Simulation of Dynamic Characteristic of Reverse Pressure Relief Valve with AMESim

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Abstract. The dynamic characteristics of reverse pressure relief valve were studied by simulation to solve the problems of the outlet pressure fluctuating and structural vibration of launch vehicle gas supply system. A simulation model was established. The pressure and displacement of valve were simulated through AMESim. The results are consistent with the experiment data. The study shows that the dynamic characteristics of the relief valve are related to the damping ratio of the moving elements, the length of the inlet and outlet pipe and the opening degree of the solenoid valve. By adjusting the damping ratio of the moving elements, the gas pressure fluctuation and structural vibration of the valve were restrained.

1. Introduction
Pressure relief valve is an important pressure regulating device in the air supply system of launch vehicle. The valve can depressurize the high pressure gas in the cylinder to a certain set value at the outlet. During the test of a pressure relief valve used in the gas supply system of launch vehicle, the pressure pulsation at the gas outlet was severe and the valve body was in a constant state of violent vibration. The vibration of the pressure relief valve not only makes the operator feel uncomfortable, but also damages the gas supply system and even leads to launch mission failure. Some scholars have established the mathematical model of pressure relief valve [1, 2, 3], and studied the dynamic characteristics of the valve by simulation [4, 5, 6].

2. Introduction for pressure relief valve
The structure of the pressure relief valve is shown in Figure 2.1. Open the inlet of the regulating chamber on the bonnet first, adjust the pressure to the set value, and then open the low-pressure outlet. In the instant of valve opening, because of the sudden drop of pressure in the low-pressure chamber, the pressure above the Piston is less than the pressure below. Under the unbalanced aerodynamic force, the piston moves, pushing the spool and spring seat upward, this increases the opening degree of the spool. The gas in the high-pressure chamber flows into the low-pressure chamber through the throttle loop at the spool. Along with the gas in the high-pressure chamber enters the low-pressure chamber, the pressure in the low-pressure chamber increases gradually. At last, the aerodynamic force in the regulating chamber, the low-pressure chamber and the force of the replacement springs reach balance state again, and the spool and the Piston reach a certain equilibrium position. At this time, the outlet pressure reaches the set value.
3. **Mathematic models**

3.1 **Vibration equation**

The moving elements (including spool, spring seat and piston) in the valve are considered as a single-degree-of-freedom system, and the vibration equation can be expressed as

\[ M \ddot{x} + C \dot{x} + K x = F(t) \]  

(3-1)

Where:  
- \( M \) - total mass of moving elements;  
- \( C \) - damping coefficient;  
- \( K \) - equivalent stiffness coefficient of spiral spring and air spring cavity;  
- \( F(t) \) - external force.

3.2 **Flow equation**

The flow equation of ideal gas equation can be expressed as

\[ Q_m = \begin{cases} \mu A P_1 \sqrt{\frac{2k}{RT_1(k-1)}} \left[ \left( \frac{p_2}{p_1} \right)^{\frac{k}{k+1}} - \left( \frac{p_2}{p_1} \right)^{\frac{k+1}{k+1}} \right] \left( \frac{p_2}{p_1} \right) > \left( \frac{2}{k+1} \right)^{\frac{k}{k-1}} \\ \mu A P_1 \sqrt{\frac{k}{RT_1}} \left( \frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \left( \frac{p_2}{p_1} \right) \leq \left( \frac{2}{k+1} \right)^{\frac{k}{k-1}} \end{cases} \]  

(3-2)

Where:  
- \( \mu \) - flow coefficient;  
- \( A \) - sectional area;  
- \( P_1 \) - inlet pressure;  
- \( P_2 \) - outlet pressure;  
- \( T_1 \) - inlet temperature;  
- \( k \) - adiabatic coefficient;  
- \( R \) - gas constant.

3.3 **State equation**

The state equation of ideal gas can be expressed as

\[ m_q = \frac{PV}{RT} \]  

(3-3)

\[ \frac{dm_q}{dt} = \frac{V}{RT} \frac{dp}{dt} + \frac{P}{RT} \frac{dv}{dt} = \frac{PV}{RT} \frac{dP}{R^2 dt} \]  

(3-4)
Where: \( m_q \)- molar mass; \( V \)- volume of cavity; \( P \)- pressure; \( R \)- gas constant; \( T \)- temperature.

### 3.4 Energy equation

According to the first law of thermodynamics, the energy equation in the cavity can be expressed as

\[
\frac{dP}{dt} = \frac{k}{v} \left( RT_1 q_1 - RT_2 q_2 + \frac{k-1}{k} \frac{dq}{dt} - P \frac{dv}{dt} \right)
\]

(3-5)

Where: \( V \)- volume of cavity; \( P \)- pressure; \( q_1 \)- inlet flow; \( T_1 \)- inlet temperature; \( q_2 \)- outlet flow; \( T_2 \)- outlet temperature; \( k \)- specific heat ratio; \( Q \)- gas heat in cavity.

### 3.5 Dynamic mathematical model

According to the above equations, the dynamic mathematical model of the pressure relief valve is established, and the following assumptions are made [7].

a) The working medium is ideal gas;
b) The specific heat ratio is a constant value;
c) The process is adiabatic;
d) No flow loss along the path.

e) Ignoring gravity;
f) The pressure, density and temperature of gas in each chamber are uniformly distributed.

\[
\begin{align*}
\dot{x} &= \frac{C}{M} \ddot{x} - \frac{K}{M} x + \frac{F}{M} \\
\frac{dP_1}{dt} &= \frac{kRT_1}{v_1} (q_1 - q_r) \\
\frac{dT_1}{dt} &= \frac{T_1}{p_1} \frac{dP_1}{dt} - \frac{RT_1^2}{p_1 v_1} (q_1 - q_r) \\
\frac{dP_2}{dt} &= \frac{kR}{v_2} (q_r T_1 - q_2 T_2) + \frac{k p_2 (A_1 - A_2)}{v_2} \ddot{x} \\
\frac{dT_2}{dt} &= \frac{T_1}{p_1} \frac{dP_2}{dt} - \frac{T_2 (A_1 - A_2)}{v_2} \ddot{x} - \frac{RT_2^2}{p_2 v_2} (q_r - q_2)
\end{align*}
\]

(3-6)

Where: \( x \)- spool displacement; \( C \)- damping coefficient; \( M \)- total mass of moving elements; \( K \)- equivalent stiffness coefficient of spiral spring and air spring cavity; \( F \)- external force; \( k \)- specific heat ratio; \( R \)- gas constant; \( v_1 \)- volume of high-pressure chamber; \( v_2 \)- volume of low-pressure chamber; \( q_1 \)- inlet flow; \( q_r \)- throttle flow; \( q_2 \)- outlet flow; \( A_1 \)- effective area of piston; \( A_2 \)- unbalanced area.

### 4. Simulation

#### 4.1 Simulation model

The simulation model of pressure relief valve is established in AMESim, shown in Figure 4.1. The parameters of the simulation model are shown in Table 4.1.

#### 4.2 Original model

According to the parameter settings in Table 4.1, the original model of pressure relief valve is simulated. The inlet pressure is 9.5 MPa, the regulating pressure is 3.8 MPa, the outlet pressure is 1.7 MPa, and the solenoid valve at the outlet is opened at 0.05 s. The results show that the displacement of the spool is about 0.75 mm when the valve reaches steady state, the maximum overshoot of the outlet pressure is about 1.8%, the adjustment time is about 0.3 s, and the vibration frequency of the spool and the outlet pressure is about 97 Hz.
Figure 4.1. Simulation model of reverse pressure relief valve

| No. | Name | Parameter | Value |
|-----|------|-----------|-------|
| 1   | Inlet pressure | Pressure   | 9.5 MPa |
| 2   | Upper spring   | Stiffness  | 20 N/mm |
| 3   | Spool          | Diameter   | 25 mm  |
| 4   | Valve seat     | Diameter   | 21 mm  |
| 5   | Lower spring   | Stiffness  | 17 N/mm |
| 6   | Piston         | Diameter   | 80 mm  |
| 7   | Moving elements| Mass       | 0.998 kg |
| 8   | Damping plate  | Diameter   | 60 mm  |
| 9   | Solenoid valve | Diameter   | 20 mm  |
| 10  | Outlet pressure| Pressure   | 1.7 MPa |

Table 4.1 Parameters of Pressure Relief Valve Model

| No. | Name                      | Parameter   | Value   |
|-----|----------------------------|-------------|---------|
| 11  | Orifice                   | Diameter    | 0.5 mm  |
| 12  | High-pressure chamber     | Pressure    | 9.5 MPa |
| 13  | Low-pressure chamber      | Pressure    | 3.8 MPa |
| 14  | Upper regulating chamber  | Pressure    | 3.8 MPa |
| 15  | Lower regulating chamber  | Pressure    | 3.8 MPa |
| 16  | Regulating pressure       | Pressure    | 3.8 MPa |

4.3 Damping ratio of the moving elements

By changing the damping ratio of the moving elements, the pressure relief valve models with different damping ratios of the moving elements are simulated. The results are shown in Table 4.2. Only by changing the damping ratio of the moving elements, the outlet pressure remains unchanged; with the increase of the damping ratio, when the overshoot of the outlet pressure decreases, the adjustment time of outlet pressure is shortened, and the vibration frequency is reduced.

Table 4.2. Comparison of simulation results under different damping ratios

| No. | Damping ratio | Outlet pressure overshoot | Adjustment time /s | Steady state pressure /MPa | First order vibration frequency /Hz |
|-----|---------------|---------------------------|--------------------|-----------------------------|------------------------------------|
| 1   | 0.1           | 1.7%                      | 0.12               | 1.706                       | 96.5                               |
| 2   | 0.2           | 1.2%                      | 0.1                | 1.706                       | 92.5                               |
| 3   | 0.3           | 0.6%                      | 0.09               | 1.706                       | 84.5                               |
4.4 Length of the outlet pipe

By changing the length of outlet pipe, the valve model with different outlet pipe length is simulated. The results are shown in Table 4.3. Only by changing the length of outlet pipe, the overshoot of outlet pressure, the adjustment time and the vibration frequency are nearly unchanged. When the outlet pipe length increases, the outlet pressure increased slightly.

| No. | Outlet pipe length/mm | Outlet pressure overshoot | Adjustment time /s | Steady state pressure /MPa | First order vibration frequency /Hz |
|-----|------------------------|---------------------------|--------------------|---------------------------|-----------------------------------|
| 1   | 1200                   | 1.8%                      | 0.3                | 1.678                     | 97                                |
| 2   | 1600                   | 1.8%                      | 0.3                | 1.706                     | 97                                |
| 3   | 2000                   | 1.8%                      | 0.3                | 1.734                     | 97                                |

4.5 Opening degree of the solenoid valve

In the range of 0 to 1 second, the opening degree of solenoid valve is set to 80%, 100% and 60%. The models of different opening degree of solenoid valves are simulated. The results show that the flow rate of low pressure outlet is proportional to the opening degree of solenoid valve; when the opening degree of solenoid valve decreases, the outlet pressure decreases, and the adjustment time of outlet pressure increases.
5. Experiment

The pressure relief valve test system is shown in Figure 5.1. Using high pressure cylinder as gas source, the pressure value of the gas source is monitored by pressure gauge, the reverse pressure relief valve studied in this paper is installed on the special fixture, and the outlet pressure is monitored by pressure sensor. The main instruments used in the experiment are sensors, signal acquisition equipment and signal processing system.

At the beginning of the test, the manual valve and solenoid valve at the inlet and outlet are opened sequentially, and the time-domain data of gas pressure at the outlet are acquainted. When data acquisition is completed, the frequency-domain data of outlet pressure are obtained by FFT transform in signal processing system.

The time-domain and frequency-domain data of outlet pressure collected in the experiment are shown in Figure 5.2. The first-order vibration frequency is 99.7Hz. The relative error between the simulation results and the experimental results is 2.8%. It shows that the simulation results are credible.
6. Conclusion
Through the modeling and simulation of the pressure relief valve, the following conclusions are obtained.

1) By increasing the damping ratio of the moving component, the outlet pressure remains unchanged, the overshoot of the outlet pressure decreases, the adjustment time of pressure is shortened, the vibration frequency is reduced, and vibration of the valve can be restrained.

2) By increasing the length of outlet pipe, the outlet pressure is slightly increased; the overshoot of the outlet pressure, the adjustment time of pressure, and the vibration frequency are nearly unchanged.

3) By increasing the opening degree of solenoid valve, the outlet pressure is slightly increased, the overshoot of the outlet pressure decreases, the adjustment time of pressure is shortened.

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