Research on Mathematical Modeling and Control Strategy of Forklift Steer-By-Wire System

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Abstract - According to the TE30 series forklift of one company, the principle and structure of steer-by-wire system (SBW) are analyzed and the mathematical models of main components of steer-by- wire system are set up. Steering motor armature current is controlled by PID algorithm. This can make the steering motor quickly and stably provide steering torque. In the real forklift driving process, in order to ensure the yaw rate stability with changeable speed and hand-wheel angle, forklift dynamic correction control strategy based on yaw rate feedback is proposed. The simulation has shown that the strategy obviously decrease the yaw rate and sideslip angle, improve the steering characteristics, and increase the operation stability of forklift.

Keywords: Forklift, SBW system, modeling, yaw rate, dynamic correction.

I. INTRODUCTION

SBW system is developed on the basis of the power steering system. It cancels mechanical connections between hand-wheel and steered wheel, and overcome steering constraint of mechanical structure. SBW system can realize active control on vehicle steering, make the vehicle light and sensitive at low speed, and make it steady and heavy at high speed.

SBW technology research started in the 20th century 50s. Some steering developers such as TRW put forward to cancel the mechanical connection between hand-wheel and steered wheel [1-3]. At the end of 60s, German Kasselmann had the similar design with electronic steering system. But due to the restriction of electronic technology and control technology, the design had failed to achieve. But the prototype of the concept of SBW system appeared. With the development of science and technology in recent years, the world large car manufacturers and research institutes have done in-depth research on SBW technology [4].

In 1990, Benz Corp began in-depth study of SBW technology, its concept car F400Carving is the application of the SBW technology [5]. In 2003, Toyota Corp of Japan showed the latest development concept car Lexus HPX at the New York International Auto Show. The car used the SBW system for the first time to realize the automatic steering control. This is the milepost of SBW system. In 2010, Toyota Corp launched another concept car FT-EVⅡwhich adopted drive-by-wire technology to realize acceleration, braking, steering etc.

Forklift is a kind of industry carrying vehicle. It is widely used in factory workshop, storehouse, port, station, airport, warehouse, distribution center and other places. Because of the characteristics of large load, small workspace and frequent steering, the requirements of forklift steering are very high, not only light, flexible and small turning radius, but also better motor performance.

According to the characteristics of the electric forklift, the control strategy of SBW system was further studied in this paper, aiming to improve electric forklift steering stability and portability. The main research content is as follows. (1) The method of reduced order modeling was applied to hand-wheel module and steering executable module of SBW system. Then use MATLAB to analyse the system. (2) Steering motor was controlled by PID control strategy to verify the stability and rapidity of SBW system. (3) In view of the actual complexity condition of forklift driving, forklift dynamic correction control strategy based on yaw rate feedback was proposed, and the simulation was also given.

II. STRUCTURE OF FORKLIFT SBW SYSTEM

Taking the SBW system of TE30 type electric forklift as an example, the basic structure and work principle of SBW system was introduced in this paper.

When the driver turn the hand-wheel (also known as the hand in forklift), the electrical signals of hand-wheel torque, angle and vehicle speed were transmitted to the main controller ECU through the sensors. ECU analyzed and calculated these signals and then sent control commands to control steering motor for vehicle wheel steering [6-9].

In SBW system, the electrical signals and ECU replace the mechanical connections between hand-wheel and steered wheel. Steering system is no longer subject to the constraints of mechanical connection. Forklift steering angle transfer characteristics and force transfer characteristics are able to design freedom. The fact has proven that the SBW system can not only improve the steering characteristics and operation stability of the forklift, but reduce the driver energy consumption compared with the traditional steering system.

The SBW system of TE30 type electrical forklift consists of three main parts, and two secondary parts. The main parts consist of hand-wheel assembly, steering execution assembly and ECU. The secondary parts consist of automatic fault prevention system and powers. The main parts are the essential part of SBW system, whereas the secondary parts can be selected according to the needs of the system [10-12]. The hand-wheel assembly is usually composed of hand-wheel, road feeling motor, torque sensor, motor driver etc. steering execution assembly is composed of hand-wheel angle sensor, current sensor, steering motor etc. The function of the ECU is to analyze the collected signals (hand-wheel angle, torque, speed), to judge the vehicle running status, send control commands to steering motor and road feeling motor.

The structure of SBW system is shown in figure 1.

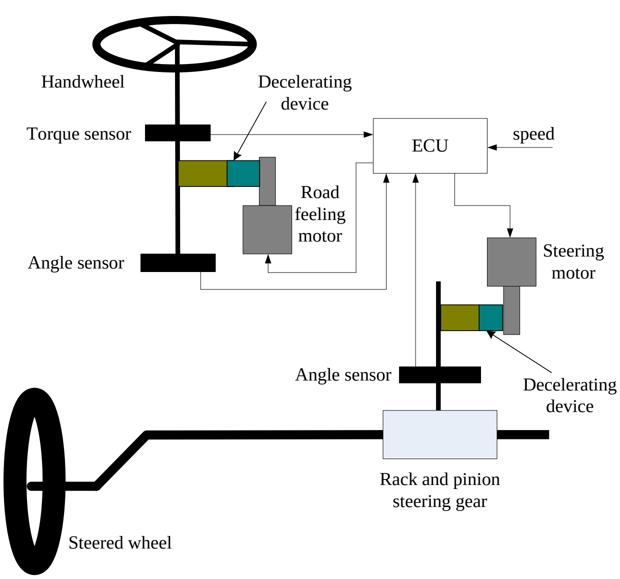

Fig.1. Structure of forklift SBW system

III. FORKLIFT SBW SYSTEM MODELING

In this section author should discuss about related research has been done in the same domain or related domains with the name of the researcher and should be mentioned in the references.

a. Description of forklift steering motion state

In the forklift steering system, the movement of vehicles can be described with the vehicle coordinate system; the centroid of the vehicle O is taken as origin of the coordinates, the vehicle running direction in the horizontal plane through the origin is taken as the position direction of X-axis, the direction parallel to the driver on the left side in the horizontal plane through the origin is taken as the position direction of Y-axis, the upward direction in the vertical plane through the origin is taken as the position direction of Z-axis. There are three motion parameters relevant to steering system; a) yaw rate, the vehicle angular velocity around Z-axis; b) side speed, the speed of the centroid of the vehicle along Y-axis; c) lateral acceleration, the acceleration of the centroid of the vehicle along Y-axis. Forklift coordinate defined in reference [13-16].

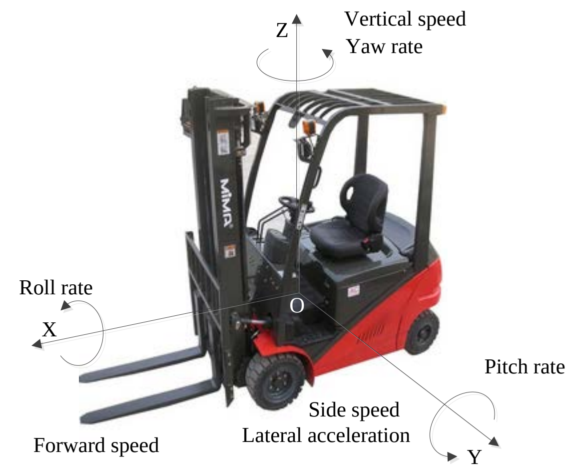

Fig.2. Diagram of vehicles coordinate

b. Mathematical models of SBW system

1. The method of reduced order modeling

In SBW system, all of the components of SBW system can be represented by mechanical components. This model is called full order physical model. This method is called full order modeling method. For simplifying system and reducing mechanical components, two or more mechanical components of full order physical model are combined into one. The obtained physical model is called reduced order physical model. The modeling method is called reduced order modeling method [17].

The object of study of this article is TE30 type electrical forklift. The nonlinear parts of the system are neglected under theory analysis. The structure is simplified reasonably. The system is simplified to contain a few important dynamic elements of SBW system physical model with the method of reduced order modeling. The important dynamic elements are hand-wheel, steering shaft, wheel gear, steered wheel. The simplified SBW system model is shown in figure 3.

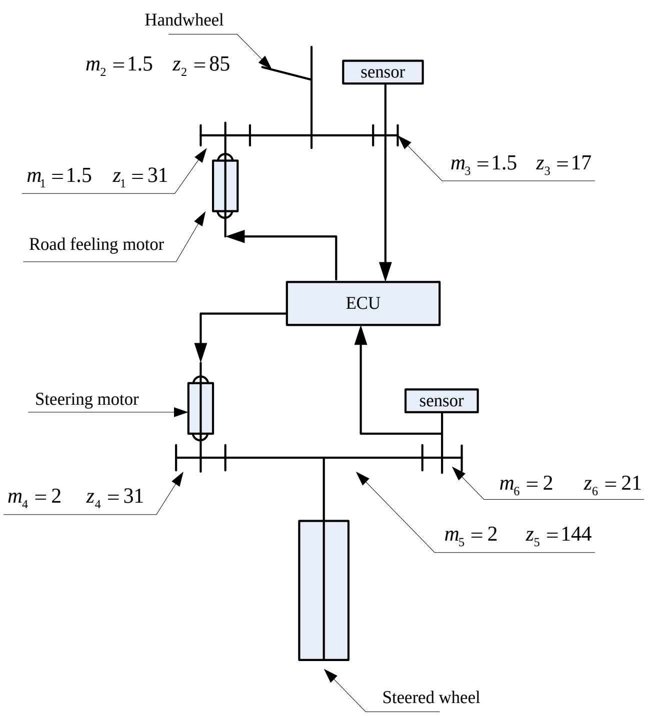

Fig. 3. Simplified schematic of forklift SBW system

The end of steering column is connected to road feeling motor with reduction gear. m_1 : Module of reduction gear. z_1 : Number of teeth of reduction gear. m_2 : Module of gear at the end of steering column. z_2 : Number of teeth of gear at the end of steering column. m_3 : Module of steering angle sensor gear. z_3: Number of teeth of steering angle sensor gear.

2. The dynamic model of hand-wheel module

(1) Hand-wheel

The hand-wheel dynamic equation

$$T_{sw}-J_{sw}\frac{d^2\theta_{sw}}{dt^2}-B_{sw}\frac{d\theta_{sw}}{dt}=T_{d1} \quad (1)$$

Use Laplace transform, so it can been written as

$$T_{sw}(s)-J_{sw}\theta_{sw}(s)s^2-B_{sw}\theta_{sw}(s)s=T_{d1}(s) \quad (2)$$

T_{sw} —torque applied on the hand-wheel; J_{sw} —rotational inertia of hand-wheel and steering column. B_{sw} —viscous friction coefficient between hand-wheel and its support; T_{d1} —torque applied on the steering column; θ_{sw} —rotation angle of hand-wheel.

(2) Road feeling motor

The mechanical characteristic equation of road feeling motor is

$$T_{m1}-J_{m1}\frac{d^2\theta_{m1}}{dt^2}-B_{m1}\frac{d\theta_{m1}}{dt}=\frac{T_{d1}}{G} \quad (3)$$

Use Laplace transform, so it can been written as

$$T_{m1}(s)-J_{m1}\theta_{m1}(s)s^2-B_{m1}\theta_{m1}(s)s=\frac{T_{d1}(s)}{G}$$

(3) The armature loop equation of road feeling motor is

$$R_1 i_{a1}+L_1\frac{di_{a1}}{dt}+k_{e1}\frac{d\theta_{m1}}{dt}=U_{a1} \quad (4)$$

Use Laplace transform

$$R_1 i_{a1}(s)+L_1 i_{a1}(s)s+k_{e1}\theta_{m1}(s)s=U_{a1}(s) \quad (5)$$

Use DC motor as road feeling motor, the relationship between electromagnetic torque and armature current is

$$T_{m1}=k_{t1}i_{a1} \quad (6)$$

Use Laplace transform it can been written as

$$T_{m1}(s)=k_{t1}i_{a1}(s)$$

(7)

J_{m1} — rotational inertia of road feeling motor; T_{m1} — electromagnetic torque of road feeling motor; B_{m1} —

viscous friction coefficient between road feeling motor and its support; θ_{m1} —the steering angle of road feeling motor; k_{e1} —back electromotive force coefficient of road feeling motor; k_{t1} — electromagnetic torque constant of road feeling motor; G —transmission ratio of road feeling motor through reduction gear to steering shaft. i_{a1} — armature current of road feeling motor; U_{a1} —armature voltage of road feeling motor; R_1 —armature resistance of road feeling motor; L_1 —inductance of road feeling motor.

Take TE30 forklift as example, the parameters which would be need for calculating was shown in table 1.

TABLE 1. HAND-WHEEL MODULE PARAMETER VALUES

Symbol	value	units
J_{sw}	0.0044	kg.m2
B_{sw}	0.3	$Nm\cdot sec/rad$
J_{m1}	0.00005	kg.m2
B_{m1}	0.02	$Nm\cdot sec/rad$
k_{e1}	0.02	$V\cdot sec/rad$
k_{t1}	0.02	$N\cdot m/A$
R_1	0.15	Ω
L_1	0.15	mH
G	27.4	—

3. Dynamic model of steering actuator

(1) Steering motor

A DC motor is used as the steering motor. The equivalent structure is shown in Figure 4.

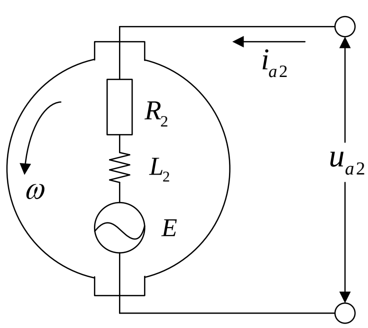

Fig. 4. The equivalent model of DC motor

According to the mechanical properties of the steering motor, we can get

$$T_{m2} - J_{m2}\frac{d^2\theta_{m2}}{dt^2} - B_{m2}\frac{d\theta_{m2}}{dt} = \frac{T_a}{G_1} \quad (8)$$

Use Laplace transform

$$T_{m2}(s) - J_{m2}\theta_{m2}(s)s^2 - B_{m2}\theta_{m2}(s)s = \frac{T_a(s)}{G_1} \quad (9)$$

According to the Kirchhoff law

$$R_2 \cdot i_{a2} + L_2\frac{di_{a2}}{dt} + k_{e2}\frac{d\theta_{m2}}{dt} = u_{a2} \quad (10)$$

Use Laplace transform, it can been written as

$$R_2 \cdot i_{a2}(s) + L_2 i_{a2}(s)s + k_{e2}\theta_{m2}(s)s = u_{a2}(s) \quad (11)$$

The electromagnetic torque equation

$$k_{t2} \cdot i_a = T_{m2} \quad (12)$$

Use Laplace transform

$$k_{t2} \cdot i_a(s) = T_{m2}(s) \quad (13)$$

T_{m2} —electromagnetic torque of steering motor; J_{m2} — rotational inertia of steering motor; B_{m2} —viscous friction coefficient between steering motor and its support; θ_{m2} — rotation angle of steering motor; T_a — output torque of steering motor; G_1 —transmission ratio of steering motor through reduction to steering shaft.

(2) The steered wheel and steering gear

The mechanical characteristic equation of steered wheel and steering gear

$$T_a - J_{wh}\frac{d^2\theta_{wh}}{dt^2} - B_{wh}\frac{d\theta_{wh}}{dt} = T_r \quad (14)$$

Use Laplace transform, so

$$T_a(s) - J_{wh}\theta_{wh}(s)s^2 - B_{wh}\theta_{wh}(s)s = T_r(s) \quad (15)$$

J_{wh} —equivalent rotational inertia of steered wheel and steering gear; B_{wh} — equivalent steering shaft friction coefficient of steered wheel and steering gear; T_r —

equivalent steering shaft steering resisting torque; θ_{wh} — equivalent steering shaft angle.

Take TE30 forklift as example, the parameters which would be need for calculating was shown in table 2.

TABLE 1. STEERING ACTUATOR MODULE PARAMETER VALUES

symbol	value	units
J_{m2}	0.00005	$kg \cdot m^2$
B_{m2}	0.02	$Nm \cdot sec/rad$
G_1	30	—
R_2	0.15	Ω
L_2	0.15	mH
k_{e2}	0.02	$V \cdot sec/rad$
k_{t2}	0.02	$N \cdot m/A$
J_{wh}	0.0044	$kg \cdot m^2$
B_{wh}	0.3	$Nm \cdot sec/rad$

IV. RESEARCH ON CONTROL STRATEGY OF SBW SYSTEM

a. Steering motor control strategy

The steering motor of SBW system was controlled by current negative feedback closed-loop PID algorithm. The current closed-loop PI control structure of steering motor is shown in Figure 5. I_{cmd} — objective current; I_d — real current.

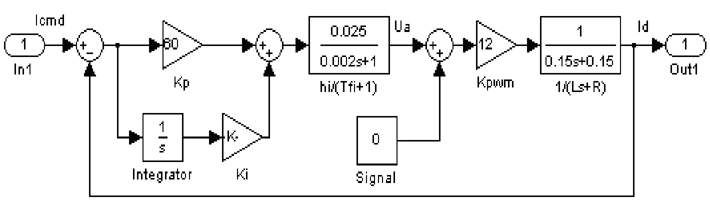

Fig. 5. Current closed-loop PI correction control structure diagram

U_a — real armature voltage of motor; K_{pwm} — voltage amplification factor controlled by PWM; $\frac{1}{L \cdot s + R}$ — The motor armature transfer function; $\frac{h_i}{T_{fi} \cdot s + 1}$ — the current feedback loop transfer function, h_i is current feedback coefficient, V/A, T_{fi} is filter time constant of current feedback; h_i =0.025, T_{fi} =0.002.

According to the mathematical model above, the system was simulated by MATLAB, taking the hand-wheel torque 2Nm as the input signal, and taking steering motor current as the out signal. Suppose the speed of forklift is 10km/h, then the objective current calculated I_{cmd} =5.4A.

b. The simulation of armature current

Figure 6 is the PI current control response result. We can see that the controller has a good following feature for objective current and could offer required power rapidly.

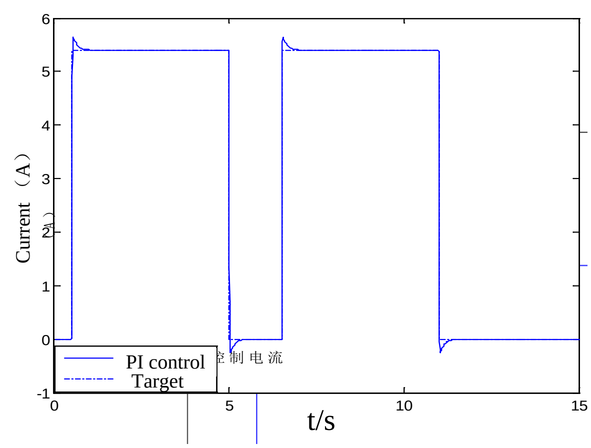

Fig. 6. Current response results of PI control

c. Dynamic correction control of SBW system

Steering flexibility means following feature to hand-wheel angle. If expected yaw rate is too small, which signify the vehicle response relative to angle of hand-wheel is slow. On the contrary if the vehicle response is fast, it would lead to decrease of operating stability and increase of driver burden. Steering sensitivity is one of the important indicators measure to flexibility.

In this paper, dynamic correction control strategy based on yaw rate feedback was proposed. The real yaw rate would be send to the SBW system to eliminate difference value between real yaw rate and objective yaw rate, and then the motion of forklift would be corrected. It will help restore stability when the forklift is in the trend of instability [17-20]. The principle of yaw rate feedback is shown in Figure 7.

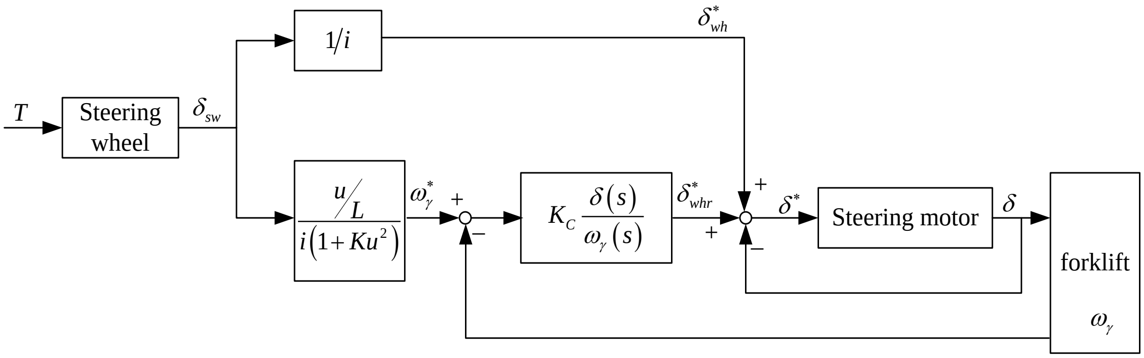

Fig. 7. Diagram of the yaw rate feedback

T —torque applied on the hand-wheel; i —steering ratio; δ_{sw} —rotation angle of hand-wheel. δ^*_{wh} —rotation angle of steered wheel decided by rotation angle of hand-wheel and steering ratio; ω^*_γ —steady yaw rate based on by 2 DOFs linear model; δ^*_{whr} —compensatory rotation angle of steered wheel calculated with yaw rate stability feedback control strategy. δ^* —ideal rotation angle of steered wheel decided by δ^*_{wh} and δ^*_{whr} ; δ — real rotation angle of steered wheel.

d. Simulation and analysis of dynamic correction strategy

The comparison simulation based on yaw rate feedback dynamic correction strategy is given in Figure 8 and Figure 9 with the running speed of 10km/h, hand-wheel torque of 2Nm. We can see that the strategy obviously decreased yaw rate and sideslip angle, improved steering characteristics, and increased operation stability of forklift.

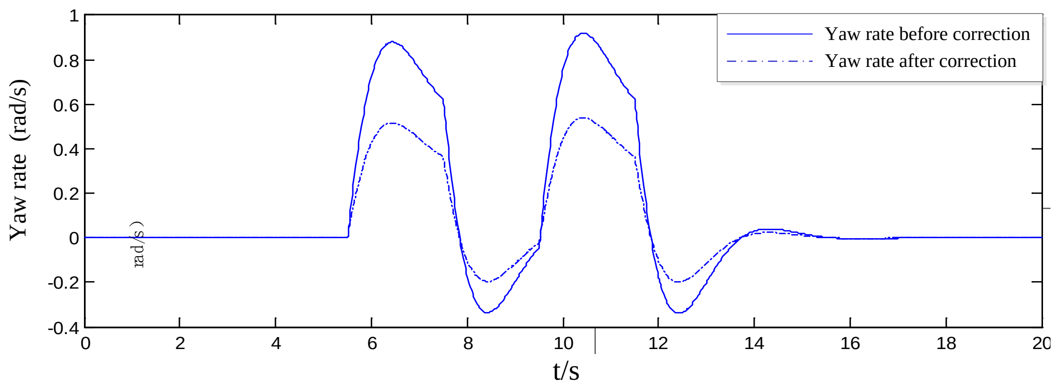

Fig. 8. Comparison diagram of yaw rate before and after correction

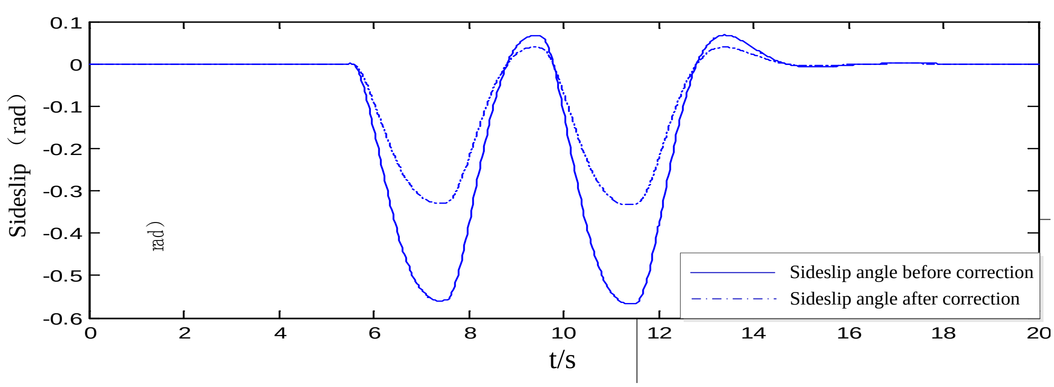

Fig. 9. Comparison diagram of sideslip angle before and after correction

V. CONCLUSIONS

Forklift is one of the important equipment for material handling. It can reduce the labor intensity of workers and improve the efficiency of handling. As the forklift is often used in small place such as factory workshop, wharf, and warehouse; and also it has a large load. So the requirement for steering system is very high. The steering system not only has a flexible steering characteristic, but also has better operation stability. Based on the requirements above, the SBW system is an inevitable trend. It overcome the restriction of mechanical structure, drastically improves steering characteristics, and even can achieve ideal steering characteristics.

The SBW system can realize active control for vehicle steering system and obviously improve the operation flexibility. The main research content is as follows. (1) Take TE30 type forklift as an example, the mathematic models of hand-wheel and steering executable module were build. (2) The armature current of steering motor was controlled by PID algorithm, which can make the motor provide torque rapidly and accurately. (3) Forklift dynamic correction control strategy based on yaw rate feedback was proposed. From the simulation, we can see that the strategy obviously decreased yaw rate and sideslip angle, improved steering characteristics.

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