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Pneumatic Fault Monitoring and Control for Sustainable Compressed Air Systems

Massimo Borg, Paul Refalo*, Emmanuel Francalanza

Department of Industrial and Manufacturing Engineering, Faculty of Engineering, University of Malta, Msida MSD2080, Malta

* Corresponding author. *E-mail address:* paul.refalo@um.edu.mt

Abstract

Sustainable development in the industrial sector has been widely explored in recent years, to achieve a carbon-neutral industry. Compressed air systems are widely used in the industrial sector. Numerous energy-saving improvements have been studied within this scope, as leaks make these systems inefficient. Nevertheless, it has yet to be seen how different optimisation techniques can be utilised to mitigate fault effects. This study shows how fault monitoring was performed on a multi-actuator system, using different time domain indicators including, mean and standard deviation. This was followed by exploring the system behaviour when pressure and flowrate control strategies were executed to minimize fault impacts. Fault monitoring, using the indicator data, was successful. For instance, as a 1 mm leak was induced and the consumption increased by 34%, the standard deviation in pressure drop reduced by 6% and the mean actuation time decreased by 13%. Though the mean in pressure drop was useful for fault monitoring other pressure indicators, including standard deviation, provided additional monitoring capabilities. During this monitoring exercise, it was also found that improved sensor accuracy resulted in less reading variations, obtaining more conclusive results and identifying faults of smaller sizes. As faults were accurately identified and characterised, it was then possible to mitigate their effects via pressure and flowrate adjustments. Results proved promising, as both contributed to air consumption decreases of 16% and 11%, respectively. Although such modifications decreased the production rate by 2-5%, the previously mentioned savings outweighed this decrease. This work highlights the need for development of fault monitoring and control systems which maintain the productivity and energy performance of pneumatic systems.

Keywords: Sustainable Pneumatic systems; Fault monitoring; Control strategies; Sensor accuracy.

1. Introduction

A carbon neutral industry has been given precedence in recent years, aiming at mitigating the adverse environmental impacts. This is especially true in the European Union (EU) with directives being published, pushing for this goal. For instance, the Green Deal Industrial plan sets down rules which help in achieving a net-zero industry by 2050 [1].

Improvements in compressed air systems (CAS) have been explored for their potential in improving the sustainable performance of industrial setups. These types of systems are widely used in industry as they possess various advantages, including cleanliness and reliability. Nevertheless, the frequent presence of faults renders them quite inefficient and expensive to run. To give perspective, leaks, being a common fault encountered in these systems, contribute to a reduction of 20-30% of the CA output [2]. Fault repair is the straightforward solution for this problem, however, CAS are quite complex and thus, fault repair is often overlooked due to the downtime.

Advancements in Artificial Intelligence (AI) have led to the concept of Industry 4.0 to be adopted across the industrial sector, where sensor data allows for autonomous system functionalities. This attracted the attention of researchers, with efforts being made to automate the fault-finding process. CAS consist of (i) the supply side, where the CA is generated and (ii) the demand-side, where the CA is conveyed to the respective

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actuators. Although both the supply and demand subsystems of CAS have been explored, Neale et al. [3] claim that demand-advancements should be prioritized as these offer the highest efficiency improvement potential, in the region of 50-70%.

In this regard, Borg et al. [4] dedicated an entire study reviewing different demand-oriented studies focusing on fault monitoring. Indeed, pressure and cycle time were underscored as having the greatest potential as they can be monitored using pre-existing equipment. Other studies also highlight the fault monitoring capabilities of these two parameters. For instance, Abela et al. [5] stated that for a single actuator system operating at 6.1 bar, a 1.6 mm leak dropped the pressure by 7%. Gauchel et al. [6] highlighted that whilst performing tests on pneumatic clamps, a leak to the extension line caused the actuation time to increase by 3%. Kulkarni et al. [7] also investigated the cycle time parameter on solenoid valves, also concluding that time is useful for fault monitoring. Studies [8], [9] by Borg et al. concluded that these parameters could also be used to characterise faults including distinguishing between continuous and intermittent faults. The use of this data gives rise to the development of a Fault Detection and Diagnosis (FDD) system where faults are: (i) detected, (ii) isolated and (iii) diagnosed.

Demand side improvements have also progressed towards optimising the system performance through control capabilities. As underscored in the review by Seslija et al. [10], multiple approaches have been explored to enhance the energy efficiency performance of systems. One of the most covered methods is the reuse of exhaust CA. By merging the meter-in and out connections of an actuator, the exhaust gas from one chamber can be reused for the actuation of the opposing chamber. According to Balgojevic et al. [11], CA savings of 20% were claimed whilst adopting this method for an actuator operating at 6 bar. Another control approach explored for sustainable improvements was the reduction of actuation pressure. As described in study [12], this is possible by installing pressure regulators to the actuators' metered connections. Positive results were reported, with the latter claiming consumption savings of 31%, for a 3 bar reduction in the return stroke. Nonetheless, it was pointed out that such adjustments impact the actuation time. For instance, it was claimed that the 3 bar reduction increased the actuation time by 30%. Though smart systems have their advantages, the use of sensors gives rise to data uncertainty, impacting the resulting conclusions [13]. In fact, studies [14], [15], which both focus on accurate control, took sensor uncertainty into consideration. The former, explicitly specified these errors during modelling in order to mitigate positional errors whilst the latter, devised computations estimating sensor errors from the collected data.

The demand for improvements in this sector has given rise to products which offer autonomous fault monitoring and control capabilities in a single package. Two examples are the 'Air Management System' by SMC [16] and the 'Smart Pneumatics Monitor' system by Aventics [17]. Both claim that using sensor data, faults could be identified. In fact, both use flowrate and pressure data, with the latter system also making use of the cycle time. With regards to control capabilities, the Aventics system offers the greatest functionality. In contrast to the control actions discussed prior, this product offers measures that mitigate fault effects. Indeed, it is claimed that autonomous pressure adjustments, via a proportional pressure regulator, reduce the CA consumption attributed to faults. Nonetheless, the cycle time has to be considered as it may be influenced.

Although research in pneumatic fault monitoring and control has progressed, these concepts have not been explored together. Furthermore, the effects of different sensor accuracies have yet to be investigated with respect to fault monitoring capabilities. The control strategies highlighted in literature focus on optimising the current system performance rather than mitigating fault effects. Only the 'Smart Pneumatics Monitor' by Aventics [17], claimed to offer control capabilities to mitigate fault effects. Yet, the proposed control strategy is performed at the expense of production output. Therefore, methods have yet to be found which mitigate fault effects whilst minimally affecting the cycle time and productivity. Given this gap, a study investigating fault monitoring and control, addressing these shortcomings, will help expand knowledge.

This study aims at addressing this gap. Sensor uncertainty was analysed to study its effects on fault monitoring. This was followed by a fault monitoring exercise on a pick-and-place system. Pressure and cycle time were explored for their use in an FDD setup as they are logged using pre-existing equipment. Finally, with detail known about the fault, including its location and size, different control functionalities were explored to mitigate fault effects, whilst minimally affecting the productivity. As a result, the following objectives were set:

- Devising an experimental plan for repeatable logging of pressure and cycle time for different fault scenarios,
- Examining impacts of sensor uncertainty with regards to FDD capabilities,
- Identifying pneumatic demand parameters useful for a reliable FDD monitoring system,
- Examining different control methods to mitigate fault effects whilst minimally impacting the cycle time.

2. Experimental Methodology

To achieve the objectives drawn up previously, experiments were performed to comprehend the system's behavior. Thus, an experimental plan was drawn to systematically perform the experiments. The aim of these tests was to identify the relationship between different input factors with respect to the system's output response. In this case study, the input factors were fault oriented: (i) leaks of sizes 0.5 mm and 1 mm and (ii) different leak locations. As [5], [6], [8], [9] claim that pressure and cycle time are reliable parameters for fault monitoring, these were chosen as the output factors.

A pick-and-place setup was used as a case study. As any other pneumatic system, this setup comprised four zones. As shown in Fig. 1, Zone 0 is responsible for generating the CA using a compressor. The CA is conditioned and regulated to a 6 bar pressure in Zone A. Then, the CA is conveyed to the valves in Zone B to be utilised by the actuators in Zone C. As illustrated, this system consisted of three actuators: horizontally mounted actuator (*H1*), vertically mounted actuator (*V1*) and a pneumatic gripper (*G1*). These actuators were used to perform a pick-and-place sequence, conveying a part vertically and horizontally across a conveyer.

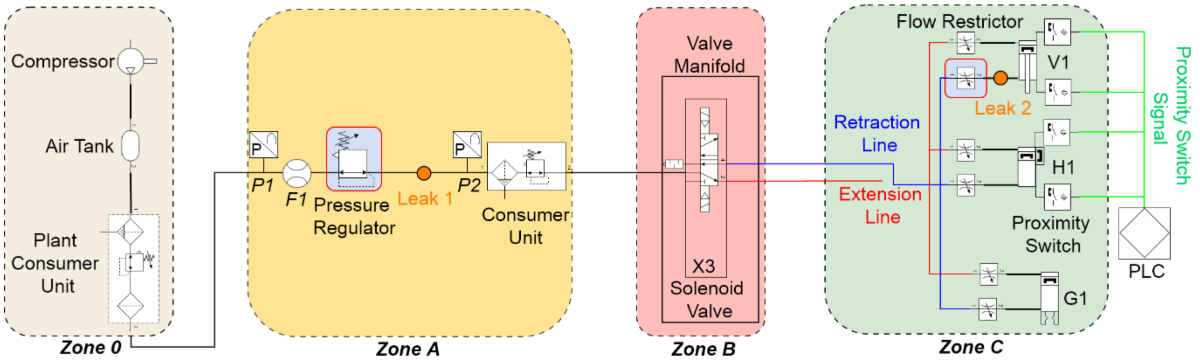

Fig. 1. Schematic diagram of the experimental setup.

Legend; ***H1***: Horizontal rod-less actuator (SMC EMY1C25G-800), ***V1:*** Vertical rod actuator (SMC MGPM12), ***G1:*** Pneumatic Gripper (Festo), ***F1:*** Flow meter (SMC PF2M7), ***P1* and *P2:*** Pressure transducer (Wika S-20).

Prior to commencing the fault monitoring analysis, the effects of sensor uncertainty had to be understood. As cycle time measurements have negligible errors, due to signals by proximity switches being virtually instant, this study focused on pressure reading variations. In previous studies [8] and [9], fault monitoring exercises were completed using the Wika A-10 pressure transducer, having a combined standard uncertainty of 0.82% [18]. To explore the effects of sensor uncertainty, whilst aiming to improve the fault monitoring capabilities, a more accurate sensor was considered for these tests. Indeed, the Wika S-20 transducer, with a 70% lower combined uncertainty (i.e. 0.25%) [19], was selected, making it possible to compare the performance of both models.

The fault monitoring exercise ensued with faults introduced in Zones A and C. In fact, leaks were induced upstream to the consumer unit and along the retraction line of *V1*. This gave rise to investigate different fault types, as leaks in Zone A were continuously active, whereas those in Zone C were intermittent. With two leak sizes at two distinct locations, five scenarios were investigated for fault monitoring, as scheduled in Table 1. To monitor the system's response, two Wika S-20 transducers were used in Zone A (i.e. *P1* and *P2*), as this configuration allowed for the pressure drop across Zone A leaks to be analysed. With *V1* and *H1* carrying out the pick-and-place sequence, the actuation time for each was recorded using proximity switches. Finally, flow meter *F1* in Zone A recorded the flowrate, to quantify the fault consumption. Data was logged using an Omron NX-102 controller.

With faults being identified and characterised, it was possible to attend to them, restoring the system performance. To do so, control methods were investigated. Faults, affect the system flow and pressure. To lessen their effects and maintain the cycle time, both parameters were altered using pressure regulators and flow restrictors. The aim of the control tests was to address actuator leaks as their location allow for control over the CA flow via the restrictor. As a result, the pressure regulator in Zone A was used to reduce the pressure to 5 bar, whilst the restrictor installed to the meter-out connection of *V1* adjusted the flow through the fault. Alterations in flow were possible by adjusting the restrictor from the fully open setting (i.e. position 11) to the restricted setting (i.e. position 8). As shown in Table 2, an additional four tests were performed to assess both control strategies for volume consumption and total cycle time.

3. Experimental Results

This section presents the main findings from the uncertainty analysis, fault monitoring exercise and control investigation. Each experimental run consisted of 30 pick-and-place cycles and data was logged every 50 ms. The error bars depict a 95% confidence interval (CI).

3.1. Uncertainty Analysis

In previous studies [8] and [9], pressure data was found reliable for fault detection. Nonetheless, it has not yet been investigated how sensor accuracy affects the reliability of an FDD system. Thus, *P1* and *P2* results compiled from study [8], using the Wika A-10 (0.82%) transducer, were compared with Wika S-20 (0.25%) findings from this study. For this comparison, the same setup was utilised, with both sensors installed in Zone A. The pressure results are shown in Table 1.

Table 1. Experiment factors together with the main results for the fault monitoring exercise.

Test	Leak Zone	Leak Size (mm)	Air Cons. (NL/cycle)	*P1* (bar)	*P2* (bar)	σ Δ*P* (mbar)	I_{Fct} Δ*P*	Avg *V1* Up (ms)	Avg *V1* Down (ms)	Avg *H1* Right (ms)	Avg *H1* Left (ms)
1	/	/	10.65	6.13	6.13	9.41	4.36	210.83	219.58	1205.00	926.67
2	A	0.5	15.54	6.09	6.07	9.24	5.15	189.17	206.25	1168.33	920.00
3	C	0.5	12.63	6.13	6.11	8.98	4.89	215.42	207.08	1195.00	925.00
4	A	1.0	25.44	6.05	6.00	13.10	5.13	184.17	206.25	1191.67	926.67
5	C	1.0	14.49	6.05	6.01	8.82	5.10	275.83	190.42	1210.00	948.33

Where Avg: Average, Δ*P*: *P1-P2,* σ: Standard Deviation; I_{Fct}: Impulse Factor; Up: *V1* retraction, Down: *V1* extension, Right: *H1* extension, Left: *H1* retraction.

As highlighted earlier, the pressure sensor used in these tests had 70% better accuracy than that of study [8]. Apart from the overall improvement in reading uncertainty, attributed to better sensor characteristics, one of the main advantages noted was that the enhanced accuracy resulted in more repeatable readings. Indeed, comparing *P1* and *P2* benchmark data, it was found that the pressure data experienced 67% and 75% less fluctuations, respectively, as shown in Fig. 2 (a). This was reflected by the difference between the maximum and minimum values, both converging together. This implies that the fault monitoring results will be more conclusive.

3.2. Fault Monitoring

Following the uncertainty exercise, where the benefits of accurate sensors for FDD systems were understood, the fault monitoring analysis ensued with pressure and cycle time monitoring of the system performance. As frequent pressure fluctuations emerge from the continuous loading/unloading of the compressor, some pressure results may be inconclusive. Consequently, the pressure drop between *P1* and *P2* (ΔP) was examined as this accounts for changes in input pressure. The use of the condition indicators, mean, standard deviation and impulse factor (defined by Equation (1)), made it possible to extract features from both parameters. Consequently, this section goes through the main findings, shown in Table 1.

The effects of both faults were first quantified and as the 0.5 mm and 1 mm leaks were induced in Zone A, the CA consumption increased by 46% and 139%, respectively. Although Zone C leaks also contributed to consumption increases, the figures were less significant as they were only present intermittently. In fact, the volume consumption for Tests 3 and 5 increased by 19% and 36%, respectively.

Data from Table 1 revealed that the standard deviation for ΔP was useful for fault monitoring. Most notably, it helped in identifying 1 mm leaks occurring in different zones. This was seen whilst faults were introduced in Zone C as the value obtained was less than their counterparts. Indeed, as shown in Fig. 2 (b) the 1 mm leak in Zone C caused 45% less fluctuations, compared to the Zone A fault, and 6% less than the benchmark. This was a result of the fault being downstream to both sensors, affecting both in the same manner. Furthermore, when the leak was in Zone A, an increase was recorded. This boiled down to its position, as it was situated between both sensors and the effects of the fault increased the fluctuations. This shows that Zone C faults also affect the pressure in Zone A, and thus faults from different zones can be detected from one area. Mean ΔP also proved useful, with 1 mm data from Zones A and C showing magnitude changes of 15% and 17% from the benchmark. Standard deviation was preferred however, as it made it easier to identify the fault zone.

The impulse factor for ΔP, also proved promising. As shown in Fig. 3 (a), for both leak sizes, the indicator recorded significant increases in the range of 12% to 18%. This was down to two reasons, either the mean value decreased more than the maximum value or the maximum value increased more than the mean value. Both instances were encountered, highlighting that this can indicate different sized faults.

$$Impulse\ Factor\ \Delta P = \frac{\Delta P_{Max}\, per\ test}{\Delta P_{Mean}\, per\ test} \qquad (1)$$

The final parameter analysed for fault monitoring was the cycle time for *V1* and *H1*. Mean data indicated that only *V1* extension and retraction data offered significant findings. Indeed, for the 0.5 mm and 1 mm leaks in Zone C, the extension time respectively decreased by 6% and 13%. This was because the fault at the actuator retraction line allowed for more CA to exhaust from the cylinder chamber during extension, causing this decrease. Though findings from the smaller fault were promising, the results were not conclusive. The retraction time continued to highlight the parameter's potential. Indeed, it helped to distinguish different fault types. To give context, for the actuator fault, the time to retract the cylinder significantly increased for both leak sizes since the fault prevented CA flow through the cylinder chamber. In contrast, faults located in Zone A, made it easier to overcome the piping frictional forces, resulting in the time to decrease. Apart from the findings from the 0.5 mm leak in Zone C, all retraction observations were conclusive. The *V1* retraction times are shown in Fig. 3 (b).

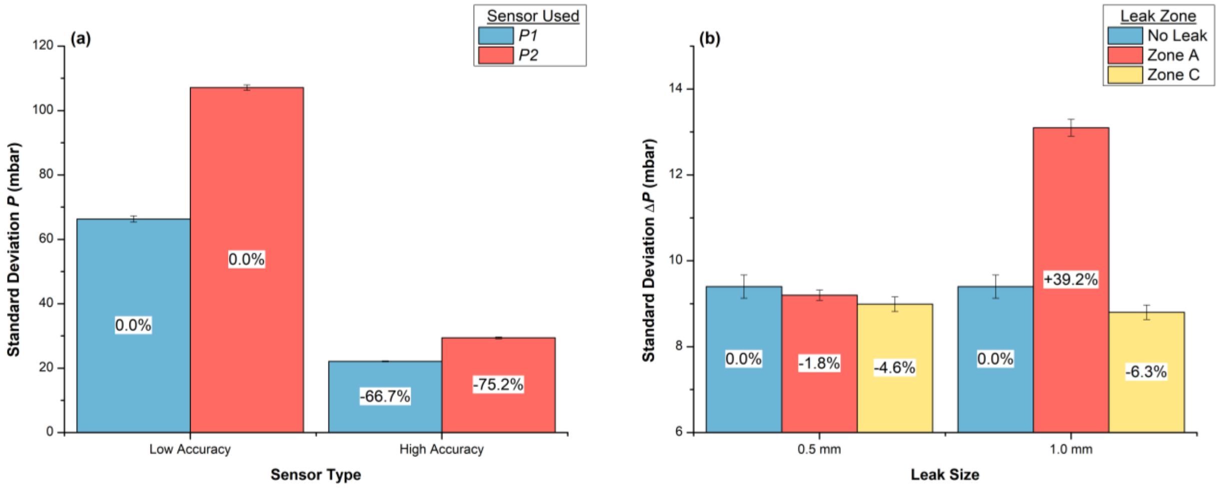

Fig. 2. (a) Standard deviation for *P1* and *P2* for different sensors; (b) Standard deviation of ΔP. Percentage difference with benchmark. Error bars width: 95% CI.

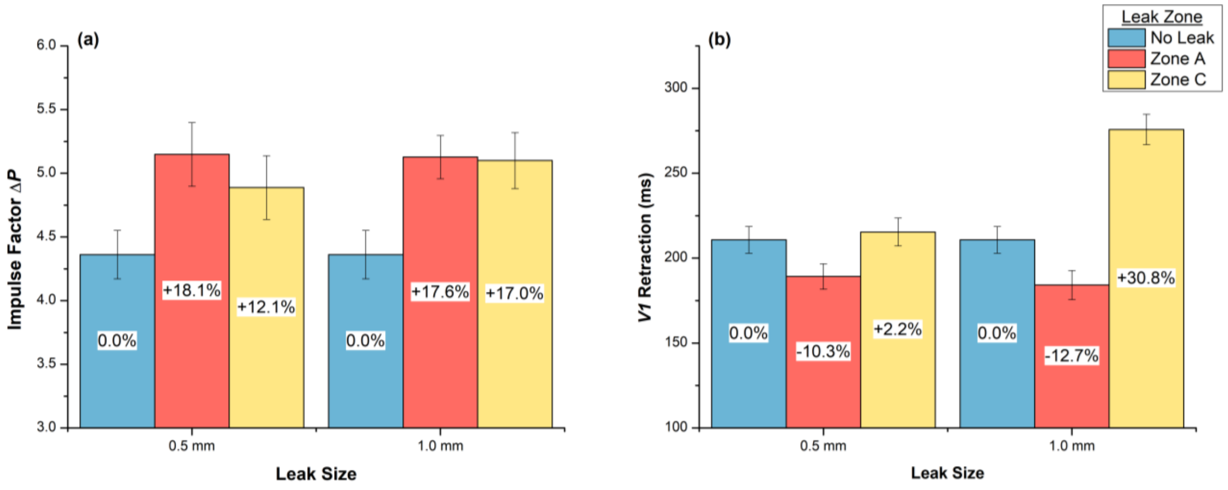

Fig. 3. (a) Impulse Factor of ΔP; (b) $V1$ average retraction phase times. Percentage difference with benchmark. Error bars width: 95% CI.

3.3. Control Capabilities

As faults were accurately identified and characterised, it was possible to directly address them, re-establishing ideal system performance. Thus, flowrate and pressure adjustments were performed, to mitigate fault effects on an actuator, whilst minimally affecting the cycle time. Adjustments were performed by: (i) reducing the system pressure in Zone A from 6 bar to 5 bar and (ii) controlling flow through the $V1$ retraction line from the fully open setting to the regulated setting. Consumption and cycle time results can be found in Table 2.

Table 2. Experiment factors and the main results for the control exercise.

Test	Control Type	Leak Zone	Leak Size (mm)	Air Cons. (NL/cycle)	Avg Cycle Time (s)
1	/	/	0	10.65	21.70
6	P	C	0.5	10.56	22.49
7	P	C	1.0	12.34	22.82
8	F	C	0.5	12.25	22.22
9	F	C	1.0	13.52	23.10

Where Avg: Average, P: Pressure adj. (6 bar → 5 bar), F: Flow adj (setting 11 (fully open) → setting 8).

As presented previously, the 0.5 mm actuator leak increased the CA consumption by 19%, whereas the 1 mm leak increased it by 36%. As both control adjustments were implemented, the consumption figures reduced noticeably. In fact, data from Fig. 4 (a) shows that pressure adjustments resulted in the consumption to decrease on average by 16% for both leak sizes. Furthermore, flowrate restrictions decreased the consumption by 3% and 7% for the small and large faults, respectively. Cycle time results, as shown in Fig. 4 (b), also proved promising. Although slight increases in this indicator were recorded, the CA savings outweighed them. To give context, as the pressure was altered, the cycle time for both leak sizes increased by around 4%, while reducing CA consumption on average by 16%. In addition, the flowrate alterations increased the cycle time by 2-5% whilst the consumption was reduced by 3-7%. One key difference between both adjustments was that pressure alterations yielded higher savings than its flowrate counterpart. This was because pressure reductions were applied to the entire system thus, irrespective of the fault, consumption reductions are recorded for all the setup. In contrast, changes made to the flowrate, solely affected the faulty area, resulting in lower saving figures. Another observation was that changes in cycle time and consumption were dissimilar for both leak sizes during the flow adjustments. The reason for this was that these alterations were fault specific, meaning that changes are amplified the larger the fault is. Thus, comparing the 1 mm leak data with its smaller counterpart, higher CA savings were recorded, whilst the cycles took longer. Ultimately, balanced adjustments in flowrate and pressure show potential that they can yield significant CA savings, with minimal time impact.

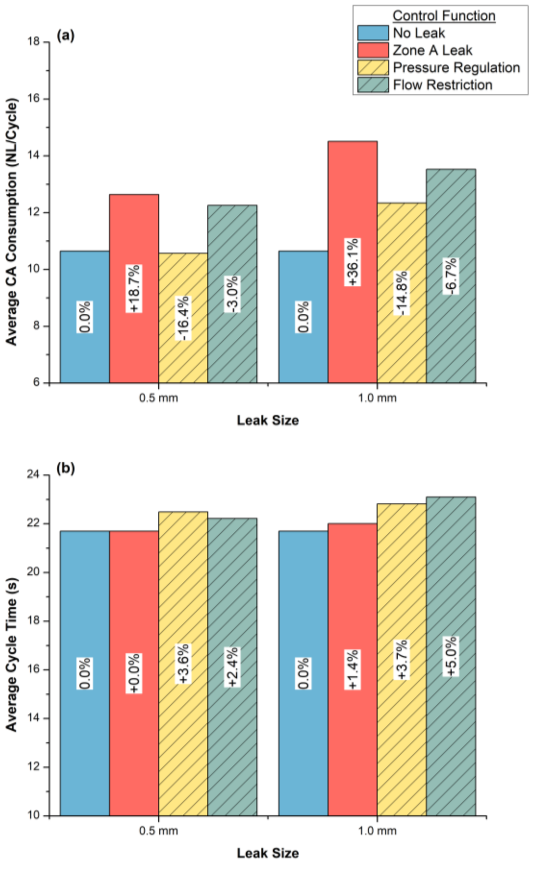

Fig. 4. (a) Average CA consumption; (b) Average cycle time. Percentage difference with leak for the control exercise. 95% CI error is negligible.

4. Conclusions

A push towards a cleaner industrial sector has instigated work in CAS aiming at improving their efficiency. In spite of significant progress in this area, a review of the state of the art resulted in a gap in knowledge. Thus, a novel fault monitoring and control exercise was performed using sensors with enhanced accuracy, whilst finding control techniques that mitigate fault impacts and maintain the production output.

Pressure sensors with different accuracies were investigated. As anticipated, it was found that sensors with 70% better accuracy, resulted in significantly less reading variations. For instance, for one of the sensors, 67% less variations were encountered. This shows that accuracy is instrumental for the development of an FDD system, as results are more conclusive.

The effects of different sized leaks were then investigated on a pick-and-place setup. Pressure drop and cycle time data was used to survey the system performance, as these can be logged without using proprietary equipment. Indeed, the use of different indicators reaffirmed that both parameters were useful for fault monitoring. For instance, an actuator leak causing a consumption increase of 36%, was identified from a 6% reduction in the standard deviation for ΔP, together with a 13% decrease in the extension time. The use of these indicators gave rise to additional system capabilities by characterising fault features, such as the location and type. Mean ΔP was also useful for fault monitoring yet, changes in standard deviation provided additional FDD capabilities. Moreover, the benefits of using accurate sensors were seen in this exercise as it was possible to identify faults of smaller sizes, i.e. 0.5 mm leaks.

By accurately identifying faults, it was finally possible to mitigate their effects via flowrate and pressure control functions. Results proved promising, as all CA savings outweighed the minimal time increases. For instance, as a 1 mm fault was present, the 36% consumption increase was reduced by 15% and 7%, for the pressure and flowrate adjustments. This was achieved, while the time only increasing by 4% and 5%.

Although this exercise contributed towards the fulfillment of an FDD and control system, further work is required. Indeed, investigating different fault types on more complex setups would help towards achieving this goal. Exploring the use of pressure and flow adjustments concurrently, to achieve balanced results between CA consumption and cycle time, would also help. Such information allows for system behavior to be better realized. This is beneficial towards the development of smart systems, as techniques such as AI, require copious amounts of data. Ultimately, monitoring and control systems reduce energy consumption of CAS, widely used in manufacturing, hence reducing the energy and carbon footprint of the products produced, achieving a cleaner industrial sector.

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