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Electric power steering system controller design using induction machine

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Abstract: An electric power steering system (EPS) is a new type of steering system developed after a mechanical hydraulic power system (MHPS) and electric-hydraulic power steering system (EHPS). In order to coordinate and solve the portability and sensitivity of the steering system optimally, taking an induction power steering system as the research object, the control algorithm of induction motor control under the EPS is studied in this paper. In order to eliminate the feed-forward performance degradation caused by the change of feed-forward parameters, an on-line identification algorithm of feed-forward parameters is proposed. It can improve the control performance of online identification among three feed-forward parameters in the T-axle motor, it improves on the robustness of feed-forward control performance, at the same time it also gives simulation and test results. This method can improve the control performance of the three feed-forward parameter online identification of the T-axis motor and improve the robustness of feed-forward control performance. At the same time, simulation and test results are given. The simulation results show that the algorithm can significantly improve the response speed and control accuracy of EPS system control.

Key words: motor induction, electric power, PID control, EPS

1. Introduction

An atomic fluorescence spectrometer (AFS) is an inevitable requirement for the future development of automatic drive, driving stability control and comfort control (variable ratio control). At present, based on safety consideration, the AFS with manual control and electric superposition combined control steering has been put into use. In terms of power steering, an EPS has rapidly developed and has become the first choice of small cars [1–3]. As a new type of automobile power steering technology, the EPS has attracted the attention of enterprises and research institutions due to its excellent performance of automatic control ability, comfort and safety. In reference [4–6], the feed-forward method is used to improve the current control algorithm of the motor in the EPS; however it does not solve the control algorithm when the motor parameters change. The common control algorithms of induction motors are briefly introduced in reference [7–8], but the real-time performance of the algorithms is poor and there is a lag, in principle.

Taking the power steering system of an induction motor as the research object, the algorithm of induction motor control under the EPS condition is studied. As a torque servo system, the EPS first requires quick and correct response of power steering output torque to the instruction value. The structure characteristic of the induction motor determines that it can simply realize high-performance torque control such as a DC brush motor and permanent magnet synchronous motor (PMSM).

2. EPS model description

2.1. Virtual simulation of EPS

The virtual simulation of an EPS includes a software simulation platform and vehicle dynamics model, the dynamics model of an electric power steering system and control system model. The built vehicle system control dynamics model is directly related to the state parameters, accuracy and effectiveness of performance evaluation, which has great significance to auto design and control research. Meanwhile, an automobile is a nanoelectromechanical system composed of many subsystems including machinery, electronics and control. A complex structure determines that it is not easy to realize the complete and correct simulation of the system under a single model. In fact, we need to complete different modeling work for a structure or simulation target as well as joint simulation through real-time data interaction on an overall model through different models.

This paper is only for the mechanical, electric system and controller system of the EPS, the external model is built by Simulink, and the dynamics model of auto and simulation, test environment are all selected and set in the Carsim software. In the whole test process of the simulation platform, the vehicle model constructed by Carsim is used to solve the state parameter of a vehicle driving in time, while the Simulink model of an electric power steering system is only responsible for solving the state parameters of a steering subsystem and decision-making of the control system. This element simulation method can quickly design a prototype model close to the actual control object, debug repeatedly on the basis of a prototype parameter until the prediction results are obtained, so that some parameters of a model can be optimized, adjusted and demonstrated. Figure 1 is the flow chart of the electric power steering system.

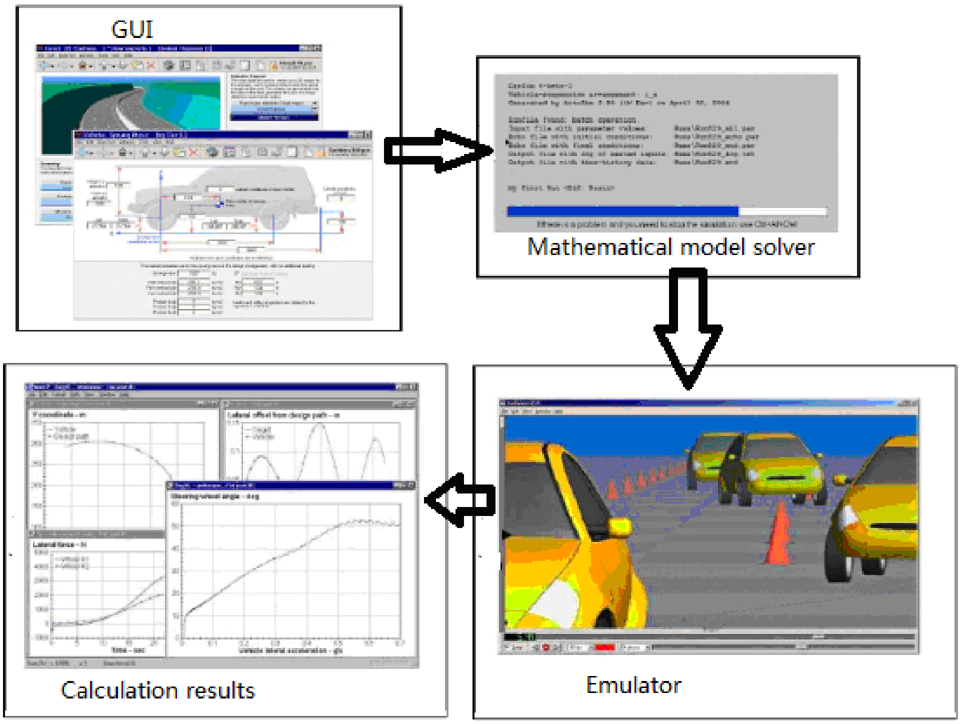


Fig. 1. Simulation of EPS

2.2. Model establishment of EPS

A steering system is an important channel for human and vehicle alternation. Whether the steering system is perfect or not has an important effect on the whole vehicle system model and simulation of control strategy. In the whole process, a steering wheel angle and steering wheel torque are the main basis for judging the feedback information of the system and are also the important indicators of EPS steering performance. In vehicle steering, the sensor senses the state parameters such as torque on a steering wheel and vehicle speed, and the controller makes logic judgment according to the torque, direction and vehicle state parameters. According to the control strategy, the motor is started when the power is needed, and the current controller adjusts the current and direction to control the control output torque. The steering wheel torque implemented by the driver and the resultant moment of power moment provided by the power motor are transmitted to the steering wheel through gear and rack mechanism, steering transmission mechanism and a universal joint to overcome the steering resistance torque, thus assisting the driver to complete the steering. If the motor is not started or the control system fails, the driver can still complete driving operation manually through the mechanical structure of the steering system. The motor runs only at the providing power stage, if it does not rotate, the system is waiting for transfer, so the power performance and fuel economy are superior to other steering systems. The operation principle of the EPS is shown in Figure 2.

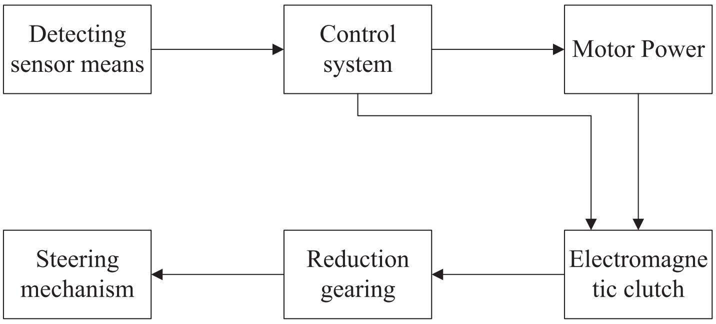


Fig. 2. The work principle of EPS

2.3. Physical model of EPS

An EPS is not only a simple connection of mechanic and electrical parts; in fact, it is a compound system [9–12] including components such as quality, an inertial element as well as damp and spring. In fact, the model of each part of the system is fully described, when using a full-order modeling method, the coupling and non-linear complex relationship in the system will increase the difficulty of work and affect the accuracy of the model. The model established according to the actual controlled plant is the basis for control system design. In order to describe the steering system conveniently, the system can be simplified and degassed without changing the basic structure of the system. The key components can be selected, equivalently combine with the mechanical parts, it can also add damp and spring in the model to get the physical model corresponding to the actual steering system. The dynamic differential equations for each part are established respectively, which is shown in Figure 3.

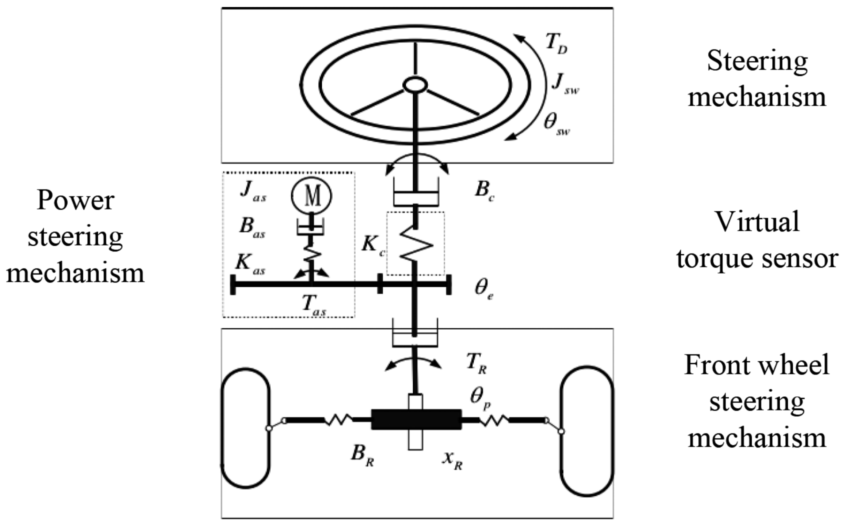


Fig. 3. EPS model

$$L\frac{\mathrm{d}i}{\mathrm{d}t} + iR + k_e\theta_m = U. \tag{1}$$

It makes dynamic analysis on the mechanical part of the motor:

$$T_D = J_{sw}\ddot{S}_{sw} + B_c D\ddot{S}_{sw} + K_c\left(S_{sw} - \theta_e\right). \tag{2}$$

In the above, T_D is the torque input of the driver steering wheel; $\ddot{S}_{sw}$ and θ_e are the steering wheel angle and the output axle angle, respectively; J_{sw}, B_c and K_c are the steering wheel, the inertia of the steering axle connected with the steering wheel, stiffness coefficient and damping coefficient.

The torsion sensor module is used to calculate the steering torque through the steering wheel.

$$T_s = K_c\left(\delta_{sw} - \theta_e\right). \tag{3}$$

In the formula, T_s is the output torque of the torsion sensor; K_c can be regarded as the stiffness coefficient of the torsion level.

A gear and rack are the most direct parts of a front steering wheel mechanism; they take the rack as the object. The steering wheel torque transmitted by the steering axle and the power moment provided by the motor form a resultant moment, which mainly overcomes a restoring resistance moment and a frictional resistance moment caused by the interaction between the steering wheel and the ground. The latter includes the resistance moment caused by the friction between the ground and the tire, the elastic deformation of the system, and the frictional torque caused by friction and damping.

$$M_R\ddot{x}_R + B_R\dot{x}_R + F_R = \frac{T_S}{R_p} + \frac{T_{as}G_{as}}{R_p}. \tag{4}$$

The equivalent gear stress on the steering tube can be obtained by the following formula:

$$M_R R_p^2\ddot{\theta}_p + B_R R_p^2\dot{\theta}_p + T_R = T_S + T_{as}G_{as}, \tag{5}$$

where

$$\theta_p = \frac{x_R}{R_p}, \qquad T_R = F_R R_p.$$

In the above, M_R is the gear quality; B_R is the damping coefficient of the rack; F_R is the steering resistance exposed on the rack; R_p is the radius of the steering wheel; T_{as} is the power motor torque; G_{as} is the speed reducing mechanism reduction ratio of the power motor; θ_p is the steering gear angle and T_R is the steering resistance moment exposed on the steering device.

Through the above dynamic equations, the Simulink model of the steering system can be obtained, which is shown in Figures 4, 5.

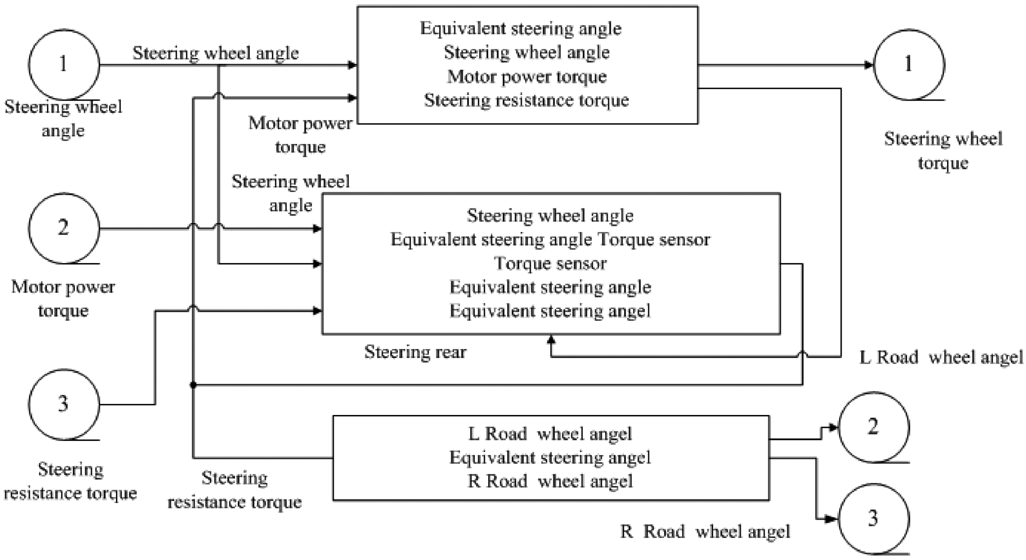


Fig. 4. Simulation model of EPS

3. Vehicle dynamics

An induction motor is a multi-input and multi-output system with high-order, non-linear and strong coupling, which is generally assumed when modeling:

1) The stator rotator and rotator winding should be completely symmetrical,

2) The surface of the stator and rotator should be smooth without slot effect,

3) The air gap magnetic potential is distributed by sine in the space,

4) Magnetic saturation effect, eddy current loss and core loss can be neglected,

5) Neglect higher harmonic.

In the EPS system, the controller designs the power characteristic curve and calculates the target current of the motor according to the input signal of the torque sensor and the speed sensor. And then compared with the detected target current of the motor, and the error between the target current and the actual current is obtained. Afterwards the controller controls the actual motor current according to the current control strategy and the target current, so that the motor can output the appropriate power moment to complete the power process. The process of implementing a control strategy is to determine the power characteristics and the tracking power characteristics. The tracking power characteristic is to track the target current according to the control theory as well as the motor armature voltage. In the EPS, because of the existence of electric control units and power motors, when the same rotation operation is carried out, the expected steering wheel torque can be combined to adjust the output torque of the motor and the percentage of general steering torque to optimize the torque realized by the driver, which can guarantee the portability of low speed steering and enhance the road feeling characteristics of the steering system at high and medium speed.

The design target of power characteristic is to match the actual steering wheel torque with the ideal steering wheel torque, and ultimately achieve the target of portability and road feel, the torque equation is as follows in EPS system:

$$T_{sw}(V,\theta) + T_{assist}(V,T_{sw}) = T_{friction} + T_{damp} + T_{inertia} + T_{return}(V,\theta). \tag{6}$$

From Formula (5), we can see that when the running state (the speed and the steering wheel angle) of vehicle is confirmed, then the steering resistance torque can be confirmed. The meanings of the power characteristic is that it can make modeling and adjustment on the steering hand power T_{sw} implemented by the driver through adjusting the percentage of the motor power torque T_{assist} in the steering torque, which can achieve or be close to the ideal steering angle. $T_{friction}$ is the steering friction moment; T_{damp} is the steering damping moment; $T_{inertia}$ is the steering inertia moment and T_{return} is the steering return moment.

In order to reflect the change of the driver's operating torque and improve the dynamic response performance of the system, the change rate of the torque can be introduced as the control variable and the current can be corrected according to the change rate. The differential compensation formula of the torque is as follows:

$$T_{Td} = K_{TD}\dot{T}_D, \tag{7}$$

where: K_{TD} is the compensation coefficient of the torque differential and $\dot{T}_D$ is the compensating moment.

For the motor applied in the EPS system, the losses caused by the friction, rotation inertia and damp would affect the steering performance and cause performance variation such as power following performance and more. In order to solve the above problems, friction compensation, damping compensation and inertia compensation are further added in the system control. The magnitude of the motor compensation current is determined by the motor rotation speed, the accelerated speed of the motor angle, steering direction as well as friction, damping, inertia conditions and more. The compensation and control simulation model are shown in Figure 5, $Icmd$ is the current control directive.

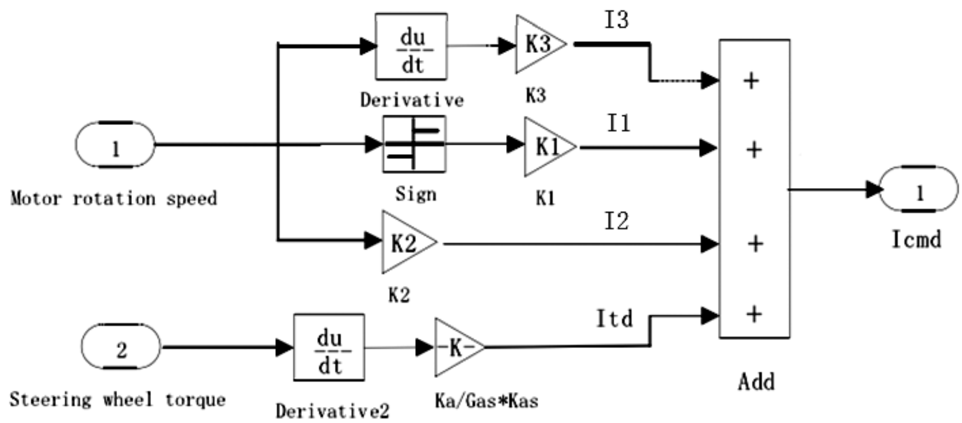


Fig. 5. Simulation model of compensation control

4. Controller design

In order to improve the response speed of the current adjustor, this paper adopts feed-forward control to make compensation for the two items, while PI feedback control deals with the control error introduced by a feedback decoupling error and the motor model error caused by a motor parameter error. Because the control tasks undertaken by the PI close-cycle control are very small, the system response performance is not excessively dependent on the adjustment of the PI parameter. The setting of the PI parameter is relatively easy and a value range is wide. The T-axle current feed-forward control flow chart of this paper is shown in Figure 6.

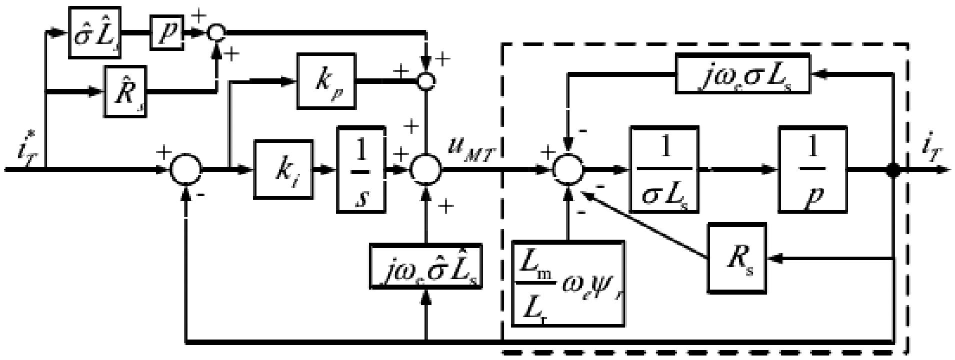


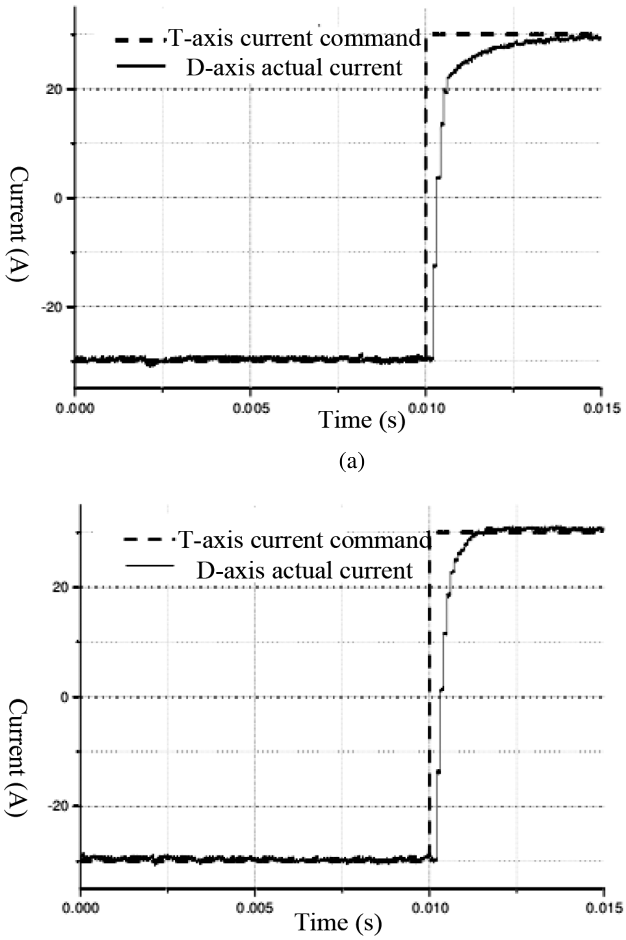
Fig. 6. Control of regular PI and feedback decoupling adjustor under synchronous coordinate system

The close-circle transmission function of the current adjustor is indicated by Formula (8). When the motor parameter is correct, the right side of the formula is constant 1, output of the current adjustor realizes output completely (it does not consider control delay). It allows experimental demonstration and comparison of the performance of the T-axle current adjustor.

$$\frac{i_{real}}{i_{ref}} = \frac{\hat{\sigma} L_s s^2 + \left[\hat{R}_s + k_p\right] s + k_i}{\sigma L_s s^2 + \left[\left(\sigma L_s - \hat{\sigma}\hat{L}_s\right) w_e j + R_s + k_p\right] s + k_i}. \tag{8}$$

For a T-axle step instruction of −30 A ∼ +30 A, the current response of the T-axle is shown in Figure 7, to adopt three kinds of current adjustment methods. It can be seen that the response speed of the T-axle current has been greatly improved when the comprehensive control method feed-forward + PI feedback is compared with the regular PI control and PI + feed-forward control.

In the current feed-forward control strategy, the stator resistance R_s is needed and the resistance parameters are very sensitive to temperature changes, so the control performance of the current adjustor with resistance misalignment needs to be considered. The stator resistance value R_s in the control algorithm is set to 0.5 times and 1.5 times of the actual value, respectively; for a step current command of ±30 A and an amplitude of 50 A, the response of a sine current command of 20 Hz frequency is shown in Figure 8. On the contrary, the current response appears to be insufficient. In order to enhance the response quality of the current, the PI parameter needs to be set again.



(b)

Fig. 7. Response of T-axle current for step command applying regular Pi control (a) and PI + feedback decoupling (b)

As shown in Figure 9, it can be seen that when there are errors between the feed-forward parameters and actual values, the control effect caused by the parameter error needs to be close-circle balanced, which will lead to the reduction of the system control performance.

In order to improve the robustness of the feed-forward control, this paper puts forward an online correction algorithm for the current feed-forward control parameter based on a least-square method. The motor parameter involved in the T-axle feed-forward and feedback decoupling control is, respectively, represented as R_s, σL_s and $L_m\psi_r/L_r$; commands $K_1 = R_s$, $K_2 = \sigma L_s$, $K_3 = L_m\psi_r/L_r$, the formula is as follows:

$$u_T = K_1 i_T + K_2\left(\frac{\mathrm{d}i_T}{\mathrm{d}t} + w_e i_M\right) + K_3 w_e\,, \tag{9}$$

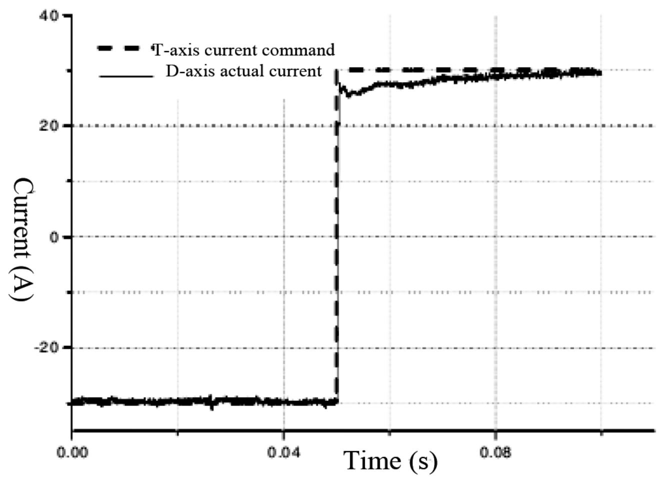


Fig. 8. Step command response of T-axle current on feed-forward control

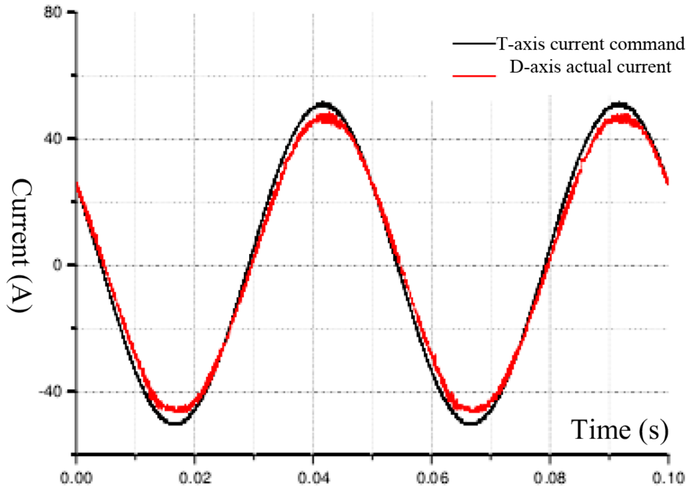


Fig. 9. Sine command response of T-axle for feed-forward control

$$u_T = \begin{pmatrix} i_T & \dfrac{\mathrm{d}i_T}{\mathrm{d}t} + w_e i_M & w_e \end{pmatrix} \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix}. \tag{10}$$

Formula (10) is a one-dimension model. There is no two-dimension matrix solving the inverse matrix in the least-square algorithm, which can reduce the calculation amount of a single chip and it is more suitable for online application. Since the model has a differential on the T-axle current, in order to avoid using differential of the detection amount, the above variables are filtered by the first order filter. The following indicator f indicates each physical amount after filtering, and

Formula (10) can be conversed as follows:

$$u_{Tf} = (K_1 \;\; K_2 \;\; K_3) \begin{bmatrix} i_{Tf} \\ i_{Tf} + (w_e i_M)_f \\ w_{ef} \end{bmatrix}. \tag{11}$$

The transmission function of the filter, for the current introduction after the T-axle filtration [14–16], converts the formula into the standard form of recursive least-square:

$$\theta(t) = \theta(t-1) + L(t)\left[y(t) - \theta(t-1)\,\varphi(t)\right], \tag{12}$$

$$L(t) = \frac{P(t-1)\varphi(t)}{\lambda + \varphi(t)^T P(t-1)\varphi(t)}, \tag{13}$$

$$P(t) = \frac{1}{\lambda}\left[P(t-1) - \frac{P(t-1)\varphi(t)\varphi^T(t)P(t-1)\varphi(t)}{\lambda + \varphi^T(t)P(t-1)\varphi(t)}\right], \tag{14}$$

of which, $L(t)$ is the gain matrix; $P(t)$ is the covariance matrix; λ is the forgetting factor ($0 < \lambda \leq 1$), it makes data valid in the limited period of time. Its aim is to emphasize the influence of new data, and old data is gradually forgotten, thus eliminating data saturation. The more of value λ, the lower speed of old data is forgotten, the greater the change of the value recognition results.

5. Simulation results and validation

It constructs an online estimation model of a current feed ward control parameter and is applied to rotor field-oriented control. Among them, the initial feed ward control value of $P(t)$ is $P0 = 1\,000 * I$. I is the unit matrix; the initial value of the parameter waited to be estimated is $\theta_0 = [0\,0\,0]^T$; the forgetting factor λ is 0.95, and the filter parameter α and β are 500, respectively. The identification result of the feed ward control parameter is shown in Figures 10–12. The identification errors of K_1, K_2 and K_3 are 1.08%, 2.60% and 0.40%, respectively.

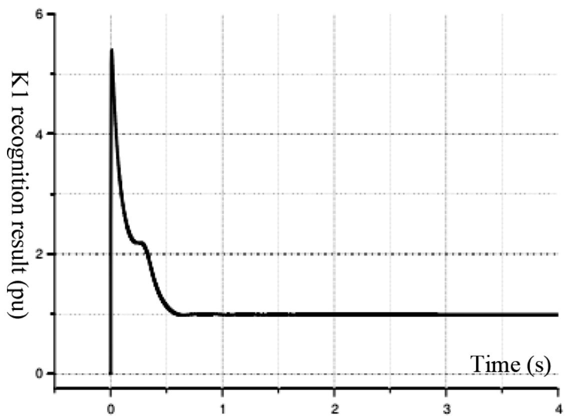


Fig. 10. The simulation identification curve of feed-forward control parameter K_1

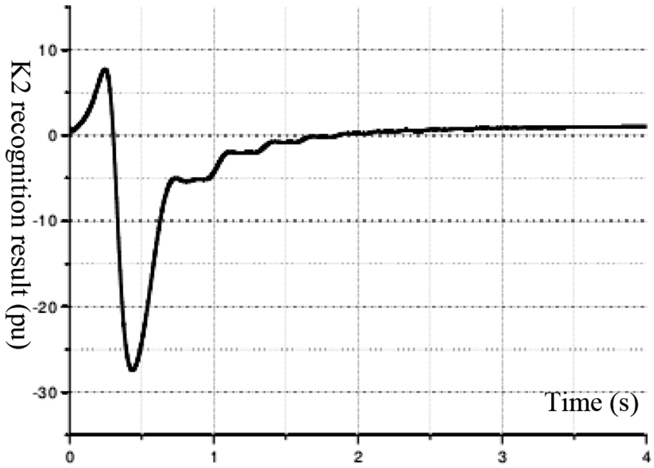


Fig. 11. The simulation identification curve of feed-forward control parameter K_2

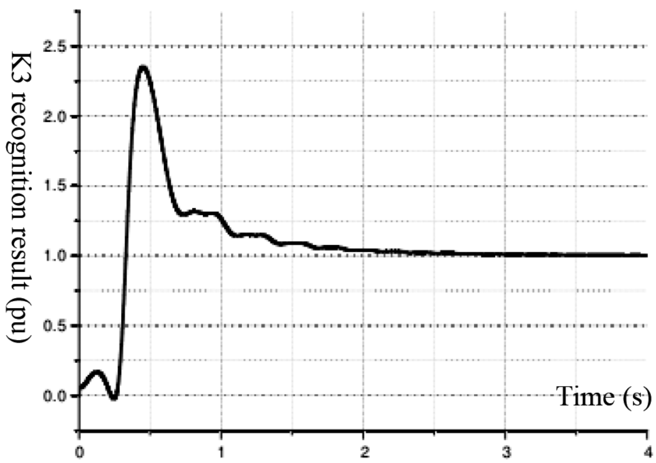


Fig. 12. The simulation identification curve of feed-forward control parameter K_3

The T-axle current that follows the curve during fast rotation is shown in Figure 13. The total control amount of the T-axle control voltage and the time process of the feed ward control amount is shown in Figure 14. It can be seen that the control effect is mainly generated by the feed ward, and the current following effect is better.

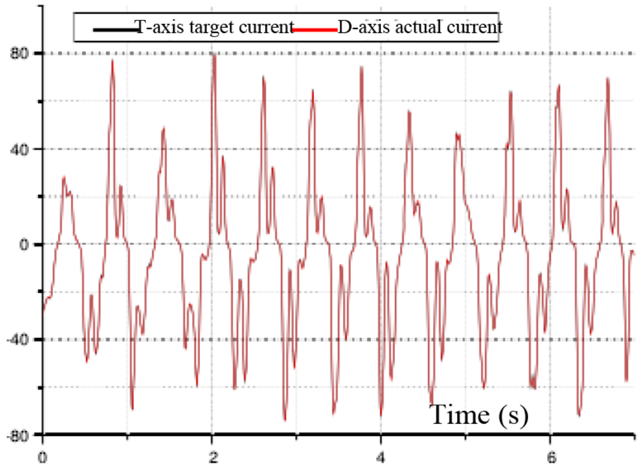


Fig. 13. The following curve of T-axle current during fast steering

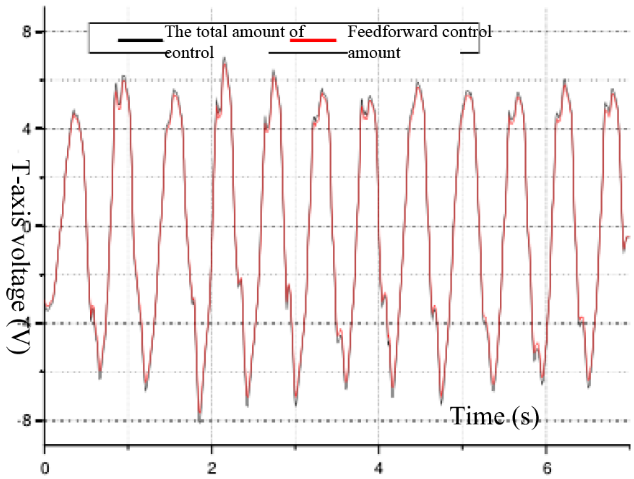


Fig. 14. The time process of T-axle total control amount and feed-forward control amount during fast steering

6. Conclusion

A steering system is an important channel for human-vehicle interaction and a key component of a vehicle. The performance of the steering system is directly related to the active and passive safety, operation stability and condition in the driving process. As a new type of electric and electronic servo system, the EPS has been rapidly developed and applied in products showing its excellent performance; it also accelerates the development of modern vehicle technology, aims at energy conservation, environmental protection, safety and comfort. This paper analyzes the performance requirements of an electric steering system. It is assumed that the system is an uncertain control object with multi-input and multi-output, non-linear and time-varying. It determines the power current according to the ideal characteristics and uses fuzzy PID+feedback decoupling to adjust the M axle current, so that it can adapt to the current control method realized by the T-axle current of the feed ward and decoupling. Meanwhile, the parameter sensitivity and current response quality of the current adjustment method are verified by experiments. The results show that the algorithm is feasible and is of significant importance in the application.

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