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FUZZY CONTROL DESIGN FOR A FOUR-WHEEL INDIVIDUAL STEERING FLEXIBLE CHASSIS

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Abstract. *This paper presents the fuzzy control design for a four-wheel individual drive and four-wheel individual steering chassis named flexible chassis, and a two-degree of freedom nonlinear steering model for flexible chassis is established based on the "magic formula" tire model and the Ackermann steering theorem at low speed. Also, a new control method based on a fuzzy strategy is proposed for the sideslip angle control of the steering model. The left front wheel steering angle was input in the simulation of chassis, and the remaining steering angles of the three wheels, which met the Ackermann theorem, were output to control the flexible chassis. A simulation comparison between front wheel steering, four-wheel proportional steering and the new fuzzy control steering model indicated that the proposed new control algorithm was effective.*

Keywords: Electric vehicle, Fuzzy control, Four-wheel independent steering, Four-wheel independent drive, Simulation

1. Introduction.

1.1. Background.

Because of environmental pollution and the global energy crisis, the electric vehicle (EV) has attracted a great deal of research interest as an effective transportation paradigm [1,2]. With each wheel independently driven and independently steered, instead of the integrated driving system and steering mechanism of a traditional vehicle, a four-wheel individual drive and four-wheel individual steering (4WID/4WIS) EV offers better driving efficiency, better control and better flexibility and maneuverability, making it a promising direction for electric vehicles [3,4]. This study proposes the fuzzy control method for a chassis called a flexible chassis (FC) [5,6], which is a 4WID/4WIS EV with in-wheel motors (IWM). Because of its omnidirectional propulsion, its main application is for use on narrow roads in a semi-closed or closed environment at low speed. In this study, an effective fuzzy control method for 4WID/4WIS FC is introduced, which is a nonlinear system. Fuzzy control was proposed in a doctoral thesis in the mid-1970s for controlling processes, catalyzing a novel research area: the application of fuzzy control theory. Today, fuzzy control theory has been employed in systems engineering, psychology, biology, economics, medicine, and many other fields, offering valuable contributions that would not otherwise be possible without precise, mathematical models.

1.2. Literature review.

The four-wheel independent steering control system is an important approach for improving the handling characteristics of a vehicle and has been long valued by domestic and foreign experts and researchers. Many developments working toward such a system have been documented in the literature. For instance, the state feedback control method, which is derived from the linear two degrees of freedom model, has been proposed [7]. A time delay control for a 4WIS vehicle using single and dual steering control strategies has also been proposed [8]. A linear quadratic regulator in multiple environments has been investigated and developed [9]. Joint control of four-wheel steering and vehicle dynamic control has also been proposed [10]. A control simulation using linear predictive control improved the steering stability to some extent [11]. Sideslip zeroing control for a 4WS vehicle has been proposed [12]. Multi-objective H_∞ optimum control for a 4WS vehicle based on yaw rate tracking has been reported [13]. A closed loop comprehensive evaluation method based on linear control theory has been proposed [14]. A variable ratio steering system using an optimum control method has been reported [15]. An adaptive model that follows control of a 4WS steering vehicle has been presented [16]. Synthesis robust control for a four-wheel steering vehicle based on yaw rate tracking has been discussed [17]. Neural network control for a 4WS vehicle based on a nonlinear model has been reported [18]. Many control methods based on the sideslip angle being set to zero without the use of the Ackermann steering principle have been demonstrated [19,20]. Other control methods based on the Ackermann steering principle have been proposed without consideration of the nonlinear characteristics of the tires [21,22].

From the above literature review, it can be seen that control methods based on two degrees of freedom or three degrees of freedom and the linear model or nonlinear model with the target being zero sideslip angle has generally been applied to controlling the four-wheel steering electric vehicles. And then various elements are selected to obtain the control strategies without considering Ackermann steering theorem. Others do take account of the Ackermann steering theorem, but the model used is built with a simple linear model using linear control strategies without taking account of the nonlinear characteristics of the tire. In this paper, a two-degree of freedom nonlinear steering model for a four-wheel individual steering electric chassis is established based on the "magic formula" tire model and the Ackermann steering theorem at low speed.

The rest of this paper is organized as follows. The introduction of the flexible chassis and its kinematic model, dynamics model and tire model are presented in Section 2. Fuzzy control algorithm is provided in Section 3. The result of the experiment is compared with simulation in Section 4, followed by the conclusive remarks and future works.

2. **The Model for the Flexible Chassis.**

The flexible chassis [5,6] is an omnidirectional and non-holonomic chassis. The omnidirectionality of the flexible chassis is maintained using four steerable and drivable wheels with a lateral offset from their attachment axes. Each wheel comprises a propulsion actuator and an electromechanical steering lock (FBD-050 from Taiwan KAIDE). The propulsion actuator consists of a DC brushless motor (in-wheel motor from BATTLE) and an electromechanical brake (EB). Steering is accomplished using the coupling of the in-wheel motor and the electromechanical steering lock. To avoid interference with the chassis, each wheel can rotate 270° around its attachment offset axis and 180° to change its direction. A passive vertical suspension is composed of springs and is used to connect the steerable wheels to the chassis, allowing the wheels to maintain contact with the ground on uneven surfaces. The FC is able to change direction by using differential steering or by changing the direction of its articulation, making the chassis omnidirectional and allowing it to move in tight areas.

2.1. **Kinematic model based on the Ackermann steering theorem.**

When automobiles are engaged in the steering process at low speed, there is very little slippage of the four wheels and the Ackermann theorem [23] can be applied. That is to say that all the wheels center on an instantaneous turning center scroll, which is shown in Figure 1. In the equations following Figure 1, the parameter α_i $(i = 1, 2, 3, 4)$ refers to the steering angle of the ith off-centered wheel; δ_i $(i = 1, 2, 3, 4)$ refers to the slip angle of the ith tire; F_i $(i = 1, 2, 3, 4)$ refers to the lateral force of the ith wheel, a and b refer to the horizontal distance between the extended line of the instant center and the front and rear axles. W refers to tread, L to the wheelbase, and O to the barycenter of an ideal state. O' is the instant turning center, r represents the distance between the right wheel and the instant center, and u and v represent the longitudinal velocity and transverse velocity, respectively. The parameter β represents the vehicle's sideslip angle; γ represents the yaw rate around the center of the vehicle's mass.

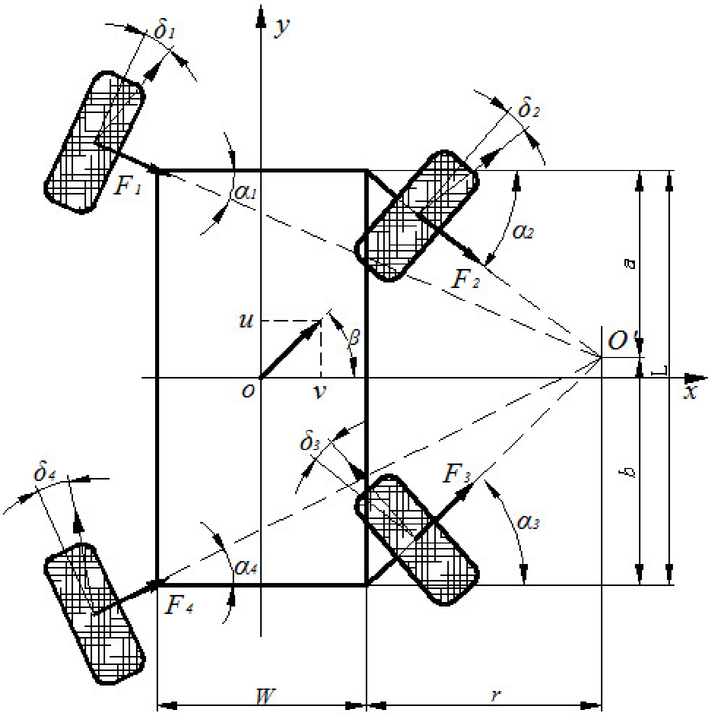


Figure 1. Low speed steering model based on the Ackermann steering principle

According to Ackermann theorem, the angular movement geometric relationship is:

$$\begin{cases} \alpha_1 = \arctan\left(\dfrac{a}{r+W}\right) \\ \alpha_2 = \arctan\left(\dfrac{a}{r}\right) \\ \alpha_3 = \arctan\left(\dfrac{b}{r}\right) \\ \alpha_4 = \arctan\left(\dfrac{b}{r+W}\right) \end{cases} \tag{1}$$

2.2. **Dynamics model.** To analyze the steering stabilization of each wheel of the four-wheel independent steering system and simplify the model of the system, the following reasonable assumptions were proposed:

a. The weight of the vehicle is evenly distributed to all four wheels;
b. The wheels are identical and the tire characteristics are ignored, because of the changes in load;
c. Ignore the role of the automotive suspension, the chassis's vertical displacement movement, the pitch motion about the transverse axis and the rolling motion of the longitudinal axis.

The dynamic equation for two degrees of nonlinear freedom [24] for the four-wheel independent steering of the flexible chassis can be expressed as:

$$mu\left(\dot{\beta}+\gamma\right)=\sum_{i=1}^{4}F_i\cos\alpha_i \tag{2}$$

$$I_z\dot{\gamma}=a\left(F_1\cos\alpha_1+F_2\cos\alpha_2\right)-b\left(F_1\cos\alpha_1+F_2\cos\alpha_2\right)+\frac{W}{2}\sum_{i=1}^{4}F_i\cos\alpha_i\left(-1\right)^{i+1} \tag{3}$$

where m is the vehicle mass, and I_z is the moment of inertia.

$$\begin{cases} \delta_1=\dfrac{v+a\gamma}{u-c\gamma/2}-\alpha_1\approx\beta+\dfrac{a\gamma}{u}-\alpha_1 \\ \delta_2=\dfrac{v+a\gamma}{u+c\gamma/2}-\alpha_2\approx\beta+\dfrac{a\gamma}{u}-\alpha_2 \\ \delta_3=\dfrac{v-b\gamma}{u-c\gamma/2}-\alpha_3\approx\beta-\dfrac{b\gamma}{u}-\alpha_3 \\ \delta_4=\dfrac{v-b\gamma}{u+c\gamma/2}-\alpha_4\approx\beta-\dfrac{b\gamma}{u}-\alpha_4 \end{cases} \tag{4}$$

2.3. **Tire model.** The traditional vehicle dynamics model is generally built using a linear tire model, and this linear tire model is provided with a side angle (less than 5 degrees), but when the side angle or lateral acceleration is large, a non-linear tire model is required. The Pacejka model (magic formula) is a semi-theoretical and semi-empirical model that can simulate the linear and nonlinear characteristics of the tire [25] and can describe the steady state. The tire lateral force equation can be expressed as:

$$F_y=D\sin\left(C\arctan\left(B\delta_i-E\left(B\delta_i-\arctan\left(B\delta_i\right)\right)\right)\right) \tag{5}$$

where crest factor $D=b_1F_z^2+b_2F_z$; shape factor $C=1.3$; factor $B=b_3\sin(b_4\arctan((b_5 F_z))/(CD))$; factor $E=b_6F_z^2+b_7F_z+b_8$; δ_i refers to tire declination, and $i=1,2,3,4$.

3. **Fuzzy Control Algorithm.**

3.1. **The design of the fuzzy controller.** The fuzzy controller can make accurate decisions to improve machining accuracy based on human operation and experience. The fuzzy controller has integral fuzzy sets, which are designed by the work conditions. These fuzzy sets come in various “flavors” such as small, medium and large. The fuzzy sets can be converted into an automatic control strategy based on a base of knowledge. Fuzzy control is an intelligent control strategy that is able to mimic human thought, allowing the creation of solutions to nonlinear problems. In this study, a two-dimensional fuzzy controller was applied, and the error of system E and its derivative error Ec were used as input variables, which may be reflected in the dynamic characteristics of the variables.

3.2. **Selection of fuzzy sets, basic domain, quantization factor and scaling factor.** The research domain selection was chosen as follows: the fuzzy domain of sideslip angle error E was $[-6,6]$; the fuzzy domain of the derivative error for the sideslip angle error Ec was $[-6,6]$; and the fuzzy domain of the angle ratio of the left front wheel and the left rear wheel was $[-1,1]$. According to the practical experience of the four-wheel independent steering system, the fuzzy basic domain of the sideslip angle error E and error derivative basic were $[-0.1,0.1]$ and $[-0.01,0.01]$, respectively, and the fuzzy basic domain of the angle ratio of the left front wheel and the left rear wheel was $[-1,1]$.

Determination of the quantization factor and scaling factor was accomplished as follows.

- Quantization factor of the sideslip angle error: $ke=6/0.1$.
- Quantization factor of the derivative error for the sideslip angle error: $kec=6/0.01$.
- Scaling factor of the control variable's output: $ku=1/1$.

In addition, the fuzzy subset of E, Ec and U was {NB, NM, NS, ZO, PS, PM, PB}, in which the parameters NB, NM, NS, ZO, PS, PM and PB are abbreviations for negative big, negative middle, negative small, zero, positive small, positive middle and positive big. The value of E represents the error and Ec represents the error rate. A triangle-type membership function was adopted for each fuzzy variable, as shown in Figures 2-4, which show the membership function curves of E, Ec, and U, respectively. The triangular membership function's operation is simple but meets the control accuracy requirements. And membership function curves of E, Ec and U share the same shape but with different domains.

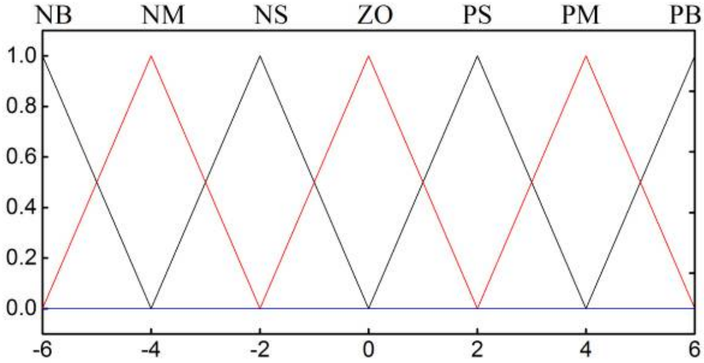


Figure 2. Membership function curves of E

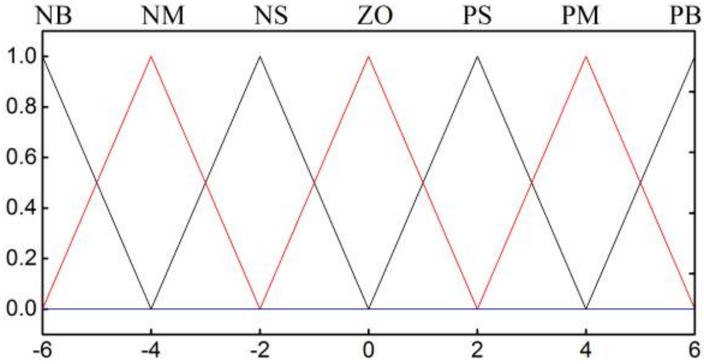


Figure 3. Membership function curves of Ec

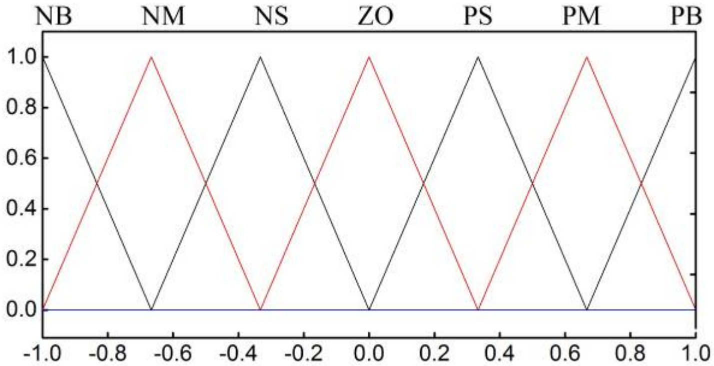


Figure 4. Membership function curves of U

3.3. **The rules of fuzzy control.** According to the actual conditions, the fuzzy system makes fuzzy judgments using a simple average method, and then calculates the anti-blur process, which is the output of the fuzzy sets that are transformed into the precise number of control variables needed to achieve the best performance. The rules for the fuzzy controller are shown in Table 1.

Table 1. Fuzzy rule table

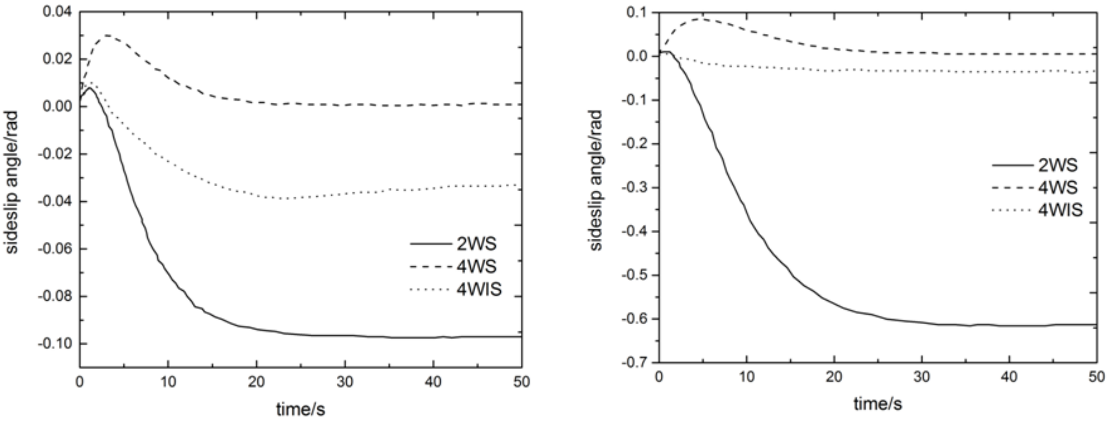
U		*E*						
		PB	PM	PS	ZO	NS	NM	NB
Ec	PB	NB	NB	NB	NB	NM	NS	ZO
	PM	NB	NB	NB	NM	NS	ZO	PS
	PS	NB	NB	NM	NS	ZO	PS	PM
	ZO	NB	NM	NS	ZO	PS	PM	PB
	NS	NM	NS	ZO	PS	PM	PB	PB
	NM	NS	ZO	PS	PM	PB	PB	PB
	NB	ZO	PS	PM	PB	PB	PB	PB

4. **Experiments and Simulation Analysis.** To verify the accuracy of the proposed four-wheel independent steering nonlinear model based on Ackermann and the efficacy of the control strategy, a comparison was conducted between the proposed model, the traditional two-wheel steering (2WS) model and the steering model based on the ratio of front and rear wheel steering (four wheel steering, 4WS). The simulation was conducted using two different input scenarios:

a. speed of vehicle is 5 m/s, and steering angle of left front wheel is 0.1 rad;

b. speed of vehicle is 8 m/s, and steering angle of left front wheel is 0.25 rad.

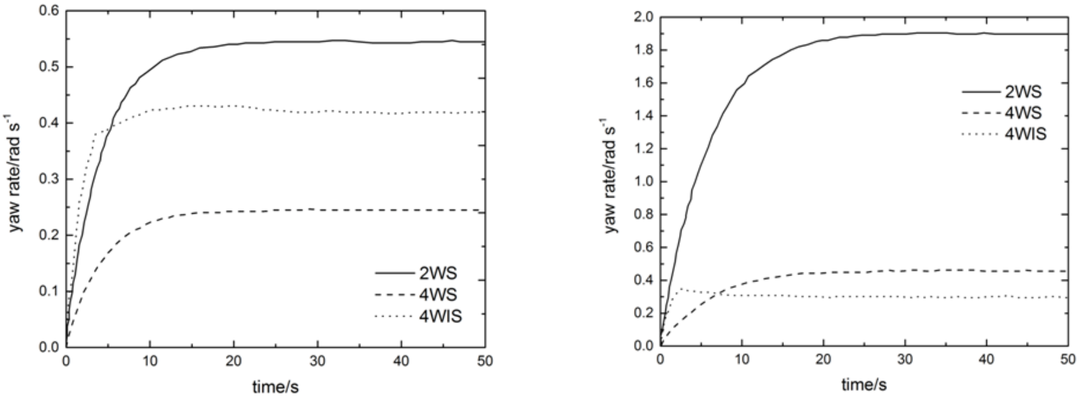
Figure 5 shows the curves of the sideslip angles in scenarios 1 and 2, which were simulated using the Matlab toolbox. The sideslip angle of the 4WS model, after a short fluctuation, can quickly attain a stable value and proceed without errors. However, the sideslip angle of the 4WIS model also attained a stable value in a very short period of time, which indicates the efficiency of the fuzzy control strategy. In addition, because of the nonlinear model, which is uncertain, the sideslip angle of the 4WIS model had a small steady-state error, but this error was within a reasonable range. The sideslip angle of the 2WS model was larger than the 4WS and 4WIS models, especially in the case of a large



(a) Sideslip angles in scenario 1

(b) Sideslip angles in scenario 2

Figure 5. Changes of sideslip angles under two different conditions



(a) Yaw rate under situation 1 (b) Yaw rate under situation 2

Figure 6. Changes of yaw rate in two different test scenarios

angle, which demonstrates that the 4WS and 4WIS models could limit the change of the sideslip angle at a moderate velocity.

Figure 6 shows the curves of the yaw rate under the two different scenarios. As shown, the yaw rate of the 2WS model with a large steering angle is very large and falls outside of the acceptable range. This occurred because the large front-wheel steering angle resulted in a larger lateral force for the front wheel, which corresponded to the tire's linear model. The yaw rate of the 4WS model increased, which was due to both the front and rear lateral forces, which had increased based on the linear tire model. This caused the vehicle's yaw rate to increase. The nonlinear tire model produced a tire lateral force in the large steering angle for the 4WIS model, which remained basically unchanged, while the larger angle of the tire resulted in a vehicle yaw rate that decreased, as shown by Equation (2).

5. **Conclusions.** Traditional modeling for a four-wheel steering vehicle has relied on a linear model that does not consider variations in the steering angle of the left and right wheels when the vehicle turns. This study proposes a nonlinear four-wheel independent steering model based on the Ackerman theorem using a fuzzy control method. Through a Matlab simulation of the vehicle at various vehicular and turning angles, the simulation results for the sideslip angle and yaw rate were found to be similar to those for the 4WS model. This proved the accuracy of the proposed model and efficacy of the control strategy at small steering angles. In the case of large steering angle conditions, the 4WIS model proved to accurately reflect the actual running state of the vehicle and the angle variation in the right and left wheels. This was believed to be more practical and accurate than the application of a nonlinear model, which was used in the 2WS and 4WS models.

In this paper, only simulations have been done, and there has been no actual testing. Therefore, for future research, an actual control system will be developed for the FC, and actual road tests will be conducted to verify the feasibility of the control system.

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