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

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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 manufacture. 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, 2007]. 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](image-url)
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 Figure 1.

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, \( d_i \) is diameter of piston orifice, \( n_i \) is the number; \( p \) is pressure on throttle slice; \( f_{r0} \) is pre-deformation of throttle slice which is decided by the fixing size to ensure right valve-opening velocity; \( r_o \) is outer radius of slice, \( r_i \) is valve mouth radius, \( r_s \) is inner radius of slice (taking the fixing size into account); \( \delta_k \) is the opening size of rebound slice, and it is equal to difference between total deformation \( f_{sk} \) and pre-deformation \( f_{r0} \) 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.

\[
Q_k = \varepsilon A_k \sqrt{2p_i \rho} \quad (1)
\]

Where, \( \varepsilon \) is the flow coefficient of throttle orifice that is decided by the type of orifice, \( p_i \) is the pressure of throttle holes, \( A_k \) is the total area, \( A_0 = h_1 l / n_i \), \( h_1 \) is the thickness of slice that with holes.

3.2 Piston orifice

Piston orifices are distributed on the piston uniformity. The diameter \( d_i \) and number \( n_i \) are both serialization, and \( d_i \) is in series, such as 1.5 mm, 1.75 mm, 2.0 mm, \( n_i \) is in series too, such as 2, 4, 6, 8. For single piston orifice with diameter \( d_i \) and length \( L_s \), its type can be selected by the ratio \( L_s / d_i \). Due to \( L_s / d_i > 4 \), according to the definition of orifice sort, piston orifice can be regarded as slim orifice. So the throttle pressure of piston orifice as follows
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 \( L_{he} = L_h + L_e \); \( \mu \) 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]

\[
v_c = \frac{v R_{ec}}{d_h}
\]  

Where, \( v \) is the oil kinematics viscosity.

So, the critical velocity of shock absorber is

\[
V_c = \frac{v A_h R_{he}}{S_h d_h} \frac{A_h}{S_h d_h}
\]

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

\[
\lambda_h = \frac{64v}{vd} = \frac{64\pi d V}{V S_h}
\]

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

\[
\lambda_h = 0.3164 \left[ \frac{4S_h V}{(n_h \pi d_h v)} \right]^{0.25}
\]

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 \( \zeta_{s1} \), \( \zeta_{e1} \) and \( \zeta_{e3} \), 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

\[
L_e = \left( \zeta_{s1} + \zeta_{e1} + \zeta_{e3} \right) \frac{\lambda_h}{d_h}
\]

### 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](image)

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](image)

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 \( F_{dk1} \).

\[
F_d = F_{dk1} \frac{V}{V_{k1}}
\]

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
\[ p_H = F_d / S_H \]  

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

\[ Q_H = \frac{\pi D_h \delta_h (1 + 1.5e^2) p_H}{12 \mu L_H} \]  

Where, \( \delta_h \) 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

\[ Q_h = Q_H - Q_R \]  

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

\[ p_h = Q_h \rho / (2A_h e^2) \]  

Before rebound valve opens, the pressure of throttle holes satisfy

\[ p_h = p_H - p_* \]

So, the design area of throttle holes is

\[ A_h = \frac{128Q_h \mu L_h}{n \pi d_h^4} \]  

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](image)

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

\[ F_D - d(V) \bigg|_{A_0} = P_d(V) - P_d \]

\[ = \int_{0}^{V_{k1}} F_{DF}(v) dv - \int_{0}^{V_{k1}} F_d(v) dv \]

Where, \( F_{DF}(v) \) 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, \( F_{DF}(v) \) can be obtained by simulation; \( F_d(v) \) is the demanded damping force characteristic function before valve opening. The physical meaning of target function \( F_{D-D}(V) \) 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](image)

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>
<thead>
<tr>
<th>Parameters</th>
<th>$A_0$ [mm²]</th>
<th>$h$ [mm]</th>
<th>$f_{s0}$ [mm]</th>
<th>$h_g$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebound</td>
<td>0.90</td>
<td>0.2605</td>
<td>0.0454</td>
<td>0.0775</td>
</tr>
<tr>
<td>Compression</td>
<td>1.60</td>
<td>0.1593</td>
<td>0.1061</td>
<td>0.2333</td>
</tr>
</tbody>
</table>

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.

6.3 Comparisons with single velocity point
The design values of throttle holes at different design velocities are shown in Table 3.

<table>
<thead>
<tr>
<th>Velocity [m/s]</th>
<th>0.10</th>
<th>0.15</th>
<th>0.20</th>
<th>0.25</th>
<th>0.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area [mm²]</td>
<td>0.71</td>
<td>0.82</td>
<td>0.92</td>
<td>1.00</td>
<td>1.08</td>
</tr>
</tbody>
</table>

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 $F_{d_{k1}}$ 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>
<thead>
<tr>
<th>Parameters</th>
<th>$A_0$ [mm²]</th>
<th>$h$ [mm]</th>
<th>$f_{s0}$ [mm]</th>
<th>$h_g$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebound</td>
<td>0.8</td>
<td>0.2559</td>
<td>0.04</td>
<td>0.1</td>
</tr>
<tr>
<td>Compression</td>
<td>1.2</td>
<td>0.1636</td>
<td>0.06</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Where, for throttle holes of rebound valve, the $l_d = 0.2$ mm, $n_d = 4$; For throttle holes of compression valve, the $l_d = 0.2$ mm, $n_d = 6$. So the design values by curve fitting optimal design method are closer to the parameters on blueprint, and the design errors are 0.1 mm² and 0.04 mm² separately.

7. PERFORMANCE TEST
7.1 Performance test
With the multi-function hydraulic vibrating test equip-
7.2 Performance verifying
The deviations of the speed characteristic of shock absorber between test and demanded are shown in Table 5.

<table>
<thead>
<tr>
<th>Velocity [m/s]</th>
<th>0.1</th>
<th>0.3</th>
<th>0.6</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebound [N]</td>
<td>175</td>
<td>608</td>
<td>984</td>
<td>1488</td>
</tr>
<tr>
<td>Compression [N]</td>
<td>155</td>
<td>289</td>
<td>437</td>
<td>670</td>
</tr>
</tbody>
</table>

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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