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Experimental Investigation of Dynamic Processes in an Electropneumatic Positioning System with High Speed Valves and PWM

Georgi Slavchev Iliev
dept. Power Engineering
Technical University of Gabrovo
Center of competence "Smart mechatronic, eco-and energy-saving systems and technologies"
Gabrovo, Bulgaria
g.iliev@tugab.bg

Hristo Nedev Hristov
dept. Power Engineering
Technical University of Gabrovo
Center of competence "Smart mechatronic, eco-and energy-saving systems and technologies"
Gabrovo, Bulgaria
christo@tugab.bg

***Abstract*— This paper presents a demonstration experimental test bench for investigating the dynamic characteristics of an electropneumatic positioning system with High Speed Pneumatic Valves (HSPV) and Pulse Width Modulation (PWM) control. A specialized virtual instrument has been developed for real-time control, data acquisition, and processing. The transient response of the electropneumatic positioning system is examined under various single-step input signals with frequencies ranging from 30 Hz to 70 Hz and varying duty cycles from 30% to 90%. The results are presented graphically, demonstrating that the system exhibits better linear characteristics compared to conventional pneumatic actuation systems.**

Keywords*— *dynamic characteristics, electropneumatic positioning system, high speed pneumatic valves, PWM control.

I. INTRODUCTION

Pneumatic actuation systems have been utilized in engineering for many years. In the past, they were primarily used for movement between two positions with end-of-travel switches due to their poor dynamic and nonlinear characteristics [4],[6],[12]. Advancements in technology, electronics, and microprocessor systems have led to a growing adoption of pneumatic actuation systems in the industry. They are widely applied in robotics, aviation, CNC machines, metallurgy, and many other technologies. These systems are environmentally friendly and energy- saving.

In most applications, pneumatic actuation systems are utilized for position control of the pneumatic actuator when using pneumatic servo valves or proportional distributors. However, pneumatic servo valves are expensive, and proportional distributors do not offer the fastest response time due to their deadband sensitivity [1]-[5],[10].

To find an alternative technical solution for the precise positioning of pneumatic actuation systems, switching valves with digital control techniques such as Pulse Width Modulation (PWM) can be used to achieve linear dynamic flow control characteristics with the fastest possible response time and significantly reduced electrical power consumption. Conventional single-stage solenoid on/off valves are bulky and have low dynamic characteristics. These valves make fine positioning control difficult due to the valve's response limitations. Therefore, a high speed switching valve is required to achieve high performance [11], [13], [16], [18], [20].

The primary reason for using PWM control for fast switching is to reduce the valve response time. These valves are characterized by miniaturization of the main overall dimensions of the housing and internal elements, as well as advanced electronics. Many researchers have applied PWM techniques in controlling pneumatic switching valves and have obtained positive results. The PWM signal frequencies used depend on the valve response time and typically range between 20 Hz and 100 Hz. The relationship between pulse width and flow rate has always been considered linear.

The standard equation for flow rate through a pneumatic valve is defined in ISO 6358 (2013) and is used in almost all mathematical models of high speed switching pneumatic valves. As a result, further in-depth research is required to examine the dynamic characteristics of electropneumatic positioning systems with High Speed Pneumatic Valves (HSPV) and PWM control. More accurate mathematical models should be

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developed to describe the dynamics of position control in electropneumatic positioning systems utilizing HSPV and PWM control [20], [21].

II. MATERIALS AND METHODS

The HSPV used in this study of the dynamic characteristics of the electro-pneumatic positioning system is the SX 12 F-AH (0.15~0.7 MPa) from SMC Japan, with a response time of less than 0.4 ms. Description and Construction of HSPV. The HSPV is designed as an electromagnetic, on-off, 2/2 valve. The plunger consists of a rectangular plate made of magnetic material with a specific geometry. During operation, the coil lifts the plunger, and when deactivated, it returns to its initial position due to pressure (a spring is not involved in the valve's operation). A specialized pneumatic demonstration stand has been developed, as shown in Figure 2, for experimental studies on dynamic processes in pneumatic actuation systems with HSPV.

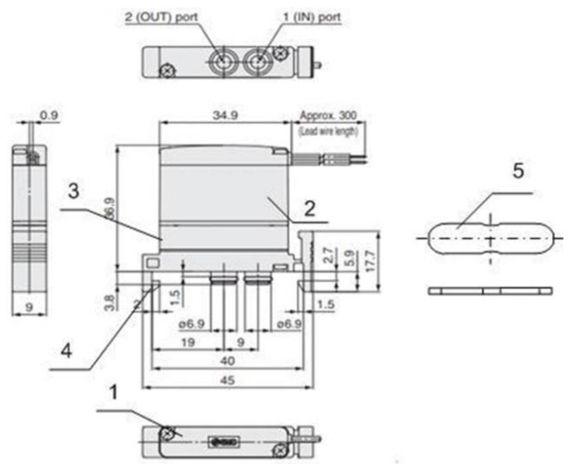

Fig. 1 Illustrates the schematic of the HSPV - SX 12 F-AH, SMC Japan.

1. Cover cap; 2. Upper panel with an electromagnetic coil; 3. Second panel housing the working zone of the plunger; 4. Lower panel with connectors for valve connection, inlet, and outlet; 5. Plunger (plate made of magnetic material).

The stand is equipped with a state-of-the-art data acquisition system (DAQ) and a specialized virtual instrument that allows real-time investigation of transient processes in the electro-pneumatic positioning system with HSPV and PWM control.

The control of the piston position in the pneumatic cylinder with a double-extended rod, "AIGNEP MJ0250125," within the electro-pneumatic system is achieved using four high-speed pneumatic valves, as shown in Figure 1. The operation is schematically illustrated in Figure 2. When all four valves are closed, the piston remains in the desired position. When Valve 1 and Valve 4 are opened, the piston moves forward. Similarly, when Valve 2 and Valve 3 are opened, the piston moves backward. The solenoid is actuated using pulse-width modulation (PWM) control, implemented through analog circuits. A virtual instrument has been created using the "LabVIEW" software for managing and investigating the dynamic processes in the electro-pneumatic positioning system with HSPV and PWM control, along with the corresponding NI interface board [4].

The closing position of the valve is determined by the maximum force generated by the flow acting on the plunger. This maximum force is equal to the force exerted by the static pressure, which in turn can be calculated based on the pressure in the closed state and the surface area over which it acts [21].

The developed virtual instrument enables both the control of the electro-pneumatic tracking system and its real-time investigation by collecting and processing data from sensors measuring displacement, flow rate, and pressure [1],[5],[10].

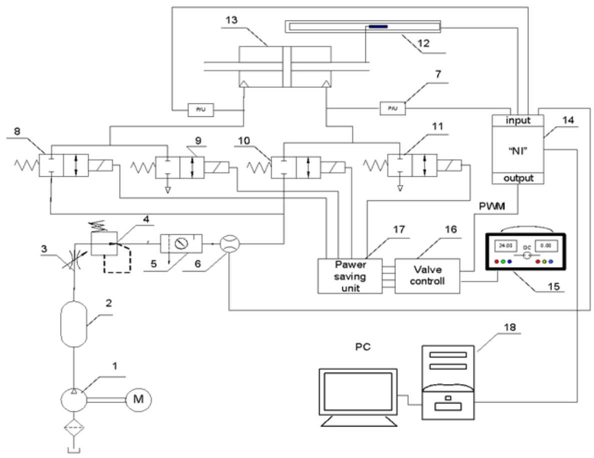

Fig. 2 Specialized pneumatic demonstration stand

1 - screw compressor; 2 - receiver; 3 – throtle valve; 4 – presure ruducting valve; 5 - air preparation system preparatory; 6 - flowmeter; 7 - pressure transducer, 8, 9, 10, 11 high speed pneumatic on/off valve; 12 - potentiometric sensor, 13 - double-rod pneumatic cylinder, 14 - terminal board (NI); 15 - power supply unit; 16 – Valve Controler, 17 - Power saving unit, 18 – PC,

The virtual instrument generates both single-step input signals and sinusoidal pulse-width modulated (PWM) control signals. The formation of single-step signals and sinusoidal voltage through pulse width modulation (PWM) is crucial for effective control of the HSPV, allowing smooth modulation depth adjustment. PWM implementation results in significant energy savings while maintaining high process control quality [4].

The measurement of input signals, piston rod displacement, flow rate, and the pressures in the left and right chambers of the double-rod pneumatic cylinder is recorded using the same virtual instrument. [10], [14], [20], [21].

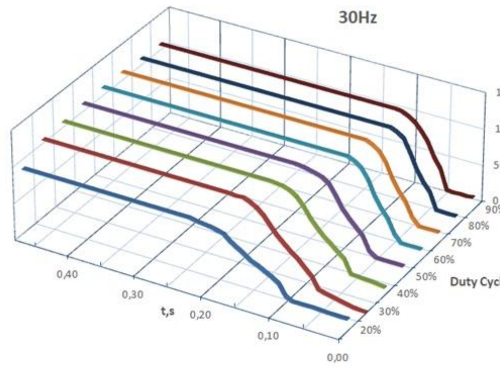

Fig. 3. Displacement of the rod of the pneumatic cylinder at a frequency of 30 Hz and different duty cycle.

Figure 3, 4, 5, 6. Shows experimental transients with PWM at frequencies of 30 Hz and different duty cycles from 30% to 90%.

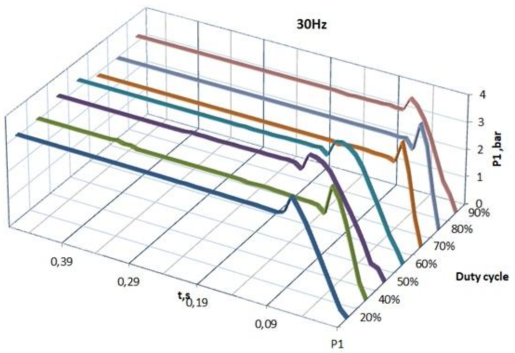

Fig. 4. Pressure drop in the left chamber of the pneumatic cylinder at a frequency of 30 Hz and a different dudy cycle.

When a single-step input signal is applied, the pneumatic cylinder rod moves a precisely defined distance and stops at the set position. The pneumatic cylinder can be controlled with different PWM frequencies and duty cycles.

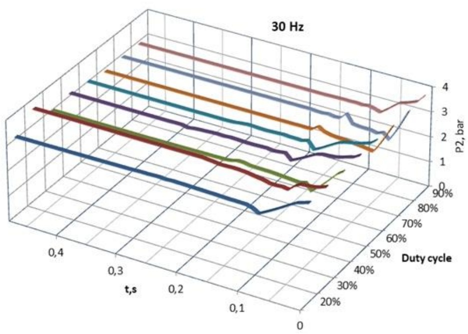

Fig. 5. Pressure washout in the right chamber of the pneumatic cylinder at a frequency of 30 Hz and a different dudy cycle.

Displacement of the rod of the pneumatic cylinder, pressure in the left and right chambers of the cylinder and the flow rate entering the electropneumatic positioning system. The results are shown graphically. The selected operating pressure for the electro-pneumatic positioning system is 4 bar.

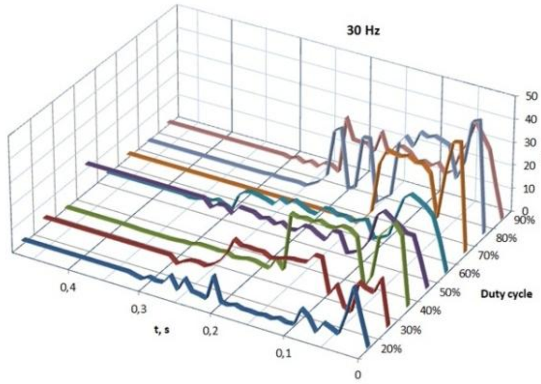

Fig. 6. Variation of the flow rate entering the electropneumatic positioning system.

Figure 7, 8, 9, 10. Shows experimental transients with PWM at frequencies of 50 Hz and different duty cycles from 30% to 90%.

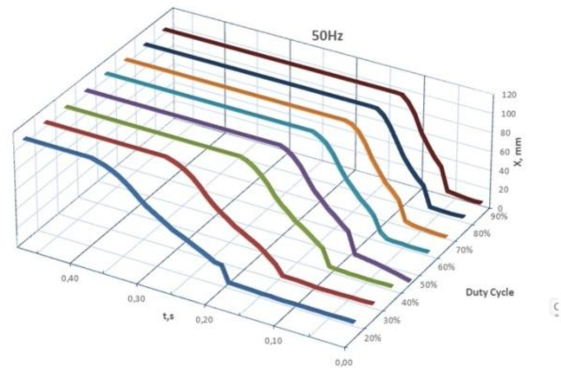

Fig. 7. Displacement of the rod of the pneumatic cylinder at a frequency of 50 Hz and different duty cycle.

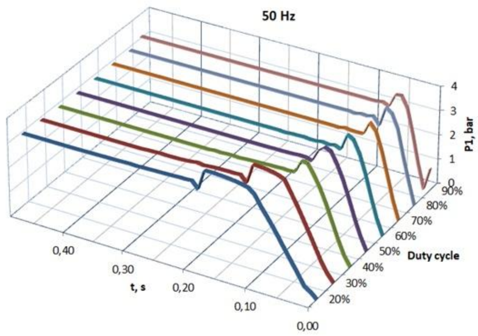

Fig. 8. Pressure drop in the left chamber of the pneumatic cylinder at a frequency of 50 Hz and a different dudy cycle.

Displacement of the rod of the pneumatic cylinder, pressure in the left and right chambers of the cylinder and the flow rate entering the electropneumatic positioning system. The results are shown graphically.

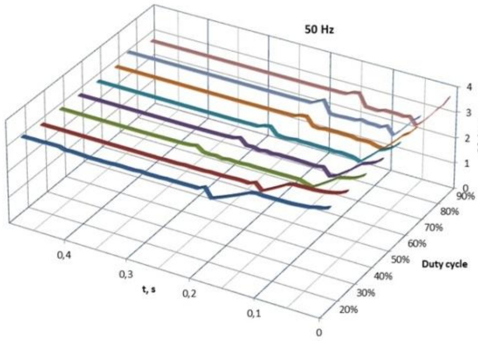

Fig. 9. Pressure washout in the right chamber of the pneumatic cylinder at a frequency of 50 Hz and a different dudy cycle.

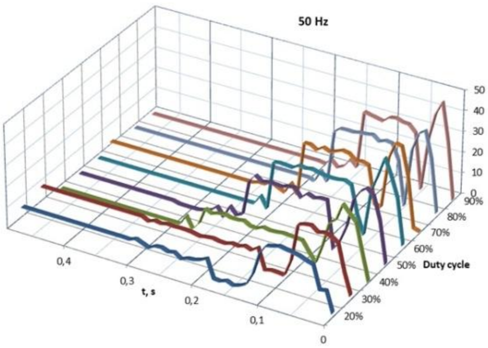

Fig. 10. Variation of the flow rate entering the electropneumatic positioning system.

Figure 11, 12, 13, 14. Shows experimental transients with PWM at frequencies of 50 Hz and different duty cycles from 30% to 90%. Displacement of the rod of the pneumatic cylinder, pressure in the left and right chambers of the cylinder and the flow rate entering the electropneumatic positioning system. The results are shown graphically.

From the resulting transients, at 30 Hz frequency and Duty Cycle change, the following is observed:

At 20% Duty Cycle, there is a time delay of the spent input signal of 0.08 seconds. The rod travel time of the pneumatic cylinder is from 0.08 to 0.22 s for a distance of 70mm. The average speed is 0.50 m/s.

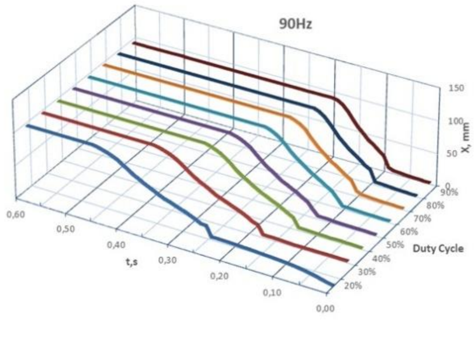

Fig. 11. Displacement of the rod of the pneumatic cylinder at a frequency of 90 Hz and different duty cycle.

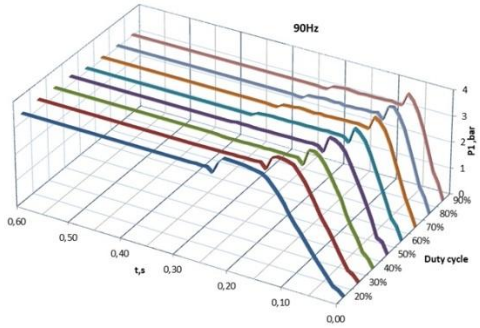

Fig. 12. Pressure drop in the left chamber of the pneumatic cylinder at a frequency of 90 Hz and a different dudy cycle.

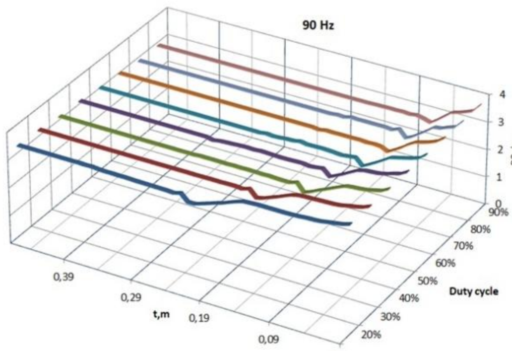

Fig. 13. Pressure washout in the right chamber of the pneumatic cylinder at a frequency of 90 Hz and a different dudy cycle.

At 90% Duty Cycle, the time delay of the spent input signal is 0.08 seconds. The rod travel time of the pneumatic cylinder is in the time range, measured in seconds, of 0.03 to 0.10 for a distance of 70 mm. The average speed is 1.00 m/s.

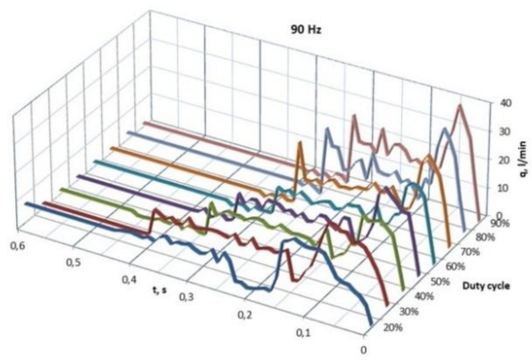

Fig. 14. Variation of the flow rate entering the electropneumatic positioning system.

The measurements and the results obtained in percent fill between 20 and 90% are described in TABLE 1

TABLE 1 EXPERIMENTAL RESULTS AT 30 HZ

Duty Cycle	30 Hz			
	Signal delay time,s	***Move time, S***	***Distance, mm***	***C, m/s***
20%	0.08	0.08-0.22	70	0.500
30%	0.07	0.07-0.19	70	0.583
40 %	0.06	0.06-0.17	70	0.636
50%	0.05	0.05-0.15	70	0.700
60%	0.04	0.04-0.13	70	0.707
70%	0.03	0.03-0.11	70	0.795
80%	0.03	0.03-0.10	70	1.000
90%	0.03	0.03-0.10	70	1.000

TABLE 2 EXPERIMENTAL RESULTS AT 50 HZ

Duty Cycle	50 Hz			
	Signal delay time,s	***Move time, S***	***Distance, mm***	***C, m/s***
20%	0.18	0.18-0.37	70	0.368
30%	0.14	0.14-0.29	70	0.467
40 %	0.10	0.13-0.24	70	0.636
50%	0.08	0.08-0.19	70	0.636
60%	0.07	0.07-0.17	70	0.700
70%	0.06	0.06-0.15	70	0.778
80%	0.05	0.05-0.13	70	0.875
90%	0.05	0.05-0.12	70	0.966

From the resulting transients, at a frequency of 50 Hz and Duty Cycle change, the following is observed:

At 20% Duty Cycle, there is a time delay of the spent input signal of 0.18 seconds. The rod travel time of the pneumatic cylinder is from 0.18 to 0.37s for a distance of 70mm. The average speed is 0.368 m/s.

At 90% Duty Cycle, the time delay of the spent input signal is 0.05 seconds. The rod travel time of the pneumatic cylinder is in the time range, measured in seconds, of 0.05 to 0.13 for a distance of 70mm. The average velocity is 0.966 m/s.

TABLE 3 EXPERIMENTAL RESULTS AT 90 HZ

Duty Cycle	90 Hz			
	Signal delay time,s	***Move time, S***	***Distance, mm***	***C, m/s***
20%	0.24	0.24-0.45	70	0.333
30%	0.17	0.17-0.36	70	0.368
40 %	0.13	0.13-0.28	70	0.467
50%	0.12	0.12-0.26	70	0.500
60%	0.10	0.10-0.23	70	0.538
70%	0.09	0.09-0.21	70	0.538
80%	0.08	0.08-0.18	70	0.700
90%	0.07	0.07-0.17	70	0.700

The measurements and the results obtained in percent fill between 20 and 90% are described in TABLE 2

From the resulting transients, at a frequency of 90 Hz and Duty Cycle change, the following is observed:

At 20% Duty Cycle, there is a time delay of the spent input signal of 0.24 seconds. The rod travel time of the pneumatic cylinder is from 0.24 to 0.45s for a distance of 70mm. The average speed is 0.333 m/s.

At 90% Duty Cycle, the time delay of the spent input signal is 0.07 seconds. The rod travel time of the pneumatic cylinder is in the time range, measured in seconds, of 0.07 to 0.17 for a distance of 70mm. The average speed is 0.70 m/s.

The measurements and the results obtained in percent fill between 20 and 90% are described in TABLE 3.

CONCLUSIONS

The experimental studies on the dynamic characteristics of the electro-pneumatic positioning system with High Speed Pneumatic Valves (HSPV) and Pulse Width Modulation (PWM) control have yielded transient processes—flow rate of the system, pressure in the left and right chambers of the double-rod pneumatic cylinder, and displacement of the cylinder rod—at different input signal values, with frequencies ranging from 30 Hz to 70 Hz and varying duty cycles from 30% to 90%.

The PWM allows to control the speed of the pneumatic cylinder with a double out rod, as well as to monitor the input signal time (delay time). The pressures in the left and right chambers of the pneumatic cylinder show instantaneous response as well as the flow rate entering the system.

The obtained characteristics confirm the improved linear properties of the electropneumatic positioning system, which allows for its broad application in the industry.

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