Modeling of Force Feedback and Research on Control Strategy of Returnability of Steering Wheel

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Abstract. A force feedback model of steering wheel was established based on mechanical analysis of the vehicle steering system. Taking driver’s preference for steering torque into consideration, a correction coefficient was introduced to this model, and a method for determining the coefficient was also put forward. To study on the steering wheel return control strategy, the relationship between torque and speed as well as voltage of the torque motor was analyzed by interpolation fitting. In addition, the simulated control model in Matlab/Simulink was set up. As for the oscillation problem, in order to improve the steering wheel returnability, Improvement of control strategy of torque motor was proposed. The model was further optimized through the research of the influence of different elastic coefficient and damping coefficient on steering wheel returnability. Finally, the real experiment proved the feasibility of the model and control strategy.

Introduction

The force feedback characteristics of steering wheel refer to the law of the steering wheel torque feedback varying with the vehicle motion state. Road condition, driver’s operation behavior and other factors will affect force feedback of the steering wheel. That the vehicle steering system has good feedback force characteristics is premise for driver to better control of the vehicle. In previous researches, Fuzzy control was applied to road feel control in steer-by-wire system[1]. Additionally, researcher analyzed automobile force by Calman filter and designed the road-feel simulation method of which was closing to the electric power steering system[2]. But these methods are relatively complex and difficult operation. This paper attempts to study a simple, practical method of building feedback model and discussing returnability control strategy.

Steering wheel force feedback model

Steering force torque feedback of steering wheel can be regarded as resistance torque transmitted from steered wheel to steering wheel, this steering resistance torque includes the friction resistance torque caused by contacting with the road and aligning torque of the steering wheel. When steering, aligning torque relevant to front wheel lateral force can not be too small in principle and the friction which has nothing to do with the front wheel lateral force should be as small as possible [3]. In this paper, the main consideration is the aligning torque of steering wheel caused by steered wheel returning. The steered wheel aligning resistance torque includes two parts: one part is caused by the tire drag which consists of air drag and tilt drag, this torque is proportional to the centrifugal acceleration; The other part is caused by kingpin inclination and displacement, this torque has nothing to do with speed, it can be calculated according to the vehicle parameters.

Aligning torque caused by tire drag can be regarded as the product of the lateral force $F_y$ and the tire drag after mechanical property of vehicle steering analyzed.
\[ M_{ZV} = F_y \cdot (\varepsilon_1 + \varepsilon_2). \tag{1} \]

Where, \( M_{ZV} \) is the aligning torque caused by the tire drag, \( \varepsilon \) is the tire drag, \( \varepsilon_1 \) is tilt drag, \( \varepsilon_2 \) is air drag.

The equation of aligning torque \( M_A \) caused by kingpin inclination and displacement is:

\[ M_A = \frac{Q_w s}{2} \sin(2\gamma) \sin \theta. \tag{2} \]

Where, \( S \) is the kingpin shift, \( Q_w \) is the wheel load, \( \gamma \) is the kingpin inclination, \( \theta \) is the front wheel angle. Considering moment of inertia and damping of the vehicle steering system, the steering wheel aligning torque can be expressed as follows:

\[ M_w = \frac{M_{ZV} + M_A}{i} + C_s \dot{\theta}_w + J_s \ddot{\theta}_w. \tag{3} \]

Where, \( M_w \) is the steering wheel aligning torque, \( i \) is the drive ratio, \( C_s \) is the damping coefficient of steering column, \( \theta_w \) is the steering wheel, \( J_s \) is the steering wheel moment of inertia.

The lateral force is the main reason for the deformation of the steering wheel, when vehicle driving, the sum of all tire lateral force are approximately proportional to the centripetal acceleration [5], i.e.

\[ F_y = m \frac{v^2 l_b}{R l}. \tag{4} \]

Where, \( m \) is the mass of vehicle, \( R \) is turning radius, \( v \) is speed, \( l \) is the wheelbase, \( l_a \) is the distance from centroid to the front wheel shaft and \( l_b \) is from centroid to the rear wheel shaft, \( k_1, k_2 \) are respectively the front and rear wheel cornering stiffness. Turning radius calculation formula:

\[ R = \frac{(l + m \frac{k_2 l_b - k_1 l_a}{k_1 k_2})}{\theta}. \tag{5} \]

The relationship between the front wheel angle and steering wheel angle can be expressed by the following equation:

\[ \theta = \frac{\theta_w}{i}. \tag{6} \]

Usually \( i \) is large, \( \theta \) is small, so it can be Simplified as \( \sin \theta \approx \frac{\theta_w}{i} \). For easily representation, two parameters are introduced.

\[ K = \frac{(mv^2 l_b)}{l^2 + m \frac{k_2 l_b - k_1 l_a}{k_1 k_2} v^2} \cdot (\varepsilon_1 + \varepsilon_2). \]

\[ K' = \frac{Q_w s}{2} \sin(2\gamma) \]

In addition, in the normal driving, driver operate slowly the steering wheel, so its angle acceleration is small, in order to simplify the model, angle acceleration can be ignored. Then \( M_w \) can be expressed as:

\[ M_w = \frac{k + K'}{i^2} \theta_w + C_s \dot{\theta}_w \tag{7} \]
Main model parameters of a vehicle are as followed: 
\[ m = 1760 \text{kg}, \ l = 2.774 \text{m}, \ \varepsilon_1 + \varepsilon_2 = 0.07 \text{m}, \ l_a = 1.04 \text{m}, \ l_b = 1.56 \text{m}, \ k_1 = k_2 = 35000 \text{N/rad}, \ S = 0.2 \text{m}, \ \gamma = 0.14 \text{rad}, \ i = 15, \ J_s = 0.01 \text{Kg/m}^2, \ C_s = 0.1 \text{N} \cdot \text{m/s/rad}. \] 

Equation (7) is obtained based on the analysis of the theory of traditional steering system without considering the influence of the power assist system, for example, when \( v = 30 \text{km/h}, \ \theta_w = \pi/3 \), according to (7) there is \( M_w = 25.88 \text{N} \cdot \text{m} \), which is significantly exceed driver's preference for the steering wheel torque obtained by General Company's test described in [6]. So a correction coefficient is introduced, (7) can be modified:

\[ M_w = C_s \dot{\theta}_w + \frac{K_w + K_v}{\lambda^2} \theta_w (8) \]

Establish the virtual prototype model in ADAMS, because steering wheel speed is small in the simulation experiment, and related coefficient of speed is small too, so the relationship between the steering torque and steering speed is neglected here. Through simulation we can get the steering torque-angle curve of the corrected system under different speeds of 30, 40, 50... 100 km/h.

By fitting the simulation curve and compared with (8), the corresponding correction coefficients are attained respectively as shown in Fig.1. With comprehensive consideration, take \( \lambda = 6 \).

\[ T = \begin{cases} 
(4 - \mu)T_3(n) + (\mu - 3)T_4(n), & (0 \leq \mu \leq 4) \\
(\mu^2 - 10\mu + 25)T_4(n) + (-\mu^2 + 10\mu - 24)T_5(n), & (4 < \mu \leq 5) 
\end{cases} \]

Where, \( T_3(n), \ T_4(n), \ T_5(n) \) are functions of the relationship between speed and torque, which is the inherent characteristic of the torque motor.

Keep constant speed, turn the steering wheel to a certain angle, then loosen the steering wheel, then the steering wheel will return back on the drive of aligning torque, which is called returnability of the

\[ \text{Fig.1. Correction coefficients of different speeds} \quad \text{Fig.2. Steer-by-wire system} \]
steering wheel. Built corresponding control model in Simulink referring to the established force feedback model. Then the return torque can be controlled by controlling the torque motor [4]. In simulation experiment, set the initial steering wheel angle for 1.5 rad, and then release the steering wheel, in the active return process, angle displacement curve of the steering wheel is shown in Fig.3.

![Fig.3. Angle displacement curve](image1)

![Fig.4. Damping module and elastic of the steering wheel module in Simulink](image2)

It can be seen from Fig.3 that the steering wheel shocks in active return process, the real experiment results are consistent with the simulation's. In order to enhance the steering wheel returnability and make sure the steering wheel returning stably and quickly, the control strategy of the motor should be improved. One feasible way is to add a damping module in the control module of the motor. Since the elastic module and the damping module output a control voltage together after added, so the torque $M_w$ concerned with steering wheel angle also need to adjust [7].

\[
M_w = (f + C_s)\dot{\theta}_w + k \left( \frac{K + K'}{\lambda l^2} \right) \theta_w \quad (9)
\]

Where, $k$ is the elastic coefficient, $f$ is the damping coefficient. The modules added in Simulink are as shown in Fig.4.

Setting different coefficients of elasticity and damping, Different return curve of steering wheel are as shown in Fig.5. By comparison, we can see, the steering wheel returns the fastest and its oscillation is minimum when $f = 0.4$.

![Different return curves](image3)

(a) $f = 0.1 \quad k = 0.6$ (b) $f = 0.2 \quad k = 0.6$
Similarly, set $f = 0.4$, change $k$, different steering wheel return curve can be gotten. However, it can be found that $k$ has little effect on the return time, but has great influence on the oscillation amplitude of the steering wheel. The smaller $k$ is, the weaker the oscillation will be. But $k$ cannot be too small in view of the fact that elastic coefficient have much to do with the steering wheel aligning torque which can affect driver’s road feel. With comprehensive consideration, $k=0.6$. In summary, when $f = 0.4$, $k = 0.6$, the returnability of steering wheel is best.

**Test results**

Test bench of the steering simulation system is shown in Figure 6. Test the result parameters acquired from the Simulation on the bench, the specific test method refer to the national standard GB / T6323. 4-1994.

When the vehicle speed is stable, spinning slowly the steering wheel, it shows that steering wheel torque and angle substantially exhibits a linear relationship. At this time, the damping module does not play a role, which is consistent with the theoretical analysis.

Set $k=0.6$, $f=0.4$, keep vehicle speed 30km/h constantly, turn the steering wheel to a certain angle, then take away hands and let it go, Results are showed in Fig.7 and Fig.8. From these two curve, we can see whether it is positive or reverse, the steering wheel can return back quickly, the oscillation amplitude is also very small, which refers good returnability of the steering wheel.
Conclusions

(1) The basic model of steering wheel force feedback was built. The correction coefficient was acquired with the help of ADAMS simulation. Then the relationship between torque and voltage, speed of the experimental torque motor was obtained through interpolation fitting. Finally, the oscillation problem affecting returnability was conquered by analyzing different elastic coefficient and damping coefficient in Matlab/Simulink. The simulation results show that, when $f = 0.4, k = 0.6$, the steering wheel can basically eliminate the oscillation and return as soon as possible which was in accordance with the real experiment results, thus verifying the correctness of the model and the control strategy.

(2) The process of modeling of force feedback in this paper is simple, the method of model updating and optimization has Strong operability, so the research provides a practical reference to products development of automobile driving simulator.

References


