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Research on the Setting of Damping Force Bandwidth of Shock Absorbers Based on Vehicle Parameters

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Abstract: With the development of shock absorber calibration technology, there is still a lack of a positive development dimension in the setting of shock absorber damping force. Based on the bench test data of shock absorbers of different types of competing models and the design principle of the relative damping ratio of shock absorbers, this paper sets the bandwidth of the relative damping ratio for recovery and compression of shock absorbers of different models at different speed points, and then sets the bandwidth of the damping force of shock absorbers. Based on the research on the theoretical optimal damping force curve of shock absorbers, it was found that the optimal damping force curve is within the set range of the damping force bandwidth, effectively verifying the rationality of the relative damping ratio bandwidth setting and providing a basis for the forward development of shock absorbers.

1. Introduction

As the core component of the suspension system, the damping force characteristics of the shock absorber directly determine the key performance indicators of the entire vehicle, such as ride comfort, handling stability and ride comfort. With the rapid development of the automotive industry and the increasingly diversified demands of consumers for driving and riding quality, fine-tuning and differentiating shock absorbers for different vehicle styles has become the key to enhancing product competitiveness. However, in terms of setting the damping force of shock absorbers, the traditional development model often relies on experience accumulation or benchmarking and imitation[1]. There are still significant deficiencies in the forward development dimension, lacking systematic theoretical guidance and design basis.

To fill this gap in forward development, this study proposes and practices a method for setting the damping force bandwidth of shock absorbers based on key vehicle parameters. The research first systematically collected bench test data of shock absorbers from various types of competing models. Based on the core design theory of the relative damping ratio of shock absorbers, an in-depth analysis is conducted on the intrinsic relationship between vehicle parameters (such as suspension stiffness, single-side sprung mass, shock absorber position lever ratio, shock absorber axis Angle and other key parameters) and the ideal damping characteristics. Based on this, for the first time, a relative damping ratio target bandwidth was constructed for different vehicle parameter combinations, spanning multiple key speed points under the recovery stroke and compression stroke[2]. Based on this bandwidth, the corresponding target bandwidth range for the damping force of the shock absorber was further derived and set.

2. Theoretical optimal damping force curve

The theoretical optimal damping force curve of shock absorbers is a key component in the design of vehicle suspension systems, as it determines the vehicle's ability to control vibrations during driving. This curve is usually calculated through dynamic modeling and optimization algorithms under specific working conditions (such as different road conditions, vehicle speeds, loads, etc.), with the aim of achieving the optimal balance among vehicle handling, comfort and stability.

2.1. The basis for setting the optimal damping force

The optimal damping force is set based on the basic parameters of the vehicle, mainly including suspension stiffness, single-side unsprung and unsprung masses, shock absorber position lever ratio, shock absorber axis Angle, tire vertical stiffness and other parameters, among which the key indicator is the setting of the optimal relative damping ratio [3];

The relative damping ratio of a shock absorber is used to assess the rate of vibration attenuation, and its calculation formula is:

$$\varphi = \frac{1}{2}\sqrt{\frac{r_m + 1}{r_m r_k}} \tag{1}$$

In the formula: φ represents the optimal relative damping ratio; r_m is the mass ratio, indicating the unsprung mass on one side compared to the unsprung mass on the other side. r_k represents the stiffness ratio, indicating the vertical stiffness of the tire to the stiffness of the upper suspension.

For the setting of the optimal damping force curve, this paper first selects the valve opening point and the maximum valve opening point for restoration and compression. It is stipulated that in the restoration stage, the valve opening point is 0.263m/s and the maximum valve opening point is 1.041m/s. During the compression stage, the valve opening point is -0.131m/s, and the maximum valve opening point is -1.041m/s.

The calculation formula for the damping force at the valve opening point during the recovery stage is:

$$F_{rk} = \frac{2V_{rk}\varphi i^2\sqrt{km}}{cos^2\beta} \tag{2}$$

In the formula: V_{rk} represents the velocity at the valve opening point, and φ is the optimal relative damping ratio. i represents the position lever ratio of the shock absorber, defined as the distance between the left and right lower arms and the vehicle body or steering knuckles compared to the distance between the center points of the lower ends of the left and right shock absorbers. k represents the stiffness of the vehicle suspension, m is the mass on one side of the vehicle's spring, and β is the Angle between the axis direction of the shock absorber and the vertical line direction.

The calculation formula for the damping force at the maximum valve opening point during the recovery stage is:

$$F_{rk\_max} = \frac{2\varphi i^2\sqrt{km}}{cos^2\beta}\left[V_{rk} + \frac{1}{\omega}(V_{rkm} - V_{rk})\right] \tag{3}$$

In the formula: V_{rkm} represents the maximum valve opening point speed during the recovery stage; ω is the safety ratio, defined as the ratio of the linear slope of the velocity characteristic of the shock absorber before the first valve opening to that before the second valve opening [4].

The calculation formula for the damping force at the valve opening point during the compression stage is the same as that during the recovery stage. The calculation formula for the damping force at the maximum valve opening point during the compression stage is:

$$F_{ck\_max} = \frac{2\mu\varphi i^2\sqrt{km}}{cos^2\beta}[V_k + \frac{1}{\omega}(V_{km} - V_k)] \tag{4}$$

In the formula: μ represents the bidirectional damping ratio, which is defined as the ratio of the maximum valve opening damping force of the shock absorber during the compression stroke to the maximum valve opening damping force during the recovery stroke.

2.2. The optimal damping force curve setting for shock absorbers of competing models

The model selected in this article is the 2023 Camry, with the following parameters, as shown in Table 1 below:

Table 1 Camry vehicle parameter table

Parameter	Front shock absorber	Rear shock absorber
Single-sided sprung mass	463	349
Unilateral unsprung mass	61	49
Tire vertical stiffness	335	314
Suspension stiffness	23.23	22.77
Leverage ratio (measurement ratio)	1.06	1.17
The Angle between the axis of the shock absorber and the vertical line	5	5
Peace ratio	2.0	1.8
Relative damping ratio	-0.45	-0.5

Based on the above vehicle parameters, the theoretical optimal damping force of the Camry model at different speed points can be derived, as shown in Table 2 below:

Table 2 Theoretical optimal damping forces of Camry at different speed points

		The theoretical optimal damping force of the front shock absorber	The theoretical optimal damping force of the rear shock absorber
Speed point (m/s)	1.041	1845	2052
	0.263	744	776
	-0.131	-371	-387
	-1.041	-839	-1026

The author conducted a bench test on the damping force of the physical shock absorber of the Camry. The test data is as follows, as shown in Table 3 below:

Table 3 Measured damping forces of Camry at different speed points

		Front shock absorber	Rear shock absorber
Speed point (m/s)	1.041	1845	2052
	0.263	744	776
	-0.131	-371	-387
	-1.041	-839	-1026

The theoretical damping force and the measured damping force are compared and analyzed as shown in the following figure 1 and figure 2:

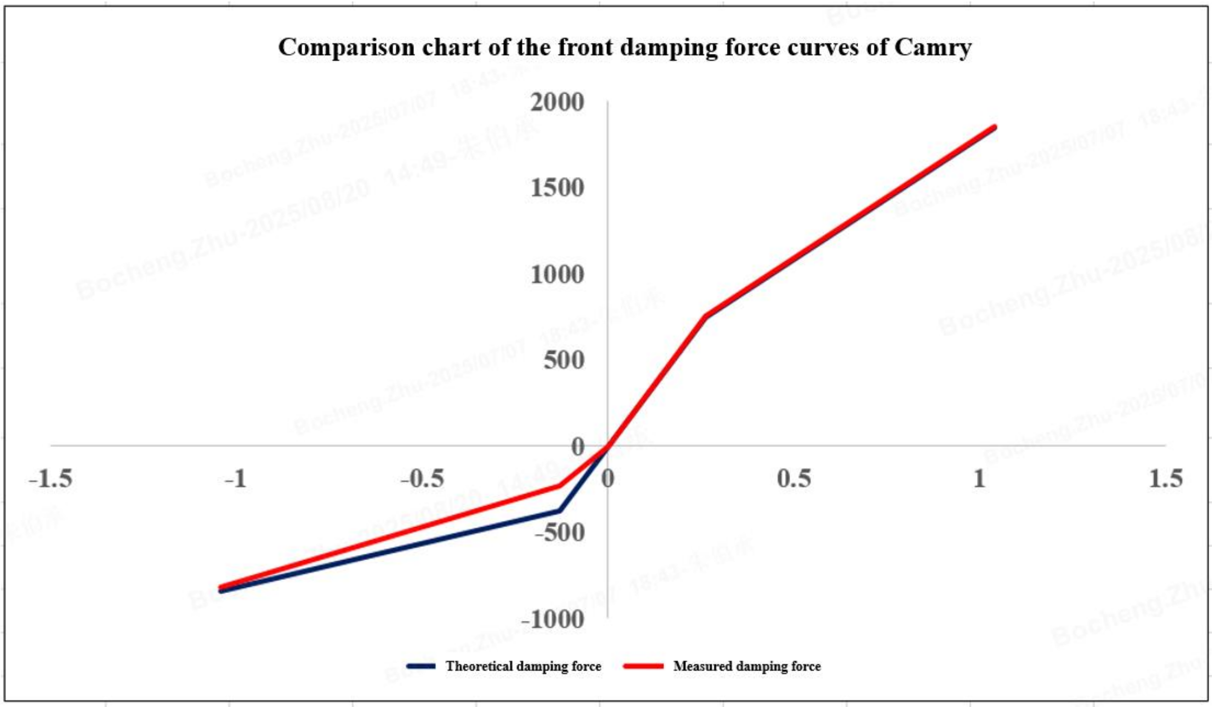

Figure 1 Comparison chart of the front damping force curves of Camry

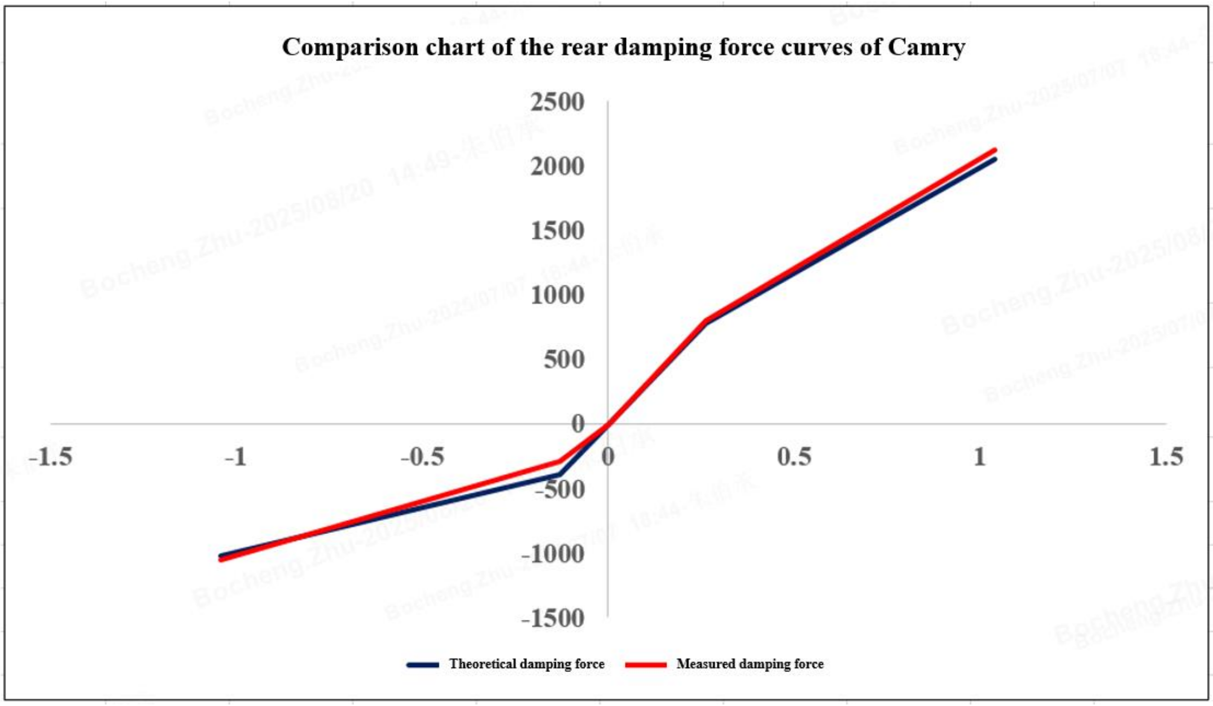

Figure 2 Comparison chart of the rear damping force curves of Camry

Through the calculation of the theoretical damping force of the front and rear shock absorbers of the Camry and the analysis of the test bench measurement data, it was found that the measured damping force of the Camry at typical speed points is very close to the theoretical damping force. Especially at high-speed points, the damping force error is only 3.21%. On the one hand, this indicates that the calculation method of the theoretical damping force is correct. On the other hand, it indicates that the shock absorber damping force design of the Camry is closely related to the vehicle parameters and can be regarded as a typical representative of the front MacPherson and rear multi-link suspension type.

3. Damping force bandwidth setting

3.1. Relative damping ratio range setting

The setting of the relative damping ratio range is related to the damping force bandwidth range under the corresponding vehicle parameters. This bandwidth range serves as an important basis for the valve system combination of shock absorbers. Therefore, the author selected shock absorbers of representative models on the market for bench testing. According to the formula, the values of the relative damping ratio at different speed points can be derived. Then, based on the upper and lower limits of the relative damping ratio at different speed points for all vehicle models, through flexible fine-tuning, the relative damping ratio setting range of the shock absorbers of this main vehicle manufacturer is set, and thereby the bandwidth range of the damping force is determined[5].

Since this paper mainly studies the damping force setting of shock absorbers for car models, the typical models selected in this paper include Camry, Corolla, ID3 and ID7, and the damping force tests of shock absorbers for each of them are conducted respectively. Through the calculation and derivation of the test data and in combination with empirical values, the following bandwidth setting of the relative damping ratio was obtained, as shown in Table 4 below:

Table 4 Set range of relative damping ratio

Front shock absorber/Rear shock absorber					
	Speed point	Restore the lower limit of the relative damping ratio	Restore the upper limit of the relative damping ratio	Lower limit of the relative damping ratio of compression	Upper limit of the relative damping ratio of compression
Low speed	0.052	0.34	0.70	0.15	0.55
	0.131	0.32	0.60	0.14	0.40
	0.263	0.24	0.50	0.12	0.28
Medium speed	0.524	0.15	0.40	0.10	0.20
	0.782	0.12	0.36	0.09	0.18
High-speed	1.041	0.10	0.32	0.08	0.18
	1.534	0.08	0.30	0.06	0.18

3.2. Damping force bandwidth setting

Based on the above setting of the relative damping ratio range, the damping force bandwidth range can be obtained. This paper takes the Camry as an example. According to the basic parameters of the Camry and the set range of the relative damping ratio, the damping force bandwidth range is obtained. The specific values are shown in the table 5 below.

After obtaining the damping force bandwidth range at different speed points, the curves of the upper and lower limits of the damping force for restoration and compression were imported into Adams/Car for verification. The differences in the K&C curves were analyzed [6], and then the rationality of this damping force range was evaluated. Through simulation analysis, it is found that both the range of roll gradient and the range of understeering degree can cover the measured values, indicating the rationality of its existence.

Table 5 Camry damping force bandwidth

Speed point	Restore the lower limit of the damping force	Restore the upper limit of the damping force	Lower limit of compression damping force	Upper limit of compression damping force
0.052	133	273	-59	-215
0.131	314	590	-138	-393
0.263	473	986	-237	-552
0.524	590	1572	-393	-786
0.782	704	2111	-528	-1056
1.041	781	2498	-625	-1405
1.534	920	3452	-690	-2071

3.3. Optimal damping force and damping force bandwidth compatibility

To verify whether the measured damping force at the valve opening point and the maximum valve opening point is within the set damping force range, the author also conducted curve analysis on the optimal damping force and the damping force setting range. The damping force curve is shown in the following figure 3 and figure 4.

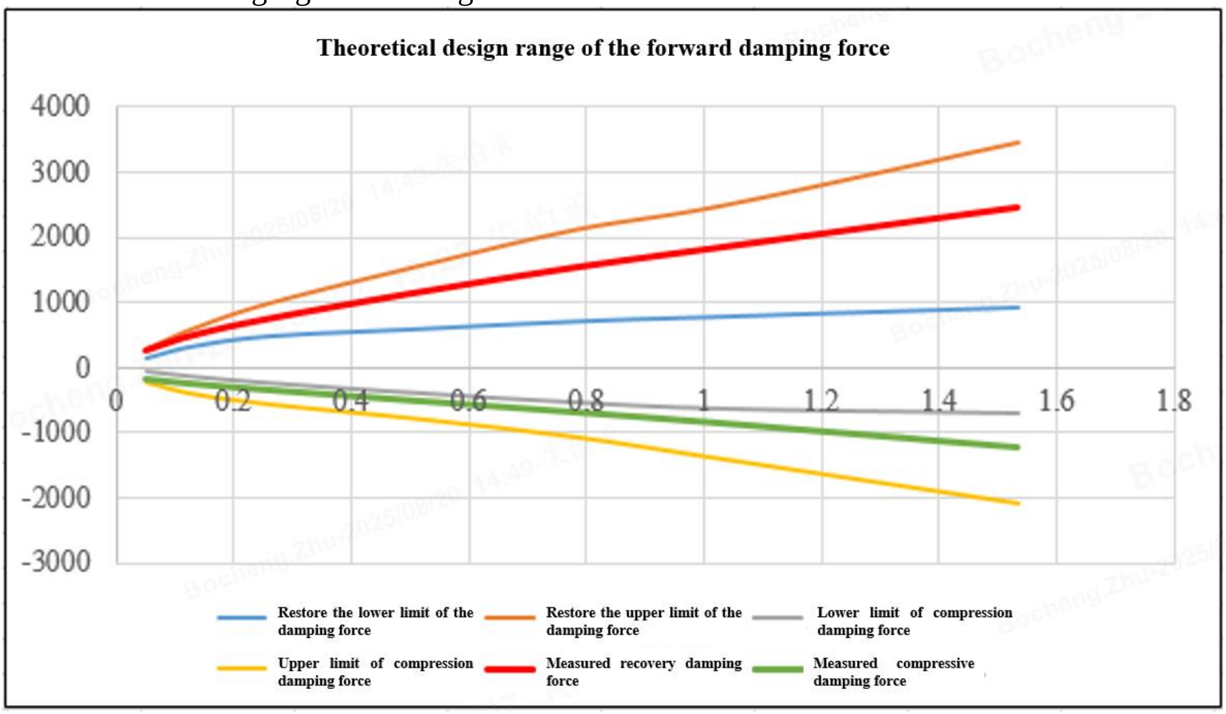

Figure 3 Theoretical design range of the damping force

By comparing the curves, it was found that the measured values of the Camry were all within the set range of the damping force bandwidth, which effectively verified the rationality of the setting of the relative damping ratio.

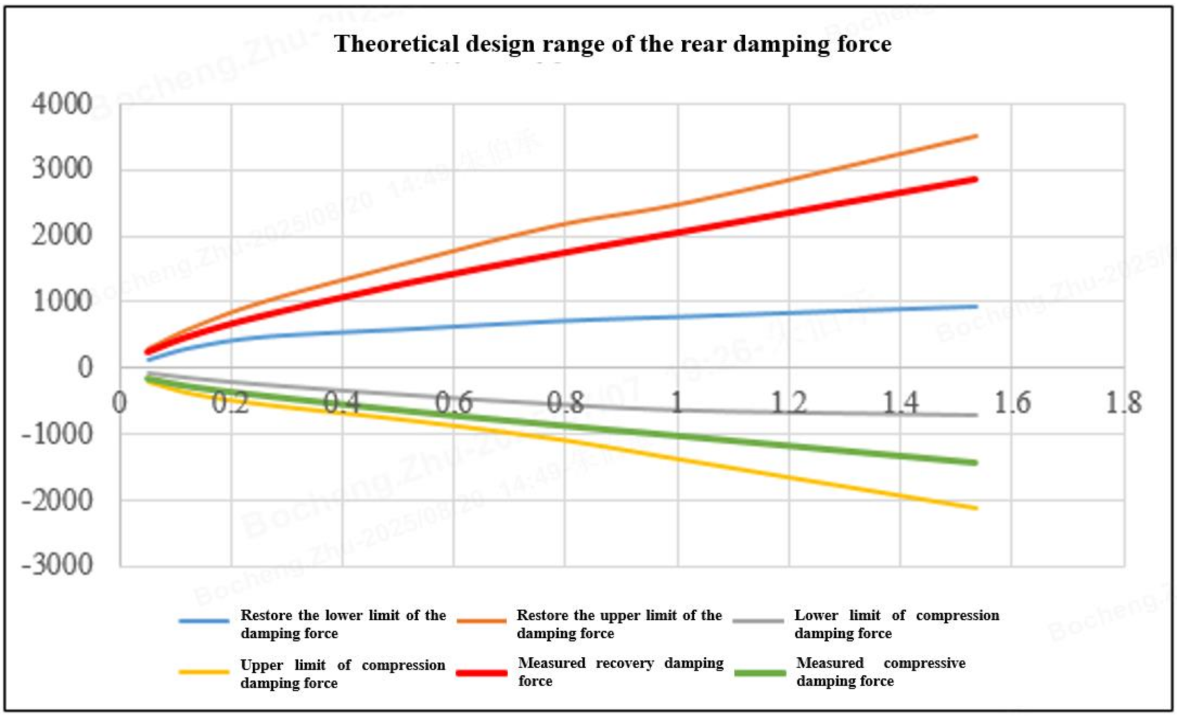

Figure 4 Theoretical design range of the damping force

4. Conclusion

Based on the Camry model, this paper validates the quantitative design principle between vehicle parameters and the damping characteristics of shock absorbers, sets the relative damping ratio range, provides a clear forward design input for the setting of the damping force bandwidth, and offers a theoretical design basis for shock absorber product engineers and property engineers, which can significantly improve the efficiency of actual vehicle calibration of shock absorbers.

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