

The Research of Fuzzy Variable Transmission Ratio for Steer-by-wire System of Electric Forklift

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Abstract—Combining with the TE30 electric forklift produced by an enterprise, the principle of Steer-by-wire (SBW) system, steering motion state, ideal steering ratio are analyzed and studied. The biggest characteristic of SBW system is that the transmission ratio is free to design. Based on the establishment of two-degree-freedom linear model of Forklift, the paper designed the nonlinear transmission ratio function on vehicle speed and steering angle with the application of fuzzy control rules. The simulation results show that the fuzzy variable transmission ratio can make the yaw velocity gain tend to be constant, also can make Forklift light sensitive at low speeds and steady heavy at high speed. In order to ensure that the yaw velocity gain does not vary with the change of speed and steering angle, this paper presents a dynamic correction control strategy based on the steady-state control for Forklift. The simulation results show that the amplitudes of yaw velocity and sideslip angle are reduced with the dynamic correction of yaw velocity feedback, also the handling stability is improved.

Index Terms— Electric Forklift, SBW System, Variable Transmission Ratio, Dynamic Correction of Yaw Velocity

I. INTRODUCTION

With the rapid development of modern forklift technology, people on the requirements of forklift steering performance are also increasing, not only steering light flexible and small steering radius, but also good mobility performance. In order to make the steering portability and handling stability meet the requirements when the Forklift steering wheel is turned in any working conditions, the forklift steering system was constantly improved. Forklift steering technology is gradually developed from Mechanical steering system, Hydraulic power steering system, Electronic-hydraulic power steering system to Electric Power Steering (EPS) system and the active steering system[1,2].

SBW system eliminates the mechanical connection between the steering wheel and the steering actuator, it can realize active steering control for the forklift steering system.

In SBW system, the electrical signal and controller replace mechanical connection mode between the steering wheel and the steering actuator, it is no longer bounded by the mechanical connection, this makes the angle transmission characteristics and force transmission characteristics of the forklift steering system are free to design, this makes the forklift steering characteristics

with a huge space for development. Practice has proved, SBW system compared with the traditional steering system improves the steering characteristic and the operation stability, reduces the driver's physical consumption[3,4,5].

The main research work of this paper is as follows:

(1) Takes TE30 type SBW forklift produced by an enterprise as an example, introduces the working principle of SBW system and the forklift steering motion coordinate system.

(2) Presents the concept of ideal transmission ratio, analysis the influence factors of ideal transmission ratio based on two-degree-freedom forklift model. Determines the ideal transmission ratio according to the value of the actual TE30 forklift, designs the variable transmission ratio function based-on fuzzy control rules, finally simulation analysis is done for the variable transmission ratio function in typical conditions.

(3) Introduces the dynamic correction of yaw velocity feedback, simulation results show that the strategy can reduce the amplitude of yaw velocity and sideslip angle, improves forklift handling stability.

II. THE PRINCIPLE OF SBW SYSTEM

SBW system is developed on the basis of the EPS system, it eliminates the mechanical connection between the steering handle and the steering wheel, overcomes the mechanical structure constraint for the steering characteristic, and can make the vehicle light sensitive at low speeds and steady heavy at high speed.

The working principle of SBW system is: when the driver turns the steering handle, torque, angle and vehicle speed signal etc. are transmitted to the main controller ECU through the sensors, ECU will send the control command after the logical analysis and calculation of these signals, directly control steering motor and realize the steering of the vehicle wheel.

Because the steering wheel is completely controlled by ECU, So the SBW system can realize the variable angle transfer characteristics of the steering system according to the actual condition of forklift.

III. THE DESCRIPTION OF FORKLIFT STEERING MOTION STATE

In the forklift steering coordinate system, taking the vehicle mass center O as the origin of coordinates, taking the forward direction of the vehicle as positive x axis in the horizontal plane passing through the origin, taking the direction on the left side of the driver as the positive y axis in the horizontal plane through the origin, taking vertical direction as the positive z axis in the vertical plane through the origin.

There are three main motion parameters relevant to the vehicle steering system, respectively: yaw velocity ω_y , that is the angular velocity of the vehicle body around z axis. Lateral velocity v , namely the vehicle mass center along the y axis speed. Lateral acceleration a_y , namely the vehicle mass center on the y axis acceleration. Forklift coordinate system is shown in Fig. 1.[6]

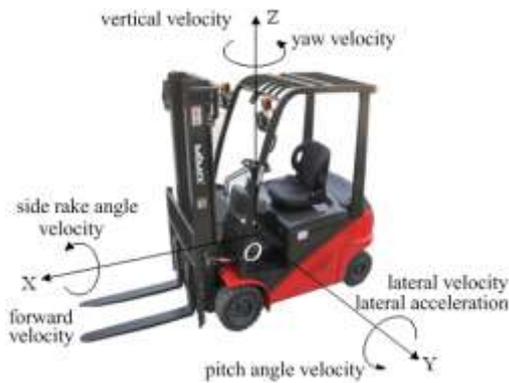


Fig. 1. Schematic diagram of Forklift coordinate system

A. The Lateral and Longitudinal Stability of Electric Forklift

Unlike ordinary passenger cars, as a logistics tool, electric forklift has a main feature that its load is variable. Relevant data shows that forklift accidents often happen because of improper stacking and excessive speed. And most of the accidents are caused by the excessive centrifugal force when the forklift is steering. This shows that, on the one hand, the main reason of such accidents is the improper stacking, however, the most important reason is the excessive speed. These make the steering security and the steering stability of electric forklift become noteworthy.

The steering stability of electric forklift refers to the lateral and longitudinal stability in the loading, unloading and transportation process when the forklift is driving on different ways. The longitudinal stability refers to the ability to prevent electric forklift from rolling over longitudinally around the axle caused by gravity and inertia force (such as forward or backward rollovers). Factors that affect the longitudinal stability are generally the forks lift speed and the forklift gantry tilt speed. Combined with the effect of inertial force, it is easy to roll over longitudinally when the center of gravity has changed caused by an excessive forks lift speed and the

forklift gantry tilt speed. However, the lateral stability refers to the ability to prevent electric forklift from rolling over and slipping laterally. When the forklift is driven on a steep slope with an excessively high or partial center of mass, or steering on a curve with a high speed, it is probably to cause lateral rolling over. And when the forklift is driven on a road in water or being braked suddenly when steering, the lateral force will be greater than the adhesive force between the wheel and the ground, then the forklift will slip. Therefore, in order to ensure the security of electric forklift, it is necessary to make the lateral and longitudinal stability conform the control requirement.

In terms of the longitudinal stability, it depends mainly on manmade control on the forks lift speed and the forklift gantry tilt speed. However, the lateral stability is affected by the speed and the steering angle of electric forklift, so it can be improved through the research on the steering speed and the steering angle. The following mainly discussed the control requirements of the lateral stability of electric forklifts.

IV. STUDY ON STEERING TRANSMISSION RATIO FOR FORKLIFT SBW SYSTEM

A. Handling Stability

Under the driver is not excessive fatigue and tension situations, forklift handling stability refers to that forklift can be in accordance with the driver intention, by operating steering system the steering wheel will travel in a given direction, when encountered outside interference, forklift keeps the ability of stable running with no interference effect[7].

Forklift handling stability is an important evaluation index of forklift active safety, the main influence factors are four physical quantities, respectively, vehicle speed, yaw velocity, lateral acceleration and vehicle mass center sideslip angle. Among them, the yaw velocity is the most important influence factor, it is the control variables to keep the lateral stability.

When the forklift mass center sideslip angle is relatively smaller, forklift cornering capability is reflected by the yaw velocity. When forklift is traveling at a certain speed, and when the yaw velocity becomes large, the turning radius will become small. That is to say, the forklift with higher yaw velocity is allowed higher speed through the same bend road.

B. The Concept of Ideal Steering Ratio

In the traditional mechanical steering system, the transmission ratio is a fixed value, this makes the system steering characteristics change in the large range.

In SBW system, the transmission ratio may be changed, by optimal setting of the transmission ratio, the steering characteristics varying with the vehicle speed change will be adjusted, it will make up for the deficiencies of traditional mechanical steering system. This variable transmission ratio is known as the ideal transmission ratio[8].

Vehicle ($\text{kg} \cdot \text{m}^2$), k_1 – Lateral stiffness of front tire (N/rad), k_2 – Lateral stiffness of rear tire (N/rad), u – the speed component in horizontal direction (km/h), v – the speed component in the vertical direction (km/h).

The above formula contains forklift quality, tire lateral stiffness, yaw velocity, sideslip angle etc. the important parameters, reflects the basic characteristics of forklift handling dynamics.

The following equation is obtained based-on the vehicle model:

$$\omega_\gamma = \frac{u(a+b)k_1k_2\delta_{wh}}{(a+b)^2k_1k_2 + (ak_1 - bk_2)mu^2} \quad (7)$$

So:

$$G_{\delta_{wh}}^{\omega_\gamma} = \frac{u(a+b)k_1k_2}{(a+b)^2k_1k_2 + (ak_1 - bk_2)mu^2} \quad (8)$$

$$G_{\delta_{sw}}^{\omega_\gamma} = \frac{u(a+b)k_1k_2}{(a+b)^2k_1k_2 + (ak_1 - bk_2)mu^2} \frac{1}{i} \quad (9)$$

Formula (9) is modified as follows:

$$i = \frac{\frac{u}{L}}{G_{\delta_{sw}}^{\omega_\gamma} \left[1 + \frac{m}{L^2} \left(\frac{a}{k_2} - \frac{b}{k_1} \right) v^2 \right]} \quad (10)$$

Where: $L = a + b$. The ideal transmission ratio is not only related with the vehicle parameters, also related with the steering angle, vehicle speed and yaw velocity.

D. Analysis of Influence Factors about the Transmission Ratio of SBW System

1) Relationship between transmission ratio and the vehicle speed & steering angle

When the fork handle angle is small, that is the steering wheel is needed to turn small angle, in order to improve the precision of steering system, it should make the steering system response “dull”, that is to say the transmission ratio value should be greater. When the forklift steering angle is increased, that is the steering wheel is needed to turn large angle, in order to guarantee the response speed, steering system should be “flexible”, at this time, transmission ratio value of system should be less, this will reduce the steering handle range of the driver and reduce the burden of driver. Thus, the transmission ratio is related to the steering angle, it is designed as the function of the steering angle, the function curve is shown in Fig. 3.

When the forklift is low speed or static steering, the larger static friction force makes the steering resistance torque is large, in order to make the steering “light”, transmission ratio should be smaller, so it will reduce the driver's physical consumption. When the forklift is at high speed, the smaller dynamic friction force makes resistance torque is reduced. In order to prevent the

forklift “floating”, transmission ratio should be greater, so the handling stability of forklift is improved[15]. Obviously, the transmission ratio is related to the vehicle speed, it is designed as the function of speed, the function curve is shown in Fig. 4.

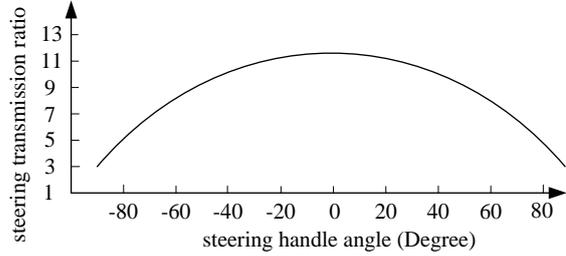


Fig. 3. The relationship between steering handle angle and transmission ratio

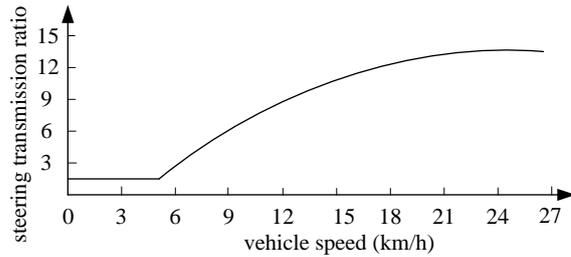


Fig. 4. The relationship between vehicle speed and transmission ratio

2) The relationship between transmission ratio and yaw velocity

When the forklift runs at a steady speed, the vehicle is in a steady state, at this time, yaw velocity ω_γ is a fixed value. Therefore, $\dot{v} = 0, \dot{\omega}_\gamma = 0$. By formula (10) of two-degree-freedom vehicle model, the steady-state yaw velocity can be obtained as follows:

$$\omega_\gamma = \frac{u/L \delta_{sw}}{i(1 + Ku^2)} \quad (11)$$

Where: K is the stability coefficient, an important index of forklift steady-state response, the unit is s^2/m^2 , its expression is modified as follows:

$$K = \frac{m}{L^2} \left(\frac{a}{k_2} - \frac{b}{k_1} \right) \quad (12)$$

Yaw velocity gain $G_{\delta_{sw}}^{\omega_\gamma}$ reflects the following performance of forklift to the input of steering angle, also known as the steering sensitivity. If the yaw velocity is too small, then the response of Forklift is too slow. Otherwise, the response of forklift is too fast, the operation stability will decrease. Yaw velocity gain is an important index of the steering flexibility.

In the traditional mechanical steering system, the transmission ratio is a fixed value, this makes the system steering characteristics varies with the change of vehicle speed. If the drivers control the steering of forklift according to the target direction, drivers must make real

time compensation to the variable steering characteristic. This increases the requirements of driver experience.

Transmission ratio of SBW system is variable, the front wheel angle can be independently controlled, that is the angle transmission ratio of the steering system can be controlled. Seen from formula (11), the transmission ratio and the yaw velocity are the function relation, yaw velocity is controlled through the change of transmission ratio, the ideal handling characteristics is achieved by designing ideal transmission ratio based-on the driver subjective evaluation.

E. Determining Method of the Ideal Transmission Ratio

When the vehicle speed is below a certain value u_1 , the transmission ratio of steering system is a fixed value i_{min} . When the steering wheel is turned to the maximum angle δ_{swmax} , the limit values of forklift front wheel angle is the δ_{whmax} , here the steering system transmission ratio is as follow:

$$i_{min} = \frac{\delta_{swmax}}{\delta_{whmax}} \tag{13}$$

When the vehicle speed increases to a certain value u_2 , lateral force provided by the tire reaches the limit value. Therefore, steering system transmission ratio can not be increased, that is the maximum value i_{max} . Thus, ideal transmission ratio of the steering system is as follow:

$$i = \begin{cases} i_{min}, & 0 \leq u \leq u_1 \\ \frac{u(a+b)k_1k_2}{(a+b)^2k_1k_2 - (ak_1 - bk_2)mu^2} \frac{\delta_{sw}}{\omega_\gamma}, & u_1 < u < u_2 \\ i_{max}, & u \geq u_2 \end{cases} \tag{14}$$

In the case of the example, the related calculation data of TE30 type SBW forklift is shown in Table 1.

Table 1. Forklift Model Parameters Table

Parameters	The physical meaning of the parameters	numerical value	unit
m	Vehicle weight	640	kg
a	Distance from mass center to the front axle	0.518	m
b	Distance from mass center to the rear axle	0.95	m
k_1	Lateral stiffness of front tire	55856	N/rad
k_2	Lateral stiffness of rear tire	55856	N/rad
u_{max}	Maximum vehicle speed	15	km/h
δ_{sw}	handle angle range	[-90,90]	Degree
δ_{wh}	Steering wheel angle range	[-90,90]	Degree

According to the formula of steering system ideal transmission ratio, $i_{min} = 1$. the sensitivity $G_{\delta_{sw}}^{\omega_\gamma} = 0.4$ is obtained based-on the test on the driver subjective evaluation and the actual data of forklift according to the State Key Laboratory of automobile dynamic simulation of Jilin University, at this time, driver's subjective feeling is best. To adapt to the various speed and driving conditions, determine $i_{max} = 13.66$, take the integer 13.

The above analysis and calculation are static results, but the actual running process of forklift is a dynamic process.

F. Control Rules Design of Fuzzy Variable Transmission Ratio

By the above analysis, transmission ratio and vehicle speed are related with the steering handle angle, but the actual operation is also associated with operating experience and thinking, it is basically not able to establish a precise mathematical model. Fuzzy control has the characteristics of intelligent, it is based on fuzzy logic and fuzzy set theory, and simulates human thinking mode, so it is an ideal method to solve the problem.

Based-on fuzzy rules, the paper designs the nonlinear transmission ratio function on vehicle speed and steering angle. The vehicle speed v and the steering handle angle

δ_{sw} are used as input, transmission ratio i is used as output, the input quantization factors are respectively K_1 and K_2 , the output proportion factor is K_3 , fuzzy control structure is shown in Fig. 5.

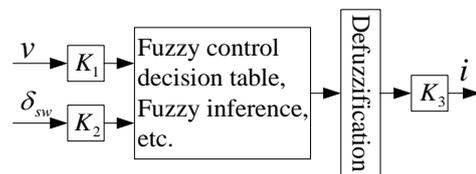


Fig. 5. Structure diagram of two dimensional fuzzy variable transmission ratio

The speed range is [0, 15]km/h for this type of forklift, handle angle range is [-90°, 90°], the calculation range of transmission ratio is [1, 13], proportion factor $K_1 = 2$, $K_2 = 1$, $K_3 = 1$. In the fuzzy control system, if the control rules are more, the description will be more accurate and vivid, but the more control rules will cause the programming difficult.

According to the control method of expert experience, in general, a linguistic variable selection is suitable for 2 to 10 language value[16,17,18]. Here the linguistic values of language variables v, δ_{sw}, i are divided into 7 levels,

respectively, PB(Positive Big), PM(Positive Mid), PS(Positive Small), Z(Zero), NS(Negative Small), NM(Negative Mid), NB(Negative Big), each level corresponds to a linguistic variables.

The vehicle speed is divided into 7 levels from low to high grade, correspondingly the transmission ratio is divided into 7 levels from low to high grade. From experience, it should improve vehicle "sensitive" at low vehicle speed, also it should improve vehicle "dull" at the high vehicle speed, when the vehicle speed increases in 10–25km/h range, transmission ratio will corresponding increase. When the steering handle angle changes from 0 degree to ±90 degree, the corresponding transmission ratio will change from the high to the low.

Fuzzy rules based on safety considerations are as follows:

$v = \{NB, NM, NS, Z, PS, PM, PB\}$, the language values are $\{0, 5, 10, 15, 20, 25, 30\}$.

$\delta_{sw} = \{NB, NM, NS, Z, PS, PM, PB\}$, the language values are $\{-90, -60, -30, 0, 30, 60, 90\}$.

$i = \{NB, NM, NS, Z, PS, PM, PB\}$, the language values are $\{1, 2, 4, 6, 8, 10, 13\}$.

According to the fuzzy rules, the steering transmission ratio curve diagram is shown in Fig. 6 by using the fuzzy control toolbox in MATLAB.

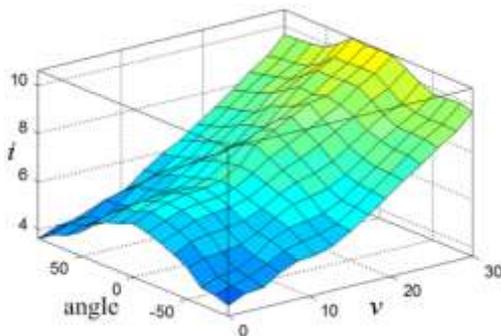


Fig. 6. The curved surface chart of steering transmission ratio

In Fig. 6: i — steering transmission ratio, $angle$ — the steering handle angle, v — forklift speed.

V. SIMULATION AND ANALYSIS

In Fig. 7, the abscissa is the steering handle angle, the ordinate is the steering transmission ratio. In Fig. 8, the abscissa is the steering handle angle, the ordinate is the yaw velocity gain. Fig. 7 and Fig. 8 respectively display the relation curves of the steering handle angle & the steering gear ratio and yaw velocity gain at the speed of 0km/h, 5km/h, 10km/h, 14km/h.

Seen from Fig. 7 and Fig. 8, at the same speed, the steering transmission ratio will decrease gradually with the increase of handle angle to the left or right, but the yaw velocity gain tends to a fixed value. With the increase of vehicle speed, steering transmission ratio increases, the corresponding yaw velocity gain slightly

increases, but the amplitude of change is not big. This shows that the steering ratio of SBW system is a function of steering angle, the yaw velocity gain will tend to a certain value, so the handling stability of forklift is improved.

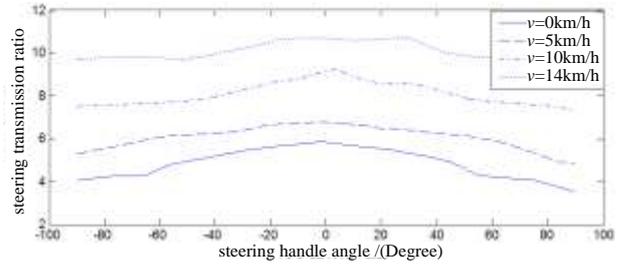


Fig. 7. Relationship between the steering handle angle and steering transmission ratio

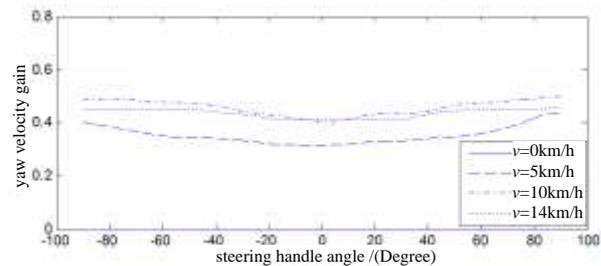


Fig. 8. Relationship between the steering handle angle and yaw velocity gain

In Fig. 9, the abscissa is vehicle speed, the ordinate is the steering transmission ratio. In Fig. 10, the abscissa is vehicle speed, the ordinate is the yaw velocity gain. Fig. 9 is the change chart of steering transmission ratio when the vehicle speed changes in the range from 0 to 15km/h and the handle steering angle is at 0 degrees, 30 degrees, 60 degrees, 90 degrees. Fig. 10 is yaw velocity gain curve.

Seen from these figures, on the same handle angle, steering transmission ratio will increase with the increase of vehicle speed, the yaw velocity gain will tend to a certain value with the increase of vehicle speed, yaw velocity gain is substantially constant when the vehicle speed reaches 5km/h. In different steering angles, steering transmission ratio will decrease with the increase of handle angle, the yaw velocity gain has a slight increase. This shows that the steering transmission ratio of SBW system will change with the change of vehicle speed, but the yaw velocity gain will tend to a certain value, so the handling stability of forklift is improved.

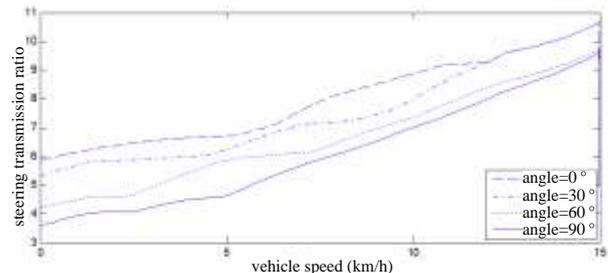


Fig. 9. Relationship between the vehicle speed and steering transmission ratio

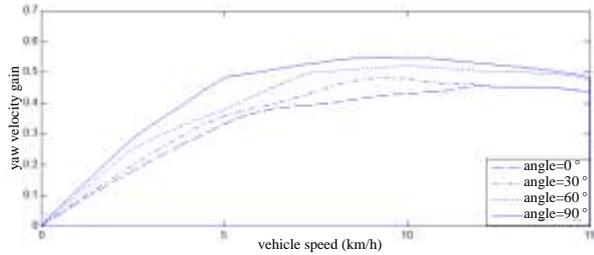


Fig. 10. Relationship between vehicle speed and yaw velocity gain

Seen from the simulation, SBW system will be sensitive in the low-speed steering, be dull in the high-speed steering, and make a few small changes to the sensitivity, the driver will need no excessive sensitivity compensation, so the operation stability of forklift is improved.

Fig. 11 is the comparison chart of yaw velocity gain between traditional steering and SBW steering. Seen from the chart, the yaw velocity gain of SBW system will tend to a steady value along with the increased speed, but the yaw velocity gain of traditional steering system will change greatly along with the speed variation, this shows that the handling stability of SBW system is better than the traditional steering system.

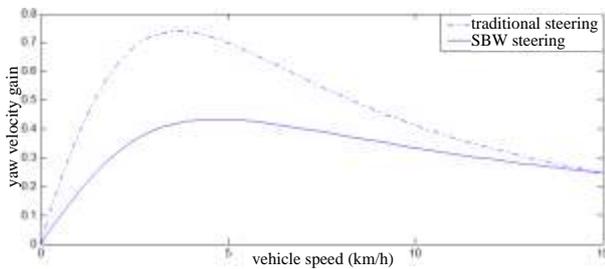


Fig. 11. Relationship comparison between the yaw velocity gain and vehicle speed

Through the study of the transmission ratio of the SBW system based on two-degree-freedom forklift model, steering transmission ratio function on vehicle speed and handle steering angle is proposed based on fuzzy rules. Seen from the MATLAB simulation, the designed Forklift transmission ratio with fuzzy rules not only meets the forklift steering requirements of light sensitive at low speeds and steady heavy at high speed, but also improves the handling stability.

VI. FEEDBACK CONTROL OF YAW VELOCITY

Yaw velocity gain is one of the important indexes to evaluate the handling performance of forklift, and changes with the change of vehicle speed. The same steering angle will produce different yaw velocity at various vehicle speeds, that is the different steering effect. In order to achieve the same steering effect at various speeds, the driver had to make adjustments and compensation to the steering action according to the driving experience, so this will increase the burden for the driver.

It is the control of steady-state significance to ensure the yaw velocity gain does not vary with the change of speed and steering angle, while the actual driving of forklift is a dynamic process. Therefore, In order to ensure the constant yaw velocity gain, Forklift dynamic correction strategy is proposed based on the steady state control[19]. The strategy will provide feedback on the real-time yaw velocity to the system, and eliminate the difference between actual yaw velocity and ideal yaw velocity, adjust the motion state of forklift actively, and recover stability when the forklift has unstable trend[20]. The principle diagram of yaw velocity feedback is shown in Fig. 12.

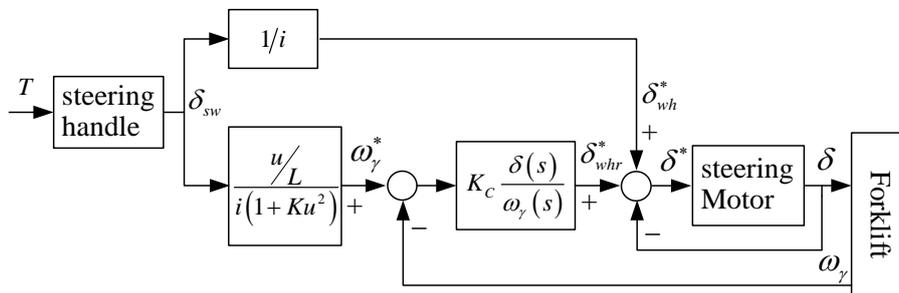


Fig. 12. The principle diagram of yaw velocity feedback

In Fig. 12, T – given torque on the steering handle by the driver, i – the steering transmission ratio, δ_{sw} – the angle of steering handle, δ_{wh}^* – the steering angle of the front wheel determined by the steering handle angle and steering transmission ratio, ω_y^* – yaw velocity obtained from two-degree-freedom linear vehicle model under steady state, δ_{whr}^* – the compensation angle of the front wheel based-on the yaw velocity feedback control strategy, δ^* – the ideal front wheel angle determined by δ_{wh}^* and δ_{whr}^* together, δ – the actual steering angle.

Fig. 13 and Fig. 14 respectively indicate that forklift is driving at the speed of 10km/h, when 2Nm square wave torque is given on the steering handle, the comparison of the simulation diagram for yaw velocity and sideslip angle is given before and after the yaw velocity feedback dynamic correction. Seen from these figures, the amplitude of forklift yaw velocity and sideslip angle is obviously decreased with dynamic feedback, the response characteristics of forklift is improved, the operation stability of forklift is increased.

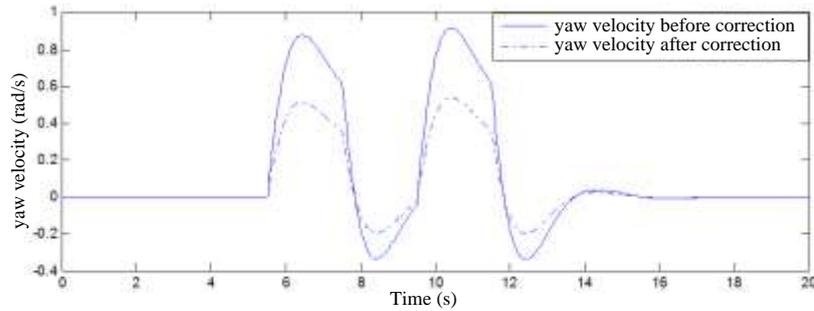


Fig. 13. Comparison chart of yaw velocity before and after correction

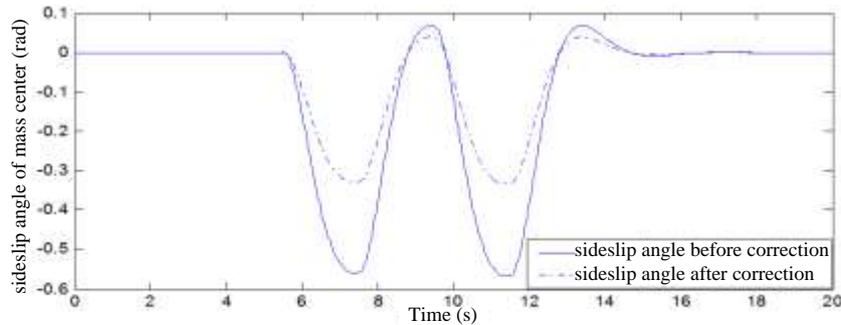


Fig. 14. Comparison chart of sideslip angle before and after correction

VII. CONCLUSION

Combining with the TE30 electric forklift produced by an enterprise, the paper describes the working principle and characteristics of SBW system, introduces the concept of ideal transmission ratio, analyzes the factors affecting the steering transmission ratio, designs the steering transmission ratio function on the vehicle speed and the steering angle based on fuzzy rules. Seen from the simulation results, variable transmission ratio can make the yaw velocity gain close to a constant value, it will greatly improve the steering characteristics, even may achieve the ideal steering characteristics. Through the yaw velocity feedback control strategy, the dynamic correction is used to the front wheel SBW, from the simulation results, the amplitudes of yaw velocity and sideslip angle are decreased, so the handling stability of forklift is improved.

SBW system is not bounded by the mechanical structure, as a significant innovation of vehicle steering system, thus it will provide a huge design space for forklift steering characteristics.

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