Research on a rodless pneumatic actuator with magnetic transfer

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Abstract
The article presents the results of experimental and numerical tests of a rodless actuator with magnetic transfer. The study concerns the dynamic operation of the actuator. A series of measurements of pressure variability as a function of the distance and speed of the actuator's operation on a real stand were performed. The study was repeated by modeling the system in the FluidSim environment. The obtained variation waveforms were compared with the real ones in order to determine the suitability of this type of tool for testing actuators.

Keywords: pneumatic drive, rodless drives

Introduction

Pneumatics is a branch of technology that deals with the production of compressed air, as well as its use for technological purposes, and driving and controlling of technical devices. Pneumatic systems have many advantages, the most important of which is the use of air as a medium in the operation of drive systems. Due to its properties, pneumatics is readily used in many fields of technology and, contrary to appearances, it belongs to very complex issues in terms of the physics of the phenomenon due to the specificity of a fluid such as air. Therefore, calculations in engineering practice are carried out only in a very simplified manner in order to estimate the values necessary for the design. It becomes necessary to conduct experimental research on real objects.

Linear pneumatic actuator

Pneumatic actuators can be divided due to the working movement into linear, rotary, swing, step, etc. [5, 6, 10, 12]. The article presents the results of experimental tests of a selected rodless linear actuator. The physical phenomena encountered during the operation of a pneumatic linear drive are very complex [2, 8]. Air, as a medium, changes its pressure parameters (from zero to ten bar) and the velocity of flow through the channels [7]. The Reynolds number in the channels varies from laminar to turbulent flows [1]. These are very large volatility scales. Due to the above, all coexisting gas parameters, such as humidity, temperature, density, and viscosity, vary within wide limits. As a result, parameters such as flow losses vary widely, all in an interactive way.

The principle of operation of the most commonly used double-acting cylinder, shown in Fig. 2.1, is essentially limited to the fact that the control valve applies pressure to both cylinder chambers alternately. The moment of change of control (direction of operation) is the change of polarity at the outputs of the distributor 2 and 4. If one chamber is filled, the opposite is emptied to the environment. In the lines supplying air to the actuator chambers, the pressure, speed, and direction of the medium flow change.

Figure 1 shows two extreme operating states of the pneumatic actuator. When the left chamber is at the maximum (working) pressure, the right chamber is at ambient pressure. There is a transition period between one and the other position of the actuator piston due to the pressure difference between the chambers. The speed of passage of the actuator piston will depend on the rate of emptying the chambers, i.e. it is related to flow losses through connections to the pneumatic elements. The article presents an experimental study on a test stand for a rodless actuator shown in Fig. 3. Additionally, the results of modeling

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a system with a rodless actuator in the FluidSim environment are shown (Fig. 7).

A rodless cylinder (Fig. 2a) is a special structure where the force is transferred, in this case, from the piston by means of the magnetic field penetrating through the cylinder walls [13]. This means that strong neodymium magnets are embedded in the piston as well as in the outer cart. The design of the rodless actuator is devoid of one major drawback that typical solutions have, i.e. leaks between the piston rod and the housing.

Research stand

The test stand shown in Fig. 3a was built on the basis of a rodless actuator with magnetic transmission, a 5/2 control distributor, pressure sensors and an optical speed converter.

The actuator used is a structure with side guides (Fig. 3b) with a stroke of 500 mm and a piston diameter of 32 mm, the force from the piston is transferred to the outer cart through the used neodymium magnets located in the piston and in the cart.

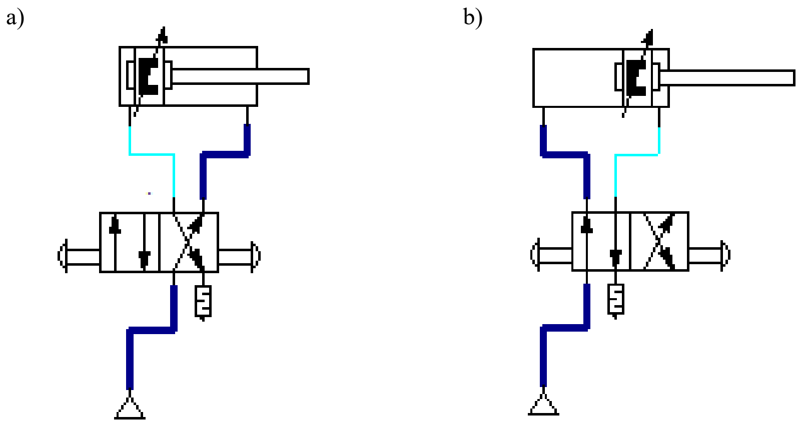

Figure 1 Diagram showing two operating states of the actuator: a) retracted, b) extended, where: blue line and arrows indicate the flow of compressed air.

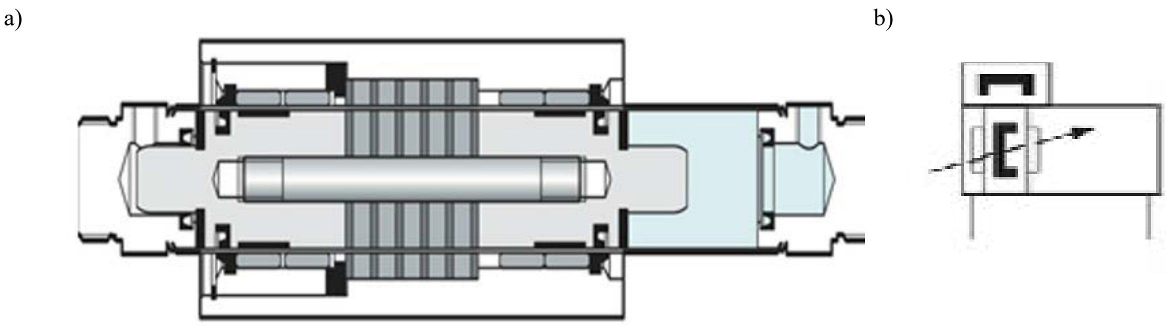

Figure 2. Schematic structure of a rodless actuator with magnetic transfer – cross-section [11].

a) b)

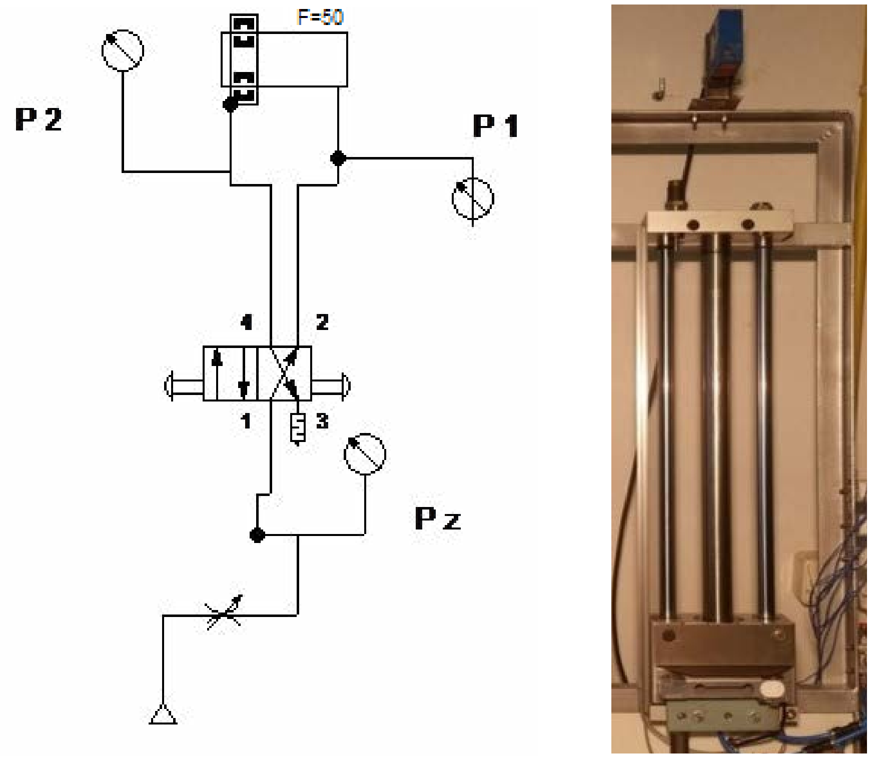

Figure 3. Test stand: a) operation diagram, b) real view of the stand, where: P1 – pressure at the outlet from the chamber, P2 – pressure at the inlet to the chamber, Pz – supply pressure.

Figure 4 shows the optical converter used in the stand for measuring the distance. The pressure levels in the chambers are measured with piezoresistive transducers P1 and P2. The Pz converter measures the pressure at the inlet of the system, i.e. the supply pressure from the pneumatic network. On the other hand, the speed of the cart is measured by the optical reflection method with the use of the FT 80 RLA triangulation transducer.

Figure 4. Optical converter for distance measurement [14].

The presented diagram (Fig. 5) of the program controls the USB1608G portable measuring system. Due to the dynamics of the phenomenon, the sampling of the system was set to 10 kHz. The remaining modules are mainly scaling and noise-eliminating digital filtering modules. The math module calculates the speed based on the distance measured by the optical reflectance converter. Measured and calculated values are displayed in the form of digital and graphical readout over time, all sampled values are saved to disk as a file.

Figure 6 shows the variability of pressures, velocities, and paths for one case. The red channel 1 shows the variability of the supply pressure, and a clear drop in pressure is visible at the time of reloading the manifold, i.e. starting. This is due to the fact that there is a short-term impulse demand for air necessary to fill the pneumatic paths between the valve and the piston. This moment is associated with a large pressure difference between the outlet and the manifold inlet, which results in a high airflow velocity, and, consequently, large losses in the supply of pressure to the system. It should be emphasized that linear pressure losses (1) on pipe sections are proportional to the square of the flow velocity [9].

$$\Delta p = \frac{l\lambda_l}{d} \cdot \frac{\varrho v^2}{2} \qquad (1)$$

where:

λl – linear loss factor;
v – average air flow velocity [m/s];
ϱ – air density [kg/m3];
l – channel length [m];
d – channel diameter [m].

The second and third channels show the variation of pressures in the actuator chambers. It is clearly visible that the pressure in one is inversely proportional to the pressure in the other. The force acting on the piston is determined by the pressure difference between the chambers at a given moment. The fourth channel shows the travel path of the piston, while the fifth channel shows the speed variation in the stroke area. One can clearly observe the time shift of the operation-displacement of the piston (channel 4, green) in relation to the time of overloading the distributor, caused primarily by emptying the opposite overload chamber (channel 2, blue).

Numerical research in the FluidSim environment

The measurement system was modeled in the software environment used to simulate and verify the FluidSim pneumatics systems in order to compare the similarity of the simulation results with the real ones. Figure 7 shows the graphs of the variability of the parameters of the tested actuator.

Comparing the graphs obtained in the real study (Fig. 6), and those obtained by simulation in the numerical way, using the FluidSim platform (Fig. 7), it is possible to notice a high result convergence with the verified correlation method [3, 4].

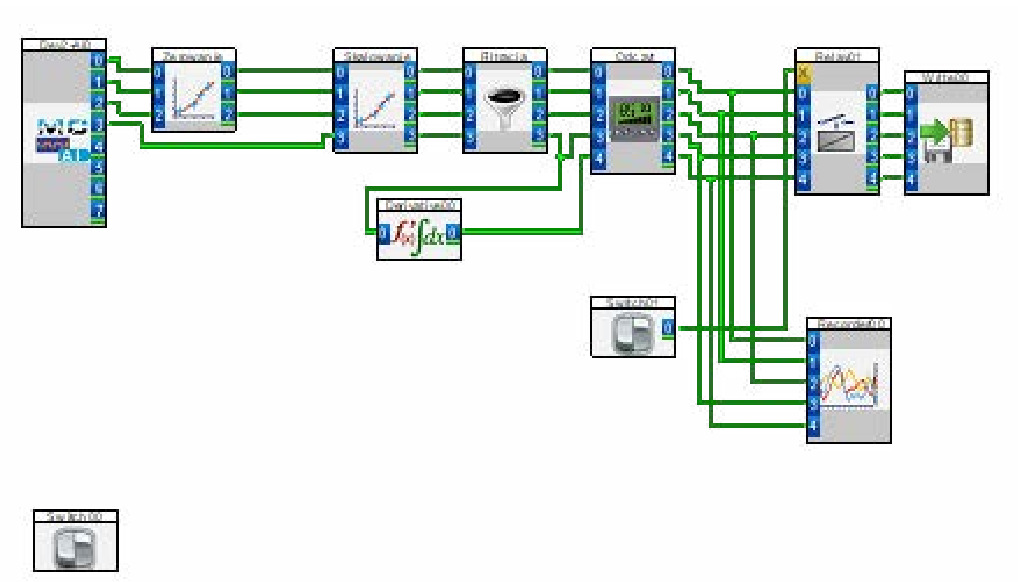

Figure 5. Diagram of the program supporting the research stand – DasyLab.

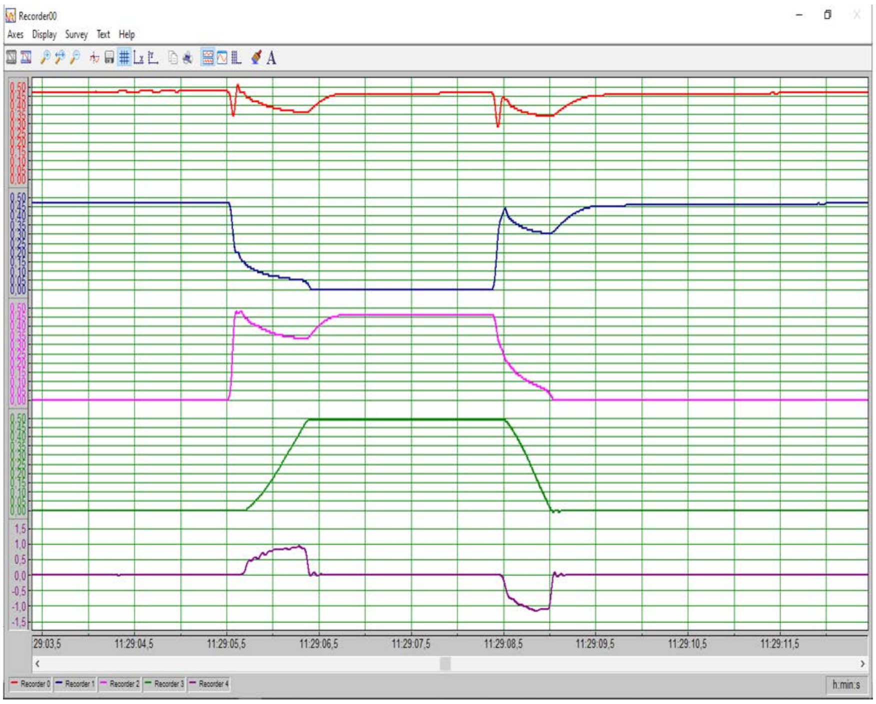

Figure 6. Graphs of the variability of pressure, distance and speed of the tested actuator.

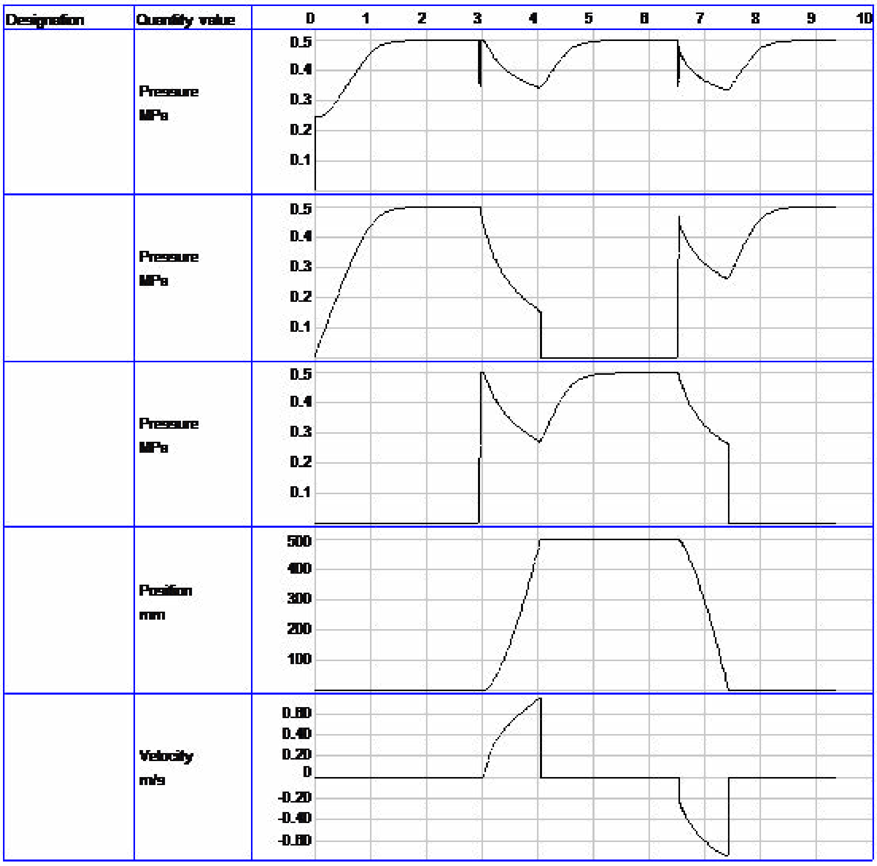

Figure 7. Graphs of the variability of the parameters of the tested actuator.

Verification of the convergence of the results of experimental and numerical research

The article aims to present the complexity of the seemingly simple phenomenon of the operation of a pneumatic actuator. Showing the nature of pressure variability and thus the traveled distance and speed of a piston-less actuator carriage. The results come from an actual experiment and simulation with the existing FluidSim software used for pneumatics and automation design. It was necessary to identify the discrepancies between theoretical and experimental calculations. One of the statistical tools for data analysis was used here, i.e. the calculation of the *r*-Pearson correlation coefficient. The concept of correlation refers to the strength of the studied interdependence of signals (functions).

The data from the experiment and calculations for interesting ranges of work variability were introduced, i.e. the parameters of pressure in the filled chamber and in the evacuated chamber, as well as the displacement of the actuator carriage. On this basis, the correlation coefficients between the signals from the calculations and the experiment were calculated, thus determining the strength of the relationship between them.

Table 1. Calculation results of the Pearson's *r* correlation coefficient

Signal	Correlation coefficient (strength of the relationship)
Pressure in chamber A	0.96 (very strong)
Pressure in chamber B	0.73 (strong)
The displacement (path) of the actuator carriage	0.998 (very strong)

Table 1 shows the calculated correlation coefficients between the signals. According to the data shown in Tab. 1, it can be seen that the links between them are very strong. On this basis, it can be concluded that the numerical method gives results very close to the real ones. The values of the coefficient lower than one indicate incomplete coverage of both signals. This is evident when observing the visual waveforms, where there are slight differences in the filling and emptying times of the chambers when the airflow direction changes. This is due to the imperfection, and, in fact, the complexity of the flow process through the system, and difficulties in modeling it with a relatively simple tool, such as FluidSim. FluidSim is a real-time engineering tool, so the flow equations need to be simplified to satisfy this condition. Regardless of the differences in the pressure area, the end effect, i.e. the cylinder output – the path of the cart, is very strongly related, because the correlation coefficient is 0.998. The calculations of the correlation coefficient, as well as the entire experiment, were carried out in the DasyLab programming environment with the use of specialized modules for statistical analyzes, in this case, the determination of the *r*-Pearson correlation coefficient.

Conclusions

As a result of the simulation of the piston-free pneumatic actuator in the FluidSim environment and the experimental research carried out on the constructed stand, a large convergence of the obtained results can be noticed, confirmed by the *r*-Pearson signal correlation method. Such verification allows for the conclusion that the use of the FluidSim tool in research and design can be very useful. The construction of the stand and the actual tests are more troublesome and in this case much more expensive than numerical tests.

Author Contributions

Conceptualization, Zygmunt Szczerba; methodology, Zygmunt Szczerba; validation, Kamil Szczerba; formal analysis, Wojciech Żyłka; writing—original draft preparation, data processing: Zygmunt Szczerba, Kamil Szczerba; writing—review and editing, Zygmunt Szczerba, Marta Żyłka, Wojciech Żyłka; supervision, Wojciech Żyłka, Marta Żyłka; project administration, Marta Żyłka; investigation, Zygmunt Szczerba; resources, Kamil Szczerba; acquisition, Kamil Szczerba K; visualization, Wojciech Żyłka, Marta Żyłka.

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