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THE PROBLEM OF POSITIONING REPEATABILITY OF LINEAR PNEUMATIC DRIVES WITH DISCRETE PROXIMITY SENSORS

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Abstract: Although electric drives are very popular and dominate in the industry, there still are areas where the compressed air is used for driving the machines. Pneumatic drives are often used in potentially explosive areas, however – due to many advantages – they have also wider applications in the industry. They also have disadvantages and the most important of them is the high variability of the speed of movement due to the sudden changes of the load. Accurate positioning of pneumatic cylinders rod or carriage requires the use of special electronic control systems, but in practice, solutions based on electronic proximity sensors are often used. In this paper, we will consider the influence of certain aspects – like the operating conditions of the actuator, type of the valve or the design of the control system – on the piston motion as well as on the repeatability of positioning.
Key words: Pneumatic drive, positioning accuracy, positioning repeatability, proximity sensors, 5/3 valve.

1. INTRODUCTION

Automation in the modern industry is mainly based on electronic control combined with electric drives. Such solutions meet the unification principle according to which, the machine should use components that are powered with the same medium (e.g. compressed air, electricity, etc.). Despite the fact that different types of electric actuators and motors dominate in the field of industrial drives, there still are areas where the compressed air is putting machines in motion. Pneumatic drives have many advantages, including:
• good mass to efficiency ratio,
• simple construction,
• the simplicity of realizing the linear and rotational motion,
• very simple control principles,
• the possibility of achieving high speeds,
• the ability of generating high force or torque.
The compressed air itself also has a number of advantages that distinguish it from other types of media:
• unlimited resources – the air is taken directly from the environment,
• the operation of compressed air equipment does not cause any pollution and the used air can be discharged directly into the atmosphere,
• compressed air retains its properties over a wide range of ambient temperatures – it is also resistant to chemicals, magnetic and electrical fields and radiation,
• compressed air does not cause explosion hazard, so it can be used in explosive atmospheres,
• due to its compressibility, compressed air can be stored in tanks and the drives can be overloaded until the full stop,
• compressed air can be used as a medium that transfers energy, as an information carrier and also as a base medium in the transport of liquids or loose solids.

Pneumatic drives are also used in robot construction, ranging from simple systems supporting or extending the robot's capabilities (Tsukagoshi et al., 2005) to complete robot manipulators. Along with the complexity of the machine and the need for high positioning accuracy, the demands on the control system and sensors that provide feedback are also increasing, (Hozdić, 2015). In most cases, special actuators are used, such as pneumatic muscles. This type of drives does not have much in common with typical piston-rod-cylinder actuators and often requires the special control system (George Thuruthel et al., 2018; Robinson et al., 2015).

This paper raises the problem of accuracy and positioning repeatability of pneumatic actuators' piston. In the further part the results of experiments will be shown, using the equipment that consisted of the basic line of pneumatic valves and electronic proximity sensors. The following sections will present the results of experiments that have been carried out in order to check the influence of various factors, such as valve type, compressed air flow control or piston load on the positioning of the drive's operating part.

2. THE CURRENT STATE OF THE KNOWLEDGE

In the simplest pneumatic drives, the positioning is often done in a mechanical manner. The first, very simple way is to use the physical limits of the actuator. In practice, the “full stroke” (“lock to lock”) positioning is very often used in the simple processes. The positioning of piston consists in physical stopping of the movement of the piston after approaching one of the end positions in the cylinder. In this way two, three or four positions could be reached with high accuracy and excellent repeatability. In order to “encode” three or four different positions, one should use a combination of two cylinders with different strokes that are coupled in series (Zaghis, 2015; Szenajch, 2019). The three-position cylinder has the both rods directed in the same way, while the four-position cylinder’s rods point in the opposites directions.

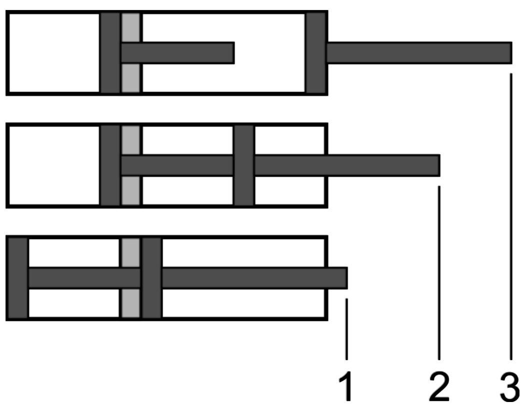


Fig. 1. The operating principle of a three-position actuator

The three-position cylinder working principle is shown in Figure 1. Such actuator has two chambers, where two pistons work independently, both having rods – one rod is invisible, hidden inside of the cylinder. In the Figure 1, the first position is indicated by “1” and occurs when both piston rods are retracted. After supplying the smaller (left) chamber with the compressed air the piston starts moving. The rod is pushing the piston in the right chamber, what – in consequence – causes the movement of the right piston’s rod. In this way the position marked with number “2” is achieved. The third position is achieved by supplying the right chamber, what causes the right piston to move. By the proper control of air flow, all combinations are possible i.e. the movements between positions 1-2, 2-3 and 1-3 (full stroke). The presented method of positioning is the simplest one, but has important disadvantage: the impact forces, generated at stroke end are considerable. This may cause adverse vibrations of machine and premature damage of the actuator.

Equally common is the method of positioning the actuator’s piston with the use of proximity sensors (Zaghis 2015; Szenajch, 2019). The proximity switches could be electrical or pneumatic one and could be triggered mechanically or contactlessly. This method requires pneumatic or electrical control system, where the valve is toggled when a limit switch is triggered. Depending on the type of limit switch, its characteristics, response speed of a control system, working medium etc., this method can introduce positioning errors in the form of a difference between the desired and actual position of the element (piston) which, by acting on the limit switch, generates a control signal. In addition, this difference will not have a constant value, what will introduce the error related to the repeatability of positioning. This issue will be analysed later in this paper.

The subject of positioning accuracy of pneumatic drives, in the vast majority of cases, is discussed in the literature with regard to the use of electronic, programmable control systems based on PLCs, mainly dedicated for robotics (Lai et al., 1990; Zhang et al., 2019) or for efficiency improvement of pneumatic drive system (Yang et al., 2009; Du et al., 2018). Advanced algorithms are often used to control such systems, allowing precise control of the operation of the system’s individual pneumatic components. At the same time, the development of pneumatic and electro-pneumatic systems is increasingly oriented towards the cyber-physical systems (Salkin et al., 2018; Faller and Feldmüller, 2015). For older machines, control systems are frequently upgraded in order to migrate the existing flexible manufacturing systems to the Industry 4.0 compliant level (Calderoy Godoy and Gonzalez Perez, 2018).

3. THE DESCRIPTION OF THE TEST BENCH

In order to carry out the test, the laboratory stand has been used for assembling the model of a hypothetical electropneumatic system. The electrical control system has been used because of the simplicity of assembly, the possibility of making quick changes and flexibility, but also because of the independence of the electrical control circuit from the compressed air circuit.

The system intended for testing was built on a laboratory bench using the following components:

- one pneumatic rodless cylinder with air-cushion absorption function:
- one 5/3 valve in two different versions, controlled electrically,
- compressed air source,
- two capacitive sensors with binary output,
- electrical pushbuttons,

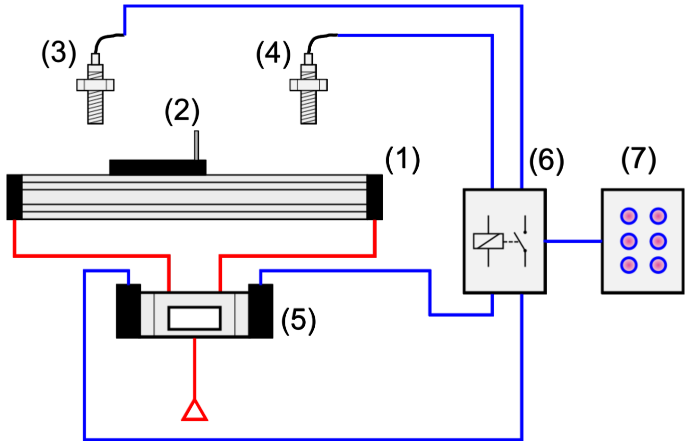


Fig. 2. The sketch of the tested system configuration (numbers are explained in text)

- electrical relays,
- 24V DC power supply unit,
- compressed air source (6 bar).

The sketch of the configuration of the tested system is shown in Figure 2. Numbers denote respectively: rodless actuator (1), position marker (2), capacitive sensors (3, 4), 5/3 monostable valve (5), relay box (6), push-button panel (7). The measurements were carried out using 5/3, monostable, “opened centers” and 5/3, monostable, “closed centers” valves, respectively – the valves have been swapped, according to the experiment demands.

3.1 The overall description of the testing procedure

The testing procedure has been ran for the following configurations:

- <u>Test 1:</u> using 5/3, monostable, "opened centers" valve, actuator without load,
- <u>Test 2:</u> using 5/3, monostable, "opened centers" valve, actuator loaded with mass (ca. 0.5 kg),
- <u>Test 3:</u> using 5/3, monostable, "opened centers" valve, actuator loaded with mass (inertia), braking with the impulse of air,
- <u>Test 4:</u> using 5/3, monostable, "closed centers" valve, actuator without load.

For each configuration, the measurement has been repeated 30 times. During the measurements, the pressure of the compressed air had a constant value of 6 bar. In order to improve positioning accuracy, the capacitive sensors are adjusted to reduce the influence of hysteresis on the marker detection. The goal was to achieve the narrowest possible range of positions where the sensor remain excited by the marker. The sensor (3) could be used for “fast switching” – it switches on the left control coil of the 5/3 valve during the carriage return, while the right coil is still powered. In this way, the passing of the valve spool through the centre position is quick enough to consider the valve as two-position one.

During the measurement, the carriage was moving from left to right. After reaching the sensor (4) detection area, the valve is switched and the compressed air supply is closed – the carriage stops. Next, the measurement is done (manually, optically), using two markers: one placed on the carriage and the second on the actuator’s body.

The electrical control system is shown in the Figure 4. The diagram is divided into two parts. The part shown in Figure 4(a) is responsible for moving the carriage during the measurement, while the part shown in the Figure 4(b) controls the other coil of the valve and realizes the return movement of the carriage.

The measurement stroke is initiated by pressing the START button. After the measurement has been done, the carriage can be returned by using the RETURN button. Before doing any measurements, several full stroke movements has been done in order to stabilize working conditions. Rodless cylinders are characterized by many points of contact, where the friction forces are generated. Doing the full stroke movements before experiment is aimed for fitting the sealing and spreading the lubricant. Moreover, there is no perfect leak tightness of any pneumatic actuators. In this case, making of full stroke movements could also stabilize the pressure conditions in both chambers of the cylinder.

4. THE DESCRIPTION OF THE EXPERIMENT

4.1 The configuration of the test bench for Test 1

In this experiment, the 5/3 monostable, “opened centers” valve has been used. The diagrams of the pneumatic part of system are shown in Figure 3. The electric control is shown in Figure 4. This test is carried out in order to obtain the pattern of positioning repeatability for mentioned system.

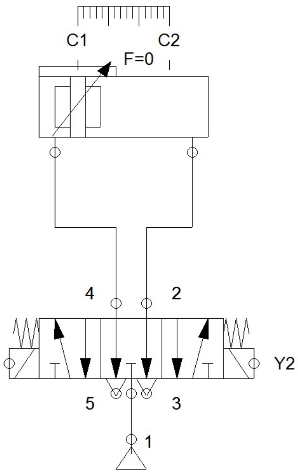


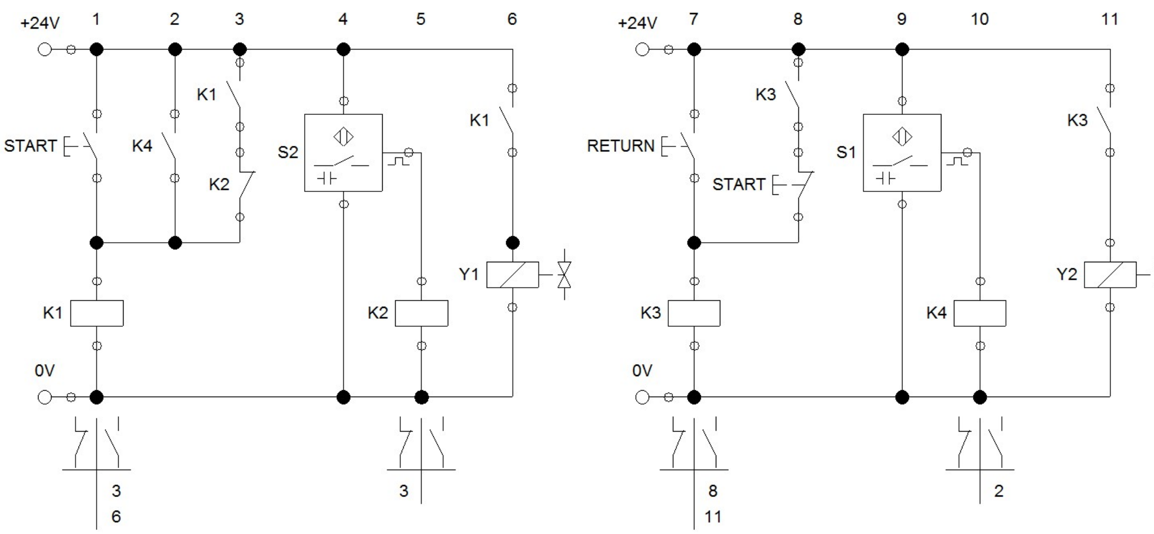
Fig. 3. The diagram of the pneumatic part of tested system with the “opened centers” 5/3 valve

4.2 The configuration of the test bench for Test 2

In this case, the pneumatic system and the electric control remain unchanged. The main difference from the previously considered system is the load mounted on the carriage. This test was carried out to verify whether the increased inertia of the carriage (due to the installation of additional mass) will have a significant impact on the repeatability of the positioning.

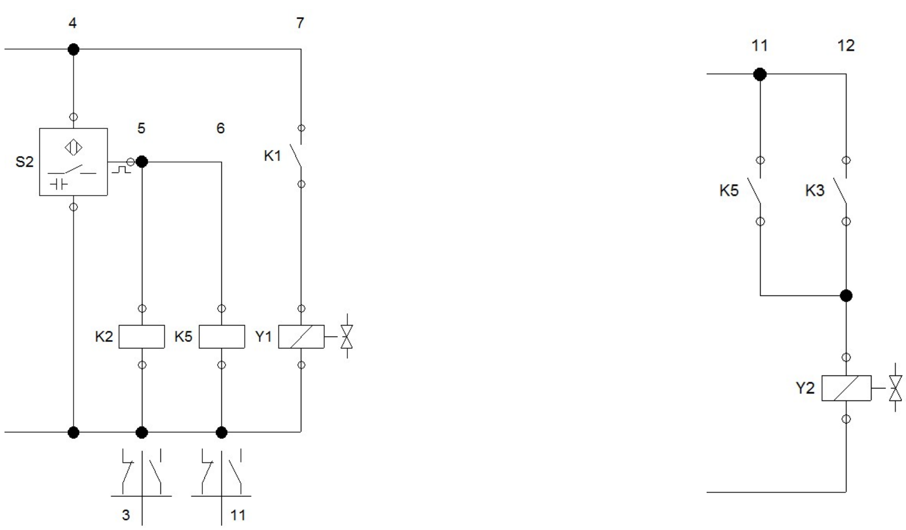
4.3 The configuration of the test bench for Test 3

The Test 3 is the continuation of the Test 2. It uses the same pneumatic configuration (as it is shown in the Figure 3), but different electrical control. The main differences concerns the 4th and 5th loops shown in the Figure 4(a) and 11th loop shown in Figure 4(b).



(a) (b)

Fig. 4. Diagrams of the electric control of the system: (a) left valve coil actuating part and (b) right valve coil actuating part



(a) (b)

Fig. 5. The realization of braking using the impulse of air: (a) the modified part of diagram shown in Figure 5(a); (b) the modified part of diagram shown in Figure 5(b)

The modified loops are shown in the Figures 5(a) and 5(b). As it could be seen, the sensor (4), described in the diagram as “S2”, generates the impulse that turns on the relays “K4” and “K5”. In turn, the relay”K5”, through the contact “K5” gives the short impulse that excites the valve coil “Y2”, while the “Y1” coil remains disabled. In this way the short impulse of compressed air is directed to the right chamber of the actuator and “brakes” the piston. Because the valve returns to the center position, both chambers are immediately drained.

4.4 The configuration of the test bench for Test 4

The Test 4 has been carried out with the use of 5/3 monostable, “closed centers” valve. The diagram of the pneumatic part is shown in the Figure 6. The electrical control system is the same like in Tests 1 and 2 and is shown in the Figure 4. The carriage has been moved without additional load.

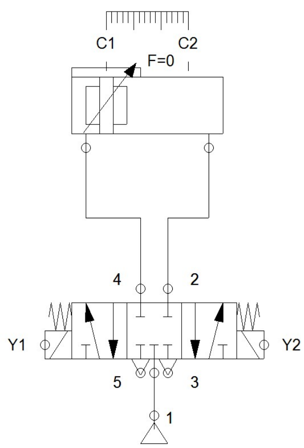


Fig. 6. The diagram of the pneumatic part of tested system with the “closed centers” 5/3 valve

5. THE RESULTS AND DISCUSSION

The results of individual tests were collected and then elaborated. First of all, it was assumed that the decisive parameter would be the repeatability of positioning, because it is directly related to the accuracy. For this purpose, the median of the range covered by 30 samples in each test was calculated separately and has been assumed as a reference value. Next, the positioning error ranges were determined, taking values from 0 to 2 mm with a 0.5 mm increment. The positioning error value above 2 mm was found to be unsatisfactory. On this basis, the graph shown in Figure 7 was created, which allocates the error values for each test to one of the specified ranges.

The rodless cylinders have higher frictional resistance than actuators with the piston rod, so the repeatability of positioning was quite satisfactory. The analysis of the graph presented in Figure 7 indicates that the best solution is to use a 5/3 “closed center” valve, because most of the measurement results have a spread of up to 0.5 mm. The solution consisting in breaking the piston using a compressed air impulse did not work at all – in this case, most of the measurements indicate a spread of over 2 mm. After mounting the load on the carriage an interesting effect has appeared in the form of improved repeatability of positioning. In this case, the frictional resistance between the carriage and the outer profile of the cylinder may have slightly increased, resulting in an unintended improvement in position repeatability.

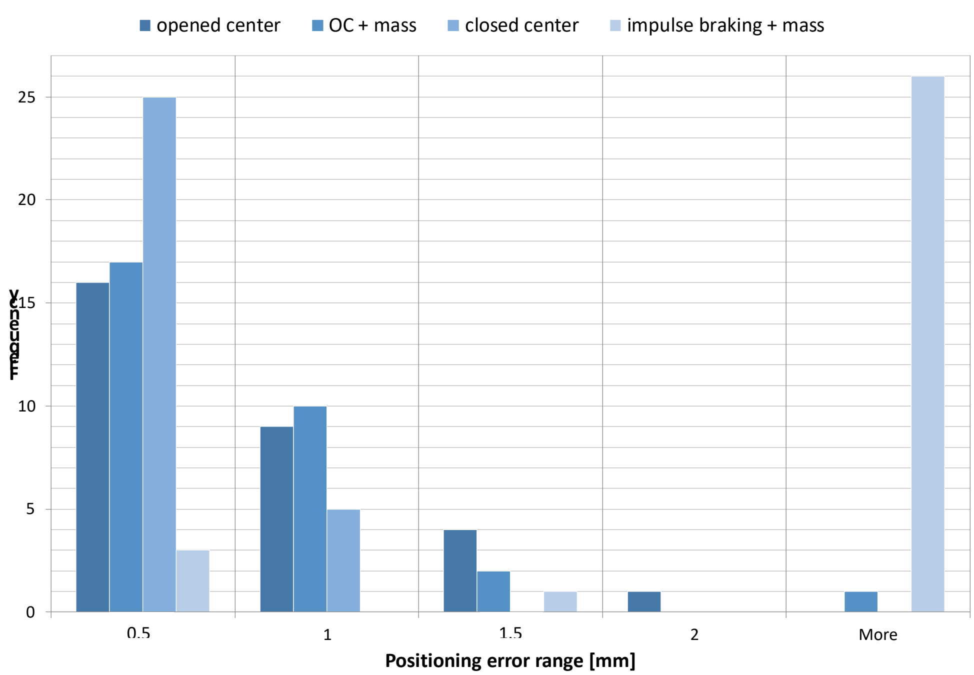


Fig. 7. The frequency of occurrence of positioning errors in particular ranges

6. CONCLUSIONS

Despite the rapid development of industrial drives technology and progress in improving positioning accuracy, the pneumatic drives are still used in industrial machinery. Due to the properties of the compressed air, the main disadvantage of pneumatic drives is the difficulty of achieving good positioning accuracy and repeatability. This paper has presented the research related to the analysis of positioning repeatability of linear pneumatic drives in combination with a simple electric, relay-based control system. The results of the tests show that even simple control systems can provide satisfactory positioning repeatability, sufficient for most of the inter-operational transport tasks or the simple manufacturing processes. However, it should be noted that the accuracy and repeatability of positioning is also influenced by the different external factors, such as the characteristics of the used proximity sensors, the response time of the mechanical and electric components or the parameters of the compressed air source. Therefore, the individual assessment of a given case is always important.

The further research will cover a wider range of pneumatic actuators in combination with different types of limit switches.

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