Research on Performance of Wire-controlled Hydraulic Steering System Based on Four-wheel Steering

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Abstract. In this paper, the steering stability and control strategy of forklift are put forward. Drive based on yawing moment distribution of rotary torque coordination control method, through analyzing the linear two degree of freedom model of forklift truck, forklift yawing angular velocity and mass center side-slip Angle of expectations, as the control target parameters system, using fuzzy controller output driving forklift steering the yawing moment, to drive rotary torque distribution, make the forklift truck to drive horizontal pendulum angular velocity and side-slip Angle tracking reference model very well. In this paper, the lateral stability control system were designed, the joint simulation in MATLAB/Simulink, the simulation results show that under the different partial load, the control system can effectively to control side forklift lateral stability, enhanced the forklift driving safety, for the side forklift steering stability study provides a theoretical basis.

1.Introduction

The steer-by-wire system is a new way to turn over the limitations of traditional steering systems due to mechanical connections[1].At present, the engineering vehicle mainly adopts two-wheel steering （Two-wheel steering, 2WS）, and the ordinary two-wheel steering vehicle has large turning radius, and has the disadvantages of slow steering response and poor stability of high-speed steering[2].The four-wheel steering[2]（Four-wheel steering, 4WS）can independently control the movement   trajectory and attitude of the vehicle. It has a small turning radius, effectively reduces the lag of the steering force and obtains better steering performance. Therefore, it is necessary to combine the steer-by-wire control technology with the four wheel steering technology to improve the driving performance of the engineering vehicles. Liang Chunming and others[3] designed the four-wheel synchronous steering system for the universal forklift, and added four-wheel steering device on the ordinary two-wheel steering system, so that the forklift could travel in any direction. Mu Xihui[4] proposed a hydraulic four-wheel steering system with double steering gear and double steering cylinder interlocking by controlling electromagnetic commutation to achieve two-wheel independent steering and four-wheel combined steering. Bekheira Tabbache[5] studies the stability of the four wheel independent driving vehicle under the extreme conditions such as braking and cornering, and concludes that the four-wheel drive system is superior to the two-wheel drive system through comparative analysis.

With the side forklift turning frequently in the narrow space, this paper adopts some control strategy, established a wire-controlled hydraulic steering system based on four-wheel steering mode; Through modeling and simulation analysis, the dynamic characteristics of the system are obtained to provide theoretical guidance for the promotion of the wire-controlled hydraulic steering system in the vehicle engineering.

2. System working principle

As shown in Figure 1, the control block diagram of wire-controlled hydraulic steering system based on four-wheel steering mode is given. It works by transmitting the steering signal of steering wheel(steering wheel angle) and speed to the electronic control unit(ECU), and the electronic control unit performs some calculation according to the corresponding control strategy and control target to obtain the desired angle of each wheel. Then, the electronic control unit converts these desired angles into voltage signals and transmits them to the electro-hydraulic steering systems of each wheel. The voltage signal drives the electro-hydraulic steering system of each wheel to control the steering of each wheel, thus obtaining the actual steering angle of each wheel(In this paper, δ is the wheel angle, subscript *if*、 *of*、 *ir*、 *or* represent inner front wheel, outer front wheel, inner rear wheel and outer rear wheel respectively).
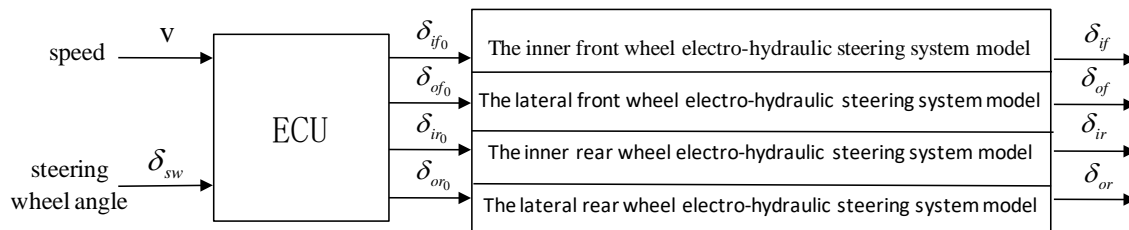

Figure 1. the control block diagram of wire-controlled hydraulic

The electro-hydraulic steering system of each wheel, which is in exactly the same form, relatively independent, is closed loop proportional position control system. The independent control of each wheel steering is ensured by parallel connection, and the coordinated control of each wheel movement is carried out by ECU.

3. System control strategy and mathematical model

*3.1 Control strategy. I*n order to improve the flexibility of engineering vehicle steering and the driving stability, a certain control strategy is needed; Since the main object of our research is the side forklift, it needs to change frequently in the narrow space, and the steering response speed is higher than that of ordinary vehicles, so as to reduce the turning radius.

Through the analysis to determine the control objectives[6] are as follows: to reduce the centroid of the sideslip angle; Low-speed turning radius is small , and the high-speed operation stability is good.; When the tire reaches its attachment limit, the response frequency is still within the operative limit.

In the four-wheel steering analysis, the vehicle is generally simplified into two-wheel model[6], that is, the two-degree-of-freedom linear model of vehicle[6].

$$\begin{bmatrix} \beta' \\ r' \end{bmatrix} = \begin{bmatrix} -\dfrac{C_f + C_r}{mv} & -(1 + \dfrac{l_f C_f - l_r C_r}{mv^2}) \\ -\dfrac{l_f C_f - l_r C_r}{I} & -\dfrac{l_f^2 C_f + l_r^2 C_r}{Iv} \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \begin{bmatrix} \dfrac{C_f}{mv} & \dfrac{C_r}{mv} \\ \dfrac{l_f C_f}{I} & -\dfrac{l_r C_r}{I} \end{bmatrix} \begin{bmatrix} \delta_f \\ \delta_r \end{bmatrix} \tag{1}$$

In the formula, m is the whole vehicle mass,*Kg*; *I* is the yaw moment of inertia around the center of mass, $Kg \cdot m^2$; v is the speed of the vehicle, m/s; β is the sideslip angle of center of mass, rad; r is the yaw velocity, rad/s; δ$_f$ and δ$_r$ are the virtual front and rear wheel angles respectively, rad; l_f and l_r are the distance from the vehicle centroid to the front and rear axis respectively, *m; C*$_f$ and *C*$_r$ are virtual front and rear wheel side stiffness(Take positive value), *N*/rad;

The meaning of each parameter in the formula is shown in [6];

According to the above control objectives, make the sideslip angle β=0, and in the steady state β′= 0 and r′= 0 ,plug that into the equation (1) ,and then simplify it:

$$\frac{\delta_r}{\delta_f} = \frac{-l_r + \dfrac{ml_f}{C_r l}v^2}{l_f + \dfrac{ml_r}{C_f l}v^2} = K_r \tag{2}$$

From the formula (2), the ratio of the virtual rear wheel angle to the virtual front wheel angle K_r is the function of the speed v, and K_r determines whether the four-wheel steering is the same phase or reverse phase; When the speed v is low, Kr < 0 indicates that the front and rear wheels turn in the opposite direction, reducing the turning radius and improving operation flexibility; When the speed v is high, Kr >0 indicates that the front and rear wheels turn in the same direction ,and it can improve stability and anti-lateral interference ability.

3.2 Relation model between wheel angle and electronic steering wheel angle. Through the dynamic analysis and calculation of the vehicle[6], the relationship between the four wheel angles and the virtual front and rear wheel angles δ_f and δ_r can be obtained:

$$\delta_{if} = \frac{1}{1-(1-K_r)w/(2l)\delta_f}\delta_f \qquad \delta_{ir} = \frac{1}{1-(1-K_r)/K_r \cdot w/(2l)\delta_r}\delta_r$$

$$\delta_{of} = \frac{1}{1+(1-K_r)w/(2l)\delta_f}\delta_f \qquad \delta_{or} = \frac{1}{1+(1-K_r)/K_r \cdot w/(2l)\delta_r}\delta_r \tag{3}$$

The virtual front wheel angle and steering wheel angle meet the following relationship[7]:

$$\delta_f = K_f^{'}\delta_{sw} \tag{4}$$

In the formula, K_f' is the ratio of the steering wheel to the virtual front wheel; δ_{sw} is the electronic steering wheel angle, °;

According to the previous formula (2), (3) and (4), in the four-wheel steering mode, the steering angle (desired steering angle) of each wheel is related to the electronic steering wheel angle, as shown in Figure 2:
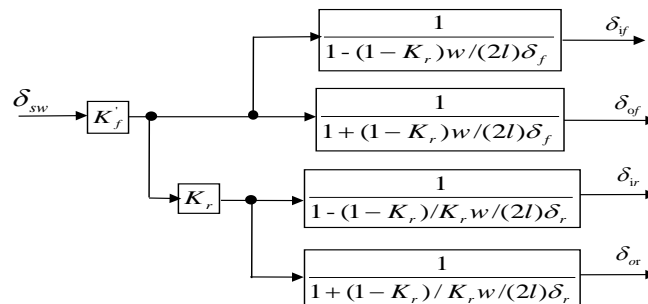

Figure 2. the relationship between desired wheel angle and electronic

3.3 The mathematical model of electro-hydraulic proportional steering system. The control block diagram of electro-hydraulic proportional steering system is shown in Figure 3，and the system consists of comparison element, controller, proportional directional valve, hydraulic cylinder, wheel

and corner sensor etc. The angle sensor feedback the actual deflection angle of the current wheel, and the system compares and calculates the angle deviation between actual deflection angle and desired deflection angle of wheel. The system translates the angle deviation into the electrical signal and transmits it to the proportional amplifier to obtain the voltage signal after power amplification so as to achieve closed-loop control.
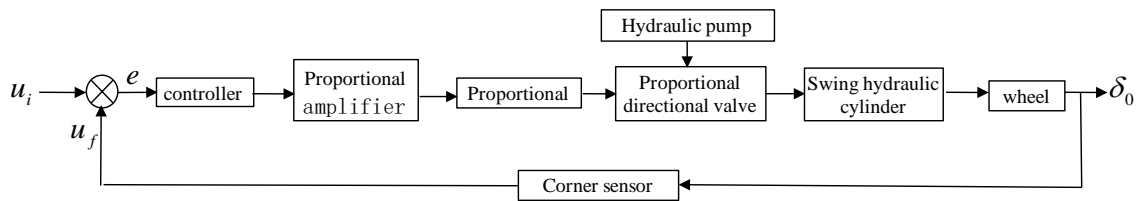

Figure 3. control block diagram of the system

Through the analysis of the working principle and characteristics concerned of the system, the transfer function of the main modules of the system is obtained. Finally, the block diagram of the whole system's transfer function model is given, as shown in Figure 4.
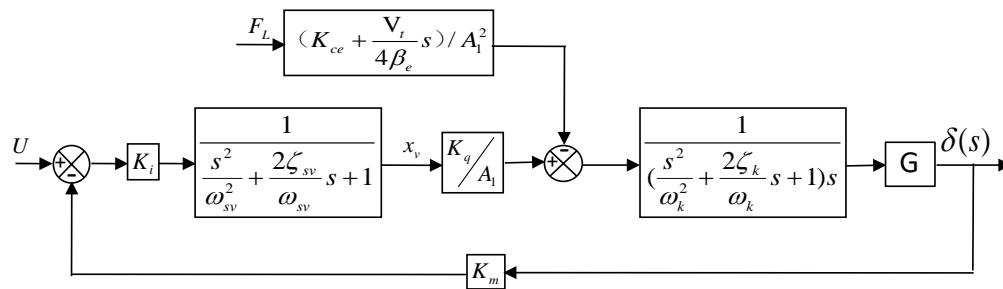

Figure 4. the block diagram of the whole system's transfer function model

4. Joint simulation of steering system

The simulation model of each wheel corner control in ECU is established by the relation between the wheel angle and the electronic steering wheel angle, as shown in Figure 5.

Based on the principle of wire-controlled hydraulic steering system, simulation mode of single-wheel electro-hydraulic proportional steering system was established by AMESim simulation software[8]. After the figure 5, PID controller and comparison element are encapsulated, the model of ECU can be obtained. Combined with the simulation model of single-wheel electro-hydraulic proportional steering system, the simulation model of four-wheel independent electro-hydraulic steering system is set up, as shown in Figure 6.

5. Simulation result analysis

In order to fully reflect the performance of the steering system and the performance advantages of the four-wheel steering system, we have simulated ordinary two-wheel steering and four-wheel steering of forklift truck these two steering modes, and the simulation results of the two are compared and analyzed.
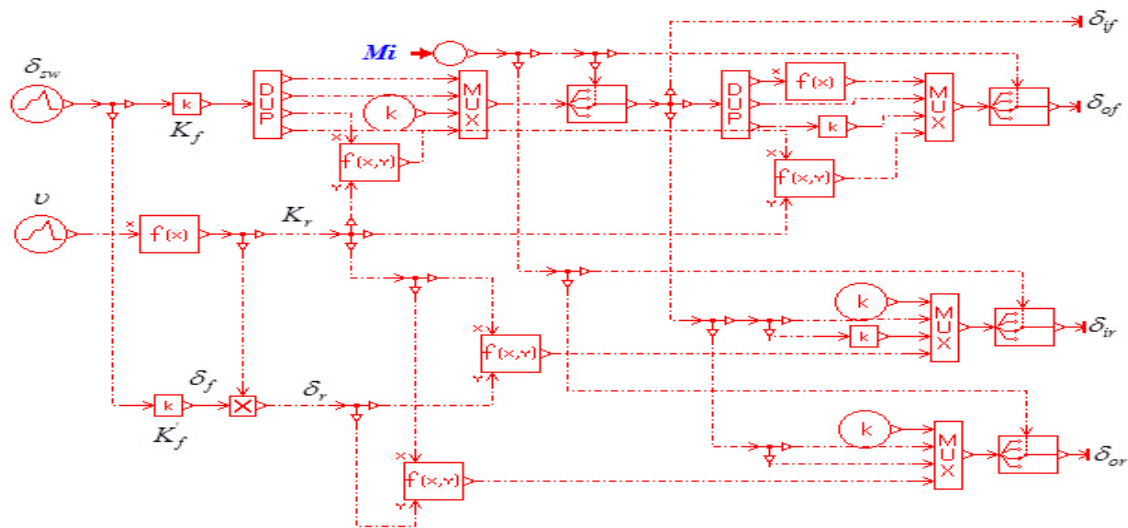
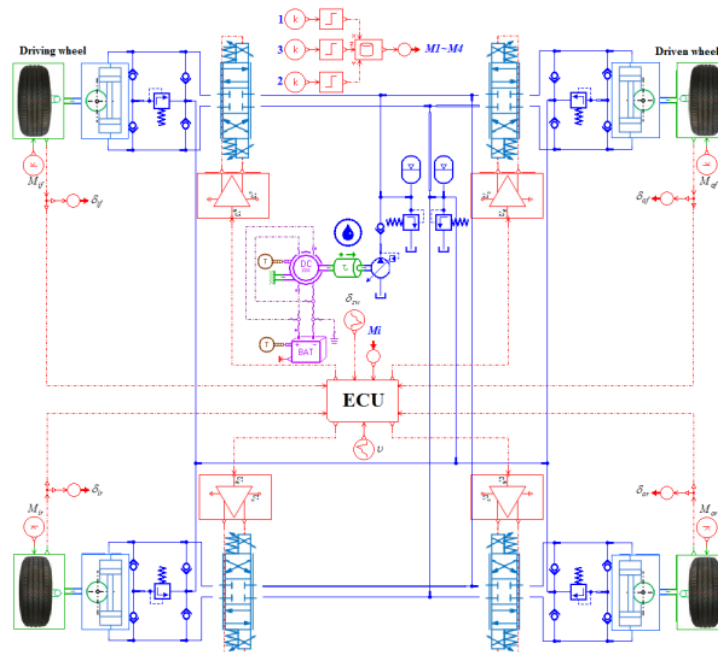Figure 5. simulation model of each wheel angle control

Figure 6. simulation model of the steering system

Select the angle input of the steering wheel as a symmetrical trapezoid, as shown in Figure 7. Since the steering wheel angle directly controls the virtual front wheel when the four-wheel is turned, the left front wheel angle of the two steering modes is unequal in the case of the same steering wheel angle input. For a better analysis and comparison of the two steering performance, we set steady state steering wheel angle of 410 degrees at the four-wheel steering and 360 degrees at the ordinary two-wheel steering to ensure that the left front wheel angle of the two steering modes is equal.
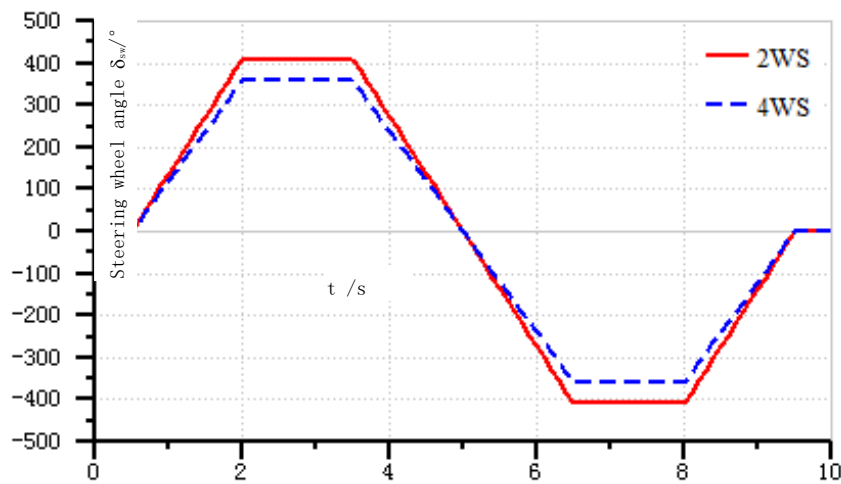
Figure 7. steering wheel angle input

5.1 Transient response and tracking error of wheel angle. The steering system under four-wheel steering mode with the above steering wheel angle input is simulated, and the transient response and tracking error of wheel angle are obtained, as shown in Figure 8.In the figure the solid line represents the theoretical value of each wheel angle, and the dotted line represents the actual value of each wheel angle.

From the simulation results, it can be seen that each wheel angles can better track the theoretical values, and the angle tracking error of the steering wheel constant angle is no more than 0.5 degrees, and the steering accuracy is higher. However, when the steering wheel angle input is zero, there is still an error of about 1 degrees, i.e., the wheel failed to return to zero. This is due to the electromagnetic hysteresis and mechanical hysteresis, and it is necessary to eliminate the repetition error by setting up the central locking mechanism to ensure that the vehicle returns to the straight driving state.
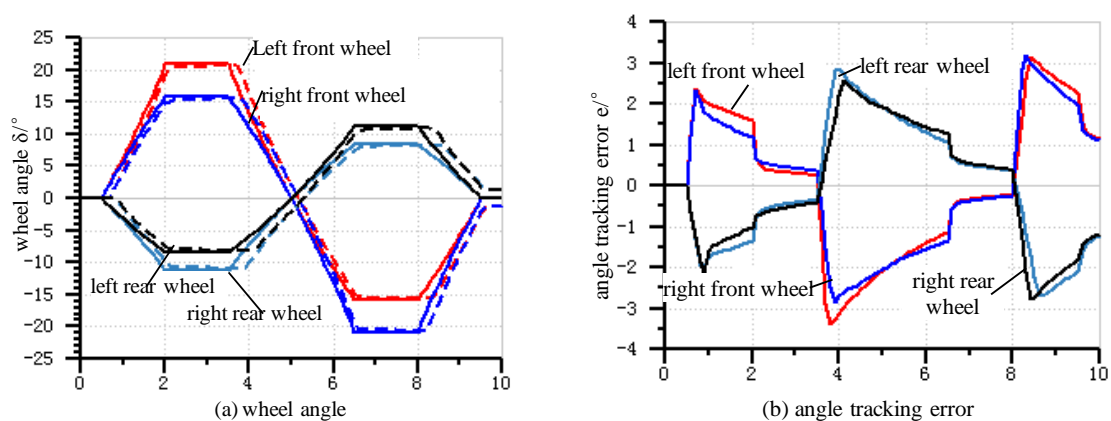

Figure 8. wheel angle response and tracking error in four-wheel steering mode

5.2 The transient response of the sideslip angle of the center of mass and the yaw velocity. Figure 9 shows the transient response of the sideslip angle and yaw velocity of the ordinary two-wheel steering mode and the four wheel steering modes under low speed respectively. It can be seen from Figure 9 (a) that, at low speed, the inverse phase four-wheel steering can be used to obtain a smaller sideslip angle of the center of mass, and the vehicle's stability is better. The forklift is low-speed vehicle, which needs frequent steering in narrow space, and its requirements for steering response speed are higher than that of ordinary vehicles. Therefore, the yaw velocity feedback is introduced[9]. From Figure 9, the yaw velocity of the four-wheel steering is greater than that of the ordinary two-wheel steering, and the sensitivity is high, and the overall rotation amplitude of the vehicle is larger, and a smaller turning radius can be obtained.

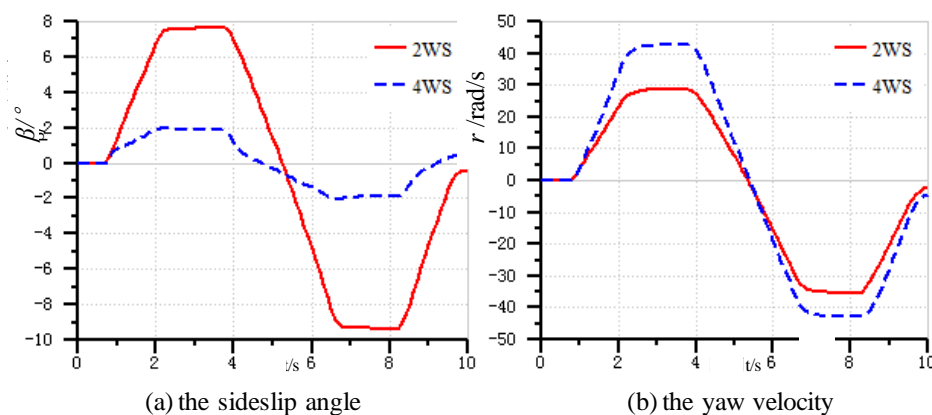(a) the sideslip angle   (b) the yaw velocity

Figure 9. the transient response of the sideslip angle of the center of mass and the yaw velocity

5.3 Stability and response speed. Figure 10 shows the stability and response velocity analysis of the steering system in the four-wheel steering mode. Figure 10 (a) show the system center of mass side-slip angle frequency response. Figure 10 (b) is the frequency response of the yaw velocity. The more the amplitude frequency curve is, the smaller the steering distortion is; and the wider the frequency band is, the better the steering stability is. The limit of the driver's steering wheel is 2Hz, and the amplitude frequency is effective at 0 ~ 2Hz. It can be seen from the figure that the bandwidth is about 1Hz and the stability is better. The smaller the phase lag in phase frequency characteristics, the faster the response speed of the vehicle steering. It can be seen from the figure that, before 0.1 Hz, there is basically no lag, and the steering system has a better following and faster response.

(a) the frequency response of sideslip angle   (b) The frequency response of the yaw velocity
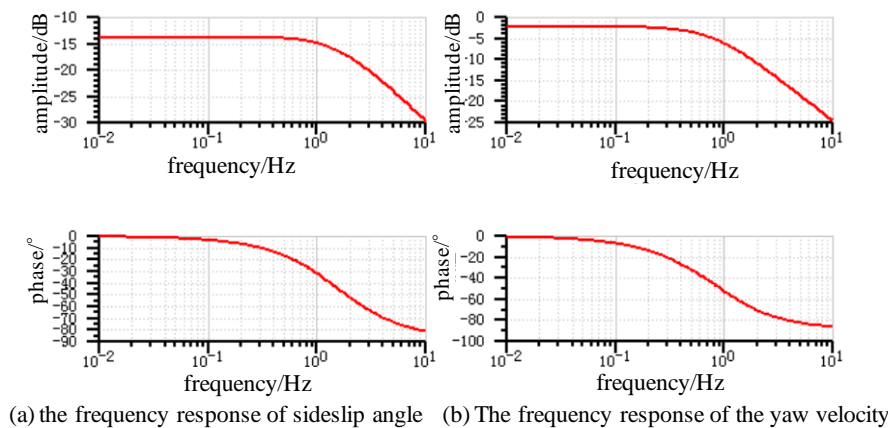
Figure 10. Steady-state characteristics of the sideslip angle of the center of mass and yaw velocity

6. Conclusion

Aiming at the working characteristics of the side forklift, wire-controlled hydraulic steering system based on four-wheel steering mode has better steering performance , and the simulation results show that: The steering system has high steering accuracy, fast response time, low system pressure and flow fluctuation, better static and dynamic performance, and meets the engineering practical requirements of side forklift truck.

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