Optimization for springs of electronic brake pedal simulator

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Abstract. Brake pedal feedback is important for drivers to judge the braking time. Electric vehicles replace hydraulic brake pedal with electronic brake pedal simulator. Such a simulator transmits brake signal with cables. Therefore, a new electronic brake pedal simulator is designed in this paper, which can allow the implementation of an arbitrary nonlinear pedal force characteristic with electromagnet and different combinations of spring. The brake pedal feedback generated by the pedal simulator was emulated with matlab/Simulink. Furthermore, the springs were optimized to determine the combination to make the feedback meet requirements suitable for drivers. The simulated results prove the excellent brake pedal characteristic with the optimal groups of springs.

1. Introduction

Electronic brake pedal simulator is an important component of Brake-By-Wire system (BBW), with less pollution and higher efficiency than hydraulic brake pedal [1]. With the pedal simulator, the brake signal in BBW is transmitted by cables, making the braking response time shorter than hydraulic brake. Different from the traditional vehicles, the pedal simulator can’t provide adequate brake feedback, which is important for driver’s braking perception during driving task [2]. Therefore, the design of the brake pedal simulator, generating the adjustable brake pedal characteristic arbitrarily like hydraulic brake, is important.

Based on the previous study [3-5], the main focus and originality of this paper depend on the structure design and performance optimization of electric brake pedal simulator. With the combination of springs, the pedal simulator can provide the basic feedback without online adjustment of brake pedal characteristic. Therefore, the electromagnet is used to generate the more precise adjustment. Then, according to the comparison between traditional and electronic brake pedal characteristic, it will be simulated with different springs to make the feedback consistent with traditional characteristic as far as possible. Through the optimization, the results confirm that three different groups of spring, adjusted by electromagnet, can provide an excellent brake pedal characteristic.

2. Structure Design Of Brake Pedal Simulator

The desired traditional hydraulic brake pedal characteristic is shown in fig 1. During the OA stage, the actuator eliminates the brake clearance, so the curve changes gently. At the stage of AB, the vacuum booster works and the force generated by vacuum booster reaches the maximum at B point, which can produce a large brake force, when drivers applying a small force on the brake pedal. During the BC
period, the brake pedal force only changes with trampling force exerted by drivers, so that the curve changes approximately linearly [6]. Therefore, the feature of the brake pedal characteristic is that it changes nonlinearly at the first two stages. In this paper, the nonlinear periods are engendered by electromagnet. The function of the springs is to provide the basic brake feedback. The structure of the electronic brake pedal simulator is shown in fig 2.

![Figure 1. Brake pedal characteristic curve of hydraulic brake system](image1)

![Figure 2. The structure of brake pedal simulator](image2)

When braking, the pedal control mechanism will produce a pedal displacement, which is transmitted to ECU by the displacement sensor. At the same time, the three springs will generate a linear force as the basic brake feedback to drivers. Once the ECU receives the signal, it will calculate the brake pedal force according to the pedal characteristic. Then, the ECU dominates the battery to generate the current, making the iron core of electromagnet provide a repulsive force to the armature, which will be transmitted to the pedal control mechanism, so that the spring tension and the repulsive force can create the brake pedal feedback.

The expression of the pedal force in this paper can be shown as follow:
Where \( F_p \) is the pedal force, \( U \) is the voltage of the iron core, \( R_0 \) is the external resistance of the iron core, \( C \) is the structure parameters of the iron core, \( f_T \) is the spring force, \( L \) is the brake pedal displacement, \( \alpha \) is the lever ratio of the pedal control mechanism, \( k_1 \), \( k_2 \) and \( k_3 \) are elasticity coefficient of springs respectively.

### 3. Optimization Of Springs

Different elasticity coefficient of springs will create a great impact on the brake feedback. According to the brake pedal features shown in fig.1, the elasticity coefficient should be small at the first stage so that the spring elastic force can change gently. During the two later stages where the brake strength gradually increases, the change range of brake pedal force increases with the brake pedal displacement becoming larger, so the elasticity coefficient should greater than the first stage. Depending on the principle that the force, imposed on the brake pedal by drivers, should be no more than 400N [7], the total force of the combinations of springs should meet the requirement.

#### Table 1. Different combinations of spring elastic coefficient

| Combinations | Coefficient of elasticity/(N*mm\(^{-1}\)) |
|--------------|------------------------------------------|
| Z1           | \( k_1=2 \) \( k_2=25 \) \( k_3=30 \) |
| Z2           | \( k_4=2 \) \( k_5=10 \) \( k_6=60 \) |
| Z3           | \( k_7=2 \) \( k_8=30 \) \( k_9=80 \) |

#### Table 2. Testing figures of passenger car

| Brake pedal displacement/mm | Brake pedal force/N |
|-----------------------------|---------------------|
| 0                           | 0                   |
| 25                          | 15                  |
| 32.1                        | 29.1                |
| 36.76                       | 50                  |
| 42.41                       | 75                  |
| 42.78                       | 76.63               |
| 44.16                       | 82.75               |
| 48.06                       | 100                 |
| 53.71                       | 125                 |
| 58.33                       | 145.42              |
| 59.37                       | 150                 |
| 68.49                       | 200                 |
| 70.75                       | 250                 |
| 73.01                       | 300                 |
| 75.72                       | 350                 |
| 77.53                       | 400                 |
| 79.79                       | 450                 |
| 82.05                       | 500                 |
Choosing three different groups of spring elastic coefficient, it is shown in table.1. The first spring is chosen with the fixed Coefficient of elasticity. The second and the third springs play a dominated role in brake pedal characteristic for the reason that they determine the brake strength. So the feature of the electronic brake pedal simulator was simulated in Matlab/simulink. The traditional passenger car was tested to achieve the target brake pedal characteristic. The figures are shown in table.2.

The result of the simulation is shown in fig.3. The third combinations under Z3 and Z1 accord with the target brake pedal characteristic best. The elastic coefficient of the second spring determines the performance of the pedal simulator. Besides, the second stage of the brake pedal characteristic represents the medium braking strength which is the most important during normal braking. Therefore, choosing the suitable elastic coefficient of the second spring can make the characteristic optimal. The elastic coefficient of the third spring determines the change of the third stage of the characteristic curve, which represents the emergency braking. It needs to have the same trend with the third stage of the characteristic curve under the help of the electromagnet.

![Figure 3. Different pedal features under different combinations of spring stiffness](image)

The changes of the spring elastic force are shown in fig.4. It is apparently that maximum force of the third combination of spring has exceeded the requirement. If the elastic coefficient of the second spring is too large, it will be difficult for drivers to reach the suitable condition what they think when braking.

The relationship between the electromagnetic repulsive force and the brake displacement is shown in fig.5. The repulsive force under Z1 is below zero at the second stage of the brake pedal characteristic due to the excessive spring elastic force. Another two curves meet the requirements that the electromagnet works in repulsion, but the brake pedal feature under Z2 is closer to the target. Therefore, following the principle above, taking the combination under Z1 as the optimal choice. There is no need for the elastic coefficient being fixed, because the brake pedal characteristic represents the change of force exerted by drivers on brake pedal, which determines the output of the brake force. The brake pedal characteristic of different types of electric vehicles can be created by the electric pedal simulator proposed in this paper. It just need to provide the same trend of target characteristic within the requirements.
4. Conclusion
In this paper, a new structure of brake pedal simulator has been designed to apply in electric vehicles. The brake pedal feedback can provided by the combination of different elastic coefficient of springs, which can satisfy the arbitrary trend of hydraulic brake pedal features with the repulsive force generated by electromagnet. Besides, through the optimization, the results confirm that the combination of spring elastic coefficient under Z1 can realize a satisfied characteristic curve in passenger cars.

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References

[1] Zheng Z A, Song C X, Lin H, et al. Research of the Brake Pedal Feel on Wire-by-Brake-System, Advanced Materials Research, China, 2013, 655 - 657: 1131 - 1135.

[2] Flad M, Rothfuss S, Diehm G, et al. Active Brake Pedal Feedback Simulator Based on Electric Drive. SAE International Journal of Passenger Cars - Electronic and Electrical Systems, 2014, 7(1):189-200.

[3] Yang L, Ze-Chang S, Wen-Bin J I. Brake pedal feeling and its influencing factors for electro-hydraulic brake system. Journal of Jilin University, China, 2015, 45 (4): 1049 - 1055.

[4] Fenzhu J I, Zhou X, Zhu W. Pedal simulator and braking feel evaluation in brake by wire system. Journal of Beijing University of Aeronautics & Astronautics, China, 2015, 41 (6): 989 - 994.

[5] Abeykoon A M H S, Ohnishi K. Implementation of pedal feeling for Brake By Wire system using bilateral control. Industrial Electronics. Japan, 2008: 1347 - 1352.

[6] Jin Z L, Guo L S, Zhao Y Q, et al. Research on Brake Pedal Emulator of Vehicle with Controllable Pedal Feeling. Journal of System Simulation, China, 2010 (12).

[7] Mortimer R G. Foot Brake Pedal Force Capability of Drivers. Ergonomics, USA, 1974, 17 (4): 509 - 513.