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Modeling and Simulating Dynamic Processes in an Electropneumatic Positioning System with PWM Control at Different Lengths of the Pneumatic Lines

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*— The electropneumatic drive system with PWM control is used in machines and equipment where it is necessary for the actuator to be positioned at a significant distance from the control valves. This leads to changes in the dynamic characteristics of the systems, depending on the length of the connecting pneumatic lines. The paper presents a mathematical model of an electropneumatic positioning system with PWM control, taking into account the length of the connecting pneumatic lines. The mathematical model has been implemented in the MATLAB Simulink programming environment. A verified and tested model has been used to simulate the dynamic processes in the pneumatic lines. Transient processes have been simulated for different lengths of lines and for various PWM control parameters.**

Keywords*— electropneumatic positioning system, modeling and simulating, pneumatic lines, PWM control.

INTRODUCTION

To achieve linear and stable operation of an electropneumatic positioning system with good dynamic characteristics using high-speed pneumatic valves, a control approach based on Pulse Width Modulation (PWM) is recommended. Many technical developments in electrical engineering utilize PWM control effectively. This method provides linearity, reliability, responsiveness, and energy efficiency for the electropneumatic positioning system. PWM signal frequencies depend on the valve's response time and typically range from 20 to 100 Hz. The main nonlinearities in the dynamic characteristics of the electropneumatic positioning system arise from the relationships between motion and pressure, pressure and flow rate, as well as friction forces in the pneumatic cylinders and changes in the length of the connecting pneumatic lines. The challenge lies in maintaining accuracy in positioning the piston of the pneumatic cylinder. A displacement feedback controller has been employed for each linear positioning model. The final version of the system controller has been developed as a PID controller. Experimental results show that this PWM-controlled PID controller can effectively handle the dominant nonlinearities of the system [11], [13], [17], [18], [21], [23], [24], [25].

To verify the mathematical model of the electropneumatic positioning system and understand its dynamic characteristics, a series of experimental studies were conducted, resulting in an accurate mathematical model and simulation model of the electropneumatic positioning system created in the MATLAB Simulink programming environment [10], [12], [14], [20], [22].

In the electropneumatic positioning system, one of the main issues is accounting for the signal delay along the pneumatic line. Most research is based on laminar flow through the pneumatic line. To find an adequate mathematical model for the mass flow rate through the pneumatic lines, it is necessary to consider the turbulent flow regime as well [1], [3], [5], [10]. It is important to evaluate positioning errors in dynamic mode [19], [20].

The mathematical model must be convenient for calculating the output mass flow rate through pneumatic lines, serving to control pneumatic positioning systems. The model can also be applied to select an effective length of the connecting pneumatic line, which affects the time delay [4], [6], [8], [21].

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I. General Regulations

Based on the mathematical model developed and described in detail in [1] and the description of the mathematical model of the pneumatic lines, taking into account their length L_t, in [2], [7] for the electro-pneumatic positioning system and the experimental studies conducted on the dynamic characteristics and operational stability of the system when controlled by pulse-width modulation of high-speed pneumatic valves and pneumatic lines of varying lengths L_t (1 m, 5 m, and 10 m) and diameters (D=6 mm; d=4 mm) at an operating pressure of 4 bar. Data from the pressure, flow rate, and displacement sensors are visualized, processed, and recorded using a custom-built virtual instrument. The experimental results were obtained from a laboratory bench developed for the purposes of the study, shown in Fig. 1 and described in [9]. For easier analysis, the results are presented graphically (1 m, 5 m, and 10 m) and diameters (D=6 mm; d=4 mm) at an operating pressure of 4 bar. Data from the pressure, flow rate, and displacement sensors are visualized, processed, and recorded using a custom-built virtual instrument. The experimental results were obtained from a laboratory bench developed for the purposes of the study, shown in Fig. 1 and described in [9]. For easier analysis, the results are presented graphically.

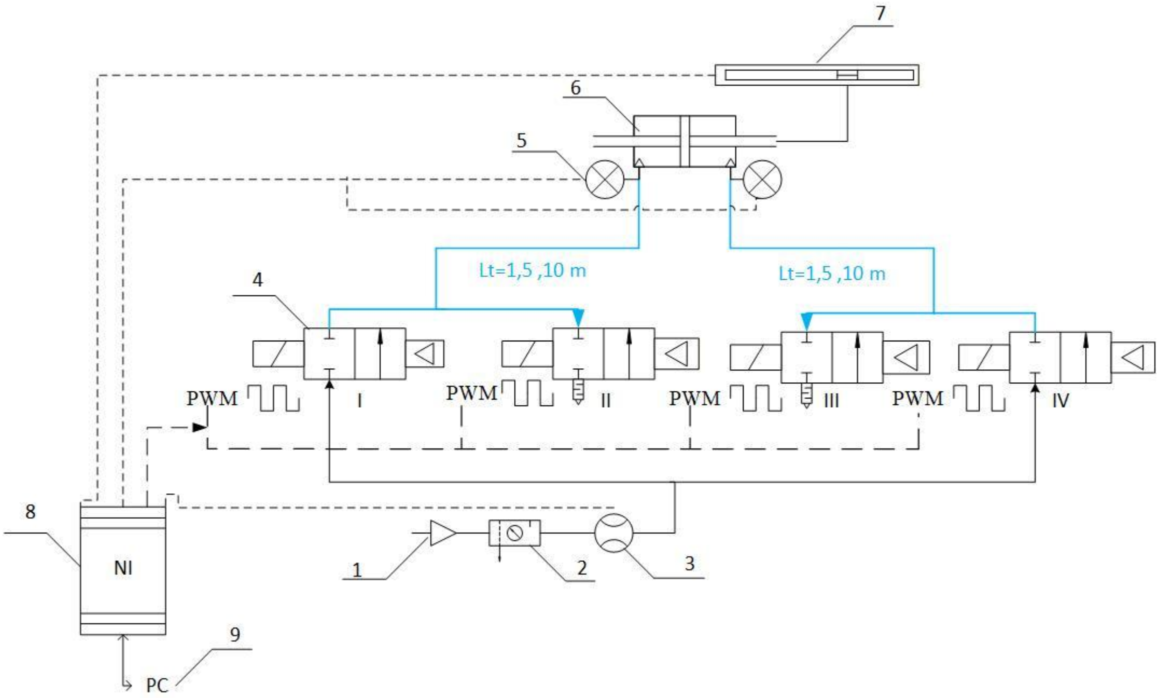

Fig. 1. Principle diagram of the experimental stand for investigating the influence of pneumatic lines with different lengths.

1. Compressed air source; 2. Air preparation unit; 3.Flow meter; 4. High-speed pneumatic valves; 5 Pressure sensor; 6 Pneumatic cylinder; 7 Displacement sensor ;8 Terminal block NI; 9 Personal computer

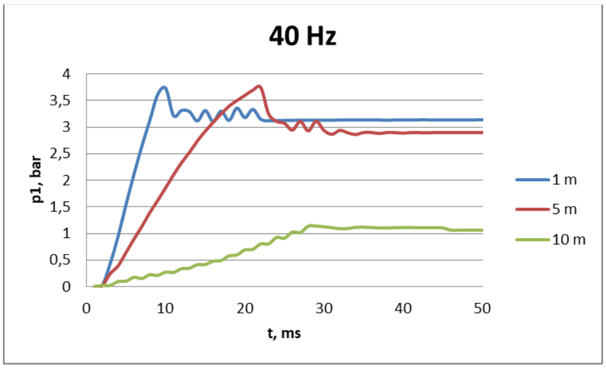

Fig. 2. Experimental data on the change in pressure p_1 entering the left chamber of the pneumatic double-acting cylinder.

Three experiments are conducted for each of the different lengths of the pneumatic lines, and the root mean square error of the measurements is calculated. For a pneumatic line length of 1 m at frequencies of 40, 60, and 80 Hz with a 50% duty cycle, data from the pressure sensors located before the inlet and outlet of the pneumatic double-acting cylinder are recorded in real time. The displacement of the pneumatic cylinder piston is recorded by the potentiometric position sensor, which also serves as the feedback to the PID controller.

Mathematical model of pneumatic lines.

The mass flow rate of the air through the line is given in [1], [2], [3], [7] the equation editor to create your equations.

$$M = \frac{R^2 L_t}{8 a_s \rho^2} \ell^{-\frac{R L_t}{2 \rho a_s}} f\left(t - \frac{L_t}{a_s}\right) \qquad (1)$$

where:
a_s -speed of sound; L_t -length of the pneumatic lines;
R -gas constant of the air; ρ -density; t -time variable.

A flow sensor is installed on the supply pneumatic line leading to the electro-pneumatic control system. The experiments are conducted similarly for pneumatic line lengths of 5 and 10 m.

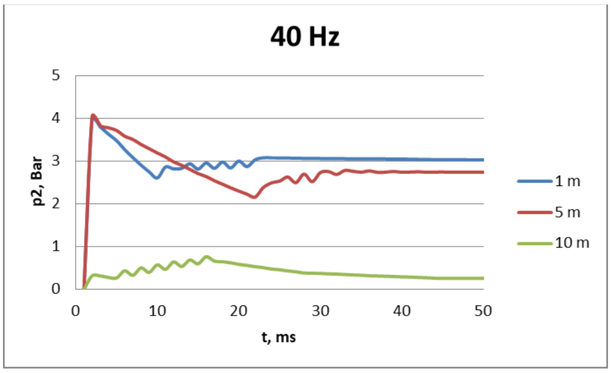

Fig. 3. Experimental data on the change in pressure p_2 exiting the right chamber of the pneumatic double-acting cylinder

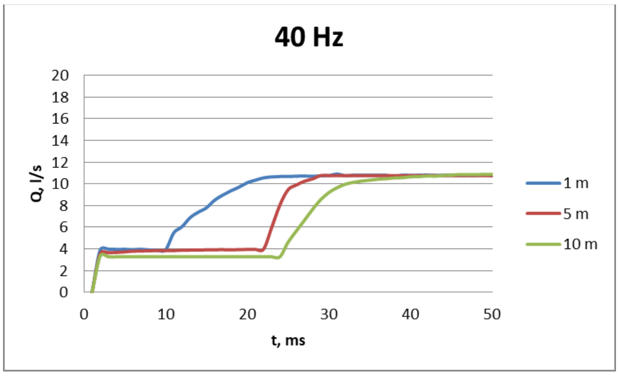

Fig. 4. Experimental data on changes in the flow rate to the electro-pneumatic positioning system

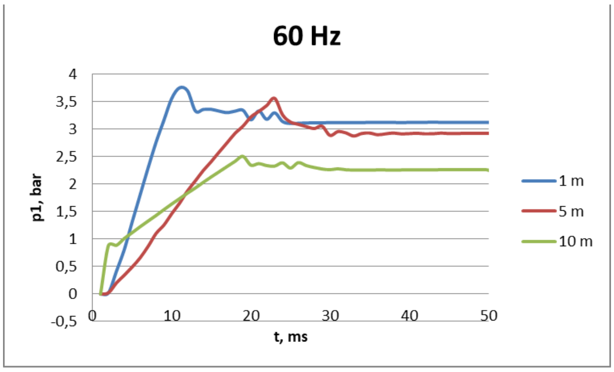

Fig. 5. Experimental data on the change in pressure p_1 entering the left chamber of the pneumatic double-acting cylinder.

In fig. 2, 3 and 4 at 40 Hz and 1 meter length of the pneumatic line, the duration of the transition process is approximately 0.30 s, with the flow rate changing to 10.7 l/s and the pressure at the inlet of the pneumatic cylinder reaching 3.15 bar, while the outlet pressure of the pneumatic cylinder is 3.08 bar.

At a frequency of 60 Hz and 1 meter length of the pneumatic line, the duration of the transition process is approximately 0.25 s, with the flow rate changing to 10.54 l/s and the pressure at the inlet of the pneumatic cylinder reaching 3.11 bar, while the outlet pressure is 3.04 bar (see Fig. 5, 6, 7).

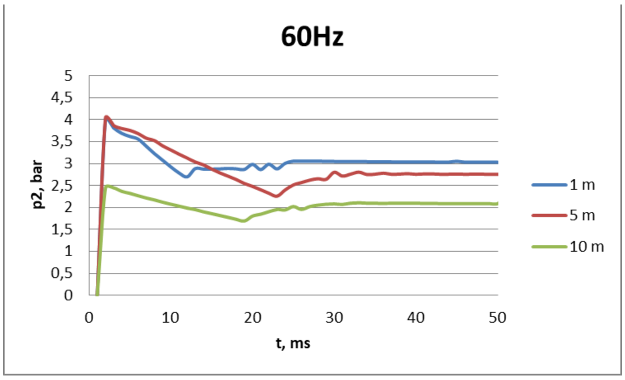

Fig. 6. Experimental data on the change in pressure p_2 exiting the right chamber of the pneumatic double-acting cylinder

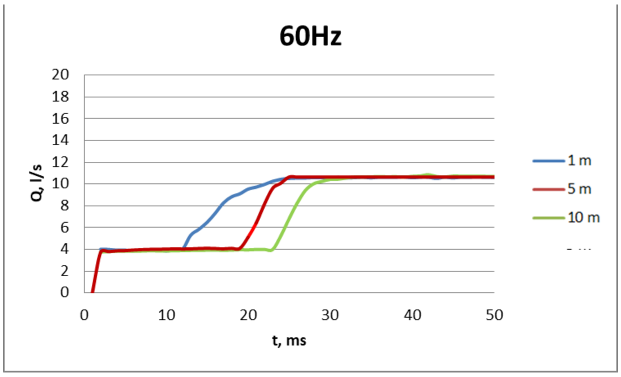

Fig. 7. Experimental data on changes in the flow rate to the electro-pneumatic positioning system

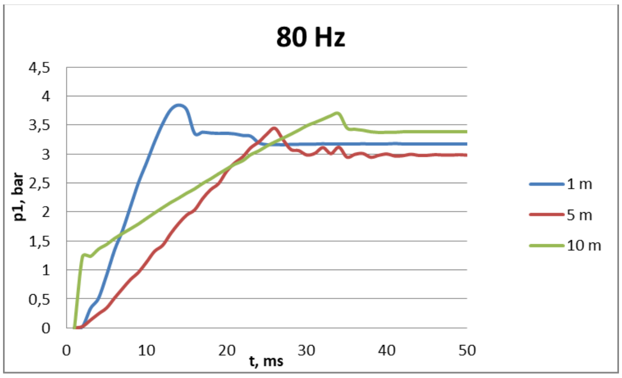

Fig. 8. Experimental data on the change in pressure p_1 entering the left chamber of the pneumatic double-acting cylinder.

At a frequency of 80 Hz and 1 meter length of the pneumatic line, the duration of the transition process is approximately 0.23 s, with the flow rate changing to 10.21 l/s and the pressure at the inlet of the pneumatic cylinder reaching 3.16 bar, while the outlet pressure is 3.05 bar see Fig. 8, 9, 10). The signal delay time along the line at 1 meter for different frequencies ranges from 0.23, 0.25, and 0.30 s, which is solely due to the PWM control and not significantly affected by the length and hydraulic resistance in the line. The experimental results for pneumatic line lengths of 1, 5, and 10 meters are presented in TABLE 1.

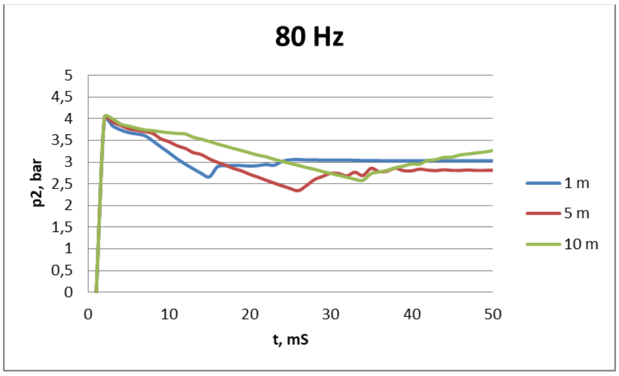

Fig. 9. Experimental data on the change in pressure p_2 exiting the right chamber of the pneumatic double-acting cylinder

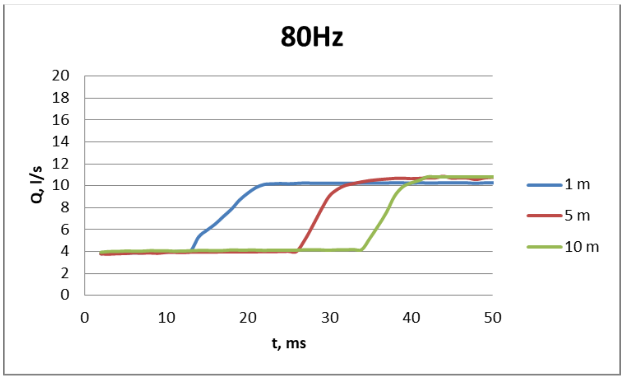

Fig. 10. Experimental data on changes in the flow rate to the electro-pneumatic positioning system

For a pneumatic line length of 5 meters, the duration of the transition processes at 40, 60, and 80 Hz is 0.58, 0.35, and 0.45 s, respectively, with noticeable differences in the changes in pressure at the inlet and outlet of the pneumatic cylinder. The flow rate reaches a value of 10.5 l/s.

The influence of the greater length of the pneumatic line is clearly observed, as it affects the shape and duration of the transition process. Here, the influence of PWM control is also evident, as it delays the signal at lower frequencies. For a pneumatic line length of 10 meters, the duration of the transition processes at 40, 60, and 80 Hz is 0.63, 0.52, and 0.55 s, respectively, with noticeable differences in the changes in pressure at the inlet and outlet of the pneumatic cylinder.

The flow rate reaches a value of 10.5 l/s. The influence of the greater length of the pneumatic line is again clearly observed, affecting the shape and duration of the transition process. It is evident that the influence of PWM control at lower frequencies again affects the signal delay.

In the MATLAB Simulink environment, a simulation model [1] of a pneumatic positioning system has been created and executed. This system consists of four high-speed pneumatic valves, a double-acting pneumatic cylinder, a PWM generator, and a PID controller.

TABLE 1 EXPERIMENTAL DATA

length Lt	*40 Hz 50% duty cycle*			
	p_1, bar	p_2, bar	Q, l/s	t, ms
1 m	**3.15**	**3.08**	**10.70**	**0.30**
5 m	**3.11**	**3.04**	**10.54**	**0.58**
10 m	**1.06**	**0.25**	**11.29**	**0.63**

length Lt	*60 Hz 50% duty cycle*			
	p_1, bar	p_2, bar	Q, l/s	t, ms
1 m	**3.11**	**3.04**	**10.51**	**0.25**
5 m	**2.93**	**2.75**	**10.55**	**0.35**
10 m	**2.22**	**2.14**	**10.64**	**0.52**

length Lt	*80 Hz 50% duty cycle*			
	p_1, bar	p_2, bar	Q, l/s	t, ms
1 m	**3.16**	**3.05**	**10.21**	**0.23**
5 m	**3.11**	**3.04**	**10.58**	**0.45**
10 m	**3.38**	**3.73**	**10.79**	**0.55**

An analysis of the simulated dynamic characteristics will also be performed, comparing the theoretical and experimental dynamic processes in an electropneumatic positioning system with high-speed pneumatic valves using PWM. The model consists of a collection of elements assembled as subsystems. The first elements are those of the compressor unit, necessary for creating and adjusting the input air parameters. Four high-speed pneumatic valves have been added to implement the desired system. Pneumatic lines with corresponding configured parameters and lengths have also been included.

A model of a pneumatic cylinder with specified operating parameters has been added, with parameters that change according to the requirements for the respective experiments. Elements for measuring the corresponding pressures and flow rates at the inlet before the pneumatic unit, as well as before and after each of the valves, have been included. PID and PWM modules have been added, with parameters that change according to the desired settings for the respective simulation. Modules for inputting and converting data from conducted and recorded experimental results from other software, necessary for verifying the model and simulation, have also been added. The comparison data is displayed on screens and presented graphically [5], [15], [16].

In Figure 11, 12, 13 the comparative results from the experiments and simulations of the displacement of the pneumatic cylinder are presented graphically, under PWM control at frequencies of 40, 60, and 80 Hz, with a duty cycle (DC) of 50%, and pneumatic line lengths of 1 m, 5 m, and 10 m. The conducted experiments and simulations have been carried out in a pneumatic positioning system using PWM with a PID controller and a specified displacement of the pneumatic cylinder piston stroke of 100 mm.

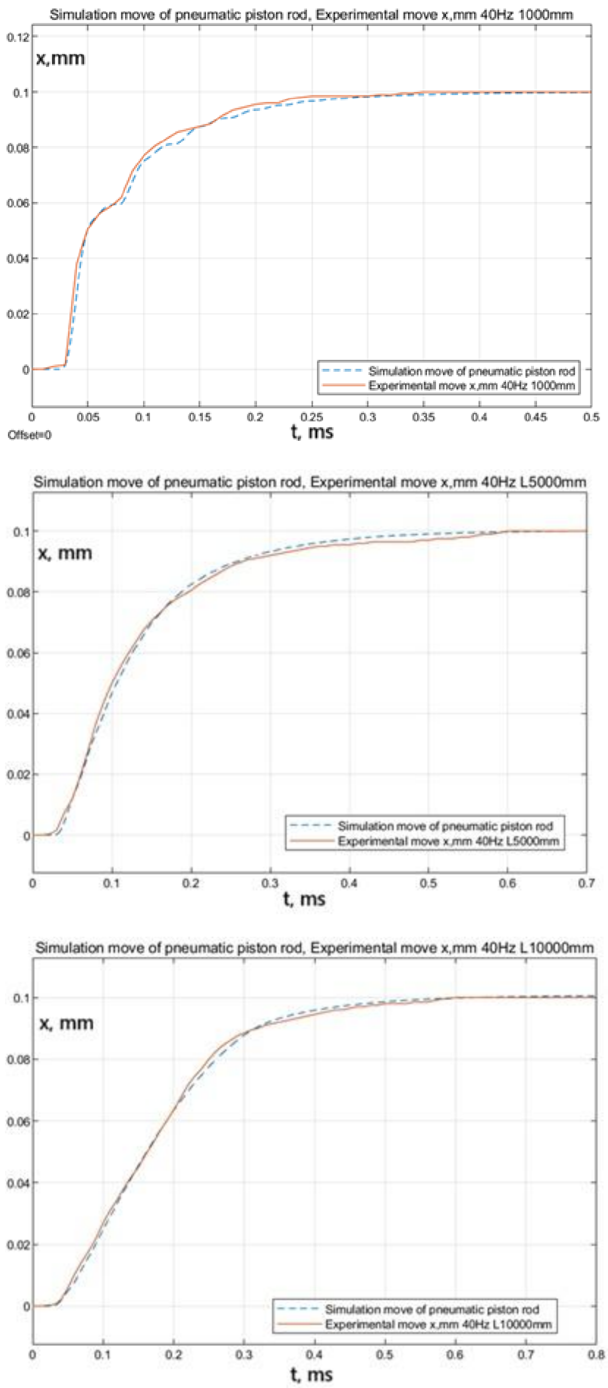

Fig. 11. Simulation move of pneumatic piston rod, experimental move 40 Hz, 1,5 and 10 m.

The presented graphs provide a concise and visually enhanced illustration of processed tabular data from the conducted experiments and the corresponding simulations. The graphs have a process duration of 0.8 s, due to the necessary longest duration for the process to be completed, specifically at 40 Hz and a 50% duty cycle with a pneumatic line length of 10 m, allowing for better visual comparison of the obtained results.

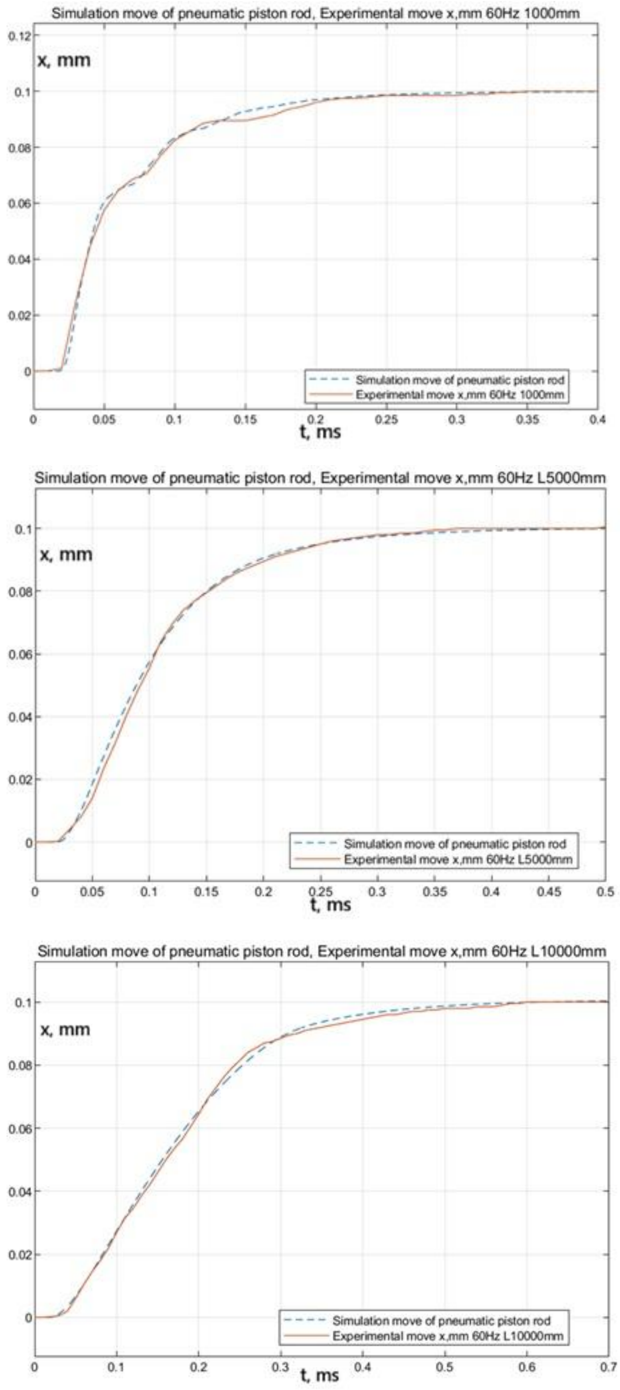

Fig. 12. Simulation move of pneumatic piston rod, experimental move 60 Hz, 1,5 and 10 m.

The input effect changes uniformly in a stepwise manner according to the input setpoint, which is the electrical voltage. The variables are presented in actual values. The value of the input signal is within the working stroke of the pneumatic cylinder.

From the experimental data and the simulation model fig. 11, 12 and 13, it is evident that the experimental curves and the theoretical data are very close.

This proves the adequacy of the model of the pneumatic lines and their influence on the dynamics of the electropneumatic tracking system with four high-speed pneumatic valves and PWM control.

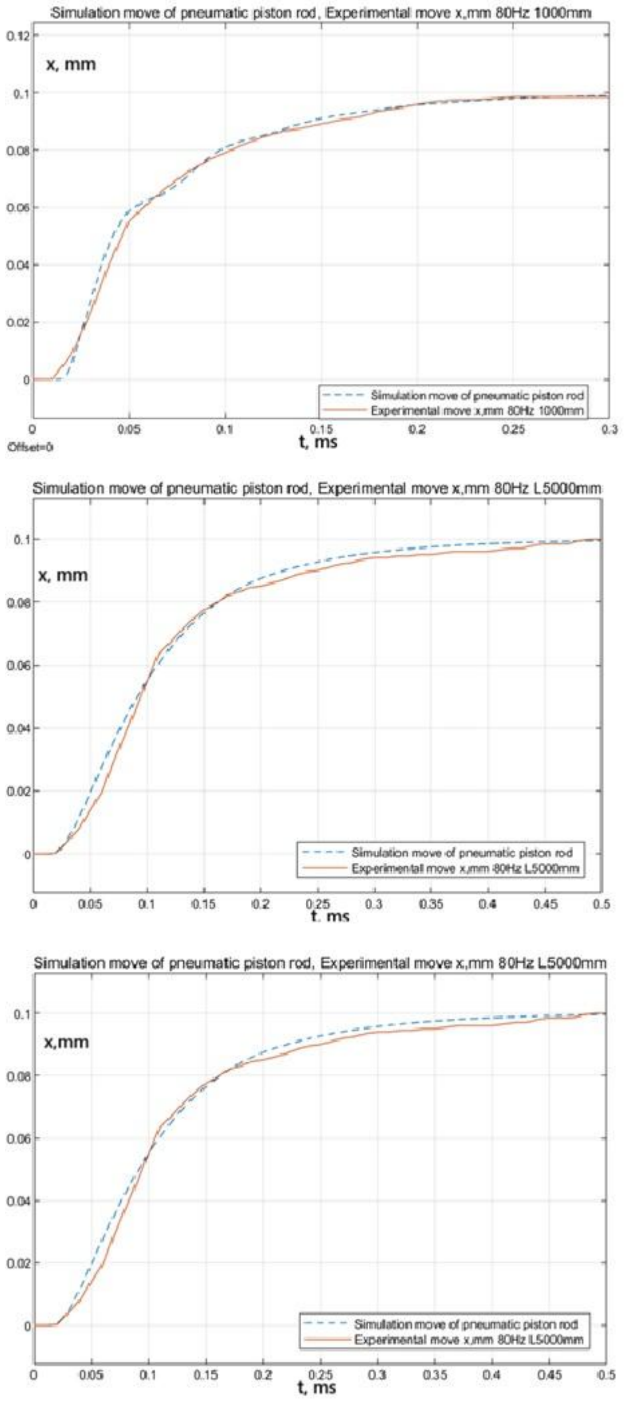

Fig. 13. Simulation move of pneumatic piston rod, experimental move 80 Hz, 1,5 and 10 m.

CONCLUSION

When comparing simulations with different lengths of pneumatic lines, the results indicate that the lengths of 5 and 10 meters significantly impact the parameters of the electropneumatic positioning system during transient processes. Longer pneumatic lines affect system dynamics, particularly regarding time delay and amplitude decay. The influence of PWM at lower frequencies, such as 40 Hz, is also evident and similarly impacts the system's performance. To mitigate the effects of pneumatic line length, it is crucial to consider these lengths and to operate at frequencies above 60 Hz in PWM control. The proposed mathematical model accounts for the mass flow rate through pneumatic lines under turbulent flow conditions, aligning well with experimental results and demonstrating its applicability. This model is sufficiently straightforward for implementation in real-time control applications. The mass flow equation shows that the flow profile at the outlet is delayed in relation to the inlet, corresponding to the time required for the wave to traverse the entire length of the tube. As a result, we can determine the effective tube length L_t associated with this time delay. Additionally, some validation experiments for the model are presented.

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