ADVANTAGES OF RESTORING ENERGY IN THE EXECUTION PART OF PNEUMATIC SYSTEM WITH SEMI-ROTARY ACTUATOR

by

Vladislav A. BLAGOJEVIĆ [*] ***and Predrag Lj. JANKOVIĆ***

Faculty of Mechanical Engineering, University of Nis, Nis, Serbia

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The need for energy savings is on the rise. Pneumatic systems, as essential parts of any branch of industry, are large consumers. The opportunities for saving energy in these systems are great. The paper presents a structure of pneumatic systems while a special emphasis is put on the saving of energy in the execution part with semi-rotary actuator by a method of restoring energy via by-pass valve. The realized energy savings are average 41.48% for conventional systems and 31.42% for servo systems for nominal operating value of pressure supply of 600 kPa. Cost effectiveness of proposed method is also presented.

Key words: *pneumatic system, restoring energy, semi-rotary actuator*

Introduction

Pneumatic systems offer many benefits in terms of small cost. They do not represent polluters and are easy for installation and maintenance, *etc.* For these and many other reasons they are used in many industries. The energy used in pneumatic systems is the energy of compressed air, which comes in special plants that are called compressors. Generally, the cost of electricity used to power air compressor in the production under pressure is around 20% of the cost of electricity for a factory. In some branches of industry, like glass industry, the cost of electricity used to power air compressor is up to 30% of the cost of electricity for that industry [1, 2]. For these and many other reasons, it is very important to carefully manage compressed air consumption. The energy savings in various parts of a pneumatic system are different. For instance, the energy savings in production compressed air part can be up to 16% and in transmission part up to 25-30% [1]. In the execution part, energy savings can be up to 45% for some actuators (symmetric or asymmetric) and work conditions (existence of external load or not) [2].

Increase of energy efficiency of pneumatic system with semi-rotary actuators as the execution part of the system is very important, and primarily depends on the type of actuator and on the applied position control algorithm. Another problem is that when the shaft reverses its movement all the compressed air from one chamber is released into the atmosphere and this is a great compressed air loss.

There are many papers dealing with the issue of production and reduction of compressed air consumption in pneumatic systems. Here are some papers listed according to the date of publishing. Sanville [3] proposed the use of a secondary reservoir in an open-loop sys-

* Corresponding author: vlada@masfak.ni.ac.rs

tem to collect exhaust air rather than vent it to the atmosphere, then reuse the stored air on the return stroke. Quaglia and Gestaldy [4] proposed a non-conventional pneumatic cylinder which has multiple chambers within one actuator for recycling of exhaust compressed air. Wang *et al.* [5] studied the use of input shaping to choose a command profile for point-to-point motions that would result in energy savings for closed loop pneumatic servo actuators, and showed that some velocity profiles could reduce energy demand relative to other profiles. Kagawa *et al.* [6] introduce the thermodynamic concept of energy to study meter-in and meter-out systems and explain their different energy consumption. Al-Dakkan *et al.* [7], decoupled a standard four-way valve into a pair of three-way servo valves, and presented a method of energy saving in the context of a servo controlled pneumatic actuator. Yang *et al.* [8] proposed retaining of proportional valve 5/3, but add a 3/2 valve for by-passing the cylinder chambers. For such realization, it is necessary to drill the actuator and install additional ports, which is not appropriate when using standard industrial components and the by-passing valve is under great workload and its service life is severely reduced. Blagojević *et al.* [9-11] proposed new way of using 3/2 valve for by-passing the cylinder chambers. Although there are many papers dealing with the issue of reduction of compressed air consumption in pneumatic systems, all of them are devoted to the pneumatic cylinders.

In order to improve energy efficiency of an execution part of the pneumatic system with semi-rotary actuator, restoring energy with applying by-pass valve [2] is used in this paper. To demonstrate the effectiveness of the proposed restoring energy [2] with applying by-pass valve on different semi-rotary actuators, it has been compared with the performance of the traditional execution part and the results are shown in paper.

Reducing compressed air consumption in the pneumatic systems with semi-rotary actuators by restoring energy

Pneumatic actuators, especially rotary actuators, are used in many different branches of industry. They are used for rotary movements, only. They can be classified into symmetric and asymmetric actuators. The asymmetric group includes: pneumatic cylinder with Scotch yoke and symmetric group includes: rack and pinion actuator, and vane type actuator.

If the needed torque is greater, the dimensions of pneumatic semi-rotary actuators are greater and the consumption of compressed air is also increasing. This consumption of compressed air is especially great in pneumatic systems, which use the same pressure level of compressed air in working and returning mode. Also, it is a well-known fact that the pressure of compressed air in the working volume of any pneumatic actuator increases and reaches the final value equal to the supply pressure of compressed air, just after the actuator shaft, reaches the end of the stroke of the pneumatic actuator. All the compressed air from previously working volume flows into the atmosphere, when the change of movement direction appears, during the returning mode. That is a great loss of compressed air, which has enough potential energy to do something else [8, 9].

The principle of restoring energy in the pneumatic systems with semi-rotary actuators is a consequence of the fact, that some of the used compressed air back into the system, again, fig. 1.

There are two ways of compressed air reuse [9], as follows.

– *1st way*: Fully compressed air reusing to move the actuator shaft in the opposite direction as a result of sufficient force to do it.

– *2nd way*: Compressed air reusing to reduce the need for a new amount of compressed air. Because, there is no enough force for back-stroke, there is a need to bring in a smaller amount of air in order to force grown enough to enable the process of movement in the opposite direction.

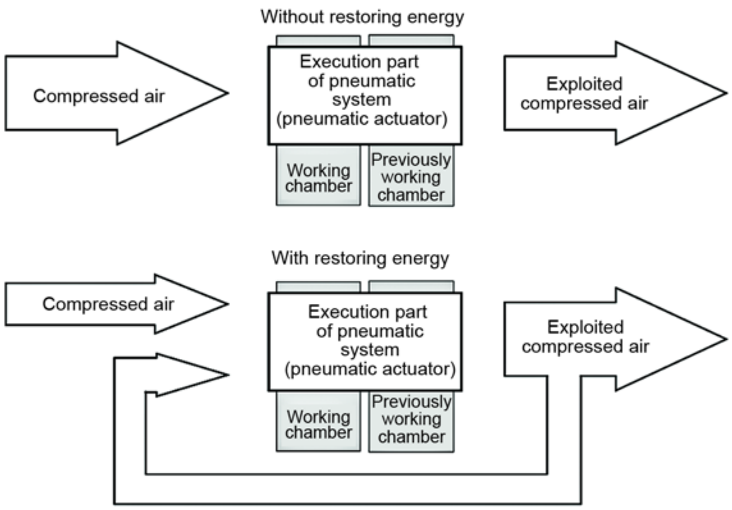

Figure 1. Basic principle of restoring energy in the execution part of pneumatic system

Pneumatic system with semi-rotary actuators and restoring energy

Restoring energy can be used for conventional, as well as pneumatic servo systems with semi-rotary actuators.

The main differences between the conventional pneumatic systems with restoring energy, fig. 2(a) and without restoring energy, fig. 2(b) are in changing directional 5/2 way valve 1.1 with 5/3 way valve 1.1 and in an additional 2/2 way by-pass valve 1.1.1. These two valves enable restoring energy by bridging the semi-rotary actuator 1.0 chambers. That is possible, when the 5/3 way valve 1.1 is in the middle position and valve 1.1.1 is activated (by-pass valve control).

The differences between servo systems with and without restoring energy are less than in the conventional systems. The only difference is in an additional 2/2 way by-pass valve 1.1.1 in the servo system with restoring energy, fig. 3(a). This valve enables restoring energy, by bridging semi-rotary actuator 1.0 chambers when the proportional valve 5/3 way is in the middle position. The proportional valve 5/3 way is the same in servo system with restoring energy, fig. 3(a) and without restoring, fig. 3(b).

The ways of savings in compressed air consumption by restoring energy in conventional and servo systems are the same.

The period of restoring energy can be up to 50% of one working cycle, especially for double acting pneumatic cylinder with Scotch yoke. Therefore, compressed air consumption can be less for a 50%, theoretically. The percentage of compressed air saving is less, in reality, because there are some factors, which have influence on consumption. These factors are: actuator type (symmetric or asymmetric), external load, an existence of a leak on the components and applied control algorithms.

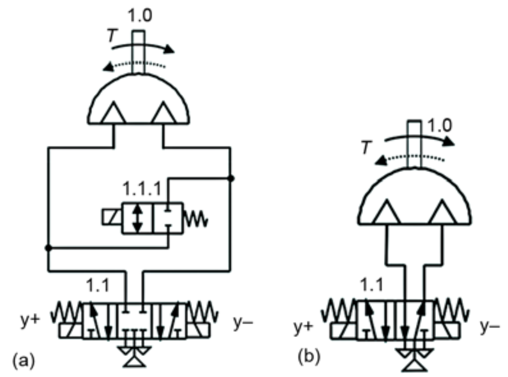

Figure 2. Conventional pneumatic system; (a) with restoring energy, (b) without restoring energy

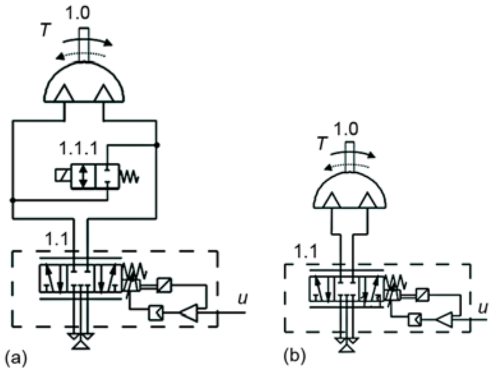

Figure 3. Servo pneumatic system; (a) with restoring energy, (b) without restoring energy

Actuator type and external load have great influence on the compressed air consumption savings. The value of savings can be up to 45% for asymmetric actuators (*1st way* of energy saving) or for existence of load torque, *T*, with constant direction, no matter on actuator type. When symmetric actuators are used, energy saving can be only up to 5%, if there is no external load. This is the result of the *2nd way* of energy saving, again.

Existence of any leaks in the components causes the reduction of the pneumatic system energy efficiency. For instance, air leaks on the tube can have a great value, or permanent compressed air leakage of directional or proportional valve in the pneumatic conventional or servo system causes fewer energy savings.

Control algorithm has great influence on the compressed air consumption savings, so it is very important to use an adequate control algorithm, because it has to enable restoring energy when there are conditions for it.

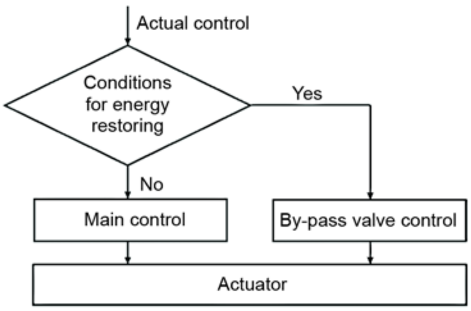

Figure 4. Energy efficient control

Energy restoring control

For designing energy efficient control of the servo and conventional pneumatic system, the control which has two control signals are used, fig 4. They are alternately activated in a following way: the by-passing control, which is applied to the 1.1.1 valve, is used for by-passing the chambers (restoring energy), and the positioning control, acting on the directional 5/3 way 1.1, fig. 2(a) or proportional valve 1.1, fig. 3(a), for the fine positioning purposes.

The first control signal, responsible for energy restoring, is simple and includes ON-OFF activation of the semi-rotary actuator by-pass valve in appropriate intervals. The by-pass valve activation occurs in the following cases:

For conventional pneumatic systems:

– if there is no load torque, *T*, or its value is very small, by-pass valve will be activated only for asymmetric rotary actuator if the piston movement is at rod side of actuator, and

- if there is a load torque, T, by-pass valve will be activated for the all rotary actuators type if the movement and the load torque have the same direction.

For servo pneumatic systems:

- the by-pass valve activation, $u_{1.1.1}$, occurs when the shaft is moving in the same direction as external load torque, and when the shaft error position, ε, is higher than the adopted value, $\varepsilon_{\text{given}}$, eq. (1) [9]:

$$u_{1.1.1} = \begin{cases} u_{\text{bv}} & |\varepsilon| \geq \varepsilon_{\text{given}} \wedge |\varepsilon_{\text{p}}| > |\varepsilon| \\ 0 & |\varepsilon| < \varepsilon_{\text{given}} \vee |\varepsilon_{\text{p}}| < |\varepsilon| \end{cases} \tag{1}$$

where ε_{p} is the previous error in the position, and u_{bv} is by-pass valve voltage activation.

Energy restoring control is engaged only if there exist the conditions set by the eq. (1) and disengaged if the value of departure from the required position is lower than $\varepsilon_{\text{given}}$.

For obtaining of a parameter $\varepsilon_{\text{given}}$, in order to simplify, it is introducing an assumption that the stopping of the drive shaft which has velocity, $\dot{\theta}_p$, during by-passing, after stopping of by-passing should be with the constant deceleration, that is $\ddot{\theta}_p = a = const$. In that situation, following is valid:

$$\varepsilon_{\text{given}} = \frac{\dot{\theta}_p^{\,2}}{2a} \tag{2}$$

Introduction of this assumption is good for two reasons: length of braking distance (period of decreasing velocity) is somewhere longer and that enables to switch to the main control a little bit earlier and it simplifies the calculation of parameter $\varepsilon_{\text{given}}$.

Second control signal, for the positioning purposes, is actually main control, fig 4. Main control can be any control from conventional to servo domain. It follows, that new way of energy efficient control is an upgrade to main control. More details about the applied main control in conventional and servo pneumatic system are shown in our previous paper [9].

Energy savings in conventional pneumatic systems with semi-rotary actuator by restoring energy

To demonstrate the control of the pneumatic system with semi-rotary actuator by restoring energy, the experimental measurements with different load torque are performed. The load torque was acting in direction of increasing the angular position of the actuator's shaft. Each test was repeated ten times. As an example, the diagrams of compressed air flow at 600 kPa pressure supply in ten working cycle for conventional pneumatic system without, fig 5(a), and with restoring energy, fig 5(b) are shown. Pneumatic cylinder with Scotch yoke 35S made by Emerson Process Management is used as an actuator. The 90 Nm load torque was 50% capacity of maximum load for this actuator at the middle of the stroke.

The compressed air consumption was measured by the FESTO Air Box device. This device enables compressed air consumption measurements in two modes with the range of pressure supply from 100 kPa to 1000 kPa. The first mode is low flow mode (10-200 L per minute) and the other is high flow mode (100-5000 L per minute).

After ten measurements, with ten cycles in each measurement, compressed air consumption of pneumatic system with pneumatic cylinder with Scotch yoke by restoring energy is 24.2 L in average, and it is less than in system without restoring energy with average consumption of 43.06 L. So, the net saving is 43.8%.

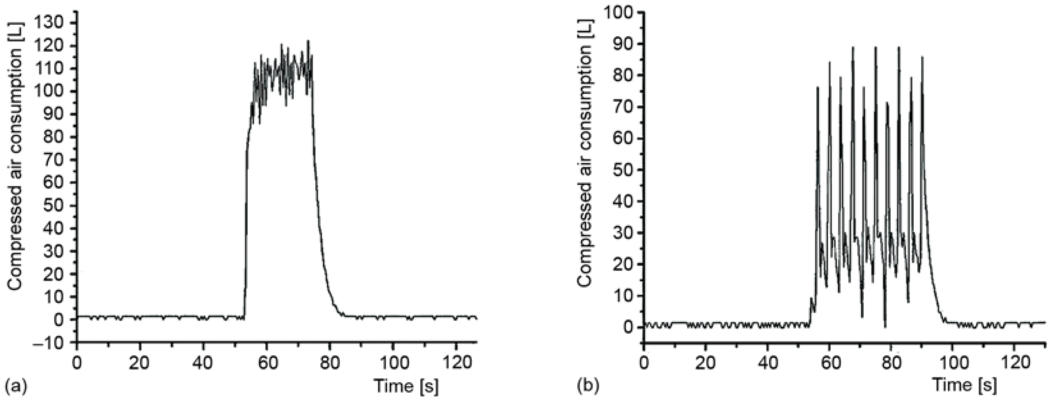

Figure 5. Diagrams of compressed air flow of conventional pneumatic system with pneumatic cylinder with scotch yoke; (a) without, and (b) with restoring energy

The measurements are also performed with different load, 50 Nm and 150 Nm and supply pressure from 400 kPa to 600 kPa at ten working cycles. Under these conditions, compressed air consumption savings of the conventional pneumatic system with restoring energy is from 37.35% to 44.34%, tab. 1. There were ten measurements performing for each pressure supply and load and the standard error was less than 0.07 and standard deviation was less than 0.16.

Table 1. Compressed air consumption of conventional pneumatic system with scotch yoke

Load	Compressed air consumption of pneumatic system (l)	Pressure supply [kPa]		
		400	500	600
50 Nm	With restoring energy	17.09	21.21	23.89
	Without restoring energy	27.28	35.36	41.66
	Saving [%]	37.35	40.02	42.65
150 Nm	With restoring energy	16.84	19.67	23.38
	Without restoring energy	27.04	35.34	41.07
	Saving [%]	37.72	44.34	43.07

After all measurements, the average compressed air consumption saving of conventional pneumatic system with restoring energy and pneumatic cylinder with Scotch yoke is 40.86% for pressure supply range from 400 kPa to 600 kPa. The average compressed air consumption saving in conventional pneumatic system with restoring energy for nominal operating value of pressure supply of 600 kPa is 42.86%.

Compressed air consumption of the conventional pneumatic system with symmetric vane type actuator DSM-12-270-P made by FESTO, and with restoring energy is from 35.78% to 41.32%, tab. 2. There were ten measurements performing for each pressure supply and load at one working cycle. The standard error was less than 0.01 and standard deviation was less than 0.03.

Table 2. Compressed air consumption of conventional pneumatic system with symmetric vane type actuator

Load	Compressed air consumption of pneumatic system (l)	Pressure supply [kPa]		
		400	500	600
0.5 Nm	With restoring energy	0.70	0.95	0.98
	Without restoring energy	1.09	1.56	1.67
	Saving [%]	35.78	39.10	41.32
1 Nm	With restoring energy		1.04	1.10
	Without restoring energy		1.66	1.80
	Saving [%]		37.35	38.89

After all measurements, the average compressed air consumption saving of conventional pneumatic system with restoring energy and symmetric vane type actuator is 38.5% for pressure supply range from 400 kPa to 600 kPa. The average compressed air consumption saving in conventional pneumatic system with restoring energy for nominal operating value of pressure supply of 600 kPa is 40.1%.

If the actuator is symmetric as rack and pinion actuator or vane type actuator and there is no load, which can be used for support of actuator movement, the saving is only up to max 5%, and it is not enough to justify investment.

When the conditions of bypassing are fulfilled, the average compressed air consumption saving of conventional pneumatic system with semi-rotary actuator (symmetric and asymmetric) and with restoring energy is 41.48% for nominal operating value of pressure supply of 600 kPa.

Energy savings in servo pneumatic systems with semi-rotary actuator by restoring energy

The results of energy saving in servo pneumatic systems with semi-rotary actuator by restoring energy are less than for the conventional pneumatic system.

The main reason is the permanent compressed air leakage of proportional valve, even in the middle position. This leakage depends on the compressed air supply (fig. 6) and starts if its value is higher than 400 kPa. There is no leakage, under this pressure value. In order to define the leakage level of proportional valve, a set of measurements was done using standard proportional valve FESTO MPYE-5-1/8-LF-010-B (fig. 6) and the standard error was less than 0.08 and standard deviation was less than 0.2.

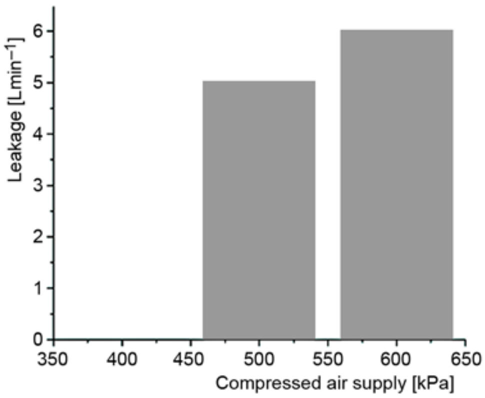

Figure 6. Compressed air leakage of proportional valve

The second reason for less energy saving in pneumatic servo system with restoring energy is that due to system state exact control (position or velocity), the by-pass control is stopped earlier, no matter if there is still fulfilled by-pass conditions.

In the most cases, servo pneumatic system with semi-rotary actuator consists of vane type actuator. So, to demonstrate the effectiveness of pneumatic servo system with restoring energy, all measurements were performed with this symmetric type of actuator and with different load.

As an example, the diagrams of compressed air flow and shaft positioning at π/2, and π, at 600 kPa pressure supply and 0.5 Nm load for pneumatic servo system with, fig. 7(a) and without restoring energy, fig. 7(b) are shown. Pneumatic actuator DSM-12-270-P made by FESTO is used as actuator.

The red box, fig. 7(a) shows the moments when restoring energy is used for movement the actuator shaft.

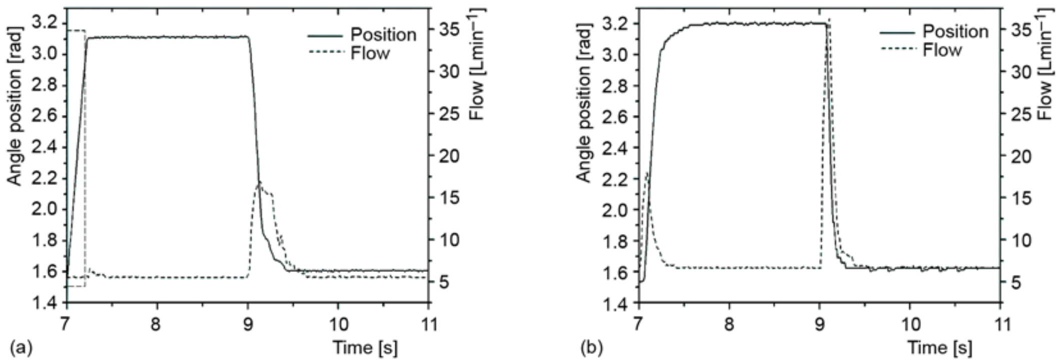

Figure 7. Diagrams of compressed air flow of pneumatic servo system; (a) with, and (b) without restoring energy

According to the previous, after ten measurements, average compressed air consumption of pneumatic servo system with restoring energy is 0.42 L and it is less than in system without restoring energy with average of 0.63 L, fig 7. Obtained saving is 33.3%. All experimental results, after ten measurements with different pressure supply and load, are shown in tab. 3. The compressed air consumption is from 29.51% to 34.48%, and the standard error was less than 0.01 and standard deviation was less than 0.03.

Table 3. Compressed air consumption of pneumatic servo system with vane type actuator

Load	Compressed air consumption of pneumatic system (l)	Pressure supply [kPa]		
		400	500	600
0.5 Nm	With restoring energy	0.37	0.38	0.42
	Without restoring energy	0.55	0.58	0.63
	Saving [%]	32.73	34.48	33.33
1 Nm	With restoring energy		0.4	0.43
	Without restoring energy		0.59	0.61
	Saving [%]		32.2	29.51

After all measurements, the average compressed air consumption saving of servo pneumatic system with restoring energy is 32.45% for pressure supply range from 400 kPa to

600 kPa. The average compressed air consumption saving in servo pneumatic system with restoring energy for nominal operating value of pressure supply of 600 kPa is 31.42.%.

Cost-effectiveness of restoring energy in the execution part of the pneumatic system

When conditions for restoring energy by bridging actuator's chambers are fulfilled, there is no need for new compressed air from supply. In that period, everything is depending to actuator's chambers pressure and forces from these pressures or external force, so the compressed air consumption is equal to zero.

In order to apply energy restoring in the execution part of the conventional pneumatic system, it is necessary to apply two components. At first, the valve 5/2 way, fig. 2(b), is changed with the valve 5/3 way, fig. 2(a), and to apply an additional 2/2 way by-pass valve for bridging actuator's chambers. So, the system realization costs are higher for the cost of two additional valves in comparison to the pneumatic system without restoring energy. Return of investment period is different for different actuators and depends on the percentage of saving accomplished by the energy efficient by-passing.

Cost-effectiveness of the proposed convectional pneumatic system with restoring energy through the return of investment periods are average 2.25 years (tab. 4), based on the same assumptions as in [8] and the price of the products of FESTO Company.

The price of the additional components is different and they depend of components type. For instance, the price of 5/3 way valve is average 293 € for standard based directional control valve type, then between 66,30 € and 194,60 € for universal directional control valve type, and between 124,90 € and 131,60 € for application-specific directional control valve. The price of 2/2 way by-pass valve is less and it is between 38,80 € and 49,20 € for universal directional control valve type and between 19,40 € and 20,70 € for application-specific directional control valve type. In this paper, the average price of additional components is used (tabs. 4 and 5).

Table 4. Return of investment period for conventional pneumatic system with restoring energy

Energy required for daily production of compressed air 600 kPa	1kW × 16 h = 16 kWh
Electric power cost	0.05 € per kWh
Number of working hours in a year	52 weeks × 5 days × 2 shifts× 8 hours = = 4160 hour per year
Annual energy costs	0.05 × 4160 = 208.05 €
Additional average costs for the by-pass 2/2 way valve	32.025 €
Additional average costs for the 5/3 way valve	162.08 €
Annual cost saving	208.05 × 41.48% = 86.3 €
Return of investment period	2.25 years

In order to apply the restoring energy in the execution part of the pneumatic servo system, it is only necessary to apply an additional by-pass valve 2/2 way for bridging actuator's chambers. So, the system realization costs are higher only for the cost of one additional valve in comparison to the pneumatic servo system without restoring energy. Return of investment periods of the proposed pneumatic servo system with restoring energy are average 0.49 years, tab. 5.

Table 5. Return of investment period for pneumatic servo system with restoring energy

Energy required for daily production of compressed air 600 kPa	1 kW × 16 h = 16 kWh
Electric power cost	0.05 € per kWh
Number of working hours in a year	52 weeks × 5 days × 2 shifts × 8 hours = = 4160 hours per year
Annual energy costs	0.05 × 4160 = 208.05 €
Additional average costs for the by-pass 2/2 way valve	32.025 €
Annual cost saving	208.05 × 31.42% = 65.37 €
Return of investment period	0.49 years

If the actuator is symmetric as rack and pinion actuator or vane type actuator and there is no load, which can be used for support of actuator movement, the saving of the conventional and servo pneumatic system with restoring energy is only up to max 5%, and it is not enough for some serious study. Then, the return of investment periods is much longer. In some cases, they can be up to 20 years.

Conclusions

The performance of the system with restoring energy can be improved in comparison with the traditional control system. Compressed air consumption saving of the conventional pneumatic system with restoring energy is from 35.78% to 44.34% or average 40.06%, for 200 kPa to 600 kPa range of pressure supply. Compressed air consumption saving of the pneumatic servo system with restoring energy is from 29.51% to 34.48%, or average 32.48% for 200 kPa to 600 kPa range of pressure supply. If the system is using pressure of nominal operating value that is 600 kPa than the average compressed air consumption saving is 41.48% for conventional system and 31.42% for servo system. Return of investment periods of the proposed conventional pneumatic system with restoring energy are average 2.25 years. If the actuator of the conventional system is symmetric semi-rotary drive, and if there is no load, which can be used for support of actuator movement, the saving is less than 5%. Then, the return of investment periods are much longer and can be up to 20 years. Return of investment periods of the proposed pneumatic servo system with restoring energy are average 0.49 years. However, as previously, if the actuator of the servo system is symmetric semi-rotary drive, and if there is no load, which can be used for support of actuator movement, which can be used for support of actuator movement, the saving is of no significance.

Main conclusion, as follows, is that through the creation of a new flow path between actuator chambers via by-pass valve and adequate energy efficient control, the system performance and energy efficiency can be significantly improved. This is possible if the actuator is pneumatic cylinder with Scotch yoke no matter on load, and for others semi-rotary drives it is very important to exist the load torque to support the actuator's movement in one direction.

Nomenclature

T – load torque, [Nm]
$u_{1.1.1}$ – by-pass valve activation, [V]
u_{bv} – value of by-pass valve voltage activation, [V]

Greek symbols

ε – shaft error position, [rad]
ε_p – previous shaft error position, [rad]
ε_{given} – adopted value of shaft error position, [rad]
$\dot{\theta}_p$ – drive shaft velocity, [ms^{-1}]
$\ddot{\theta}_p$ – drive shaft deceleration, [ms^{-2}]

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