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Comparison of Proportional and PWM Pneumatic Control in Terms of Positioning and Compressed Air Consumption

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Abstract—**In this paper is shown a comparison of proportional pneumatic control and Pulse Width Modulation (PWM) pneumatic control in terms of positioning and compressed air consumption. All experimental tests were performed on a device for lifting and holding of the workpieces, which consists of one vertically mounted rodless cylinder with integrated vacuum gripper. In the case of the proportional pneumatic control, cylinder piston is always positioning in the correct position, but position losses are recurring during the time (in majority of cases, the position loss is 4 mm). As the control system constantly returns the cylinder piston to the desired position, that increases the compressed air consumption. In the case of the PWM pneumatic control, the position error is occurring (in majority of cases, the absolute value of the relative position error is less than 2%), but there is no position loss during the period of workpiece holding, i.e. there is no additional compressed air consumption. The compressed air consumption differential is approximately 18.6%. In addition, in case of Meter-out control in combination with previously defined types of control, the positioning is more accurate but the compressed air consumption slightly increases with decreasing the opening level of the one-way flow control valve.**

Keywords- proportional pneumatic control; PWM pneumatic control; Meter-out control

I. INTRODUCTION

Pneumatic control systems have been successfully surviving in an ever-changing world of technology for decades, so many modern industrial processes would be inconceivable without them. Pneumatic cylinders in particular have a significant role as a linear drive unit, due to their relatively low cost, ease of installation and maintenance, simple and robust construction, availability in various sizes and stroke lengths, etc.

In the long period of time pneumatic cylinders were used only to realize the elementary movements between two end positions (bang-bang control) with no possibility of setting an intermediate position. In these cases, the control is performed without feedback, by simply activating or deactivating (on-off) the directional control valves, which can enable or block the compressed air flow, change the direction of movement of the pneumatic actuator, etc. Accordingly, the directional control valves control the path of compressed air and the direction of flow is indicated by an arrow in their symbols. This type of the pneumatic control plays a major role in cases of relatively simple tasks of the industrial automation, such as, for example, many tasks in the handling technology (clamping workpieces, moving workpieces, positioning workpieces, orienting workpieces, separating workpieces, stacking workpieces, etc.). It is clear that this type of the pneumatic control will exist in the future, also.

However, there are the more complex control problems, such as, for example, assembly of modular products, inserting different workpieces in the press, placing electronic components on the board, quality control, etc. In these cases, it is necessary to perform an additional positioning in some intermediate positions and precise performance is required (for example, within tenths of a millimeter). It cannot be solved with conventional directional control valves, but by using various control techniques, such as proportional pneumatics [1] - [3] and digital pneumatics [4] - [8].

In the first case are used components that have the ability to control the flow during the movement of the actuator, in proportion to their input value. A typical representative of this group is the pneumatic proportional valve [9]. It has a position-controlled spool that converts an analogue input signal into a corresponding opening cross-section at the valve outputs. In this way, the flow is continuously controlled and enables the positioning of the pneumatic cylinder in one of the intermediate positions. The actual position of the cylinder piston is determined by using the appropriate displacement encoder, measuring the voltage or electric current (analogue signal) and performing the appropriate conversion. The main control

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device monitors and compares the actual position of the cylinder piston with the desired position (set point). The difference between actual and desired value (position error) is applied as feedback to generate an appropriate control action (input signal for proportional valve) to bring the controlled position of the cylinder piston to the same value as the set point. Thus, such control system consists of the main control device for position control, the pneumatic proportional directional control valve, the pneumatic actuator and the displacement encoder.

In the second case is used digital pneumatics [4]. Digital pneumatics means pneumatic control systems having discrete valued component(s) actively controlling system output [10]. Two fundamental branches of digital pneumatics are pneumatic control systems based on parallel connection and based on switching technologies. While in parallel connected systems have plurality of parallel connected components and the output is controlled by changing the state combination of the component, in the case of switching technologies, an individual or several components are activated quickly and continuously by using appropriate control methods. These components are exclusively on-off, fast-switching directional control valves. The most commonly used control method is PWM, alone or in combination with one of the other known control methods [11]. It should be noted that the valves must have a very short time of state change (enabled flow/blocked flow). Otherwise, if the pulse width is shorter than the time of opening/closing the valve, it will not react. Accordingly, the world's major manufacturers of pneumatic equipment have recently developed dedicated, specific valves that have a very short opening and closing time. One example is the monostable, normally closed, 3/2-way solenoid valve MHE3-MS1H-3/2G-1/8, by Festo [12], with “on” switching time of only 2.3 ms and “off” switching time of only 2.8 ms.

The main goal of this paper is to compare proportional and PWM pneumatic control [13] in terms of positioning and compressed air consumption. In [14] is shown that the proportional valve technique has better tracking characteristics than PWM control technique. In [2] is shown that the control scheme of proportional valve is better than those of the PWM control with fast-switching solenoid valves, and the control scheme of 3/2-way fast-switching solenoid valve is superior to that of 2/2-way fast-switching solenoid valve for the system with multi-channel soft actuators. Considering the cost, the control scheme of PWM control with 3/2-way fast-switching solenoid valve is the most suitable choice. In [15] is shown that the Dynamical Adaptive Backstepping-Sliding Mode Control (DAB-SMC) works best with the proportional valve. The performance, however, deteriorates by more than twofold, once the system utilizes the PWM control with the low-cost fast-switching solenoid valves of 3/2-way or 2/2-way configurations.

In this investigation, all experimental tests were performed on a device for lifting and holding the workpieces. It consists of one vertically mounted rodless cylinder with integrated vacuum gripper, which is used for gripping and holding the workpieces.

The paper is organized as follows: Section 2 shows two types of control of the device for lifting and holding the workpieces in detail: the proportional pneumatic control (the application of proportional valve) and the PWM pneumatic control (the application of four 2/2-way fast-switching solenoid valves). In addition, the data collection method related to the positioning and compressed air consumption is explained. The obtained results are presented and discussed in Section 3. Finally, the most important conclusions are drawn in Section 4.

II. EXPERIMENTAL PART

A. Proportional pneumatic control system

A purposefully developed controller which is used in this case is Soft-Stop SPC11-MTS-AIF, industrial controller by Festo [16]. It enables fast movement into the physically determined end positions and one or two selectable intermediate positions. The end positions can be set by means of fixed stops. The end position cushioning, movement to the intermediate positions and manual positioning are electronically controlled [16]. Accordingly, by using this controller, it is enabled to stop the piston of a vertically mounted rodless cylinder in four positions: two end positions (lower and upper) and two arbitrarily defined intermediate positions.

A parameterization and commissioning of the controller are enabled through the screen and buttons, as well as through digital inputs and outputs. That process is done automatically, by starting the mode for learning and memorizing defined positions (Teach mode). Therefore, during commissioning, the end positions (cylinder end positions or position of the fixed stops) as well as the desired intermediate positions are “learnt” by the SPC11.

The parameterization was performed in accordance with the manufacturer's manual [16], taking into account all the necessary conditions. Thus, for example, in order to reduce the fluctuations in the operating pressure, a compressed air reservoir with volume of 24 l was placed before the service unit. As the volume of the reservoir should be at least four times as large as the volume of the drive used [16], we chose a with volume of 24 l. Also, the tubes between the proportional directional control valve and the rodless cylinder are arranged symmetrically. It is necessary to mentioned that during the teach procedure the SPC11 can recognize faulty drive tubing or incorrectly set parameters. The teach procedure must therefore be carried out again if the tubing is disconnected and then reconnected, or if any of the parameters are modified [16].

In addition to the SPC11 controller, in this case a Programmable Logic Controller (PLC) CPX-CEC, by Festo, was used for control of monostable, 5/2-way solenoid, directional control valve. The valve was connected with the vacuum gripper, which is used for gripping and holding the workpieces in the required time. That 5/2-way valve is used in the function of normally closed, 3/2-way directional control valve, which is enabled by blocking the appropriate outlet connection.

Finally, for the realization of the experimental device, the following equipment from the manufacturer Festo was used (Fig. 1) [13]:

1. displacement encoder MME-MTS-600-TLF-AIF;
2. rodless cylinder DGPL-25-600-PPV-A-B-KF-SH-D2;
3. Soft Stop controller SPC11-MTS-AIF;
4. 5/3-way proportional directional control valve MPYE-5-1/8-LF-010-B;
5. vacuum gripper which consists of vacuum generator VAK1/4 and suction cup VAS-75-1/4-NBR;
6. service unit FRC-1/8-DB-7-MINI;
7. monostable, 5/2-way solenoid, directional control valve VUVS-L20-M52-MD-G18-F7, in function of 3/2-way valve;
8. one-way flow control valve GRA-1/4-B;
9. PLC CPX-CEC.

For easier understanding of the device operation, the pneumatic control scheme of proportional control is shown in Fig. 2. The 5/3-way proportional directional control valve, the monostable, 5/2-way solenoid, directional control valve, the one-way flow control valve, the rodless cylinder and the vacuum gripper are marked with 1V1 (Fig. 1, position 4), 2V1 (Fig. 1, position 7), 1V2 (Fig. 1, position 8), 1A (Fig. 1, position 2) and 2A (Fig. 1, position 5), respectively.

B. PWM pneumatic control system

The most common realizations of PWM pneumatic control systems with rodless cylinder involve configurations with two

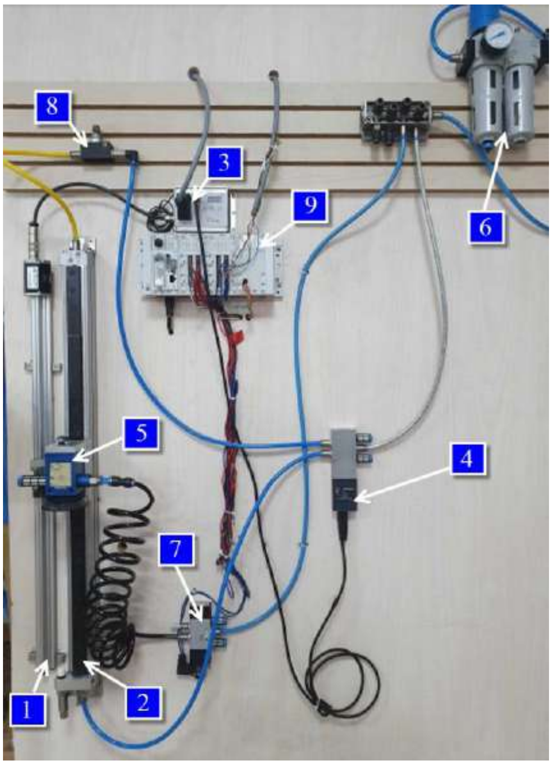

Figure 1. Physical realization of proportional pneumatic control

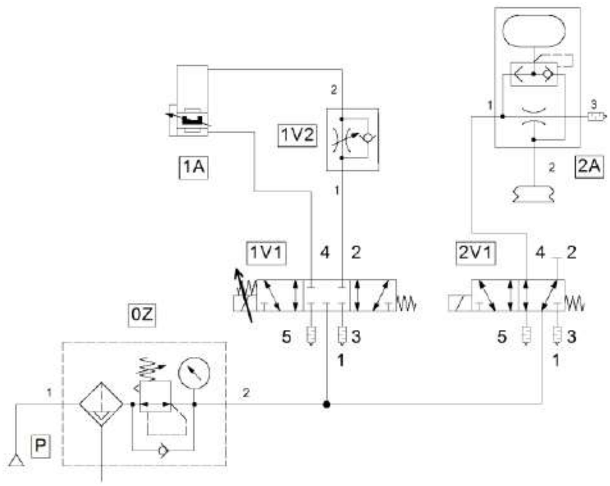

Figure 2. Pneumatic control scheme of proportional control

3/2-way fast-switching solenoid valves and with four 2/2-way fast-switching valves [2], [15]. In the first case, if both valves are deactivated (blocked flow), the both cylinder chambers are connected to the atmosphere. By bringing the input signal to the solenoids of the both valves, the both cylinder chambers are connected to the compressed air supply and the positioning process of cylinder piston starts. In the second case, two valves in pair are used for movement of cylinder piston in one direction, and another pair of valves is used for movement of cylinder piston in oposite direction. The first valve from pair is used to connect cylinder chamber with compressed air supply and the second valve is used to connect another cylinder chamber to the atmosphere. The main advantage of this type of control is holding position of cylinder piston without additional compressed air consumption, which is realized with deactivation of all valves (blocked flow).

Four monostable normally closed, 3/2-way fast-switching solenoid valve, with very short “on” and “off” switching time were used for PWM pneumatic control of the experimental device. These valves were used in funciton of 2/2-way directional control valves. It was realized by blocking the appropriate outlet connections of 3/2-way directional control valves. PLC CPX-CEC, by Festo, was used for control of these directional control valves. Additionally, this PLC was used for the control of monostable, 5/2-way solenoid, directional control valve (valve for vacuum gripper) like in case of proportional pneumatic control.

Finally, for the realization of PWM control of the experimental device, the following equipment from the manufacturer Festo was used (Fig. 3) [13]:

1. rodless cylinder DGPL-25-600-PPV-A-B-KF-SH-D2;
2. vacuum gripper which consists of vacuum generator VAK1/4 and suction cup VAS-75-1/4-NBR;
3. monostable, 5/2-way solenoid, directional control valve VUVS-L20-M52-MD-G18-F7, in function of 3/2-way valve;
4. four monostable, normally closed, 3/2-way fast-switching solenoid valves MHE3-MS1H-3/2G-1/8,
5. one-way flow control valve GRA-1/4-B;

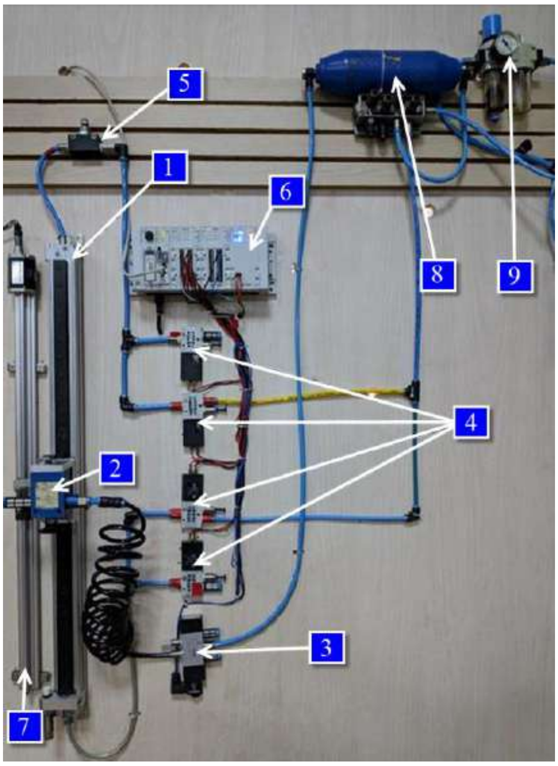

Figure 3. Physical realization of PWM pneumatic control

6. PLC CPX-CEC;
7. displacement encoder MME-MTS-600-TLF-AIF;
8. an additional compressed air reservoir VZS-0.75;
9. service unit FRC-1/8-DB-7-MINI.

For easier understanding of the device operation, the pneumatic control scheme of PWM control is shown in Fig. 4. PWM control was realized in combination with Meter-out control (using one-way flow control valve 1V5, Fig. 3, position 5), where the PWM signal was used only to activated and deactivated the fast-switching directional control valve 1V4 (Fig. 3, position 4). That valve allows flow of the exhausted compressed air from cylinder chamber into the atmosphere. A pair of fast-switching directional control valves 1V2 (Fig. 3, position 4) and 1V4 was used to move the cylinder piston upwards (lifting the workpiece), whereby the valve 1V2 was connected to the compressed air supply and the valve 1V4 was under PWM control and regulates flow of the exhausted air depending on the position error. The position error was calculated in the appropriate time intervals, as the difference between the desired and actual position of cylinder piston, which was measured using a displacement encoder. Based on the position error, the PWM duty cycle was formed and the directional valve 1V4 was further controlled via that PWM signal. Regulated access to the desired position in this case was provided by PD controller. The PD tuning parameters were determined by a Ziegler-Nichols method.

The directional control valves 1V1 and 1V3 (Fig. 3, position 4) were used to move the cylinder piston in the opposite direction (return of the piston to the initial, final lower position). Since during the experimental testing the emphasis was placed on positioning only in case of the lifting workpieces

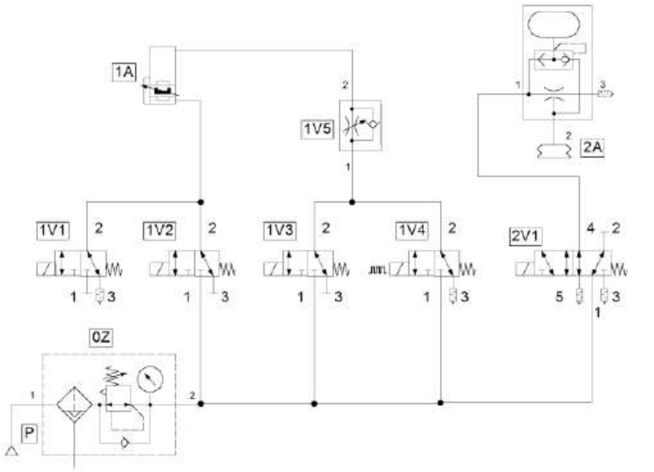

Figure 4. Pneumatic control scheme of PWM control

but not during return stroke without load, those the PWM control with PD controller was not used during return, but the piston was slowed down to avoid shocks.

In addition, monostable, 5/2-way solenoid, directional control valve 2V1 was used to control vacuum gripper, like in the case of proportional control.

C. *Determining of the actual position of the cylinder piston and compressed air consumption*

In order to determine the position accuracy and repeatability and to determine compressed air consumption, eight different measurements were performed. Each of measurement was repeated for five times, in order to obtain more accurate results. The experiments were performed in such a way to enable the workpiece (weighing approximately 3.7 kg) lifting to the upper end position of the cylinder piston (600 mm), with stopping at arbitrarily defined intermediate positions in two different ways [13]:

1. stopping in two intermediate positions (the first is at 17% of the total stroke length - 102 mm and the second is at 51% of the total stroke length - 306 mm);
2. stopping in one intermediate position which is at 83% of the total stroke length (498 mm).

Both previously defined device operation modes were performed with an opening level of the one-way flow control valve of 80% and 50%, which resulted in four different operation modes. Further, operation modes were realized in the case of proportional pneumatic control as well as in the case of PWM pneumatic control. So, it resulted in eight different operation modes. The actual position of the cylinder piston and compressed air consumption were measured for each of them.

The determining of the actual position of cylinder piston was performed directly from the PLC. It should be noted that for this purpose was used a dedicated measuring module, CPX-CMIX, which was connected to the displacement encoder via CAN communication.

Due to low flow, the compressed air consumption was determined indirectly, by measuring the pressure differential Δp in the compressed air reservoir. For that purpose, a differential pressure gauge was developed at the Faculty of Technical Sciences in Novi Sad. It consists of three components (Fig. 5):

1. sensor units with associated control electronics [17];
2. power supply;
3. base unit - PLC FC660, by Festo.

The sensor unit contains two MBS 3000 pressure transmitters, by Danfoss [18]. The base unit was used to receive data from the sensor unit and print it on the user's computer screen. Using the appropriate PLC software and user application (Fig. 6), the read data from PLC (blue rectangle in the lower right part of the Fig. 6) was converted into an excess pressure value in bars (red rectangle in the left part of the Fig. 6).

The input port of the compressed air reservoir with volume of 24 l, that was installed before the service unit, was connected to the input port of the differential pressure gauge. The output port of the differential pressure gauge was an atmospheric pressure. The excess pressure value in the compressed air reservoir was measured at the beginning and end of one cycle of lifting and holding. Based on the measured values, the pressure differential Δp in the compressed air reservoir was calculated. Using Boyle–Mariotte law, assuming the temperature remains unchanged, the compressed air consumption was calculated using formulas 1 to 3:

$$V_1 = p_1 \cdot V_R / p_{atm}; \quad (1)$$

$$V_2 = p_2 \cdot V_R / p_{atm}; \quad (2)$$

$$Q = V_1 - V_2 = (p_1 - p_2) \cdot V_R / p_{atm} = \Delta p \cdot V_R / p_{atm}; \quad (3)$$

where V_1 is volume of the compressed air at pressure p_1 (at the beginning of the cycle), V_2 is volume of the compressed air at pressure p_2 (at the end of the cycle), V_R is 24 l (volume of compressed air reservoir), p_1 is absolute pressure in compressed air reservoir at the beginning of the cycle, p_2 is absolute pressure in compressed air reservoir at the end of the cycle, Δp is the pressure differential and Q is compressed air consumption in Nl.

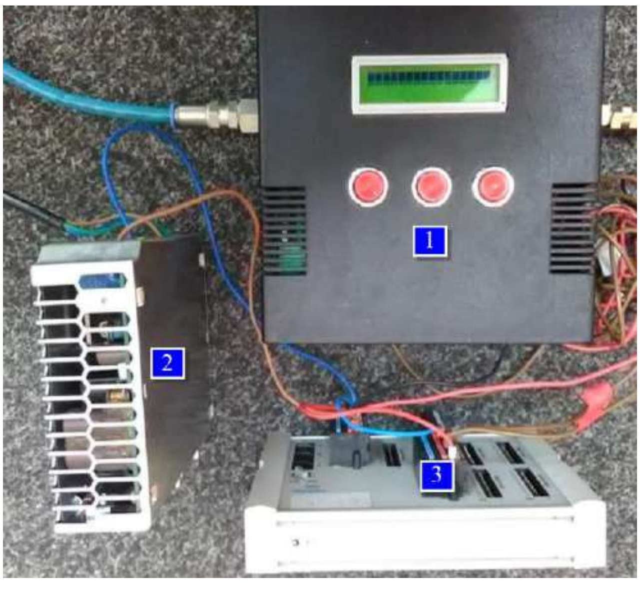

Figure 5. The differential pressure gauge

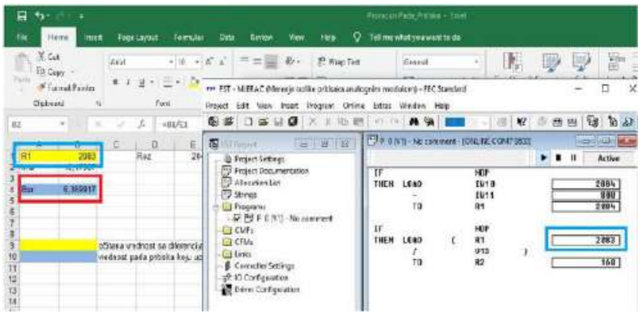

Figure 6. Determining the pressure value in the compressed air reservoir

III. RESULTS AND DISCUSSION

A several important facts were founded after the experiments were executed:

1. In the case of the proportional pneumatic control, cylinder piston was positioned in the correct position always, i.e. the position error was approximately zero. Defined intermediate positions as well as the opening level of one-way flow control valve do not affect the position accuracy and repeatability. Thus, the position accuracy and repeatability of proportional pneumatic control is rated as excellent. On the other hand, in the case of the PWM pneumatic control, the position error generally occurred (Fig. 7 and Fig. 8). In majority of cases, the absolute value of the relative position error was less than 2%. But, if the opening level of the one-way flow control valve was 50%, the absolute value of the relative position error was less than 2% always. Further, it is necessary to mentione that the absolute value of the relative position error was above 1% only in the case when the desired position was at the beginning of cylinder stroke i.e. 102 mm. But, if the opening level of the one-way flow control valve was 80%, the absolute value of the relative position error for that position was above than 1% in majority of cases, while if the opening level of the one-way flow control valve was 50%, the absolute value of the relative position error for that position was above than 1% just in one case. This appeared due to limitations in the system. In general, the speed profile of the cylinder piston has an approximately trapezoidal shape. So, the acceleration is higher at the beginning of the stroke due to the supply of compressed air. In the middle and before the end of the stroke, it is easier to achieve a constant speed of cylinder piston, with a slight deceleration as it approaches the given position. The positioning is more accurate, especially in case of lesser degree of the opening level of the one-way flow control valve. Accordingly, the accuracy of the positioning is rated as satisfactory. The distribution of the results in terms of the absolute value of the relative position error is small, so the repeatability of the positioning is rated as good. Overall, the position accuracy and repeatability of PWM pneumatic control is rated as good.

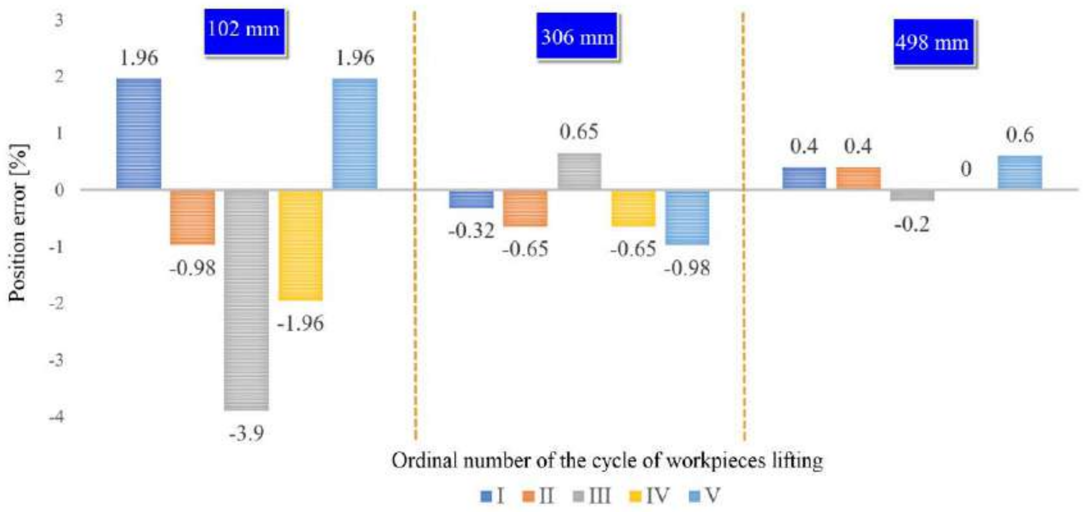

Figure 7. Position error with PWM pneumatic control and opening level of the one-way flow control valve of 80%

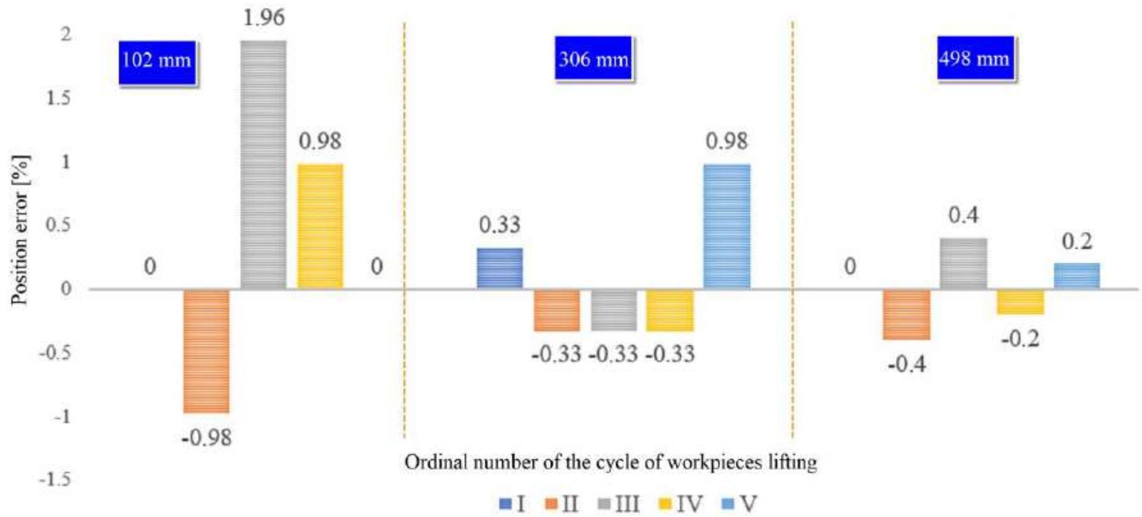

Figure 8. Position error with PWM pneumatic control and opening level of the one-way flow control valve of 50%

2. In the case of PWM pneumatic control, there was no position loss in the observed time period after positioning (during the period of workpiece holding). Defined intermediate positions do not affect the position loss. Thus, the position holding of PWM pneumatic control is rated as excellent. On the other hand, in the case of proportional pneumatic control, the position loss generally occurred (Fig. 9 and Fig. 10). Namely, one second after positioning, the cylinder piston slide vertically downward. In that sense, there was an oscillation of the piston position because the control system would constantly return it to the desired position. In majority of cases, the position loss was 4 mm. So, the most significant loss was in the case in which desired intermediate position was 102 mm. There was a position loss of 3.92%. Accordingly, the position holding of proportional pneumatic control is rated as satisfactory. Due to Meter-out control, the opening level of one-way flow control valve do not affect the position loss but only the speed of return to the desired position.

3. The compressed air consumption was significantly lower in the case of PWM pneumatic control in comparison with proportional pneumatic control (Fig. 11 and Fig. 12). The compressed air consumption differential is approximately of 18.6%. The defined intermediate positions do not affect compressed air consumption differential. Furthermore, the opening level of one-way flow control valve slightly affects the compressed air consumption. Namely, the compressed air consumption was lower in the cases when the opening level of the one-way flow control valve was 80%. The compressed air consumption differential is approximately up to 1%.

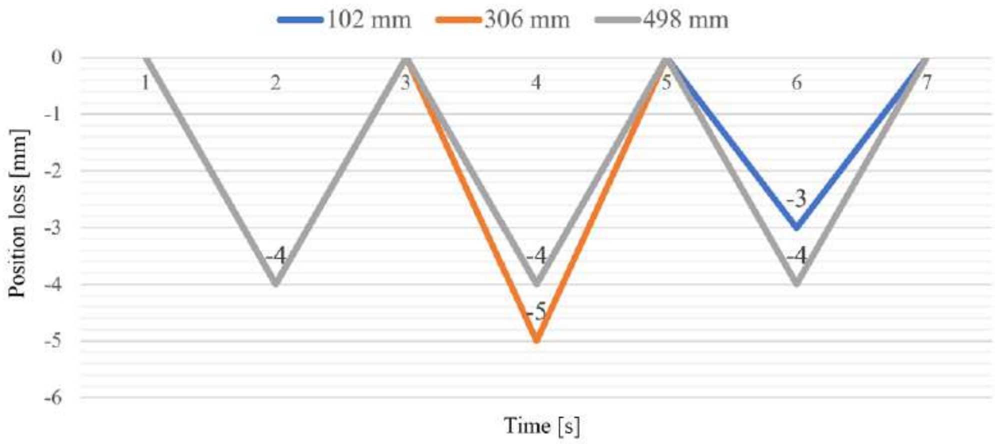

Figure 9. Position loss with proportional pneumatic control and opening level of the one-way flow control valve of 80%

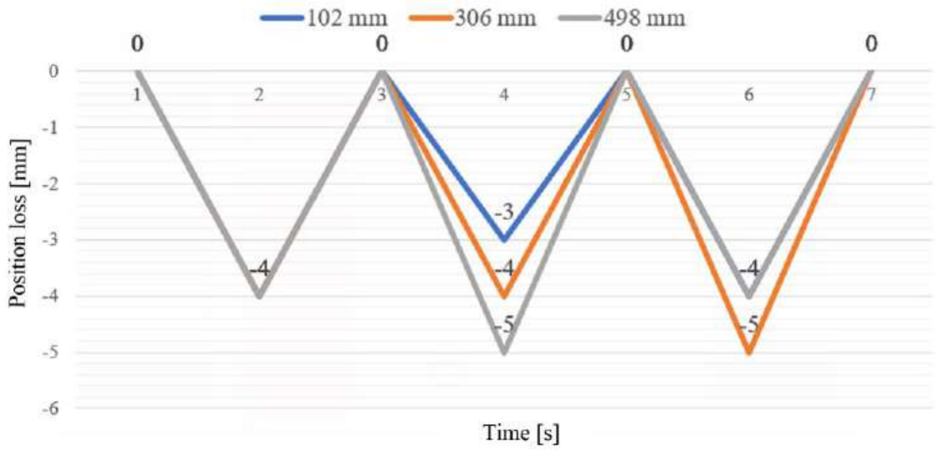

Figure 10. Position loss with proportional pneumatic control and opening level of the one-way flow control valve of 50%

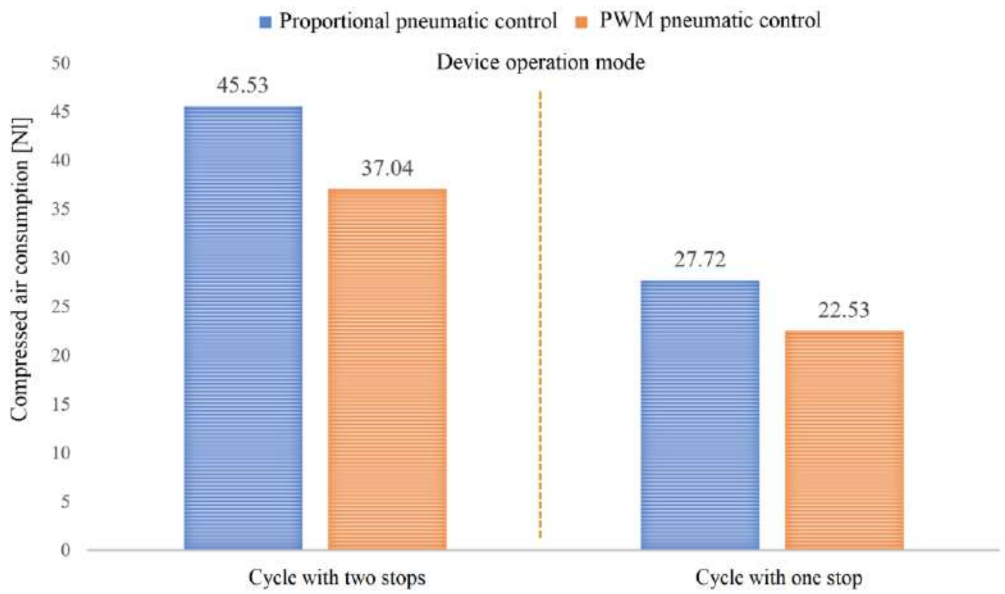

Figure 11. Compressed air consumption at opening level of the one-way flow control valve of 80%

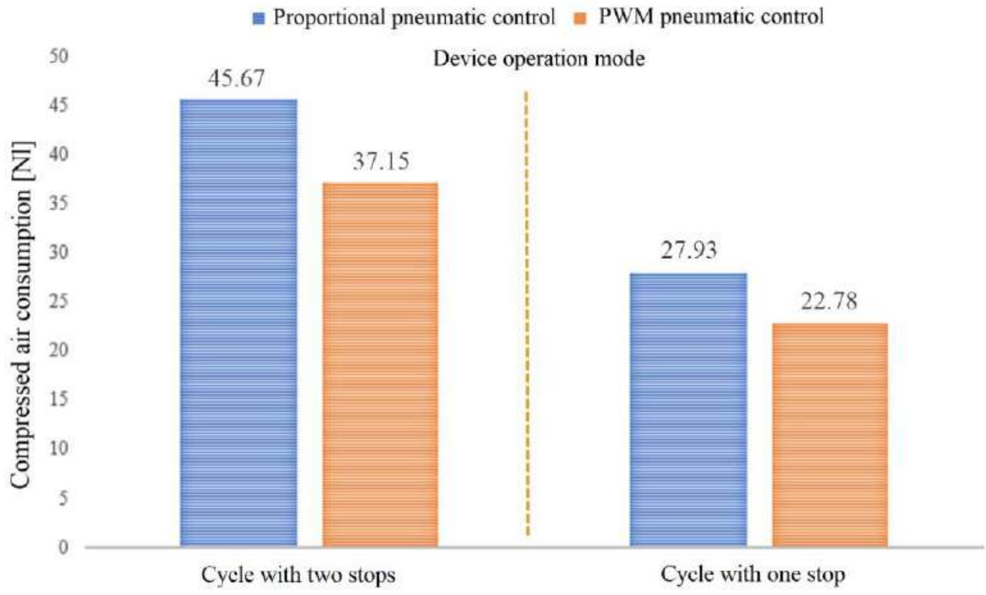

Figure 12. Compressed air consumption at opening level of the one-way flow control valve of 50%

IV. Conclusion

In this paper is shown a comparison of proportional and PWM pneumatic control in terms of positioning and compressed air consumption. All experimental tests were performed on a device for lifting and holding of the workpieces.

The results show that, in the case of the proportional pneumatic control, cylinder piston is positioning in the correct position always, but the position loss generally is occurring during the time. The control system constantly returns the cylinder piston to the desired position, which increases the compressed air consumption. On the other hand, in the case of the PWM pneumatic control, the position error generally is occurring, but there is no position loss in the observed time period after positioning (during the period of workpiece holding) i.e. there is no additional compressed air consumption. Further, in case of Meter-out control in combination with previously defined types of control, the positioning is more accurate in cases of lesser degree of opening level of the one-way flow control valve. On the other hand, the compressed air consumption slightly increases in accordance with decreasing the opening level of the one-way flow control valve.

Based on all the above, the user has the ability to choose the type of control depending on whether the criterion is the position accuracy and repeatability or higher energy efficiency of the system (lower compressed air consumption).

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