Research Article

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Pneumatic actuator positioning with pilot controlled check valves

https://doi.org/10.2478/mme-2021-0003
Received Apr 17, 2020; accepted Dec 14, 2020

Abstract: Tests of accuracy and repeatability of the pneumatic cylinder positioning in intermediate positions using a check valve are presented. The tests were performed under different loads and for different piston speeds and operating pressure in a pneumatic system with throttle check valves and an optical linear displacement sensor measuring the position of the actuator rod. Assessment of the effect of the cylinder performance parameters on the accuracy and repeatability of piston rod positioning was done and limitations and possible applications of the pneumatic cylinder positioning in intermediate positions with a check valve were identified.

Keywords: Pneumatic actuator, position control, accuracy and repeatability

1 Introduction

Pneumatic actuators are generally used in many machines and devices for automation of production, automatic devices and robots, and means of transport. Pneumatic actuators are most likely to be used when the actuated mechanism stops in end positions of the actuator rather than in intermediate positions. This group of actuators is very often used, for example, in grippers as they have only two predefined positions – open and closed.

Advantages of pneumatic actuators include:

- simple design
- relatively low cost of the device
- low weight of both the device and the operating medium, for example, compared to liquids used in hydraulic systems
- gradual build-up of forces and the possibility to regulate the character of their intensification
- use in explosive environments

Disadvantages of pneumatic actuators include:

- difficulty in achieving uniform motions due to high compressibility of the operating medium
- generating smaller forces compared to hydraulic systems
- difficulty in maintaining accuracy of kinematic parameters of the movement when changes in load on the system occur
- problematic position control at intermediate points between end positions

On consideration of the advantages and disadvantages listed above, using pneumatic actuators makes sense for both practical and economic reasons, which is why it would be important to eliminate any constraints on their use, for example, in automated assembly systems and on automated technological lines where multiple, rather than just two, positions of the drive are required. Issues concerning accuracy and repeatability of position control of the actuator in intermediate positions are particularly relevant given that pneumatic actuators are a viable alternative to electric drives, mainly for reasons of cost-effectiveness. The decision to purchase a pneumatic actuator of a specific size can be made based on the kinematic requirements and loads on the actuator during its operating cycle. If the actuator is to be used to drive a mechanism that only stops in end positions, accuracy and position control are not an issue. A major problem arises when the actuator is to stop in intermediate positions. A standard pneumatic linear actuator has two static piston positions – the end positions. For intermediate piston positions, a more complex actuator control system providing positional feedback is required. Complete with a pneumatic actuator, position measurement coupled with a control system, the servopneumatic system represents such a system. One of the many ways in which such a servo mechanism can operate involves, for example, connecting an actuator with position sensors and check valves.

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However, in terms of performance, the parameters of repeatability and accuracy of an actuator position control with check valves are of great importance.

To date, the literature has been dominated by reports discussing applications of customized control systems and analyses of the ways in which the accuracy of position control of pneumatic actuator systems is sought to be improved through appropriate and targeted intervention into the control system by including n-way valves to control the actuator. The accuracy of positioning of the table with pneumatic cylinder was enhanced to the level of ±20 nm positioning error by means of the control system equipped with the fuzzy controller and velocity signal compensation [1]. The paper of Hamiti *et al.* [2] presents the application of an analog controller part (inner loop) and a digital controller part (outer loop) in a new control scheme for the pneumatic servo system. The analog feedback reduces the complexity of the system and the nonlinearities, which consequently stabilizes the system. Shih and Ma [3] present an application of the fuzzy control technology and modified differential control method to control the position of a pneumatic rodless cylinder. With this method the control accuracy of the pneumatic cylinder is under 0.1 mm with or without loading. To enhance the accuracy of positioning of the pneumatic cylinder, a proportional integrator derivative (PID) controller and fuzzy logic controller (FLC) are applied [4]. The method is to enhance valve behavior and reduce the delay in opening and closing. The research includes both modeling and experimental verification. Sato and Sano [5] show a practical controller design method for repeatable positioning of pneumatic cylinder actuator. With that method, the accuracy of the cylinder positioning was 50 nm.

The issue of the accuracy of position control pneumatic actuator systems is critical in these considerations. According to the latest review of the research trends in servo pneumatic positioning systems [6], the best positioning accuracy of pneumatic device as reported by Carneiro and Almeida [7] is ±5 µm for 280 mm stroke length. The hybrid approach containing the pneumatic actuator for macro movement and piezo actuator for micro movement is successfully applied in order to achieve long range and accurate positioning [8–11]. In the review, the conclusion was drawn that there are certain limitations to hybrid actuator applications (they cannot be employed in wet, dusty, chemically aggressive atmosphere and in the presence of radiation and electromagnetic fields). It follows that fully pneumatic systems with highspeed and accurate positioning ability are still in great demand.

Consequently, we decided to proceed with experiments that would allow us to determine intermediate position control accuracy and repeatability of the actuator with standard check valves without introducing customized modifications to a standard control system. The tests were carried out under different operating conditions (loads) and air supply of the pneumatic system.

2 Position measurement systems

To measure the outstroke position of the piston rod of the pneumatic actuator used in the test, MONOSASHI-KUN high precision stroke reading cylinder with built-in linear magnetic scales and a CEU5P-D counter by SMC were used. The principle of operation of the measuring system is illustrated in Figure 1.

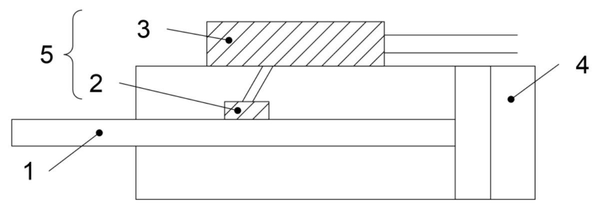

Figure 1: Schematic diagram of the MONOSASHI-KUN measurement system: 1 – magnetic scales, 2 – sensor head, 3 – signal amplifier, 4 – actuator, 5 – sensor assembly

The value of the outstroke position of the piston rod (1) where the magnetic scales are located is measured by the sensor head (2). The scales consist of alternating magnetic and non-magnetic elements. Magnetic field changes with the movement of the piston rod, which is detected by the magnetic field detector located in the sensor head (2). Signals received from the sensor head (2) are sent as pulse signals to the signal amplification system (3). The MONOSASHI-Kun encoder has a resolution of 0.1 mm and accuracy of ±0.2 mm. The stroke reading cylinder works together with the CEU5P-D multi counter, which displays the value of the position (Figure 2).

Figure 2: CEU5P-D multi counter by SMC

The counter displays the current position of the piston rod read by the position measuring encoder. It can also signal that the actuator piston rod has reached a pre-recorded position by displaying symbols in the bottom right corner of the display. The tolerance within which the counter is to signal the position of the actuator for preset positions can also be defined. When the actuator reaches a preset position, its numeric symbol is indicated on the counter display. The counter also has a stop detection function. The described piston rod position measurement system is used as a component of positional feedback to control the actuator operating cycle by an operator programmable Unitronics Controller M-90 OPLC and serves as an auxiliary measurement in the process of determining the accuracy and repeatability of the actuator positioning.

Laser sensor optoNCDT ILD 2220-2 from MICRO-EPSILON was used to measure the position and determine the positioning accuracy and repeatability of the piston rod positioning for the actuator.

The sensor can be used to measure distance by applying a method called triangulation. A semiconductor laser of less than 1 mW served as a light source. The sensor resolution is 0.03 μm, and the measuring range is 2 mm. The sensor features an automatic calibration function.

To test the accuracy and repeatability of the pneumatic actuator positioning, a laser sensor optoNCDT ILD 2220-2 was used as the main measurement sensor. The MONOSASHI-KUN sensor together with the CEU5D-P multi counter was applied as an auxiliary position measurement kit and was used to control the positioning of the pneumatic actuator in the middle of the measuring range of the main sensor and to read out position values when the piston rod moved outside the measuring range of the laser sensor.

3 Experimental setup

The test bench for examining the accuracy and repeatability of position control of a pneumatic actuator with a check valve was built at the pneumatics laboratory of the Institute of Machine Tools and Production Engineering of Lodz University of Technology. The schematic diagram of the pneumatic tubing and electrical wiring of the system is shown in Figure 3.

The test bench includes an air preparation unit, a valve controlling flow direction, a pneumatic drive, throttle check valves with pilot operated check valves, a OPLC, and a sensor measuring the position of the piston rod of the cylinder. The OPLC is tasked with controlling the movement of the pneumatic drive, which operates in a closed-loop cycle that

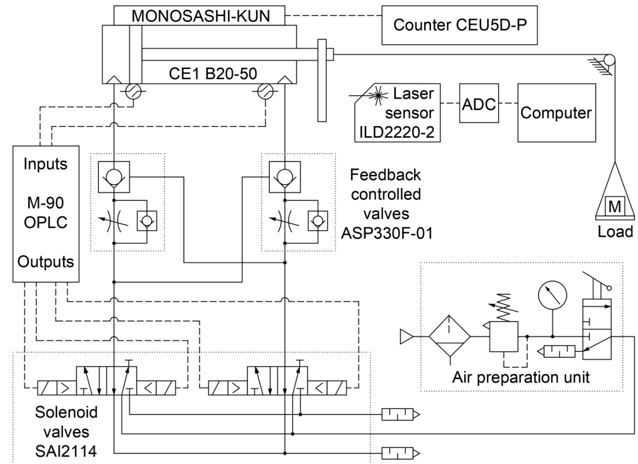

Figure 3: Schematic diagram of the test bench

is repeated several times. The controller activates the movement of the actuator from the home position to the position where the measurement is carried out, and next, once the measurement is completed, it effects the return of the actuator to the home position. To signal the home and end positions, a reed switch mounted on the actuator is used.

The pneumatic drive used for the tests is a CE1 B20-50 rod actuator from SMC. The bore size of the cylinder is 20 mm and the stroke length is 50 mm. The drive has no cushioning in end positions. Operating pressure range is between 0.05 MPa to 1 MPa with a maximum speed up to 500 mm/s. Additionally, the actuator is provided with a rod anti-rotation system. The cylinder's piston is equipped with a magnet, which enables position measurement. The cylinder has a slit to mount a sensor indicating the position of the piston. Additionally, the actuator is fitted with the MONOSASHI-KUN linear position encoder from SMC, described earlier.

SMC throttle check solenoid valves SAI2114 operated by OPLC, along with pilot operated check valves ASP330F-01 were used to control the speed of the pneumatic drive.

Three physical properties can be controlled during the tests of accuracy and repeatability of the pneumatic drive: pressure of the medium supplied to the actuator, speed of the actuator, and the load. The pressure is controlled by a reducer included in the air preparation system. Adjustment can be performed within the range from 0.2 MPa to 0.6 MPa with a resolution of 0.1 MPa. Speed is controlled with throttle check valves mounted on the pneumatic drive connections. Valve adjustment results in a reduction or an increase in air flow, and thus a change in the speed of the actuator. For each series of the tests, with the working pressure constant, three speed values were selected. The load on the pneumatic drive is controlled with weights. The mass of the load can be changed from 1 kg up to 4 kg in 1 kg increments.

4 Research methodology

The tests were carried out in accordance with the objectives underlying the design of the test bench. Prior to the tests, the position of the actuator was determined.

Before starting a series of measurements, pressure was set using a reducer installed in the air preparation unit, and its value was read by a manometer. The speed of the piston rod of the pneumatic actuator was set by adjusting the throttle check valve control screw. Stroke speed was computed based on the data acquired from the laser sensor. The load was modified by placing weights on the weighing pan. The actuator operating cycle, including the planned number of reiterations, was established with the OPLC application software. There were 30 repetitions in each series at constant values of pressure and load to enable statistical analysis of test results.

5 Test results

The measurement data from each test comprised of 30 repetitions were saved in spreadsheets. Next, deleted from each spreadsheet were the initial and final runs, which showed changes in the piston position while approaching and leaving the measurement point. An arithmetic mean was then calculated for the remaining number of samples to average the values of the actuator position during the measurement.

Positioning accuracy was calculated with the following formula (1):

$$AP_p = \sqrt{(\overline{x} - x_c)^2} \tag{1}$$

where: AP_p – positioning accuracy of the actuator, $\overline{x}$ – the average value of the actuator position, x_c – the value of the reference (measurement) position.

On the basis of the results, for each pressure value, surface charts were created illustrating the changes in the positioning accuracy depending on the rod stroke speed and load.

Figure 4 presents changes in positioning accuracy of the pneumatic cylinder for an operating pressure of 0.2 MPa.

The results presented in the chart (Figure 4) indicate that the accuracy of the rod positioning decreases with increasing stroke speed. The highest accuracy was achieved at 27.3 mm/s and a load of 3 kg, while the lowest at 34.3

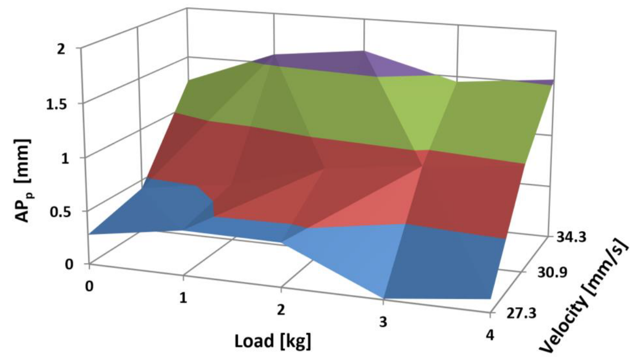

Figure 4: Positioning accuracy at an operating pressure of 0.2 MPa

mm/s and a load of 2 kg. Considerable variation in positioning accuracy for the different speed values may be attributed to too low pressure of the compressed air supplied to the actuator chambers.

The next chart shows the relation between the pneumatic cylinder positioning accuracy, piston rod stroke speed, and mass of the load for the working medium pressure of 0.3 MPa (Figure 5).

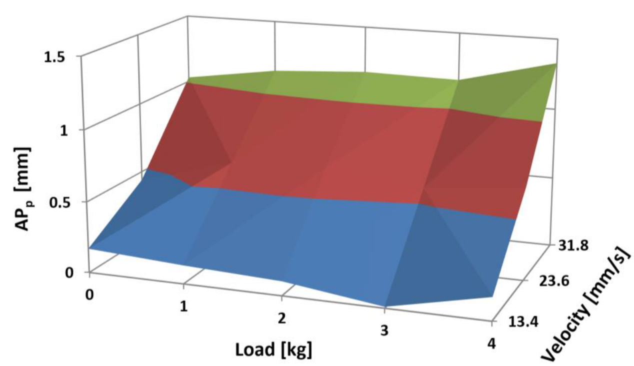

Figure 5: Positioning accuracy at an operating pressure of 0.3 MPa

The highest accuracy was observed when the piston rod moved at a speed of 13.4 mm/s and a load of 3 kg, while the poorest accuracy was recorded when the cylinder had reached a speed of 31.8 mm/s and worked under a load of 4 kg. Fluctuations in positioning accuracy values only occur at a speed of 13.4 mm/s, which means that the drive speed was too slow. The rod moved in steps, which could have affected the positioning accuracy. For the remaining situations, positioning accuracy deteriorated proportionally with increasing piston stroke speed and load.

The following chart shows the relation between positioning accuracy, change in the rod stroke speed, and load at a compressed air pressure of 0.4 MPa (Figure 6).

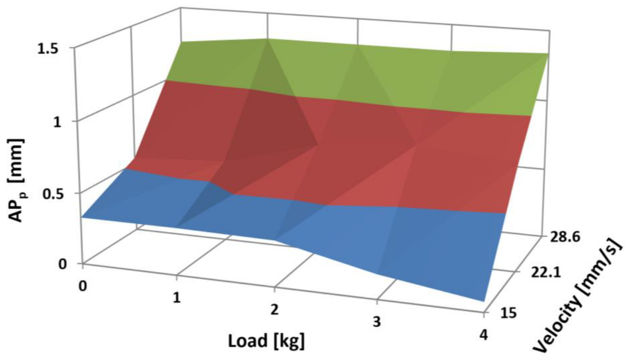

Figure 6: Positioning accuracy at an operating pressure of 0.4 MPa

The system achieved the greatest accuracy with a rod stroke speed of 15 mm/s and a load of 4 kg. The lowest accuracy was observed at 28.6 mm/s and a load of 4 kg. In this case, for a piston stroke speed of 15 mm/s, the positioning accuracy of the pneumatic cylinder increased with the system load. In other cases, the accuracy decreased proportionally to the increase in speed of the pneumatic drive and the load under which the actuator operated.

Figure 7 shows the relation between the positioning accuracy of the pneumatic drive, its speed, and the load under which it operates at an operating pressure of 0.5 MPa.

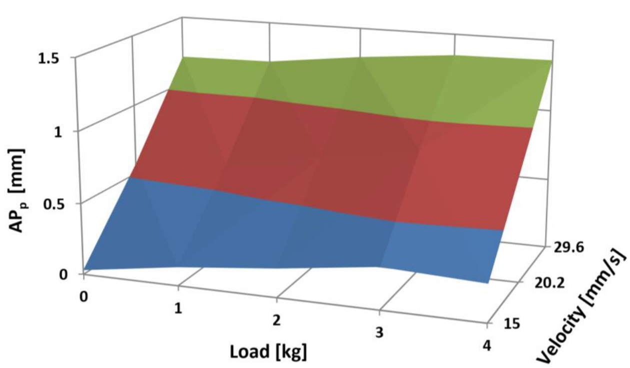

Figure 7: Positioning accuracy at an operating pressure of 0.5 MPa

A conclusion that follows from the chart (Figure 7) is that positioning accuracy is directly proportional to the piston rod stroke speed and the load bearing on the system. The highest accuracy was achieved when the piston rod moved at 15 mm/s and operated under no load, while the lowest accuracy was observed for 29.6 mm/s and a load of 4 kg.

The next chart presents the relation between the accuracy of the pneumatic drive positioning, piston rod stroke speed, and the load under which the pneumatic system operates at an operating pressure of 0.6 MPa (Figure 8).

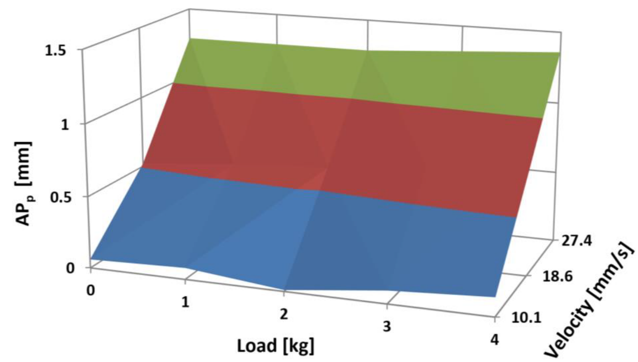

Figure 8: Positioning accuracy at an operating pressure of 0.6 MPa

In this case, for a speed of 10.1 mm/s, the positioning accuracy varied with the increase in the load on the pneumatic cylinder. However, in this case, the accuracy was actually the highest for this speed and did not exceed 0.1 mm within the load range from 0 kg to 3 kg. The poorest accuracy was recorded for a speed of 27.4 mm/s when the actuator operated under a load of 4 kg.

The positioning repeatability error was calculated according to the following formula (2):

$$RP_l = \bar{l} + 3S_l \tag{2}$$

where: RP_l – positioning repeatability error for the tested pneumatic actuator, $\bar{l}$ – average deviation of a position from the mean value, S_l – standard deviation of the mean value. The average deviation of a position from the mean value was calculated with the formula (3):

$$\bar{l} = \frac{1}{n}\sum_{j=1}^{n} l_j \tag{3}$$

where: l_j – deviation of the j-th position from the mean position value. This deviation was calculated with the equation (4):

$$l_j = \sqrt{\left(x_j - \bar{x}\right)^2} \tag{4}$$

The standard deviation of the mean value was calculated with the formula (5):

$$S_l = \sqrt{\frac{\sum_{j=1}^{n}\left(l_j - \bar{l}\right)^2}{n-1}} \tag{5}$$

The results of experiments proved that the repeatability error was not affected to a significant extent by the air supply pressure. The trends of the repeatability error versus load or velocity are not influenced by the air supply pressure except the case of the pressure 0.2 MPa when the actuator does not act properly especially under greater loads.

Based on the results, the surface chart presented in Figure 9 was created for the air supply pressure of 0.6 MPa, illustrating the repeatability error depending on the piston rod stroke speed and load.

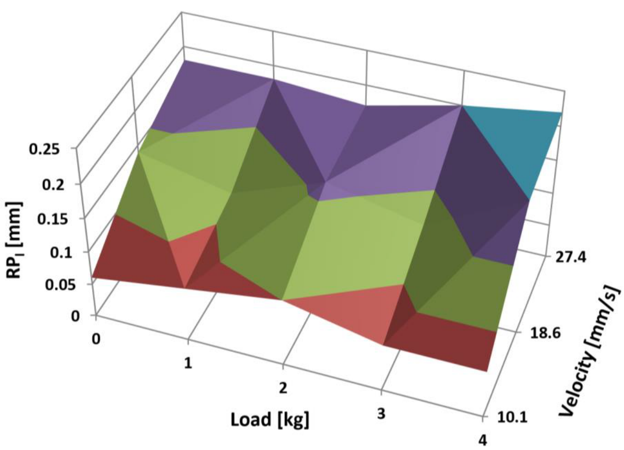

Figure 9: Repeatability of positioning at a pressure of 0.6 MPa

Here, the repeatability error value is proportional to the speed of the pneumatic drive and the load under which the actuator operates. The best repeatability was achieved when the actuator operated at 10.1 mm/s without load. The worst repeatability was observed when the piston rod moved at 27.4 mm/s and was under a load of 4 kg.

6 Conclusions

The tests reported above allowed us to analyze the accuracy and repeatability of positioning of the pneumatic actuator in intermediate positions, at different loads, speeds, and pressures, and with the use of pilot operated check valves.

Investigating the accuracy and repeatability of pneumatic actuator positioning by means of a pilot operated check valve allows for an improved application of the pneumatic actuator in high precision positioning systems. Based on the conducted tests, drives can be designed for mechanisms with positioning standards enabling the use of pneumatic drive systems and control systems. In many contexts, where there is a need to automate a production or an assembly process, a positioning accuracy of 0.1 mm with high repeatability is sufficient to meet the design requirements for the constructed drive system. Being able to know the accuracy and repeatability of positioning makes it possible to decide in which applications a pneumatic drive can be used. Consequently, a pneumatic drive can be considered as a viable alternative to electric or hydraulic drives not only because of its cost-effectiveness but also because of its technical capacity.

Furthermore, installation of a pneumatic workstation allows for a greater use of an environmentally friendly medium. Adequate accuracy and repeatability of a system positioning provides for extended deployment of pneumatic drives in explosion hazard areas. Use of pneumatic drives to create specific applications can increase work safety by minimizing the risk of electric shock.

The following conclusions can be drawn from the study:

- The tests showed that the positioning accuracy, at pressures ranging from 0.4 MPa to 0.6 MPa, deteriorates in a way that is roughly directly proportional to the piston rod stroke speed and system load. For repeatability, the same relation is observed. This can be explained by the fact that as the load and speed increase, the inertia of the entire system increases, which causes a deterioration in the positioning accuracy and repeatability.
- At a pressure of 0.2 MPa, no straightforward relation between the positioning accuracy of the actuator, the speed, and the load of the system could be observed. Under this pressure, too low stroke speed when the actuator was unloaded resulted in its stepping motion. As a result, positioning accuracy and repeatability were very poor. Once the load was increased, the situation improved. Stepping motion of the rod is caused by incorrect parameters of the pneumatic system supply and such situations should be absolutely avoided during design. Such a situation is also dangerous since it can lead to damage to the actuator. The reason was the application of too low pressure of the working medium, which made the system insufficiently rigid to support the piston as it approached the preset position. The system operating under this pressure was unstable.
- At a sufficiently low speed but high enough to prevent the piston rod from stepping, the positioning accuracy of the pneumatic cylinder was about 0.1 mm. The best accuracy was achieved at 0.6 MPa, speed of 10.1 mm/s, and no load. In those conditions during the experiments, the repeatability error achieved its minimal value of 0.06 mm. The high accuracy and low repeatability error result from the application of a sufficiently high supply pressure, which ensured that the system achieved optimal rigidity that allowed it to attain the best positioning accuracy.
- Application of pilot operated check valves may lead to the miniaturization and simplification of the con-

trol system for pneumatic cylinders whose operating cycle requires high-precision control of the piston rod stopping in intermediate positions between the end position bumpers.

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