Implementation and Experimental Validation of a Time-Controlled Quick-Exhaust for Downstream Throttled Pneumatic Drives

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Downstream-throttled pneumatic cylinders are frequently utilized as actuators for motion tasks due to their cost-effectiveness, durability, and robustness. However, they are often regarded as energy-inefficient. This paper presents a novel approach to enhance efficiency by focusing solely on controlling the exhaust air. The proposed system utilizes a time-controlled pneumatic-mechanical quick-exhaust valve, which allows high acceleration at the start of the stroke and subsequent deceleration via conventional downstream throttling. Building on a previous lumped-parameter simulation study, this work details the technical implementation of the concept and provides experimental results that assess its performance and robustness. Comparative tests with a conventional downstream-throttled system demonstrate that the cylinder can be downsized by at least one size, thereby substantially reducing air consumption. However, this improvement comes at the cost of reduced robustness, which necessitates further investigation. The paper covers the entire development process from the initial concept, over the component design, robustness studies and improvements up to a final experimental validation of its dynamic behaviour and compressed air savings in direct comparison to a conventional downstream-throttled drive.

Keywords:
pneumatics,
pneumatic cylinder,
energy efficiency,
energy-saving circuit,
exhaust control

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1 Introduction and state of the art

Pneumatic drives are widely utilized in industrial automation for point-to-point motions due to their simplicity, reliability, cost-effectiveness, and high power density [2]. Their operation relies on the pressure differential between the supply pressure acting on the active chamber and the back-pressure in the passive chamber. Typically, this back-pressure is regulated using downstream throttling (DT) to control the actuator's movement. However, downstream throttled systems are often considered inefficient because they consume the maximum amount of compressed air regardless of the load conditions [3].

Research on improving the efficiency of pneumatic cylinders can be divided into three categories: (1) design and parametric measures, (2) energy saving circuits (ESC), and (3) energy-saving systems [4]. The first category includes methods to optimize design and operating parameters, such as using different pressure levels for the extension and retraction stroke, reducing dead volume, and ensuring proper cylinder dimensioning. A well-known heuristic dimensioning approach by Doll et al. [5] compares a cylinder's eigenfrequency ω_0 to the required dynamics ω_f, thereby defining the *pneumatic frequency ratio* $\Omega = \omega_f/\omega_0$. An actuator is considered well-dimensioned if the pneumatic frequency ratio is between 1.1 and 1.7 [5].

ESCs enhance the efficiency by modifying the system structure for a specific load case [6]. Modifications may be upstream (e.g., early air shut-off via a 5/3 valve [7]) or downstream (e.g., storing exhaust air [8]). Recent research emphasizes combining upstream and downstream measures, such as the *combined throttling approach* [9], the *cross-flow circuit* [10] or the more complex *3-phase movement circuit* by Krytikov et al. [11] [12], which subdivides the motion into acceleration, deceleration with exhaust feedback, and fixation. The third category comprises mostly digitized energy-saving systems (e.g., a five-valve bridge circuit [13]) that offer both flexibility and efficiency for a variety of load cases [14].

Reese et al. [9] have developed a metric for evaluating the efficiency of ESCs. This metric involves comparing the consumed air mass and achieved cycle time of the ESC with the theoretical result of a well-dimensioned downstream throttled system performing the same motion task [9]. The normalized air saving $\Delta m_{\mathrm{norm},x}$ of system x is calculated by

$$\Delta m_{\text{norm},x} = 1 - \left(\frac{m_{\text{air},x}}{m_{\text{air},DT}}\right) \cdot \left(\frac{t_{\text{Cycle},x}}{t_{\text{Cycle},DT}}\right)^2, \tag{1}$$

with m_{air} denoting the air mass consumption and t_{Cycle} the cycle time. Finally, the relative compressed air saving $\Delta m_{\text{rel},x}$ can be expressed as a function of the relative increase in cycle time $\Delta t_{\text{rel},x}$ and the normalized air saving:

$$\Delta m_{\text{rel},x}(\Delta t_{\text{rel},x}, \Delta m_{\text{norm},x}) = \frac{m_{\text{air},DT} - m_{\text{air},x}}{m_{\text{air},DT}} = 1 - \frac{1 - \Delta m_{\text{norm},x}}{(\Delta t_{\text{rel},x} + 1)^2} \tag{2}$$

Building upon the relationship between air consumption and cycle time, Reinertz et al. [1] developed a novel pneumatic-mechanical ESC to enhance the efficiency of pneumatic drives. Their approach focuses on reducing the cycle time of downstream throttled pneumatic drives, while keeping the component and commissioning expenses low [1]. By reducing the cycle time, the reciprocal quadratic relationship between air consumption and cycle time is exploited. In contrast to the conventional downstream throttled system, the novel system is extended by a switchable quick-exhaust (SQE) valve to initially increase the cylinder velocity. The SQE valve remains active during the initial and mid-part of the stroke, after which it is deactivated, allowing the exhaust air to flow solely through a downstream throttle arranged in parallel. This transition ensures that the cylinder speed is decreased by the downstream throttle, effectively preventing overloading the pneumatic end-cushion. This sequence is comparable to the movement phases of the *3-Phase Movement Circuit*. Compared to the *3-Phase Movement Circuit*, the novel system has two key differences: (1) The SQE valve is a purely pneumatic-mechanical component, which reduces the commissioning and control effort and (2) it focuses solely on the downstream, which is simpler and reduces installation space. In a preliminary feasibility study using a lumped parameter simulation, Reinertz et al. [1] showed that the cylinder can be downsized by at least one size with the novel system. However, they emphasized the necessity of experimental validation to confirm the concept's effectiveness.

This work aims to bridge this gap by providing technical implementation details and presenting experimental results of the novel system. The following sections are organized as follows: Section 2 describes the technical implementation of the proposed approach, Section 3 discusses the experimental setup and procedures, and

Section 4 presents the experimental results. Finally, Section 5 concludes this work and provides an outlook for future work.

2 Switchable quick-exhaust valve

Quick-exhaust valves provide a straightforward measure to enhance the velocity of pneumatic drives by reducing the back-pressure [15]. However, the integration of these valves must be managed carefully to prevent overloading the pneumatic end cushion. Excessive velocities or very low back-pressures can overload the end cushion, potentially causing damage to components or the load.

Rager et al. [16] investigated the energy-optimal operation of a pneumatic cylinder using a bridge circuit with an adaptive open-loop control. The findings of the study suggest that the energy-optimal trajectory is a sequence of an acceleration phase and a braking phase to reduce the cylinder velocity before it reaches the end cushion [16].

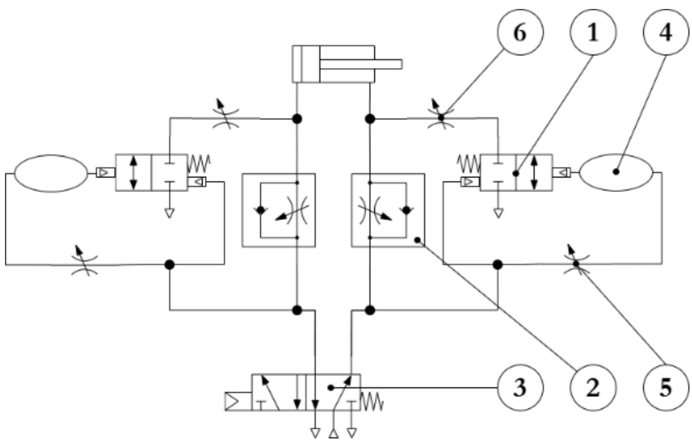

Figure 1: Schematic representation of the technical implementation of a downstream throttled actuator with a switchable quick-exhaust valve.
Source: own

This understanding of sequential acceleration and deceleration to protect the end cushion forms the foundation of a novel performance-enhancing approach involving the use of SQE valves. As described in patent DE102023104570B3 [17], this concept is realized by implementing SQE valves in parallel with the conventional downstream throttles used for deceleration. As a result, the air in the passive cylinder chamber can be exhausted more rapidly through the low-resistance path of the open SQE valve, in contrast to the downstream throttle, thereby preventing the high back-pressure that would otherwise slow down the cylinder movement. A schematic representation of this advanced system is shown in Figure 1, and its method of operation is elaborated below.

The quick-exhaust (see Figure 1) is achieved by switching the SQE valve (1), arranged in parallel with the downstream throttle (2). The switching is based on the pressure drop in the pneumatic line that connects the downstream throttle of the cylinder to its directional control valve (3). When the direction of motion is reversed, i.e., when the active and passive chambers are switched, the pressure in this line suddenly drops. This pressure gradient is detected by comparing the line pressure with the pressure in a pneumatically damped dead volume (4). If a sufficient pressure difference arises due to a rapid pressure drop in the line, an additional cross-section is opened for venting the passive chamber. The parallel venting via the exhaust throttle and additional cross-section results in the desired quick-exhaust. The dead volume of the SQE valve is connected to the line via an adjustable throttle (5) so that the pressure in the dead volume follows the line pressure with a defined delay. The size of the dead volume, the cross-section of the damping throttle, and a minimum differential pressure specified by spring pressure for opening the SQE valve determine the duration of the quick-exhaust purely pneumatically and mechanically. To enable the utilization of the valve with varying cylinder sizes, the initial design was modified using an additional throttle (6) that defines the resistance of the quick-exhaust path compared to the downstream resistance.

Standard pneumatic components were utilized for the technical implementation of the SQE valve and the associated circuit, as illustrated in Figure 2. The circuit is connected to the cylinder via an adapter (7), which, in addition to the downstream throttle (2) and the throttle for controlling the quick-exhaust (6) (not mounted in the figure), also includes a pressure sensor (8) for measuring the chamber pressure. The actual SQE valve is designed as a low-friction, pneumatically actuated 5/2 directional control valve. One of the end caps has been replaced by a specially manufactured cap containing a spring that acts on the valve spool.

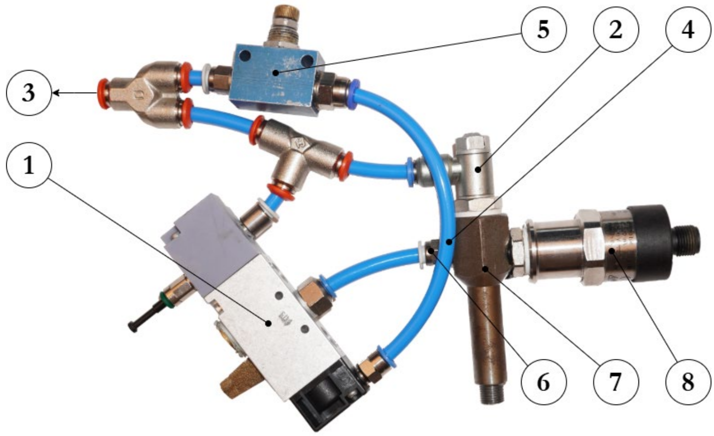

Figure 2: Technical implementation of the switchable quick-exhaust valve.
Source: own

3 Experimental setup

The novel system, described in Section 2, was experimentally investigated using a test rig for pneumatic cylinders. The test bench, which is described in detail in [9], enables the systematic study of various efficiency-enhancing concepts by measuring the cylinder dynamics under adjustable operating conditions. In addition to other measured variables, the cylinder position, the pressure in the cylinder chambers, and the air mass consumption are recorded. Using this setup, two distinct series of measurements were conducted: (1) to compare the novel system's performance with a conventionally downstream throttled system, and (2) to assess the robustness of the novel system with respect to the length of the pneumatic lines, which connect the directional control valve and the cylinder.

3.1 Measurement of the system performance

In the first series of measurements, the performance of the two systems was evaluated performing various movement tasks using different cylinder sizes. The air mass consumption of the novel system is normalized using Equation 1 to enable a direct comparison of its efficiency with the conventional system. Before data acquisition, each system is optimally adjusted to the motion task, so the cylinder has a minimum movement time without overloading the pneumatic end cushion. Ideally, the impact velocity at the end of the stroke is zero.

To ensure accurate results, 55 cycles are recorded for each load case. The initial three cycles and the last two cycles are excluded from evaluation to ensure stable dynamic behavior. The supply pressure is set to 7 bar_{abs}, and the pneumatic line between the 5/2 directional control valve and the cylinder measures 1 m in length with an internal diameter of 4 mm. The investigated cylinders have a diameter of 20, 25, and 32 mm, a length of 0.2, 0.32, and 0.5 m, and a moving mass of 10 and 15 kg. This results in a total of 18 load cases investigated.

To contextualize these findings in existing research, a comparison is made with measurement results from a study by Boyko et al [6]. In this study, the ESCs *supply air cut-off*, *short circuit*, and *3-phase circuit* are examined for cylinders with a diameter of 32 and 50 mm and a length of 0.2 m. For comparison with the novel system, the load case of a well-dimensioned cylinder without additional external forces is utilized. The calculation of the relative cycle time $\Delta t_{\mathrm{rel},x}$ is determined by the relative moving time of the extension $\Delta t_{\mathrm{rel},e}$ and retraction strokes $\Delta t_{\mathrm{rel},r}$ and the respective pneumatic frequency ratio, as shown in Equation 3.

$$\Delta t_{\mathrm{rel},x} = 1 + \left(\Delta t_{\mathrm{rel},e} - 1\right) \cdot \frac{\Omega_e}{\Omega_e + \Omega_r} + +(\Delta t_{\mathrm{rel},r} - 1) \cdot \frac{\Omega_r}{\Omega_e + \Omega_r} \quad (3)$$

3.2 Measurement of the system robustness

In the second series of measurements, the robustness of the novel and conventional system regarding the length of the pneumatic line between the cylinder and the controlling directional control valve was investigated. To this end, both systems were optimally adjusted for pneumatic line lengths of 1 m, 4 m, and 6 m, using a cylinder with a piston diameter of 25 mm, a length of 0.5 m and a moving mass of 10 kg. Subsequently, the velocity profile of 55 cycles was recorded. In this series, we investigated how varying the line length affects the SQE valve's switching behavior by installing two additional pressure sensors on each SQE valve to measure the pressure on both sides of the valve spool.

4 Results and discussion

Figure 3 depicts the dynamic behavior of a cylinder with a piston diameter of 25 mm, a length of 0.32 m, and a moving mass of 10 kg under both SQE valve and DT configurations. The SQE valve allows faster air exhaust at the beginning of the movement followed by a deceleration through downstream throttling. As shown by the pressure curves, the back-pressure in the system equipped with SQE valves is substantially lower than in the system with DT. Correspondingly, the velocity curve indicates higher acceleration and greater maximum velocity in the novel system.

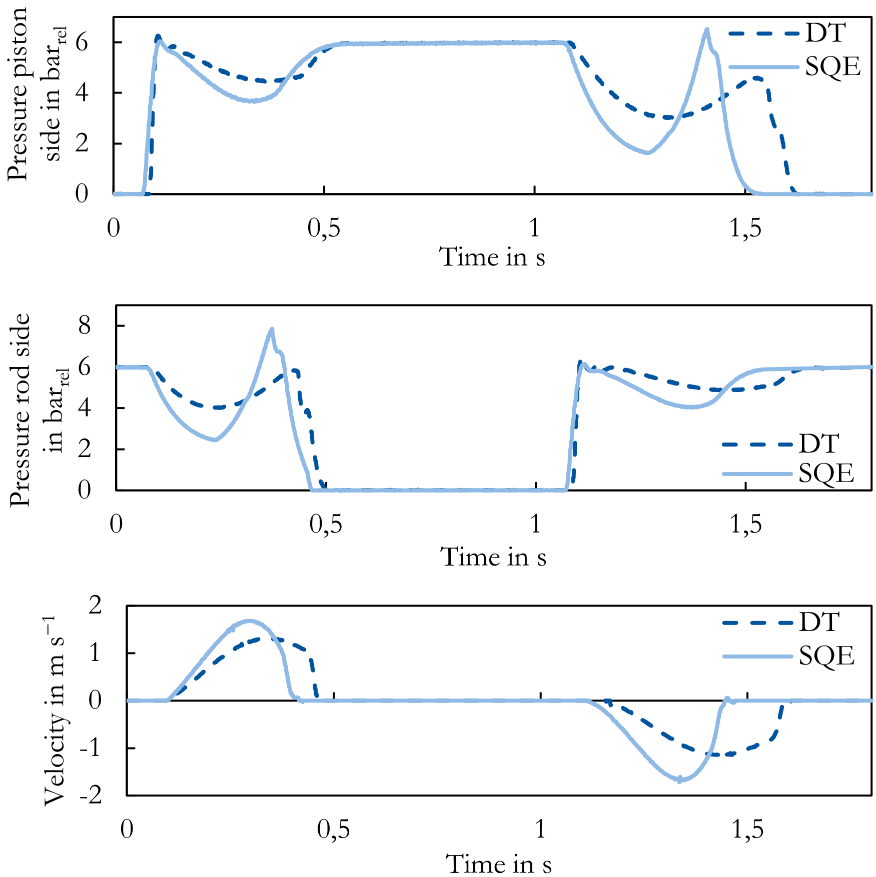

Figure 3: Experimental results of an actuator with a diameter of 25 mm, a stroke length of 0.32 m and a moving mass of 10 kg using downstream throttling (DT) and a switchable quick-exhaust (SQE).

Source: own

The switching point of the SQE valve is discernible in the pressure curve by the rising back-pressure. This increased back-pressure not only decelerates the cylinder but also enhances the capacity of the pneumatic end cushion. Consequently, even though the cylinder enters the end cushion with a higher velocity, it still decelerates sufficiently to keep the final impact velocity at a minimum level. As a result, implementing the SQE valve significantly shortens the cycle time from 0.94 to 0.78 s. Although most of the time reduction originates from the increased velocity during movement, the faster exhaust of the passive chamber also diminishes the delay time caused by the pressure adaption during retraction of a differential cylinder, as described by Reinertz et al. [3]

4.1 System performance

The measured movement times of the cylinders equipped with an SQE valve and a moving mass of 10 kg are summarized in Figure 4. In addition, the quick-exhaust duration is shown. For comparison, the movement time of the DT system is included. Two general trends apply to both systems: first, movement time typically decreases with increasing piston area, and second, the extension stroke usually finishes faster than the retraction stroke because of the smaller piston surface in the rod-side chamber. It can also be observed that movement time increases with cylinder length, as traveling a longer distance without a higher acceleration naturally prolongs the stroke.

As seen in Figure 4, all cylinders equipped with the SQE valve exhibit significantly shorter movement times than those operating with DT. This performance gap widens with the cylinder length. The effect of piston diameter on the SQE valve dynamic is more subtle. Its impact becomes clearer when focusing on how long the quick-exhaust valve remains open. In most of the cases considered, the proportion of the quick-exhaust time ranges from 40 to 60 % of the movement time. For a cylinder diameter of 32 mm, the proportion of time spent with the SQE valve open can exceed 80 % of the stroke for cylinder lengths of 0.32 m and 0.5 m. This phenomenon arises because the same SQE demonstrator was tested for every cylinder. When the SQE valve is undersized relative to a large piston area or long cylinders, the cylinder effectively experiences some additional back-pressure during the quick-exhaust phase. This back pressure decelerates the movement, allowing the valve to remain open for a longer duration without overloading the end cushion.

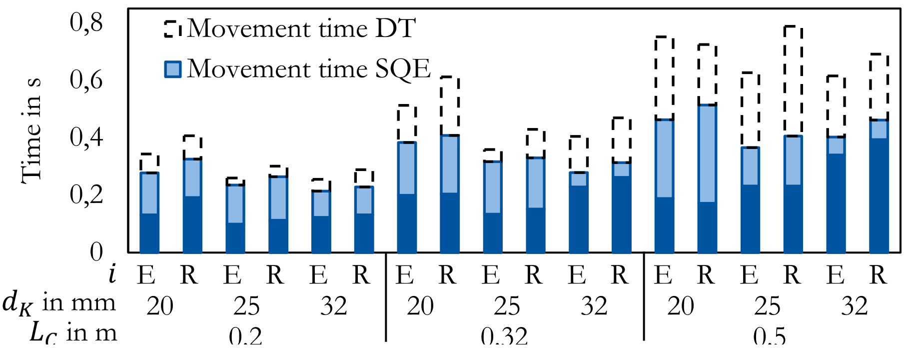

Figure 4: Movement time and quick-exhaust time of cylinders with different piston diameters d_K and cylinder lengths L_C, equipped with a switchable quick-exhaust (SQE) valve and a moving mass of 10 kg. The index i denotes the extension stroke ($i = E$) or the retraction stroke ($i = R$).

Source: own

Figure 4 shows for example, that a cylinder measuring 0.2 m in length and 32 mm in diameter can be downsized by one size yet maintain the same cycle time if SQE valves are used. For the cylinders with the lengths 0.32 and 0.5 m, the piston diameter can be reduced by at least two sizes under the same supply pressure without sacrificing performance. Smaller cylinder dimensions are advantageous because they substantially lower both acquisition costs and air consumption. Although increasing the moving mass to 15 kg prolongs the cycle time because of greater inertia, the overall difference in performance between DT and SQE configuration is similar to that observed at 10 kg.

As the cylinder length increases, the air consumption per cycle increases as well for both the DT and SQE system. However, cylinders equipped with SQE valves exhibit a slightly higher consumption due to the presence of supplementary components, which introduces additional dead volume. However, given the reduced cycle time of the novel system, there is a strong reduction in normalized air consumption. For cylinders with a length of 0.2 m, the advantage is negligible; however, as the cylinder length increases, the discrepancy in air consumption between the two systems becomes more evident. It is noteworthy that the moving mass exerts minimal influence on these efficiency gains, also comparable trends are observed for every piston diameter that was investigated.

Equation 2 is employed to calculate isolines corresponding to constant normalized air savings. These isolines, depicted in Figure 5, provide a framework for comparing the two systems. The isoline marked with zero represents no efficiency gain or loss relative to DT. Operating points to the left indicate enhanced efficiency, while those to the right reflect a decrease.

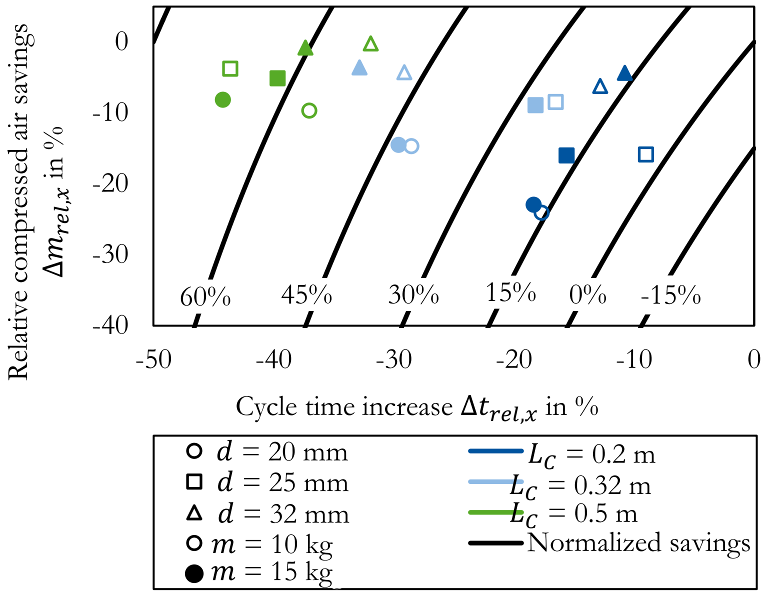

Figure 5: Efficiency map of a cylinder with a piston diameter of d, a length of L_C and a moving massof m.

Source: own

Figure 5 demonstrates that the SQE valve yields higher efficiency throughout the tested parameter space. While the normalized air savings of cylinders with a length of 0.2 m are the lowest, with values ranging from 0 to 30 %, cylinders with a length of 0.5 m demonstrate the highest normalized air savings, ranging from 45 to 75 %. The moving mass has minimal influence on these results, as nearly identical trends emerge regardless of the mass.

Also, the piston diameter does not significantly affect the improvement of energy-efficiency. Despite the fact that the SQE valve is undersized for the cylinder with a diameter of 32 mm, the efficiency gains remain comparable to those obtained with other piston diameters investigated. Notably, for 0.32 m cylinder lengths, the energy-efficiency enhancement is even higher than that of smaller diameters, suggesting that an extended quick-exhaust phase compensates for an undersized valve.

A comparison of the normalized air savings achieved using the SQE valve with the results of other ESCs shows that the normalized air savings are in a medium range when only comparing cylinders with a length of 0.2 m. The novel system demonstrates superior efficiency in comparison to the short circuit, attaining results that are analogous to the supply air cut-off circuit within the range of 0 to 30 %. The 3-phase circuit exhibits a substantially higher degree of air savings in comparison with the novel system, at approximately 75 %. However, the novel system demonstrates comparable values when utilizing longer cylinders. Due to the absence of data concerning the other ESCs, the competitive dynamics of the circuits at extended cylinder lengths remain uncertain.

Compared to other ESCs, especially the 3-phase circuit, the novel system exhibits reduced commissioning and control effort, as well as lower component costs. These results underscore the system's viability while highlighting the need for further research to refine the SQE valve design and perform a more extensive study comparing different ESCs.

4.2 System robustness

Downstream throttled systems can be operated under various operating conditions, due to their robustness. Consequently, the second series of measurements investigated the impact of the pneumatic line length on the switching behavior of the SQE valves, thereby assessing the robustness of the novel system. Figure 6 illustrates the velocity curves of the extension stroke resulting from different pneumatic line lengths for a cylinder with a piston diameter of 25 mm, a length of 0.5 m and a moving mass of 10 kg.

As illustrated in the Figure 6, the length of the pneumatic line exerts a comparable influence on the dead time of both systems. However, a clear distinction emerges when comparing the movement time of both systems. With pneumatic lines of 1 m length, the maximum velocity of the system equipped with SQE valves is shown to be approximately double the maximum velocity of the downstream throttled system, while maintaining a low impact velocity at the end of the stroke. The movement time decreases from approximately 0.68 s to 0.40 s by using the SQE-valves in this case. Increasing the length of the pneumatic lines results in a substantial reduction in maximum velocity of the novel system. Consequently, the movement time is prolonged to 0.57 s at a length of 4 m and 0.55 s at a length of 6 m. In contrast, the DT system's movement time changes only minimally. Because of an unstable swtiching behavior of the SQE valves at 6 m line length, no optimal cylinder setting was found. The only possible setting lead to an increased impact velocity, visible as oscillations at the stroke end.

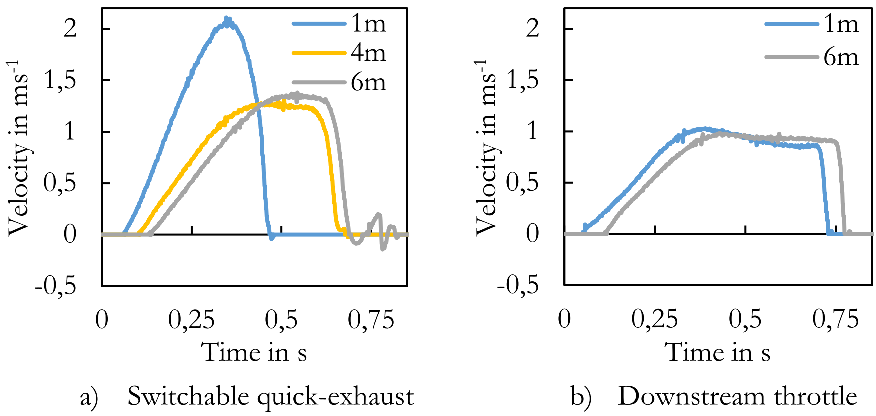

Figure 6:Cylinder velocity with varying pneumatic line lengths.
Source: own

Figure 7 illustrates the pressure difference between the two pressure signals of the SQE valve for the three investigated line lengths. Additionally, the switching point in time and the gradient of the pressure difference is shown for each curve. The figure shows the underlying rationale for the challenging adjustment with longer pneumatic lines. Longer lines result in a slower decline of the pressure in the line. To ensure an opening of the SQE valve, it is necessary to reduce the cross-section of the time controlling throttle, thereby ensuring that the pressure in the dead volume lags the pressure in the pipe. However, this results in a prolonged duration of the quick-exhaust. To avoid overloading the end cushion, the cross-section of both the downstream throttle (number 2 in Figure 2) and the quick-exhaust path (number 6 in Figure 2) must be reduced, which in turn lowers the maximum velocity.

Another negative effect of longer pneumatic lines is the lowered gradient of the pressure difference during the switching point. The greater the gradient, the more reliable the valve switches. However, given the necessity of lowering the cross-section of the time controlling throttle with extended lines, the gradient experiences a decline, as illustrated in Figure 7. This results in a more unstable switching behaviour.

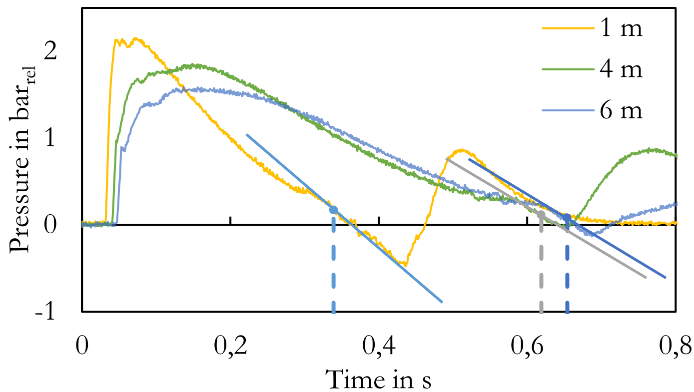

Figure 7: Pressure difference between the switching signals of the switchable quick-exhaust valve for different pneumatic line lengths.
Source: own

In summary, while performance benefits remain measurable even with extended pneumatic lines, the system's robustness is lower than that of a conventional downstream-throttled system.

5 Conclusion and Outlook

This work presents experimental results for a novel approach aimed at improving the dynamic performance of downstream-throttled pneumatic drives. By employing SQE valves as a pneumatic-mechanical solution, the system achieves lower cycle times. This reduction in cycle time is significant due to the relationship between cycle time and air consumption in pneumatic-drive sizing. Therefore, the shorter cycle times can be transferred into reduced air consumption.

The results demonstrate that downsizing a cylinder by at least one size is feasible using the SQE system. Notably, longer cylinders show even greater performance improvement when equipped with the quick-exhaust valve. Moreover, the findings indicate a substantial potential for enhancing energy efficiency in pneumatic drives, since the improvements are comparable to state-of-the-art ESCs while requiring less commissioning and control effort.

Regarding robustness, the experiments show that cylinders with an SQE valve can be operated with different pneumatic line lengths but exhibit lower robustness than conventional downstream-throttled systems. This lower robustness leads to a diminished performance increase and higher impact velocities at the end of the stroke when using longer pneumatic lines.

Despite these promising results, several challenges remain to be addressed in future research:

- Control strategies or system modifications that increase the robustness of the new system must be investigated.
- A systematic study of how the SQE valve affects cycle times is necessary to integrate it into cylinder-dimensioning procedures.
- Advancing the system beyond a laboratory demonstrator and integrating the lessons learned will enable comprehensive cost-effectiveness analysis, incorporating both manufacturing expenses and potential energy-cost savings.

Acknowledgments

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