IMPROVING ENERGY EFFICIENCY IN COMPRESSED AIR SYSTEMS
Practical Experiences

by

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This paper presents practical experiences of savings within compressed air systems with special attention to the compressed air end uses, particularly in pneumatic control systems. Firstly, the systematic approach to energy savings is presented. Secondly, various energy-saving measures, encompassing system analysis and harmonization of production and consumption, minimisation of losses (leak prevention strategy, identification and quantification of leakages), possibilities for reducing pressure drop on filters, and three methods for optimization of pneumatic control: by-pass control, PWM control, and usage of exhaust air have been reviewed. Finally, energy conservation of a complex robotic cell with installed electric and pneumatic devices is shown.

Key words: *compressed air systems, energy efficiency, pneumatic control*

Introduction

Compressed air is a reliable power source that is widely used throughout industry and in service sectors due to its ease and safety of production and handling. In most industrial facilities, compressed air is necessary for some aspects of their operations. On average, compressed air represents approximately 10% of industrial electricity consumption. Compressed air is generated on-site and its generation is energy intensive what gives users a greater control over its usage and quality [1].

The versatility, safety and flexibility of compressed air as an energy carrier promote its use as an important utility. Yet, there is a shortage of information on the energy efficiency of a typical compressed-air system [2].

Some environmental regulations, like *The Packaging Directive in European Union*, are pressing manufacturers to comply with environmental regulations. Therefore, the topic of compressed air systems (CAS) efficiency has recently become a focus of many new research projects. The development of modern mechatronic systems, which can retrieve significant information about the leaks and possible system inefficiencies has a lot of influence in these efforts [3-5]. In that sense, retrofit solutions, remanufacturing and energy efficiency improvements are significant part of green manufacturing initiatives [6, 7]. Many innovative ways are needed, including many different improvements, in order to enable companies to run

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their processes more efficiently. To meet the energy efficiency challenge, industry must include changes in companies' policies in a production.

The CAS are one of the most expensive energy carriers in industry. For example, average electricity consumption of the compressed air systems in European Union is estimated to be 10% of the overall electricity consumption in industry [8]. This percentage varies from 10%, in Serbia, to 40% in China [9, 10]. The CAS are targeted as a field full of possibilities for energy savings. The percentages of potential savings may vary significantly. Measures for increasing energy efficiency also enable prolongation of the component's life cycle, reliable work, the reduction of total operation costs, and many other advantages. Comprehensive overview of possibilities for increasing energy efficiency is given in [2, 11, 12].

In this paper we will present the systematic approach to increasing energy efficiency of compressed air systems. After discussing the system analysis and harmonization of production and consumption we will encompass investigation about minimisation of losses, leakage of compressed air, non-destructive testing methods, influence of pressure drop on compressed air filters and optimization of work regime. Also, we will describe the control methods of pneumatic actuators. At the end we will present the optimisation method of complex automated robotic cell taking in account energy efficiency.

Systematic approach

The system for production, preparation, and distribution of compressed air must operate in correlation with final users of compressed air. Production of compressed air, on one side, and consumption, on the other side, are the parts of a unified system and they never work separately.

Systematic approach to increasing energy efficiency of compressed air systems [11] consists of eight steps (fig.1). This approach is suitable for implementation in the process of designing a completely new system of compressed air or in the process of improving the existing system, which is more often the case.

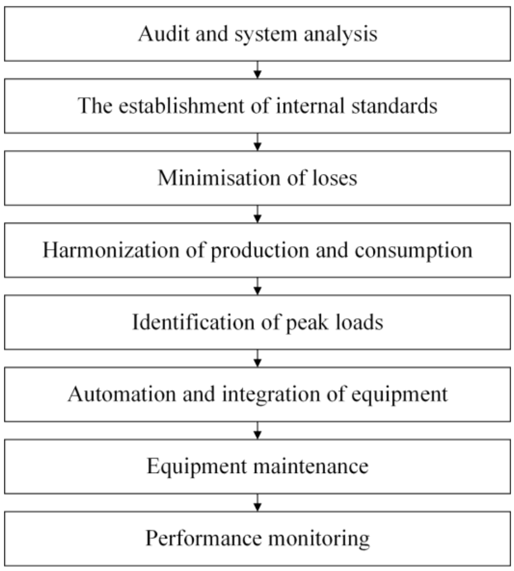


Figure 1. Steps of systematic approach

The eight steps of this systematic approach are:

(1) *Audit and system analysis.* This step includes a detailed examination (audit) and analysis of the systems for the production, storage, and distribution of compressed air, on one side, and analysis of the consumers' needs on the other side. During this analysis the system characteristics, characteristics of consumption and characteristics of a production of compressed air have to be encompassed. The main goal of air supply system optimization is balancing production needs with air supply capacity at any given moment [3].

(2) *The establishment of internal standards.* After the audit and analysis follows defining the policy for the system of compressed air and the establishment of internal standards. They have to be followed during determination of consumption characteristics and conditions for use of compressed air in specific applications. It includes defining of the pressure in the main line (header), adequate pressure and flow level as well as appropriate level of compressed air quality for every consumer of compressed air.

(3) *Minimisation of losses.* One of the most important steps in systematic approach is to minimise the losses. The importance of this step becomes even more important if we have in mind the fact, that significant amount (in some systems up to 50%) of compressed air is spent on various losses, which, in most cases, can be remedied quickly and efficiently without large investments. There are a number of measures that can be used for minimisation of losses and increasing of energy efficiency [2, 12].

(4) *Harmonization of production and consumption*. Harmonization of production and consumption aims to identify the real needs for compressed air without disruption of production process. It is necessary to ensure a regular supply of sufficient amounts of compressed air [3].

(5) *Identification of peak loads.* In this step, it is necessary to identify situations where peak loads occur, from the entire load profile. These information enable proper dimensioning of compressed air distribution system and give support in determination of reservoir capacity. Reservoir is necessary in order to provide enough air with minimum energy consumption.

(6) *Automation and integration of equipment.* This step encompasses computer integration and automation of all devices in the system. Development of an automated system need to allow monitoring, control, and proper maintenance of the compressed air system.

(7) *Equipment maintenance*. Equipment maintenance has a very large impact on the energy efficiency of compressed air systems. Inadequate maintenance may result in additional energy costs, the weak performance of the system, shortening of the service life of components, etc. Due to a large influence on the energy efficiency, this step should be under special attention.

(8) *Performance monitoring*. Performance monitoring establishes well-balanced and efficient system that stays within the demanded characteristics [11].

In the following chapters, some examples of improving energy efficiency connected with some of above mentioned steps are given.

System analysis and harmonization of production and consumption

The main goal of optimization of air supply system is harmonization of production needs with air supply capacity at any given moment. By connecting output and input variables in a pneumatic manufacturing system, better energy efficiency might be achieved. Hence, platforms for optimization and better planning should be developed. In the paper [3], a suggestion is given for one possible optimization model for the production of bottled water.

The manufacturing system that was optimized and analyzed during this study was a specific compressed air system intended solely for high-pressure compressed air consumers – PET Blowers. Its operating pressure ranged from 32 and up to 40 bar. The initial design of pneumatic system optimization, during this research, was that each one of the four compressors is attached to a single blower (fig. 2a).

As a result of this research, a suggestion was given that high-pressure compressors, linked to four individual lines for blowing PET bottles, should be linked to one high-pressure tank (fig. 2b). In this way, the reliability of the system was increased. During this research, discrete event simulation methods were used to verify a proposed solution and to assist researchers in determining an optimal design of an air supply system. The solution given was based on a suitable combination of PET bottle blowers work cycles, which would better meet the total demand for compressed air. To replace multiple compressors with a single compressor station for multiple PET blower lines is a difficult task, because, in general, compressors are from different manufacturers, each one with their own control systems, and with specific energy efficiency characteristics. Hence, choosing the right combination of existing compressors in order to better control production of compressed air, and to improve reliability and energy efficiency, was a challenge that needed careful planning, calculations, and discrete event simulation.

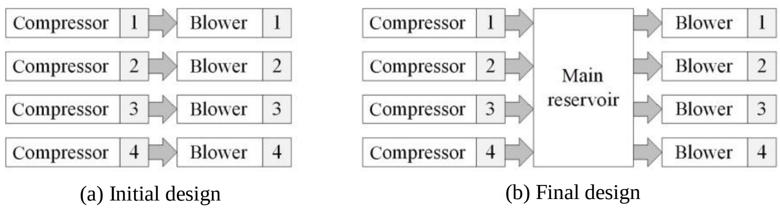


Figure 2. Initial (a) and final (b) design configuration of compressors and blowers for water bottle manufacturing system [3]

The obtained results clearly indicate an increase in energy efficiency. That means that by simply connecting the compressors to a joint reservoir and implementing a specific PLC Control based on discrete event simulation methods, the energy efficiency is improved, along with an increase in reliability. The design solution that was suggested was to use sequential controllers to turn on and off any of the four given compressors. These pneumatic system components should be integrated through a local network and controlled from a distributed location. No previous attempts have been made to connect and build CAS on 40-bar level in this way. Furthermore, the given procedures for verifying energy efficiency yield and compressors' control are general and can be used for energy efficiency optimization of multiple PET blowing in the same location for companies considering revitalization, or for the design of a new production site.

Energy efficiency increase of 4.44% is significant because the factory is working 330 days in a year with an average of 15 hours of daily production. The total saving in one year is 115,775 kWh.

Minimisation of losses

This chapter encompasses several very important issues that can be met in industrial production, such as leakage, pressure drop and inappropriate working regimes.

Leakage of compressed air

Leaks are the most visible and most significant contributors to compressed air losses. Leakage rate varies between 20% and 40% of the total air usage [3]. In order to reduce leaks and increase energy efficiency it is necessary to detect leaking spots and remove causes of leaks. If it is possible, firstly, it is useful to quantify the value of leakage and after that, it is easier to determine next steps in leakage removal and prevention.

Leakage quantification

Leakage quantification is possible with several well-known methods [13]. They are based, mostly, on the measurement of compressor operation time, although flow gauges, ultrasound detectors, and infrared (IR) thermography are also gaining popularity [14].

Ultrasound technology and IR thermography belong to the group of non-destructive testing (NDT) methods.

Ultrasound is the sound with the frequency above the upper limit of human hearing. Ultrasound technology utilizes sound waves that are beyond human perception, and ranges between 20 kHz and 100 kHz. The ultrasound testing method is widely used in industrial applications. Wide spectrum of sounds is mostly generated by cavitation or turbulence of air molecules under the pressure, which flow out into the atmosphere through orifices, cracks, and seams. Numerous factors affect the flow, the size, shape, and configuration of leak orifice, temperature and humidity of expelled air, *etc*. Ultrasound method has the limitation by the background noise, which is generated within the system and its environment. Advantage of the ultrasound leak detection lies in its versatility, speed of detection, ease of use, ability to perform on shop floor, and ability to detect various types of leaks. Scanning of the tested area reveals leak locations quickly and easily.

Infrared technology uses IR thermovision cameras to display and measure thermal energy radiated by an object. The thermal, or IR energy, represents light emission, which is invisible to the human eye, due to high wavelength. This method is very suitable for usage in compressed air systems, because the occurrence of malfunction or air leak is accompanied by temperature change.

In order to establish prerequisites for compressed air leak quantification using ultrasound and IR technology, there were conducted a series of experiments on pneumatic hoses and steel pipes. The results of these experiments are published in [4, 15]. During these experiments, the intensity of sound generated by air leak from a pneumatic hoses and pipes was measured, as well as the change of air temperature at the orifice through which the air was released. In order to establish the real quantity of air that spout through the orifices, parallel to noise level, and temperature change, compressed air flow was measured at each of the orifices.

In the case of flexible hoses, ultrasound should be used for leakage detection for all the dimensions of orifices, but for the quantification purposes only for smaller leaks, precisely, for the leaking with the sound level up to the 74 dB. If the sound level is higher than 74 dB, IR camera should be used for leakage quantification and it will give a reliable estimation of leakage. Therefore, quantification of bigger losses due to the leakage through the orifices 1.3-2.0 mm is not able with ultrasound detector, but it is steel possible with the IR camera [4].

In other case, leakage on the steel pipes, the application of ultrasound method is not possible, because the noise levels for all examined orifice diameters and pressure levels were the same (75 dB). However, IR thermal imager obtained much more reliable results. Applying IR thermography for the leakage quantification purposes requires a thermal contrast at leak locations. Those contrasts are relatively low for small leaks, so IR technology is not that precise for orifices smaller than 1.0 mm. However, the reliability and accuracy of the results are hampered by sources with weak radiation, and conditions of extreme lighting [15].

Leakage removal

One beverage product plant from Serbia had large problems with machines for glass bottles packing and palletising. Loses of compressed air were extremely high, maintenance operations were very frequent and as a result, the production process was not continuous [16].

Packing machine was inserting glass bottles into the plastic crates. The machine consisted of three carriers with four rows and seven heads in each carrier. Each head is dedicated for handling one bottle.

The main problem was with the rubber, which is placed into the head. During the operation, the rubber had worn out, causing air leaks. Therefore, it was necessary to change the damaged rubber.

The first step in the solution of this problem was compressed air consumption measurement. Consumption was measured on the carrier row with and without damaged heads. Comparing these results, it was easy to determine loses of compressed air on the single head. The next step encompassed replacement of damaged rubber with the new one. After that, measurement was repeated and the better results are obtained, as is shown in fig. 3.

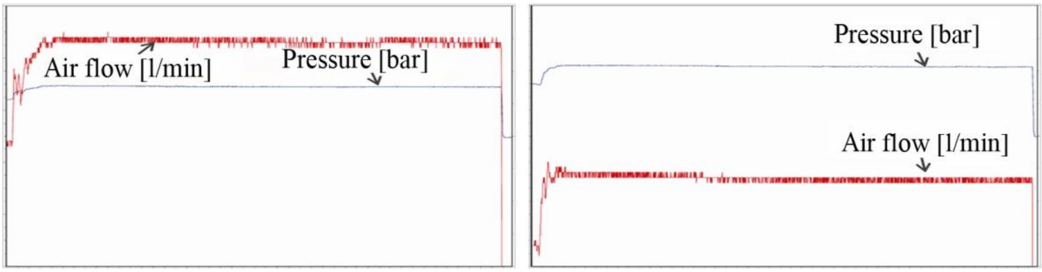


Figure 3. Compressed air flow on the first row before (left) and after (right) replacing the head

If we take into consideration that this machine is performing 900000 cycles per year, we get 290 x 900000 = 261000 Nm^3 of compressed air savings per year. It roughly equals to savings in one year of 87,000 kWh.

Pressure drop on filters

There are many pollutants that can be found in the compressed air, and all can be classified as solid particles, water, and oil. In order to obtain usable compressed air from the atmospheric air, with a certain degree of purity, it is necessary to apply different types and number of compressed air filters.

The main assumption is that it is possible to reduce the pressure drop in the system for distribution of compressed air with appropriate use of certain number of filters and way of their installation on the distribution network.

The pressure drop in compressed air filters depends on the flow and pressure of air during its flowing through the filter and the degree of filtration of the filter. As the air pressure drop is an important indicator of the efficiency of the filter, thus determining the real pressure drop is of great importance.

The idea behind planned experimental research is based on achieving the least possible pressure drop, using two or three compressed filter installed in parallel, instead of one, or even applying filter larger than necessary, if this is possible and economically justified.

Each manufacturer of compressed air filter defines a nominal value of pressure drop, in the product documentation [17]. However, these values may vary from the actual values. For example, at a flow rate of 600 NL/min, and a certain pressure, the filter has a certain pressure drop Δp_1. If this filter is replaced with exactly the identical two filters installed in parallel, a flow rate of 600 NL/min will be distributed among them, so that 300 NL/min of compressed air will flow through each of them. By reducing the flow, lower pressure drop occurs (Δp_2). This will bring a significant reduction in pressure drop in amount of Δp_1-Δp_2 (fig. 4).

If the certain filter is replaced with three identical filters installed in parallel, the air flow of 600 NL/min will be allocated to these three filters in amount of 200 Nl/min. This will result in pressure drop Δp_3 and the total reduction of the pressure drop will be Δp_1-Δp_3, as can be seen in fig. 4.

Preliminary measurements were conducted on particulate filters with degree of filtration 40 and 5 micron and working pressure 4 bar. Pressure drop was measured on single filter, two and three identical filters installed in parallel, and on filter that is larger than necessary. Obtained results, for 5 micron filters are presented in fig. 5. As can be seen, the basic assumption has been confirmed [18].

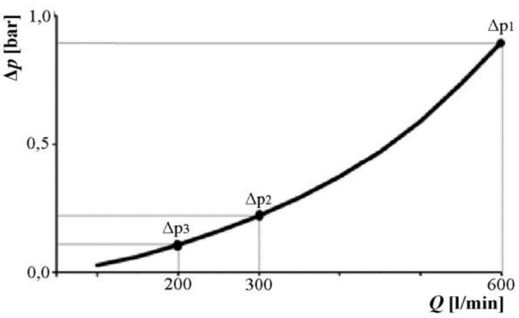


Figure 4. Pressure drop on compressed air filters as a function of an air flow [18]

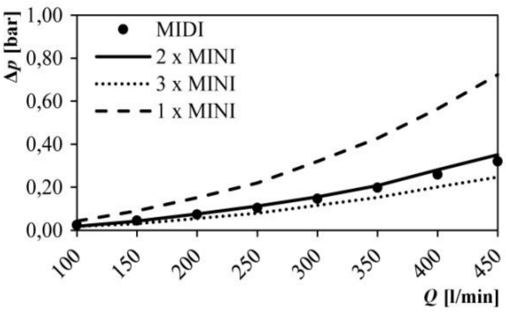


Figure 5. Pressure drop on particulate 5 micron filters and working pressure 4 bar

As it can be seen from the diagram, if one filter that is making Δp of 0.58 bar is replaced with three filters of the same type positioned in parallel, Δp will drop to 0.2 bar. So, savings of 0.38 bar is obtained. As it is well-known that 1 bar of pressure reduction gives approximately 7% of energy savings for the 4000 hours of yearly operation of the filter, we are getting savings of 896 kWh. Knowing that factories have a hundreds of filters we can get the insight of possible savings.

The goal was to determine whether the total pressure drop will be lower if the filter is replaced with two or three identical types of filters installed in parallel. The future measurements will encompass, in case where other working conditions remain at the same level, different types of filters (particulate and coalescing), different air flow and working pressure, while the pressure drop is planned to be experimentally determined for each particular case.

Optimization of work regime

The problem with so many machines and devices is that they are running in a not optimized regime. We will illustrate this on the example of pallet machine [16]. The vacuum gripper, as a part of pallet machine, picks paperboard from the stock and places it on the pallet. One pallet has five paperboards between each level. In addition, each level of pallet contains packages of the plastic bottles. Vacuum griper has four suction cups, and vacuum is generated on the Venturi principle. This machine had energy inefficient work regime and losses of compressed air were huge. The measurement was carried out and it was determined that vacuum griper consumed huge volume of compressed air for this type of applications.

Big problem with this vacuum gripper is in its work regime. Immediately, after placing one paperboard on the pallet, it picks up the next one and holds it in the upper position until the new row of bottle packages is not placed on the pallet. That period lasts 20-30 seconds, in average. During that time, vacuum is generated constantly. In some unpredictable situations of malfunctions in the production line for forming bottle packages, the upper position of vacuum gripper with the paperboard, might last dozens of minutes, or even several hours in cases of big accidents. Over that time, compressed air is consumed for generating vacuum. This is an inefficient way for consuming the compressed air and the costs are rapidly increasing.

Recommended procedure for optimising the vacuum griper encompasses three steps:

(1) Work regime improvement with reprogramming the controller that regulates vacuum gripper.
Vacuum gripper should be reprogrammed in such a way that, after placing the last bottle package on the pallet, it picks up the paperboard from the stock. Current time of 20-30 seconds would be reduced to 5-6 seconds for consuming compressed air for generating the vacuum.

(2) Vacuum generator replacement with the generator with integrated air saving circuit.
Vacuum generator with air saving circuit generates the vacuum up to defined level and after that switches off. When the vacuum level falls below the required range, vacuum generation is activated automatically (fig 6). The main point of this type of vacuum generator is that it does not generate vacuum constantly. There is a tolerance range within which the vacuum level can vary. When the vacuum level falls down below the level necessary for picking and placing the paperboard, vacuum starts generating again.
Implementing the vacuum generator with integrated air saving circuit, air consumption would be reduced from 315 L/min to 50 L/min.

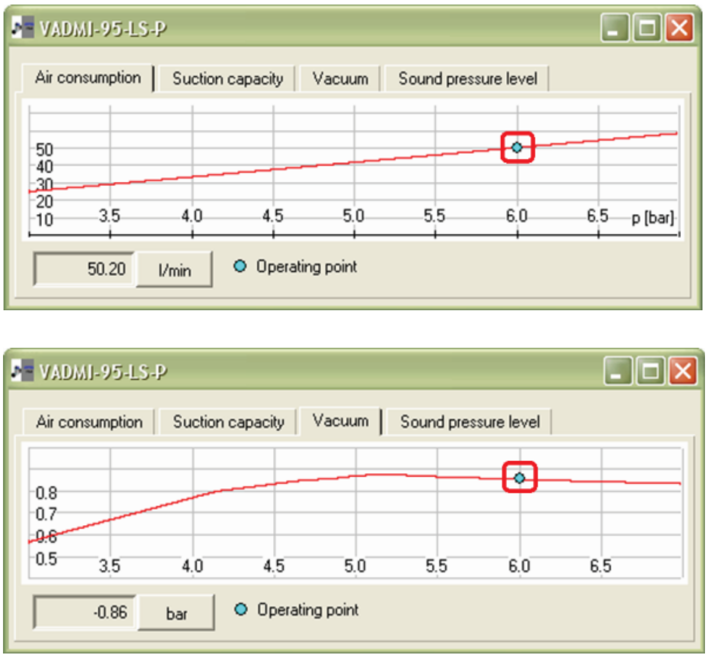
(3) Reducing the pressure level.

Diagrams of the compressed air consumption for generating vacuum and vacuum level of the vacuum generator, with integrated air saving circuit, is presented in fig. 6.

As it can be noticed from fig. 6, the highest level of vacuum is at the level of 5.2 bar. If we reduce the initial pressure level of 6 bar to 5.2 bar, savings of 6.7 L/min can be achieved, fig. 7.

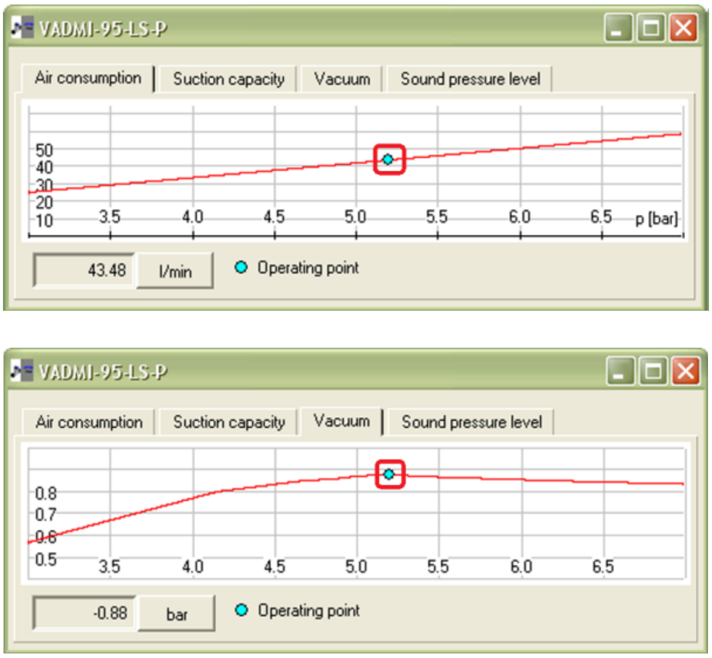
Pneumatic control systems

Pneumatic control systems play very important roles in industrial automation systems owing to the advantages of low cost, easy maintenance, cleanliness, ready availability and cheap power source, *etc.* [19]. A number of methods are identified for improving of energy efficiency of pneumatic control systems. It is shown in the paper [20] that some velocity profiles of servo pneumatic actuator can increase energy efficiency. Kagawa *et al.* [21], introduced the thermodynamic concept of exergy to study meter-in, meter-out systems for the velocity control of pneumatic actuators, and explain their different energy consumption. Many other measures are listed in [2, 12].



(a)
(b)

Figure 6. Compressed air consumption (a) and vacuum level (b) at pressure level 6 bar



(a)
(b)

Figure 7. Compressed air consumption (a) and vacuum level (b) at pressure level 5.2 bar

If servo control is required by means of the pneumatic actuator, it is necessary to use proportional valve in order to control pressure in cylinder chambers. A significant problem with servo pneumatic actuators is how to achieve accuracy in positioning. The higher the positioning accuracy, the higher the compressed air consumption is. Regardless of the type, the proportional valve is the most expensive component of the pneumatic servo system, as well as the significant consumer of compressed air, which, in many cases, may diminish the above-mentioned advantages of pneumatic drives.

In this overview, we are showing two different ways of avoiding the use of traditional proportional technologies. One is trying to avoid the use of proportional energy most of the time with the application of the bypassing of cylinder chambers. Another one is avoiding proportional valves completely by using pulse width modulation (PWM) control with on/off valves. The third approach for increasing the energy efficiency of pneumatic control systems, given in the third part of this chapter, is dealing with the usage of exhausted compressed air from the cylinder chambers that are previously collected in additional reservoir.

Motion control using by-pass

Increase of energy efficiency during positioning of cylinders is very important, and this primarily depends on the type of actuator and on the applied control of position. Traditionally, during the change of the direction of piston motion, all the compressed air from the previous working chamber is released in the atmosphere, and the new quantity of compressed air is introduced into the other chamber. Therefore, irreversible losses of compressed air energy occur. The paper [22] presents a new solution of the positioning control algorithm that unifies digital control of variable structure, sliding working mode and inter chamber cross-flow.

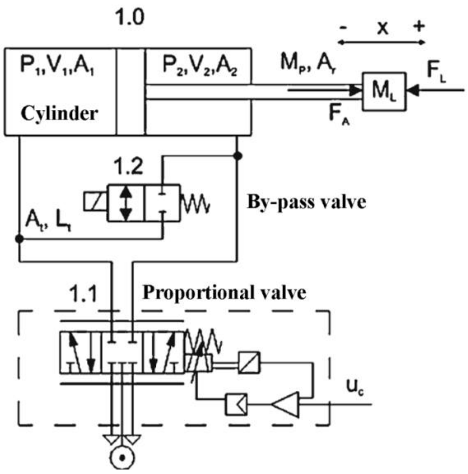


Figure 8. Pneumatic circuit of the servo system for positioning with by-pass valve control [22]

The idea is to use portion of compressed air from the previous working chamber entirely or partly for the reverse motion of the cylinder. This can be accomplished by adding another 2/2 valve, designated as 1.2 in fig. 8. This new valve establishes the connection between the driving chambers of the actuator at a given moment, *i. e.*, at the moment of piston motion reversal [22]. The basic idea was illustrated in the pneumatic circuit, presented in fig. 8.

For designing energy efficient control of a servo pneumatic system, the two parts control is used. They are alternately activated in a following way:

- I part for restoring energy (by-passing the chambers),
- II part for the fine positioning purposes.

The first part of control, referring to the energy restoring is simple, and it means ON–OFF activation of the actuator by-pass valve in appropriate intervals. The by-pass valve activation occurs when the piston is moving, and when the position error is higher than the adopted value.

Energy efficient control of the servo pneumatic actuator system utilizing by-pass valve and digital sliding mode exhibits good properties regardless of what part of it is engaged at a given moment. This is reflected in the accuracy and robustness of control on one hand, and compressed air consumption reduction, on the other hand. It is shown that in some application cases increase of energy efficiency can be up to 29.5%. Implementation of the proposed control is very simple, and does not call for a significant investment, and it is possible to use standard components without any alterations.

The PWM control

For the control of pneumatic actuator using on/off valve there may be two basic configurations, one of which requires two 3/2 electromagnetic valves (fig. 9) and the second one, requiring four 2/2 electromagnetic valves (fig. 10) [23, 24].

Servo position control can be achieved with cheap, standard, on/off valves, and commercially available programmable logical controller (PLC). Control of a pneumatic actuator using pulse width modulation (PWM control) is a good alternative to control using proportional valve. Typical system of PWM control can be considered as a configuration with two 3/2 valves where each valve is connected to one cylinder chamber and works in regime of *charging* or *discharging* of that chamber. These 3/2 fast on/off electromagnetic valves can be used instead of proportional valves and servo valves.

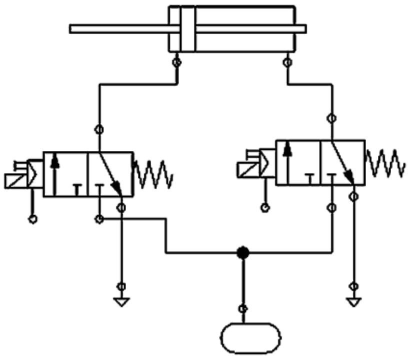


Figure 9. Pneumatic circuit of examined system [24]

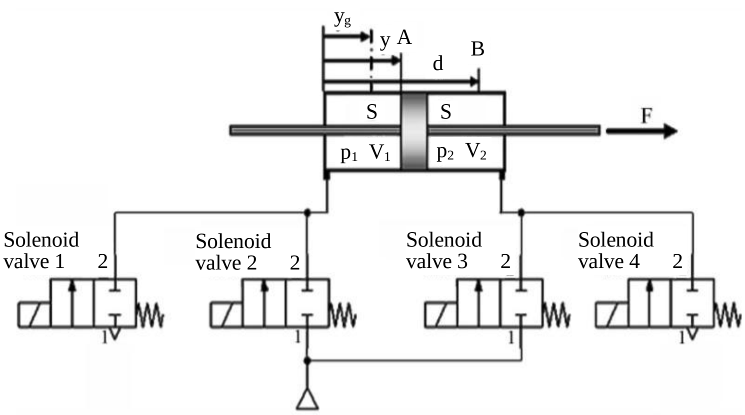


Figure 10. Pneumatic circuit of for PWM control with four 2/2 valves

In the case of PWM control, the valve is either entirely open or entirely closed and the control is done by the amount of holding time of the valve in its final positions. Therefore, the valve delivers discrete quantities of fluid mass whose amount depends on the command. If the frequency of valve opening and closing is much bigger than the limit frequency of the system, the system reacts to the mean value of discrete flow. The PLC can be used to realize the PWM control of the pneumatic actuator.

The classical PWM control system with two 3/2 valve leads cylinder chambers to the *charging* or *discharging* for all periods of control, so that average chambers pressure depends on the duty cycle of control impulses. The air flow exists even though the reference position is reached with the required accuracy. The method of forming a command signal is described by eq. (1):

$$u_{1,2} = \begin{cases} u_k \text{ for } \leq dT \\ 0 \text{ for} > dT \end{cases} \tag{1}$$

where d is the duty cycle and it is calculated according to the law d = 0,5 ± $f(e)$.

Modified PWM control system is proposed in paper [24], introducing a state of the actuator when the reference position is reached with the required accuracy and then both chambers are connected to the operating pressure. In this way, the flow of air stops and the savings were achieved in the consumption. The method of forming a command signal is described with the eq. (2):

$$u_{1,2} = \begin{cases} u_k \text{ for } t \leq dT \\ 0 \text{ for } t > dT \\ u_k \text{ always for } |e| \leq \varepsilon \end{cases} \tag{2}$$

The mentioned control system was experimentally confirmed on the pneumatic circuit that is presented in fig. 9. The difference is in the introduction of one more condition, that takes into account the absolute size of the tracking error. If this value is less than the pre-set value ε, on both coils the voltage u_k is sent, which causes both cylinder chambers to be connected to operating pressure. This method of control leads to smaller fluctuations in the transition process because the air flow stops immediately after reaching the stationary state.

Standard PLC was used for position measurement, error calculation, and PWM signal generation. The PLC was also used for data acquisition and data display.

After the series of measurements, it can be concluded that PWM principle of control gives a good quality of the signal tracking at the considerably lower costs and that PLC with standard program support can be used for its realization [25].

Classical PWM control has a wider application, but in the view of energy efficiency, it is very unsatisfactory. Therefore, its application could be recommended for small pilot valve or in cases where it is necessary due to asymmetric load of actuator.

The characteristic of meter-out PWM control method is that one chamber is connected to the operating pressure and the other is connected to the atmosphere or operating pressure in accordance with the PWM signal. To change the direction of pistons motion the role of chambers should be changed. The method of forming command signals can be described with eq. (3):

$$\begin{gathered} u_2 = \begin{cases} u_k \text{ for } t \leq dT \\ 0 \text{ for } t > dT \end{cases} \text{ and } u_1 = u_2, \text{ for } e < 0 \\ u_1 = \begin{cases} u_k \text{ for } t \leq dT \\ 0 \text{ for } t > dT \end{cases} \text{ and } u_2 = u_1, \text{ for } e > 0 \end{gathered} \tag{3}$$

Duty cycle d now varies in the interval $0 < d < 1$.

The comparison of three previously described PWM control methods, from the aspect of energy efficiency yields that the lowest consumption has meter-out (80.4% less consumption then classical and 50% less than modified), then modified PWM control and after that classical PWM control. During the movement of the piston, the meter-out control opens only one chamber, while in the modified both cylinder chambers open, so the consumption of air in this case is exactly twofold. In these two ways of control, there is no air consumption at the end of the motion, while the classical PWM control keeps on opening both chambers after the end of the motion, which results in drastically increased air consumption.

Use of exhaust air

Used compressed air from the pneumatic actuator can be collected in a separate reservoir for its later use. This can increase energy efficiency of the pneumatic system. The aim is to achieve savings in the compressed air consumption and improvement of energy efficiency but without loss of the dynamic working characteristics of pneumatic systems.

In order to prove this statement experimental measurement was performed. Pneumatic installation with additional tank was formed as shown in fig. 11.

As it can be seen, pneumatic installation consisted of double rod cylinder, a potentiometer for measuring the piston position, two 3/2 normally closed valves, non-return valve, additional tank. Compressor power unit supplied the installation. Control and data acquisition were performed using a PLC.

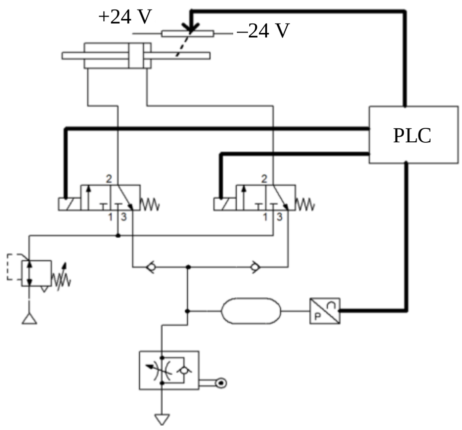


Figure 11. Pneumatic circuit of experimental installation [26]

Two types of experiments were performed:

(1) The air was discharged from the actuator to the additional tank, alternatively from both chambers and the pressure in the tank was increasing until the actuator stopped;
(2) The pressure in the tank was fixed to constant initial value and the actuator was then activated by step input signal. This procedure was repeated for several values of initial reservoir pressure to investigate the possible change of dynamic characteristics of the actuator during the process of filling the reservoir and the consequential increase in tank pressure.

Dynamic properties of the tested cylinder were not exacerbated by the installation of additional tank until air pressure ratio in the tank and working pressure is less than 0.52. Compressed air, which was collected in the additional reservoir, can be used to drive another cylinder, in case that the lower value of the pressure from the additional reservoir is sufficient. In subsequent experiments, applying pressure boosters to amplify the pressure in additional reservoir on the sufficient level have to be investigated [26].

Automation and integration of equipment

In a scope of computer integration and automation, pneumatic systems should cooperate with all other devices and automated machines in the system as well. In that sense, interest question is raised concerning optimization of a complex robotic cell [27].

Energy conservation of a complex robotic cell can be achieved in many different ways. Various utilities and various parameters that are used in complex robotic cell should be observed as a part of an integral approach.

The main problem with enhancing the energy efficiency of a complex robotic cell is in one-sided approach. Roboticists concentrate on parameters, such as trajectories, velocity, and others, which are directly related to robot's function, whereas other utilities are usually neglected. On the other side, plant engineers mainly focus on consumption and operation of the utilities and devices.

Complex robotic cell, utilising not only electric but also pneumatic elements can be optimised having in mind productivity, energy efficiency of electric devices, and energy efficiency of compressed air devices within complex robotic cell. Productivity criterion is the first one in order of relevance. After satisfying constraint of maximal productivity, requirements for energy efficiency of electricity and compressed air devices could be fulfilled.

Increasing energy efficiency is considered as a way to reduce manufacturing costs and contribute to the better preserving of energy resources as well as the preservation of environment while maintaining some imposed functional requirements.

The optimisation of such complex robotic cell involves three key steps:
(1) An identification of possible approaches in complex robotic cell optimisation,
(2) An identification of parameters of influence on electricity and compressed air consumption, and
(3) Experimental evaluation of the proposed approaches with a recommendation for the optimal one, meeting the requirements of maximal productivity and energy efficiency.

The optimisation of such complex robotic cell is possible in three different ways, as is presented in fig. 12. The experimental evaluation of each approach showed that electric and compressed air parameters could not be observed separately, because most of them influence each other. For the complex robotic cells that use electricity and compressed air for their operation, we found the following method optimal:
(1) Establishing the primary criterion (maximal productivity, minimal manufacturing costs, *etc.*).
(2) Parameters that influence the electricity consumption should be optimised first. Those parameters are related to robot itself and other electric devices within a robotic cell.
(3) Parameters related to compressed air consumption should be adjusted according to constraints given by the robot and applied criterion [27].

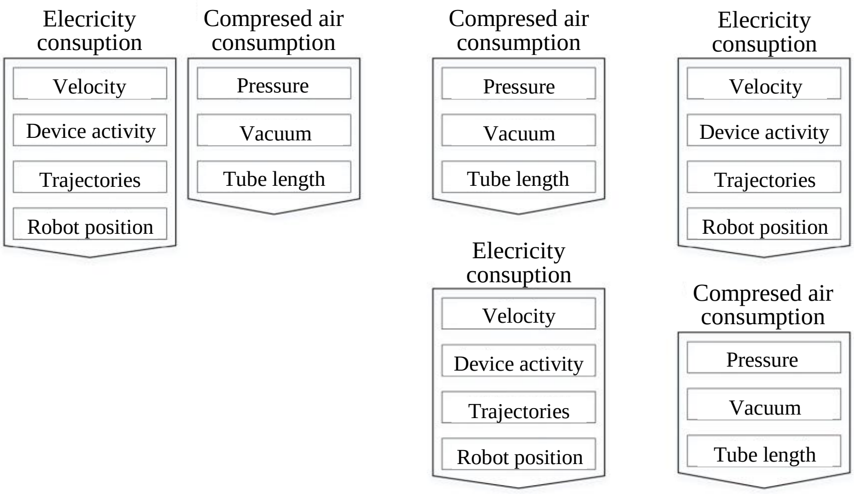


Figure 12. Approaches in complex robotic cell optimization [27]

Conclusions

There exist various energy saving strategies that can be applied within compressed air systems. Compressed air systems should be designed, implemented, and managed to satisfy user demands respecting efficient utilisation. However, all energy efficiency measures have to improve functioning of compressed air systems, achieving savings and preserving environment.

Good control and management often lead to increased energy efficiency of compressed air systems. The first step should be to raise the awareness of all the people involved in the compressed air optimization, pointing out all the benefits that can be achieved. With the presented systematic approach, it is possible to establish energy efficient structure of compressed air system, either during reconstruction of an existing system or design of the new one.

As can be seen, improvements and savings are possible in all stages of compressed air utilisation, from filtration, execution, function within a complex systems, etc. All the improvement measures have to enable the rational spending and efficient production, preparation, distribution and application of compressed air in all phases of the lifecycle of the compressed air system. The application of the measures for an energy efficiency increase in compressed air systems enables prolongation of the component's life cycle and the reduction of total operation costs, that in turn increases the economic quality of the working process.

Nomenclature

p – gauge pressure [bar]

Δp – pressure drop [bar]

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