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Energy Efficiency of Pneumatic Actuating Systems with Pressure-Based Air Supply Cut-Off

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Abstract: To exploit the energy-saving potential of pneumatic actuator systems, various energy-saving circuits have been developed in recent decades. However, the principle of a pressure-based air supply cut-off has only been considered to a limited extent. This article introduces a possible pneumatic circuit solution for this principle and evaluates it via simulation and measurement of the saving potentials and limits of the developed circuit for typical industrial drive tasks. The conducted investigation shows the suitability of the developed energy-saving circuit, especially for the reduction of the actuator oversizing, achieving energy savings of 71% without performance loss. Conversely, applying this principle to an already well-sized cylinder comes with limitations and requires additional damping. The final economic analysis demonstrates that the application of the circuit could achieve comparatively short amortisation times of approx. 1.9 years for a setup with standard pneumatic components.

Keywords: energy efficiency; pneumatics; compressed air systems; pneumatic actuators; energy-saving circuit; cut-off circuit; expansion circuit

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1. Introduction

In modern automation technology, pneumatic actuators play a vital role due to their numerous advantages, such as the high power density, simple realisation of point-to-point movement, and low investment costs. However, rising energy prices, political requirements, and growing awareness of climate change are increasingly bringing the attention of the industry to the issue of energy efficiency [1]. Pneumatic drive technology is particularly faced with this problem, as it typically has higher energy consumption and, therefore, higher operating costs compared with its main competitor, electromechanics.

Nevertheless, pneumatics still possesses an enormous saving potential of approx. 40%, which corresponds to 6.4 TWh/a or 3.03 million t CO_2 in Germany alone [2,3]. To exploit this potential at the actuator level, various energy-saving measures, such as leakage detections systems, methods for demand-oriented dimensioning as well as energy-saving circuits, have been developed for pneumatic actuators over the last few decades. In the present article, the focus is on the usage of cut-off energy-saving circuits.

1.1. Types of Energy-Saving Circuits

Energy-saving circuits include all the circuits that deviate from standard meter-in or meter-out pneumatic circuits in terms of their structure and whose purpose is to reduce the amount of compressed air supplied to the system. A detailed overview of their state of the art is provided, e.g., in [4–7]. This section outlines the current energy-efficient solutions and highlights cut-off (expansion) circuits.

For the most common energy-saving circuits, the following classification may be proposed (see Figure 1):

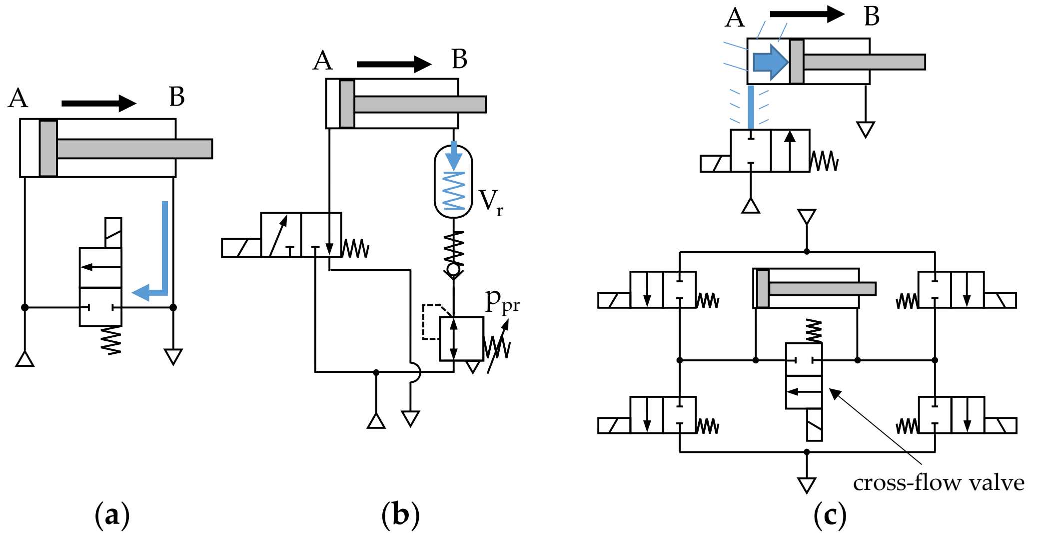


Figure 1. Basic principles of energy-saving circuits: (**a**) short (cross-flow) circuit; (**b**) exhaust air storage circuit; and (**c**) above: cut-off (expansion) principle, below: expansion bridge circuit with an additional cross-flow valve.

a. Short (or cross-flow) circuits. For this, the cylinder piston chamber A and the rod chamber B are interconnected during the extension movement in a manner where the air discharged from chamber B is directed into chamber A (refer to Figure 1a) instead of being released unused into the environment. Consequently, the volume of compressed air needed for the extension movement is minimised, leading to energy savings of up to 40%. This circuit design has been previously studied in works such as [8,9] and developed into a market-ready solution by SMC Corporation [10,11].

b. Exhaust air storage circuits. Here, the exhaust air from the cylinder chamber B is employed for the return stroke of the cylinder, as shown in Figure 1b. The piston moves against a gas spring preloaded by a pressure regulator, making this circuit comparable to a single-acting cylinder with an adjustable spring. The gas spring stiffness can be adjusted by selecting the reservoir volume V_r and the preload pressure p_{pr}, which can be determined according to the method presented in [7].

The idea of the exhaust air being saved in pneumatics, as presented in [12], was examined in a large number of publications (e.g., [13,14]). With the exhaust air storage strategy developed in [15], energy savings of 22% could be achieved in a handling system. It is also possible to convert the exhaust air energy into other forms of energy, e.g., electrical [16,17] or hydraulic [18], or to return the exhaust air back to the compressor, thus building a so-called closed pneumatic circuit (see [19–21]).

c. Cut-off (or expansion) circuits. In this case, the compressed air supply is shut off during the cylinder piston movement (see Figure 1c), allowing the compressed air already supplied to expand and to drive the cylinder piston without further air consumption. This operating principle was described in [22] and is mostly implemented using a so-called bridge circuit. The bridge circuit typically comprises four electrically operated 2/2-way valves in a bridge arrangement, as demonstrated in, e.g., [23]. Occasionally, a fifth 2/2-way valve (cross-flow valve) is added to integrate the cut-off circuit's operating principle with a short circuit [24].

Cut-off circuits with independent metering valve control have been the focus of research for a long time due to their increased control flexibility, as the cylinder chambers can be separately pressurised, exhausted or closed off individually, eliminating the need for flow-control valves. With this circuit type, large energy savings could be achieved in various literature sources. In [25,26], Doll et al. used a genetic algorithm to select the most suitable cut-off time point, demonstrating up to 80% compressed air saving over a standard actuator circuit. Hu et al. studied the application of the bridge circuit on a vertically mounted cylinder [27]. The robustness and applicability of the bridge circuit for different cylinder sizes was analysed in [28,29]. The bridge circuit as a purchasable product is distributed by Festo SE & Co. KG as part of the VTEM solution [30].

1.2. Principles of Air Supply Cut-Off

In general, the implementation of the air supply cut-off can be based on three different physical principles (see Figure 2):

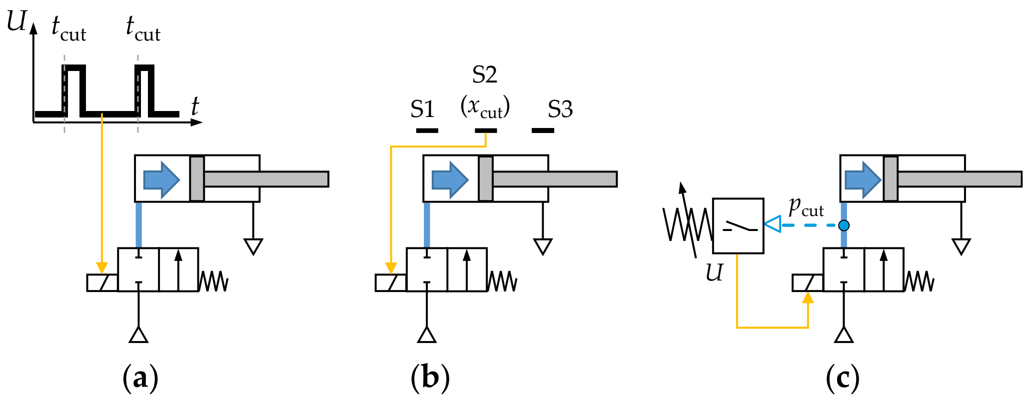


Figure 2. Principles of air supply cut-off: (**a**) time-based; (**b**) position-based; and (**c**) pressure-based.

a. Time-based. This can be considered the most common variant, since no additional proximity or other sensors are required in this case. The cut-off time of the air supply is defined solely by programming the switching (cut-off) time of the directional control valves. Several publications discussed the optimal and automated selection of the cut-off time, demonstrating methods to achieve a 60–80% reduction in air consumption even for well-sized cylinders in some cases [25,26,29,31].
b. Position-based. This principle involves initiating air supply cut-off once the actuator reaches a predefined position, ascertainable through proximity sensors or a distance measuring system. Padovani and Barth considered in their work [32] a cut-off at half of the cylinder stroke for a large range of typical cylinder strokes, reaching air consumption reduction of approx. 70% in each case. Merkelbach and Murrenhoff have analysed the exergy efficiency of a position-based cut-off at 3/4 and 7/8 of an 800 mm cylinder stroke and demonstrated a savings potential of up to 50% [9].
c. Pressure-based. In this case, the air supply is cut off as soon as the pressure in the driving chamber is sufficient to reach the end position of the cylinder. In Yusop's dissertation [33], a mathematical method for determining the minimum pressure necessary for the cut-off via predicting the system's actuation with an actuator model is developed. The effect of this method is compared with a standard pneumatic circuit and an end-stroke cut-off actuation, achieving energy savings of up to 80% and 43.5%, respectively.

Most known research on the topic of pressure-based air supply cut-off deals exclusively with end-stroke cut-off actuation, whose aim is to prevent unnecessary compressed air supply after the piston reaches the stroke end. Reese et al. proposed a novel upstream throttle with an integrated pressure-controlled shut-off function activated towards the end of the stroke [34]. Implementing such a concept requires an additional starting aid, which needs to be integrated into the circuit or the throttle itself.

Another example of this principle is a pressure-controlled 5/3 directional control valve in the patent [35]. The valve design there ensures the valve is locked in its middle position upon completion of the cylinder return stroke, as driven by the pressure in the piston rod side chamber. This prevents unnecessary compressed air supply to the pressure chamber, reducing consumption during the return stroke.

It can be stated that only a few examples of pressure-based supply cut-off are known in the literature. Yusop's dissertation [33] is the only known source where such a cut-off occurs during cylinder motion. However, in his research, a double-rod, double-acting cylinder with a piston diameter of 125 mm was considered moving a mass of 10 kg at an operating pressure of 1.5 and 2.5 bar_{rel} and with a piston extension time of approx. 1.4 s. As described in Section 2, this cylinder was consequently highly oversized for the task, making it simple to achieve significant energy savings without any performance loss in comparison to standard pneumatic circuits.

The motivation for this article is therefore to present an energy-saving circuit with a pressure-based cut-off during cylinder movement and to evaluate its savings potential and its impact on performance in well-sized and oversized cylinders using the example of a single-rod, double-acting cylinder, which is more common in modern pneumatic systems. In contrast to the systems described in [33–35], in which the air supply cut-off occurs only once per stroke, this study considers a system with a multiple-time cut-off during the movement.

2. Definition of Example Drive Tasks

In the following, the proposed pressure-based cut-off circuit is to be examined using the example of two specific drive tasks and compared with the standard circuit.

For the demand-oriented dimensioning of a pneumatic cylinder for a defined drive task, the eigenfrequency-based approach presented in [36] is used here. The basic principle of this approach is to evaluate the pneumatic frequency ratio (PFR) Ω between the theoretically possible dynamics of an actuator (expressed via the frequency Ω_0) and the system dynamics required by the actuator task (frequency Ω_f) according to Equation (1):

$$\Omega = \frac{\Omega_0}{\Omega_f} = \frac{t_S}{2 \cdot \pi} \cdot \sqrt{\frac{c}{m}}, \tag{1}$$

where t_S is the stroke time (extension or retraction), c the air spring stiffness, and m the moving mass. In this way, the cylinder is regarded as a mass restrained between two springs, the stiffness of which is defined by the compressed air contained in both chambers. The exact definition of this stiffness is provided, for example, in [37]. Subsequently, the total stiffness of a single-rod pneumatic cylinder can be expressed as follows:

$$c = \frac{A_A^2 \cdot n \cdot p}{V_A + V_d + V_t} + \frac{A_B^2 \cdot n \cdot p}{V_B + V_d + V_t}, \tag{2}$$

where A_A and A_B are the piston area and the work area on the rod side, respectively, n the polytropic index, p the supply pressure, V_A and V_B the chamber volume in the middle cylinder position for chamber A and B, respectively, stroke time (extraction or retraction), V_d the cylinder dead volume (assumed equal for the piston and rod chamber), and V_t the tubing volume (assumed equal for the piston and rod chamber).

According to [36], well-dimensioned cylinders have a PFR within the range of Ω = 1.1…1.7. Pneumatic cylinders with PFR values above this range are considered to be oversized, whereas PFR values below 1.1 correspond to under-dimensioned cylinders, for which, e.g., external hydraulic shock absorbers would be needed. In comparison, the cylinder presented in [33] would have a PFR of Ω = 17.6 for the task parameters defined there and is therefore highly oversized.

For this study, two drive tasks with practice-oriented PFR values are defined according to Table 1, for both of which a pneumatic cylinder DSNU-32-200-PPV-A with the piston diameter D = 32 mm, rod diameter d = 12 mm, and a tube PUN-8 with the inner diameter $d_{t,inn}$ = 5.5 mm is chosen. With this cylinder, both tasks can be fulfilled. The only difference between them is the moving mass, which is significantly lower in Task 1, making the chosen cylinder oversized for it. In the case of Task 2, the cylinder can be considered as well-sized for the defined task parameters.

Table 1. Drive task requirements.

Parameter	Task 1 (Oversized)	Task 2 (Well-Sized)
Supply pressure p (bar_{abs})	7	
Stroke h (mm)	200	
Additional external force F_{ext} (N)	0 *	
Valve–cylinder distance l_{vc} (m)	0.5	
Extension time t_e (s)	0.30 ± 0.02	
Retraction time t_r (s)	0.33 ± 0.02	
Moving mass m (kg)	3	12
PFR, extension: Ω_e (-)	2.6	1.3
PFR, retraction: Ω_r (-)	2.8	1.4

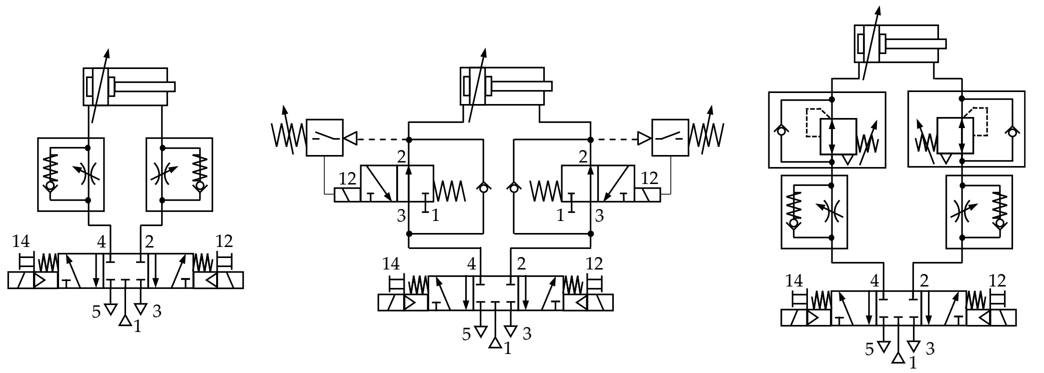
* Friction force only.

3. Simulation and Validation

In a further step, a standard meter-out circuit as well as a cut-off circuit are simulated and measured for the given tasks.

3.1. Circuit Design

In the case of the standard meter-out circuit, two exhaust air throttles GR-QS-8 are chosen for adjusting the velocity of the selected cylinder. A 5/3 directional control valve of type MVH-5/3G-1/4-B is used to change the direction of the movement. The complete pneumatic drive is shown in Figure 3a.



(**a**) (**b**) (**c**)

Figure 3. Standard pneumatic meter-out circuit (**a**) and energy-saving solutions: (**b**) pressure-based air supply cut-off circuit; and (**c**) double-sided pressure regulators.

To implement a pressure-based air supply cut-off by means of standard pneumatic components, the circuit according to Figure 3b is proposed in this article. The cut-off for the respective cylinder chamber is performed by an additional 3/2-way valve between the 5/3-way valve and the cylinder. For this study, two MHE-3 3/2 directional control valves are selected. The electrical cut-off signal for the 3/2 valves is generated by an electropneumatic pressure switch in the respective cylinder chamber (Herion 31 D for the piston-side chamber A and Norgren 18 D for the rod-side chamber B). As can be seen in Figure 3b, the meter-out throttles are completely removed from this circuit, so that the piston velocity is set solely by selecting the appropriate cut-off pressure.

Additionally, the performance and energy efficiency of the proposed cut-off circuit are to be compared with a circuit with pressure reduction on both sides, as shown in Figure 3c, which represents the conventional way of compensating for the oversizing. For this, two pressure regulators VRPA-CM-Q8-E are installed in the standard meter-out circuit between the cylinder and the exhaust throttles.

3.2. Simulation

To prove the suitability of the cylinder and its periphery for the requirements specified in Table 1, a simulation model of the actuator is first created according to the drive structure in Figure 3. In this study, a one-dimensional (lumped parameter) modelling is applied for the description of single components of the pneumatic drive system. The mathematical model is developed in the simulation software SimulationX 4.0 using the existing pneumatics library. To describe the behaviour of the pneumatic cylinder (in particular, the end pneumatic cushioning and the friction force), the model of a standard meter-out pneumatic drive presented in [38] is used. In the model, the friction force is approximated with a modified Stribeck function containing a velocity-dependent and a pressure-dependent component according to Equation (3):

$$F_{fr} = b_0 + b_1 \cdot p_{AB-} + (F_{FS.0} + F_{FS.1} \cdot p_{AB-} - F_{FC}) \cdot e^{\left(-\frac{|\dot{x}|}{v_S}\right)} + (k_{v.0} + k_{v.1} \cdot p_{AB-}) \cdot |\dot{x}|^{\alpha}, \quad (3)$$

where F_{fr} is the total friction force, b_0 and b_1 the friction force biases, $p_{AB-} = |p_A - p_B|$ the differential pressure between chambers A and B, $F_{FS.0}$ and $F_{FS.1}$ the static friction, F_{FC} the Coulomb friction, $\dot{x}$ the piston velocity, v_S the Stribeck velocity, $k_{v.0}$ and $k_{v.1}$ the friction coefficients, and α the velocity exponent.

For the parameterisation of the meter-out and end-cushioning throttles, the approximated conductance functions based on the measurement data provided in [38] are used. The parameterisation of the 3/2 valves, pressure regulators, and pressure switches, which are added to the initial model [38], is carried out with the help of catalogue data.

The main purpose of the simulative investigation for the pressure-based cut-off circuit is to find the appropriate combination of minimum cut-off pressure on both sides at which the travel times required in Table 1 still can be achieved. The lower the cut-off pressure that can be set, the greater the compressed air savings that can be attained.

As a first step, the cut-off pressures p_{cutA} and p_{cutB} on both sides are varied at a fixed sonic conductance value for the end-cushioning throttles. The travel times and the corresponding compressed air consumption are recorded for each combination. Furthermore, it is of utmost importance to determine the impact energy at the stroke end of each cut-off pressure combination. Exceeding the permissible value can lead to increased wear and damage to the cylinder. According to the data sheet of the chosen cylinder DSNU-32-200-PPV-A, the permissible kinetic energy is set at $E_{kin.perm}$ = 0.4 J.

Figure 4 shows exemplarily the results of a cut-off pressure variation in a range between 1.5 and 2.5 bar_{abs} at a fixed sonic conductance of C_{ec} = 7.5 Nl/(min·bar). The dotted area in each diagram represents a combination with the met boundary condition regarding the kinetic energy ($E_{kin} < E_{kin.perm}$). The minimum values of travel time and energy consumption are shown in red.

In the course of the combining process, it has become apparent that the cut-off pressure in the opposite chamber (e.g., pressure p_{cutB} during extension stroke) has no influence on the impact energy of the cylinder piston. With the cut-off pressure in the opposite chamber increasing, the cylinder piston has to overcome an increasingly higher resistance, potentially resulting in higher travel times. However, the increase in the travel time is negligible, as the opposite cylinder chamber is rapidly exhausted of compressed air due to the missing meter-out throttling (flat slope of the isolines in Figure 4). As expected, the decrease in cut-off pressure of Chamber A also leads to reduced energy consumption.

As a second step, the cut-off pressure in the pressurised chamber and the sonic conductance of the end-cushioning on the opposite cylinder side, respectively (e.g., p_{cutA} and C_{ecB} for the extension stroke), are varied. The purpose is to find a combination of cut-off pressure and end-cushioning setting that would allow the cylinder to extend or retract within the minimum time and without exceeding the permissible kinetic energy at the stroke end.

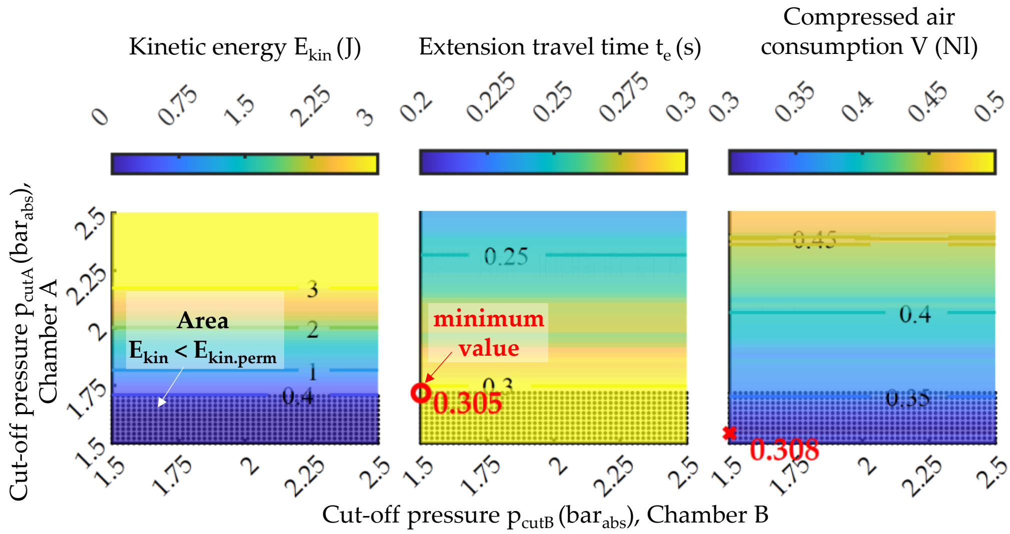


Figure 4. Influence of the cut-off pressure variation in both cylinder chambers on the extension movement at constant end-cushioning throttle opening C_{ec} = 7.5 Nl/(min·bar).

The combination results shown in Figure 5 demonstrate the ability of the circuit to achieve the minimum travel times of t_e = 0.325 s for extension and t_r = 0.337 s for retraction in the case of the oversized cylinder, which corresponds approximately to the desired values specified in Table 1. This allows the pressure to be reduced from p = 7 to approx. 1.7 bar_{abs}, which corresponds to an expected reduction in air consumption of ca. 70% per double stroke.

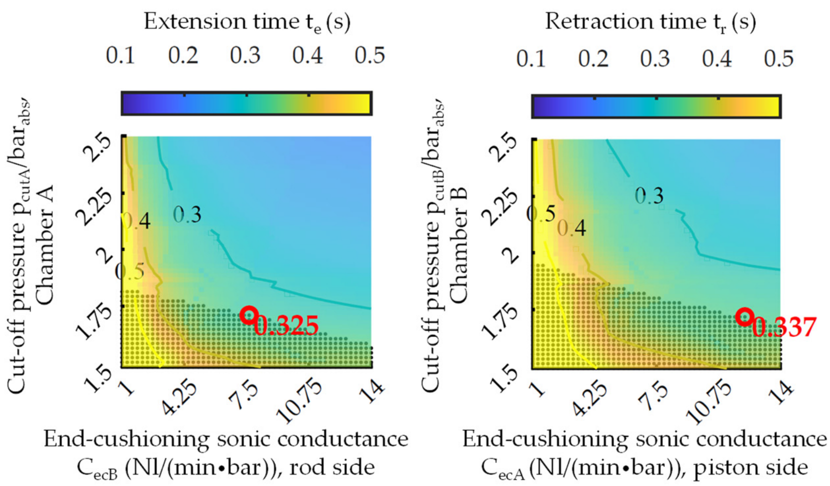


Figure 5. Influence of the cut-off pressure variation and end-cushioning sonic conductance on the travel times of Task 1 (oversized cylinder).

Task 1 represents the lower threshold of oversizing, above which even more significant energy savings are achievable without sacrificing performance. Since exploring further oversized tasks (Ω > 3) would not yield additional insights into the energy-saving potential, additional cases of oversizing are not considered in this context.

With a well-sized cylinder, however, it is not possible to comply with the specified travel times (see Figure 6) due to the lack of exhaust air throttling, without which it is necessary to slow down the cylinder in order not to exceed the permissible kinetic impact energy. The minimum travel times are therefore t_e = 0.640 s and t_r = 0.651 s, which are more than twice the travel times of the reference. Faster travel times are possible in principle but require a higher cut-off pressure and lead to faster wear to the cylinder due to significantly increased impact energy.

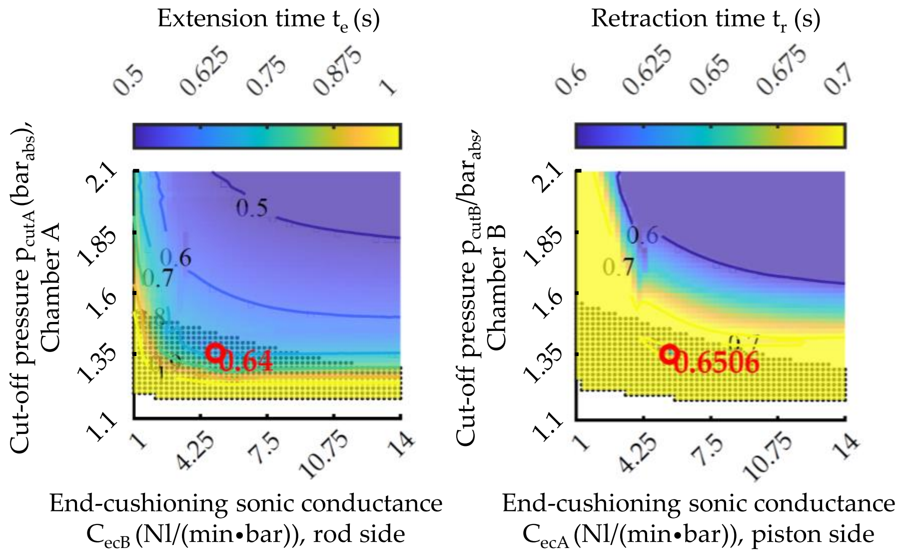


Figure 6. Influence of the cut-off pressure variation and end-cushioning sonic conductance on the travel times of Task 2 (well-sized cylinder).

In a further step, the combinations found are examined and validated via measurement.

3.3. Measurement and Validation

For the measurement, a test rig is designed, as shown in Figure 7. The measuring system contains the position sensor for the cylinder as well as two pressure sensors.

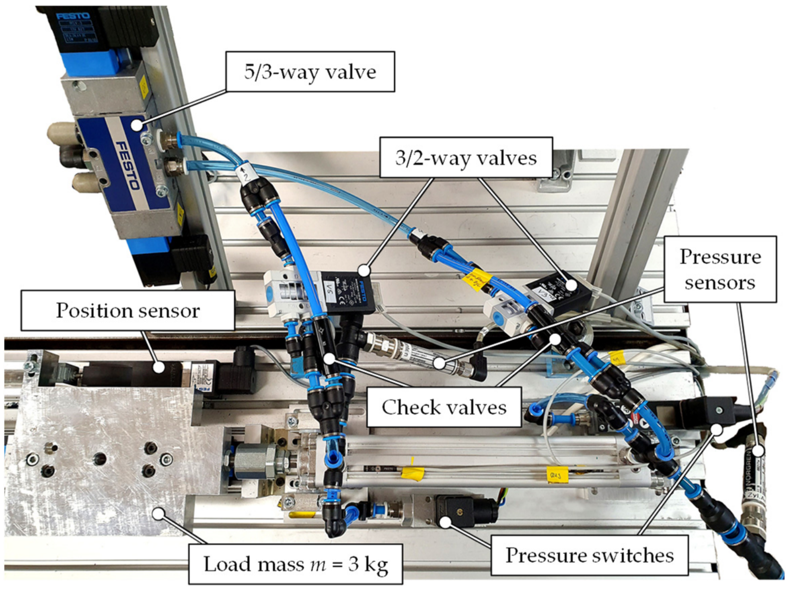


Figure 7. Test rig for pressure-based air supply cut-off.

3.3.1. Task 1: Oversized Cylinder

Figure 8 demonstrates the simulation and measurement results for a double stroke of the oversized cylinder with meter-out throttling, cut-off circuit, and doubled-side pressure regulators shown in Figure 3 during the performance of Task 1 according to Table 1. It can be seen that the measurement results demonstrated good correlation with the simulation, so that the model can be considered validated. The greatest deviations were observed in the dynamic pressure cut-off process of the cut-off circuit due to the complex parameterisation of the pressure switches and their hysteresis. However, this hardly affected the estimation of the travel time.

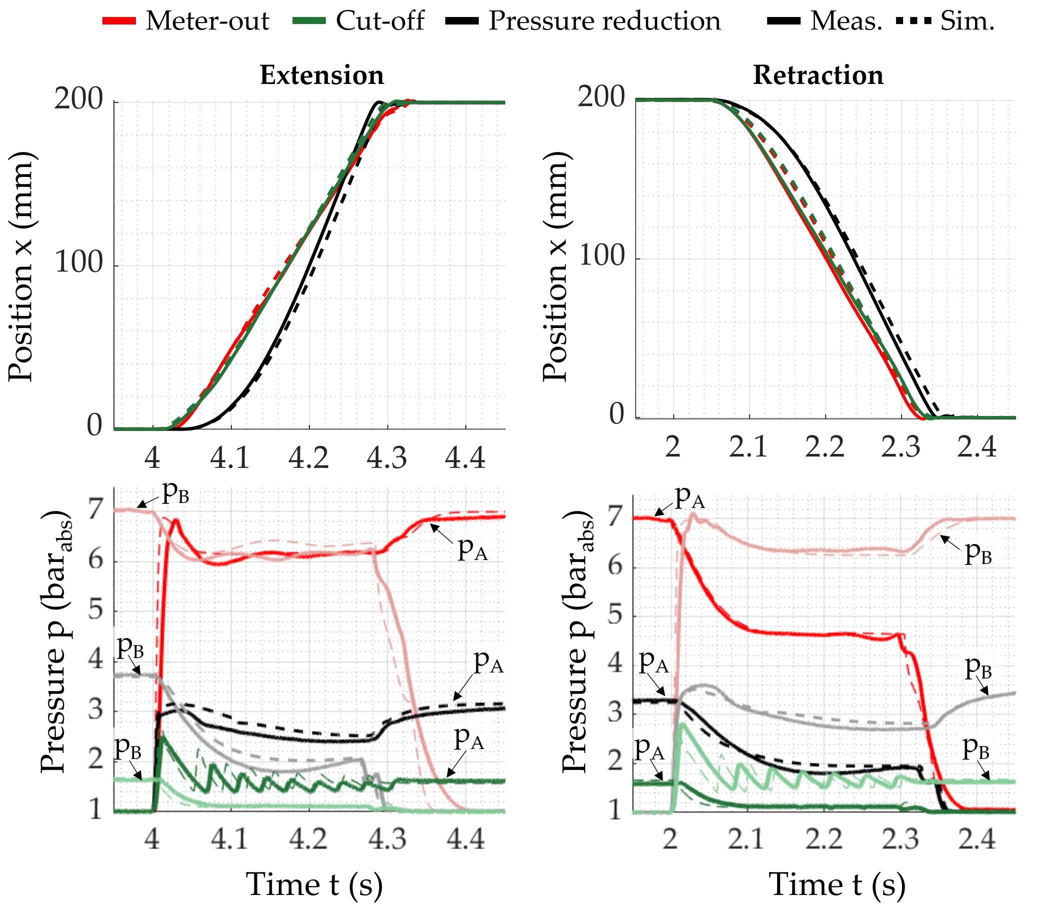


Figure 8. Task 1 (oversized cylinder, load mass m = 3 kg): Simulation and measurement results for the meter-out, cut-off, and pressure-reduction circuit.

As a result of the deviation between the simulation model and the test bench, and due to the inertia and hysteresis of the pressure switches, the set cut-off pressures deviated slightly from the optimum settings determined during the simulation. Table 2 illustrates the values set during the measurement.

Table 2. Cut-off circuit settings for Task 1 for the optimum operating point.

Parameter	Sim.	Meas.
Cut-off pressure $p_{Cut,A}/p_{Cut,B}$ (bar$_{abs}$)	1.72/1.72	1.3…1.4 */1.5
End-cushioning sonic conductance C_{ecB}/C_{ecA} (Nl/(min·bar))	7.6/12.2	7.5/12

* For the pressure switch Herion 31 D, the lower and upper pressure limits must be specified.

As can be observed in the pressure signal of the cut-off circuit in Figure 9, the 3/2-way valve closes as soon as the set cut-off pressure of $p_{Cut} \approx 1.4$ bar$_{abs}$ is exceeded. The inertia of the 3/2-way valves and pressure switches allows the pressure to rise higher than the specified cut-off value. In the closed state of the valve, the supplied air expands as the cylinder piston continues to move and the chamber pressure consequently decreases. On falling below the set pressure p_{Cut}, the 3/2-way valve opens again, allowing further compressed air supply. This process repeats itself several times until the end position is reached, providing the cylinder operation with some similarity to a pulse-width modulation control. However, this behaviour is an inherent feature of the proposed circuit and does not require any special programming.

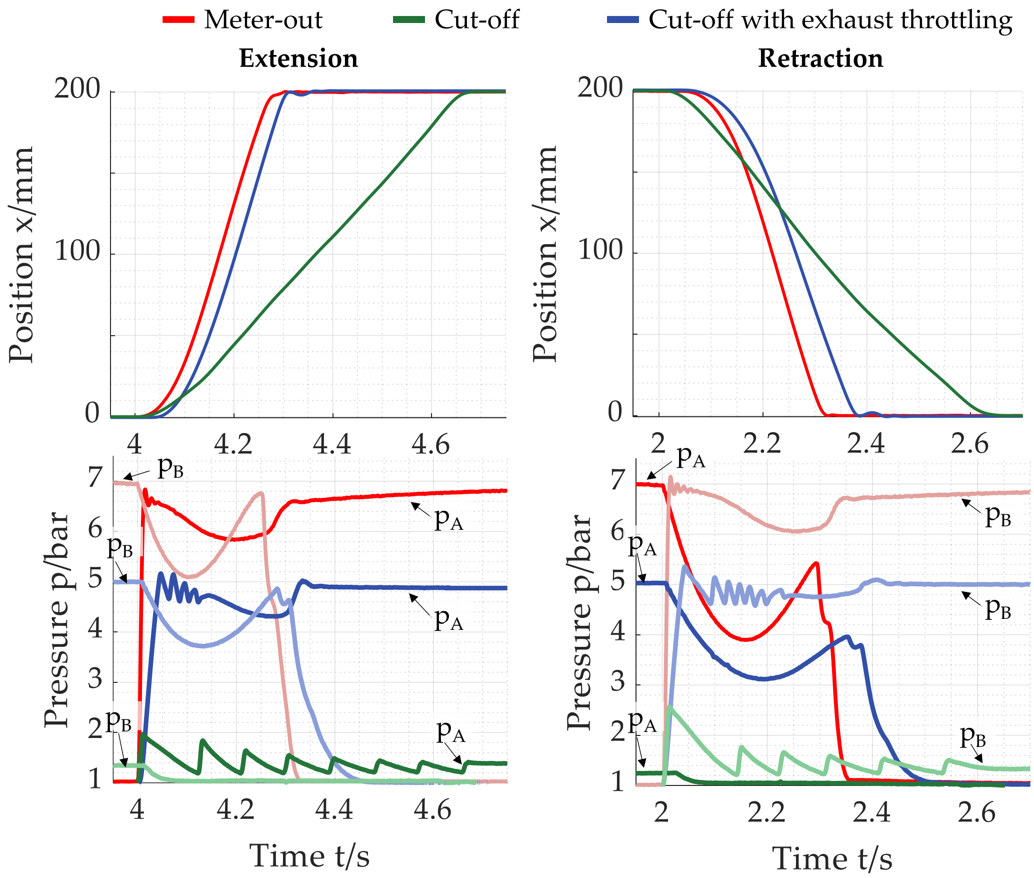


Figure 9. Task 2 (well-sized cylinder, load mass m = 12 kg): Measurement results for meter-out circuit and cut-off circuit with and without additional exhaust throttling.

Table 3 summarizes the performance and energy consumption of the investigated circuits achieved during the measurement. All three circuits were able to achieve the specified travel times within the tolerance range. The pressure reduction circuit exhibited an increased speed in the end positions, which had to be absorbed by the end-cushioning. The cut-off circuit yielded the largest energy saving of 71% compared to the meter-out reference.

Table 3. Performance and energy consumption of the investigated circuits during Task 1.

Measured Parameter	Meter-Out	Cut-Off	Pressure Reduction
Extension time t_e (s)	0.314	0.304	0.310
Retraction time t_r (s)	0.332	0.341	0.365
Air consumption per cycle V (Nl)	2.20	0.64	1.21

3.3.2. Task 2: Well-Sized Cylinder

The simulation conducted in Section 3.2 suggested that the travel times would no longer be met when using the cut-off circuit without exhaust air throttling. The measurements performed with a higher load mass of m = 12 kg and the end-cushioning and cut-off settings that corresponded largely to the simulation (s. Table 4) confirmed the expected slower travel times above which no impact occurs, as can be seen in Figure 9 and Table 5.

To counteract this deterioration in performance, the original cut-off circuit was supplemented with exhaust air throttling on both sides between the cylinder and the 3/2-way valves. Figure 9 also shows the exemplary operating point of the cut-off circuit with exhaust air throttling. This makes higher operating pressures and therefore faster travel times possible, albeit at the expense of energy efficiency.

Table 4. Cut-off circuit settings for Task 2 for the optimum operating point.

Parameter	Sim.	Meas.
Cut-off pressure $p_{Cut,A}/p_{Cut,B}$ (bar_{abs})	1.36/1.36	1.17…1.22 */1.2
End-cushioning sonic conductance C_{ecB}/C_{ecA} (Nl/(min·bar))	4.9/5.5	5/5.5

* For the pressure switch Herion 31 D, the lower and upper pressure limits must be specified.

Table 5. Performance and energy consumption of the investigated circuits during Task 2.

Measured Parameter	Meter-Out	Cut-Off	Cut-Off w. Throttling
Extension time t_e (s)	0.299	0.663	0.354
Retraction time t_r (s)	0.324	0.645	0.432
Air consumption per cycle V (Nl)	2.20	0.58	1.59

As can be seen from the movement trajectory, the braking process of the cut-off circuit with exhaust air throttling poses a challenge: the impact energy cannot be absorbed completely without vibrations. To address this challenge, it is necessary to implement further active braking strategies, such as described in [39]. However, this can further increase the complexity of the circuit.

4. Cost-Effectiveness Assessment

Since the proposed cut-off circuit involves higher acquisition costs compared to standard pneumatics, it is also necessary to assess its payback time. As the use of the cut-off for a well-sized cylinder is not advisable in terms of performance, the TCO evaluation is performed using the example of Task 1. This corresponds to a retrofit of an oversized cylinder with a double-sided pressure reduction or the proposed cut-off circuit.

The assumed acquisition costs (see Table 6) are based on the information provided on the website of Festo SE & Co. KG. Since a valve manifold can simultaneously operate multiple pneumatic drives, its acquisition price is only partially taken into account (1/4 of its total price).

The calculation of the energy costs is based on the following assumptions:

- Number of double strokes (DS) per year: 2000 DS/h × 8 h × 1 shift × 240 days/a = 3,840,000 DS/a
- Compressed air costs: 0.02 €/Nm^3

Table 6. Assumed acquisition costs.

	Standard Circuit/Pressure Reduction			Cut-Off Circuit	
Qty	Item	Price *, EUR	Qty	Item	Price *, EUR
1	Cylinder	114	1	Cylinder	114
2	Flow control valve	27	2	3/2 valve	70
¼	Valve manifold and PLC	397	2	Check valve	32
2	Proximity sensor	36	2	Pressure switch	86
1 m	Tubing	1.5	¼	Valve manifold and PLC	397
	Fittings and silencers	20	2	Proximity sensor	36
	Standard circuit total:	**658.5**	1 m	Tubing	1.5
2	Pressure regulator	53		Fittings and silencers	44
	Pressure reduction total:	**764.5**		**Cut-off circuit total:**	**1004.5**

* Net price per item without discount.

All the other TCO-components, such as shipping, commissioning, maintenance and dismounting costs, are neglected for the comparison, as these can be assumed to be approximately identical for all the circuits.

As shown in Figure 10, the payback time of the cut-off circuit for the considered operating conditions is around 1.9 years. Based on a Germany-wide automation industry survey [40], the reasonable payback period for energy-saving solutions can be assumed to be 2.5 years. Consequently, both energy-saving solutions appear acceptable in terms of the payback time. Moreover, considering that the assumed compressed air costs are in the lower price range (0.02. . .0.03 EUR/Nm^3 according to current industry experience), the cut-off circuit could achieve overall faster amortisation.

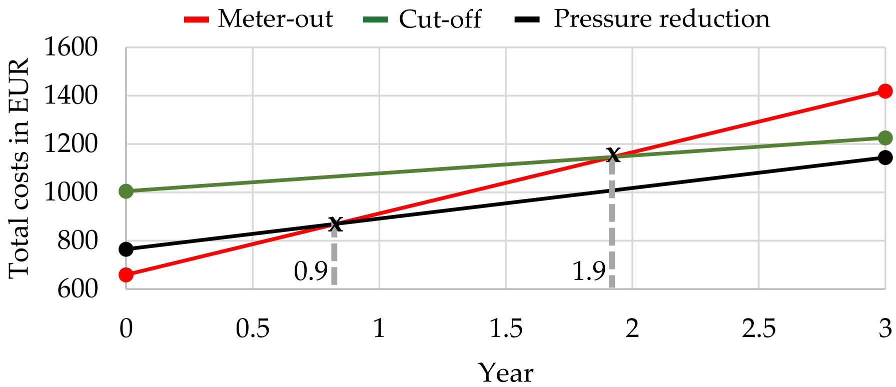


Figure 10. Total cost development and amortisation of the energy-saving circuits for Task 1.

5. Discussion

In this paper, a novel principle for a pressure-based air supply cut-off during cylinder movement was considered. Contrary to previous work [33], the investigation explored both a well-dimensioned and an oversized single-rod cylinder, thus covering a broader spectrum of industry-relevant scenarios. Another distinctive feature compared to [33–35] was the implementation of multiple cut-offs during the stroke. Furthermore, the theoretical payback time of the proposed circuit has been evaluated.

Using a selected example, it was demonstrated that the circuit is particularly suitable for compensating for the oversizing of cylinders by reducing the compressed air consumption by 71% while maintaining the same performance. Compared to a classic double-sided pressure reduction with the same travel times, which has achieved energy saving of 45%, more energy could therefore be saved. In the case of greater oversizing ($\Omega > 3$), even higher savings are achievable.

Higher acquisition costs for the cut-off circuit lead to a longer amortisation period (1.9 years compared to 0.9 for pressure reduction), which, however, is still acceptable according to the current findings [40] and can be shortened via mass production and integrating corresponding components. If designed as a single component containing a shut-off valve, a pressure switch and a check valve, the cut-off circuit can be simply adjusted mechanically similar to a conventional pressure reduction valve, resulting in a significantly lower price. Additionally, the energy costs and the number of double strokes per hour in the economic calculation provided in Section 4 were set comparatively low so that the economic situation presented corresponded to an unfavourable scenario. Higher stroke rates and energy costs would significantly shorten the amortisation period.

In the case of an already well-sized cylinder, the circuit has shown itself unsuitable for reducing the energy consumption, leading either to a significant deterioration in its travel times or to a significant excess of its impact energy. This, in turn, results in faster cylinder wear. The reason for this is the reduced back pressure during the movement of the cylinder due to the absence of exhaust air throttling. As a result, there is not enough energy available to slow down the accelerated load mass properly. Traditional exhaust air throttling in the form of throttle valves on both sides only provides a limited solution. The potential for improving the application of this circuit therefore lies in enhancing the braking behaviour, e.g., by introducing an active braking process similar to [39]. Another negative aspect of the multiple cut-off is the potentially faster wear of the 3/2-way cut-off valves through the increased switching times.

6. Conclusions

Overall, in its present configuration, the proposed circuit can be directly applied for retrofitting an oversized cylinder in the context of a typical motion task. Compared to other cut-off principles, such as time- or position-based cut-off, the considered pressure-based principle is potentially easier to commission, especially if designed as a single component, as proposed above. It does not require any additional control signals, such as the switch-off time or position of the intermediate proximity sensor, which are needed to be implemented in the PLC programme. However, the greater setting flexibility of the time-based cut-off due to the separate actuation of the valve control edges proposed in [25–30], which allows for improving the cylinder damping and its safe application also for well-sized cylinders, is not to be denied.

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