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FUNCTIONAL OPTIMIZATION OF PNEUMATIC SYSTEMS USING EFCV

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Abstract: *This article explores the use of electric flow control valves (EFCVs) to improve more precise management and continuous monitoring. The study emphasizes the advantages of integrating these valves into existing control systems to achieve precise and efficient speed control. By allowing for seamless adjustments from the control panel, electric flow control valves eliminate the need for individual adjustments at each valve, simplifying system synchronization. Simulated tests using Automation Studio software and physical experiments on an experimental bench were conducted to validate the effectiveness of these valves. The results confirm their capability to provide accurate and easy speed regulation. Additionally, the cost-effectiveness and improved handling of the pneumatic system further highlight the practicality and efficiency of utilizing electric flow control valves for optimizing performance and synchronization in complex pneumatic systems.*

Key words: *speed control, Electric Flow Control Valves, pneumatic system, regulation, synchronization, low costs.*

1. INTRODUCTION

The evolution of automation technologies has highlighted the pivotal role of pneumatic systems across various industrial sectors [1]. A critical challenge in this arena is regulating piston speed and synchronizing these systems, with inaccuracies or inefficiencies leading to compromised system performance and potential increases in operational costs or failures [2]. The introduction of electric flow control valves presents an effective solution, simplifying the complex process of system synchronization, and providing precise speed regulation [3].

Traditional methods of speed regulation in pneumatic systems often necessitate manual adjustments at each valve [4]. However, the advent of electric flow control valves offers a more efficient and sophisticated alternative. These valves enable operators to make adjustments remotely from a control panel, eliminating the need for manual interventions at each valve site [4]. Such remote operability aligns with the principles of Industry 4.0, where intelligent automation and data exchange in manufacturing technologies are the norm [5].

The adoption of electric flow control valves in robotic workstations can significantly enhance operational efficacy through:

Precise Speed Regulation: Electric valves facilitate refined speed modulation in pneumatic systems, leading to safer and more accurate handling of assemblies.

Simplified Synchronization: These valves can be integrated into existing control systems, obviating the need for individual valve adjustments and simplifying synchronization.

Increased Efficiency: Precise adjustment and improved synchronization can enhance operational efficiency, reducing time for operations and augmenting productivity.

Flexibility and Adaptability: The valves enable quick adaptability to different assembly configurations, allowing swift changes in speed and force settings.

Centralized Monitoring and Control: The integration enables centralized control and monitoring of all valves, enabling real-time operational adjustments.

The integration of electric flow control valves enhances precision, synchronization, and efficiency in assembly handling processes.

Consequently, this leads to cycle time reduction and productivity increase.

This study underscores the efficacy of these valves, through a unique amalgamation of simulation and physical experiments. Our approach is unique, as it combines simulated tests using Automation Studio software with physical experiments on an experimental bench to evaluate the performance of these valves [7].

It demonstrates the practical and cost-effective benefits of integrating these valves in pneumatic systems, particularly relevant in the Industry 4.0 context.

2. PNEUMATIC SYSTEMS AND ELECTRIC FLOW CONTROL VALVES

Pneumatic systems function based on the principle of using compressed gas, typically air, to transmit power [7]. These systems play a vital role in numerous automation technologies, with the speed control of pneumatic mechanisms directly impacting overall efficiency and reliability [8].

One critical element in this speed control is the flow control valve. These valves modulate the flow rate within the system, thereby determining the speed of operations [9]. Until now, most pneumatic systems have employed manual flow control valves. These valves, although functional, present several challenges [10]. Manual adjustments can often lack precision, leading to inefficiencies and synchronization issues in the system [10].

In response to these challenges, electric flow control valves offer an innovative solution. They provide a means to control the flow rate, and consequently, the operational speed of pneumatic systems more accurately and efficiently [11].

3. THE ADVANTAGE OF ELECTRIC FLOW CONTROL VALVES IN EXISTING CONTROL SYSTEMS

Electric flow control valves offer a significant advantage over their traditional manual counterparts. One of the most pronounced benefits is the potential for remote operation. In the contemporary industrial landscape, the ability to remotely control and regulate systems is increasingly essential [12]. Electric flow control valves allow for this distant operation, adding a layer of convenience and versatility to system control [12].

Furthermore, electric flow control valves can be seamlessly integrated into digital control systems. With the rise of Industry 4.0 and smart manufacturing technologies, this capability can greatly enhance system efficiency and performance [13].

Despite these clear advantages, the application of electric flow control valves in pneumatic systems remains under-explored. This study aims to delve into the capabilities of these valves, their effectiveness in enhancing speed control and synchronization in pneumatic systems, and the implications of their integration into Industry 4.0 environments [14].

4. EXPERIMENTAL PROCEDURES AND SIMULATION TESTS

To evaluate the efficiency of flow control with electrically actuated valves used to reduce the influence of the air compression phenomenon, the study relied on testing through simulation and experimentally on a specially designed stand, four basic elements of pneumatics:

- The speed of a piston in a pneumatic system is significantly influenced by the pressure variation in the system. This relationship can be established both mathematically and through physical tests on a test bench.
- The speed of a piston in a pneumatic system is significantly affected by the load it must move. This relationship can be established both mathematically and through physical tests on a test bench.
- The redesigned one-way control valve incorporating an electric motor and enabling remote control entering the Industry 4.0 era will outperform traditional designs in terms of pneumatic system efficiency.
- Automatic and remote speed adjustment capability in the redesigned one-way flow control valve will allow effective control of speed variations induced by pressure variations and load changes, thereby improving operational flexibility and reliability of pneumatic systems.

To test these hypotheses, we adopted a two-pronged approach involving simulation tests and physical experiments.

The theoretical underpinnings of this study derive from the following formula, which calculates the speed of the piston by considering the balance between the force applied by compressed air and the force exerted by the load.

v = sqrt((2*(F_fluid_push-Load))/(ρ * A_push))

where:
v - Piston Speed (m/s)
F_fluid_push - Fluid Force (N). This is calculated as the product of pressure P and the piston area A_push.
A_push -Area of the Piston (m²). This is computed using the formula for the area of a circle, pi*(d/2)^2, where d is the piston diameter.
P - Pressure (Pa). In the code, this is converted from bar to Pascal by multiplying by 1e5 since 1 bar is equal to 1e5 Pa
Load - Force (N). In the code, this is converted from kilograms to Newtons by multiplying by 9.81, the acceleration due to gravity, since 1 kg under Earth's gravity is 9.81
ρ -Density of Air (kg/m³)

This equation, rooted in the kinetic energy principle, presumes an ideal system devoid of losses due to friction or other factors. Represents the velocity of a piston in a pneumatic system (a system powered by compressed air) considering the air pressure, the load on the piston, the piston's area, and the air's density [15].

The premise is that when the fluid force surpasses the load, the surplus force will accelerate the piston. The piston's speed can then be computed from the kinetic energy equation, assuming an ideal system with no losses due to friction or other factors [16].

Using this equation, two sets of simulations were performed in MATLAB - one for each of the first two hypotheses. For hypothesis 1, the speed of the piston was calculated while varying the pressure of the fluid (F_fluid_push), holding other parameters constant. This simulation provided insights into the relationship between the fluid pressure and the piston speed.

For hypothesis 2, the speed of the piston was calculated by varying the load on the piston, with all other parameters held constant. The simulation revealed the relationship between the load and the piston speed.

Furthermore, a 3D graph was plotted to show the interaction effect of the fluid pressure and the load on the piston speed, combining the two hypotheses.

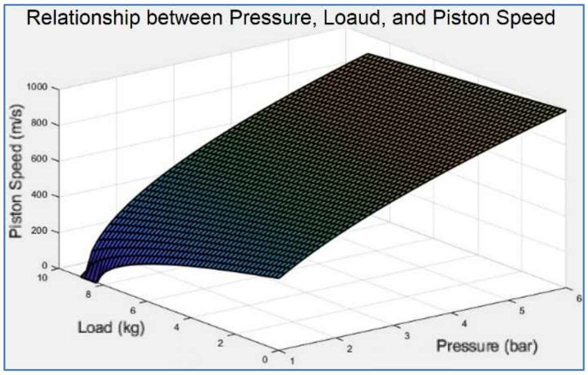


Fig.1. Relationship between Pressure, Load, and Piston Speed

The next phase of the study involved confirming these simulation results with physical experiments on an experimental bench. The details of these experiments will be provided in the subsequent section.

In the simulation tests, we used Automation Studio software, a comprehensive tool for simulating and analyzing the dynamics of pneumatic systems [17]. We created a model that represented a typical pneumatic system, incorporated an flow control valve for speed regulation, and manipulated different parameters to assess their impact on system performance [18].

This software allowed the construction of a pneumatic system that closely mimicked the actual setup in practice, thereby providing an environment for more accurate and realistic testing. In the application of the Automation Studio software for this study, a series of visuals were generated to offer a more comprehensive understanding of the pneumatic system and the implications of our hypotheses.

The image of figure 2 is a comprehensive depiction of the pneumatic system with all its components. It offers a visual guide to understand the interconnectivity and functioning of various elements within the system.

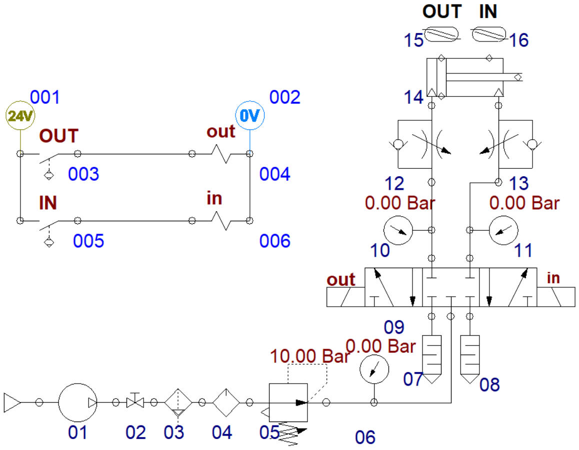
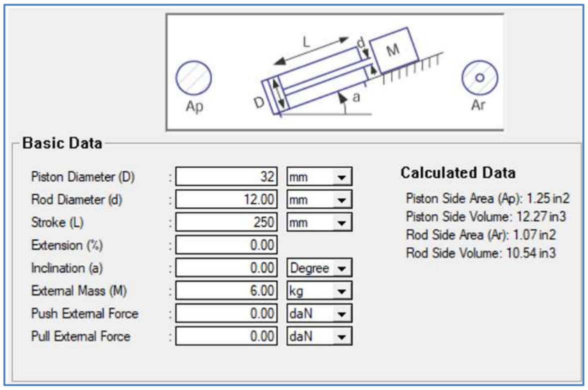


Fig.2. Pneumatic System Diagram and control scheme created in the Automation Studio software

01	Compressor
02	Shut-off valve Normally Close (2-Way)
03	Filter and Separator
04	Lubricator
05	Variable Pressure Regulator
06	Pressure Gauge
07-08	Silencer
09 5/3	Way NC - Double Electrical Control
10-11	Pressure Gauge
12-13	Variable Non Return Throttle Valve
14	Double-Acting Cylinder
15-16	Magnetic Sensor
001	Power Supply 24 Volts
002	Common (0 Volts)
003-005	Proximity Switch Normally Open
004-006	Solenoid, DC/ AC

Fig. 3. System components pneumatic and control created in the Automation Studio . software.



Basic Data

Piston Diameter (D)	32	mm
Rod Diameter (d)	12.00	mm
Stroke (L)	250	mm
Extension (%)	0.00	
Inclination (a)	0.00	Degree
External Mass (M)	6.00	kg
Push External Force	0.00	daN
Pull External Force	0.00	daN

Calculated Data

Piston Side Area (Ap): 1.25 in2
Piston Side Volume: 12.27 in3
Rod Side Area (Ar): 1.07 in2
Rod Side Volume: 10.54 in3

Fig.4. Piston configuration created in the Automation Studio software

To carry out the tests in the Automation Studio software. the components of the pneumatic system were chosen as close as possible to the existing components on the experimental bench. The components were set with the desired values for the tests. See Figure 4 where the piston parameters have been set.

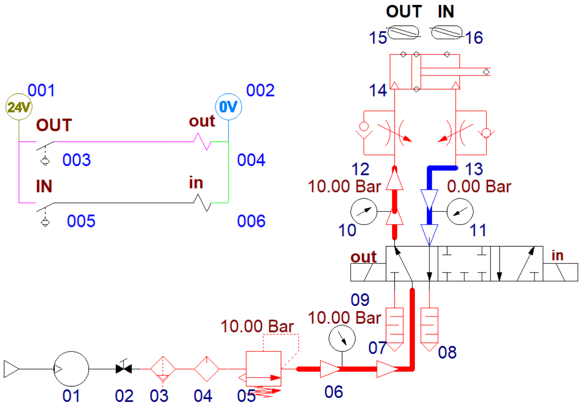
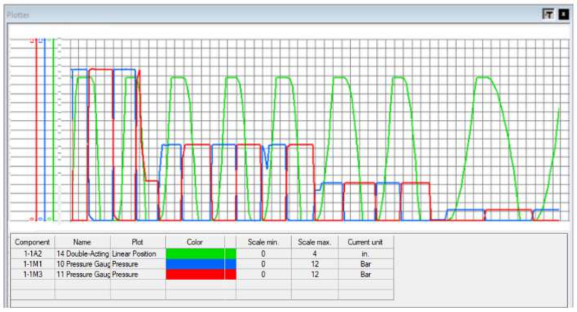


Fig.5. Simulated Pneumatic Scheme created in the Automation Studio software

This image offers an operational perspective to the static pneumatic system. It shows the system in action, thereby providing a dynamic view of the movements and interactions within the system.

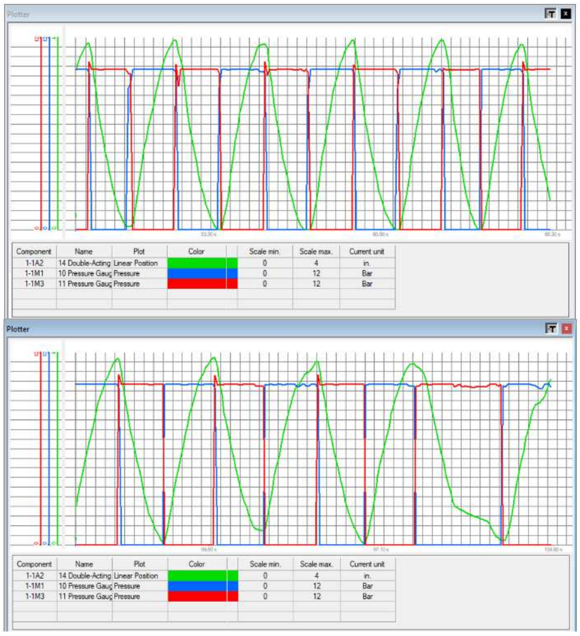


Component	Name	Plot	Color	Scale min.	Scale max.	Current unit
1-1A2	14 Double-Acting	Linear Position	🟩	0	4	in.
1-1M1	10 Pressure Gaug	Pressure	🟦	0	12	Bar
1-1M3	11 Pressure Gaug	Pressure	🟥	0	12	Bar

Fig.6. Graph of System Pressure Variation vs. Piston Speed created in the Automation Studio software

This graph validates hypothesis 1 by presenting a clear visual correlation between the system's pressure variation and the speed of the piston. It provides a quantifiable measure to understand the impact of pressure changes on the system's operational speed.

According to hypothesis 2, these two graphs illustrate the relationship between the variation of the loads on the piston and its speed. In the first graph it can be seen that the piston makes 8 strokes with a load of 6kg and in the second graph it can be seen that the piston makes 6.5 strokes with a load of 12kg. It provides a tangible demonstration of how changing load affects system efficiency and speed.



Component	Name	Plot	Color	Scale min.	Scale max.	Current unit
1-1A2	14 Double-Acting	Linear Position	🟩	0	4	in.
1-1M1	10 Pressure Gaug	Pressure	🟦	0	12	Bar
1-1M3	11 Pressure Gaug	Pressure	🟥	0	12	Bar

Component	Name	Plot	Color	Scale min.	Scale max.	Current unit
1-1A2	14 Double-Acting	Linear Position	🟩	0	4	in.
1-1M1	10 Pressure Gaug	Pressure	🟦	0	12	Bar
1-1M3	11 Pressure Gaug	Pressure	🟥	0	12	Bar

Fig.7. Graph of piston speed versus piston load variation created in the Automation Studio software

Each of these visuals, derived from the Automation Studio software simulations, contributes significantly to the analysis and validation of the hypotheses. They bridge the gap between theoretical assumptions and practical understanding, thereby enhancing the credibility and applicability of the study.

For the physical experiments, we set up an experimental bench that replicated a pneumatic system with an electric flow control valve. The bench setup facilitated physical manipulation of variables, enabling us to observe the system's response and efficiency under various operational conditions [18].

Through these methodologies, we aimed to offer a comprehensive evaluation of the performance and potential advantages of integrating electric flow control valves into pneumatic systems.

Figure 8 presents the block diagram of the pneumatic system used in the tests. The system comprises an electronic component, highlighted in red, and a pneumatic part, depicted in blue. This straightforward setup is designed to yield precise results, supporting the exploration of the efficacy of electric one-way flow control valves in speed regulation.

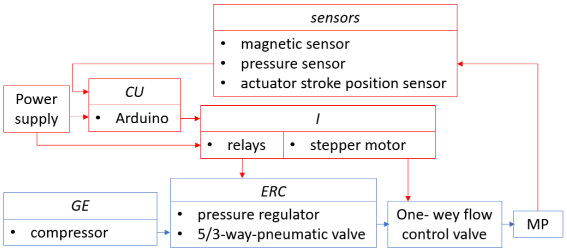


Fig.8. Block diagram of the pneumatic system

The model in Figure 1 serves as a conceptual framework rather than a basis for a mathematical study. Addressing its mathematical complexity would necessitate specialized computational methods. This research, however, focuses on the practical aspect of speed regulation using electric one-way flow control valves.

In the system, the supply voltage is directed to the Arduino controllers - 5V DC to the Command Unit (CU), which communicates with the Interface (I). The pneumatic cylinder (Pneumatic Motor - PM) connects to the Regulation and Control Element (RCE) via I and magnetic sensors at each end. The Energy Generator (EG) feeds compressed air to the RCE.

The RCE, commanded by I, sends the compressed air into the cylinder, generating mechanical work to move the load. Meanwhile, CU analyzes the sensor data and commands the stepper motor via I to regulate the piston's speed by adjusting the one-way flow control electric valves. This setup underscores the efficiency of integrating electric flow control valves in existing control systems for remote speed regulation.

In the context of the experimental investigations performed in this study, Figure 9 outlines the block diagram of the pneumatic system implemented for the tests. The system comprises an electronic component, depicted in red, and a pneumatic component, illustrated in blue. The explicit simplicity of this arrangement is intentionally designed to facilitate precise and lucid results, thereby enabling a gradual and secure progression in the research.

Figure 9 shows the diagram of the electronic components.

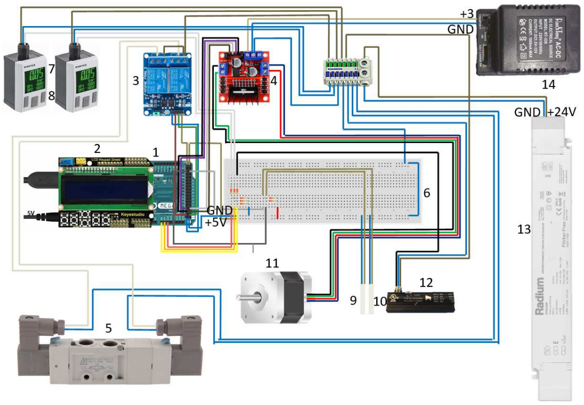


Fig.9. Block diagram of the pneumatic system: 1- Arduino Mega 2260, 2- Lcd shield, 3- Mode 2 relay, 4- Bridge H, 5- Pneumatic distributor 5/3, 6- Breadboard, 7,8- Pressure sensors, 9,10- Magnetic sensors, 11- Stepper motor, 12- pneumatic analog sensor, 13- 220-24V transformer, 14- transformer 220-1.5V

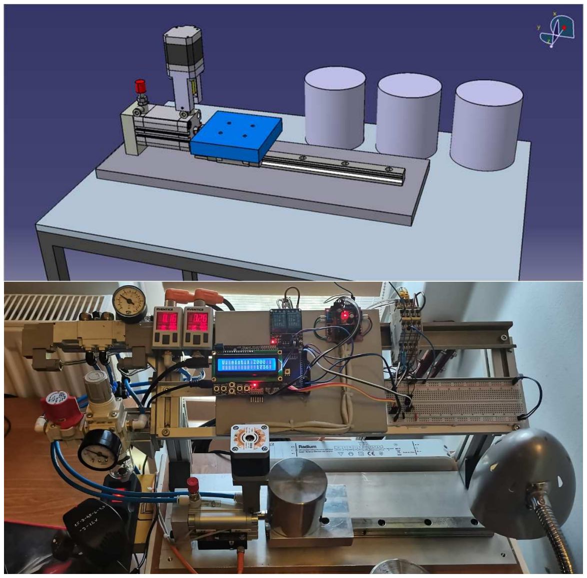


Fig.10. 40mm Actuator with Electric One-Way Valve

Our investigation into the effectiveness of electric flow control valves in pneumatic systems was supported by a meticulously designed experimental bench. This bench was crafted using Catia, a 3D computer-aided design (CAD) program, which allowed for easy interchangeability of different pneumatic actuators during testing.

As displayed in Figure 10, a model of a 32mm diameter pneumatic actuator with a stroke length of 40mm is shown equipped with an electric one-way flow control valve. This experimental setup enabled us to thoroughly investigate our primary subject of interest.

Subsequently, in Figure 11, we present another model of a pneumatic actuator, this one with a diameter of 32mm and a longer stroke length of 250mm. This variation in stroke length allowed us to examine how different actuator dimensions might influence speed regulation when using electric flow control valves.

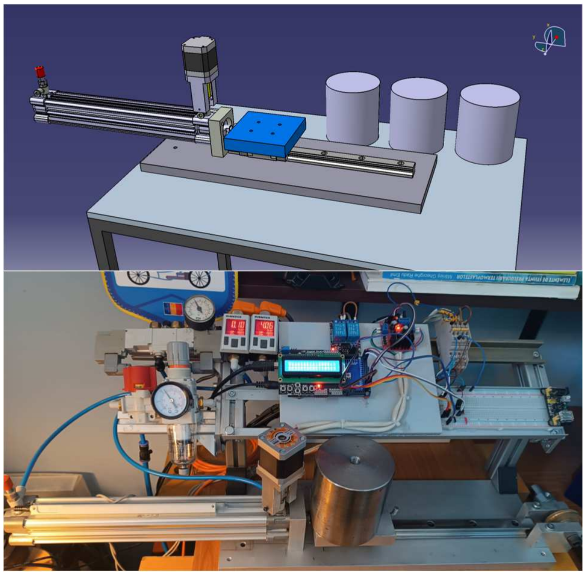


Fig.11. 250mm Actuator with Electric One-Way Valve

The comprehensive system, depicted designed using Catia, was used to simulate real-world pneumatic system scenarios. This facilitated our investigation into various conditions, pressures, and loads, allowing us to gain a detailed understanding of the performance of electric flow control valves.

By using this experimental bench, we obtained robust data that helped validate our hypotheses, offering valuable insights into the use of electric flow control valves in pneumatic systems. The findings derived from this setup are discussed in the following sections.

4.1 Simulation Test Results

Our study commenced with the mathematical modeling of the two hypotheses using MATLAB, an efficient platform for computation and simulation.

Firstly, the influence of pressure variation on the speed of a piston in a pneumatic system was investigated (hypothesis 1). This relationship was mathematically established and visualized in a graphical form. The graph, as displayed in

Figure 12, is a representation of this relationship and suggests a significant influence of pressure variation on the piston speed.

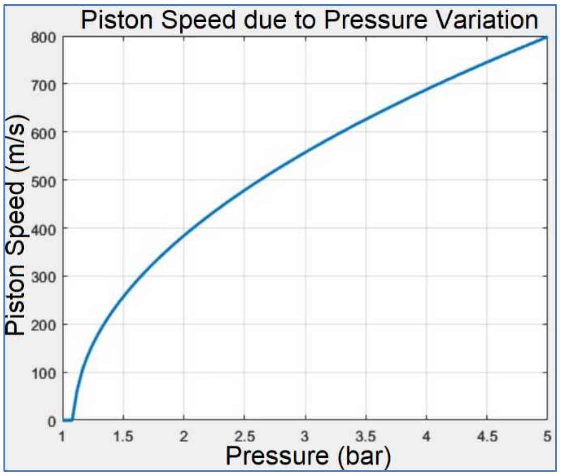


Fig.12. Piston Speed due to Pressure Variation

Next, we explored the effect of varying loads on the piston speed in a pneumatic system (Hypothesis 2). Once again, this relationship was formulated mathematically using MATLAB, and the resulting graph is exhibited in Figure 13. The graph illustrates a notable change in piston speed with varying loads, thereby mathematically corroborating hypothesis 2.

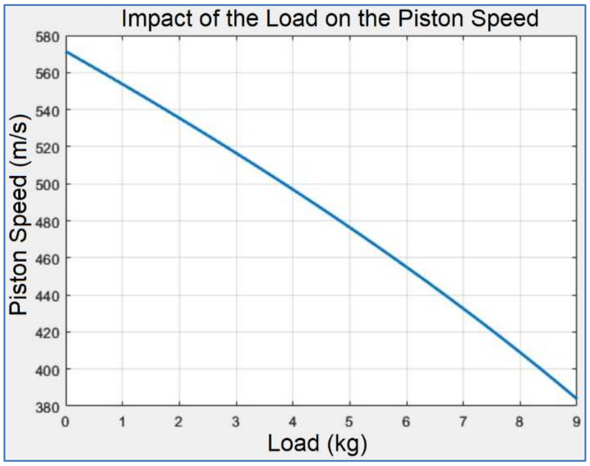


Fig.13. Impact of the Load on the Piston Speed

To complement the results from MATLAB, the formulated hypotheses were simulated using Automation Studio software. The graphs derived from these simulations aligned with the trends observed in the MATLAB models, further strengthening the validity of Hypotheses 1 and 2.

4.2 Experimental Test Results

The experimental study aimed at investigating two key aspects of the electric flow control valves in the pneumatic system.

Aspect 1: Control Panel Adjustment

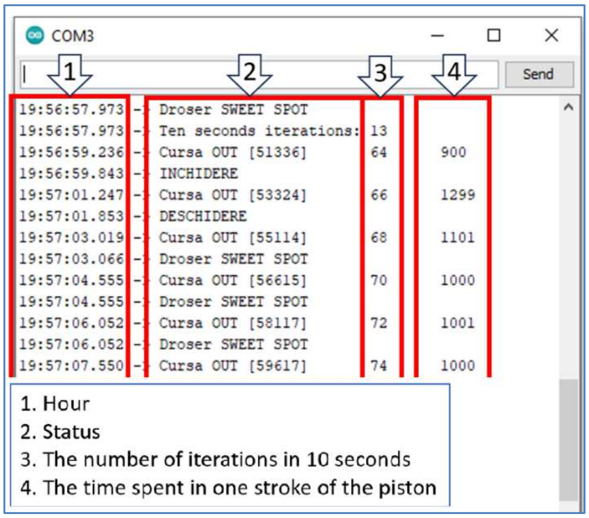
The first aspect analyzed the feasibility of adjusting these electric flow control valves via a control panel. The findings of the experimental study were affirmative, demonstrating an efficient and precise adjustment procedure. The system accommodates granular control, allowing for incremental step-by-step adjustments of the stepper motor.

Aspect 2: Automatic Speed Regulation

The second aspect investigated the possibility of integrating an automatic speed adjustment loop with the help of these valves. The experimental bench was equipped with an Arduino microcontroller to collect data from the sensors, which monitored the piston's speed. The Arduino's programming was able to detect changes in the piston speed and correspondingly adjust the stepper motor controlling the electric flow control valve. If the speed dropped, the valve would open more, increasing the speed. Conversely, if the speed was too high, the valve would close slightly, reducing the speed. If the piston speed was within the set tolerance, the valve position remained unchanged, maintaining the speed.

Data acquisition from these tests is illustrated in Figure 14. The four columns represent the time, system status, the number of iterations in 10 seconds, and the time spent in one stroke of the piston, respectively. The different states include "Droser sweet spot," indicating the desired piston speed and the optimal valve position, "Blockage," where the piston speed is too high and the valve is closed more, and "Opening," where the piston speed is too slow and the valve is opened more. These results highlight the effectiveness of automatic speed adjustments in maintaining the desired piston speed.

Figure 15 shows the display of the experimental bench. The first line where V. pist is displayed represents the set piston speed. The second line shows the status and the measured time.



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19:56:57.973 - Droser SWEET SPOT
19:56:57.973 - Ten seconds iterations: 13
19:56:59.236 - Cursa OUT [51336]       64      900
19:56:59.843 - INCHIDERE
19:57:01.247 - Cursa OUT [53324]       66      1299
19:57:01.853 - DESCHIDERE
19:57:03.019 - Cursa OUT [55114]       68      1101
19:57:03.066 - Droser SWEET SPOT
19:57:04.555 - Cursa OUT [56615]       70      1000
19:57:04.555 - Droser SWEET SPOT
19:57:06.052 - Cursa OUT [58117]       72      1001
19:57:06.052 - Droser SWEET SPOT
19:57:07.550 - Cursa OUT [59617]       74      1000
```

1. Hour
2. Status
3. The number of iterations in 10 seconds
4. The time spent in one stroke of the piston

Fig.14. Data acquisition from experimental tests

The program will command the stepper motor to increase or decrease until it enters the tolerance range of the set time, in this case 2000 ms. As seen in figure 14, where the time of 1000 ms was set, the piston speed enters the tolerance in three iterations and then keeps it constant with a deviation of 1 ms.

Fig.15. The display of the experimental bench with the three statuses

5. DISCUSSION AND CONCLUSION

Our research, deploying a distinctive combination of simulated tests with the Automation Studio software and physical experiments on an experimental bench, delves into the efficiency of electric flow control valves in enhancing speed regulation in pneumatic systems. The findings corroborate the advantages identified in the introduction and exhibit the practical implications of these valves, further highlighting their value in the context of Industry 4.0.

Precise Speed Regulation: Our experimental results affirm that the incorporation of electric flow control valves brings about enhanced precision in speed regulation. The capacity to adjust clamping or release speed finely in line with specific system requirements not only improves the handling of parts/assemblies but also boosts operational safety.

Simplified Synchronization: The integration of these valves into existing control systems offers simplified system synchronization. This obviates the need for individual valve adjustments, thereby simplifying the programming and timing of the activity and leading to more efficient system operations.

Increased Efficiency: Through precise adjustment and improved synchronization, the adoption of electric flow control valves has shown to augment efficiency in operational processes. This optimisation of speed and accuracy results in decreased operational times and enhanced productivity.

Flexibility and Adaptability: The flexibility provided by electric flow control valves allows for quick adjustments and adaptations to various configurations or sizes of parts/assemblies, thereby catering to differing application requirements without necessitating major hardware changes or physical interventions.

Centralized Monitoring and Control: By integrating electric flow control valves into the existing control system, it is possible to centrally monitor and control all the valves. This provides an overview of the activity and enables real-time adjustments and optimizations to maximize efficiency.

The use of electric flow control valves, therefore, can introduce more precise control, improved synchronization, and increased efficiency in the process of clamping and fixing parts/assemblies. These advantages contribute to reducing cycle time and thereby, increasing productivity. Our study not only reiterates the capacity of electric flow control valves to offer accurate speed regulation but also underscores their cost-effectiveness and simplified system handling, further emphasizing their applicability and efficiency in the context of Industry 4.0.

Summary of Findings

Our initial simulations, conducted using Automation Studio software, presented two hypotheses regarding the speed regulation of pneumatic pistons. The first hypothesis, that a variation in system pressure impacts piston speed, and the second, that piston loads can likewise affect speed, were both supported through the mathematical modeling of our MATLAB simulations.

In our subsequent experimental tests, we observed that electric flow control valves indeed enable precise and effortless speed regulation. Not only did these valves allow for easy manipulation from the control panel, but when integrated into an automatic system, they successfully maintained a set piston speed within acceptable tolerances, correcting speed variations by adjusting valve openness as required.

Implications of Findings

These findings have significant implications for the industry. The integration of electric flow control valves into pneumatic systems can enhance system synchronization and performance while reducing operational costs. Moreover, they can be smoothly incorporated into existing control systems, improving system handling and providing operators with remote control capabilities.

Limitations and Future Work

Despite our positive findings, we acknowledge potential limitations in our study, such as the assumed ideal system in our simulations with no losses due to friction or other factors. Our future work will aim to address these limitations, incorporating more complex and realistic scenarios in our simulations. Moreover, we intend to explore additional features and potential applications of electric flow control valves in the automation industry. We also encourage further research into the utilization of electric flow control valves in different pneumatic system configurations and various industrial applications.

Our work has successfully demonstrated the efficacy of electric flow control valves in pneumatic speed control, contributing valuable knowledge to the field of automation technology. With continued exploration and research, we expect these innovative components to play an increasingly prominent role in the future of industrial automation.

Acknowledgement:
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Îmbunătățirea reglării vitezei în sistemele pneumatice cu drosele electrice de control al debitului

Acest articol explorează optimizarea funcțională a sistemelor pneumatice prin utilizarea EFCV pentru a îmbunătăți managementul mai precis și monitorizarea continuă. Studiul subliniază avantajele integrării acestor supape în sistemele de control existente pentru a obține un control precis și eficient al vitezei. Permițând ajustări fără întreruperi de la panoul de control, droselele electrice de control al debitului elimină necesitatea ajustărilor individuale la fiecare supapă, simplificând sincronizarea sistemului. Folosind Automation Studio, pentru testele de simulare, au fost efectuate experimente software și fizice pe un banc experimental pentru a valida eficacitatea acestor supape. Rezultatele confirmă capacitatea acestora de a oferi o reglare precisă și ușoară a vitezei. În plus, rentabilitatea și manevrarea îmbunătățită a sistemului pneumatic evidențiază în continuare caracterul practic și eficiența utilizării droselelor electrice de control al debitului pentru optimizarea performanței și sincronizarea în sistemele pneumatice complexe.

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