Modeling and Simulation of Conical Poppet type Relief Valve with Damping Spool

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Abstract: *This paper deals with the simulation of poppet type pressure relief valve with damping spool to analyze transient response. Mathematically explained the performance characteristics of this valve based on original research carrying out on the compound pressure relief valve and related to hydraulic pressure control valve. Pressure control valves allow establishing sequences in hydraulic operations via scaling the pressure in different parts of the system. The equations describing the dynamic performance the valve are deduced and simulated in the MATLAB/SIMULINK software.*

Keywords*: Damping spool, pressure, relief valve, simulation, transient response.*

1. Introduction

Pressure control valves are used to select pressure levels at which particular parts of the circuit must work; they control actuator force, avoid hydraulic system damage, power wastage and circuit overheating. Relief valves are used in hydraulic circuits as safety valves; they are normally closed and open whenever circuit pressure overcomes a certain value. In order to insure fluid tightness and therefore minimize leakage, poppet element is usually of conical or spherical.
In the case of a direct-operated relief valve, the poppet is actually a spring-supported mass. This mass-spring system is subjected to very low viscous friction and spring material structural-damping forces. Then, in the steady state, this valve may suffer from sustained oscillations of the poppet, which results in observable pressure oscillations. Therefore, it is necessary to add a damping spool to the valve. Figure 1 shows a direct operated pressure relief valve with a damping spool.
Relief valves are connected with high-pressure and return low-pressure lines. They are used to limit the maximum operating pressure in the high-pressure lines. The relief valve consists mainly of a poppet, loaded by a spring. The poppet is pushed by the spring to rest against its seat in the valve seating. The spring pre-compression force is adjusted by a spring seat screw.

2. Valve structure and operation

Figure 1 shows a schematic of the studied direct-operated relief valve. The poppet is subjected to spring, inertia, flow reaction forces and pressure forces. The poppet rests against its seat as long as the pressure force is less than on the forces on the spring side of the poppet element. These forces are equal when the pressure reaches the cracking pressure. For further increases of pressure, the poppet is displaced and the oil flows from the high-pressure line to the return line.

The valve consists of a poppet valve (2), rigidly attached to a damping spool (1). The poppet is loaded by a spring of stiffness krv. The spring is pre-compressed by an adjustable pre-compression distance, x. When the valve is not operating, the spring pre-compression force (krv xo) pushes the poppet against its seat. The seat produces an equal seat reaction force FSR. When the input pressure Pis increased, the liquid flows to the damping chamber through the radial clearance of the damping spool, Qd. The pressure, Pd, increases and acts on the damping spool. When the valve is closed, the pressure Pat the valve inlet chamber does not produce any axial force on the moving parts.

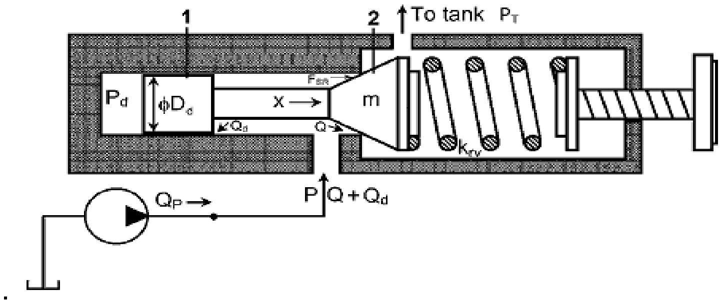

Fig. 1. A direct-operated relief valve connected to a pump supply

But, as the poppet valve opens, the poppet area subjected to inlet pressure A_p , becomes less than the damping spool area A_d. The pressure Pacts on the area difference (A_d– A_p) to the left.
Neglecting the seat reaction forces, the motion of the damping spool and poppet is governed by the spring force, the jet reaction force, inertia force, damping force and the pressure forces. When the pressure force (P_d A_d) exceeds the forces on the spring side, the poppet displaces, opening the path from the inlet port to the drain port, with a pressure P_T. The variation of the pressure P_d is resisted by the radial clearance, which throttles the connection of the inlet port with the damping spool chamber. The relief valve is connected to the delivery line of a fixed displacement pump rotated by a constant speed. A bypass valve is connected to the pump delivery line to control the loading pressure.

3. Mathematical modelling

This section deals with the deduction of a mathematical model describing the dynamic performance of a relief valve with damping spool.

Assumptions

- The outlet pressure is assumed to be equal to the atmospheric pressure.
- A stable supply to the valve inlet port is ensured.
- The spring stiffness is constant.
- Cd (Re) is a discharge coefficient at the valve inlet which in general depends on the Reynolds number, although this dependence will be neglected in our subsequent analytical and numerical investigation.
- The effect of the transmission lines was neglected

The dynamic behaviour of the valve is described by the following set of mathematical relations. The dynamic model can be obtained by adding the inertial force and viscous damping force into the steady state force balance equation and including an equation relating the rate of pressure change to the net dynamic flows. The system relief pressure will be higher than the preset cracking pressure due to both the mechanical and hydraulic spring forces existing when relief flow is passing through the valve. This is normally called a pressure override.

The Poppet Valve Throttling Area

The following mathematical expressions for the poppet area, A_p, subjected to the pressure P and poppet valve throttle area A_t, were deduced.

$$A_{po}(x) = \pi x sin\theta \{d_p - x\, sin\theta\, cos\theta\} \quad (1)$$

$$A_p = \frac{\pi}{4}\{d_p - 2x sin\theta cos\theta\}^2 \quad (2)$$

The motion of the poppet under the action of pressure, viscous friction, inertia, and external forces is described by the following equation:

$$P_d A_d + F_{SR} - P(A_d - A_p) = m\frac{d^2x}{dt^2} + f\frac{dx}{dt} + k_{rv}(x_0 + x) \quad (3)$$

Seat Reaction Force

The poppet displacement in the closure direction is limited mechanically. When reaching its seat, a seat reaction force takes place due to the action of the seat stiffness and structural damping of the seat material. These two effects are introduced by the equivalent seat stiffness ks and damping coefficient Rs.

$$F_{SR} = \begin{cases} 0 & x > 0 \\ k_S |x| - R_s \frac{dx}{dt} & x < 0 \end{cases} \quad (4)$$

Flow rate through the radial clearance of the damping spool:

$$Q_d = \frac{\pi D_d c^3}{12\mu l}(p - p_d) \quad (5)$$

Flow rate through the poppet valve:

$$Q = C_d A_{po} \sqrt{\frac{2p}{\rho}} \quad (6)$$

Continuity equation applied to the damping spool chamber:

$$Q_d - A_d \frac{dx}{dt} = \frac{V_o + A_d x}{\beta} \frac{dp_d}{d_t} \quad (7)$$

Pump flow rate:

$$Q_p = Q_t - \frac{p}{R_L} \quad (8)$$

Continuity equation applied to the poppet chamber:

$$Q_p - Q_d - Q_r = \frac{V}{\beta}\left(\frac{dp}{dt}\right) \quad (9)$$

In the steady state, the valve poppet reaches equilibrium under the action of the pressure forces, spring force, and jet reaction forces.

4. Computer simulation

A fluid power circuit mathematical model is a collection of nonlinear flow equations associated with components together with flow continuity and force equations applicable to components and actuators. The equations put together in the form of block diagram using a comprehensive library of mathematical functions in the MATLAB Simulink package.

The system has one linear differential equation for force and a nonlinear differential equation for flow-rate continuity, the nonlinear component being due to the poppet back chamber volume changes with time. The use of differential equations and linearized differential equations opens up a powerful analysis avenue to aid the understanding of the dynamic behaviour of fluid power circuits.

Equations (1) to (9) describe the dynamic behavior of the valve system. These equations were used to develop a computer simulation program i.e. MATLAB/SIMULINK, which was employed to plot the valve’s dynamic characteristics. The simulation program runs for the transient response of valve pressures to step input flow rate.

This simulink block diagram contains the appropriate mathematical models, inputs, and plotting facilities, as shown in Fig. 2. The dynamics exists at the opening of the poppet, because of the sudden application of the flow rate, these effects are very fast and have more effect on the dynamic response of the valve system.

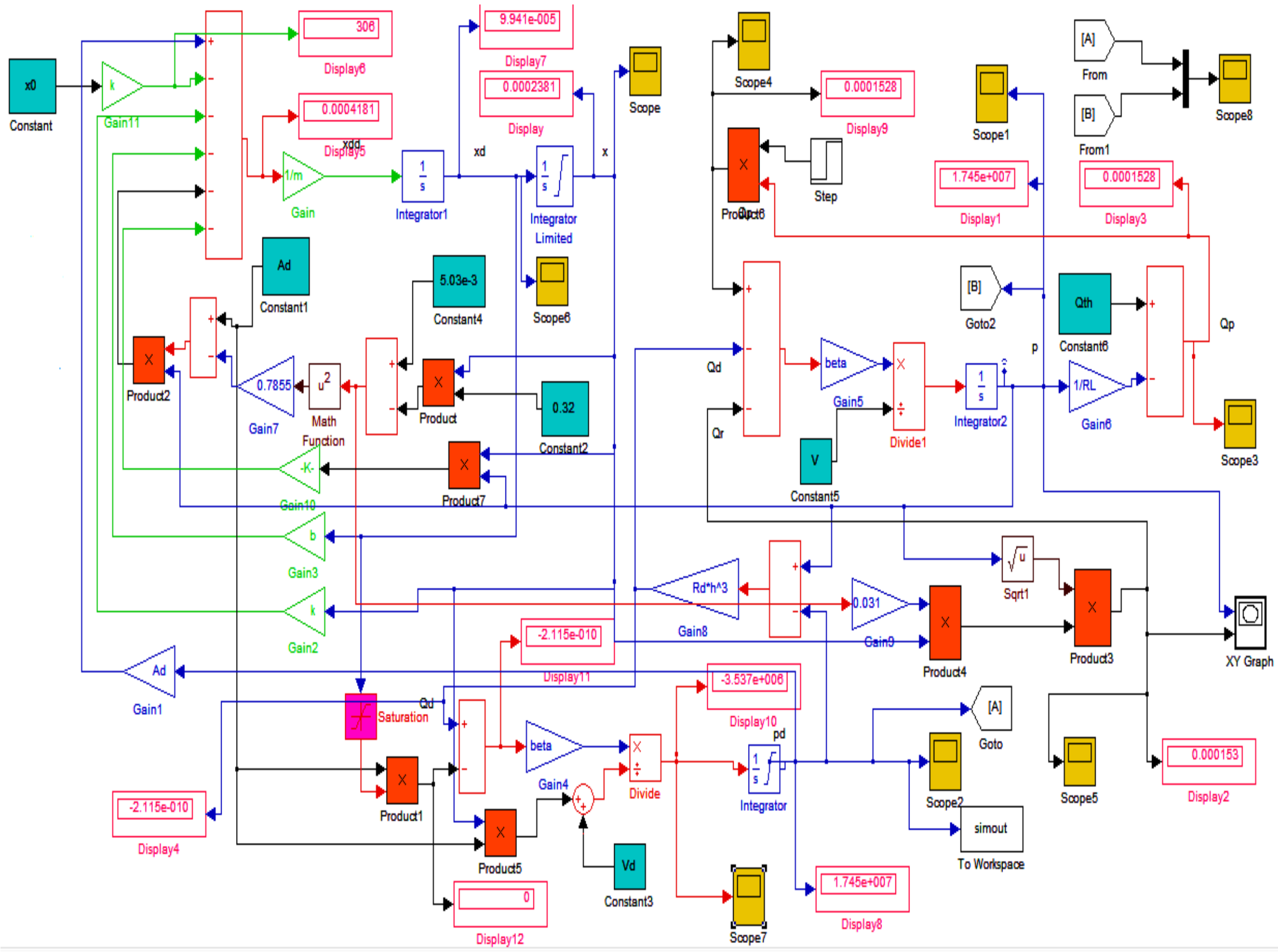

Fig. 2. Simulink Model of Pressure Relief Valve with damping spool

5. Results and discussion

The settling time is defined as the time the system takes to reach a steady state condition, while the peak time refers to the time the system takes to achieve its peak condition after the first overshoot with the same input. The transient response indicates a condition where both the settling and peak times are in the appropriate range.

The transient response of the valve was simulated for step supply flow rate. The simulink program runs for different values of the damping spool radial clearance. The transient response of valve input pressure was simulated and plotted.

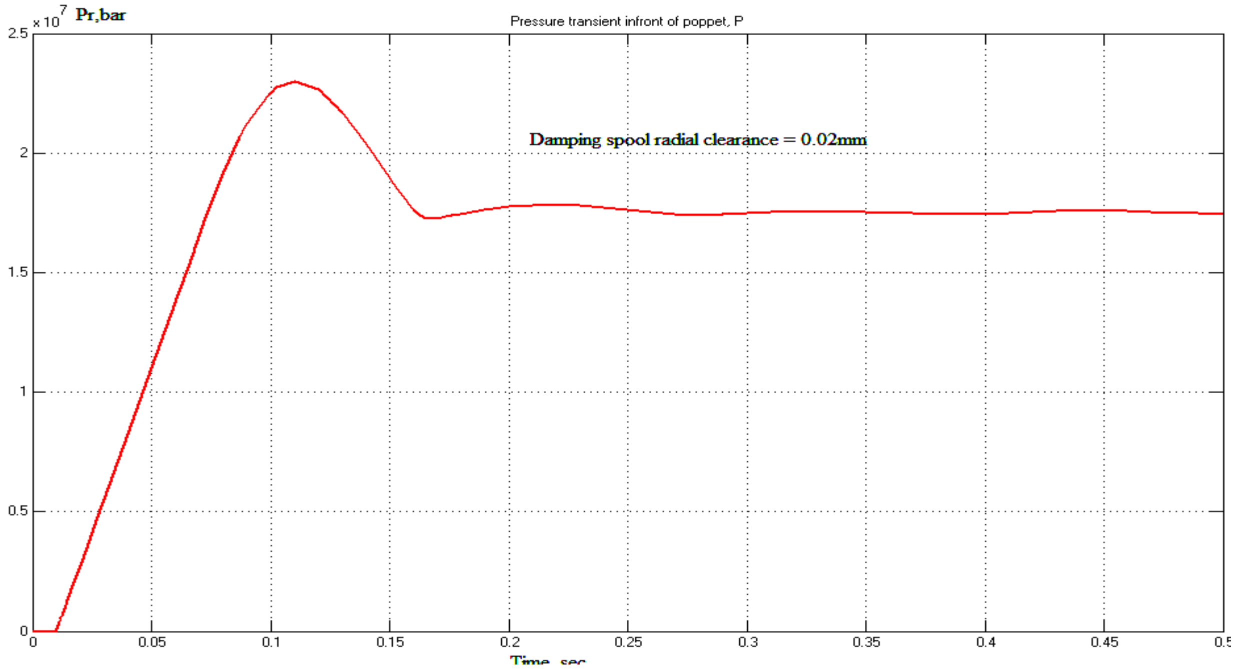

Fig. 3. Transient response of relief valve pressure for damping spool radial clearance of 0.02 mm

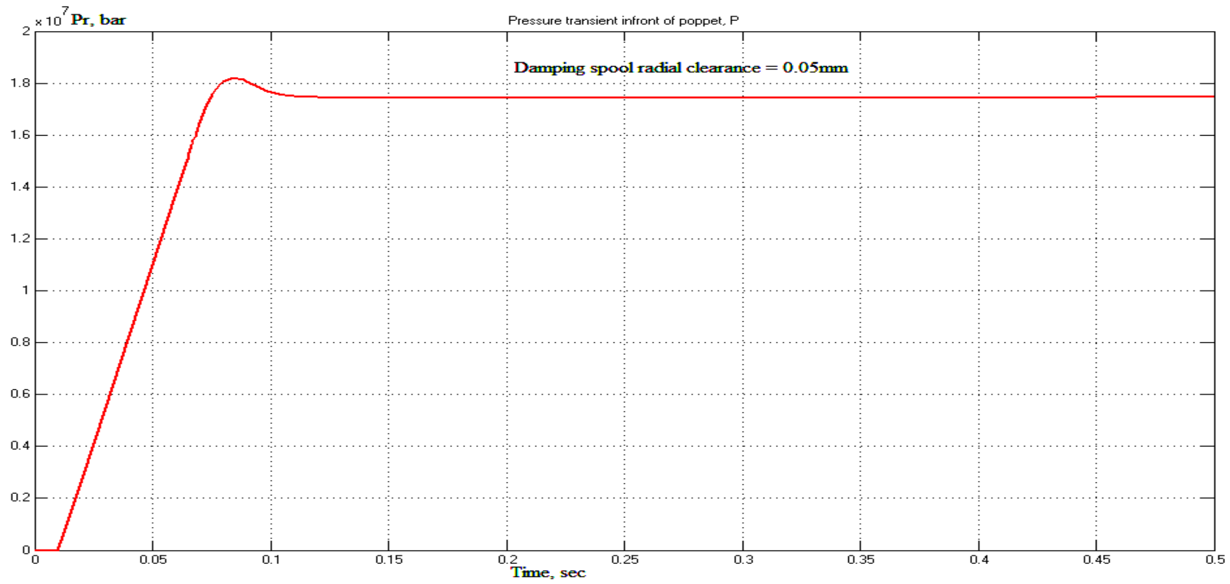

Fig. 4. Transient response of relief valve pressure for damping spool radial clearance of 0.05 mm

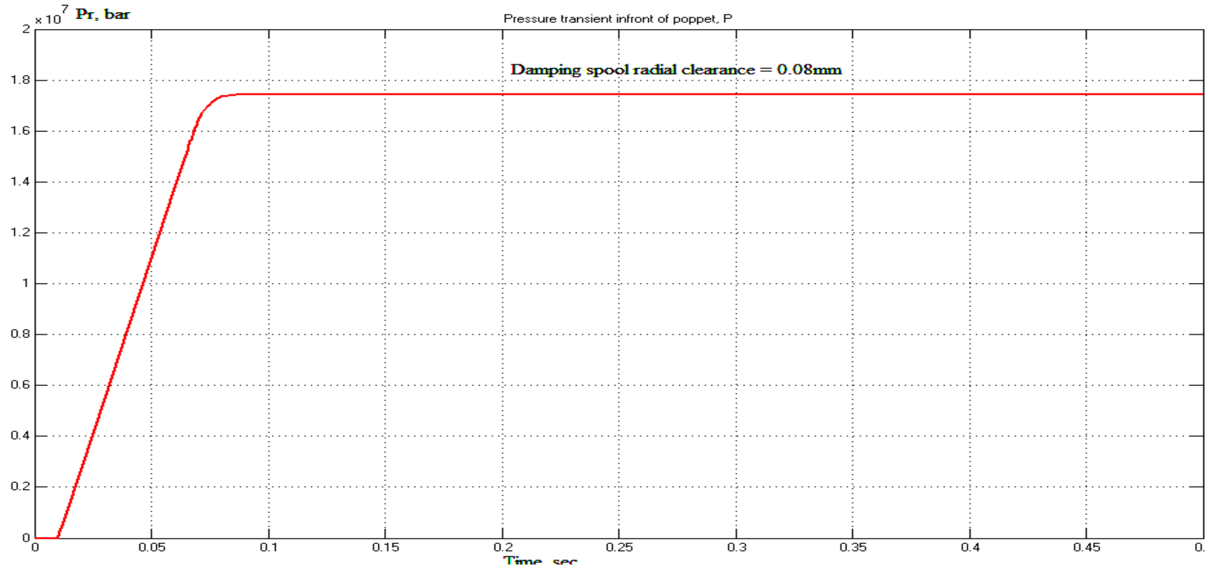

Fig. 5. Transient response of relief valve pressure for damping spool radial clearance of 0.08 mm

TABLE 1. Response

Radial clearance, mm	Overshoot, bar	Peak time T_o, ms	Rise time T_r, ms	Settling time T_s, ms
0.02	55	100	65	200
0.05	8	84	50	100
0.08	zero	zero	50	90

The simulation results show that the radial clearance has a significant effect on the valve response. For smaller radial clearances, the flow rate into the damping spool chamber is throttled and the pressure building in this chamber is delayed. The poppet takes a longer time to open, which results in greater pressure overshoot. For higher radial clearance of 0.08 mm, the overshoot is not observed and also rise time is less.

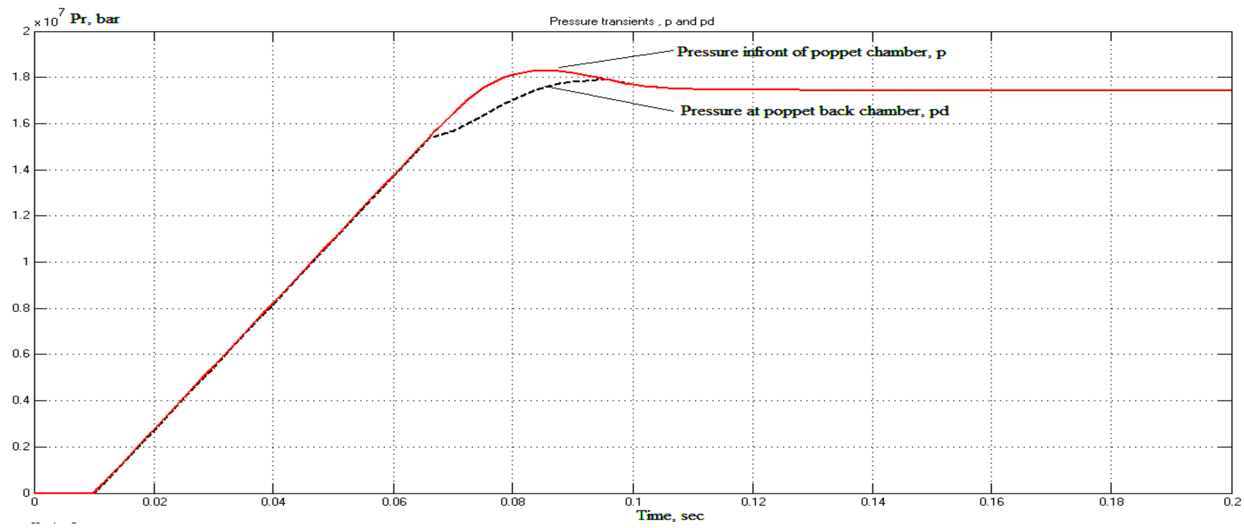

Fig. 6. Pressure transient curves of poppet front chamber and back chamber for damping radial clearance of 0.05 mm.

It is observed that pressure in front of poppet chamber and poppet back chamber remain same. It indicates that, for further analysis chambers can be considered as a single poppet chamber.

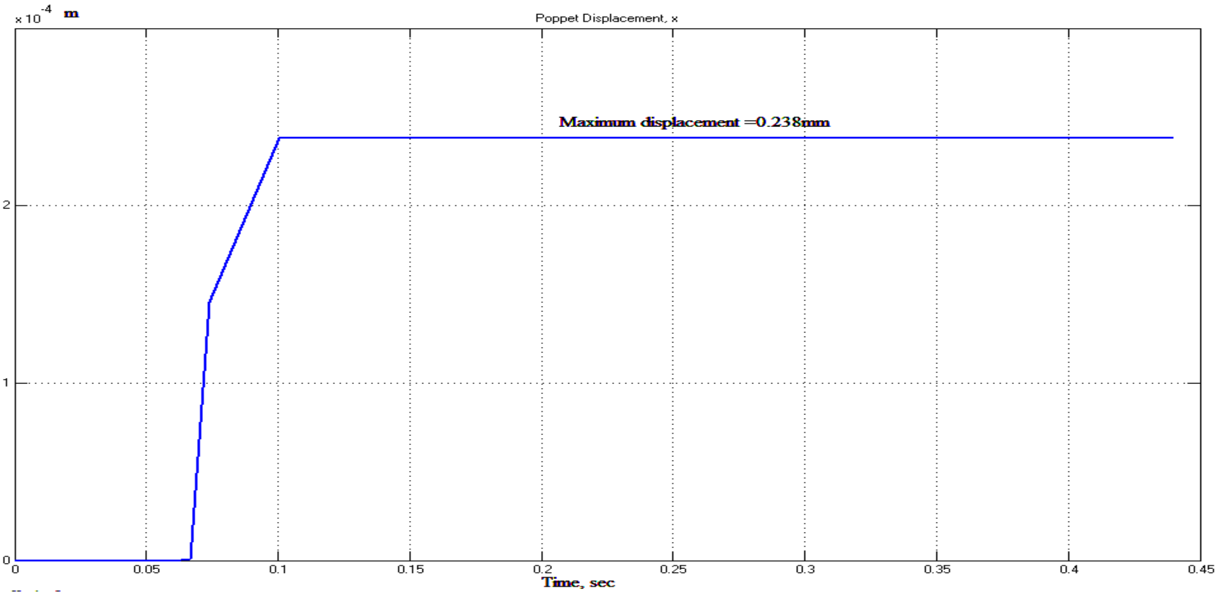

Fig. 7. Poppet displacement response

Referring to the above displacement curve, it is observed that valve gets opened after 55 ms and takes 35 ms to open completely to settled down to the final displacement of 0.238 mm.

6. Conclusion

Considering the transient response curves, it indicates that the poppet relief valve with damping spool has an excellent ability to reduce the pressure oscillations in the steady-state part of the response. In this study pressure oscillations not appear in the steady state part.
An important advantage of this simulation model is that its simplicity allows it to be used for a wider variety of system parameters. This model can be used in predicting application trends that may occur under various operating conditions, some of which may be difficult to create experimentally.

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NOMENCLATURE

A_d=Damping spool area, m^2
$A_{P=}$Poppet area subjected to pressure, m^2
A_{po}=Throttle area, m^2
β =Bulk modulus of oil, Pa
c =Radial clearance of the damping spool, m
C_d=Discharge coefficient
D_d=Damping spool diameter, m
f =Equivalent spring structural damping and piston friction coefficient, Ns/m
F_s=Seat reaction force, N
K_{rv}=Spring stiffness, N/m
k_s=Equivalent seat material stiffness, N/m
L =Damping spool length, m
m =Mass of the moving parts, kg
P =Valve inlet pressure, Pa
P_d=Pressure in the damping chamber, Pa
P_T=Return pressure, Pa

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