Effect of air chamber and oil properties on damping characteristics of single-tube pneumatic shock absorber

Hongtuo Liu and Fangwei Xie
School of Mechanical Engineering, Jiangsu University, Zhenjiang, China

Kai Zhang
Bosch Automotive Products (Suzhou) Co., Ltd, Suzhou, China, and
Xinxing Zhang, Jin Zhang, Cuntang Wang and Hao Li
School of Mechanical Engineering, Jiangsu University, Zhenjiang, China

Abstract

Purpose – The shock absorber is an important component of vehicle suspension that attenuates the vehicle vibration. Its running state directly affects the performance of the vehicle suspension. The purpose of this paper is to quantitatively study the relationship between damping characteristics and air chamber and oil properties in single-tube pneumatic shock absorber.

Design/methodology/approach – Combined with the principle of fluid dynamics and hydraulic transmission technology, the rebound stroke and compression stroke mathematical models, and damping characteristics simulation model are established to investigate the effect of the air chamber and oil property on damping characteristics.

Findings – Research results show that the initial pressure of the air chamber is the key parameter which influences the damping characteristics of the shock absorber. The change of the initial pressure has more impact on damping force, and less impact on the speed characteristic; the initial volume of the air chamber almost has no effect on the damping characteristics. The density and viscosity of the oil have certain influence on the damping characteristics. Therefore, selecting suitable damping oil is very important.

Originality/value – Using Matlab/Simulink software to build simulation models, its results are very accurate. The conclusions can provide a theoretical reference for the structure design of a single-tube pneumatic shock absorber.

Keywords Damping characteristics, Damping force, Fluid dynamics, Single-tube pneumatic shock absorber

Paper type Research paper

1. Introduction

Shock absorber plays an important role in the vehicle suspension system. As the main damping element of the vehicle chassis, shock absorber not only affects the comfort of the vehicle, but also has a great impact on the safety and controllability of the vehicle (Zhang et al., 2003). Single-tube pneumatic shock absorber (Basso, 2010) is a new type of vibration damper developed since the 1960s and 1970s. Compared with the traditional shock absorber, single-tube pneumatic shock absorber is filled with compressed gas (Ju et al., 2014), which can significantly improve the critical velocity of shock absorber and effectively eliminate the outer characteristic distortion (Xu, Li, Zhang and Yang, 2011; Shan et al., 2014), improve damper performance and the quality of vehicle suspension system (Oluwole, 2012; Hamersma and Schalk, 2014).

The authors would like to acknowledge the support of the National Natural Science Foundation of China (51675234, 51205170), the Natural Science Foundation of Jiangsu Province (BK2012292), the Special Program of the China Postdoctoral Science Foundation (2013T60502) and the Science and Technology Support Program of Zhenjiang (SYF320150130267).
Using simulation software to analyze the effect of each parameter on the damping characteristics of single-tube pneumatic shock absorber is one of the topics at the forefront in the field of automobile shock absorber (Liu et al., 2013; Xu, Li, Zhang, Zhang and Li, 2011). The internal oil hole, opening speed and opening size of throttle valve (Zhou and Guo, 2008; Chen and Gu, 2008; Zhou et al., 2009), the piston velocity, oil density and the viscosity, the initial pressure and initial volume and other parameters of the air chamber are the key factors influencing the performance of shock absorber. Domestic and foreign researchers have conducted many research works on the analysis of experiments (Wang et al., 2014; Li et al., 2012), the establishment of mathematical models and simulation (Fan and Anderson, 1990; Darin et al., 2001; Yao et al., 2011), parametric design of the shock absorber (Bao, 2015; Sonnenburg, 2014), especially, the influence of structure parameters on the indicator diagram and velocity characteristics (Xiao et al., 2014; Yang et al., 2014). However, there are fewer studies on the influence of parameters such as oil properties, air chamber pressure and volume on the damping characteristics, which resulted in the design of single-tube pneumatic shock absorber with a certain degree of blindness. This paper will carry out corresponding research in order to reveal the influence of parameters such as oil properties, air chamber pressure and volume on damping characteristics, and provide theoretical basis for the design and manufacturing of shock absorber.

2. Structure of single-tube pneumatic shock absorber

Figure 1 is the schematic diagram of single-tube pneumatic shock absorber, which includes the following six components: the cylinder base installed in the cylinder, floating piston, piston valve system (the integration of rebound valve and compression valve), limit spring, piston rod and guide seat. The internal cavity of the shock absorber is separated into two parts by the floating piston, the closed space formed by the cylinder base and the floating piston is named air chamber, and formed by guide seat and floating piston is called liquid chamber. The air chamber is full of high-pressure nitrogen, which will make the oil that is isolated by the floating piston generate backpressure. Then the oil can timely absorb and supply the volume change from the movement of the piston rod, and avoid the distortion phenomenon and improve the working stability.

In order to describe shock absorber working condition conveniently, generally speaking, the chamber between the piston valve system and the guide seat is rebound chamber and the chamber between the piston valve system and the floating piston is compression chamber. The main damping components during rebound stroke of shock absorber consist of rebound hole, rebound valve and constant orifices, and during compression stroke include compression hole, compression valve and constant orifices. The components which generate damping force during the stroke of rebound and compression are different, but their generation principle is fundamentally the same.

3. Establishment of mathematical model of single-tube pneumatic shock absorber

The single-tube pneumatic shock absorber is a complex nonlinear system, and its damping property is affected by many factors, such as working environment temperature (Liang and Zhao, 2015), fluid flow characteristics, friction force of the piston rod, the damping caused by

![Figure 1. Schematic diagram of single cylinder pneumatic shock absorber](image_url)

Notes: 1 – cylinder base; 2 – floating piston; 3 – piston valve; 4 – limit spring; 5 – piston rod; 6 – guide seat
fit clearance and movement stroke. Considering all factors, damping solution formula will be too complex and solving process is tedious, and it is difficult to gain the final results. In order to facilitate the research on damping characteristics, we need to ignore some factors during the process of modeling analysis, and its assumptions are as follows:

1. in a working procedure, the temperature of the fluid inside the shock absorber is constant;
2. the internal fluid is incompressible, and there is no bubble produced during the working process;
3. pressure is equal in the same area at any time during the course of movement;
4. ignoring the oil mass and its change; and
5. ignoring the fluid loss of the system.

3.1 Rebound stroke modeling
According to the analysis of the structure of shock absorber, the physical model of internal pressure field can be obtained. Assuming that the internal oil pressure of the rebound chamber is $P_1$ the internal pressure of the compression chamber and air chamber is $P_2$ and $P_3$ respectively. By simplifying the complex physical model of the shock absorber, the shock absorber is equivalent to the hydraulic system which is composed of series and parallel of different valves in different chambers, so the solution of the damping characteristic of the shock absorber is converted to the force analysis (Lee and Moon, 2005) of the hydraulic system.

Based on the analysis of the internal pressure field model, it is known that the magnitude of the damping force is related to the structure size of the valve system. The movement process of the shock absorber is shown in Figure 2, when the rebound chamber pressure is not big enough to open the rebound valve slices, the whole oil will go through the constant orifices and then enter into the compression chamber. When the rebound chamber pressure reaches the critical value of the damping superposition valve slices, the oil passes the constant orifices and holes in rebound valve flowing into the compression chamber. Therefore, the rebound stroke modeling analysis can be divided into two kinds of working conditions of before and after opening the valve.

Before opening the rebound valve of the shock absorber, the flowing state of internal fluid is as shown in Figure 3(a). Under this condition, assume that the movement velocity of piston is $v_{k1}$ and the magnitude of rebound damping force is $F_{k1}$. After opening the rebound valve, the flowing state of internal fluid is as shown in Figure 3(b). Under this condition, assume that the piston movement speed is $v_{k2}$ and the magnitude of rebound damping force is $F_{k2}$. The range of speed is $0 \leq v_{k1} < v_{f1} \leq v_{k2} < v_{f2}$, in which $v_{f1}$ is the critical value.
of opening velocity of rebound valve, and $\nu_{y2}$ is the critical value of piston movement velocity when the opening of rebound valve plates reaches the maximum value.

By calculation, before opening the valve, the formula of damping force during the rebound stroke is:

$$F_{k1} = \frac{\pi}{4} (d_a^2 - d_b^2) \left\{ a_1 \left[ a_1 - \sqrt{\frac{(a_1^2 + 4a_2a_3)}{2a_2^2}} \right] + \frac{a_3}{a_2} + \frac{P_0V_0}{V_0 + \frac{\pi d_b^2}{4} \nu_{k1}} \right\}$$

$$- \frac{\pi}{4} d_a^2 \left( \frac{P_0V_0}{V_0 + \frac{\pi d_b^2}{4} \nu_{k1}} \right) + f$$

(1)

And, after opening the valve, the formula of damping force during the rebound stroke is:

$$F_{k2} = \frac{\pi}{4} (d_a^2 - d_b^2) \left\{ \frac{2b_3}{b_1-b_3} \left[ b_3 - \sqrt{b_1b_3^2 + b_2^2(b_3^2-b_1)} \right] + \frac{c^2-b_3^2}{b_1-b_3} \right\}$$

$$- \frac{\pi}{4} d_a^2 \left( \frac{P_0V_0}{V_0 + \frac{\pi d_b^2}{4} \nu_{k2}} \right) + f$$

(2)

### 3.2 Compression stroke modeling

By analyzing the damping force of the compression stroke, the solution method can also be divided into two situations of before and after opening the valve, which is similar to the rebound stroke. The detailed analysis is as follows.

Before opening compression valve of the shock absorber, the flowing state of internal fluid is as shown in Figure 4(a). Under this condition, assume that the piston movement velocity is $\nu_{k2}$ and the magnitude of compression damping force is $F_{k2}$. After opening the compression valve, the flowing state of internal fluid is as shown in Figure 4(b). Under this condition, assume that the piston movement speed is $\nu_{y2}$ and the magnitude of compression damping force is $F_{k2}$. The range of speed is $0 \leq \nu_{k2} < \nu_{y1} \leq \nu_{k4} < \nu_{y2}$, in which $\nu_{y1}$ is the critical value of opening velocity of the compression valve, and the $\nu_{y2}$ is the critical value of piston movement velocity when the opening of compression valve slices reaches the maximum value.
By calculation, before opening the valve, the formula of damping force during the compression stroke is:

\[
F_{k3} = \frac{\pi d^2_a}{4} \left( \frac{P_0 V_0}{V_0 - \frac{\pi d^2_b}{4} v_{k3} t} \right)
- \frac{\pi}{4} \left( d^2_a - d^2_b \right) \left\{ \frac{P_0 V_0}{V_0 - \frac{\pi d^2_b}{4} v_{k3} t} - \frac{c_1}{2c_2} \sqrt{c_1^2 + 4c_2c_3} \right\} + f
\]

After opening the valve, the formula of damping force during the compression stroke is:

\[
F_{k4} = \frac{\pi d^2_a}{4} \left( \frac{P_0 V_0}{V_0 - \frac{\pi d^2_b}{4} v_{k4} t} \right)
- \frac{\pi}{4} \left( d^2_a - d^2_b \right) \left\{ \frac{P_0 V_0}{V_0 - \frac{\pi d^2_b}{4} v_{k4} t} - \frac{2d_3e}{\left( d_1 - d_3 \right)^2} \sqrt{d_1e^2 + d_2^2 \left( d_3^2 - d_1 \right)} + \frac{e^2 - d_3^2}{d_1 - d_3^2} \right\} + f
\]

4. Simulation model establishment of the single-tube pneumatic shock absorber

Using Matlab/Simulink software to build simulation models (Avesh and Srivastava, 2012), the first step is to select the signal type according to the relevant parameters, and select the appropriate time interval. By changing the parameters of the signals to change the shock absorber working conditions, the simulation results of damping characteristics are obtained under different conditions. Specific simulation flowing chart is shown in Figure 5. First, values of the structural parameters should be defined, and set movement parameters of the excitation. Because the working conditions of shock absorber can be divided into rebound stroke and compression stroke, the piston velocity \( V \) can be regarded as the judging condition to determine whether the shock absorber is in rebound stroke or compression stroke. After the judgment is finished, it is necessary to solve the damping force according to the corresponding stroke model, and get the damping force and other related data, so as to draw the indicator diagram and speed characteristic diagram.

The simulation model consists of three basic modules: excitation signal generating module, analysis and calculation module for the internal flow and pressure and the
calculation module of rebound damping force or compression damping force. In order to conveniently study the effects of different parameters on damping characteristics, the parameters of each module are designed as variables. The excitation signal comes from the motion displacement of the piston, which is usually set as sine or cosine signal with certain amplitude and frequency to simulate the testing conditions of shock absorber. Piston movement changes the internal flow field in the cylinder. According to the law of flow conservation, the total flow caused by the movement of piston is equal to the sum of flow volume through each valve holes, which is the main idea of building a model. The flow relationship can be derived through the piston movement speed, then the internal pressure can be derived through the internal flow relationship and finally the damping force of the corresponding rebound stroke and compression stroke can be solved. The initial structural parameters of shock absorber are shown in Table I, setting the value of related parameters in Matlab m-file according to the Table I, thereby the damping force of the shock absorber can be worked out. Based on the calculated data, the curves of damping characteristics can be obtained in Matlab.

5. Influence of air chamber on damping characteristics of the shock absorber
5.1 Effect of air chamber’s initial pressure
Keeping other parameters unchanged in the Matlab simulation program, the parameters of gas initial pressure are respectively set as 1, 1.5, 2, 2.5 and 3 MPa. In the Simulink model, the

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Value</th>
<th>Parameter name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air chamber volume</td>
<td>0.05 L</td>
<td>Piston rod diameter</td>
<td>14 mm</td>
</tr>
<tr>
<td>Air chamber pressure</td>
<td>1 MPa</td>
<td>Rebound valve flow coefficient</td>
<td>0.62</td>
</tr>
<tr>
<td>Oil density</td>
<td>850 kg/m³</td>
<td>Compression valve flow coefficient</td>
<td>0.67</td>
</tr>
<tr>
<td>Oil viscosity</td>
<td>20 cp</td>
<td>Rebound valve outer radius</td>
<td>16 mm</td>
</tr>
<tr>
<td>Rebound hole (number × diameter)</td>
<td>3×8 mm</td>
<td>Compression valve outer radius</td>
<td>16 mm</td>
</tr>
</tbody>
</table>

Table I: Initial structural parameters of shock absorber
same sinusoidal displacement excitation signal is given to simulate, finally to get the comparison diagram of damping characteristic.

According to the simulation results of Figure 6, it is shown that the initial inflation pressure has a certain effect on damping characteristics from the comparison diagram of the indicator characteristic and speed characteristic. When the inflation pressure increases, the rebound damping force reduces, and the compression damping force increases. When the inflation pressure rises up to 3 MPa, the rebound damping force is much less than the compression damping force, which is not consistent with the actual situation. Generally, the damping force during the rebound stroke should be larger than that during the compression stroke, because the spring also has bearing capacity during the compression stroke. Therefore, it is the best that the gas pressure of the pneumatic shock absorber is 2-2.5 MPa.

5.2 Effect of air chamber’s initial volume
Keeping other parameters unchanged in the Matlab simulation program, the parameters of gas initial volume are respectively set as 0.05, 0.15 and 0.25 L. In the Simulink model, the same sinusoidal displacement excitation signal is given to simulate to get the comparison diagram of damping characteristic.

According to the simulation results, as shown in Figure 7(a), the magnitude of the damping force decreases as the air chamber’s volume increases. But overall, it has little

![Figure 6. Effect of initial pressure of nitrogen chamber on damping characteristics](image)

Notes: (a) Indicator diagram; (b) speed characteristic diagram

![Figure 7. Effect of initial volume of nitrogen chamber on damping characteristics](image)

Notes: (a) Indicator diagram; (b) speed characteristic diagram
effect on the damping force with less fluctuation. As shown in Figure 7(b), the volume’s change has little effect on the speed characteristics, and it has almost no effect on the opening speed of the valve.

6. Influence of oil properties on damping characteristics of the shock absorber

Damping of the shock absorber is produced when oil goes through different holes. Therefore, oil property is one important factor that affects the damping features, which mainly depend on two factors of density and viscosity.

6.1 Effect of oil density

Keeping other parameters unchanged in the Matlab simulation program, the parameters of oil density are respectively set as $\rho = 400$, $\rho = 800$ and $\rho = 1,200$ kg/m$^3$. In the Simulink model, the same sinusoidal displacement excitation signal is given to simulate to get the comparison diagram of damping characteristic.

According to the simulation results as shown in Figure 8, the change of the oil density affects the damping characteristics of the shock absorber. As shown in Figure 8(a), with the increase of the oil density, the rebound and compression damping force also increase. As shown in Figure 8(b), the difference of oil density also affects its velocity characteristics.

6.2 Effect of oil viscosity

Keeping other parameters unchanged in the Matlab simulation program, the parameters of oil density are respectively set as $\mu = 10$, $\mu = 20$ and $\mu = 30$ cp. In the Simulink model, the same sinusoidal displacement excitation signal is given to simulate to get the comparison diagram of damping characteristic.

According to the simulation results as shown in Figure 9, the change of oil viscosity affects the damping characteristics of shock absorber. As shown in Figure 9(a), with the increase of oil viscosity, the rebound and compression damping force increase obviously. As shown in Figure 9(b), it can be known that different oil viscosities also affect its speed characteristics. With the increase of oil viscosity, the opening speed of valves of piston will be reduced. Due to the relevance of oil temperature and viscosity, the influence rules of oil temperature on the damping characteristics are similar to the oil viscosity. As the temperature increases, the oil viscosity decreases, therefore the damping force decreases.

![Figure 8. Effect of oil liquid density on damping characteristics](image)

**Notes:** (a) Indicator diagram; (b) speed characteristic diagram
7. Conclusion
Combined with the principle of fluid dynamics and hydraulic transmission technology, the rebound stroke and compression stroke mathematical model, and damping characteristics simulation model are established to study the effects of air chamber and oil properties on damping characteristics of a single-tube pneumatic shock absorber. Summaries are as follows:

(1) The initial pressure of the gas chamber is the key parameter to affect the damping characteristics of the shock absorber, and it also has a larger effect on damping force, but less impact on the speed characteristics. Too small pressure will cause idle stroke, and too large pressure will lead to the fact that damping force of compression stroke is larger than that of rebound stroke, which is not consistent with the actual situation. Generally, the air chamber pressure is set as 2-2.5 MPa.

(2) Both oil density and viscosity have a certain impact on the damping characteristics of the shock absorber. Therefore, it is critical to select appropriate oil density, generally selected as $\rho = 850 \text{ kg/m}^3$. The overall heat dissipation should be considered when designing the structure of the shock absorber, to ensure that the oil temperature remains in an appropriate range during the working process.

(3) Air chamber volume has almost no effect on the damping characteristics of the shock absorber. Therefore, the air chamber volume should make corresponding adjustments according to the specific working conditions and installation requirements. In order to reduce the overall length of shock absorber, smaller volume of the air chamber is usually given priority.

References


Corresponding author
Fangwei Xie can be contacted at: xiefangwei@ujs.edu.cn

For instructions on how to order reprints of this article, please visit our website: www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: permissions@emeraldinsight.com