DESIGN AND EVALUATE CONTROLLER FOR POWER STEERING SYSTEM

THIẾT KẾ VÀ ĐÁNH GIÁ BỘ ĐIỀU KHIỂN CHO HỆ THỐNG LÁI TRỢ LỰC ĐIỆN

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(Received: September 18, 2023; Revised: October 22, 2023; Accepted: October 24, 2023)

Abstract - The integration of Electric Power Steering (EPS) in automobiles is crucial to reduce the steering effort for drivers while ensuring optimal steering performance to aid in vehicle control. The EPS system mandates a minimum 2Nm torque input from the driver to initiate steering wheel movement in all conditions. Key components of the electric power steering system include the torque sensor, DC motor assistance, current sensor, and an Electronic Control Unit (ECU). This study is dedicated to mathematically modeling and characterizing the EPS System. We have developed a mathematical model for column-assisted front-wheel steering using Newton's equations of motion. The controller for our model was designed based on assist characteristic curves and algorithmic control. Test results demonstrate that our self-designed ESP controller, utilizing an innovative motor control approach, significantly enhances ease of steering and controllability perception. Furthermore, it meets the specified criteria for steering performance.

Key words - Electric vehicle; Electric Power Steering System; State-space; PID controller.

Tóm tắt - Việc tích hợp hệ thống lái trợ lực điện (EPS) trên ô tô là rất quan trọng nhằm giảm bớt nỗ lực đánh lái cho người lái, đảm bảo hiệu suất lái tối ưu. Hệ thống EPS yêu cầu người lái phải có mô-men xoắn tối thiểu 2Nm để bắt đầu chuyển động vô lăng trong mọi điều kiện. Các thành phần chính của hệ thống EPS gồm cảm biến mô-men xoắn, hỗ trợ động cơ DC, cảm biến dòng và Bộ điều khiển (ECU). Nghiên cứu này hướng đến mô hình hóa toán học và mô tả đặc tính của Hệ thống EPS. Chúng tôi đã phát triển một mô hình toán học cho hệ thống lái bánh trước sử dụng phương trình chuyển động của Newton. Bộ điều khiển cho mô hình của chúng tôi được thiết kế dựa trên các đường đặc tính hỗ trợ và điều khiển thuật toán. Kết quả thử nghiệm chứng minh rằng bộ điều khiển tự thiết kế giúp tăng cường khả năng lái và khả năng điều khiển và đáp ứng các tiêu chí quy định về hiệu suất lái.

Từ khóa – Xe điện; hệ thống lái điện; không gian trạng thái; bộ điều khiển PID.

1. Introduction

Electric Power Steering (EPS) systems have had a notable evolution, gaining prominence in contemporary automobiles and often replacing conventional hydraulic power steering systems [1]. The preference for EPS is notably seen in the domain of electric vehicles, owing to its lightweight construction and high efficiency. In addition to its energy efficiency, EPS offers other benefits that contribute to an enhanced driving experience. One of the key advantages of an Electric Power Steering (EPS) system is in its small and lightweight design [2], [3]. In contrast to hydraulic power steering systems that depend on a hydraulic pump, fluid reservoir, and a network of hoses, Electric Power Steering (EPS) utilizes an electric motor that is linked to the steering column. The implementation of this simplified configuration not only results in a decrease in the overall weight of the vehicle, but also obviates the need for a hydraulic fluid system, thereby mitigating the potential for leaks and minimizing maintenance demands. The decrease in weight has particular benefits in the context of electric vehicles (EVs), since each pound that is saved has the potential to enhance battery longevity and increase overall efficiency. In addition, the Electronic Power Steering (EPS) system improves the comfort of drivers by offering adjustable assistance that is dependent on the prevailing driving circumstances. The system can modify the degree of steering assistance, hence facilitating maneuverability in situations characterized by low velocities, such as parking or navigating through constricted areas [4]. As the velocity of the vehicle escalates, the level of assistance diminishes, so affording the driver a steering experience that is more authentic and cohesive. The significance of adaptability is especially apparent in the context of electric cars, since the immediate delivery of torque might have distinct implications for steering dynamics in comparison to conventional internal combustion engine vehicles.

EPS has a substantial role in enhancing driving safety, particularly while operating at high velocities. When operating a vehicle at high speeds on the highway, the Electronic Power Steering (EPS) system can decrease the level of steering assistance provided or perhaps disable the system altogether. The intentional decrease in aid serves to guarantee that the driver retains a strong and accurate command over the vehicle, hence reducing the probability of excessive correction and augmenting stability. This particular attribute is of great significance in situations involving abrupt lane changes or defensive actions, when the operator must effectively retain command throughout arduous circumstances. EPS, or Electronic Power Steering, assumes a pivotal function in advanced driver assistance systems (ADAS) and autonomous driving technologies, in addition to its inherent safety advantages. The precise steering control offered by Electric Power Steering (EPS) is crucial for the effective implementation of advanced functionalities like lane-keeping assistance, adaptive cruise control, and automatic parking [5]–[7]. These systems use Electric Power Steering (EPS) to make exact changes to the vehicle's steering angle in order to maintain its position inside the lane or to perform accurate parking maneuvers without the need for human interaction. Electric Power Steering (EPS) has revolutionized the automotive industry by offering a lightweight, efficient, and adaptable steering solution. Its advantages extend beyond energy efficiency, encompassing improved driver comfort, enhanced safety, and critical support for advanced driver assistance systems. As electric vehicles continue to gain traction in the market, EPS is poised to play an even more prominent role in shaping the future of automotive technology. However, it is noteworthy that the ongoing progress in technology is giving rise to thought-provoking inquiries: In order to address the growing requirements for safety and performance, it is essential to explore methods for optimizing electric power steering systems. Dedicated efforts are being made by researchers and engineers to effectively use real-time data and sensors in order to develop intelligent control systems [8]–[11]. This study primarily focuses on the theoretical aspects of the electric power steering system. It delves into various topics, including the communication circuit between the computer and the model, which is facilitated through the use of the LabVIEW program for control. Furthermore, the paper explores the design of the computer simulation interface and the arrangement of the model.

The system has been purposefully designed to accommodate mobile wheels and includes features such as a driving position and virtual reality apparatus. These elements allow users to immerse themselves in the sensation of operating a vehicle. The ultimate goal is to optimize and enhance the cognitive capabilities and ergonomic performance of the electric power steering system.

2. Eps System Model

2.1. EPS System Structure

In this study, the electric power steering system's structure is depicted in Figure 1***:***

- Steering Wheel: This is the part of the system that the driver interacts with to control the vehicle's direction.

- Main Steering Shaft: The main steering shaft is a critical mechanical component that connects the steering wheel to other parts of the system, enabling the transmission of driver input.

- DC Power Steering Motor: This motor is responsible for assisting the driver's steering input, making it easier to turn the wheel, especially at low speeds or when parking.

- Torque Sensor: The torque sensor measures the amount of force or torque applied by the driver to the steering wheel. This information is crucial for the system to provide appropriate steering assistance.

- Rack Displacement Sensor: This sensor helps monitor the movement and position of rack which is part of the steering mechanism.

- Engine Rotation Angle Sensor (Encoder): The engine rotation angle sensor, often implemented as an encoder, tracks the position and rotation of the vehicle's engine. This data can be vital for the power steering system to adjust steering assistance based on the vehicle's operating conditions.

- NI MyRio: The NI MyRio, is a data acquisition and control device from National Instruments. It may be used to interface with and control various aspects of the electric power steering system, such as data collection, sensor integration, and possibly even control algorithms.

The physical prototype was constructed within our laboratory (see Figure 2).

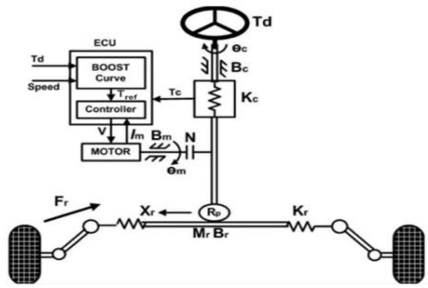

Figure 1. *Model of EPS electric power steering system [6]*

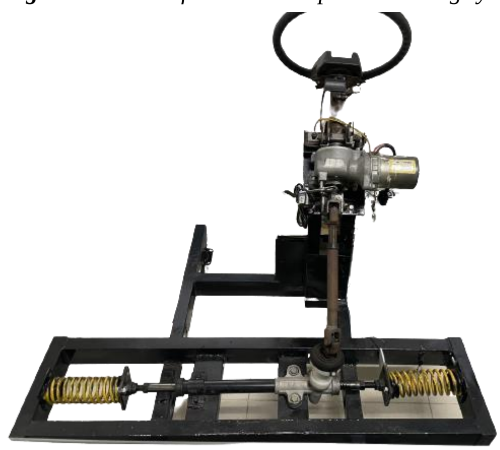

Figure 2. *Physical model*

2.2. Mathematical model of the EPS system

The mathematical model of the EPS system is presented as follows [6]:

$$\begin{cases} J_s\ddot{\theta}_s = T_d - K_s(\theta_s - \theta_r) - B_s\dot{\theta}_s \\ J_{eq}\ddot{\theta}_m = K_s\frac{\theta_s}{i_m} - \left(\frac{K_s}{i_m^2} + \frac{K_r.r_p^2}{i_m^2}\right)\theta_m - B_{eq}.\dot{\theta}_m + K_t.I_m - \frac{r_p}{i_m}.F_r \\ L_m\dot{I}_m = -R_mI_m - K_t\dot{\theta}_m + U \end{cases}$$

With:

$$J_{eq} = J_m + \left(\frac{r_p^2}{i_m^2}\right).m; \quad B_{eq} = B_m + \left(\frac{r_p^2}{i_m^2}\right).B_r$$

$$\theta_m = i_m.\theta_r \qquad \theta_r = \frac{x_r}{r_p}$$

It can be written as:

$$\begin{cases} J_s\ddot{\theta}_s = T_d - K_s\theta_s + K_s\frac{\theta_m}{i_m} - B_s\dot{\theta}_s \\ J_m + \left(\frac{r_p^2}{i_m^2}\right).m.\ddot{\theta}_m = K_s\frac{\theta_s}{i_m} - \left(\frac{K_s}{i_m^2} + \frac{K_r.rp^2}{i_m^2}\right)\theta_m \\ \quad -\left(B_m + \left(\frac{r_p^2}{i_m^2}\right).B_r\right).\dot{\theta}_m + K_t.I_m - \frac{r_p}{i_m}.F_r \\ L_m\dot{I}_m = -R_mI_m - K_t\dot{\theta}_m + U \end{cases}$$

The explanations for the symbols are presented in the Table 1.

Table 1. *Explanations for the symbols*

Name	Symbols	Value	Unit
Torque of inertia of the steering wheel and steering column.	*Js*	0.004	Kg.m^2
Viscous damping of steering column.	*Bs*	0.36	N.m/(rad/s)
Steering column stiffness	*Ks*	115	Nm/rad
Motor and reducer stiffness.	*Km*	125	Nm/rad
Motor gear ratio.	*im*	7	
Viscous damping of rack and pinion	*Br*	653.2	N/(m/s)
Mass of the rack and pinion.	*m*	5	kg
Rack stiffness.	*Kr*	91061	Nm/rad
Jet action on the rack	*Fr*	-	N
Steering column pinion radius.	*rp*	0.007	m
Steering wheel rotation angle.	*θs*	-	rad
Engine rotation angle.	*θm*	-	rad
The angle of rotation of the posts.	*θr*	-	rad
Viscous damping of motor shaft.	*Bm*	0.0004	N.m/(rad/s)
Moment of inertia of an electrically assisted motor	*Jm*	0.00018	Kg.m^2
Motor current	I_m	-	A
Motor inductance	L_m	0.0056	H
Motor resistance	R_m	0.37	Ω
Motor torque constant	*Kt*	0.05	N.m/A

2.3. Control model of EPS system

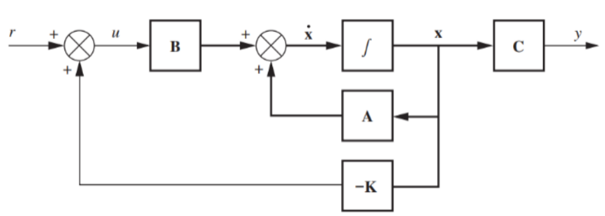

Figure 3. *Constructing the response variable K*

The PID (Proportional-Integral-Derivative Controller) algorithm provides optimal correction of deviations, increased response speed, reduced overshoot, and limited oscillations. The PID algorithm utilizes a combination of three sets of components: proportional, integral, and differential. All 3 components play a role in bringing the deviation to zero. The PID is the most popular controller in the industry because of its ease of application, and for its consistent control quality. Specifically, PID controllers are commonly used in DC motor control, robotics, systems in automobiles, pressure control, transmission tapes, etc.

The expression of the PID algorithm is:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt} e(t)$$

Another model to simulate is a state-space controller, as represented in Figure 3. The objective is to determine the K matrix to be used as a parameter for the simulation model. The K matrix can be calculated from the state-space equations which are derived from mathematical equations [7]:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

The matrices A, B, C, D are represented as follows:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -\frac{K_s}{J_s} & -\frac{B_s}{J_s} & \frac{K_s}{J_s . i_m} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \frac{K_s}{J_{eq} . i_m} & 0 & -\left(\frac{K_r . r_p^2 + K_s}{J_{eq} . i_m^2}\right) & -\frac{B_{eq}}{J_{eq}} & \frac{K_t}{J_{eq}} \\ 0 & 0 & 0 & -\frac{K_t}{L_m} & -\frac{R_m}{L_m} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ \frac{1}{Js} \\ 0 \\ 0 \\ 0 \end{bmatrix} . \mathrm{T_d}\,; \; C = \begin{bmatrix} 0 & 0 & \frac{r_p}{i_m} & 0 & 0 \end{bmatrix} . \begin{bmatrix} \theta_s \\ \dot{\theta}_s \\ \theta_m \\ \dot{\theta}_m \\ I_m \end{bmatrix} ; \; D = 0$$

3. Simulations, Experiments and Results

3.1. System control with K matrix

After obtaining the matrices of the equation of state, the next step is to use the algorithms entered into the Matlab software for simulation [8], [9].

The simulation results show the characteristic lines of the K matrix and the characteristic lines of the transmitting function when there is no K matrix (Figure 4).

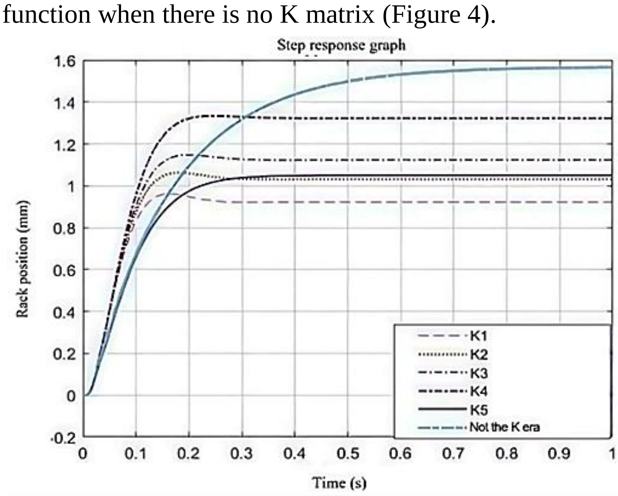

Figure 4. *Simulation results with K matrix*

According to the technical requirements of the steering system, the control system does not have an overshoot for the system to operate smoothly and the stability time (Setlling Time) must be fast, so choose the K5 matrix to continue to include in the model control algorithm.

3.2. System control simulation with PID

The PID algorithms with Matlab Simulink are shown in Figure 5. The PID parameters are described in Table 1, while Table 2 outlines the characteristic parameters of the system when using the PID algorithm. Comparing the simulation results in Figure 6 and Figure 4, it can be seen that the setpoint value when using the PID controller is much better than when using the K matrix. In other words, the rack position is controlled more accurately when using the PID controller compared to the K matrix. Therefore, we will use the PID controller in the experiment.

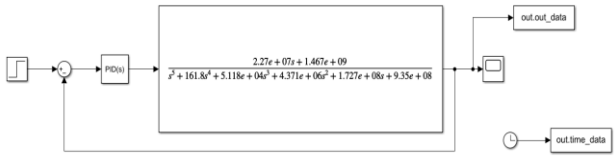

Figure 5. *Diagram of simulation of PID algorithm with Matlab Simulink software*

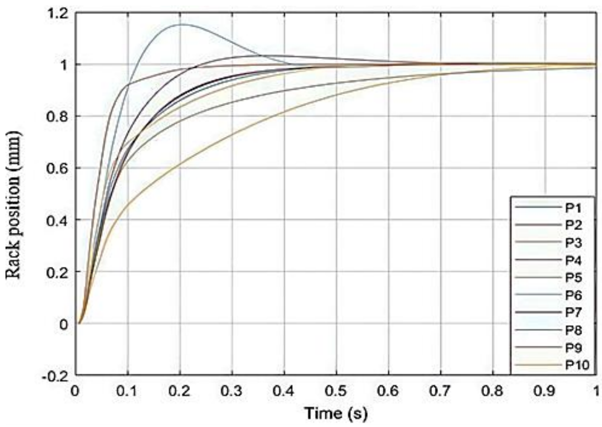

Figure 6. *Simulation results with PID algorithm*

Table 2. *PID parameters in simulation*

Ministry	*P*	*I*	*D*	*Kc*	*Ti*	*Td*
1	1.036	6.221	0.014	1.036	0.166	0.015
2	2.000	12.048	0.008	2.000	0.166	0.015
3	0.500	3.012	0.030	0.500	0.166	0.015
4	1.036	9.333	0.014	1.036	0.111	0.015
5	1.036	4.047	0.014	1.036	0.256	0.015
6	1.036	18.500	0.014	1.036	0.056	0.015
7	1.036	6.241	0.005	1.036	0.166	0.005
8	1.036	6.241	0.003	1.036	0.166	0.003
9	1.036	6.241	0.001	1.036	0.166	0.001
10	1.036	6.241	0.042	1.036	0.166	0.043

Table 3. *Characteristic parameters of the system when using the PID algorithm in simulation*

Ministry	*Kc*	*Ti*	*Td*	Settling time (s)	Peak time (s)	Rise time (s)	Over shoot (%)
1	1.036	0.167	0.016	0.426	0.893	0.220	0.029
2	2.000	0.166	0.015	0.206	0.994	0.072	0.008
3	0.500	0.166	0.015	0.795	1.000	0.506	0.000
4	1.036	0.111	0.015	0.509	0.364	0.140	3.197
5	1.036	0.256	0.015	0.734	1.000	0.351	0.000
6	1.036	0.056	0.015	0.376	0.200	0.078	15.200
7	1.036	0.166	0.005	0.402	0.980	0.202	0.000
8	1.036	0.166	0.003	0.397	1.000	0.198	0.000
9	1.036	0.166	0.001	0.392	1.000	0.195	0.000
10	1.036	0.166	0.043	0.391	1.000	0.194	0.000

3.3. Application of PID controller on the physical model

The PID controller is applied on the physical model as shown in Figure 2. The data collected from experiments are presented in Tables 4, 5.

Table 4. *Power, voltage, and current intensity measured on the motor*

Ministry	*P(w)*	*U(v)*	*I(A)*
1	2.58	0.41	6.25
2	2.97	0.44	6.71
3	2.83	0.43	6.55
4	3.10	0.45	6.86
5	2.97	0.44	6.70
6	2.65	0.42	6.34
7	3.29	0.47	7.06
8	2.80	0.43	6.51
9	2.76	0.43	6.46
10	3.22	0.47	6.92

Table 5. *Characteristic parameters of the system when using the PID algorithm in experiment*

Ministry	Settling time (s)	Peak time (s)	Rise time (s)	Over shoot (%)
1	13.08	7.31	5.91	4.16
2	19.47	7.62	5.98	11.87
3	12.62	7.56	5.81	9.20
4	16.28	6.46	4.94	14.31
5	11.36	7.36	5.26	11.72
6	9.75	7.24	5.89	5.62
7	10.40	6.56	5.16	17.62
8	17.53	6.66	5.56	8.55
9	12.37	6.46	5.63	3.51
10	18.03	6.63	5.14	15.37

The experimental results are shown in Figures 7, 8, 9. From these results, some following statements can be drawn:

When changing K_C, the larger it is, the faster the response speed, up to a certain level, the system will lose stability, the overshoot will be large.

When the T_i changes, the larger it is, the slower the transitional response, too large, the large surges will occur causing instability.

When changing T_d, T_d helps to stabilize the system if the coefficient is chosen correctly, the larger the T_d coefficient, the smaller the ridiculous jump.

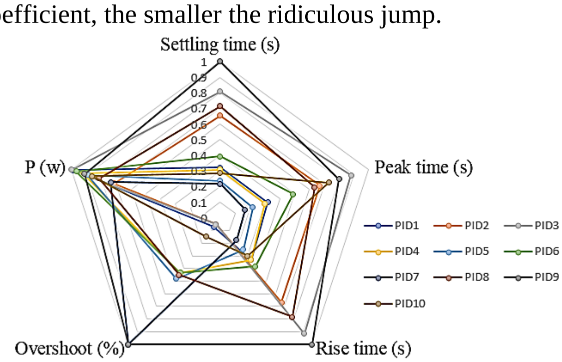

Figure 7. *General chart of 5 PID evaluation characteristics*

Figures 8 and 9 depict the following:

- The average torque of the driver without power assist is 14.18(Nm).

- The average torque of a person with power assist is 8.06 (Nm)⇨ The support ratio of the power assist motor is 100 – (8.06/14.18 * 100) = 43.2%.

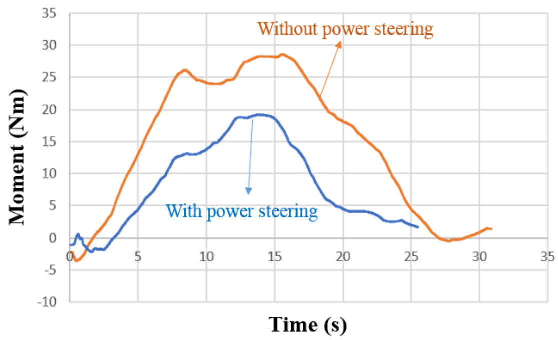

Figure 8. *Graph of the driver's torque value from 0° - 450° over time*

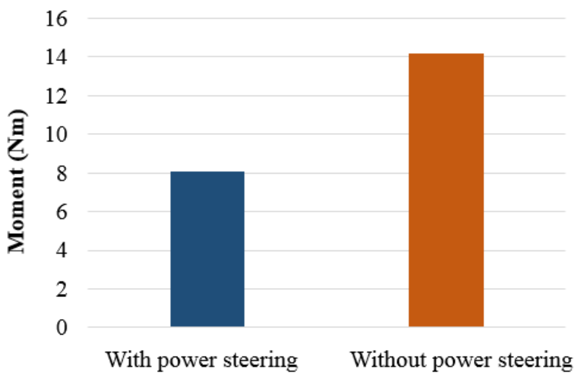

Figure 9. *Graph of average driver torque value*

4. Conclusions

The built electric power steering system model performs the following functions: surveying the characteristic lines of the torque sensor and the driving characteristics of the power motor, simulating the Mc resistance torque signal acting from the road surface to the steering wheel through the mass placed on the model, Build a central controller with the function of collecting torque sensor signal input signals, then calculate to control the power motor appropriately, displaying voltage quantities to the torque sensor, power motor control current. With this model, we can use the survey dike to set the control of the electric power steering system, thereby offering the optimal solution depending on the driving conditions. In addition, the electric power steering system model is also used to teach in schools, giving students more access to reality. Research results have contributed to the development and optimization of electric power steering, which offers many benefits for safety, performance and utility of driving. The future of automotive technology will be shaped by advances in this area, and this topic has already played an important part in that direction.

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