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Modelling and Simulation of Dynamic Processes of Pneumatic Lines

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***Abstract*. The paper presents the simulation of dynamic processes of pneumatic lines using the program "SIMULINK" from the product "MatLab". Simulation is a process of forming, preparing and entering a mathematical model in a computational environment and obtaining the results of the calculations performed in this environment. The mathematical model of the pneumatic line to be simulated is according to previously presented equations. For the simulation of the dynamic processes, various real parameters of the dimensions and lengths of the pneumatic lines with the corresponding coefficients are introduced into the model. The simulation of the transient responses was carried out with stepwise variation and sinusoidal input signal supplied by the set point device and pneumatic line lengths of 1 m, 5 m and 10 m. The simulation output data were output to the interface in the form of graphs showing the dependence of the observed quantities, the input and output pressure through the pneumatic line, and the input and output flow rates. From the mathematical model and the experiments performed, it can be concluded that the transient responses in the simulations correspond to the dynamic processes of pneumatic lines of different lengths.**

Keywords: pneumatic line, simulation, mathematical model, experiments.

I. INTRODUCTION

Electropneumatic positioning systems are widely used in modern industry. Due to the compressibility of air, the unfavourable friction characteristics in pneumatic devices and the need for different lengths of pneumatic connecting lines, complex control models are required. Electropneumatic drive systems are often applied in the drives of industrial robots, manipulators, machines and equipment, which are subject to a number of requirements related to their operation in static and dynamic modes. The experimental study of pneumatic lines of different lengths allows to compile adequate mathematical models to be used for the study and design of pneumatic systems of high quality that meet the modern requirements of industry. Mathematical modelling plays an increasingly important and defining role in modern engineering research. This is primarily due to the fact that established and proven models are used to simulate and solve problems in actuator systems using the powerful computational complexes developed in recent times [1],[2],[4].

In this way, many more factors influencing the dynamics of the systems can be taken into account, and a comparison can be made between the different mathematical models and the experimental studies performed.

It is known that the study of dynamics for any pneumatic- or hydraulic system is directly dependent on the variation of the main parameters in the connecting lines [2],[3],[4]. In the study of dynamic processes in pneumatic actuator systems, some authors neglect the influence of pneumatic lines. This is possible in some cases, but in others it leads to inadequacy of mathematical models and real processes of the system.

In pneumatic actuation systems, one of the main problems is the consideration of the signal delay along the pneumatic line. Most studies are based on laminar flow through the pneumatic line. In order to find an adequate mathematical model for the mass flow through them, it is necessary to consider the turbulent flow regime [1-15].

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II. Mathematical Modelof Pneumatic Lines

We're examining a cylindrical tube (line) on Fig. 1 with length L_t.The mass flow rate of the air through the line is [1]:

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

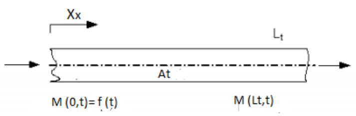

Fig. 1. Pneumatic line.

Where:

a_s	denotes the sound speed;
ρ	is the air dencity;
L_t	cylindrical tube with length
t	time variable
R_r	the tube resistance
A_t	tube cross-sectional area

III. Experimental Investigation Of Dynamic Processes In Pneumatic Lines

In order to verify the obtained mathematical model for the flow through pneumatic lines, it is necessary to experimentally investigate the dynamic processes in the pneumatic lines at different input. The scheme shown in Fig. 2 is of the established experimental rig [4]. Step and sinusoidal input signal are used to obtain the experimental dynamic processes.

IV. Research Methodology

A step input signal is applied to a discrete electro-pneumatic directional valve (6) controlled by an electrical switch (13). Pneumatic lines (D = 8 mm, d = 6 mm) (17) with lengths Lt (1 m, 5 m and 10 m) at an operating pressure of 5 bar are tested. Data from pressure and flow transducers at the inlet and outlet of the pneumatic line are visualized, processed and recorded by an automated real-time data acquisition and processing system.

In the process, the signals from the application and flow sensors, the input signal from the signal generator are fed to the terminal board which facilitates the user in initially switching on external signals by means of rows of terminals which are numbered and labeled.

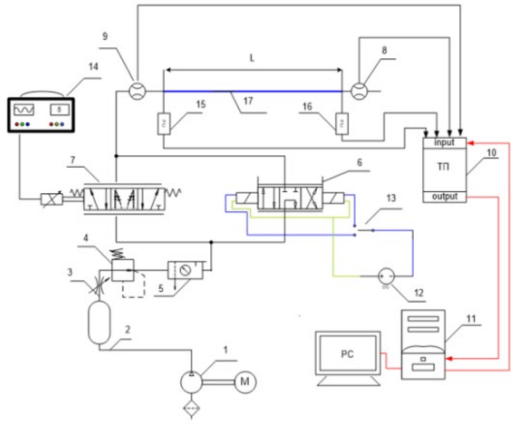

Fig. 2. Schematic of the experimental stand for the study of dynamic processes in pneumatic lines.

1 - screw compressor; 2 - receiver; 3 - stopcock; 4 - safety valve; 5 - air preparation system preparatory; 6 - discrete distributor; 7 - proportional directional control valve; 8, 9 - flow meters; 10 - interface board; 11 - personal computer; 12 - power supply unit; 13 - switch; 14 - signal-generator; 15, 16 - pressure sensors; 17 - pneumatic line.

Additional passive elements in the analog signal path are easily connected to the terminals. In this way, RC-filters, dividers or current signals can be implemented. The signals are processed with a virtual instrument in the LabView environment, using a DAQ board NI PSIe-6351. It is an analog-to-digital 16-bit converter, using a sampling rate in the range 200...2000 samples/sec on each hardware channel. Preliminary calibration of the incoming signals from the sensors was performed in order to work in natural measurement units.

An external signal generator supplies to the terminal board a reference sinusoidal signal, serving as a time reference. Another virtual instrument, a multi-function frequency generator, was also constructed to perform the same tasks as the external signal generator. Both are used in the experiments, their choice depends on the specific needs of the experiment.

V. Virtual Tool

For the purpose of the experiment, a virtual tool was developed to perform the following main functions Fig. 3:

Read the input channels in the following order:

- Measure the input signal;
- Measuring the pressure at the beginning of the pneumatic line;
- Measure the pressure at the end of the pneumatic line;
- Flow measurement at the beginning of the pneumatic line;
- Flow measurement at the end of the pneumatic line.

Fig. 3. User interface of the developed virtual tool.

The next function is the transition in natural units of each of the measured channels. The ability to record to a text file all input signals from a given point in time is provided. The user interface also sets the values of the recording speed, accuracy for recording to the output text file and defines the input tasks to be performed by the virtual instrument [3], [4]. In order to generate a control signal fed to the system input, a multi-function frequency generator was developed to generate an output signal with a sinusoidal shape and the ability to change frequency from 0.01 Hz to 100 kHz, amplitude from 0.01V to 10 V - Fig. 4.

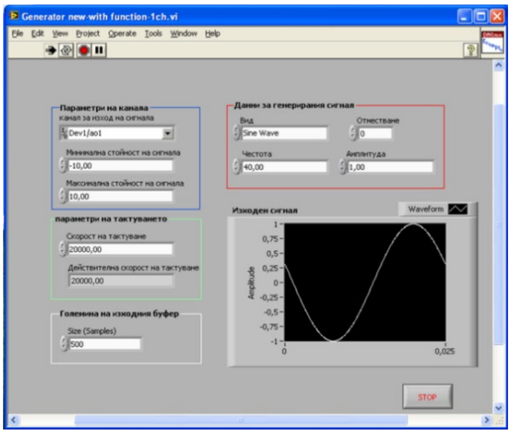

Fig. 4. Multifunction Frequency Generator User Interface.

Fig. 5 and Fig. 6 show the pressure and flow step responses at the inlet and outlet of the pneumatic line at 1 m length and 6 mm diameter. The flow and pressure values are dimensionless with respect to their maximum value.

The duration of the step responses under the flow rate variation Fig. 6. is about 0.15 s with the delay time 0.05s.

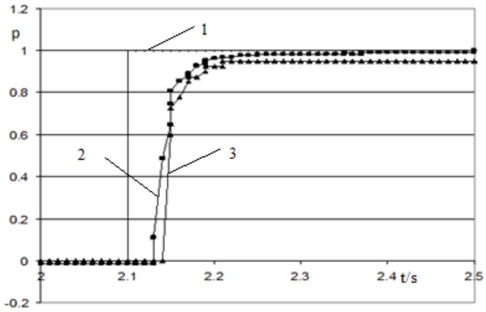

Fig. 5. Pressure at inlet (2) and outlet (3)of pneumatic line at 1 m length; (1) step input signal. (The pressure values are dimensionless with respect to their maximum value).

The transient process under the pressure variation is about 0.10s with the net delay time 0.03s. The steady-state output pressure value is less than the input pressure, Fig. 5. which is due to the hydraulic resistances in the line.

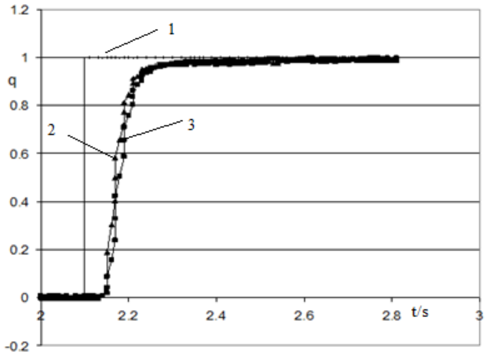

Fig. 6. Pneumatic line inlet (2) and outlet (3) flow at 1 m length; (1) step input signal (The flow values are dimensionless with respect to their maximum value.).

The Fig. 7 and Fig. 8. the pressure and flow step responses at the inlet and outlet of the pneumatic line are shown for a length of 5 m and a diameter of 6 mm.

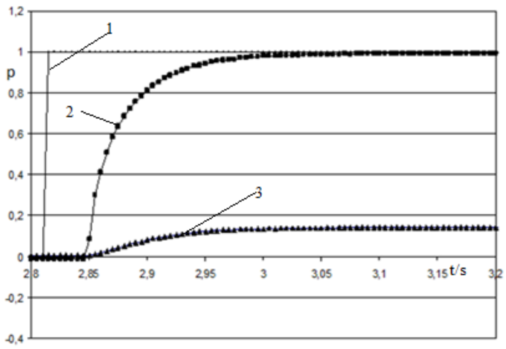

Fig. 7. Pressure at inlet (2) and outlet (3) of pneumatic line at 5 m lengt; (1) step input signal (The pressure values are dimensionless with respect to their maximum value).

The duration of the transition process for a pneumatic line length of 5 m is shown in Fig. 7. The flow rate variation is about 0.25 s with a delay time of 0.07 s. In Fig. 8. the transient process at pressure variation is about 0.15s with a net delay time of 0.05s

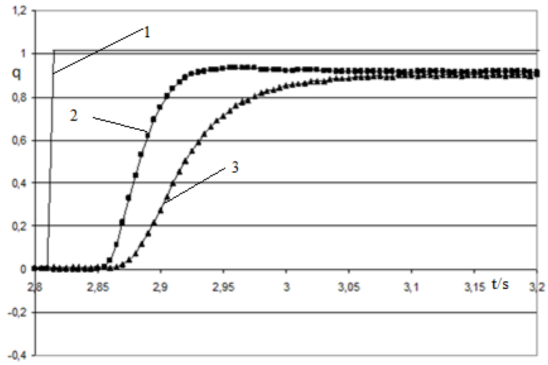

Fig. 8. Pneumatic line inlet (2) and outlet (3) flow at 5 m length; (1) step input signal (The flow values are dimensionless with respect to their maximum value).

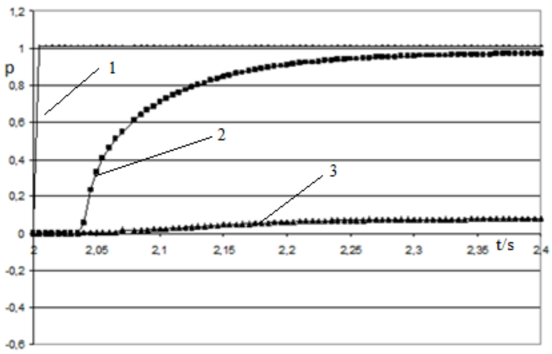

Fig. 9. Pressure at inlet (2) and outlet (3) of pneumatic line at 10 m length; (1) step input signal (The pressure values are dimensionless with respect to their maximum value).

Fig. 9 and Fig. 10 show the pressure and flow step responses at the inlet and outlet of the pneumatic line at 10m length and 6mm diameter.

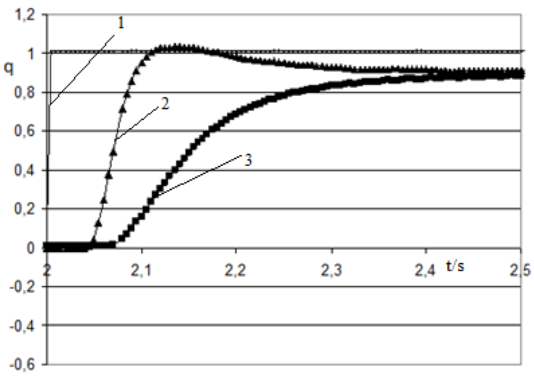

Fig. 10. Pneumatic line inlet and outlet flow at 10 m length; (1) step input signal (The flow values are dimensionless with respect to their maximum value).

The duration of the transient process for a pneumatic line length of 10 m, the flow rate variation is about 0.40 s with a delay time of 0.08 s Fig. 10. and the transient process for pressure variation is about 0.25 s with a delay time of 0.06 s Fig. 9.

When comparing the results of the study of the processes in pneumatic lines of 1m, 5 m and 10 m length, the significant influence of the larger length of the pneumatic line is observed, which affects the shape and duration of the process for flow variation changes from 0.15 to 0.40 s, and the delay time from 0.05 to 0.08 s, and the transient process at pressure variation is from 0.10 to 0.25 s, with the delay time from 0.03 to 0.06 s.

VI. Experimental Study Of Transients In A Pneumatic Line Of Varying Length With Sinusoidal Input Signal

The conduct of the experiment is analogous to the previous one, where the input signal is replaced by a sinusoidal signal set by a signal generator.

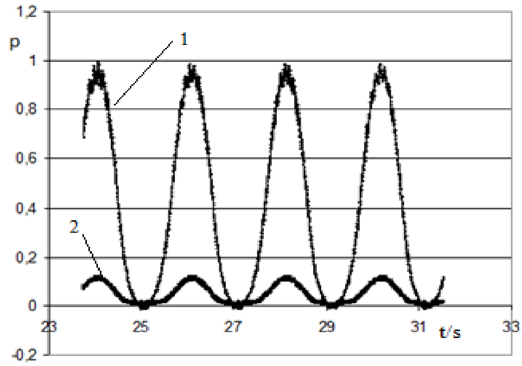

Fig. 11. Pneumatic line inlet (1) and outlet (2) pressure at 5 m length, frequency 0.5 Hz (The pressure values are dimensionless with respect to their maximum value).

A 5 m long pneumatic line was tested at different input signal frequencies of 0.3 and 0.5 Hz.

The results of the experiment-the variation of pressure and flow at the inlet and outlet-are shown in Fig. 11 to Fig.12. The corresponding flow rates and pressures are dimensionless with respect to their maximum value.

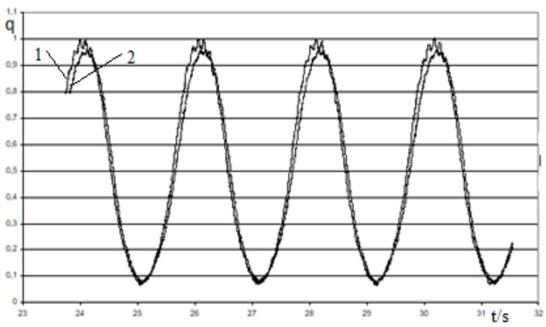

Fig. 12. Pneumatic line inlet (1) and outlet (2) flow at 5 m length, frequency 0.5 Hz (The flow values are dimensionless with respect to their maximum value).

Figure 13 and Figure 14 show the inlet and outlet flow rates and pressures for a pneumatic line length of 5 m, a frequency of 0.3 Hz and a voltage of 5 V.

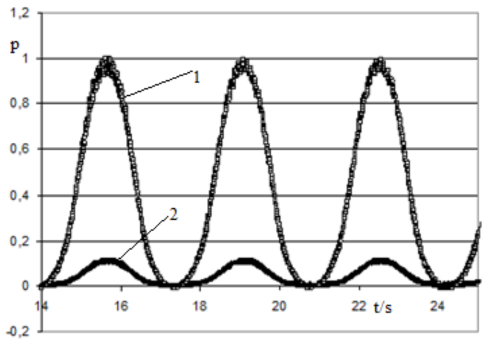

Fig.13. Pneumatic line inlet (1) and outlet (2) pressure at 5 m length, frequency 0.3 Hz (The pressure values are dimensionless with respect to their maximum value).

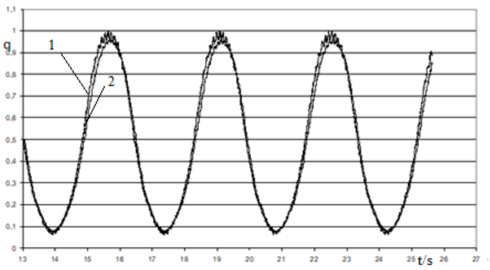

Fig. 14. Pneumatic line inlet (1) and outlet (2) flow at 5 m length, frequency 0.3 Hz (The flow values are dimensionless with respect to their maximum value).

As with step responses, transients in a sinusoidal signal show the influence of the pneumatic line length on flow and pressure variation in the dynamic regime. Phase delay and change in amplitude of the signals are observed. To study the influence of pneumatic lines in detail, it is necessary to fully investigate their frequency characteristics [1], [3],[4].

VII. Modelling And Simulation Of Dynamic Processes Of Pneumatic Lines

Simulation is the process of forming, preparing and entering a mathematical model into a computing environment and obtaining the results of the calculations performed in this environment. The mathematical model of the pneumatic line to be simulated is according to equation (1).

The simulation of dynamic processes in the pneumatic line model is carried out using MatLab SIMULINK. The block diagram of the simulation model is shown in Fig. 15.

For the simulation of the dynamic processes, various real parameters of the dimensions and lengths of the pneumatic lines with the corresponding coefficients are introduced into the model.

The model shown in Fig. 15 was created using the MatLab SIMULINK and the resulting values of the dynamic processes are presented as graphs.

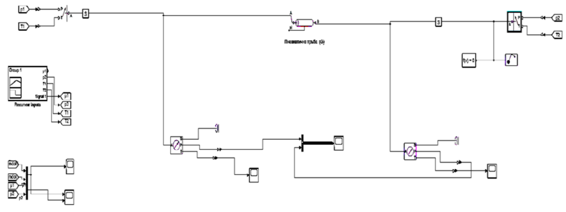

Fig. 15. Simulation model of pneumatic lines in MatLab.

The simulation of the transients has been carried out with step input supplied by the setter and with pneumatic line lengths - 1 m, 5 m and 10 m. The simulation outputs were output to the interface in the form of graphs showing the dependence of the observed quantities, the inlet and outlet pressure through the pneumatic line, and the inlet and outlet flow rates.

From the simulations performed on the mathematical model, the transients are observed at different lengths (1m, 5m and 10 m) of the pneumatic lines and when the main observed quantities (pressure and flow rate) change on both sides of the line - inlet and outlet.

The flow and pressure values in the simulation model plots are presented dimensionless with respect to their maximum value.

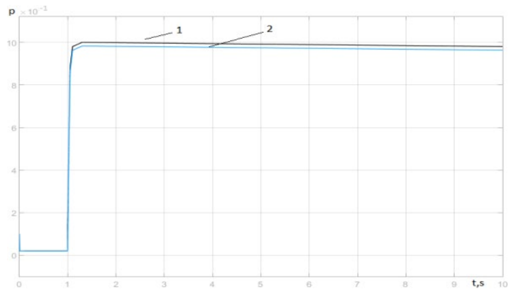

Fig. 16.a. Pressure at the inlet (1) and outlet (2) of a 1 m pneumatic.

At = 1 m the time of the transient process is between 0.1 and 0.15 s. It is clearly evident that the plots are almost identical for the inlet and outlet signals, from which it can be concluded that for a pneumatic line length of 1 m there is no large signal delay, which is analogous to the experimental results Fig.16. a. and Fig. 16.b. discussed in this chapter.

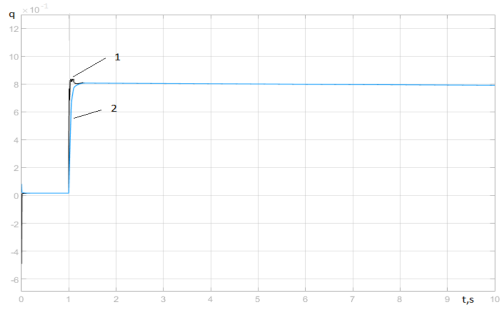

Fig. 16.b. Flow rate at the inlet (1) and outlet (2) of a 1 m pneumatic line.

At = 5 and 10 m pneumatic line length, the transition time is 0.25-0.4 s. There is a clear signal mismatch at the inlet and outlet, from which it can be concluded that there is a signal delay at pneumatic line lengths of 5 m and 10 m, which is analogous to the experimental results Fig. 16.c. and Fig. 16.f.

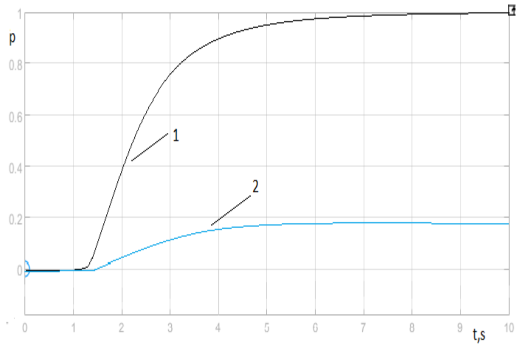

Fig. 16.c. Pressure at the inlet (1) and outlet (2) of a 5 m pneumatic line.

To better evaluate the tracking accuracy, the input and output signals are dimensionless. The analysis performed on the obtained results proves that the mathematical model is adequate and suitable for use.

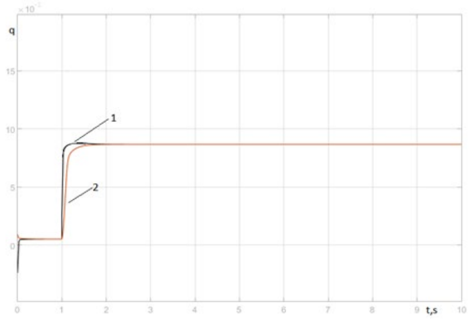

Fig.16.d. Flow rate at the inlet (1) and outlet (2) of a 5 m pneumatic line.

Simulation of the transients is also carried out with a sinusoidal input of 0.5 Hz supplied by the setpoint device.

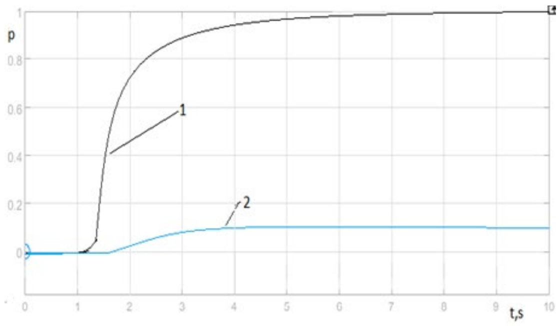

Fig. 16.e. Pressure at the inlet (1) and outlet (2) of a 10 m pneumatic line.

The simulation outputs for pneumatic line lengths of 1 m, 5 m and 10 m are output to the interface in the form of graphs depending on the observed quantities - inlet and outlet pressure and inlet and outlet flow through the pneumatic line. As a result of the conducted simulations the following conclusions can be drawn:

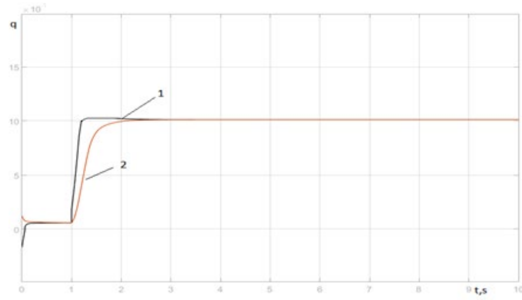

Fig. 16.f. Flow rate at the inlet (1) and outlet (2) of a 10 m pneumatic line.

Simulation of the transients is also conducted with a 0.5 Hz sinusoidal input signal fed through the setpoint device. The simulation outputs for 1 m, 5 m and 10 m pneumatic line lengths are output to the interface in the form of graphs - inlet and outlet pressure and inlet and outlet flow through the pneumatic line.

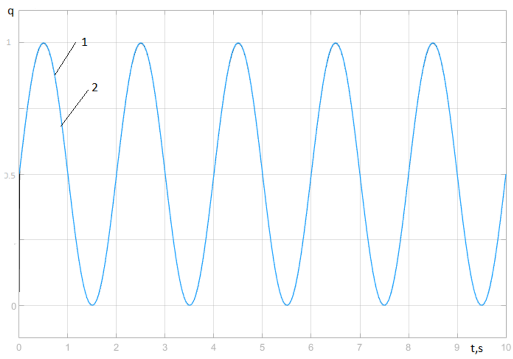

Fig. 17.a. Input (1) and output (2) pressures at 1 m pneumatic line and 0.5 Hz frequency.

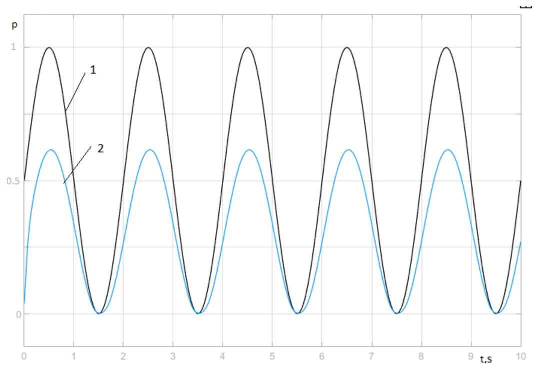

Fig. 17.b. Input (1) and output (2) pressures at 5 m pneumatic line and 0.5 Hz frequency.

At a frequency of the input sinusoidal signal of 0.5 Hz, a phase delay in the order of 50 – 60 Fig. 17.b and a decrease in the signal amplitude are observed, which corresponds to the experimental results Fig. 11. and Fig. 12.

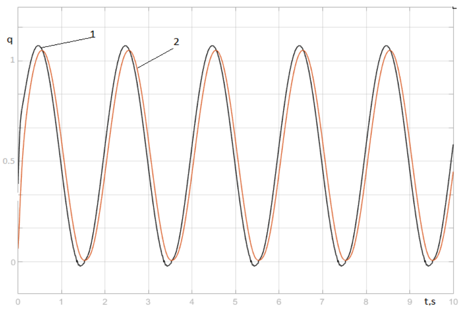

Fig. 17.c. Inlet (1) and outlet (2) flow rates at 5 m pneumatic line and 0.5 Hz frequency.

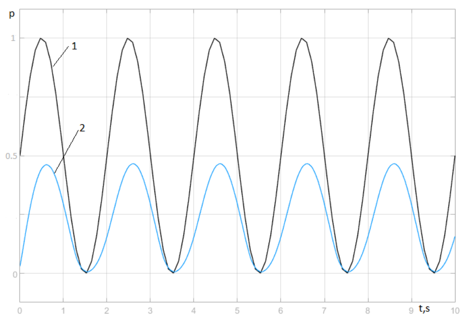

Fig. 17.d. Input (1) and output (2) pressures at 10 m pneumatic line and 0.5 Hz frequency.

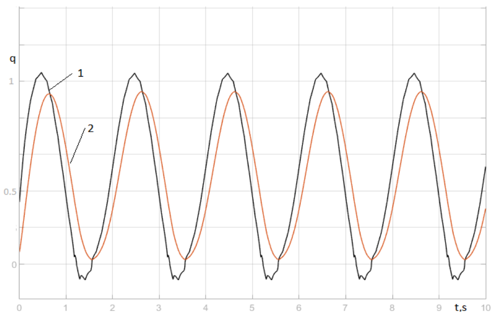

Fig. 17.e. Input (1) output (2) flow rate at pneumatic line 10 m and frequency 0.5 Hz.

For better estimation of tracking accuracy, the input and output signals are dimensionless. From the mathematical model thus presented and the experiments performed, it can be concluded that the transients in the simulations correspond to the dynamic processes of pneumatic lines of different lengths.

VIII. Conclusion

The proposed mathematical model of pneumatic lines with consideration of the signal delay along their length is an adequate tool for the determination of flow and pressure in unsteady operating modes of pneumatic systems. This mathematical model is used to obtain the mass flow rate through the pneumatic lines in turbulent flow regime. Using Fourier analysis, a new approach is applied to the study of pneumatic lines that is different from those previously described in the literature [7],[9],[10],[13]. From the study, it was found that pneumatic lines have nonlinear dynamic characteristics, delay (for flow rate 0.05 to 0.08 s, 0.03 to 0.06 s for pressure) and transient time (for flow rate 0.15 to 0.40 s , 0.10 to 0.25 s for pressure) depend on the length of the lines, the pressure and flow rate in them, and the frequency of their change. The results obtained by numerical simulation were compared with the experimental data, and excellent agreement was found.

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