PM	PM	PS	ZO	NS	NM	NM
	PS	PS	PS	ZO	NS	NS	NM	NM
	PM	PS	ZO	NS	NM	NM	NM	NB
	PB	ZO	ZO	NS	NM	NM	NB	NB

Table 3: Fuzzy control rules parameters of Δk_i

		de						
	Δk_i	NB	NM	NS	ZO	PS	PM	PB
e	NB	NB	NB	NM	NM	NS	ZO	ZO
	NM	NB	NB	NM	NS	NS	ZO	ZO
	NS	NB	NM	NS	NS	ZO	PS	PS
	Z	NM	NM	NS	ZO	PS	PM	PM
	PS	NS	NS	ZO	PS	PS	PM	PB
	PM	ZO	ZO	PS	PS	PM	PB	PB
	PB	ZO	ZO	PS	PM	PB	PB	PB

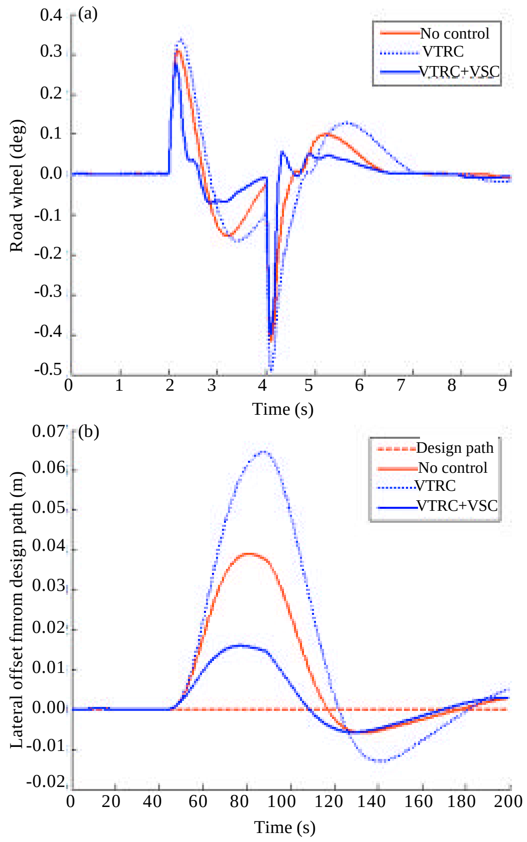

Fig. 6: Simulation results of the straight path test

characteristics at high speed, when running on the road surface of uneven friction coefficient, the vehicle adjust slow and its yaw velocity value is high. In the same condition, adding VSC, the AFS controller reduces the value of the yaw velocity, makes the curve of the yaw velocity converge quickly and effectively enhances the vehicle stability.

Figure 6b shows the lateral offset curves on this straight path test under control of VTRC and VTRC and VSC, respectively. As shown in Fig. 6b, in this condition, the maximum of the lateral offset is 0.0388 m with no controller. The maximum of the lateral offset is 0.0645 m controlled by AFS controller only with VTRC. The maximum of the lateral offset is 0.0158m controlled by AFS controller with VTRC and VSC. AFS controller with VTRC and VSC reduces the lateral offset caused by the one-sided wheels of vehicle on the low friction coefficient surface and enhances the surroundings adaptability and driving safety.

CONCLUSION

This study proposes the control strategy of AFS that integrates the controller of variable transmission ratio and the vehicle stability controller. The controller of variable transmission ratio applies the fuzzy sliding-mode control method. The vehicle stability controller employs the fuzzy PI control method. The simulation model of AFS controller is established according to this strategy. The simulation results show that AFS controller can get over steer characteristics at low speed and under steer characteristics at high speed. Additionally, it enhances the control stability effectively and promotes the environment adaptability and driving safety.

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