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Dynamic analysis of a pilot-operated two-stage solenoid valve used in pneumatic system

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ABSTRACT

A dynamic model was developed to study the dynamic characteristics of a pilot-operated two-stage solenoid valve used in pneumatic system. The dynamic model couples motion of the valve spindle with fluid in the system. While solving the system equations, vibration of the valve spindle, characteristics of the pressure-flow across valve orifices, pressure variation in valve chambers are taken into consideration. The model is validated by experimental results. With this model, the stability and dynamic response of the valve system for different operating conditions were discussed. The study identifies some critical parameters, which have significant effect on the dynamics of the system. A review of the obtained results indicate that the solenoid valve undergoes soft self-excited vibration, period-one hard self-excited vibration, period-two vibration, period-four vibration leading to stable working with the quasi-steadily increase in supply pressure or supply flow rate. Increasing in diameter of valve orifice d_b or decreasing in pre-compression of the valve spring z_0, half-cone angle of the valve spindle α, diameter of valve orifice d_a would improve anti-disturbance capacity and increase stable region of the solenoid valve.

1. Introduction

The performance of a pneumatic system is strongly influenced by the dynamic characteristics of its control valves [1,2]. As an important pneumatic element, a pilot-operated two-stage solenoid valve is extensively used in industrial circuits. As a control element, a pilot-operated solenoid valve has better performance in a system compared to a direct operated valve, due to its better pressure override characteristic. With the addition of a pilot stage valve, the main stage and the pilot stage valve couple together with fluid, which makes the design and analysis of the valve more difficult than the direct operated valve.

In general, the design of a pneumatic system which must meet a specified dynamic response is a more demanding task. As a change in the steady state of a system may involve dynamic transients, the dynamic effects of disturbances must be considered. A typical example of such effects is self-excited vibration in the valve, which means the system undergoes instability. To avoid the possibility of such occurrence, the dynamic analysis of the valve must be considered in designing a pneumatic system.

The complex dynamic interactions between the fluid and the valve components can be investigated using modeling and simulation techniques. Several dynamic models have been proposed for control valves. Ray [3] and Watton [4] studied the dynamics of a single stage pressure relief valve, where several simplifications were made to use the transfer function formulation technique. Davies [5] used a system identification approach using time series analysis to study the dynamic

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Nomenclature

A_d, A_u	flow area of the upstream control valve and downstream control valve
A_m, A_p	flow area of the main stage valve and pilot stage valve
A_{s1}, A_{s2}	area of the spindle and area of the fluid jet inside the valve seat
C_a, C_b	flow coefficient of orifice *a* and orifice *b*
C_m, C_p	flow coefficient of the main valve and pilot stage valve
C_v	velocity coefficient of the flow rate
d_a, d_b	diameter of orifice *a* and orifice *b*
d_p	diameter of main valve seat
e	restitution coefficient
F_f	fluid force acting on the valve spindle
F_p	pressure difference force acting on valve spindle
k	isentropic exponent
k_s	stiffness of the valve spring
l_a, l_b	length of orifice *a* and orifice *b*
m	mass of the valve spindle
p_a, p_b, p_c, p_d	pressure in chamber *a*, *b*, *c*, d
Q_a, Q_b	flow rate through orifice *a* and orifice *b*
Q_m, Q_c	flow rate through main stage valve and pilot stage valve
t	time of transient
$z, \dot{z}, \ddot{z}$	valve displacement, velocity and acceleration
δ	viscous damping coefficient
ρ	density of working fluid

characterization and effects of operating conditions of a two-stage pressure relief valve. However, in their studies, the model of pressure relief valve was simplified greatly, and the high order dynamics were neglected. Dasgupta et al. [6–9] analyzed the dynamic response of direct operated pressure relief valve and pilot-operated pressure relief valve with bondgraph technique, where some structural parameters which have significant effect on the transient response of the valve were indentified. Maiti et al. [10] analyzed the static and dynamic performance of a proportional pressure relief valve where the simulation results were obtained with bondgraph technique and validated by experimental results. Chin [11] proposed a detailed model and conducted a study on the dynamics of two-stage pressure relief valve where the responsiveness of the system's performance with respect to the changes of some critical parameters was investigated. Misra et al. [12] proposed a model to study the mechanism of self-excited vibration of a single stage control valve and indentify some structural parameters controlling instability of the valve. Hayashi et al. [13–15] conducted studies on a direct operated pressure relief valve and a pilot-operated pressure relief valve with great simplifications to the valve structures. The studies analyzed the stability of the systems and the effect of supply pressure on dynamic behavior of the valves. However, most of the researchers except for Misra et al. [12] studied pressure relief valve, fluid in downstream piping of the valve is not included. In addition, none of the reviewed papers considered the compressibility of the fluid in both valve chambers and piping.

The present study deals with the complete dynamic analysis of a pilot-operated two-stage solenoid valve system, which includes solenoid valve, upstream and downstream piping. A dynamic model, using nitrogen as working fluid, considering compressibility of the working fluid, coupling motion of the valve spindle with fluid is developed. With this model, the stability and dynamic response of the valve for different operating conditions were discussed. In addition, effects of some important structural parameters on dynamics of the valve were obtained. The present study gives a better understanding of the dynamic nature of the valve.

2. Description of the solenoid valve system

The pneumatic system studied in this paper is shown in Fig. 1. The whole system consists of five elements: gas cylinder, upstream and downstream control valve, upstream and downstream piping and the solenoid valve under study.

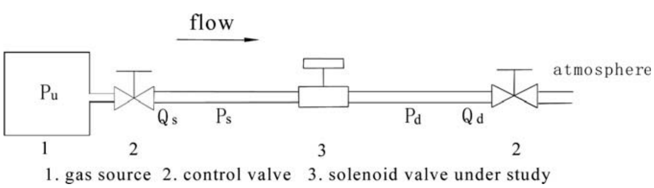

Fig. 1. Schematic diagram of the solenoid valve system.