

Investigations of Response Time Parameters of a Pneumatic 3/2 Direct Acting Solenoid Valve Under Various Working Pressure Conditions

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Abstract— In pneumatic circuits, a solenoid valve is a key component for controlling and directing pneumatic energy. The solenoid valve functional performances are defined as response time parameters with respect to its actuations in terms of direction changing time. This paper aims to present response time parameters of solenoid valves under various working pressures. An experimental setup is employed in order to measure response time with reference to the input signals. The response time plays significant role for evaluating the valve performance in sensitive applications. The response time parameters includes the on delay, the off delay, the on time, the off time, the cycle time and the switching frequency. In this experimental investigation the influence of various input pressure conditions is recorded and tabulated. Valves with varying orifice diameter are employed and the investigation reveals the influence of orifice diameter in response time variations. The newly-proposed six response time parameters can be used to rate and select the appropriate valve for various industrial applications.

Keywords-Pneumatic 3/2 solenoid valve; Response time; Switching frequency

I. INTRODUCTION

Pneumatic control systems provide low cost automation to the industry with the added benefits of easy maintenance and greener environment. This technology aims to great flexibility in the energy used in intricate machine parts and complex manufacturing activities using a cheap power source [1]. Pneumatic systems come with a good weight/power ratio, which makes them suitable for numerous applications in industries. In pneumatic applications, actuators are the resultant working element of transferring pneumatic energy into mechanical energy. The actuators' movements are controlled by directional control solenoid valves. Subsequently actuators are subjected to high friction forces which directly lead to a low output of the system. The actuator speed is the critical operation for controlling the subsequent machine activities. The servo-pneumatic switching valve has been widely used in the industry [2-4]. The valve response time has attracted considerable work to enhance its responsiveness based on

various designs. Pulse Width Modulation (PWM) has been proposed to control the velocity and the position of the pneumatic cylinder in [3]. The pneumatic actuators functionality has been presented as a linear time varying mathematical model in [5]. The static characteristics of PWM have been discussed with a mathematical model for calculating maximum operating modulation ratio in [6]. In continuation to this, Modified Pulse Width Modulation (MPWM) has been implemented to control hydraulic actuators in [7]. The servo system considered in [8] described the performance evaluation method, whereby the desired force can be controlled in steady-state working condition with speed disturbance. A pneumatic servo-system proposed in [9] was realized with digital on-off valves, instead of high cost proportional valves, to obtain a satisfactory dynamic performance by using modulation techniques. The MPWM techniques are linked with performance deterioration due to the abrupt change in external loads and have been further rectified in [10] with the use of learning vector quantization neural networks (LVQNN). The dynamic model was then implemented with a new solenoid valve to describe the switching characteristic in [11]. The switching type on-off valves (small in size, simple in construction, low cost, high flow rate gain) are preferred for the control of pneumatic actuators. The evaluation method described in [12], investigated the performance of electro-pneumatic valves used in air-powered engines and analyzed the on delay time, the full opening/closing time along with the seating velocity of the valves. In [13], further investigation of the dynamic analysis of a pilot-operated two-stage solenoid valve used in pneumatic system was conducted. The development [14] of Al-Fe soft magnetic materials led to the redesign of the structure of magnetic circuits employed to achieve rapid response and strong magnetic force.

A PWM-driven pneumatic fast switching valve was presented in [15] to identify spool position at various conditions. Two types of electro-pneumatic valves are used for the control of the fluid flow of a pneumatic actuator. These are the continuously acting servo/proportional valves and the on-off switching valves [15]. The response of these valves is a

critical operation for the control of the subsequent actuator speeds. The servo/proportional valves are used to achieve high linear control accuracy in pneumatic actuators, but their complex structure leads to high cost. The other type of on-off type solenoid valves are subgrouped as direct acting solenoid valves and pilot operated.

This work focuses on the establishment of a measuring kit for measuring both coil and valve response time parameters with testing procedures. Investigation of response time behavior against various working pressures is presented. Response time parameters such as: on delay, off delay, on time, off time, cycle time and switching frequency are investigated. Valves with varying orifice diameters are employed and the investigation reveals the influence of nominal diameter in response time variations.

II. RESPONSE TIME PARAMETERS

The response time of a solenoid valve is measured as the lagging time or time delay between the input and output signals. The response time of the solenoid valve can be analyzed as the response of the solenoid coil and of the mechanical valve. The response time parameter of coil is used to calculate the switching frequency for blowing applications. Similarly, the response time of the mechanical valve is calculated based on the lagging time (or time delay) between the input (electrical signal) and the output (pressure). This valve uses as an input a dc supply to deliver the pressurized air. The air output response depends on the following factors namely: area of the air flow passages throughout the circuit, fitting/connector's internal diameters, mounting positions and the distances from the cylinder, directional control, flow control and rapid relief valves' nominal width for air flow, pipe/tube internal diameters and working element frictional force.

The response time parameter and measurement methods are discussed in [10, 16] as characteristics of the on/off solenoid valve. These characteristics are focused on the control of the position of a pneumatic cylinder in the system. This includes dead-time, the rise time of valve and the maximum current. Additional parameters are the: valve opening signal, on duty ratio of valve for one MPWM cycle, MPWM cycle time and continuous time.

The parameters are analyzed in [11] considering the static and dynamic characteristics of the valve by solving equations, using mathematical models in MATLAB and Simulink. The parameters of disc time delay, disc travel time and total opening time of the valve are presented. Total closing time is defined as the sum of closing delay time and the disc travel time of the valve closing. The analysis in [15] illustrates plots and compared graphs for current consumption rates at 24 V and 15 V versus time to attain the maximum rated current, used to find out the spool position against duty cycle.

The parameter discussion in existing works reveals that the integrated approach of input signals and final pressure output of valve responsive time needs further improvement. The valve response time parameters are investigated under the integrated conditions of signal input and output pressure. The response

parameters are on delay (t_1), on time (t_2), off delay (t_3), off time (t_4), Coil's switching frequency (CSF), Valve's working frequency (VWF).

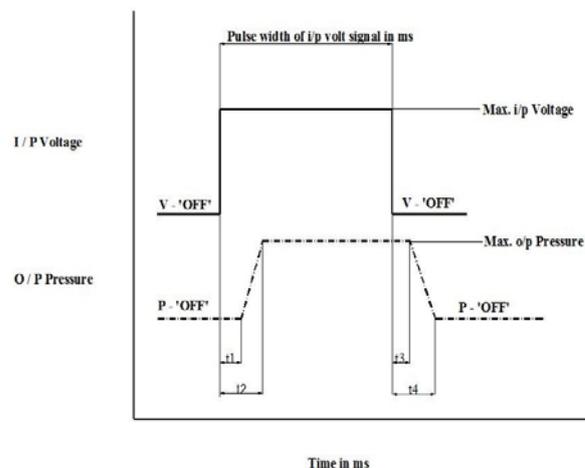


Fig. 1. Response Parameters Diagram

The response time parameters are illustrated in Figure 1 for 24 V signal input and output pressure. The input signal curve shows the supply input time, pulse width and supply off time. The line pressure curve indicates the pressure on, maximum output pressure and pressure off. On delay (t_1) is measured as the lagging time or time difference between the coil energizing and the pressure just starting to shoot-up. On time (t_2) is measured as the maximum (100%) inlet air pressure that reached the outlet. Off delay (t_3) is measured as the lagging time or time difference between the coil de-energizing and the pressure just starting to decrease from the maximum. Off time (t_4) can be defined as the time taken to shut off the valve pressure completely. The response time is measured in milli seconds (ms) and Coil's switching frequency (CSF) and Valve's working frequency (VWF) are calculated as:

- Coil's switching frequency (CSF) = $1000/(t_1+t_3)$ Hz
- Valve's working frequency (VWF) = $1000/(t_2+t_4)$ Hz

III. RESPONSE TIME MEASURING KIT

A response time measuring experimental test kit includes the compressor unit, the air pressure reservoir with a capacity of 3000 mm³, the pressure regulator and the response time measuring unit. The response time measuring unit is presented in Figure 2 with a of 3/2 normally closed solenoid valve as a test specimen, a pulse generator, a pressure transducer, a cathode ray oscilloscope (CRO), a 24 V DC Power supply and a relay unit. Pressure transducer (4-20 mA) and pulse generator (24 V DC signals and pulse width ranging from 1 to 999 ms) are preferred in this unit to get more accuracy and a better least count value.

The working principle of the measuring kit is represented in Figure 3. The regulated input air pressure is supplied to the solenoid valve, which is fixed in the measuring unit. The pulse generator generates a 24 V DC input signal to the 8 Watt coil,

which causes the plunger movement. The plunger movement permits the air flow from the upstream to the downstream side.



Fig. 2. Response time measuring unit

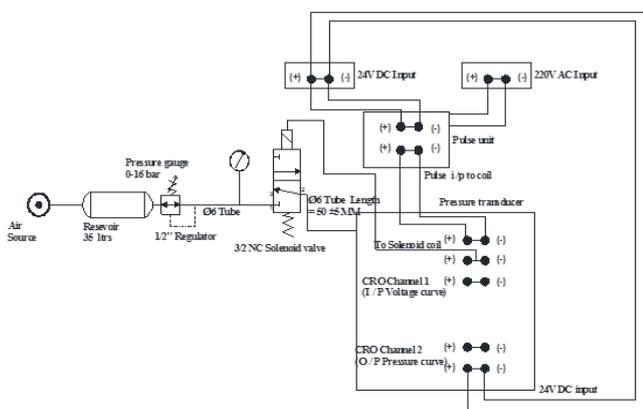


Fig. 3. Block diagram of measuring kit

The pulse generation is predefined as 30 ms to ensure the maximum opening of plunger movement. The measurement procedure of the current in the solenoid valve applied, is the one proposed in [11] with the ‘ON’ signal applied to the valve for 100 ms. The current was measured from the voltage drop across the resistance, which is serially connected to the solenoid valve. The measured current is captured as an input voltage signal graph in the CRO unit. Simultaneously the pressure transmitter senses and converts the downstream pressure to the corresponding output signal which is captured as an output pressure graph in the CRO unit. Fixed and movable cursors are available in the CRO output for measuring the time lagging or time difference of input supply and output pressure.

IV. RESULTS

Two types of 3/2 NC solenoid valves with different orifice diameters are employed to measure the four response parameters namely t1, t2, t3 and t4. Further, CSF and VWF are calculated. The response parameters of the solenoid valve of orifice diameter of 1.2 mm are presented in Table I and for the

one with orifice diameter of 2.5 mm are presented in Table II. Seven tests are conducted with pressure ranging between 1 bar and 7 bar as shown in Table I and II.

TABLE I. SOLENOID VALVE OF 1.2 mm ORIFICE DIAMETER.

Test No.	Input air pressure (Bar)	t1 (ms)	t2 (ms)	t3 (ms)	t4 (ms)	CSF (Hz)	VWF (Hz)
1	1	14	40	8	43	22	83
2	2	14	61	8	73	22	134
3	3	14	66	8	82	22	148
4	4	14	68	8	92	22	160
5	5	14	70	8	95	22	165
6	6	14	71	8	113	22	184
7	7	14	72	8	116	22	188

TABLE II. SOLENOID VALVE OF 2.5 MM ORIFICE DIAMETER.

Test No.	Input air pressure (Bar)	t1 (ms)	t2 (ms)	t3 (ms)	t4 (ms)	CSF (Hz)	VWF (Hz)
1	1	11	20.0	10	18.4	21	38.4
2	2	11	21.0	10	25.6	21	46.6
3	3	11	23.6	10	32.8	21	56.4
4	4	11	24.8	10	38.4	21	63.2
5	5	11	25.6	10	42.0	21	67.8
6	6	11	25.7	10	46.4	21	72.1
7	7	11	27.1	10	55.6	21	82.7

V. DISCUSSIONS

The above parameter data reveals that t1 for the 1.2 mm orifice is 14 ms and for the 2.5 mm orifice is 11 ms. Similarly, t3 is 8 ms for the 1.2 mm orifice and 10 ms for the 2.5 mm orifice. The study reveals t1 and t3 to be constant for varying pressure conditions. The difference between t1 and t3 is 6 ms for the 1.2 mm valve and 1 ms for the 2.5 mm valve. This implies that an increase in nozzle diameter brings down the gap between t1 and t3. The increase in orifice diameter of the valve reduces t1 due to the increase of thrust to the plunger whereas t3 increases due to the time delay in exhausting. The input pressure correspondingly increases t2 and t4 in both valves. The double increment of orifice diameter (1.2 mm to 2.5 mm) causes a 50% reduction in the total cycle time (VWF). In Figure 4, the valve working frequency for various pressure ranges is plotted for the 1.2 mm orifice and the 2.5 mm orifice valves.

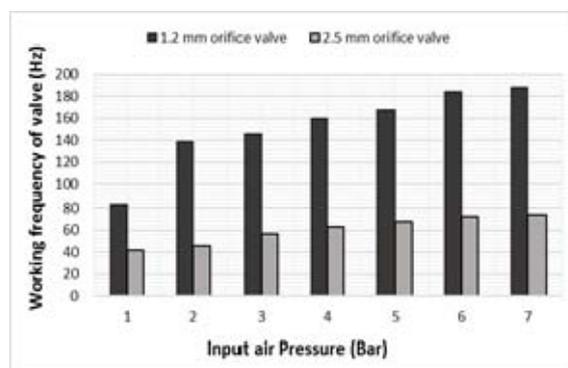


Fig. 4. Input air pressure Vs. Valve’s working frequency

The on delay time t_1 reveals the behaviour of electro-mechanical component's response with respect to the input signal during magnetisation whereas the off delay time t_3 shows the behaviour during de-magnetisation. The response time parameter of coil i.e; t_1 & t_3 are the very important parameters required to calculate the switching frequency for blowing and sorting applications where the outlet pressure is opened to atmosphere. Similarly the on time t_2 and t_4 can be used to calculate the working frequency of the valve at loaded conditions of any pneumatic system (valve's outlet pressure is connected to any type of pneumatic actuator).

VI. CONCLUSIONS

In this paper, the behavior of the response time parameters of pneumatic solenoid valves with various working pressures is investigated with the establishment of measurement methods and test results. Four parameters are measured and the remaining 2 parameters are calculated for two types of valves. The importance and the usages of each and every response parameter are discussed. It is shown that the orifice diameters and input pressure influence the response parameter and the cycle time of the valve. This work can be extended further in order to reduce the difference between on delay and off delay timings with increased orifice diameter.

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