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An Experimental Study of the Frequency Response of an Electropneumatic Positioning System with a Rodless Cylinder Four High Speed Pneumatic Valves and PWM Control

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***Abstract*— This paper presents an experimental investigation into the frequency response of an electropneumatic positioning system, which includes a rodless pneumatic cylinder and four 2/2-way high speed pneumatic valves operated via pulse width modulation. The experimental procedures are captured and analyzed in real-time using a dedicated virtual instrument. The amplitude and phase Bode plots for the electropneumatic positioning system were obtained through experimentation and subsequently analyzed, leading to the identification of the system's critical frequency. The findings are illustrated through various graphs.**

Keywords — Frequency response, electropneumatic positioning system, critical frequency, rodless pneumatic cylinder.

I. Introduction

Electropneumatic positioning systems are characterized by structural simplicity, reliability, and the ability to implement rapid work cycles. Various types of valves are used for controlling pneumatic actuators, such as pneumatic cylinders with different constructions and purposes – most commonly, they are three types: proportional, servo valves, and high speed electromagnetic valves with PWM control. The use of proportional valves and servo valves allows for smooth control; however, these solutions are characterized by their higher commercial price and more complex construction, requiring maintenance by specialized personnel. Therefore, due to the simplicity and reliability of controlling electropneumatic positioning systems, in recent years, high speed electromagnetic valves type 2/2, controlled by pulse-width modulation (PWM), have been used in a number of practical applications, offering an excellent alternative at a lower commercial price. PWM control allows for effective regulation of flow and pressure but leads to the emergence of specific dynamic processes in the electropneumatic positioning system. This necessitates a more in-depth investigation of the dynamic processes in pneumatic systems using fast-acting 2/2 electromagnetic valves and PWM control [3], [6].

For the analysis of electropneumatic positioning systems and the synthesis of control algorithms, frequency characteristics (amplitude-frequency and phase-frequency) are widely used to describe the dynamic properties of the system. Experimental determination of frequency characteristics allows for a detailed study of their features and the creation of mathematical models that can be used to design systems with a high level of reliability and accuracy. The difference in the design of pneumatic cylinders will lead to a difference in the dynamics of the system. Therefore, research in this area is necessary when applying cylinders without rod construction [1], [7], [9], [10]. It is important to evaluate positioning errors in dynamic mode [15].

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II. MATERIALS AND METHODS

For the experimental investigation of the frequency characteristics of an electropneumatic tracking system with a pneumatic rodless cylinder, a laboratory workbench has been developed (see Fig. 1). The developed virtual instrument in the LabVIEW environment represents a control and measurement system for the electropneumatic positioning system, implemented through pulse-width modulation of high-speed pneumatic valves. The virtual instrument is designed for experimental studies and precise positional control of pneumatic actuators, utilizing a closed-loop control system with feedback on displacement (position) and a PID controller to generate the control action. The virtual instrument consists of a user panel and a block diagram, which together implement the measurement, processing, control, and visualization of the measured and controllable quantities in real time [8].

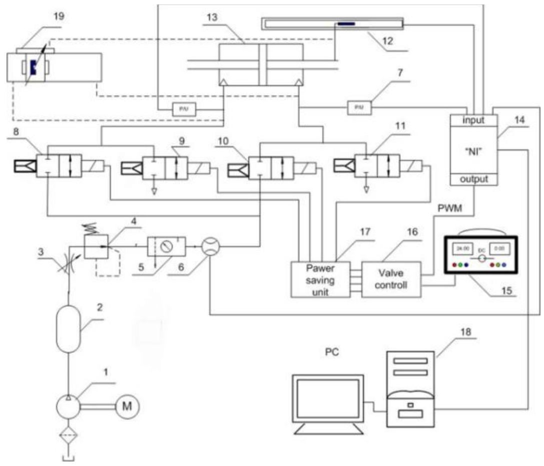

Fig. 1. General view of the experimental stand for capturing frequency characteristics.
1 - screw compressor; 2 - receiver; 3 – throtle valve; 4 – presure ruducting valve; 5 - air preparation system preparatory; 6 - flowmeter; 7 - pressure transducer, 8, 9, 10, 11 high speed pneumatic on/off valve; 12 - potentiometric sensor, 13 - double-rod pneumatic cylinder, 14 - terminal board (NI); 15 - power supply unit; 16 – Valve Controler, 17 - Power saving unit, 18 – PC,19- rodless pneumatic cylinder

The user panel provides an interface for entering set values (see Fig. 2), selecting the control mode, adjusting the regulator parameters, and graphically visualizing the displacement of the rodless pneumatic cylinder, as well as the pressures, flow rates, and control signals (see Fig. 3), [3], [6], [12], [13].

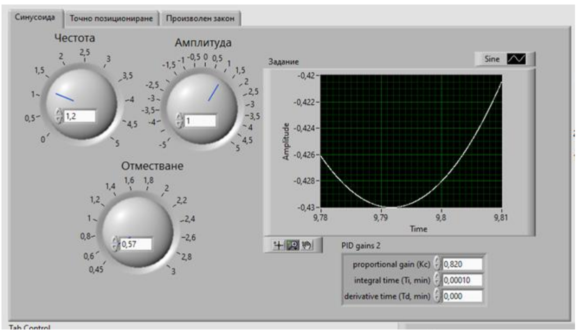

Fig. 2. Panel provides an interface for entering set values.

The block diagram implements the control logic, algorithms for calibrating the measurement channels, and the formation of PWM signals for the high-speed pneumatic valves. The system uses analog input channels to measure the essential physical quantities necessary for the operation of the electropneumatic positioning system.

By changing the output voltage of a potentiometric sensor, the linear displacement of the rodless pneumatic cylinder is measured, which serves as feedback in the control block. Additionally, the pressures in the left and right chambers of the pneumatic cylinder and the flow rate of the supplied compressed air to the electropneumatic positioning system are measured, allowing for the analysis of dynamic processes in the electropneumatic positioning system with PWM control.

The control outputs of the virtual instrument provide voltages realized in the form of pulse-width modulated signals, which sequentially control the motion of the rodless pneumatic cylinder in both forward and reverse directions. The PWM signal enables the paired switching of the high speed pneumatic valves and ensures continuous flow regulation. To ensure accurate measurement, calibration of all measurement channels has been implemented.

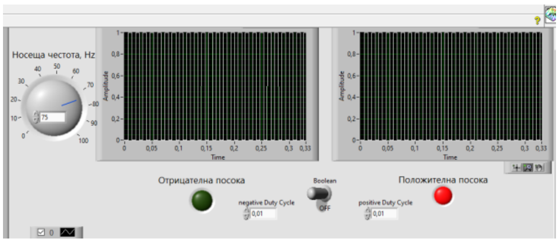

Fig. 3. Formation of PWM signals.

The input analog signals, represented as voltages, are converted in the virtual instrument into real physical quantities through linear dependencies defined by the characteristics of the sensors used. The pressure, flow, and displacement channels are pre-calibrated. The main control algorithm is implemented through a PID controller operating in a closed loop with feedback on displacement. The set position of the rodless pneumatic cylinder is compared with the currently measured position, and the resulting error serves as input to the controller. The PID controller generates a control signal based on the proportional, integral, and derivative components, allowing for good dynamics, minimal steady-state error, and stable system operation. The output of the controller is used to generate a pulse-width modulated signal that controls the electropneumatic high-speed valves. By changing the fill ratio of the PWM signal, the supplied airflow to the rodless pneumatic cylinder is regulated, ensuring smooth and precise movement. The virtual instrument is designed to implement an input law for specifying the movement of the pneumatic rodless cylinder, including a sinusoidal input law used for investigating dynamic characteristics and obtaining its frequency response. The investigated system consists of the following elements: a screw compressor, four high-speed pneumatic valves for on/off control, a pneumatic rodless cylinder „Camozzi 52M2P32A0450", as well as measuring equipment, a regulator, and an energy-saving block. The position control of the pneumatic cylinder with a double-acting piston is achieved through four HSPV "SX 12 F-AH valves, which operate as follows: when all four valves are closed (Off), the piston remains in the desired position. When valve 1 and valve 4 are open (On), the piston moves to the left. Similarly, when valve 2 and valve 3 are open, the piston moves to the right, thus performing reciprocating motion (see Fig. 3). The solenoid is activated by PWM control [1], [2], [4], [11], [14], [15].

Eigenfrequency (Critical) – This refers to the rate at which the input signal changes that the electropneumatic system can effectively respond to. The system's frequency response is illustrated through two graphs:

Amplitude-Frequency Response (AFR)

This graph shows the ratio of the amplitude at measured frequencies to that at very low frequencies, expressed in decibels (dB) and plotted on a logarithmic scale. An amplitude ratio of -20 dB indicates that the amplitude at a specific frequency is ten times smaller than the amplitude at low frequencies. The collection of amplitudes for all measured frequencies results in the amplitude-frequency response.

Phase-Frequency Response (PFR)

This measures the delay of the output signal relative to the input signal, expressed in angular degrees. A phase delay of 360° signifies that the output signal lags by one complete cycle. The graphical representation of the phase shift as a function of frequency is known as the phase-frequency response.When the amplitude of the input signal changes by 10%, the cylinder should only move a small distance, allowing it to respond to such variations even at higher frequencies. The amplitude and phase characteristics deviate from the horizontal line primarily at high frequencies. If the input signal amplitude changes by 90%, the distance the pneumatic cylinder must travel increases ninefold, making it struggle to follow variations in the input signal. Deviations from the horizontal line are also observed at low frequencies.

Critical Frequency

The critical frequency is determined from the amplitude-frequency response and is identified as the frequency at which the amplitude falls to 70.7% or -3 dB.

The limitations of using HSPV- "SX 12 F-AH (0.15~0.7 MPa) SMC Japan" with PWM control are defined by the maximum pressure specified by the manufacturer.Procedure for Conducting the Experiment

The selected operating pressure for the experiment is set at 4 bar (the experiment can be conducted at various pressures).

The operating parameters for the virtual instruments created for the experiment have been configured. A sinusoidal input signal with various amplitudes — 1 V, 1.3 V, and 1.6 V—and a frequency ranging from 0.1 Hz to 1.4 Hz has been set. The PWM control of the high-speed pneumatic valves is also set to a frequency of 70 Hz and a duty cycle of 50%. The initial position of the electropneumatic tracking system has been established. After preliminary tests of the control and measurement loops, the experimental study begins. The obtained results, input signals, and set output signals are displayed on the screen, recorded, archived, and processed for graphical representation [1], [5].

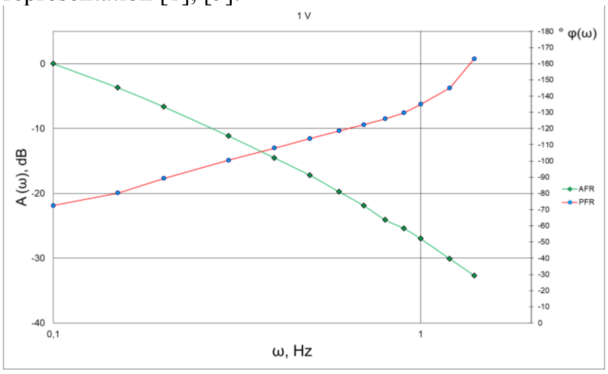

Fig. 4. AFR and PFR at an input signal amplitude of 1V.

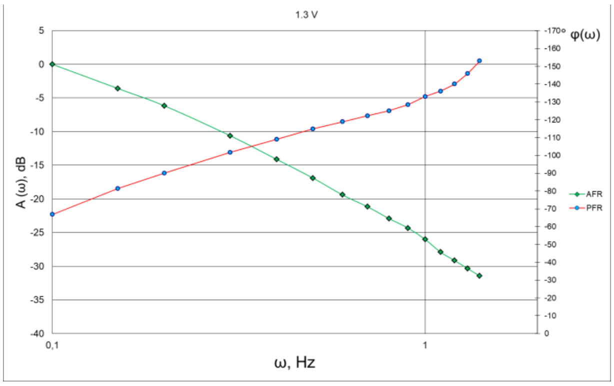

Fig. 5. AFR and PFR at an input signal amplitude of 1.3 V.

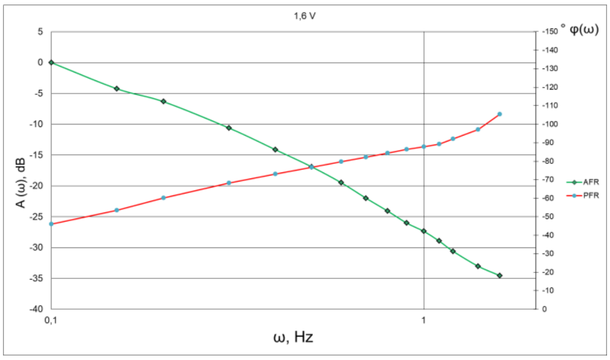

Fig. 6. AFR and PFR at an input signal amplitude of 1.6 V.

III. RESULTS AND DISCUSSION

Figure 4, 5, 6 presents the amplitude-frequency (AFR) and phase-frequency response (PFR) of the pneumatic positioning system at an input signal amplitude of 1, 1.3 and 1.6 V. The experiment is repeated as many times as necessary to eliminate errors.

For the experimental analysis of the frequency characteristics of the pneumatic positioning system, it is assumed that the instruments have significantly smaller time constants than those of the system being tested. In practice, their transient processes occur much more quickly, and they are regarded as ideal first-order aperiodic units with time constants that are much smaller than the time constant of the system being investigated [1], [5].

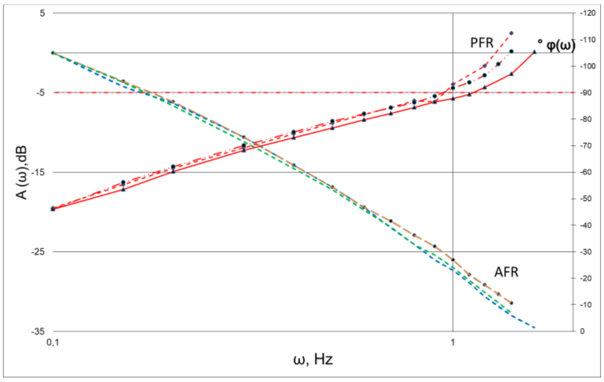

Fig. 7. Aamplitude-frequency and phase-frequency response of an electropneumatic positioning system with a rodless cylinder at input signal amplitudes of 1, 1.3 and 1.6V.

CONCLUSIONS

The electropneumatic tracking system, featuring PWM control, high-speed pneumatic valves, and a rodless pneumatic cylinder, has a critical eigenfrequency of -90° at control signal amplitudes of 1, 1.3, and 1.6 V, ranging from 0.95 to 1.1 Hz.

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