Steering Control Method of Mobile Forklift Based on Sensing Signal

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Abstract. Because the steering control method of the mobile forklift has the problem of large steering deviation, a steering control method of the mobile forklift based on sensing signal is designed. Using the yaw rate calculated by the two-degree-of-freedom front wheel steering model as the ideal value, the steering variables of the mobile forklift truck are obtained, the rotation angle relationship between the two steering wheels is coordinated, the types of steering mechanisms are identified, the linear two-degree-of-freedom model is constructed, the desired steering curve corresponding to the steering wheel is written into the compensation controller, and the steering control mode is optimized by using sensing signals. Experimental results show that the steering deviation between the designed steering control method and the other two methods is 3.257°, 5.466° and 5.486° respectively, which indicates that the steering deviation decreases with the combination of sensing signals.

Keywords: Sensing signal · Mobile forklift · Steering control · Motion variable · Sideslip angle of centroid · Yaw rate

1 Introduction

According to the relevant records, the earliest forklift is used for the loading and unloading of military materials at the airport. It is a single-stage gantry forklift modified from a car by Clark Company. Forklifts were put into use during the Second World War because of the need to move military supplies and the high handling efficiency of forklifts that could not be compared with manual work. After the Second World War, with the development of the world automobile industry, the sales and technology of forklifts also developed rapidly. With the development of society and economy, people's pursuit of efficiency is gradually improving, so forklifts are more and more involved in economic development and social construction. Forklifts, also known as forklifts, automatic lifts, forklifts, versatile loaders, etc., is a forklift to take goods to put the mechanical device, is one of China's top 10 construction machinery equipment, is mainly used in freight yards, factories (machinery manufacturers, textile mills, etc.), docks, commercial sites (such as shopping malls, etc.), airports and construction sites, because of its compact body, short axle distance, rotation is flexible, is now widely used in the social national

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economy vehicles and tools. Since the steering torque of the vehicle can be easily determined by the steering motor, the yaw angle can be predicted by a linear vehicle model of the steering system and an observer after the yaw rate and steering angle are measured.

The main function of a forklift truck is to transfer, stack, store and transport the goods. With the development of social production and science and technology, the performance of forklifts has been gradually improved, and the number and variety of forklifts have increased significantly. Forklifts can also be divided into internal combustion forklifts powered by fossil fuels and mobile forklifts powered by electricity (storage forklifts are also very widely used mobile forklifts) [1, 2] according to the different types of power. On the contrary, the mobile forklift has the advantages of low noise, high reliability, easy operation, environmental protection and energy saving, and has won more and more forklift buyers in the development process. According to the different contact ways between the wheels and the ground, it can be divided into track-type forklift and trackless forklift, which is widely used at present. According to the position of the fork can be divided into straight moving forklift and side moving forklift. Although the proportion of internal combustion forklifts is relatively high and the market share of mobile forklifts is relatively low, the ratio of forklifts to internal combustion forklifts is changing, and the proportion of mobile forklifts is increasing year by year, especially electric storage forklifts, electric storage forklifts have entered an accelerated growth cycle. Then according to the predicted side-slip angle, the system uses a feedback control to carry out effective steering intervention to achieve the correct steering operation.

2 Steering Control Method of Mobile Forklift Based on Sensing Signal

2.1 Obtain Steering Motion Variables for Mobile Forklifts

Yaw rate, sideslip angle of center of mass and steering radius are important factors to evaluate steering performance of forklift. Moving forklift handling stability of the first choice of variables should be considered to select the parameters that can be directly measured or can be estimated. The yaw rate is related to the trajectory retention. When the sideslip angle of the center of mass is close to 0, the yaw rate determines the attitude of the forklift. When the sideslip angle of the center of mass is small, the yaw rate determined by the linear two-degree-of-freedom model is relatively stable for the vehicle motion. The yaw angle and yaw rate of the moving forklift can be regarded as the first target of the main motion variables of the control system, and the yaw rate of the moving forklift can be measured by gyroscope and other instruments, and the yaw angle of the moving forklift can be real-time estimated by the state observer. The yaw rate gained from the two-degree-of-freedom front wheel steering model is taken as an ideal value, and the yaw rate gain of the four-wheel steering vehicle is similar to that of the front wheel steering vehicle, so the driver will not feel great change. The centroid sideslip angle is often used to describe the trajectory keeping problem.

Compared with the traditional steering control system of forklifts, the control target of the stability of the mobile forklift mainly includes two aspects: (1) The high speed operation of the mobile forklift requires the stability and safety of the mobile forklift, that is, the response value of the centroid yaw angle of the mobile forklift should be controlled near zero degree, and the yaw rate of the mobile forklift should be smaller than that of the traditional steering control system. When driving a forklift, the driver expects the forklift to run along the axis, that is, the speed of the vehicle coincides with the longitudinal axis of the vehicle. (2) When the mobile forklift runs at a low speed, it is required that the mobile forklift can improve the mobility of the mobile forklift while maintaining stability, that is, the response value of the centroid angle of the mobile forklift should be as close to zero as possible, and the yaw angle speed of the mobile forklift is larger than the value of the traditional steering control system. Therefore, the formula of ideal yaw rate and pavement adhesion condition is as follows:

$$W = \frac{\phi / H}{\frac{\phi}{H^2}(1-\gamma)^2} \tag{1}$$

In formula (1), ϕ represents the road adhesion coefficient, H the gravitational acceleration, and γ the lateral acceleration of the vehicle. Therefore, the ideal yaw rate must satisfy the constraint conditions:

$$|\eta| \le \left|\frac{\phi \times H}{\phi}\right| \tag{2}$$

In order to improve the transient response, the ideal yaw rate is modified according to formula (2) by referring to the approximate first-order pure lag system of the sideslip angle of the ideal center of mass in order to improve the transient response, if only taking the constant η as the ideal yaw rate will cause the vehicle yaw rate to oscillate greatly under the condition of the step signal of the yaw angle:

$$\eta' = \min\left(\left|\frac{\phi \times H}{\phi}\right|\right)(\varepsilon) \tag{3}$$

In formula (3), the ε represents the first-order inertia response time constant. To sum up, the sideslip angle and yaw rate of the moving forklift are selected as the main motion variables of the control system. Because of the limitation of working environment and working property, the working speed of forklift truck can not be too large, but the tire sideslip angle is small in this case. The handling stability of a forklift is the ability of the forklift to follow the driver's direction through the steering system and the steering wheels, and to resist interference and keep the forklift running steadily when it encounters external interference. Forklift handling stability, stability of the good or bad will directly affect the handling of the good or bad degree, so collectively known as handling stability. The handling stability of a forklift is closely related to the sideslip angle and yaw rate of the center of mass. When the sideslip angle of the center of mass is small, the yaw rate is usually used to describe the steering characteristics of forklifts, and the yaw rate can reflect the driver's driving intention. When the sideslip angle of the centroid is large, the yaw rate can no longer reflect the steering characteristics of the forklift, because the larger the sideslip angle of the centroid, the lower the control ability of the driver to the lateral motion of the forklift. Therefore, the sideslip angle and yaw rate of the center of mass are important physical parameters to describe the handling stability of forklift.

2.2 Identify the Type of Steering Structure

The steering structure of a forklift truck is a complete set of mechanisms used to control the steering wheel or articulated frame's azimuth and deflection angle, which ensures the forklift truck driver can control the driving direction of the forklift truck. Forklift drivers can make the corresponding steering action according to the operation needs and the driving environment. Forklift truck steering is light and flexible, small turning radius, good maneuverability and rear wheel steering. There is a serious internal leakage in the steering process, which leads to the disorder of the relationship between the steering wheel and the wheel, so the driver can not predict the steering angle of the vehicle according to the position of the steering wheel in the process of driving, so the current position of the wheel can only be determined by turning back repeatedly, which greatly increases the labor intensity of the driver.

Mobile forklift steering system according to the steering mode, there are two kinds of single-axis steering and bi-axis steering. Single-axis steering mode is mainly used in three-wheeled forklifts. The rear wheels are usually connected to the frame by two tires side by side. The single-axis steering mode is simple and does not need any additional steering mechanism to coordinate the steering angle relations between the steering wheels. The steering is flexible and the steering maneuverability is better. In addition, it is found that the leakage operation of the solenoid valve has the same mechanism and effect as the internal leakage of the steering system, and the steering system is out of sync by reducing the flow of oil in the steering cylinder. At present, four-wheel steering forklift belongs to two-axle steering. In this kind of steering, two forklift wheels rotate around different axes. This kind of steering needs to add steering mechanism to coordinate the angle relation between two steering wheels, which is relatively complex.

When the steering mechanism works, the steering wheel drives the valve core of the full hydraulic steering gear to rotate, and the high-pressure oil enters the steering cylinder through the full hydraulic steering gear to push the piston rod to move. Among them, the full hydraulic steering gear is the measuring device of the full hydraulic steering system to ensure that the steering wheel angle input and the wheel angle into a fixed ratio. The double axle steering mode is simple in structure and good in performance. Therefore, the double axle steering mode is mostly used in four-wheeled mobile forklifts. In order to ensure that the two steering wheels of forklifts can rotate at the same time, they need to be connected with certain structure, and the steering mechanism should be the same when the forklifts move left and right. As an open-loop control system, the steering accuracy and stability of the full hydraulic steering system can not be guaranteed. The steering deviation generated by the system cannot be automatically eliminated, resulting in a disorderly relationship between the steering wheel and wheel position [3]. Therefore, it is necessary to analyze and solve the steering deviation. Because the steering angles of the two wheels are different when steering, the steering mechanism generally adopts a trapezoidal structure. The steering structure of a forklift truck is shown in Fig. 1:

As can be seen from Fig. 1, the steering structures of forklifts mainly include single trapezoidal steering structure, double trapezoidal steering structure and crank slider structure. When steering, the axes of all wheels are required to intersect at a point called the steering center, so as to ensure that the forklift wheel makes pure rolling motion when steering. If the wheel slides with the ground, it will increase the resistance of motion,

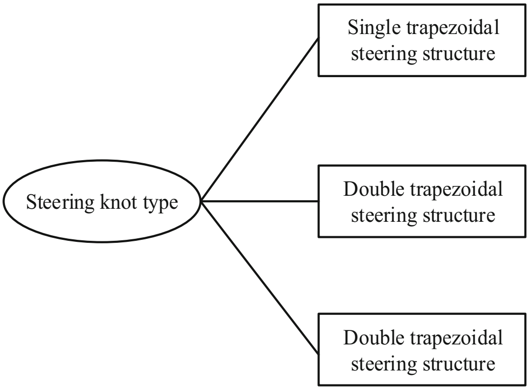

Fig. 1. Steering structure type of forklift truck

thereby speeding up tire wear and reducing the service life of the tire. One of the main features of mobile forklifts is that the working device for loading and unloading goods is placed in the front of the forklift truck and is suspended in front of the wheel supporting the forklift [4]. The main reason of steering deviation of full hydraulic steering system is internal leakage of oil in full hydraulic steering system. At present, the full hydraulic steering gear equipped with cycloidal valve type, this type of full hydraulic steering gear has the advantages of flexible operation, long reliable life, compact structure and easy to arrange, and can realize the manpower steering when the engine is off, so it is widely used in the steering system of forklifts, loaders, cranes and other low-speed and heavy-duty vehicles.

Fork is used to lift and fork cargo parts, through the gantry lifting mechanism to drive the fork to complete the lifting of goods, through the control of hydraulic cylinder mechanism connected with the gantry, fork can also complete the pitching and pitching, relying on these two movements. Plus the forklift truck forward and backward, forklift can easily complete the cargo support, lift, stacking, stacking and other processes, the frame is equipped with a roof rack, the roof rack structure is simple, can provide a good view to the driver, facilitate the driver to observe the surrounding environment [5]. Another feature is that the working device adopts telescopic portal frame and time-saving lifting pulley block, which enables the forklift truck to obtain a larger lifting height under the condition of smaller shape height, improves the passability of the forklift truck and expands the use scope.

2.3 Construction of Linear Two-Degree-of-Freedom Model

Although the L2DOF model only considers the lateral and lateral motion of the forklift and ignores the nonlinear factor of the tire, the simplification of the vehicle model meets the requirements of the vehicle kinematics. In front of the driving axle is the lifting structure of the forklift truck, behind is the frame of the forklift truck. The lifting structure is mainly composed of the door frame, the fork frame and the fork. The tilt of the door frame is controlled by the hydraulic cylinder, and the chain drives the fork frame and the fork to complete the lifting of the goods. The maneuverability and stability of mobile forklift can be divided into two aspects, one is maneuverability, the other is stability. The maneuverability of the forklift means that the forklift can be driven according to the driver's steering intention without deviating from the predetermined track. The dynamic equations of the model are as follows:

$$\begin{cases} (h_1 + h_2)\,\sigma + \frac{1}{\alpha}\|h_1 - h_2\| = \frac{1}{L(\mu)^2} \\ (h_1 - h_2)\,\sigma + \alpha + \frac{1}{g} = L(\mu) - E \end{cases} \tag{4}$$

In formula (4), h_1 stands for centroidal to front wheelbase, h_2 stands for centroidal to rear wheelbase, σ stands for mass of the whole vehicle, α stands for centroidal angle, L stands for steering wheel angle, μ stands for vehicle inertia, g stands for yaw stiffness of front tire, and E stands for yaw stiffness of rear tire. It is equipped with electronic instruments, seats, fans and transmitters for forklifts. The relevant parts of the steering system and the counterweight are installed in the rear part of the forklift. The engine provides power for the forklift, while providing additional stability torque for the longitudinal stability of the whole forklift. Stability is the ability of a forklift to keep steady when disturbed by the outside world, and avoid dangerous situations such as tail wagging and overturning when steering at high speed. The lifting of the forklift can be regarded as a simple lever action, the balance weight above the steering bridge can provide additional stable torque, can increase the quality of the forklift lifting goods.

The steering characteristics of the forklift are mainly characterized by the yaw rate. When the speed of the forklift is constant, the bigger the yaw rate is, the faster the speed is allowed, and the better the turning performance and stability is. In order to ensure the flexibility of forklift, the brake system of forklift is installed on the driving axle. Emergency braking can easily cause the whole forklift to lean forward and longitudinal instability. When synchronous steering control is carried out, the desired steering curve corresponding to the steering wheel and wheel is firstly written into the compensation controller.

When vehicle steering, the steering wheel angle sensor and wheel angle sensor detect the steering wheel and wheel angle respectively, input the detected steering wheel angle into the desired steering curve to calculate the desired wheel angle, and then compare the desired wheel angle with the actual wheel angle. If the steering deviation is greater than zero, the solenoid valve is opened to compensate the steering cylinder with oil, and then the synchronous steering is realized. However, if the wheel angle is too large or the road surface is too complex or the adhesion coefficient is too small, the bigger the sideslip angle of the center of mass of the forklift is, the worse the trajectory keeping ability is, and the driver can not reflect the steering intention of the driver in real time, the smaller the control ability of the driver for the side motion and the yaw motion is, and the dangerous situation such as rollover slip and forklift driving a circle is easy to occur. In this case, the adaptive compensation can be realized by adjusting the opening of the solenoid valve, and the compensation precision and compensation stability are improved.

2.4 Sensor Signal Optimization Steering Control Mode

Sensing signals can be used for gas leak detection, and their prior information plays an important role in signal processing. They provide a systematic research direction for measuring the probability of signal vectors. According to the gas detection technology, the sensing signal carrying gas information can be obtained. Considering the drift of hardware or optical structure, the noise with unknown statistical characteristics in the environment, etc., it is necessary to combine some signal processing algorithms to improve the signal-to-noise ratio and detection precision of the system when detecting the gas concentration or retrieving gas parameters. A lot of research has been done on the closed form of signal apriori.

When gas leakage occurs, according to the detected gas concentration, it is also necessary to combine with some signal processing algorithms to locate the gas leakage source quickly and accurately. For example, Gibbs distribution is to use Laplace matrix to evaluate the probability of image, and the smoothness degree measured by Laplace operator can be used to judge the probability of signal. The role of steering control is to control the direction of forklift, and then achieve steering purposes. The steering process of forklifts can be summarized as steering force through steering transmission and other devices to make the steering wheels deflect at a certain angle to achieve forklifts steering. Through the analysis, for the four-wheel steering mode in line with the existing driving habits, driving vehicles on the driver's requirements are relatively easier. Of course, whether four-wheel steering or four-wheel steering is faced with the need for a four-wheel steering system, the system response and control accuracy can not be verified, the structure is complex, high cost, high risk, very challenging. Considering the working environment of forklifts, most forklifts work in narrow environment such as warehouse, wharf and so on. Loading and transporting heavy goods need very frequent steering. In general, forklift steering system generally has the following steering control requirements: operation to be light, steering action to be sensitive, tracking to be good, steering handling stability to be high.

In addition, the four-wheel conditional steering mode cannot realize the parallel movement of vehicles and the ordinary steering mode (the so-called ordinary mode means that two wheels are fixed in parallel on the coaxial line and the other two wheels are deflected), so in order to realize the parallel movement of vehicles and the traditional ordinary driving mode, the driving mode selection switch needs to be added in the design. For example, when the speed of a forklift is low, the yaw rate of the forklift is usually expected to be increased while the turning radius is reduced, so that understeer can be avoided. After comprehensive consideration, the steering scheme of the vehicle is determined to be: the combination of the four-wheel conditional steering mode and the driving mode. The control circuit makes real-time control and adjustment according to the position of the four wheels, and responds to the driver's steering wheel's control. This model is the "guide point" in the body of the longitudinal axis of the line, the following to the left side forklift as an example to establish mathematical models. On the contrary, when the speed of forklift truck is high, the driver usually hopes not to be too sensitive, because when the steering wheel angle is too sensitive, the driver is prone to nervous state of mind when driving at high speed, easy to misuse the steering wheel and other dangerous behaviors. Therefore, when driving at high speed, the driver usually hopes that the yaw angle speed can be appropriately reduced relative to the steering wheel angle to enhance the driving safety. In the normal driving mode: the driver in the normal driving mode, the side forklift two front wheels according to the steering wheel rotation angle to turn, and two rear wheels keep motionless turn angle is zero. Thus it can be seen that the turning radius and yaw rate can reflect the steering maneuverability of forklift.

The steering flexibility of a forklift usually refers to the turning ability of the forklift, especially in narrow space, which can better reflect the steering flexibility of the forklift. The geometric aspect can be described by turning radius, and the kinematic aspect can be described by vehicle speed and yaw rate. The steering angle of the front two wheels is not limited by mechanical devices such as steering rocker. By using the control of the steering angle controller, the steering stability of forklift truck is improved and the tire friction loss is reduced. The control strategy of isometric reverse rotation of front and rear wheels is a kind of control strategy summed up according to the driver's driving experience of forklift truck. The isometric reverse rotation in the name refers to the control strategy that the virtual front wheel rotation angle and the rear wheel rotation angle are equal and opposite directions. The main idea of the control strategy of isometric reverse rotation of front and rear wheels is to control the center of the instantaneous rotating shaft of forklift truck to the horizontal line of the longitudinal center of the truck body, which is very in line with the driver's driving habit. The lateral force in the coordinate system shall be calculated according to the working conditions of the omnidirectional side forklift under normal driving conditions with uniform speed. The calculation formula is as follows:

$$G = \frac{|k + t|^2}{\|\arctan(\varpi - k)\|} \tag{5}$$

In formula (5), k represents the curve peak factor, t represents the curve shape factor, and ϖ represents the curve curvature factor. On this basis, the right front wheel of a forklift is selected as an example for the calculation of the wheel sideslip angle. The speed of the geometric center of the right front wheel around the center of mass of the whole vehicle is:

$$y = \frac{l\sqrt{p^2/q^2}}{\psi} \tag{6}$$

In formula (6), l represents the distance from the front wheel axle to the center of mass, p represents the horizontal drift of the curve, q represents the vertical drift, and ψ represents the vertical load on the tire. The control of isometric reverse rotation of front and rear wheels can not only reduce the turning radius of the forklift, but also improve the flexibility of the electric forklift. The control of isometric reverse rotation of front and rear wheels also satisfies the Ackermann theorem for three-wheel full steering forklifts. In the mode of in-situ steering, when the driver chooses this mode, the four wheels turn to the angle set by the electronic control unit at the same time, and the forklift turns in any direction under the control of the driver with the center of the whole vehicle as the center. The steering mode provides great convenience for the side forklift to turn around in situ, and improves the mobility of the side forklift in a narrow environment. In order to ensure that the three tires and the road surface of the electric forklift truck are in the state of pure rolling, the virtual front wheel angle and the geometric constraint are used to control the two front wheel angles respectively. The tire under pure rolling condition can exert its mechanical characteristics to the utmost extent, and reduce the wear of electric forklift tire under non-pure rolling condition.

3 Simulation Experiment

3.1 Experimental Preparation

Using MATLAB/SIMULINK platform for simulation analysis. In addition, in order to analyze the effect of joint fuzzy control, the ideal values of yaw rate and sideslip angle of center of mass are obtained by ideal model. ADAMS can create mechanical system simulation model, and MATLAB can build control model. Joint simulation uses the same physical prototype model. If two software are simulated independently and separately, we need to create the system model under two different software environments. Under the high speed simulation of the mobile forklift, the speed of the forklift is 2. Skm/h, the forklift is simulated under the stepping condition. Given the three-wheel angle, the signal jump of the rear wheel is 1.57 rad, the signal jump of the left front wheel is 2.32 rad, the signal jump of the right front wheel is 0.75 rad, and the input angle is given the virtual front wheel angle.

Through the ADAMS own interface and MATLAB/Simulink combined use, to achieve the control of data exchange between variables. In order to establish the joint simulation model, we need to connect ADAMS/View and MATLAB/Simulink through ADAMS/Control tools, create state variables in ADAMS/View, define them as output and input variables, establish the control system model in MATLAB, and exchange the output values of ADAMS as the input values of MATLAB between two software. Especially, the steady state performance of forklift steering is emphasized and the steady state value is observed. The steering performance of forklift truck under sinusoidal condition is studied.

3.2 Experimental Results

In order to verify the feasibility of the control method, the steering control method of mobile forklift based on singular value decomposition and envelope analysis are selected to carry out simulation experiments. The steering deviations of the three methods are tested under different steering angles. The experimental results are shown in Table 1–5.

Table 1. Steering angle 500° steering deviation (°)

Number of experiments	Steering control method of mobile forklift based on singular value decomposition	Steering control method of mobile forklift based on envelope analysis	Steering control method of mobile forklift
1	8.945	8.554	6.548
2	9.036	8.692	5.615
3	9.122	9.307	6.142

(*continued*)

Table 1. (*continued*)

Number of experiments	Steering control method of mobile forklift based on singular value decomposition	Steering control method of mobile forklift based on envelope analysis	Steering control method of mobile forklift
4	8.877	8.546	6.646
5	9.613	9.112	5.849
6	9.250	8.456	6.945
7	9.163	9.001	5.331
8	8.489	8.748	6.128
9	8.331	9.316	6.489
10	9.004	8.549	5.002
11	8.557	9.055	5.221
12	9.161	8.748	5.031
13	8.944	9.163	6.111
14	9.033	9.224	5.499
15	8.247	9.218	5.336

As can be seen from Table 1, the average steering deviation of the steering control method of the designed mobile forklift truck and the other two steering control methods of the mobile forklift truck is 5.860°, 8.918° and 8.913° respectively; as can be seen from Table 2, the average steering deviation of the steering control method of the designed mobile forklift truck and the other two steering control methods of the mobile forklift truck is 4.238°, 7.189° and 7.346° respectively; as can be seen from Table 3, the average steering deviation of the steering control method of the designed mobile forklift truck and the other two steering control methods of the mobile forklift truck is 3.181°, 5.205° and 5.180° respectively; as can be seen from Table 4, the average steering deviation of the steering control method of the designed mobile forklift truck and the other two steering control methods of the mobile forklift truck is 1.892°, 3.710° and 3.889° respectively; as can be seen from Table 5, the average steering deviation of the designed mobile forklift truck and the other two steering control methods is 1.13° and 2.306° respectively. The experimental results show that the bigger the steering angle is, the smaller the steering deviation is, and the experimental results of the steering control method are always lower than the other two methods. Because the method in this paper takes the yaw rate calculated by the two-degree-of-freedom front wheel steering model as the ideal value, the steering variables of the mobile forklift are obtained. A linear two-degree-of-freedom model is constructed, and the expected steering curve corresponding to the steering wheel is written into the compensation controller, and the steering control method is optimized by using the sensor signal to reduce the angle error.

Table 2. Steering angle 750° steering deviation (°)

Number of experiments	Steering control method of mobile forklift based on singular value decomposition	Steering control method of mobile forklift based on envelope analysis	Steering control method of mobile forklift
1	7.364	7.104	4.316
2	7.458	7.649	4.125
3	7.063	7.315	4.691
4	7.442	7.422	4.157
5	6.948	7.244	4.2033
6	7.431	7.106	4.879
7	7.009	7.370	4.221
8	7.066	6.987	4.166
9	6.994	7.451	4.021
10	6.849	6.844	4.334
11	7.124	7.216	4.159
12	6.997	7.469	3.988
13	7.118	7.336	4.173
14	7.645	8.154	4.125
15	7.332	7.522	4.007

Table 3. Steering angle 500° steering deviation (°)

Number of experiments	Steering control method of mobile forklift based on singular value decomposition	Steering control method of mobile forklift based on envelope analysis	Steering control method of mobile forklift
1	6.141	4.316	2.316
2	5.154	6.977	3.011
3	5.216	6.522	5.565
4	5.489	4.167	3.228
5	5.147	5.844	2.974
6	4.889	4.019	3.104
7	5.006	5.490	2.967

(*continued*)

Table 3. (*continued*)

Number of experiments	Steering control method of mobile forklift based on singular value decomposition	Steering control method of mobile forklift based on envelope analysis	Steering control method of mobile forklift
8	4.667	5.337	3.114
9	5.553	5.108	2.879
10	5.022	4.977	3.455
11	4.987	5.313	2.964
12	5.216	4.879	3.117
13	5.337	5.112	3.020
14	4.987	4.415	2.844
15	5.266	5.226	3.161

Table 4. Steering angle 1000° steering deviation (°)

Number of experiments	Steering control method of mobile forklift based on singular value decomposition	Steering control method of mobile forklift based on envelope analysis	Steering control method of mobile forklift
1	3.145	4.030	1.698
2	3.158	3.946	1.596
3	4.005	3.889	2.036
4	3.874	3.849	2.102
5	3.015	3.569	2.137
6	4.112	4.221	1.948
7	3.648	3.878	1.869
8	3.554	4.101	1.774
9	4.022	4.033	2.016
10	3.694	3.948	1.555
11	4.017	3.665	1.644
12	3.898	4.121	2.077

(*continued*)

Table 4. (*continued*)

Number of experiments	Steering control method of mobile forklift based on singular value decomposition	Steering control method of mobile forklift based on envelope analysis	Steering control method of mobile forklift
13	3.121	3.447	1.495
14	4.516	4.119	2.316
15	3.878	3.515	2.117

Table 5. Steering angle 1250° steering deviation (°)

Number of experiments	Steering control method of mobile forklift based on singular value decomposition	Steering control method of mobile forklift based on envelope analysis	Steering control method of mobile forklift
1	2.546	2.005	1.002
2	1.826	1.848	0.645
3	2.331	2.695	1.214
4	2.548	1.463	1.588
5	3.144	2.316	0.948
6	2.008	2.169	1.131
7	2.105	1.944	1.252
8	3.014	2.165	1.055
9	2.642	2.588	1.441
10	2.849	1.996	1.033
11	1.948	2.131	1.145
12	2.113	2.455	1.015
13	1.879	1.878	1.002
14	2.615	2.116	1.143
15	1.022	1.787	1.088

4 Conclusion

Because the forklift needs to turn frequently, the driving state has been in the dynamic process, and the three control methods are derived from the mathematical model, belongs to static control. Therefore, the linear two-degree-of-freedom model of mobile forklift is introduced as the ideal reference model and method verification model. In this paper, the non-step problem of steering system after active steering is studied, and a full hydraulic synchronous steering system is designed to realize steering synchronization by compensating steering oil cylinder. Based on the constant yaw rate gain control and constant lateral acceleration gain control, the variable transmission rate control based on combined gain control and steering efficiency control is designed. It provides a reference for determining the expected steering curve for hydraulic steering vehicles and other hydraulic steering machinery. At the same time, the simulation results show that the steering control method of the mobile forklift is better than that of the control for the forklift. Because of the influence of the research condition, this paper does not consider the influence of eccentric load on the lateral stability of forklifts.

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