International Journal of Control and Automation
Vol. 9, No. 8 (2016), pp.169-180
http//dx.doi.org/10.14257/ijca.2016.9.8.17

The Simulation for the Electro-Hydraulic Power Steering Assisted Control System of Electric Motor Coach

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Abstract

With its energy-saving and green & non-pollution feature, the electric motor coach has been become the focus of public attention, but it also brought the new challenge for the steering system and the matching assisted control system. In this paper it made the introduction for the principle and structure of electro-hydraulic power steering control system, and also carried out the modeling and simulation for the assist characteristic, motor model, steering control valve and assisted control system of the electro-hydraulic power steering assisted control system, finally established the EHPS model and its assisted control system model by using MATLAB/Simulink, to build the practical foundation of the electro-hydraulic power steering assisted control system in the car.

Keywords*: Electric motor coach; Hydraulic, steering; Control, assistant*

1. Introduction

EHPS shall be a typical representative for the development direction of future car's power steering system. The electro-hydraulic power steering control system synthesizes multiple disciplines, is the integration of many technologies, it really show the application of mechanical-electrical integration in the cars, its future development direction will be: not only solve the contradiction of steering system between the light weight and flexibility, but also reduce the energy consumption and improve the handling stability of the cars. In this topic it focuses on the simulation analysis on the electro-hydraulic power steering assisted control system and the study on its control strategies, to make the .theory foreshadowing and technological reserve for the research and development on the electro-hydraulic power steering assisted control system products. Based on such foundation, through establishment of EHPS experiment bench to certify whether the system control strategy has the feasibility accordingly and the reasonability of its power steering characteristics, it founds the practical base for the R & D of the electro-hydraulic power steering assisted control system on the cars. It shall also have the great significance for promoting the development of relative industries such as machinery, sensor and electric devices and improving the electronization level of national auto industry.

2. The Controlling Structure of Assisted Control System.

2.1. Control Valve

The control valve (also named as turning valve) is one of the most important components of the electro-hydraulic power steering assisted control system, it mainly include the spool valve, valve body, torsion bar and pinion. The upper end of

ISSN: 2005-4297 IJCA

control valve shaft was connected with the torsion bar through the pin, and the end part of torsion bar is connected with steering-gear through the pin also, thus the control valve will be connected with the steering gear through the torsion bar. The bottom end of control valve is inserted in the groove of the gear and connected with the steering gear through the pin and rotated with the gear together. There are both one small gap on the bilateral of control valve shaft and the gear cross-section respectively, so that when the steering wheel is turning left or right, the torque from steering column will make the torsion bar twisted, the control valve shaft shall rotate a Δ amount of clearance relative to the gear. The rotation angle shall be corresponded with the flow area inside the valve gap, and it controls the flow quantity inside the hydraulic circuit. Even if the power steering hydraulic pipeline is damaged or engine is flamed out, the rotation of control valve shaft shall also directly transmit the torque to the steering gear, in order to realize the manual steering.

2.2. Electric Pump Assembly

Inside the oil suction cavity, the teeth of main driven gear are continuously separated and engaged by each other, this results in the increasing sealed volume of oil pump on one side of oil suction always and finally forms the vacuum, and the oil fluid inside the oil tank has been sucked into oil chamber under the atmospheric pressure effects. By the end the hydraulic oil shall be taken from the oil suction cavity on the right side into the oil pressure cavity through the rotation of gear. Through the constant engaging movement between the teeth of the main driven gear inside the oil pressure cavity, the gear in the oil pressure cavity is continuously entering in engagement accordingly, thus results in that the sealed volume of oil pump has been becoming smaller increasingly on the side of oil pressure; due to the .extrusion the hydraulic oil is constantly exhausted out off and entered in the oil supply pipeline, therefore the oil suction and oil pressure process of gear pump is completed. If the driving/ driven gear keeps rotation status, the power steering oil pump shall keep sucking and exhausting the oil continuously, then to provide the power-assisted steering for the whole system.

2.3. The Sensor for Power Steering Device

The inductive position sensor can carry out the non-contact measurement on the angular displacement, it can not only meet the critical requirement of the using environment and all kinds of loads, but also have the most important characteristic of the voltage meter sensor - that is usually so called the ratio measurement technology. Same as other angular sensor, it mainly consists of the rotor and stator. The stator on the PCB consists of: electronic component for signal processing, induction receiving coil and exciting coil. The rotor is a piece of sheet metal with simple punch process. After power the exciting coil shall generate the electromagnetic field and enable the rotor generating induced current accordingly. The first inductive coupling between the rotor and receiving coil shall not be affected by the angular position, its main function is to transmit the energy to the rotor in the way of inductive coupling. The second inductive coupling shall relate to the position between the rotor and stator, the range value of voltage on the stator depends on the relative position, the voltage signal in the coil shall be amplified and rectified by the signal processing unit and proportionally output in pair, to form the relative information of the sensor.

3. Modeling and Analysis of the Electro-Hydraulic Power Steering Assisted Control System

3.1. The Modeling and Analysis on Steering Power Characteristic

While driving the car, the steering resistance will decrease as the speed increased, meanwhile the tacking characteristic of the power from the system shall also reduce as the increased angular velocity of the steering wheel. For the lower speed of car moving, the torque of steering resistance is quite large, in order to assure the steering portability, it can increase the steering power by improving the motor speed; while the car moving in higher speed, the torque of steering resistance will reduce, in order to keep enough strength of road sense, it can reduce the steering power by reducing the motor speed. According to analysis, the relation curve for motor speed and car speed can be designed as following:

$$N = \begin{cases} f_1(V) & 0 \le V < V_1 \\ f_2(V) & V_1 \le V < V_2 \\ N_{min} & V \ge V_2 \end{cases} \quad (1)$$

There, $f_1(V)$、 $f_2(V)$ are the linear function in decreasing as the increased car speed respectively, N_{min} is the minimum rotary speed provided by the motor. 。

While the steering angle of the steering system is increased, the piston inside the power hydraulic cylinder shall move in a higher speed, meanwhile the Flux of needed hydraulic oil shall also be even bigger. To supply enough power, it may need further higher motor speed accordingly. So the relation between the motor speed and the steering angular velocity can be designed as following:

$$N = \begin{cases} N_{max} & 0 \le \omega < \omega_1 \\ f(\omega) & \omega_1 \le \omega < \omega_2 \\ N_{min} & \omega \ge \omega_2 \end{cases} \quad (2)$$

In above equation N_{max} is the maximum rotary speed provided by the motor, $f(\omega)$ 是 is the linear function decreased as the car speed increase.

3.2. Motor Modeling and Analysis

Currently the domestic studies on the permanent magnet brushless direct current motor are all aimed to the general three-phase motor; however in comparison with the three-phase motor, the four-phase motor shall have more potentials with its speed regulating system and possess more wider controlling resources, with more controlling modes available for use. For the direct current motor has followed voltage equation:

$$\mathrm{U} = RI + \frac{dy}{dt} \quad (3)$$

After certain simplified requirements, it can get the voltage equation for the four-phase brushless direct current motor as following:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \\ U_d \end{bmatrix} = \begin{bmatrix} R & 0 & 0 & 0 \\ 0 & R & 0 & 0 \\ 0 & 0 & R & 0 \\ 0 & 0 & & R \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \end{bmatrix} + \begin{bmatrix} L & 0 & 0 & 0 \\ 0 & L & 0 & 0 \\ 0 & 0 & L & 0 \\ 0 & 0 & & L \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \\ \dot{I}_d \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \\ E_d \end{bmatrix} \quad (4)$$

Among the equation, U_a, U_b, U_c, U_d are the momentary values of the voltage for the four-phase stator winding of motor, I_a, I_b, I_c, I_d are the momentary values of the phase current for the four-phase stator winding of motor, E_a, E_b, E_c, E_d are the momentary values of the counter electromotive forces for the four-phase stator winding of motor, R is the resistance for the four-phase stator winding of motor. L is the inductance for the phase stator winding on the motor wing.

While each phase winding of the stator have the same constant of counter electromotive force, its counter electromotive force equation shall be:

$$E_i = K_e \omega_m \quad i = a、b、c、d \qquad (5)$$

There, K_e is the constant of counter electromotive force; ω_m is the angular velocity of motor rotation. Thus the voltage equation of the four-phase brushless direct current motor shall be simplified as following form:

$$L_m \dot{I} + R_m I + K_e \omega = U \qquad (6)$$

There L_m is the inductance matrix of the winding, R_m is resistance matrix of the winding, ω is angular velocity matrix of motor rotation.

3.3. Steering Control Valve Modeling and Analysis

In the electro-hydraulic power steering assisted control system the rotary valve is such a key component, whether its performance is good or not shall impact the performance of the whole steering system. The analytic model of rotary valve is shown in Figure 1. The inflow of rotary valve Q_s shall flow in the oil groove F via the oil supply hole E. Then the inflow Q_s is divided into Q_1 and Q_2, Q_1 flows to the left, via the gap A_1 between the valve is flows into oil groove A. Such inflow shall be further divided into two parts, among them the Q_A flows in the power steering oil cylinder, and the remained inflow $Q_1 - Q_A$ will flow in the oil groove C via the gap A_3 between the valve , then via the oil return hole it flows into the low-pressure area of spool valve. The inflow Q_2 flows to right, entering into oil groove B via the gap A_2 between valve, meeting with the inflow Q_B from oil cylinder. The flow rate $(Q_2 + Q_B) = Q_4$ shall enter in the oil groove D via the gap A_4 between the valve, then via the oil return hole flow into the low-pressure area of the spool valve.

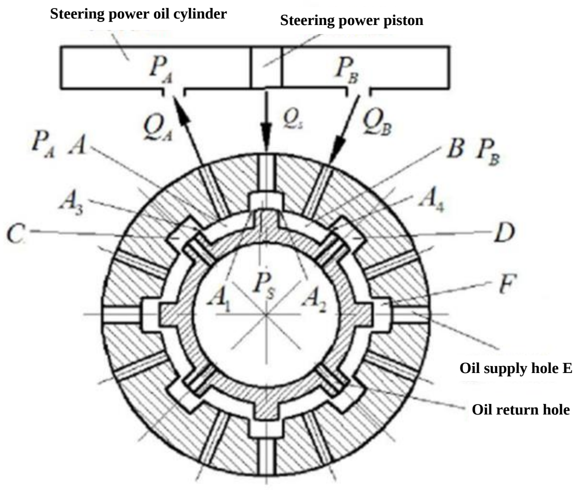

Figure 1. The Analytic Model of Steering Valve

While the steering torque acting on the steering wheel, the torsion bar will be twisted accordingly, enables the spool valve rotating a certain angle relative to the valve body, then the flow area for both the gap A_1 and A_4 between valve will be increased, and the flow area for both the gap A_2 and A_3 between valve will be reduced. According to the flow equilibrium principle, it can get followed equation:

$$\begin{cases} Q_1 = 0.5(Q_S + Q_A) \\ Q_2 = 0.5(Q_S - Q_B) \\ Q_3 = 0.5(Q_S - Q_A) \\ Q_4 = 0.5(Q_S + Q_B) \end{cases} \quad \ldots\ldots (7)$$

From the thin wall orifice theory of the hydraulic principle, there shall be followed equation:

$$Q_i = C_q A_i (2\Delta P_i / \rho)^{0.5} \quad (i = 1,2,3,4) \ldots\ldots (8)$$

Among the equation, Q_S is the oil inflow of rotary valve, Q_i is the oil flow through the gap i between the valve, Q_A and Q_B are the input and output oil flow of the power cylinder respectively, C_q is the flow coefficient for the gap between the valve, A_i is the flow area of the gap i between the valve, ΔP_i the pressure difference on the two sides of the gap between the valve, ρ is the density of hydraulic oil. The it can get the:

$$\begin{cases} Q_1 = C_q A_1 \sqrt{\dfrac{2(P_s - P_A)}{\rho}} \\ Q_2 = C_q A_2 \sqrt{\dfrac{2(P_s - P_B)}{\rho}} \\ Q_3 = C_q A_3 \sqrt{\dfrac{2(P_s - P_T)}{\rho}} \\ Q_4 = C_q A_4 \sqrt{\dfrac{2(P_B - P_T)}{\rho}} \end{cases} \quad \ldots\ldots (9)$$

Among above equation, P_s、P_A 、 P_B、P_T are the output pressure of power steering pump, oil input pressure of the steering power cylinder, oil return pressure of the steering power cylinder and the oil pressure of oil tank respectively.

For the valve port, the pre-opening gap between the spool valve and valve holder, by changing the geometry characteristic of the spool surface can change the sense of vehicles steering. When there's a torque on steering wheel, the input shaft will transmit the torque onto the low end of torsion bar, this will cause the twist of torsion bar, enables the spool rotating a certain angle $\Delta\delta_S$ relative to the valve body. The gap area flowing to the left cylinder is A_1, and the gap area flowing to the right cylinder is A_2 .to take the right flowing as example, the calculating equation for A_1 and A_2 will be：

$$A_1 = NL(W + R(\delta_S - \delta_{pi})) \quad \ldots\ldots (10)$$

$$A2 = \begin{cases} NL(W - R(\delta_S - \delta_{pi})) & \delta_S - \delta_{pi} \le W / R \\ 0 & \delta_S - \delta_{pi} > W / R \end{cases} \quad \ldots\ldots (11)$$

For the structure of hydraulic steering valve is symmetric, so the gap area between the valve $A_1 = A_2$, $A_3 = A_4$, L is the axial length of the rotary valve port, W_2 is the pre-opening gap width of the rotary valve port while on the neutral position, R is the radius the spool of rotary valve cooperating with the valve holder, N is the quantity of the rotary valve ports. .

While establishing the flow equation for hydraulic cylinder, the flowing effect of the hydraulic oil through the valve port should be considered accordingly. Even the hydraulic oil's compressibility and inertia shall bring severe impact on the high frequency performance of steering system, beneath the 5~10hz frequency their impact can also be ignored. Meanwhile not considering of the outside leakage of oil, it shall get:

$$Q_A = Q_B = A_p \frac{dS_R}{dt} \tag{12}$$

Based on $A_1 = A_2$, $A_3 = A_4$, the equation of P_s、P_A、P_B can be:

$$P_A - P_T = \frac{\rho}{8(C_q A_2)^2}\left(Q_S - A_P \frac{dS_R}{dt}\right)^2 \quad 13)$$

$$P_B - P_T = \frac{\rho}{8(C_q A_1)^2}\left(Q_S + A_P \frac{dS_R}{dt}\right)^2 \tag{14}$$

$$P_S = \frac{\rho}{8(C_q A_2)^2}\left(Q_S - A_P \frac{dS_R}{dt}\right)^2 + \frac{\rho}{8(C_q A_1)^2}\left(Q_S + A_P \frac{dS_R}{dt}\right)^2 \tag{15}$$

3.4. The Assisted Control System Designing and Modeling

In this paper, it mainly start from the requirement of the system assistant characteristic to design the control strategy, to realize the real-time control on brushless direct current motor, providing enough assistant along with the changes of steering wheel rotation angular velocity while the vehicle is driven at low speed, ensuring the portability of steering; or providing proper assistant along with the changes of steering wheel rotation angular velocity while the vehicle is driven at higher speed, enabling the driver having good road sense and ensure the handling stability of vehicle, at the same time, saving energy. The flow diagram of EHPS control strategy is shown in Figure 2.

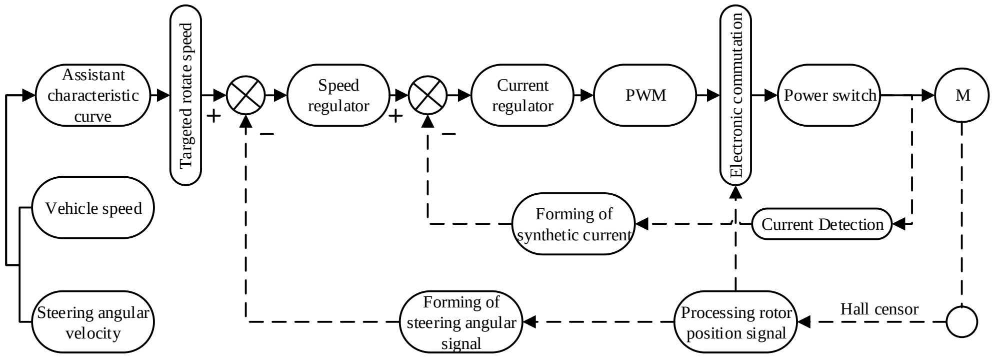

Figure 2. Diagram of EHPS System Control Process

From above diagram it can be seen that, the control process mainly includes two closed loop, they are respectively the closed loop regulation on speed and current, it's such a typical brushless direct current motor speed regulation system with dual closed loop.

The key factors: measurement, comparison and implementation. The key point for measurement is the variables, then to compare with the expected value, to adjust and correct the system response value by using such difference. After the correct measurement and comparison, how to use it for the correction and adjustment on the status shall be the key point for application of the feedback theory in automatic control. Through several decades of development, the PID controller has been got the wider application in industrial control, among current industrial control, most of control closed loop adopted the PID algorithm, and so many advanced control were accomplished by taking it as basis. The PID controller consists of proportion structure (P), integration structure (I) and differential structure (D). While making design and correction on control system, the PID control system shall have very obvious superiority, and its basic principle can be presented by equation as following:

$$G(s) = K_P + \frac{K_I}{s} + K_D s \tag{16}$$

The PID controller has the application in a wider range, and its use is also very flexible - only by setting three parameters K_P、K_I、K_D

Excitation flux and armature current are the two key factors to generate the torque in the direct current motor, because there's no coupling occurred between above two parties and they can be controlled separately by the current, so the direct current motor shall have very good controlling performance and faster dynamic response while regulating the speed. The speed regulation control is based on the motor speed equation. Specific to the direct current motor, there's following equation

$$n = \frac{U - RI}{C_e \Phi} \tag{17}$$

There n is the rotate speed, U is the armature voltage, R is the total resistance of armature circuit, I is the armature current, and C_e、Φ are the electrical potential constant and excitation flux respectively.

4. Assisted Control System Modeling and Simulation

In order to set up the kinetic model, the front wheel and steering mechanism have been simplified towards the steering column. The calculating model for steering shaft established in the MATLAB/Simullink is shown in Figure 3. In such model, it takes the angular velocity of steering wheel and rack displacement as the input, the output is the torque of steering wheel. The calculating model for steering shaft gear and rack is shown in Figure 4.

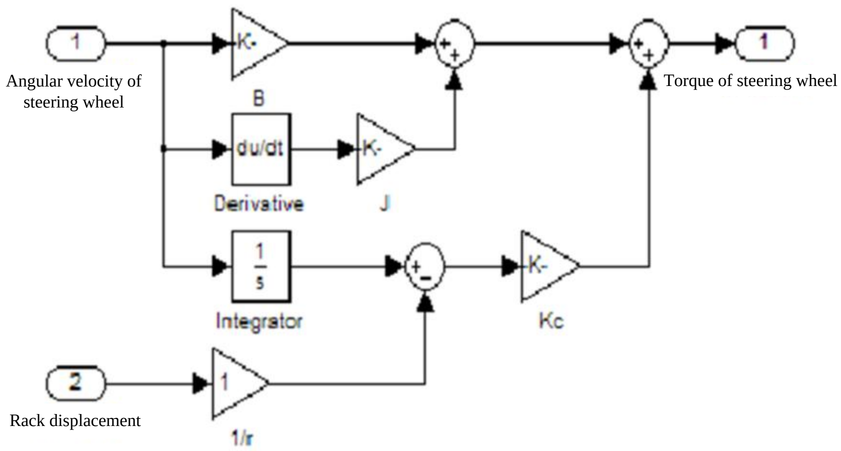

Figure 3. Calculating Model for the Torque of Steering Wheel

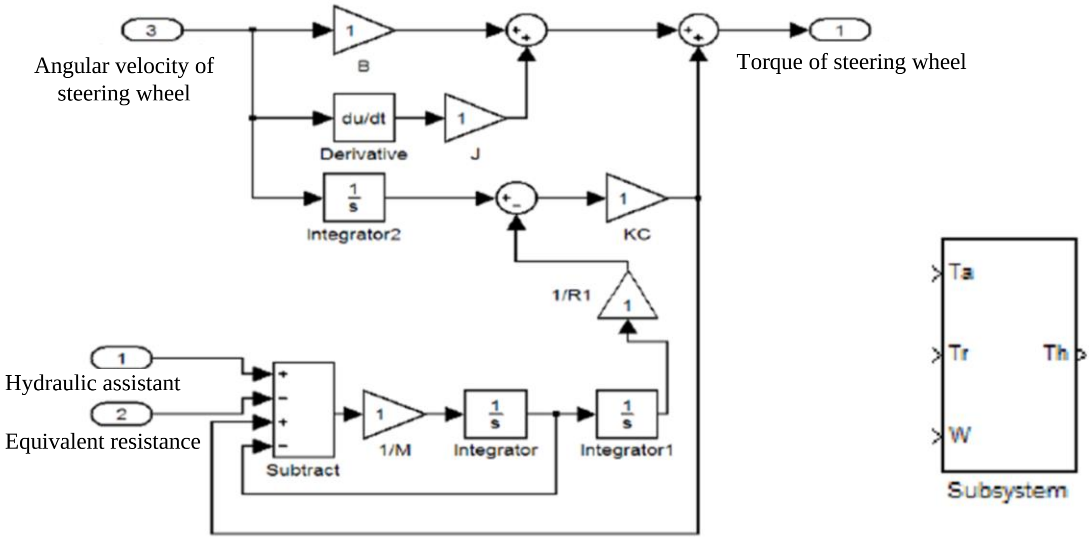

Figure 4. Calculation Model of Steering Shaft Gear and Rack

The motor model is shown in Figure 5

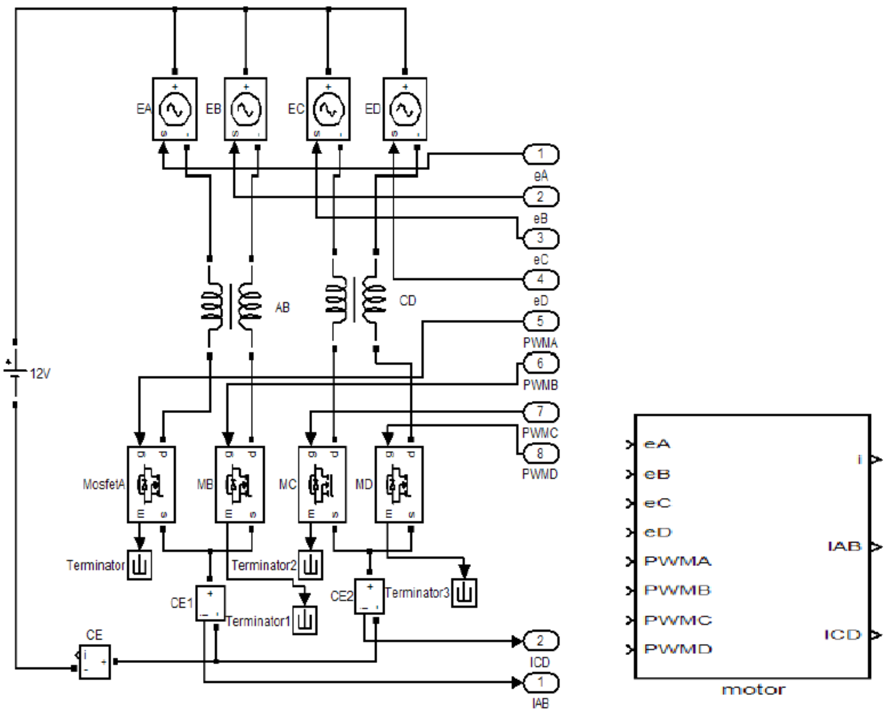

Figure 5. Motor Model

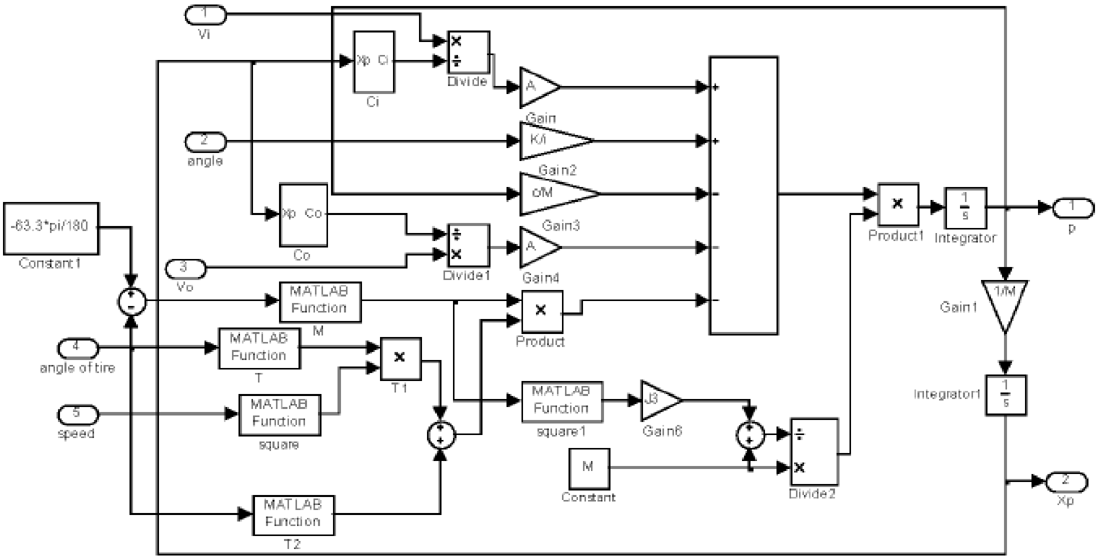

Figure 6. Solving Model for Equivalent Momentum of Piston and Piston Rod

The solving model for the equivalent momentum of piston and piston rod is shown in Figure 6. Finally the model for the EHPS system and its assisted control system can be get as per Figure 7 shown.

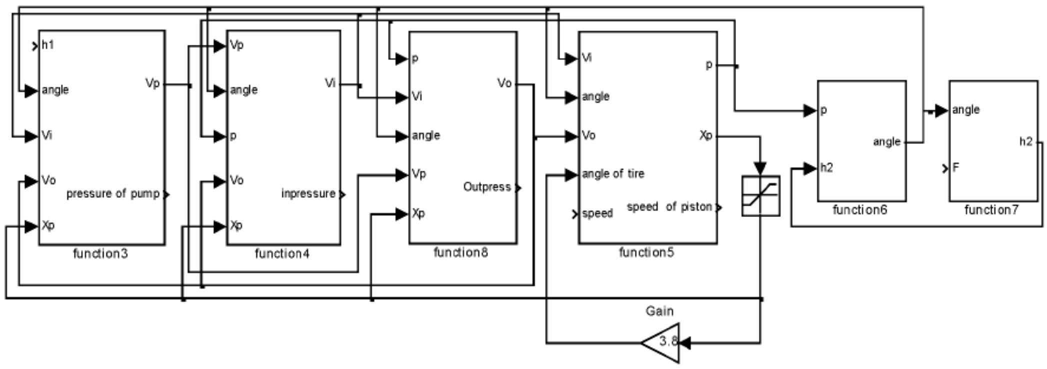

Figure 7. Model for the System and Its Assisted Control System

To certify the liability of such system simulation, under the set driving speed of 20km/h it can get the relation between the motor speed and angular velocity of steering wheel as per Figure 8 shown, the relative error is 1.21%, the response curve of assistant torque is shown in Figure 9. It can be seen that the result of the system simulation is proved well by comparison with the true situation.

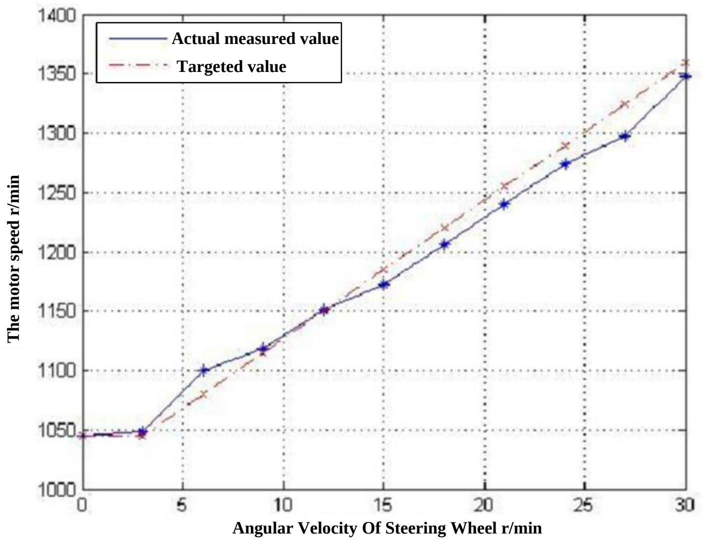

Figure 8. Diagram for the Relation between Motor Speed and Angular Velocity of Steering Wheel

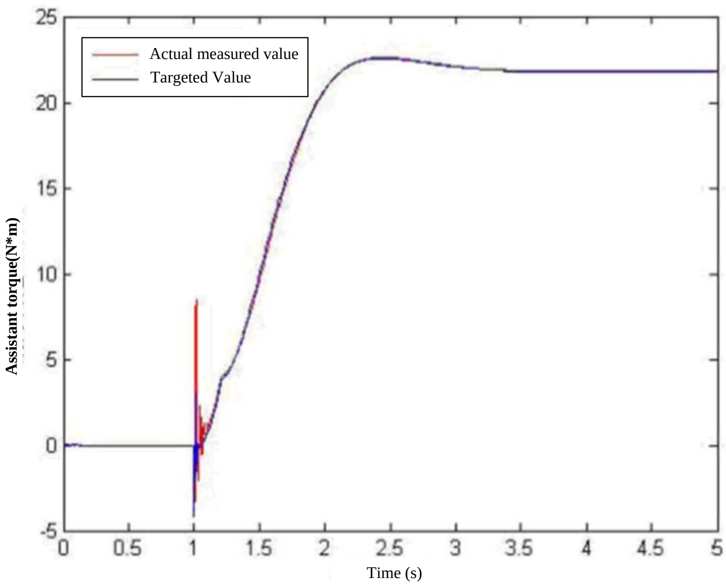

Figure 9. Response Curve of Assistant Torque

5. Conclusion

In this paper, based on structural constitution and working principle analysis of the electro-hydraulic power steering assisted control system, it made the detailed analysis on the factors that influencing the working characteristic of the electro-hydraulic power steering assisted control system, analyzed the control strategy of the electro-hydraulic power steering assisted control system, studied the relation of both the vehicle speed and motor speed, and the angular velocity of steering wheel and motor speed, then designed the assistant characteristic curve of the system, established the EHPS model and its assisted control model by using

MATLAB/Simulink, to provide the practical foundation for the application of the electro-hydraulic power steering assisted control system on vehicle.

Acknowledgement

The research is supported by Natural Science Fund project in Jiangsu Province(BK20131217), and Science and technology project in Huaian(HAG2013050)

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