ISSN 1453 – 7303 **"HIDRAULICA" (No. 1/2025)**
Magazine *of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics*

Experimental Evaluation of the Dynamic Response of Pneumatic Actuators Depending on Constructive and Operational Parameters

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Abstract: *The paper presents the experimental tests conducted in the Pneumatics Laboratory of the Research Institute for Hydraulics and Pneumatics INOE 2000-IHP on the factors influencing the dynamic behavior of medium and high-pressure pneumatic actuators. The tests were performed on two actuator size types from FESTO (DNCKE-100-200-PPV-A and DNCKE-40-130-PPV-A).*
The tests were carried out under no-load conditions and aimed to evaluate: the step response at three points of the stroke at a constant pressure of 8 bar; the response to a sinusoidal signal with an initial amplitude, ranging from the minimum to the maximum value, for three stroke values; and a test to highlight the dynamic performance of the actuators depending on the type of seals and the materials used, as well as the level of machining (quality of the cylinder sleeves and rod surfaces).

Keywords: *Pneumatic actuators, dynamic behavior; influencing factors*

1. Introduction

When developing procedures and protocols for testing pneumatic systems with pneumatic actuators, it is essential to consider their functional characteristics in both static and dynamic conditions, as well as the parameters that define these behaviors. Recent studies highlight the importance of standardized methodologies adapted to the current requirements of modern pneumatic systems, which incorporate advanced control algorithms, innovative materials, and solutions for compensating nonlinearities caused by air compressibility [1],[2].
The actuator systems analyzed in this paper are not merely "classic" pneumatic actuation systems but rather advanced servo systems integrated into automated control architectures. In this context, the development of experimental protocols must take into account current industry trends, such as the integration of advanced sensor technology (high-resolution pressure, position, and force sensors), the use of predictive models based on artificial intelligence to optimize performance, and the implementation of adaptive control strategies to mitigate hysteresis and compressibility effects [3],[4]. Consequently, experimental procedures require a complex approach that enables an accurate evaluation of dynamic performance under variable operating conditions.
The factors influencing their behavior, as well as the methods used to improve their accuracy [5]:

1.1 Main factors influencing the dynamic behavior of medium and high-pressure pneumatic actuators:

- Piston diameter and actuator stroke
- Type of sealing
- Machining quality of the rods and cylinder sleeves
- Difference between piston diameter and rod diameter
- Compressed air quality (level of pollutants in the compressed air and methods used for their removal, compressibility of gas and liquid phases, humidity and condensation, pressure, and flow rate)

1.2 Methods and means of increasing the precision and dynamic performance of medium pressure pneumatic actuators [5]:

To enhance the accuracy and dynamic performance of medium-pressure pneumatic actuators, various methods and means are employed, including design optimization, the use of advanced materials, and the implementation of modern control techniques. Some of the most effective methods include:

- **Optimization of actuator design**

• Reducing internal friction by using low-friction seals and materials with a low coefficient of friction.
• Improving the guidance of the piston and rod to minimize positioning deviations and premature wear.
• Using progressive damping chambers to prevent mechanical shocks at the stroke ends.
• Increasing rigidity and reducing hysteresis
- Using lightweight yet durable materials (aluminum alloys, composites).
- Minimizing internal clearances and elastic deformations of mechanical components.
- Reducing the stick-slip phenomenon through precision finishing of contact surfaces.
• Utilization of sensors and feedback systems
- Position sensors (LVDT, optical encoder, magnetostrictive sensor) for precise stroke measurement.
- Pressure and flow sensors for real-time monitoring and adjustment of operating parameters.
- Closed-loop feedback to correct position and speed deviations.
• Advanced control of air pressure and flow
- Proportional pressure regulators for fine-tuned force variation.
- Proportional control valves and servo valves for fast and precise response.
- Advanced control algorithms (adaptive PID, fuzzy logic, model predictive control - MPC) for dynamic actuator motion adjustment.
• Reducing the effects of air compressibility
- Using air pre-filling to reduce response delay.
- Regulating the temperature of compressed air to minimize density variations.
- Implementing compensatory algorithms to model thermodynamic effects.
• New technologies and innovative solutions
- Integrating hybrid pneumatic actuators (pneumo-electric or pneumo-hydraulic) to improve precision.
- Using smart materials (e.g., electroactive elastomers, flexible structures with shape memory) to optimize dynamic response.
- AI-based control systems for automatic adaptation to operating conditions.

These methods significantly contribute to improving the accuracy and dynamic performance of pneumatic actuators, making them more efficient for industrial and automation applications.

2. Experimental stand

The tests, conducted on two size types of medium-pressure pneumatic actuators (DNCKE-100-200-PPV-A and DNCKE-40-130-PPV-A), highlight the main influencing factors and methods regarding their dynamic behavior.
The tests will be performed under no-load conditions and will consist of:
a. **Step response** at three points of the stroke, at a constant pressure of 8 bar;
b. **Response to a sinusoidal signal** with an initial amplitude, ranging from the minimum to the maximum value, for three stroke values;
c. **Test to highlight the dynamic performance of the actuators** based on the type of seals and materials used, as well as the level of machining (quality of the cylinder sleeves and rod surfaces).
It was previously mentioned that as the size of the actuators decreases, the quality of the component surfaces, as ensured by the manufacturers, increases. The test will consist of comparing the response diagrams for step and sinusoidal signals for both analyzed actuators, under the same testing parameter values.

2.1. Testing Conditions

Based on the pneumatic schematic shown in Fig. 1, two testing stands were built in the Pneumatics Laboratory of IHP Bucharest (Fig. 2). These stands differ in terms of the mounting fixtures for the DNCKE-100-200-PPV-A and DNCKE-40-130-PPV-A actuators on the workbench, as well as the pneumatic connections compatible with the two actuator size types.

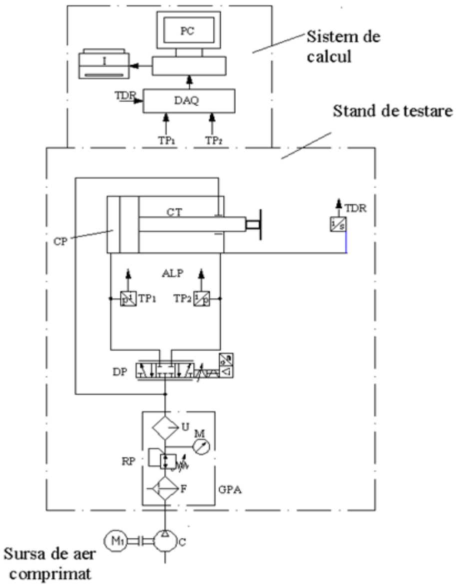


Fig. 1. The pneumatic schematic of the test stand

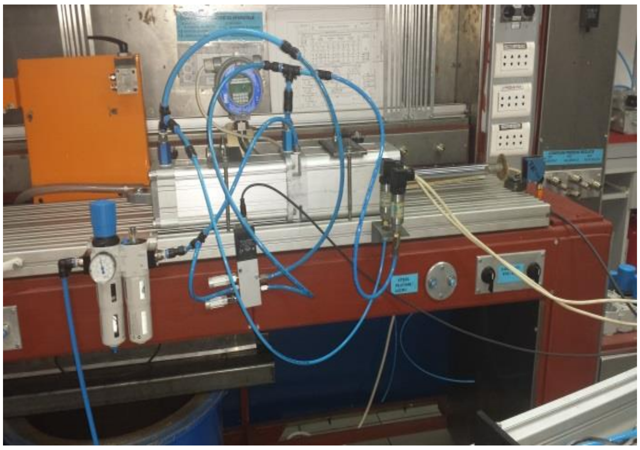


Fig. 2. The test stand for the medium-pressure actuator DNCKE-100-200-PPV-A

The test stand for the medium-pressure actuator DNCKE-100-200-PPV-A is designed to evaluate its dynamic performance under controlled conditions. The setup includes mechanical, pneumatic, and electronic components that allow for precise monitoring and control of the actuator's response.

Key Elements of the Test Stand:

1. Mechanical Setup:
- **Mounting structure** – A rigid frame to secure the actuator in place.
- **Guides and fixtures** – Ensure stability and alignment during testing.

2. Pneumatic System:
- **Compressed air supply** – Delivers air at 8 bar via an air preparation unit.
- **Air preparation unit** – Consists of a filter, regulator, and lubricator to ensure clean and stable airflow.
- **Proportional control valve** – Modulates the airflow to the actuator.
- **Pressure sensors (p1, p2)** – Measure the pressure in the actuator's chambers.

3. Sensor and Data Acquisition System:
- **Position sensor (LVDT or optical encoder)** – Tracks actuator displacement.
- **Flow sensors** – Measure air consumption and flow rate.
- **USB-6218 Data Acquisition Board (DAQ)** – Captures real-time signals from sensors.

4. Control System (LabVIEW-Based):
- **PID controller** – Adjusts actuator performance based on feedback.
- **Step and sinusoidal signal generator** – Simulates different operational scenarios.
- **Graphical interface** – Displays test parameters and real-time graphs.

The test stand configuration (Fig. 2) ensures accurate evaluation of response time, positioning accuracy, damping characteristics, and the impact of control parameters on the actuator's performance.

The testing program, developed in the LabVIEW environment, consists of block diagrams that automate the testing process. The results, including diagrams and databases, are automatically saved.

At the input of the USB-6218 data acquisition board, voltage signals from the pressure transducers (corresponding to the two chambers of the tested actuator) and the displacement transducer (reflex) are fed. One of the two analog signal outputs of the acquisition board is used to control the proportional valve in the testing setup [6].

The power supply for the proportional equipment solenoids, sensors, and data acquisition board is provided by a dual-channel power source, as shown in Fig. 3.

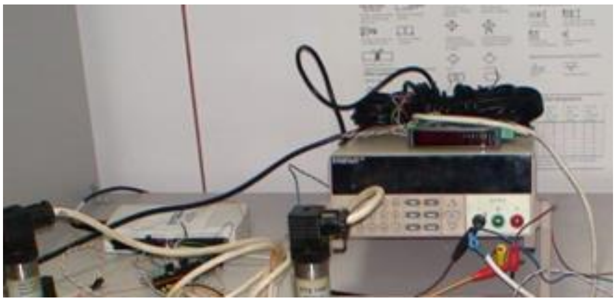


Fig. 3. Two-channel supply source

In the automatic control system used for operating pneumatic actuators, the automatic controller (RA) processes the error signal ε, which is obtained from the linear-additive comparison of the input variable xi and the feedback variable x_r within the comparison element. The controller then outputs a control signal x_c for the actuator.
Current information about the automated process is obtained using the feedback transducer (TR) and is processed by the automatic controller (RA) according to a specific control law, which defines the automatic regulation algorithm (control law) [7], [8].

2.2 Step response at three stroke points at constant pressure

The program schematic for determining the step signal response, developed in the LabVIEW environment, illustrates the control logic and data processing flow used to analyze the dynamic behavior of the pneumatic actuator under step input conditions.

Key Components of the LabVIEW Schematic:

- **Step signal generation module** – creates a sudden change in the input position.
- **Data acquisition system** – collects real-time signals from position, pressure, and velocity sensors.
- **PID control block** – applies proportional control adjustments based on feedback.
- **Graphical display and logging module** – visualizes and records the actuator's response.
- **Processing unit** – analyzes response parameters such as rise time, settling time, overshoot, and damping.

The schematic, as shown in Fig. 4, provides a structured representation of how the LabVIEW-based automation is implemented for evaluating the step response characteristics of the pneumatic actuator.

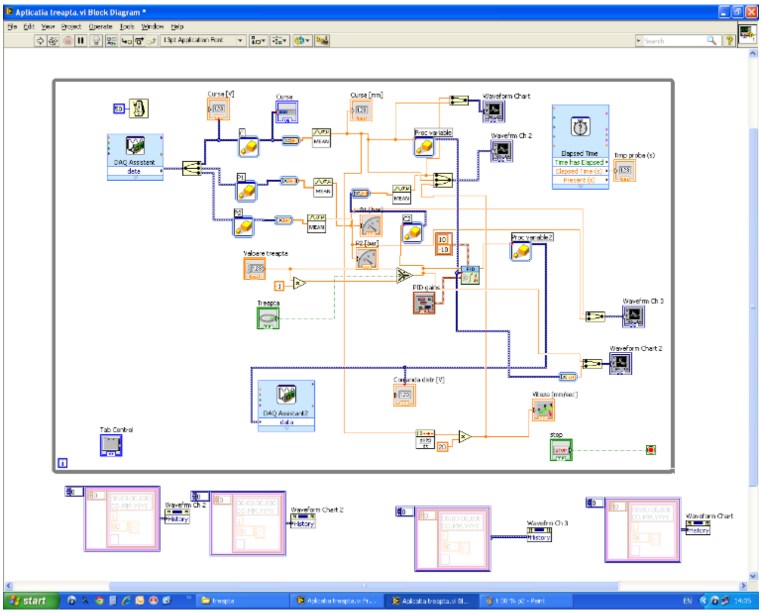


Fig. 4. The program schematic for determining the step signal response, developed in the LabVIEW environment

The tests are conducted at an operating pressure of 8 bar, at three stroke length points—30%, 60%, and 100% of the stroke value specified by the actuator manufacturer—for different values of the proportionality factor kc of the PID automatic controller.
In Window 1 (screenshot), Fig. 5, the following elements are displayed: prescribed position, actual position, velocity, amplitude variation over time, PID parameter values of the automatic controller, and step value.

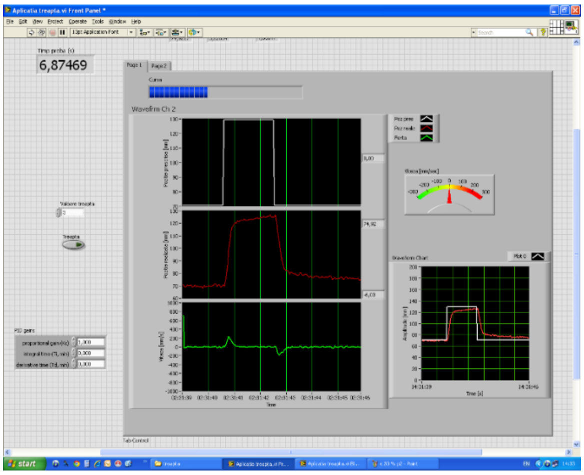


Fig. 5.

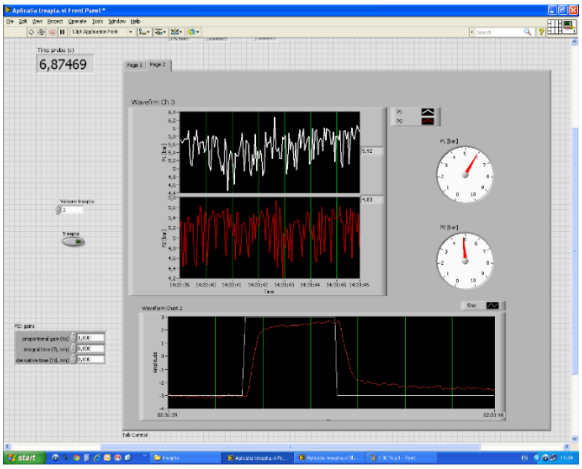


Fig. 6.

The application for a stroke length of 30% of the total stroke, at an operating pressure of 8 bar, with a proportionality factor kc = 1.000 of the PID automatic controller, for the medium-pressure pneumatic actuator DNCKE-100-200-PPV-A

In Window 2, Fig. 6, the following elements are displayed: pressures in the piston chamber (p1) and rod chamber (p2), amplitude, PID parameter values of the automatic controller, step value, and test duration.
The graphs obtained from running the program, corresponding to the two application windows, are shown in Fig. 7.

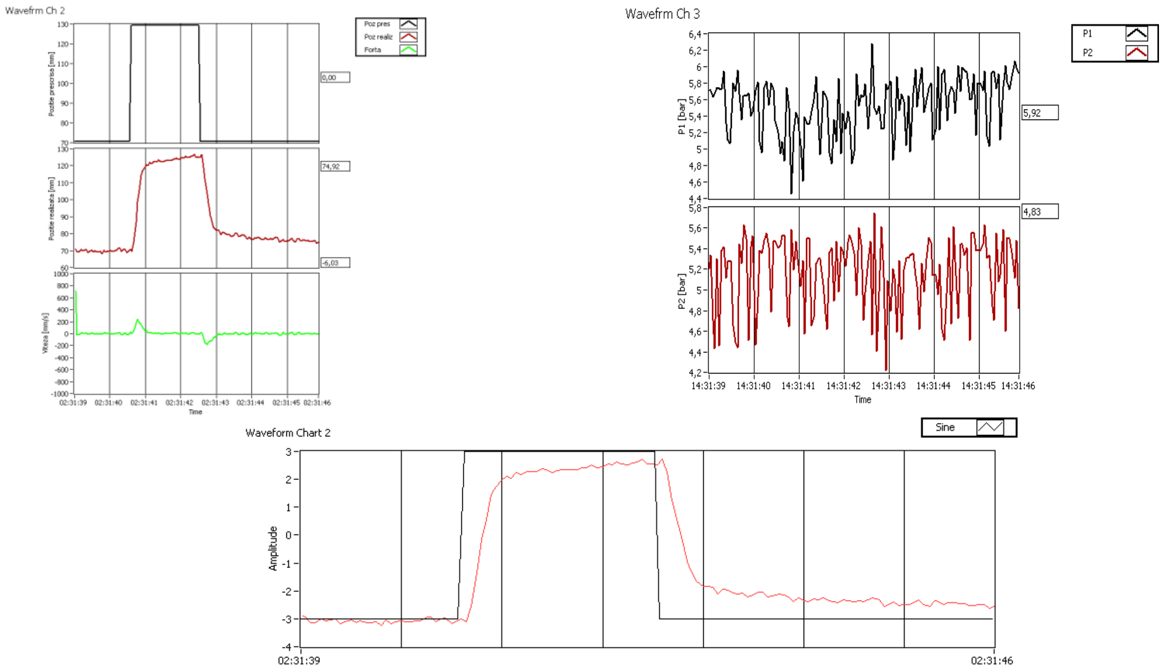


Fig. 7. The appearance of the graphs obtained during the tests regarding the step signal response of the medium-pressure pneumatic actuator DNCKE-100-200-PPV-A

The appearance of the graphs obtained during the tests regarding the step signal response of the medium-pressure pneumatic actuator DNCKE-100-200-PPV-A provides insights into its dynamic behavior under sudden input changes. These graphs typically illustrate:

- Step response curve – showing the actuator's reaction to abrupt position changes.
- Rise time and settling time – indicating how quickly the actuator reaches and stabilizes at the desired position.
- Overshoot and damping characteristics – assessing response stability and precision.
- Velocity profile – visualizing acceleration and deceleration phases.
- Pressure variations in the actuator chambers (p1 and p2) – analyzing air compression effects.

These graphical representations are essential for evaluating the actuator’s control accuracy, response time, and overall performance under step input conditions.

2.3 Response to a sinusoidal signal with initial amplitude, from minimum to maximum value, for three stroke value

The program schematic for determining the sinusoidal signal response, developed in the LabVIEW environment, illustrates the control logic, data acquisition, and processing flow used to analyze the dynamic behavior of the pneumatic actuator.
This schematic includes:

- Signal generation module for applying a sinusoidal input to the actuator.
- Data acquisition block to capture position, pressure, and velocity signals from sensors.
- PID control algorithm to adjust the actuator’s response.
- Real-time graphing and data storage for further analysis of system performance.

The schematic, as shown in Fig. 8, provides a structured visualization of the LabVIEW-based automation used for testing and evaluating the actuator's sinusoidal response characteristics.

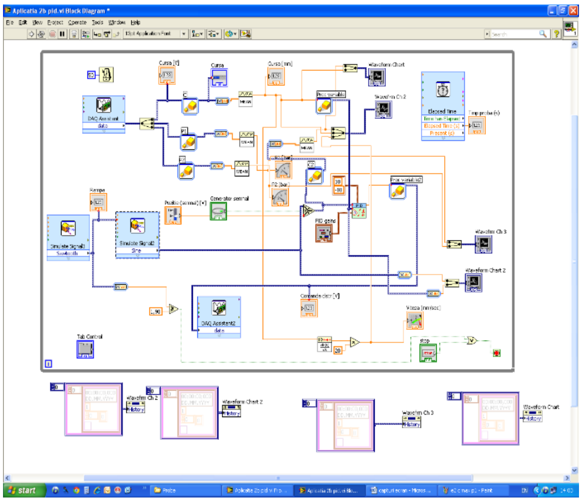


Fig. 8. The program schematic for determining the sinusoidal signal response, developed in the LabVIEW environment

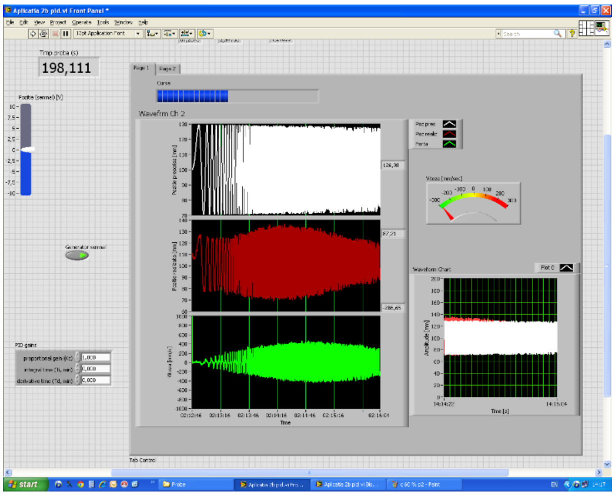


Fig. 9. Window 1 of the application for a stroke length of 30% of the total stroke, at an operating pressure of 8 bar, with a proportionality factor Kc = 1.000 of the PID automatic controller, for the medium-pressure pneumatic actuator DNCKE-100-200-PPV-A

The tests are conducted at an operating pressure of 8 bar, at three stroke length points—30%, 60%, and 100% of the stroke value specified by the actuator manufacturer—for different values of the proportionality factor kc of the PID automatic controller.
In Window 1, Fig. 9, the following elements are displayed: prescribed position, actual position, velocity, amplitude variation over time, PID parameter values of the automatic controller, and signal generator status. These graphical representations help in understanding the actuator's dynamic response, stability, and precision under the given operating conditions.

In Window 2, Fig. 10, the following elements are displayed: pressures in the piston chamber (p1) and rod chamber (p2), amplitude, PID parameter values of the automatic controller, signal generator status, and test duration.
The graphs obtained from running the program, corresponding to the two application windows, are shown in Fig. 11.

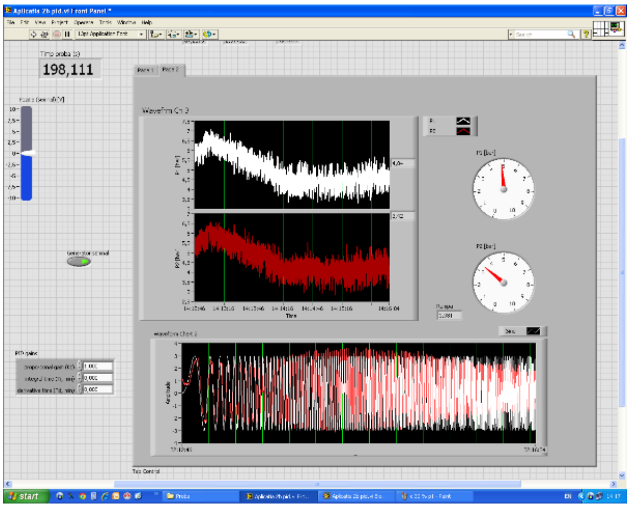


Fig. 10. Window 2 of the application for a stroke length of 30% of the total stroke, at an operating pressure of 8 bar, with a proportionality factor Kc = 1.000 of the PID automatic controller, for the medium-pressure pneumatic actuator DNCKE-100-200-PPV-A

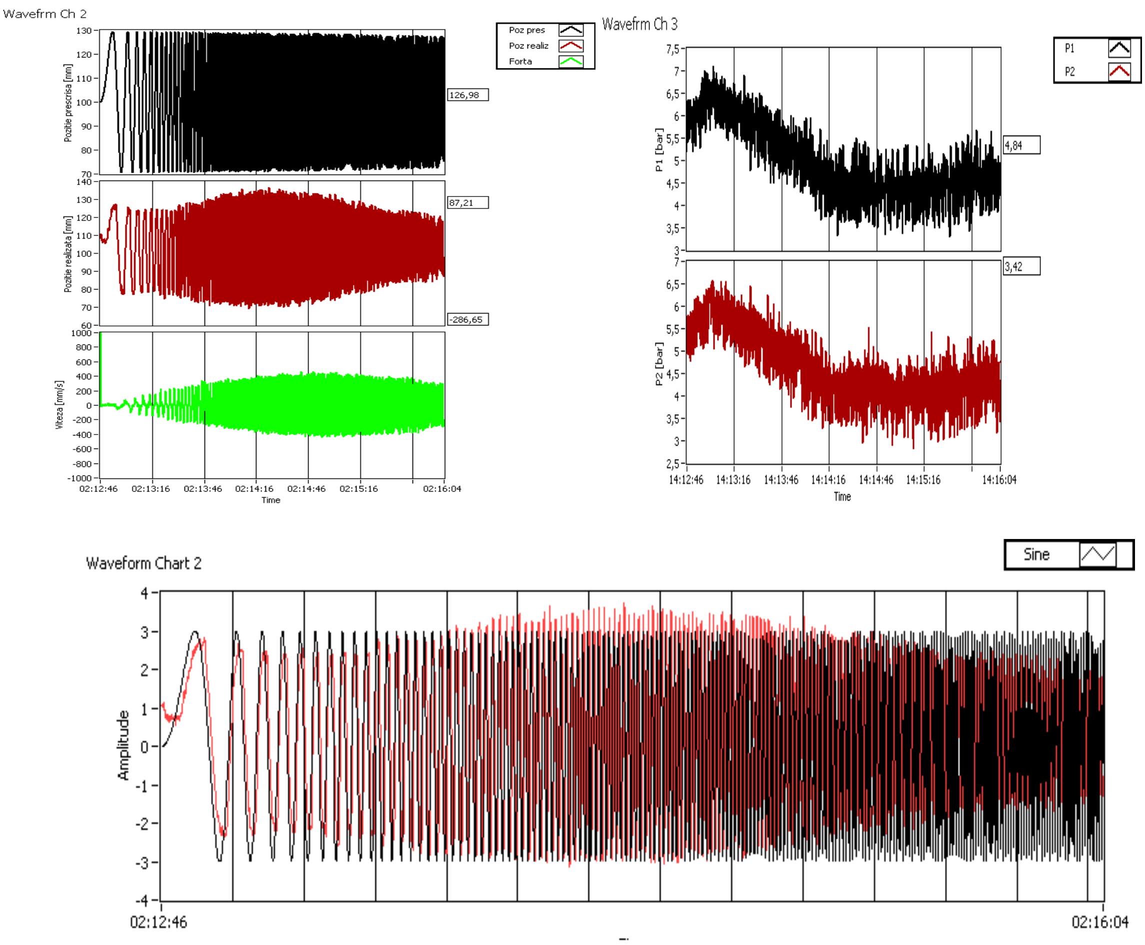


Fig. 11. The appearance of the graphs obtained during the tests regarding the sinusoidal signal response of the medium-pressure pneumatic actuator DNCKE-100-200-PPV-A

2.4. Dynamic Performance of Actuators Depending on the Type of Seals, Materials Used, and Machining Level (Surface Quality of Cylinder Sleeves and Rods)

The main factors and methods influencing the dynamic performance of medium and high-pressure pneumatic actuators—such as the type of seals, materials used, and machining level (surface quality of cylinder sleeves and rods)—have been theoretically analyzed by consulting specialized literature:

2.4.1 Effect of Size (Dimensions) on Forces

Reducing the size of execution elements affects the magnitude of force (or torque) developed. Example: In electrostatic actuators, the mechanical work per unit volume (Fl/l^3) is inversely proportional to the square of the length, meaning that the mechanical work developed by electrostatic force increases as the size decreases [5]. Example: For certain actuators, reducing dimensions below a specific limit results in forces (or torques) smaller than the resistive forces (friction, gravity).

2.4.2 Increasing the Strength of Materials Used

Materials with exceptional mechanical properties: Monocrystals and amorphous whisker-type materials (very short fibers) have up to 1000 time higher strength than polycrystalline materials of the same chemical composition. This is due to the absence of grain boundaries, leading to lower wear and fewer error sources.
The relationship between size reduction ($\lambda = l1/l2$) and material strength is given by: $c\sigma = \sigma 1/\sigma 2 = 1/\lambda$, meaning that components reduced by a factor of λ must be made of materials λ times stronger.

2.4.3 Significant Surface Effects

At the micron level, $L_2 > L_3$, meaning that surface-related effects dominate over volume-related effects.
Examples:
- Chemical corrosion becomes significant when associated with electrical phenomena.
- Microtribology effects: In flat surfaces and sliding bearings, the friction coefficient (μ) increases significantly as size decreases.
- Adhesion, friction, capillarity, surface tension, etc., become more dominant than mass effects (inertia).

To address these issues, the following approaches are necessary:
- Minimizing contact surfaces in mechanical couplings and applying special coatings.
- Replacing sliding friction with rolling friction.
- Elastic support of moving elements.
- Using low-viscosity lubricants.
- Implementing advanced lubrication methods, such as gas (hydro) static or dynamic lubrication, magnetic levitation, or electrostatic levitation.

2.4.4 Decreasing Machining Precision

- Tolerance reduction is not proportional to size reduction.
- If $\lambda = l_1/l_2$ (nominal size ratio), at the same machining precision, the tolerance ratio is $T_1/T_2 = 3\lambda$.
- As the nominal size decreases, machining precision must increase.

2.4.5 Speed-Dimension Dependency

- The relationship between speed v [mm/s] and size L [mm] varies significantly compared to conventional actuators.
- According to similarity theory, reducing dimensions by a ratio of $\lambda = l_1/l_2$ leads to:

- Mass reduction by $cG = \lambda^3$
- Acceleration increase by $ca = \lambda^{-1}$ (a component reduced by λ can be accelerated λ times more)
- Moment reduction by $cM = \lambda^3$

Advantages of Actuation Elements Compatible with Mechatronic Technology

Compared to conventional actuators, mechatronic-compatible execution elements offer:
- Higher power-to-weight ratio
- Lower environmental impact
- Longer operational lifespan

- Adjustable motion parameters
- Higher operational safety
- Compactness
- Simplified construction (fewer moving parts)
- Submicron positioning accuracy [5]

Application Domains:

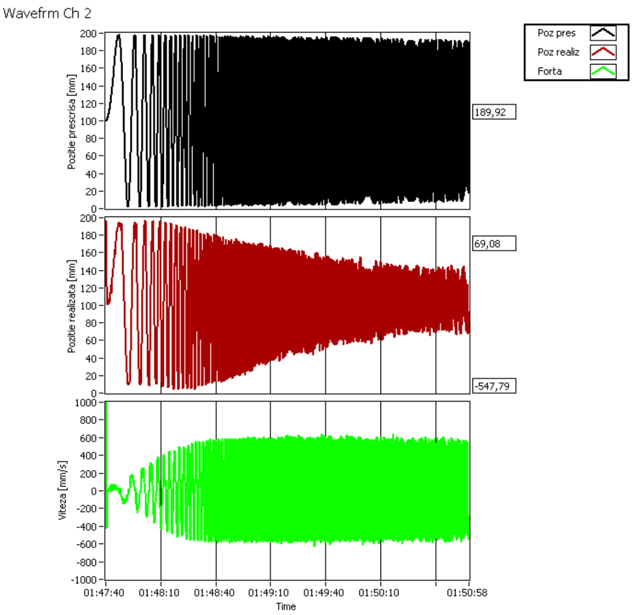
These advancements apply to various fields, including: Robotics and micro-robotics: Machine tool actuation; Structural components in various equipment; Automotive industry; Aerospace industry; Defense industry; Consumer goods industry; Medical engineering

3. Conclusions

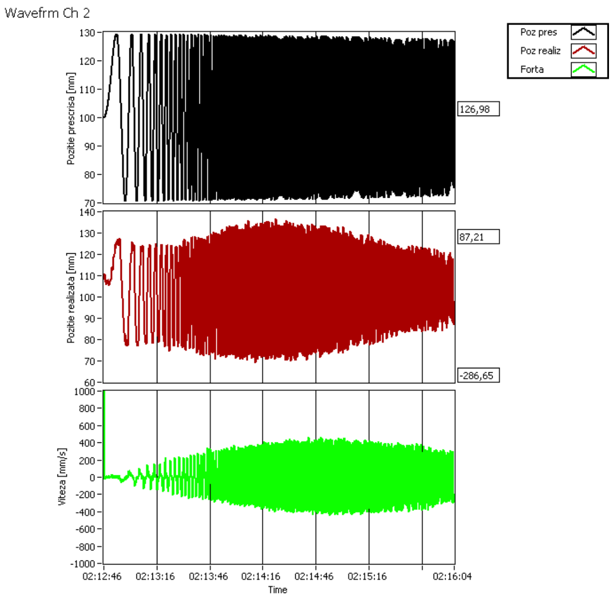
1. The experimental studies on the main factors and methods influencing the dynamic behavior of medium and high-pressure pneumatic actuators were carried out on two size types of medium-pressure pneumatic actuators (DNCKE-100-200-PPV-A and DNCKE-40-130-PPV-A).
2. The tests regarding the step and sinusoidal signal responses, the determination of the starting pressure, and the influence of the automatic controller parameters within the automatic control system (PID) were performed in the LabVIEW environment.
3. The influence of dimensions, the type of seals and materials used, the machining level (quality of the cylinder sleeves and rod surfaces), and the quality of the working fluid on the dynamic performance of the actuators was analyzed based on research in the field presented in the specialized literature.
4. The temperature of the working fluid was strictly maintained at the standard value of 25°C.
5. The operating pressure (at the inlet to the actuator chambers), regulated by the pressure regulator of the air preparation unit, was set at 8 bar.
6. The automatic controller used was of the P (proportional) type, with the proportionality factor (amplification) kc being the only variable parameter in the automatic control system.

Test conclusions

Actuator DNCKE-100-200-PPV-A

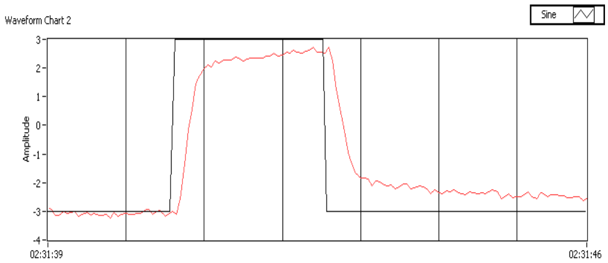


Stroke 100 %

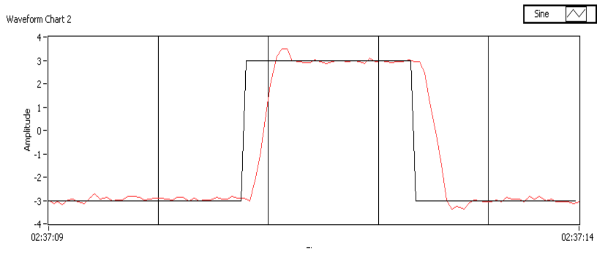


Stroke 30 %

At the same values of the PID controller parameters, it is observed that amplitude attenuation begins within the first third of the frequency range (0…2 Hz).

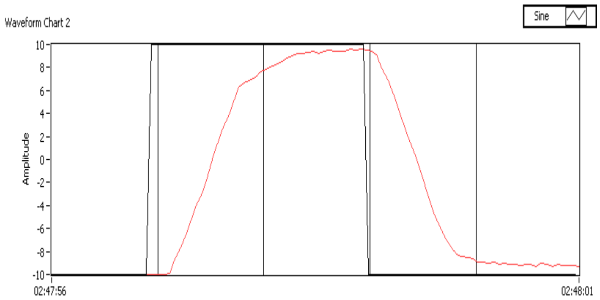


Stroke 30 % Kc = 1

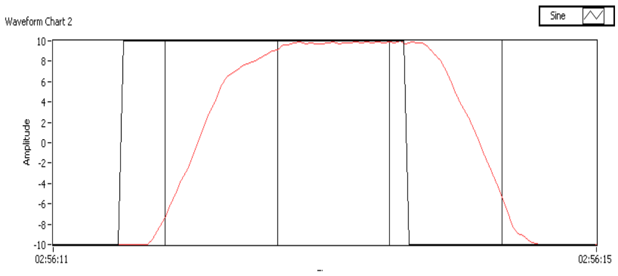


Stroke 30 % Kc = 4

With an **increase in Kp**, an **improvement in response time and positioning accuracy of the cylinder rod** is observed rod is observed.



Stroke 100 % Kc = 1



Stroke 100 % Kc = 50

At the maximum stroke of the large-size pneumatic actuator, the response is delayed and cannot be improved by increasing the Kc parameter.
Given the large volume of the cylinder chambers, the response could be enhanced by increasing the available airflow rate.

Acknowledgments

This work was carried out through the Core Program within the National Research Development and Innovation Plan 2022-2027, carried out with the support of MCID, project no. PN 23 05.

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