Design Method for Throttle Holes Area of Telescopic Shock Absorber for Small Electric Vehicles

Changcheng Zhou [1], Zhiyun Zheng [2], and Xueyi Zhang [3]

[1] *School of Transport and Vehicle Engineering, Shandong University of Technology, greatwall@sdut.edu.cn*
[2] *College of Information Engineering, Zhengzhou University, iezyzheng@zzu.edu.cn*
[3] *School of Transport and Vehicle Engineering, Shandong University of Technology, zhangxueyi@sdut.edu.cn*

Abstract
Throttle holes area of telescopic shock absorber for electric vehicles influence the ride comfort, driving harshness and the other parameters design. For the non-linearity relation of the design area of throttle holes with the design velocity, there is no any accurate and reliable method for throttle holes area design of telescopic shock absorber. In this paper, analyzed the various damping factors affecting design, it was established that the mathematics model of throttle holes area by single velocity value. Studied the method of optimal design, the target function of curve fitting optimal design for throttle holes was constructed. A practical design example of throttle holes area with this method is given, and the designed result was compared with that by single velocity, and shown on the blueprint of telescopic shock absorber manufactory. The performance test was conducted for the telescopic shock absorber developed with the new design methods in laboratory, and the test results were compared with the design target value. The experiment results show that the design method of curve fitting optimal for the area of throttle holes is correct, and the designed values are reliable.

Keywords
electric vehicle, telescopic shock absorber, throttle holes area, design method, curve fitting

1. INTRODUCTION
Shock absorber as one of pivotal part of suspension system plays an important role in running of automobiles [Takashi et al., 2007]. At present, the widely applied shock absorber of vehicle is telescopic-damper [Zhou et al., 2006]. The damping force of shock absorber derives from the throttle pressure which generates as oil passing through the throttle orifice and throttle slot, and it can damp the relative motion between sprung mass and un-sprung mass effectively to improve the smoothness and control stability of automobiles [Heliang et al. 2004]. During the regular running, velocities of compression and rebound stroke are low and less than valve-opening velocity. So, mostly time, the damping characteristic of shock absorber is determined by the area of throttle holes A_0.

Valve parameters design is a pivotal problem worried shock absorber design and development all through [Chen and Han, 2001]. So far, there is no any precise and reliable design method at home and abroad [Zhou and Gu, 2006]. Generally, for valve parameters design, firstly fix on some parameters by experience and then do trial and error meanwhile modification, finally fix on the ultimate parameters [Shim et al, 2005]. In this process, for the area design of throttle holes, just make simple design by single velocity point. Due to the non-linearity of damping characteristic of shock absorber [Zhou and Gu, 2007], select different design velocity point will obtain different results, so it is difficult to find precise and reliable parameters, and also can't satisfy needs of practical design and produce.

The paper takes the rebound valve of shock absorber for example, analysed structure of damping component and rules of fluid flow, and established the target function and optimal design method of curve fitting for throttle holes by the relations of throttle pressure and flux.

2. PRINCIPLE OF SHOCK ABSORBER
Twin-tube shock absorber is a familiar configuration of telescopic-damper, there are four valves inside in

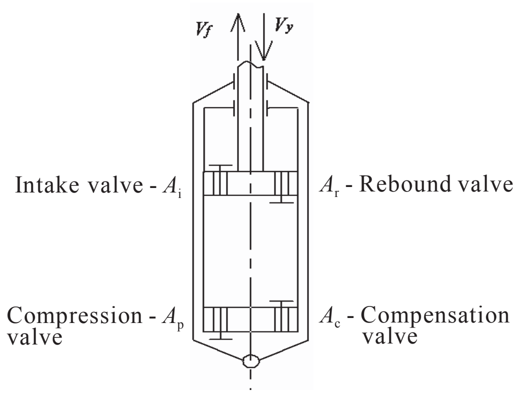

Fig. 1 Schematic diagram of shock absorber

all, and they are rebound valve, compression valve, intake valve and compensation valve. Among them, rebound valve and compression valve are largely responsible for the characteristic of shock absorber. Schematic diagram of typical twin-tube shock absorber is shown in Figure1.

At rebound stroke, rebound valve and compensation valve work. The fluid in rebound chamber flows to the compression chamber through rebound valve by pressure difference, meanwhile a part of fluid in reservoir chamber flows to the compression chamber through compensation valve. The throttle resistance comes out as fluid passes through the rebound valve and compensation valve. At compression stroke, intake valve and compression valve work. By the pressure difference, a part of fluid in compression chamber flows to the rebound chamber through intake valve, meanwhile another part of fluid flows to the reservoir chamber through compression valve, and throttle resistance generates as fluid flows through the intake valve and compression valve. When piston moving velocity is lower than valve-opening velocity, throttle pressure mainly depend on fluid passing through throttle holes; otherwise, throttle pressure depend on fluid passing through throttle orifice as well as throttle slot which is controlled by the deformation of throttle slice. At one velocity, the product of throttle pressure and corresponding action area is the damping force.

3. ANALYSIS OF DAMPING

Rebound valve consists of rebound slice which locates piston underside and piston under-surface, the basic components include piston orifice, throttle slice, throttle holes and down-check ring. Schematic diagram is shown in Figure 2.

In Figure 2, d_h is diameter of piston orifice, n_h is the number; p is pressure on throttle slice; f_{rk0} is pre-deformation of throttle slice which is decided by the fixing size to ensure right valve-opening velocity; r_b is outer radius of slice, r_k is valve mouth radius, r_a is inner radius of slice (taking the fixing size into account); δ_k is the opening size of rebound slice, and it is equal to difference between total deformation f_{rk} and pre-

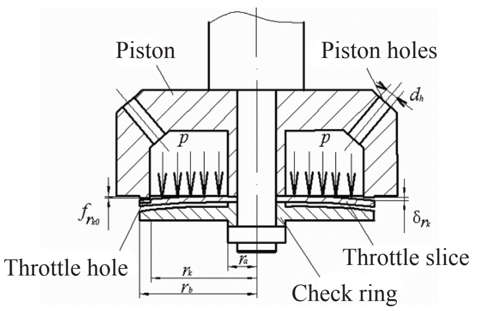

Fig. 2 Schematic diagram of rebound valve

deformation f_{rk0} of slice.

For the design of throttle holes area, it should take the piston orifice, the piston slot and local throttle loss with suddenly expansion, and shrinkage and direction change into account.

3.1 Throttle holes

Throttle slice of rebound valve is composed of superposition slices with small gaps and not, and the rectangular cross-section of these gaps forms the throttle holes area. The configuration diagram of throttle slice with gaps is shown in Figure 3.

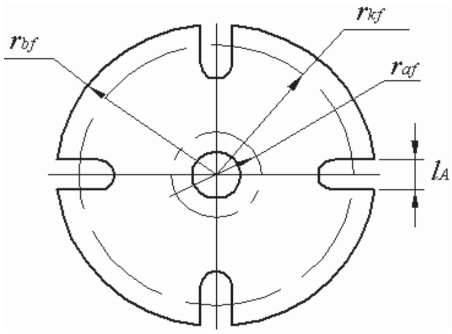

Fig. 3 Configuration diagram of throttle slice

In Figure 3, l_A is the width of throttle holes; l is the length, and $l = (r_b - r_k)$.

The total area of throttle holes is settled by the thickness, width of slice and number of holes. For single throttle holes, its area is $A_{0i} = \delta l_A$, circumference is $l_C = 2(\delta + l_A)$ and hydraulic diameter is $d_{HA0} = 4A_{0i} / l_C$. Which type of orifice belongs to thin-walled orifice or slim orifice can be judged by the ratio of throttle hole's length and hydraulic diameter l / D_{HA0}. So, the relation between throttle pressure and flux can be expressed as follows. [Zhang, 2005]

$$Q_{A_0} = \varepsilon A_0 \sqrt{2 p_0 / \rho} \tag{1}$$

Where, ε is the flow coefficient of throttle orifice that is decided by the type of orifice, p_0 is the pressure of throttle holes, A_0 is the total area, $A_0 = h_1 l_A n_A$, h_1 is the thickness of slice that with holes.

3.2 Piston orifice

Piston orifices are distributed on the piston uniformity. The diameter d_h and number n_h are both serialization, and d_h is in series, such as 1.5 mm, 1.75 mm, 2.0 mm, n_h is in series too, such as 2, 4, 6, 8. For single piston orifice with diameter d_h and length L_h, its type can be selected by the ratio L_h / d_h. Due to $L_h / d_h > 4$, according to the definition of orifice sort, piston orifice can be regarded as slim orifice. So the throttle pressure of piston orifice as follows

$$p_h = \frac{128 Q_0 \mu_t L_{he}}{n_h \pi d_h^4} \tag{2}$$

Where, p_h is the pressure of piston orifice; L_{he} is the equivalent length, the value is equal to sum of the physical length and the local loss calibrated length, that is $L_{he} = L_h + L_e$; μ_t is the dynamic viscosity of fluid.

3.2.1 Pathway throttle loss

Let piston orifice is smooth orifice, the critical Reynolds value R_{ec} is 2300. So, the critical velocity v_c of fluid flow through the piston orifice is as follows. [Zhang and Yang, 2004]

$$v_c = \nu \, R_{ec} / d_h \tag{3}$$

Where, v is the oil kinematics viscosity.
So, the critical velocity of shock absorber is

$$V_c = \frac{v_c A_h}{S_h} = \frac{A_h \nu \, R_{ec}}{S_h d_h} \tag{4}$$

Where, S_h is the annular area between piston cylinder and piston rod.
When velocity of shock absorber $V < V_c$, the flow regime of fluid in piston orifice is laminar flow, and the pathway throttle loss coefficient is

$$\lambda_h = \frac{64\nu}{vd} = \frac{64 n_h \pi d_h \nu}{V S_h} \tag{5}$$

Where, v is the velocity of oil.
When velocity of shock absorber $V > V_c$, the flow regime is turbulent flow, and the pathway throttle loss coefficient is

$$\lambda_h = 0.3164 \, [4 S_h V / (n_h \pi d_h \nu)]^{-0.25} \tag{6}$$

By analysis above, pathway throttle loss coefficient of piston orifice is relative to velocity. Hence, the parameters design and characteristic analysis of shock absorber should adopt corresponding pathway throttle loss coefficient by the flow regime of fluid in piston orifice. As devise the area of throttle orifice, the moving velocity of shock absorber $V < V_c$, so the fluid analysis should be acted by laminar flow.

3.2.2 Local throttle loss

When fluid flows through the piston orifice and valve cavity, there are three local throttle losses, and they are suddenly shrinkage, expansion and direction change, and corresponding coefficients are ζ_{h1}, ζ_{h2} and ζ_{h3} respectively. Total local throttle loss can be computed by superposition principle, and converted into pathway throttle loss coefficient. Therefore, the conversion formula of equivalent length of piston orifice is

$$L_e = (\zeta_{h1} + \zeta_{h2} + \zeta_{h3}) \, \lambda_h / d_h \tag{7}$$

4. DESIGN OF THROTTLE HOLES AREA

The demanded velocity characteristic of shock absorber can be described by two manners, namely characteristic number and curve. For example, the demanded piecewise linear curve of velocity characteristic of shock absorber for an automobile is shown in Figure 4.

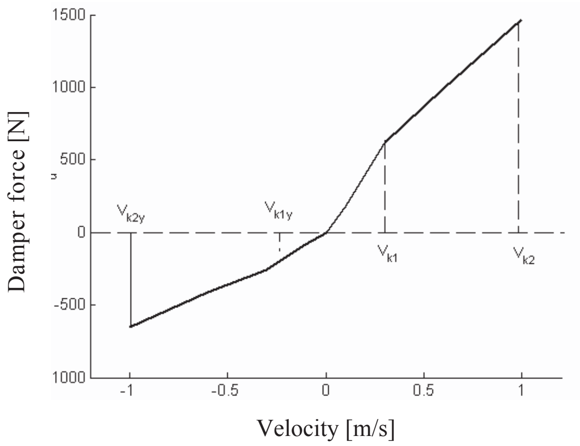

Fig. 4 Demanded velocity characteristic

Where, V_{k1} and V_{k2} are first and second valve-opening velocity separately.
At rebound stroke, the velocity of shock absorber $V < V_{k1}$, and oil paths is shown in Figure 5.

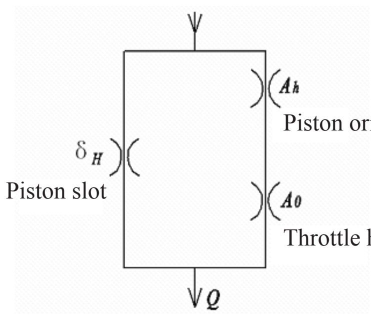

Fig. 5 Oil paths before rebound valve opening

Before valve opening, the damping force at any velocity point V can be obtained by first valve opening velocity V_{k1} and corresponding damping force F_{dk1}.

$$F_d = F_{dk1f} V / V_{k1f} \tag{8}$$

Before valve opening firstly, the velocity of shock absorber is V and $V < V_{k1}$, and corresponding damping force is F_d. So, the pressure of the piston slot is

$$p_H = F_d / S_H \tag{9}$$

And the relation between flux of piston slot Q_H and throttle pressure p_H is

$$Q_H = \frac{\pi D_h \delta_H^3 (1+1.5e^2) p_H}{12\mu_t L_H} \tag{10}$$

Where, δ_H is the slot size between piston and cylinder; e is eccentricity of piston; D_h is the diameter of piston; L_H is the length of piston slot.
Thus the flux of piston orifice as follows

$$Q_0 = Q - Q_H \tag{11}$$

Where, Q is the total flux from rebound chamber to compression chamber, and $Q = VS_H$.
The piston orifice and throttle holes are in series, that is $Q_0 = Q_h$. By (2), in view of local throttle loss, the throttle pressure of piston orifice is as

$$p_h = \frac{128 Q_0 \mu_t L_{he}}{n_h \pi d_h^4} \tag{12}$$

By (1), the throttle pressure of throttle orifice can be expressed as follows.

$$p_0 = Q_0^2 \rho / (2A_0^2 \varepsilon^2) \tag{13}$$

Before rebound valve opens, the pressure of throttle holes satisfy $p_0 = p_H - p_h$, that is

$$\frac{Q_0^2 \rho}{2A_0^2 \varepsilon^2} = \frac{F_d}{S_h} - p_h \tag{14}$$

So, the design area of throttle holes is

$$A_0 = Q_0 \sqrt{\frac{\rho}{2\varepsilon^2 [F_d / S_h - p_h]}} \tag{15}$$

Combining (10), (11) and (12) with (15), the area design formula of throttle holes at given velocity point can be obtained. It is known that make use of different design velocity point V and corresponding damping force F_d, the design results of throttle holes are different.

5. OPTIMAL DESIGN OF THROTTLE HOLES AREA

The design area of throttle holes varies with the design velocity point. This area has effect on the valve opening velocity of shock absorber and velocity characteristic before valve opening, furthermore influence the design thickness of throttle slice, namely the velocity characteristic after valve opens.
The valve opening velocity of shock absorber is relative to the area value of throttle holes and the slice thickness as well as pre-deformation. Base on the single velocity design, the optimal design method of throttle holes area was studied.

5.1 Optimal design target function

The design area of throttle holes A_0 varies with the design velocity, so the corresponding velocity characteristic before valve opening is different, which is shown in Figure 6.

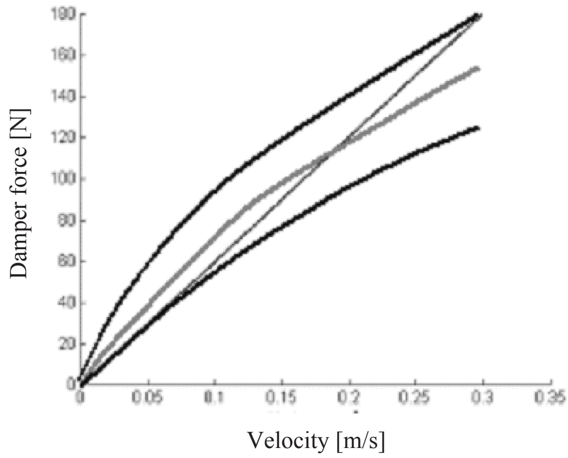

Fig. 6 Velocity characteristic at different design area before valve opening

The purpose of optimal design target function is to search the optimum design velocity within first valve opening velocity and devise the area of throttle holes meanwhile ensure the minimum difference between designed velocity characteristic and demanded.
Defining the enclosed area by velocity characteristic curve at design area A_0 and velocity range [0, V_{k1}] as the power of shock absorber P_D before valve opening, and the demanded power of shock absorber P_d is enclosed area by demanded velocity characteristic curve of shock absorber and velocity internal [0, V_{k1}]. As the minimum difference between P_D and P_d comes out, the designed velocity characteristic curve approaches to the demanded velocity characteristic curve. So, the optimal design target function of throttle holes area is as

$$F_{D\text{-}d}(V)|_A = P_D(V) - P_d = \int_0^{V_{k1}} F_{DV}(v)dv - \int_0^{V_{k1}} F_d(v)dv \tag{16}$$

Where, $F_{DV}(v)$ is the damping force characteristic function of shock absorber before valve opening, which corresponds with design area of throttle holes at design velocity point.
In conditions of structure of shock absorber was given, $F_{DV}(v)$ can be obtained by simulation; $F_d(v)$ is the demanded damping force characteristic function before valve opening. The physical meaning of target function $F_{D-d}(V)|_A$ is the difference between designed

shock absorber power P_D and demanded power for shock absorber P_d. It is known that the optimal design velocity of target function is existent. The optimal design target function reaches minimum at the optimal design velocity point.

5.2 Optimal design value of throttle area

As target function approaches to minimum, the corresponding design area of throttle holes is optimum.

The curve of target function vs. design area of throttle holes A_0 is shown in Figure 7.

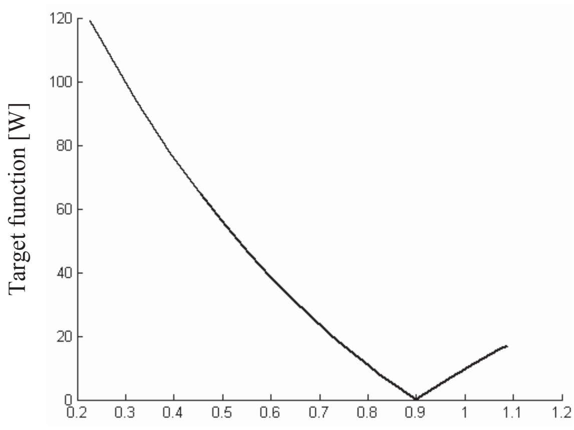

Fig. 7 Curve of target function vs. design area

So, as long as the characteristic parameters and the shock absorber structure parameters are given, the optimal designed area of throttle holes A_0 can be obtained by the process of curve fitting optimal design method.

6. DESIGN INSTANCES

6.1 Demanded characteristic of shock absorber

Take the shock absorber of an automobile for example, the demanded first valve opening velocity is V_{k1}, for rebound valve V_{k1} = 0.3 m/s, and for compression valve V_{k1} = 0.1 m/s. The demanded velocity characteristic values and deviation are shown in Table 1.

Table 1 Demanded characteristic value

Velocity [m/s]	0.1	0.3	0.6	1.0
Rebound [N]	180±64	620±92	990±110	1465±150
Compression [N]	150±54	260±60	410±80	650±120

6.2 Optimal design values

Based on the demanded velocity characteristic of shock absorber and make use of curve fitting optimal design method to devise the area of throttle holes. The optimum design values of valves are shown in Table 2. The width and number design of throttle holes should be based on the design area value as well as thickness of throttle slice with 0.1 mm.

Table 2 Design values of valves parameters

Parameters	A_0[mm^2]	h[mm]	f_{rk0}[mm]	h_g[mm]
Rebound	0.90	0.2605	0.0454	0.0775
Compression	1.60	0.1593	0.1061	0.2333

So, for throttle holes of rebound valve, the design results are l_A = 1.5 mm, n_A = 6; For compression valve, the design results are l_A = 2 mm and n_A = 8.

6.3 Comparisons with single velocity point

The design values of throttle holes at different design velocities are shown in Table 3.

Table 3 Design value of throttle holes area at single velocity point

Velocity [m/s]	0.10	0.15	0.20	0.25	0.30
Area [mm^2]	0.71	0.82	0.92	1.00	1.08

In Table 3, the design areas of throttle holes at different design velocity points are various, and the deviations are larger than curve fitting optimal design method.

At present, the conventional design method for throttle holes area is just that make use of the first valve opening velocity V_{k1} and corresponding damping force F_{dk1} to design. So, it is difficult to obtain the reliable and precise design values of throttle holes with the conventional design method.

6.4 Comparison with the manufactory blueprint

The parameters of rebound valve and compression valve on blueprint of shock absorber are shown in Table 4.

Table 4 Design parameters on blueprint

Parameters	A_0[mm^2]	h[mm]	f_{rk0}[mm]	h_g[mm]
Rebound	0.8	0.2559	0.04	0.1
Compression	1.2	0.1636	0.06	0.2

Where, for throttle holes of rebound valve, the l_A = 0.2 mm, n_A = 4; For throttle holes of compression valve, the l_A = 0.2 mm, n_A = 6. So the design values by curve fitting optimal design method are closer to the parameters on blueprint, and the design errors are 0.1 mm^2 and 0.04 mm^2 separately.

7. PERFORMANCE TEST

7.1 Performance test

With the multi-function hydraulic vibrating test equip-

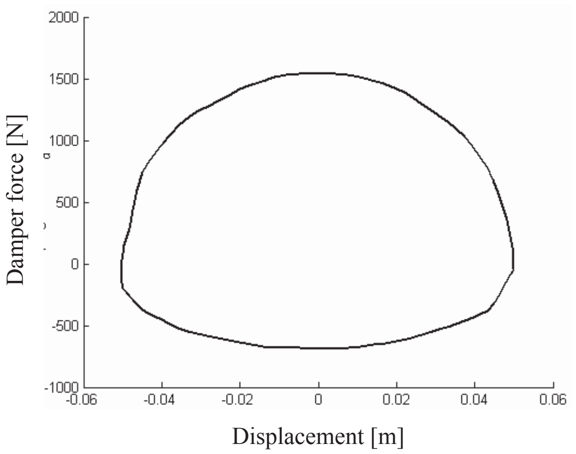

Fig. 8 Indicator diagram by test

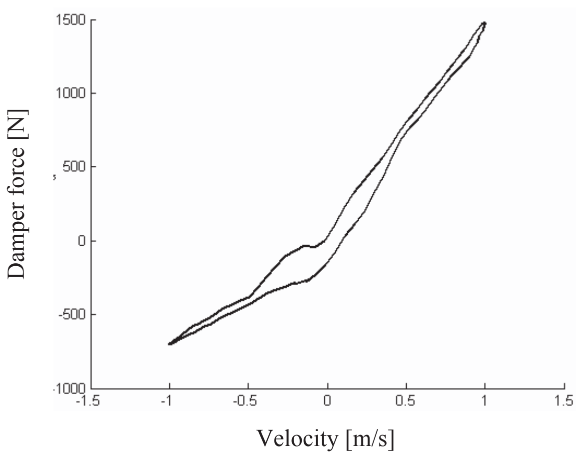

Fig. 9 Speed characteristic curves by test

ment, the characteristic of designed shock absorber was tested. The velocity characteristic and indicator diagram are shown in Figure 8 and Figure 9 separately.

7.2 Performance verifying

The deviations of the speed characteristic of shock absorber between test and demanded are shown in Table 5.

Table 5 Demanded characteristic value

Velocity [m/s]	0.1	0.3	0.6	1.0
Rebound [N]	175	608	984	1488
Compression [N]	155	289	437	670

The characteristic values of shock absorber by test close to the demanded values highly. Hereinto, the maximal relative error of rebound stroke is –2.77 %, the compression stroke is 11.15 %, and far less than the demanded maximal relative error. It is shown that the curve fitting optimal design method is correct and the design parameters with it are precise and reliable.

8. CONCLUSIONS

By the study of curve fitting optimal design method for throttle holes area, the comparison between design parameters and the demanded as well as the analysis of characteristic test, the results show that

(1) For the throttle holes area design, it needs to consider the influence of laminar and turbulent flow as well as various local throttle losses, then establish the exact math modelling based on single velocity point design.
(2) The relations between design parameters of throttle holes and velocity are non-linear. The design results vary with the design velocity.
(3) There is an optimum design velocity point in the target function of curve fitting optimal design, and corresponding design parameters of throttle holes at this velocity point are optimum.
(4) The design values of throttle holes area by curve fitting optimal design method correspond excellently with the blueprint of manufactory, and performance test results close to the demanded greatly. It is shown that the design method is right, and the design parameters are reliable.
(5) After the design parameters of throttle holes are finished, the thickness of throttle slice could also be designed by curve fitting optimal design method. So this optimal method has important reference and application values in parameters design of shock absorber.

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