Shock Absorber Modeling and Simulation Based on Modelica

Yuming Hou, Lingyang Li, Ping He, Yunqing Zhang, Liping Chen
CAD Center, Huazhong University of Science and Technology, China
zhangyq@hust.edu.cn

Abstract

The purpose of shock absorbers are to dissipate impact energy, and control tire force variation, the shock absorber has great influence on both ride and handling performance of vehicles, and a great many previous researches have been done on modeling and simulation of the shock absorber. In this paper, a detailed model of shock absorber is established, which contains rebound chamber, compression chamber, piston valve assembly, base valve assembly and so on. Those models are built using modelica language, modelica is a language for modeling of physical systems, designed to support effective library development and model exchange. It is a modern language built on a causal modeling with mathematical equations and object-oriented constructs to facilitate reuse of modeling knowledge.

Keywords: shock absorber; ride; handling; Modelica

1 Introduction

Shock absorber is widely used on vehicle. The purposes of the shock absorber are to dissipate the energy accumulated by the suspension spring displacement. The damping of the shock absorber for compression motion is usually less than that of rebound motion, in such a case, less force is transmitted to the vehicle when crossing a bump. By comparison, the shock absorber provides more damping force for rebound motion in order to dissipate energy stored in the suspension system quickly [1]. When the shock absorber is operated, hydraulic oil is passed between chambers via a system of hydraulic valves, and the damping effect is accomplished by the resistance of the oil when flowing through the valves. For the importance of the shock absorber on vehicle ride and handling performance, it is necessary to establish an accurate mathematical model of shock absorber, and there is a great wealth of literatures devoted to the modeling and simulation of the shock absorber. Herr [2] presented a computational fluid dynamics method combined with a dynamic modeling technique. Which used to study the flow and performance of automotive hydraulic dampers / shock absorbers. Simms [3] established a non-linear hysteretic physical shock absorber model, and the processes utilized to identify the constituent parameters, and the model is validated by comparing simulated results to experimental data for a test damper, for three discrete frequencies of sinusoidal excitation of 1, 3 and 12 Hz. Talbott [4] presented a mathmatical model of a gas-charged mono-tube racing damper. The model includes bleed orifice, piston leakage, and shim stack flows, and also includes models of the floating piston and the stiffness characteristics of the shim stacks. Chavan [5] study the damper lag and hysteresis which are the important parameters affecting the dynamic response of the hydraulic shock absorbers, and the response of the suspension unit to road excitation strongly influences motorcycle ride comfort.

Modelica is a freely available, object-oriented language for modeling of large, complex, and heterogeneous physical systems. It is suited for multi-domain modeling, for example, mechatronic models in robotics, automotive and aerospace applications involving mechanical, electrical, hydraulic and control subsystems, process oriented applications and generation and distribution of electric power. Models in Modelica are mathematically described by differential, algebraic and discrete equations. No particular variable needs to be solved for manually. A Modelica tool will have enough information to decide that automatically. Modelica is designed such that available, specialized algorithms can be utilized to enable efficient handling of large models having more than one hundred thousand equations. Modelica is suited and used for hardware-in-the-loop simulations and for embedded control systems.

2 Shock Absorber Modeling

The shock absorber is one of the most important elements in a vehicle suspension system. For analyzing the influence of the uncertain parameters on the response of the shock absorber, a detailed analytical model of the shock absorber is necessary. The first step of establishing the analytical model is to understand the physics of the shock absorber. Fig. 1 shows the schematic of the shock absorber. The shock absorber mainly consists of rebound chamber, compression chamber, reserve chamber, piston valve assembly and base valve assembly. When the piston valve assembly moves up and down, pressure differential is generated between the rebound chamber and the compression chamber, also there is pressure differential between the compression chamber and the reserve chamber. The pressure differential forces the fluid to flow through the valves and orifices. The damping force during the compression and rebound stoke are produced on account of the resistance offered by the fluid in flowing through the valves and orifices [6].

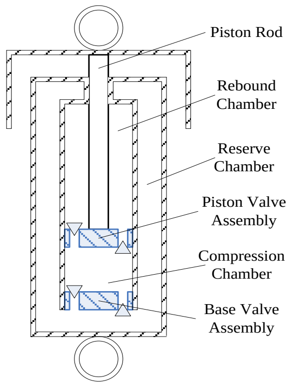
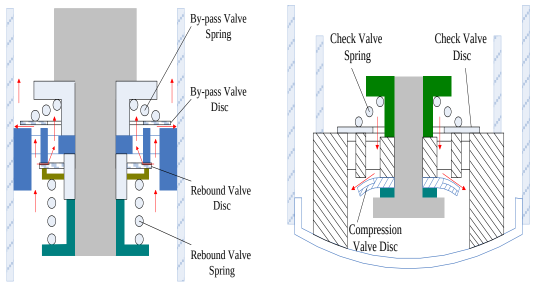


Fig. 1 The Schematic of the shock absorber

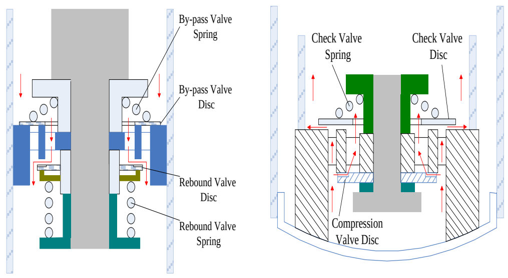
During the compression, the piston rod moves down and pushes the fluid in the compression chamber flowing to the rebound chamber and reserve chamber. The detailed structures of the piston valve assembly and the base valve assembly are given in Fig. 2, the fluid paths during the compression are also shown in the figure.

As shown in Fig. 2(a), the by-pass valve and rebound valve are essential non-return valves, during the compression, the rebound valve disc is closed, but there are four orifices on the rebound valve disc allow the fluid flow through, cross the holes of piston body and by-pass valve disc to the rebound chamber. The by-pass valve disc opens only if the pressure differential between the compression chamber and the rebound chamber reaches the preload of the by-pass valve spring. In Fig. 2(b), the check valve is closed, and before the pressure differential between the compression chamber and reserve chamber reaches the preload of the compression valve disc, the compression valve will be closed. But the fluid can still pass through the four orifices on the compression valve disc. When the pressure differential exceeds the preload, the compression valve will be opened.



(a) (b)

Fig. 2 Fluid paths through the piston valve and base valve during the compression stoke



(a) (b)

Fig. 3 Fluid path through the piston valve and base valve during the rebound stoke

During the rebound, fluid in the rebound chamber was forced flowing to the compression chamber, the missing oil equivalent to the rod volume extracted from the rebound chamber is complemented from the reserve chamber to the compression chamber, and the flow paths are shown in Fig. 3.

In Fig. 3(a), the by-pass valve is closed, when the pressure differential between the rebound chamber and the compression chamber is lower than the preload of the rebound valve spring, the rebound valve is also closed, but the fluid will pass through the orifices on the disc. And when the pressure differential reaches the preload, the rebound valve disc will be opened. As depicted in Fig. 3(b), the compression valve is closed, and the fluid will flow through the orifices on the disc from reserve chamber to compression chamber. And the check valve will be opened when the pressure differential between the reserve chamber and the compression chamber reaches the preload of the check valve spring.

From discussed above, an equivalent scheme of the shock absorber is built in Fig. 4.

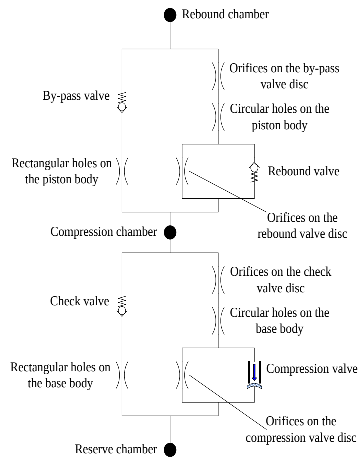


Fig. 4 The equivalent scheme of the shock absorber

For a generic orifice or a hole, the flow rate Q can be expressed as a function of the pressure drop Δp:

$$Q = CA\sqrt{\frac{2\Delta p}{\rho}} \tag{1}$$

Where, C is the flow coefficient, A denotes the flow area of the orifice, ρ is the density of the oil.

The modelica code of the orifice is given in Fig. 5.

```
model Constant
    Damper.Interfaces.HyLibProps Prop;
    import Modelica.Constants.pi;
    parameter Real Cq = 0.7 "The flow coefficient";
    parameter Real area = 1.5e-006 "The cross area";
    parameter Real rho = 900 "The density of the oil";
    parameter Real k1(unit = "1", min = 0) = 10. "laminar part of orifice model";
    final parameter Real k2 = 1 / (Cq * Cq);
    final parameter Real hd = 2 * sqrt(area / pi);
    Real dp;
    Real q;
    Interfaces.Hydraulic.Port_A Port_AConstant annotation (extent = [- 110, - 10; - 90, 10]);
    Interfaces.Hydraulic.Port_B Port_BConstant annotation (extent = [90, - 10; 110, 10]);
    annotation (Diagram, Icon(
equation
    dp = Port_AConstant.p - Port_BConstant.p;
    q = (sqrt(k1 ^ 2 * Prop.nu ^ 2 * Prop.rho ^ 2 + 8 * hd ^ 2 * k2 * noEvent(abs(dp)) * Prop.rho
      - k1 * Prop.nu * Prop.rho) * hd * Modelica.Constants.pi / (8 * k2 * Prop.rho);
    Port_AConstant.q = noEvent(if dp >= 0 then q else - q);
    Port_AConstant.q + Port_BConstant.q = 0;
end Constant;
```

Fig. 5 The modelica code of the orifice

For a check valve with spring preload, the formula given below describes the relation between the flow rate Q_v and pressure drop Δp_v:

$$Q_v = \begin{cases} 0 & if \;\; \Delta p_v \le \Delta p_0 \\ Cl_b \dfrac{(\Delta p_v - \Delta p_0)A_{disc}}{k_s}\sqrt{\dfrac{2\Delta p_v}{\rho}} & if \;\; \Delta p_v > \Delta p_0 \end{cases} \tag{2}$$

Where, Δp_0 is the preload of the spring, k_s denotes the stiffness of the spring, l_b represents hydraulic perimeter of the valve disc. A_{disc} is the area which oil pressure acts on the valve disc. The modelica code of the check valve is shown in Fig. 6.

```
model CheckValve
    extends Valves.CheckValvePartial;
    annotation (Documentation(info = "<HTML><P>Model <I>CheckValveNoStates
    parameter Modelica.SIunits.Pressure pclosed(final min = 0) = 100000. "pressure to start opening the valve";
    parameter Modelica.SIunits.Pressure popen(final min = 0) = 125000. "pressure to open valve completely";
    parameter Modelica.SIunits.Diameter diameter(min = 0.) = 1.e-003 "diameter of equivalent orifice";
    parameter Real GLeak = 1.e-012 "conductance of leakage";
    parameter Real k1(unit = "1", min = 0) = 10. "laminar part of orifice model";
    parameter Real k2(unit = "1", min = 0) = 2. "turbulent part of orifice model, k2 = 1 / C_d^2";
    Boolean closed(start = false) "valve closed, only leakage";
    Boolean open(start = false) "valve wide open";
    Real bopen;
    Modelica.SIunits.VolumeFlowRate qopen;
    annotation (Icon(
equation
    closed = dp < pclosed;
    open = dp > popen;
    qopen = (sqrt(k1 ^ 2 * Prop.nu ^ 2 * Prop.rho ^ 2 + 8 * diameter ^ 2 * k2 * noEvent(abs(popen)) * Prop.rho)
          - k1 * Prop.nu * Prop.rho) * diameter * Modelica.Constants.pi / (8 * k2 * Prop.rho);
    bopen = qopen / (popen - pclosed);
    Port_A.q = if closed then dp * GLeak else if open then (sqrt(k1 ^ 2 * Prop.nu ^ 2 * Prop.rho ^ 2
            + 8 * diameter ^ 2 * k2 * noEvent(abs(dp)) * Prop.rho)
            - k1 * Prop.nu * Prop.rho) * diameter * Modelica.Constants.pi / (8 * k2 * Prop.rho)
            + dp * GLeak else (dp - pclosed) ^ 2 * bopen / (popen - pclosed) + dp * GLeak;
    assert(popen > pclosed, "Parameter popen MUST be greater than parameter pclosed.");
end CheckValve;
```

Fig. 6 The modelica code of the check valve

The mathematical model of the compression valve is presented as below:

$$Q_c = \begin{cases} 0 & if \;\; \Delta p_c \le \Delta p_{c0} \\ Cl_{bc}\delta\sqrt{\dfrac{2\Delta p_c}{\rho}} & if \;\; \Delta p_c > \Delta p_{c0} \end{cases} \tag{3}$$

$$\delta = \frac{\Delta p_c}{E_c h^3}[(9r_1^4 + 8r_1^3 r_2 - 18r_1^2 r_2^2 + r_2^4)/6 - 4r_1^3 r_2 \ln(r_1/r_2)] \tag{4}$$

Where, Q_c is the flow rate through the compression valve, Δp_c is the pressure drop, l_{bc} denotes the hydraulic perimeter of the compression valve disc, δ represents the deflection of the disc, E_c is the elastic modulus of the disc, h is the thickness of the disc. r_1 and r_2 are the outer and inner contact radius between the disc and the compression valve body. Fig. 7 shows the modelica code of the compression valve.

```
model CompressionValve
    Damper.Interfaces.HyLibProps Prop;
    import Modelica.Constants.pi;
    parameter Modelica.SIunits.Force fpre = 10 "The preload of the valve plate";
    parameter Modelica.SIunits.Area A = 2.e-004 "The area of the valve plate";
    parameter Modelica.SIunits.Length lp = 6.e-002 "The perimeter of the valve plate";
    parameter Modelica.SIunits.Length h = 4.5e-004 "The thickness of the valve plate";
    parameter Modelica.SIunits.Length r1 = 1.9e-002 "The outer radius of the valve plate";
    parameter Modelica.SIunits.Length r2 = 8.e-003 "The outer radius of the washer";
    parameter Real E = 200000000000. "The elastic modulus";
    parameter Real Cq = 0.7 "The flow coefficient";
    parameter Real Aleak = 1.e-007 "The leak area";
    parameter Real rho = 900 "The density of the oil";
    parameter Real k1(unit = "1", min = 0) = 10. "laminar part of orifice model";
    final parameter Real pcrack = fpre / A;
    final parameter Real k2 = 1 / (Cq * Cq);
    Real dp;
    Real q;
    Real delta "The bend deflection of the valve plate";
    Real area;
    Real hd;
    Interfaces.Hydraulic.Port_A Port_AConstant annotation (extent = [- 110, - 10; - 90, 10]);
    Interfaces.Hydraulic.Port_B Port_BConstant annotation (extent = [90, - 10; 110, 10]);
    annotation (Diagram, Icon(
equation
    dp = Port_AConstant.p - Port_BConstant.p;
    if noEvent(dp <= pcrack) then
        delta = 0;
    else
        delta = (dp - pcrack) * ((9 * r1 ^ 4 + 8 * r1 ^ 3 * r2 - 18 * r1 ^ 2 * r2 ^ 2
                + r2 ^ 4) / 6 - 4 * r1 ^ 3 * r2 * ln(r1 / r2)) / (E * h ^ 3);
    end if;
    area = delta * lp + Aleak;
    hd = 2 * sqrt(area / pi);
    q = (sqrt(k1 ^ 2 * Prop.nu ^ 2 * Prop.rho ^ 2 + 8 * hd ^ 2 * k2 * noEvent(abs(dp)) * Prop.rho)
        - k1 * Prop.nu * Prop.rho) * hd * Modelica.Constants.pi / (8 * k2 * Prop.rho);
    Port_AConstant.q = noEvent(if dp >= 0 then q else - q);
    Port_AConstant.q + Port_BConstant.q = 0;
end CompressionValve;
```

Fig. 7 The modelica code of the compression valve

3 Simulation

A shock absorber simulation model is established using MWorks/Modelica software, as shown in Fig. 8, the model contains the rebound valve, by-pass valve, check valve, compression valve, rebound chamber, compression chamber, reserve chamber, the mass of the piston and so on. The input of the simulation model is a sine displacement to the piston rod. And Fig. 9 shows the response of the damping force vs the velocity of the piston. Fig. 10 shows that the response of the damping force vs the displacement of the piston

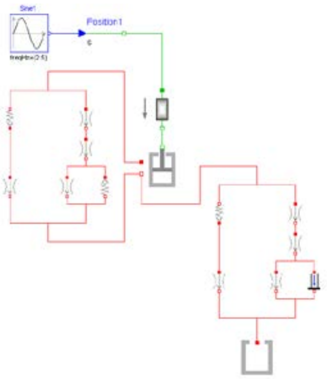


Fig. 8 The simulation model of the shock absorber

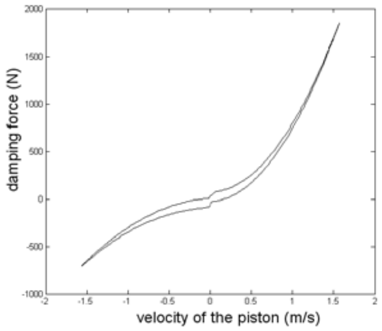


Fig. 9 Response of the damping force vs the velocity of the piston

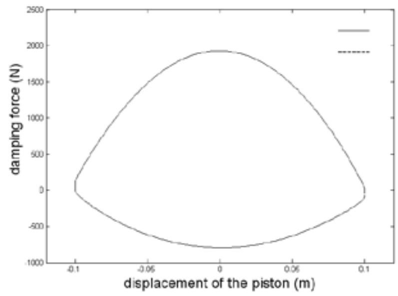


Fig. 10 Response of the damping force vs the displacement of the piston

4 Conclusions

In this paper, the mathematical model of the shock absorber which contains rebound chamber, compression chamber, piston valve assembly, base valve assembly is given in the paper, then a simulation model is established using MWorks/modelica software, the simulations are performed to evaluate the damping force of the shock absorber. The results shows that the Modelica language is available for modeling multi-domain physical system.

Acknowledgement

This work was supported by the National High-Tech R&D Program, China (No. 2009AA044501).

References

[1] S. Subramanian, R. Surampudi and K. R. Thomson. “Development of a Nonlinear Shock Absorber Model for Low-Frequency NVH Applications,” SAE paper 2003-01-0860.

[2] F. Herr, T. Mallin, J. Lane and S. Roth. “A Shock Absorber Model Using CFD Analysis and Easy5,” SAE paper 1999-01-1322.

[3] A. Simms and D. Crolla. “The Influence of Damper Properties on Vehicle Dynamic Behaviour,” SAE paper 2002-01-0319.

[4] M. S. Talbott and J. Starkey. “An Experimentally Validated Physical Model of a High-Performance Mono-Tube Damper,” SAE paper 2002-01-3337.

[5] C. B. Chavan, M. K. Venkata, R. Babu and R. Bharat. “Experimental Study on Effect of Damper Lag on Motorcycle Ride Comfort,” SAE paper 2006-32-0096.

[6] L. C. Andreotti and S. N. Vannucci. “Shock Absorber Mathematical Modeling,” SAE paper 982959.