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Electric Hydraulic Power Steering System Design Based on Electric Motor Coach of Mixed H2/H∞ Control

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Abstract

The Electric motor coach has become the focus of attention for its energy saving and green non-polluting, but it also poses a new challenge to feedback aspects of steering system and steering feeling. To enhance high-speed handling road sense, this article suggested using genetic algorithm to optimize mixed H2/H∞ system for boosting steering feeling control ability of hydraulic power steering system of electric motor coach based on analyzing electric hydraulic power steering system and feedback torque mathematical model of steering wheel. Simulation result showed that the accumulative error between torque feedback of steering wheel and wheel load torque is obviously reduced after optimization, and the feedback feeling of drivers to road sense has been strengthened.

Keywords: *Electric Hydraulic; Power Steering System; Design; Electric Motor Coach; H2/H∞ Control*

1. Introduction

As the development of automotive electronic technology, the power electronic technology has been widely used on automobile, electronization and modular of automobile have been an inexorable trend for its own development. Electric buses have become the focus of attention for its energy saving and green non-polluting. Beijing will be adding 900 electric buses to major bus lines this year, by 2017, the proportion of electromobile will be promoted from 5% to 20% in the buses of Beijing. Due to electric motor coach possesses characteristics of heavy weight, long running time and high safety factor *etc*, it has become the key matter for the development of electric coach motor in search of a kind of safe and reliable as well as energy-saving electrical power steering. In a moving vehicle, the drivers required to constantly alter driving direction in accordance with road condition, while steering gear of vehicle is the device, which mainly includes steering control mechanism, steering linkage mechanism and steering actuators, for drivers to alter and reset direction. As the different speed of a motor vehicle, the nature of friction force the drive overcame is also different. When a vehicle is in a state of parking or in low speed driving, it gives priority to the static friction force between tire and ground, with great friction force comes with great torque, and hard steering of steering wheel that a driver imposes, which easily leads to the drivers to be tired, therefore, there is a need to provide a greater power. The force of friction turns into sliding friction or rolling friction when the vehicle at a high speed and the friction force will be decreased, if the pushing force remains the same, the driver's steering will have a tendency to be excessively careless and and loses the accurate

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judgement to road conditions, namely loses road sense, which will make an impact on traffic safety to drivers. This article analyzed the effect of related design parameters of electric hydraulic power steering system on dynamic behavior of reverse disc feedback torque, came up with optimum design method of system parameter based on optimized road sense and optimized road sense system by using mixed H_2/H_∞ control system of genetic algorithm optimizing.

2. Principles of Electric Hydraulic Power Steering System

2.1. EHPS Principle

Set electric hydraulic power steering system of Mark YS6120DG pure electric bus in Jiangsu Jiangyin Changlong Vehicles Co. , Ltd. an example to carry out the study, the tire of this type of electric bus is Michelin XZUS (tubeless), the standard is 275/70R22.5, steering gear is Shashi Jiulong power steering gear D56, transmission ratio is 23, no-load quality is 11,000 kg, matched battery quality is 1,500 kg, full load quality is 18,500 kg and the length of it is 6.1 meter. The EHPS system mainly comprises steering wheel, steering column, steering gear box, oil tank, controller, oil hydraulic pump, electric machine, vehicle speed sensor and steering wheel angular velocity sensor *etc*. The structure diagram as shown in Figure 1

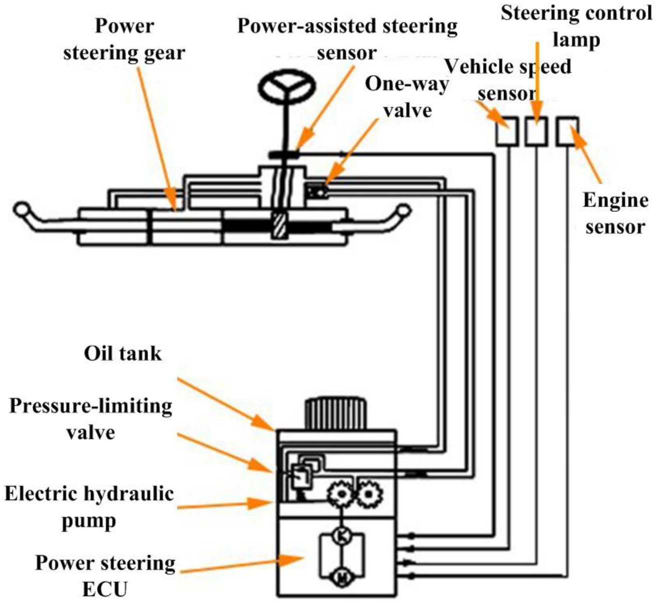

Figure 1. EHPS Structure Diagram

The Electronic control unit (ECU) of steering system is the same as ECU of electronic control fuel injection system (EFI), both are connected networking with CAN data bus, which may make a comprehensive share signal and conduct their respective control. Based on various demand, when steering situation is altering, it will output different current value to adjust and control oil pressure and flux output by electric pump. The oil pump of EHPS is driven by continuous current dynamo, the revolving speed will be altered when changing drive current, with different current value to drive electrical machine and oil pump as the need of pump oil based on diverse situation when in steering. The pressure-limiting valve on pump case is used to protect from overvoltage. The maximum flow of it is 8~12L/min; full oil pressure is no lower than

6MPa. The steering wheel almost remains motionless when a vehicle is in a state of straight driving, electric oil pump remains rotating as a lower revolving speed, hydraulic oil flow back to oil tank through control valve, working principle of it as shown in Figure 2.

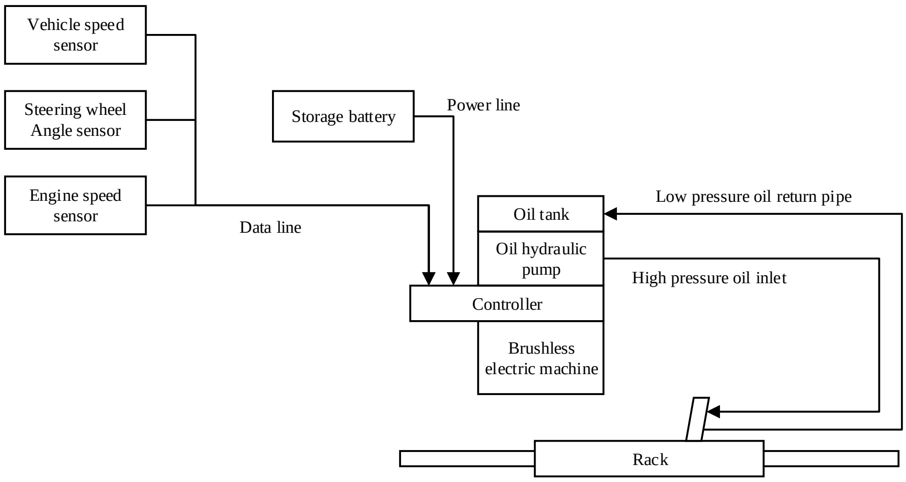

Figure 2. Working Principle Diagram of EHPS

2.2. Steering Road Sense

EHPS takes angular speed, travel speed and engine speed as main signal, ECU will ensure the size of pushing force provided according to the up and down of travel speed, namely provide relevant hydraulic pressure by controlling revolving speed of electric hydraulic pump, only when input signal meets the needs of steering wheel is out of in-between position as well as the revolving speed of engine is greater than 0. With low travel speed comes with higher hydraulic oil flow, the control flow of it as shown in Figure 3. Therefore, the system may provide a rather major pushing force when a vehicle is triggered or in low speed driving to make steering more easier; when the travel speed is going up, the system will keep a favorable road sense by reducing pushing force provided to make a driver won't feel the vehicle is light as a feather. EHPS will immediately enter into emergency operation mode designed, which it still remains functions of mechanical steering, in advance when there's a problem in angular velocity transducer of steering wheel or abnormal condition of system cased by other reasons, however, the steering becomes extremely heavy because of the lack of power.

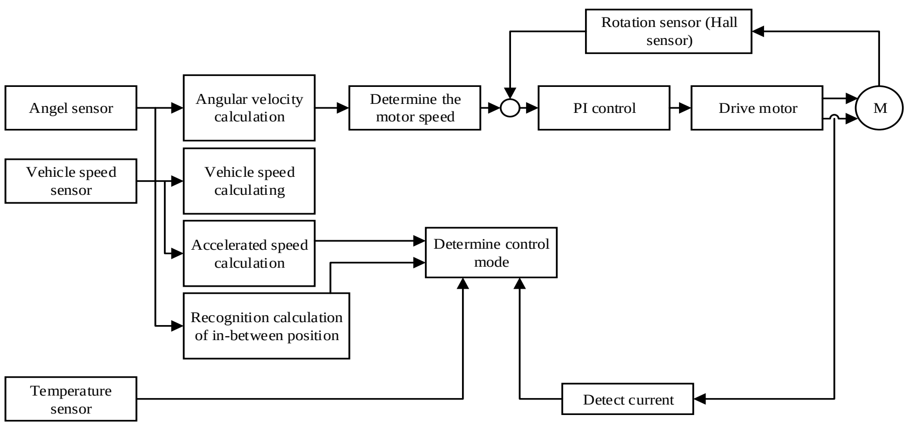

Figure 3. Control Flow of EHPS

The feedback effect of vehicle wheel and steering mechanism makes the drivers feel the acting force of pavement to vehicle, namely steering feeling. However, not all of vehicles to requirements of road sense are the same. The drives need to grasp information of road surface, which requires higher road sense, accurately when vehicles are frequently running on highway due to ensuring the safety of drivers. in contrast, owing to travel speed is limited, the running vehicles on congested roads of big cities requires a higher steering portability and no higher demands for road sense.

3. Analysis of Mathematical Model of Steering Wheel Torque Feedback

3.1. Analysis of Hydraulic Damping Coefficient

Piston motion of hydraulic cylinder piston cases alteration of valve port flow of rotary valve, leads to transformation of hydraulic pressure value of booster and the variation quantity alters as the transformation of hydraulic cylinder piston velocity of booster, which are featured with kinetic damping. As shown in Figure 4, the flow goes through throttle valve port can be calculated with flow formula of pipe orifice:

$$Q = C_d A \sqrt{\frac{2}{\rho} \Delta P} \tag{1}$$

Where, Q is hydraulic oil flow, C_d is flow coefficient of valve port, A is flow passage area of regulator orifice of rotary valve, ΔP is differential pressure of both ends of regulator orifice and ρ is density of hydraulic oil.

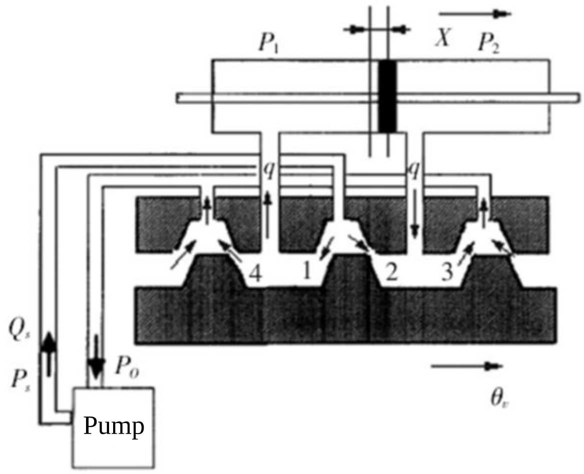

Figure 4. Partial Structure Diagram of Cross-Sectional Area of Rotary Valve

The symmetry of rotary valve structure suggested that the pressure value of left chamber of hydraulic cylinder is

$$P_1 = \frac{(Q_{s0} - 0.5 S_A x)^2}{C_d^2 [A_0 - \omega R(\delta_h - i\delta_\omega)]^2} \tag{2}$$

Where: Q_{s0} is half oil hydraulic pump flow; S_A is net sectional area of piston; A_0 is initial area of valve port; ω is width of valve port; R is radius of valve element and x is movement speed of piston. In knuckle mechanic, the movement speed of piston and steering speed of steering wheel have a linear relationship, the relationship between the two is

$$x = \delta_\omega l_p \tag{3}$$

Where, l_p is steering tie rod versus arm of force of steering master pin. The relationship between steering wheel torque and deformation of torsion bar is

$$M_{s\omega} = k_h(\delta_h - i\delta_\omega) \tag{4}$$

From (2)- (4), we may calculate the pressure value of left and right chamber of hydraulic cylinder is:

$$\begin{cases} P_1 = \dfrac{(Q_{s0} - 0.5S_A\delta_w l_p)^2}{C_d^2[A_0 + wRM_{sw}/k_h]^2} \\ P_2 = \dfrac{(Q_{s0} - 0.5S_A\delta_w l_p)^2}{C_d^2[A_0 - wRM_{sw}/k_h]^2} \end{cases} \tag{5}$$

The power value of hydraulic cylinder is arithmetic product of left and right pressure difference and active area of piston:

$$\mathrm{F}_{zhuli} = (P_2 - P_1)\cdot S_A \tag{6}$$

Unfold equation (5) near the equilibrium point with linearization as variable of steering angular velocity of vehicle wheel, then

$$F_{zhuli} = (P_{10} - P_{20})S_A - P_{s0}S_A^2\delta_w l_p / Q_{s0} \tag{7}$$

In the equation: P_{10} and P_{20} are pressure values of left and right chamber of hydraulic cylinder when steering angular velocity of vehicle wheel x is zero (steady-state condition); P_{s0} is pressure value of hydraulic cylinder outlet when steering angular velocity of vehicle wheel is zero. Equation (7) showed that the alteration of power torque value of wheel steering has a linear scale with steering angular velocity of vehicle wheel, Hydraulic damping coefficient can be denoted as:

$$\mathrm{b_t} = \mathrm{P_{s0}}S_A^2 l_p^2 / Q_{s0} \tag{8}$$

From the above, hydraulic damping coefficient is related to steering wheel torque, rigidity of torsion bar, valve port parameters, active area of hydraulic cylinder and flow of oil hydraulic pump.

3.2. Analysis of Hydraulic Power Coefficient

If hydraulic power torque is ensured under a certain of setting travel speed condition, then

$$\mathrm{M_{liju}} = l_p S_A(P_1 - P_2) \tag{9}$$

Where, P_s is pressure difference of both ends of hydraulic cylinder, $\mathrm{M_{liju}}$ is power torque. Take equation (4) and (5) into (9), then

$$\mathrm{C}_f = \frac{2Q_{s0}^2\omega Rl_p S_A}{C_d^2 k_h i}\left(\frac{1}{(A_0 - wRM_{sw}/k_h)^3} + \frac{1}{(A_0 + wRM_{sw}/k_h)^3}\right) \tag{10}$$

From equation (10), hydraulic power coefficient is also related to steering wheel torque, rigidity of torsion bar, valve port parameters, active area of hydraulic cylinder and flow of oil hydraulic pump.

3.3. Damping Ratio Analysis of Hydraulic Power System

For regular second-order dynamic systems, the dynamic response of it has close relationship with damping coefficient of system, vibration of output will be enlarged when damping coefficient is minor, and output response will be slow when damping coefficient is big, both of these two conditions are undesirable for vehicle steering system. It can be seen that system damp between 0.4 to 0.8 is relatively appropriate from control theory. To analyze damping ratio of transfer function of steering wheel torque feedback for different working conditions, the damping ration of some example system under the condition of different flow rate and different steering wheel torque is calculated in this article, a relative damping ratio of system is calculated with (11).

$$\xi = \frac{\dfrac{b+b_t}{k_h i^2 + C_f k_h i^2}}{2\sqrt{\dfrac{J_w}{k_h i^2 + C_f k_h i^2}}} \tag{11}$$

It can be seen that the variation range of damping ration of hydraulic power steering system is rather larger and it has a great impact on facticity of steering wheel torque feedback. How to make the vehicle is provided with favorable dynamic highway feeling is one of design objectives of electric hydraulic power steering system.

4. Mixed H2/H∞ Controller Design Optimized Based on Genetic Algorithm

4.1. Overview of Control System

The block diagram of mixed H_2/H_∞ control as shown in Figure 5, of which K(s) is controller, G(s) is controlled object, w is external input signal including reference input signal, sensor noise and interference signal, u is output control signal, y is measurement signal, Z_2 and Z_∞ is output evaluation signal including tracking error and actuator output and regulating error, equation of state as shown in equation (12).

$$\begin{cases} x = Ax + B_1 w + B_{2u} \\ z_\infty = C_{1\infty} x + D_{1\infty 1} w + D_{1\infty 2} u \\ z_2 = C_{12} x + D_{121} w + D_{122} u \end{cases} \tag{12}$$

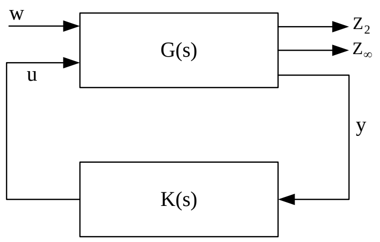

Figure 5. Structure Diagram of System Control

4.2. Design of Mixed H2/H∞ Control

Translate H_∞ issue into linear matrix inequality and solve it with an equation, the controller can be calculated with relatively direct matrix manipulation, there is no restrictions to system model, as to system shown in Figure 5, the inequation (13) is established when and only when there exists a symmetric positive definite matrix x and matrix w.

$$\begin{bmatrix} AX + B_{2w} + (AX + B_2 w)^T & B_1 & (C_{1\infty} X + D_{1\infty 2} w) \\ B_1^T & -I & D_{1\infty 1}^T \\ C_{1\infty} X + D_{1\infty 2} w & D_{1\infty 1} & -I \end{bmatrix} < 0 \tag{13}$$

Then $u = w^* \left(X^*\right)^{-1} x$ is a H_∞ controller of state feedback of system shown in Figure 5. Multiply coefficient matrix in the model by appropriate constant, respectively, which may make closed-loop system is provided with a given H_∞ performance γ_∞, namely

$\|T_{z\infty}w\| \le \gamma_\infty$. The controller of γ_∞ which possesses H_∞ performance is an optimized H_∞ controller for γ_∞ of the system.

H_2 performance is provided with eminent performance quality, H_2 norm of transfer function matrix represents steady-state output covariance when system is simulated by white noise input signal, therefore, with small norm of H_2 comes with small random jamming of system. Design a state feedback control $u = Kx$, then H_2 performance of the system can be donated as shown in equation (14).

$$\begin{cases} x = (A + B_2K)x + B_1w \\ z_2 = (C_{12} + D_{122}K)x + D_{121}w \end{cases} \tag{14}$$

Closed loop transfer function as shown in equation (15).

$$T_{wz_2}(s) = (C_{12} + D_{122}K)(sI - A - B_2K)^{-1}B_1 + D_{121} \tag{15}$$

H_2 norm of the coefficient is:

$$\|T_{wz_2}\|_2 = Trace\left[\frac{1}{2\pi}\int_{-\infty}^{+\infty} T(jw)T^*(jw)dw\right]^{0.5} \tag{16}$$

4.3. Mixed H2/H∞ Controlled Optimized by Genetic Algorithm

Genetic algorithm is a kind of randomized search algorithm imitating biological natural selection and natural genetic mechanism, the process of applying it to mixed H_2/H_∞ controller is:

(1) Coding: the control rate of controller obtained from H_∞ performance is encoded to constitute individual P.

Initial group setting: different γ_∞ optimized controller is obtained by adjusting γ_∞ of H_∞ performance, then obtains $P_j\ (j = 1,2,\cdots,N)$ of N individuals, the initial group is composed of N individuals.

Fitness function: as to mixed H_2/H_∞ issue in this article, the objective function is $\varphi = \|T_{z_2w}\|$, take penalty function $\varepsilon \times \sum_{j=0,1} m_j$, there are:

$$m_j = \begin{cases} 0 & g_j \le \gamma_j \\ 1 & g_j > \gamma_j \end{cases} \tag{17}$$

Where m_j is penalty function of normalization, ε is penalty coefficient, the optimized fitness function of final genetic algorithm is

$$f = M - \left(\varphi + \varepsilon \times \sum_{j=0,1} m_j\right) \tag{18}$$

5. System Simulation

Establish a model according to steering gear ZF8098 of YS6120DG pure electric bus and optimize simulation calculating, the major parameter of ZF8098 steering gear as shown Table 1. Set driving situation as highway 100km/h, lateral acceleration is 0.2 steering situation (median driving condition is in common use on highway), total aligning torque of turning vehicle wheel is 144N·m, design the ideal steady state feedback torque of steering wheel as 2.5N·m, hydraulic power torque is 94N·m obtained from calculation. The result of system step response as shown in Figure 6, it can be seen that the accumulative error between steering wheel torque feedback of system and wheel load torque is significantly reduced after optimization, the feedback feeling of drivers to road sense is enhanced.

Table 1. Major Parameter of ZF8098 Steering Gear

Steering wheel diameter (m)	0.5	Transmission ratio	22.21-26.21	Input torque (N.M)	8-12	Oil pump volume (L/min)	16-22
Power cylinder diameter(mm)	117	Tilt angle of arm shaft	±47°	Output torque(N.M)	5500	Center distance (mm)	90
Applicable front axle-load (kg)	8300	Total number of coils	6.5	Highest use of oil pressure (Mpa)	15	Piston stroke (mm)	38.925x2

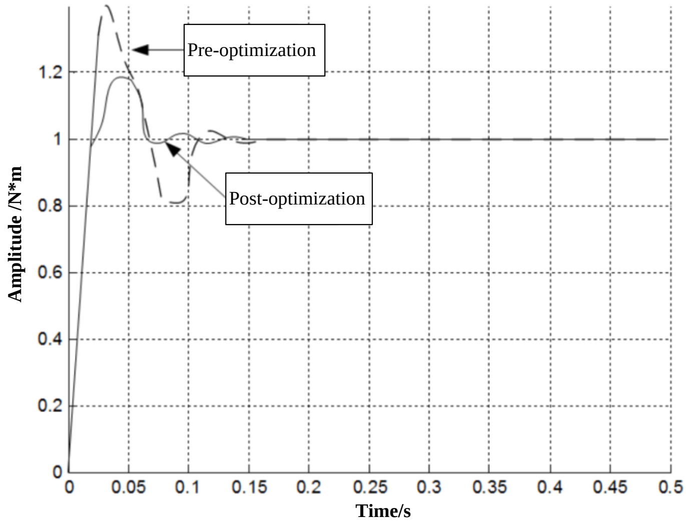

Figure 6. The Result of System Step Response

In order to illustrate optimized effect in an even better fashion, this article used simulation system of vehicle directional steering to make a input simulation calculation of impulsive load for unoptimized and optimized system., the simulation result as shown in Figure 7. Through comparison in partial enlarged graphic in the diagram, it can be seen that the response error of optimized system is superior to the one before optimization, which enhances highway steering sense quality of vehicles.

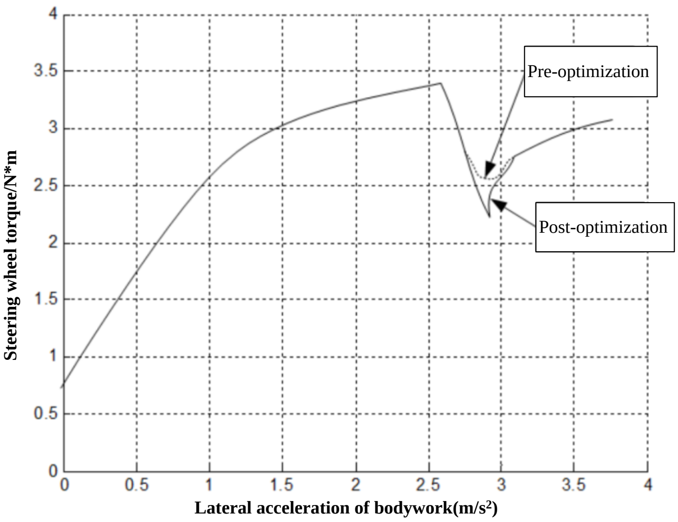

Figure 7. Simulation Result of System Load Response

6. Conclusion

This article has presented that the hydraulic steering system parameter as an objective of optimal road sense feedback to optimizing method and model so as to enhance road sense of vehicle high speed handling based on the analysis of mathematical model of steering wheel torque feedback, and optimizing mixed H2/H∞ control with genetic algorithm to enhance control ability of steering feeling for hydraulic power steering system of electric buses, an example of simulation calculation has been carried out in the end proving the accumulative error between steering wheel torque feedback of system and wheel load torque is significantly reduced after optimization, the feedback feeling of drivers to road sense is enhanced.

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