CONDITION MONITORING OF PNEUMATIC MACHINERY WITHOUT OPERATION INTERRUPTION

ROBERT RAKAY, ALENA GALAJDOVA, MAREK VAGAS

Technical University of Kosice, Faculty of Mechanical Engineering, Kosice, Slovakia

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e-mail to corresponding author: robert.rakay@tuke.sk

The article deals with an example of a non-invasive measurement of the system. The proposed system is suitable in cases where the equipment analysed must be monitored without interrupting its function. The measurement demonstration can serve as proof of the concept of monitoring the state of moving parts of technical systems, such as hydraulic pumps, pressure pumping stations, and large ventilation systems, where mechanical damage prediction is very important because repair is very costly.

KEYWORDS

condition monitoring, IO-link, maintenance, industrial automation, machine health

1 INTRODUCTION

With the current development and use of sensors and transducers, it is possible to extend the life of machines and predict future damage to the machinery. In the context of this trend, various monitoring tools, advanced sensor systems, and modern IoT solutions are created to monitor the condition of technical equipment and its parts in factories.

Currently available hardware tools with a combination of the latest software solutions, which are often “open-source”, create a good basis for this purpose. Data collection, processing, and prediction are very important nowadays, as part of the Industry 4.0 philosophy. Their use is important not only for safety reasons but also in terms of efficiency and economic factors. The hardware solutions of modern sensors not only offer basic measurements of technical parameters but also provide information on the current state of such a sensor, i.e., internal temperature, power supply, etc. [Peterka 2020, Vagas 2020].

With such improved sensor devices, we can not only collect up-to-date information but also predict future conditions such as machine failures and damage [Abramov 2015].

Every advanced manufacturer tries to reduce machine failures and maintenance costs. This can be achieved through better monitoring. In classical automated production systems, the control part is a normal PLC or a programmable logic controller. It is involved in monitoring the system, checking, and, in case of emergency, stopping the ongoing process. In case we would like to monitor or expand our system, even routine system change requires system shutdown, hardware and wiring reconfiguration, and control logic reprogramming to obtain the required information and results [Vagas 2011, Sarga 2022].

With the proposed example of a measuring system, it is not necessary to interrupt the running processes. This type of solution can function as a stand-alone system and is also suitable for temporary installation [Beniak 2019].

The introduction of IO-Link technology has brought the possibility of enhanced monitoring of available characteristics and another wide range of metadata - e.g. number of cycles, power supply conditions, etc.

The processing of additional data leads to a deeper understanding of the condition and further characterization of the machine [Cacko 2014a].

With monitoring mechanical devices with stand-alone tools like the Balluff CMTK we can combine the advantages of IO-Link technology with the automated evaluation unit and partially open-source software tools. The output of such monitoring systems is not only simple numerical or binary information about the condition of the followed characteristic but also understandable visualization with configurable tools and databases for further processing.

The principle of such condition monitoring systems is in the following figure (Fig. 1).

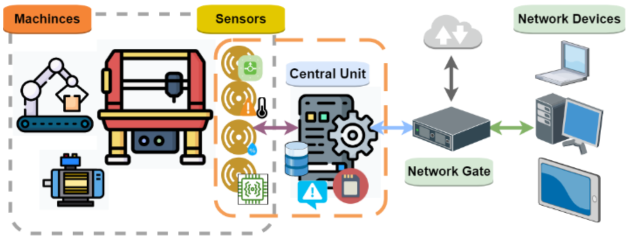


Figure 1. Condition monitoring principle

Every machine whether automated or not should work reliably during its planned operating life. That machine should be maintained for that purpose. The maintenance is currently focused on monitoring and diagnostics of those operation characteristics, which are manifested by rising temperature, increased sound, and vibration [Cacko 2014b]. Besides that, we can monitor a few additional selected characteristics. We should also note that the lifecycle of the machine should be divided into stages like development, and mounting commissioning up to the normal operation [Sarga 2012, Kelemenova 2020, Virgala 2021]. Proper maintenance during the operation of the mechanical device for its reliable operation is equally important as the design and building of the machinery. The focus of the modern engineering solution should be aimed at preventing damage or malfunction and not on repairing it after the failure. Besides that, we want the effective, reliable, and safe operation of the machinery. The main goal of the maintenance can be described with 3 basic requirements: achieving maximum productivity, optimizing the performance of machinery, and ensuring safe operation. A more complex task is in the field of predictive maintenance, where we focus on monitoring the machinery's current status. This kind of maintenance is not realized on fixed time-based intervals, but on change of watched parameters. For this purpose, it's necessary to understand and check the status of the machinery part during normal operation. By doing that we can prevent unplanned breakdowns and shutdowns [Koroleva 2020, Vysocky 2020, Prada 2021]. The optimal goal is to have the right information at the right time to make the right decision. If we can measure a change during the normal operation of the machinery or its parts, we know which part of the system requires replacement or repair. Also, we can manage to increase the effectiveness of the spare part orders, we can plan more efficient downtimes, and increase the security of personnel. The additional data results in shorter and less costly planning. The explained solution brings further advantages such as longer equipment life, higher safety on the field, fewer accidents with negative consequences for the environment, and optimized management of spare parts [Janos 2017, Pecovsky 2020].

2 MAINTENANCE AND DIAGNOSTICS

Maintenance of machines and their parts is essential for a long-life cycle. Although there are a number of factors that point to the importance of maintaining one of the most important, is still costs. Household appliances, usually work without any maintenance, so we will “repair” them only when a failure occurs — this is called reactive maintenance. More expensive systems such as hydraulics, pneumatics, or electromechanics require regular inspections and revisions — this is preventive maintenance. In particular, proactive and predictive maintenance has been created to prevent unexpected failures. Predictive maintenance focuses on the actual condition of the machine, while the proactive goal is to eliminate the cause of the deteriorated condition.

In the current technical diagnostics of machines and their subsystems, in addition to a well-thought-out methodology and experience, modern diagnostic techniques must increasingly be used, using many different physical measurement principles and making full use of electronics. An external reaction or manifestation of a diagnosed object can be examined during normal function (activity) or in scenarios created for the diagnostics. Diagnostics without disassembly have a special and today strongly preferred position in the system of technical diagnostics, which detects the condition of the machine and its parts in the assembled state and under normal operating conditions.

The measurement of machinery “health” is usually aimed at the following parameters:

- Diagnostics of operation - measurement operation parameters and comparison to previous values.
- Tribodiagnostics - stands for lubricant analysis.
- Thermodiagnostics - measurement of temperatures (places or surfaces). It can indicate increased friction or resistance.
- Ultrasonic diagnostics.
- Electrodiagnostics.
- Vibration diagnostics – Signal of vibration carries information about the cause of vibration and with processing we can catch the emerging or developing defect. A lot of the mechanical devices include some kind of rotational movement, and this is one of the most detailed diagnostic methods. This topic is very complex and measurements are based on the following types of sensors:
  - deflection sensors
  - speed sensors (speedometers)
  - acceleration sensors (accelerometers).

3 HARDWARE

There are various solutions for the technical diagnosis of the system. While some of them are stand-alone devices, others can be directly integrated into the main control system of automated production systems. The currently available technical means can be divided into 3 main categories:

Stand-alone systems – this category represents the most accurate technical devices and sensor systems. Usually, a separated signal processing unit is required, which communicates with a PC and specialized software. The main advantage of this type is the precise measurement; however, the costs are high, and the knowledge of the stand-alone systems is not simple.

Integrated systems- another form of measurement is a direct application of measurement apparatus to the control system like the PLC or PAC. Nowadays used programmable controllers provide very high computing power with different communication interfaces. With that advantage, a wide range of sensors can be used and can provide information on the status of the machine. However, the big disadvantage is, that if we want to upgrade an existing system with a new sensor it's usually demanding, and mechanical and software configuration is needed to successfully implement them.

Integrable systems – a very interesting type of measurement system is offered by multiple vendors of automation tools, where it's possible to implement a measurement system without interruption of running operation. Also, this kind of system is suitable for further communication with desired devices of the network. Usually, these systems use open-source software tools and support most of the industry-based communication protocols. An example of an Integrable system is the BALLUFF CMTK Kit.

3.1 Balluff CMTK

As there are many applications that are running for years and decades with older hardware, a need for some kind of “gate” solution was generated. The CMTK or Condition Monitoring Tool-Kit represents a hardware and software set. It combines a processing unit, IO-Link sensor interface, and software based on so-called open-source solutions. This system not only supports the Balluff sensors but also based on the IO-Link standardized communication can easily process signals of any vendor sensor that comes with the IO-Link interface. The BAV central unit supports 2x LAN connections for the PC and network communication. [BAV Datasheet 2022] With the 4x M8 IO-Link connections it's possible to connect 4 sensors and to control 4 simple digital outputs. Because of the integrable memory card, we can save data locally and it's not necessary to have a direct network connection. The summary of the technical specification is in the following table (Table 1).

Table 1. BAV technical specifications [BAV Datasheet 2022]

Specs	BAV main unit
Network interfaces	2x LAN: RJ45
IO-Link interface	4x M8 (4-pin/ A-type)
Processor	1.8 GHz/400 MHz
RAM capacity	2 GB
Memory	8GB EMMC
Working voltage	20-30 VDC

While the processing unit is a very useful device without any sensor it is unusable.

Table 2. BCM sensor technical specifications [BCM sensor Datasheet 2022]

Specs	Balluff BCM sensor
Frequency band [Hz]	2-3200
No. of axes	3
Velocity RMS band [mm/s]	0-220 (at 79,4 Hz)
Acceleration RMS band [g]	0-16
Contact temperature band [°C]	0-70
IP protection	IP 67, IP 68, IP 69K
Connector	M12x1- Male (3 Pin)
Input data	20 bytes

For machine condition monitoring, Balluff created the BCM sensor. It's suitable for non–invasive monitoring of machinery and its parts, with measurement of vibration characteristics, contact temperature, and atmospheric pressure. With its IO-Link functionality, the sensor also provides data on its internal statuses like sensor overheating, dirt contamination, power quality, and others. This sensor also can be connected to a standard IO-Link master device, but this requires additional hardware configurations. The main technical specification of the sensor is in the following Table 2 [BCM Datasheet 2022].

Two pneumatic sensors were connected to the main BAV unit as additional data sources. As a digital pressure switch, the SCM ISE20 was added. Its main technical specification is in the following Table 3 [ZSE sensor Datasheet 2022].

Table 3. ZSE sensor technical specifications [ZSE sensor Datasheet 2022]

Specs	SMC ISE20 sensor
Rated pressure [MPa]	-0.1 to 2
Repeatability	±0.2 % F.S.
IO-Link	V 1.1
Input data	2 bytes

To measure the flow rate of the pressurized air a digital flow switch was used. The PF3A701H main technical specification is in the following Table 4 [IM PF3A sensor Datasheet 2022].

Table 4. PF3A sensor technical specifications [PF3A sensor Datasheet 2022]

Specs	SMC PF3A701H sensor
Rated flow range [L/min]	10 to 1000
Min. resolution [L/min]	1
IO-Link	V 1.1
Input data	4 bytes

4 SOFTWARES AND COMMUNICATION

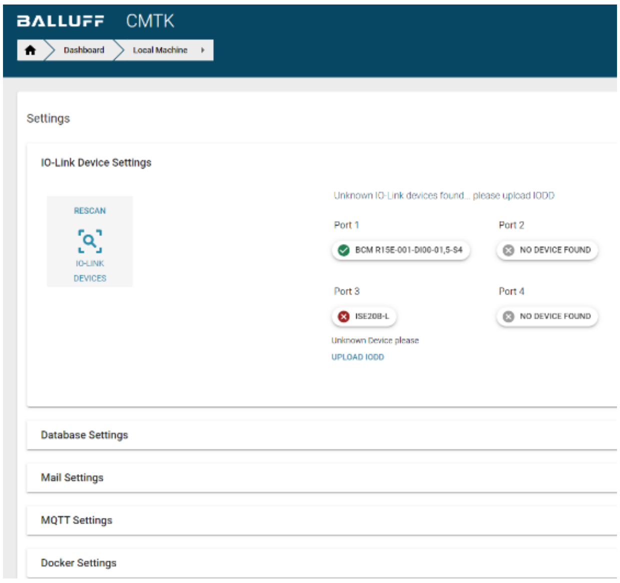
As a modern IIoT solution the CMTK is running through a local webserver and using open-source software tools such as Node-Red and Grafana. Of course, based on the ethernet interface a classic PLC control system can be connected to the main unit and access the sensor data. This kind of configuration is more complex and requires additional hardware and software tools, which are not part of this article.

The other option to implement the proposed measurement system is to use the integrated webserver interface. The device can work with a direct connection to the PC or via a DHCP server on the local network. The configuration process starts with a user administration and opens the Main view. In the Main view, we find our created devices and tools for network settings, alarms state monitoring, and user administration. The interface provides additional editors for system configuration:

- *IO-Link Device Settings*
- *Database Setting*
- *Mail Settings*
- *MQTT settings*
- *Docker Settings*

After the initialization process, the device updates the connected sensor and if any of them is not recognized via the IODD file we can implement the sensor identification. The next figure shows the connected sensors and the additional configuration options (Fig. 2).

The process of window configuration is very intuitive with the Grafana tools. With the use of them, additional graphic elements were created. An example of the Grafana configuration is in the following Figure 3.



BALLUFF CMTK

Dashboard > Local Machine

Settings

IO-Link Device Settings

RESCAN IO-LINK DEVICES

Unknown IO-Link devices found... please upload IODD

Port 1: BCM R15E-001-DI00-01,5-S4

Port 2: NO DEVICE FOUND

Port 3: ISE20B-L

Unknown Device please UPLOAD IODD

Port 4: NO DEVICE FOUND

Database Settings

Mail Settings

MQTT Settings

Docker Settings

Figure 2. Configuration window of local machine

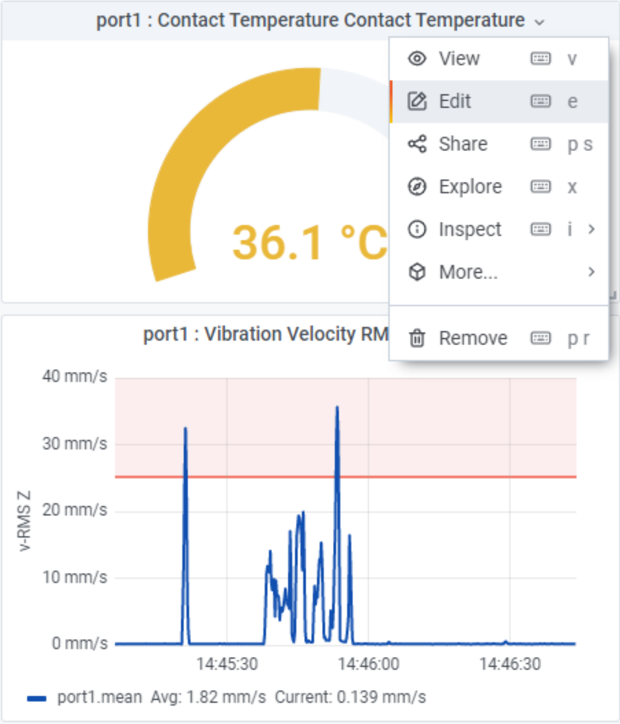


Figure 3. Grafana tools

All the measured data is transferred via the BAV unit using Node-Red to the InfluxDB database. From that database, the values are automatically queued to the Grafana. And on the webserver optionally we can categorize and separate the measured values into groups, visual objects, and other indicators. Nonetheless, all the measured data is stored and is available to download into tables form or text files for further processing.

Based on the measured values additional reactions can be implemented into the visualization system, like the alarm colors, which are shown on the Main view (Fig. 4).

Figure 4. Main view without/with alarm state

4.1 IO-Link

Is a standardized I/O communication technology for sensors and actuators. The IO-Link is not a systematic Fieldbus, but works under the logic level of these fieldbuses. The topology usually requires a master module, with multiple IO-Link ports. To the master module, the device is connected via a 3-wire, non-shielded cable. The power supply and the data transfer are provided all in one. The communication is point-to-point. IO-Link brings additional advantages, like access to not only measured data but also to sensor health, statistics for outputs, and dynamic sensor configurations. The transfer speed is categorized from 4.8 kbaud/s up to 230.4 kbaud/s in the IO-Link specification V1.1. Every device with this type of interface has a unique IODD file. To access any device via the control unit device profiles were created. Their role is to define the data structure, data content, and basic functions.

Within IO-Link and devices the following data types are available:

- *process data,*
- *actual value,*
- *device data,*
- *event data.*

4.2 MQTT

The Message Queuing Telemetry Transport is a communication protocol primarily created for M2M (machine-to-machine) communication. It was developed as a “very lightweight” protocol for message transmission between the sender and receiver. The main goal was to minimalize the payload and the requirements on the power supply while maintaining reliability with some level of guaranteed quality of delivery. These goals bring the MQTT between the ideal protocols for IoT and M2M and for mobile applications where the sources are limited.

The current applications of this protocol are everywhere around us, where easy connectivity is required: in home automation, in laboratories, for message transfer based on the current position, but also for implementation via Amazon Web Services and other cloud providers are available.

The MQTT is based on the TCP/IP principle and provides lossless, duplex communication. There are 3 levels of service quality (QoS 0, 1 and 2).

This protocol works with so-called “topics”, clients, and brokers. The topic represents the variable where we save the current value in the case of measurement. The Client is a program or a device that creates the connection with the server. It can publish or subscribe a message to a topic. The broker is a program or a device, which acts as a gateway or central node between the publishers and the subscribers of the network.

5 MEASUREMENT SETUP

The following setup for measurement was created as a proof of concept. An air compressor SIL-AIR 50/9 was measured during the cycles of pressurization and discharge. The discharge of pressurized air was regulated by a manually operated throttle valve. The following scheme describes the measurement setup (Fig 5).

The compressor with the connected sensors is in Figure 6. The signals were directly processed in the BAV unit and a visualization of their time relations was created. While the signal data is communicated via IO-Link, the BAV uses the MQTT protocol to transfer them. Based on that it's possible to easily implement this form of the measurement system in the nowadays used IoT and IIoT complexes. Additionally Fig. 6 includes detailed view of the BCM sensor and the BAV unit.

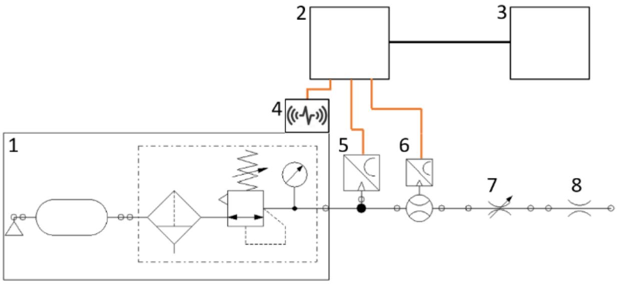


Figure 5. Measurement setup scheme

1-compressor
2- BAV unit
3- PC
4- BCM sensor
5- Pressure sensor
6- Flow sensor
7- Throttle valve
8- Nozzle

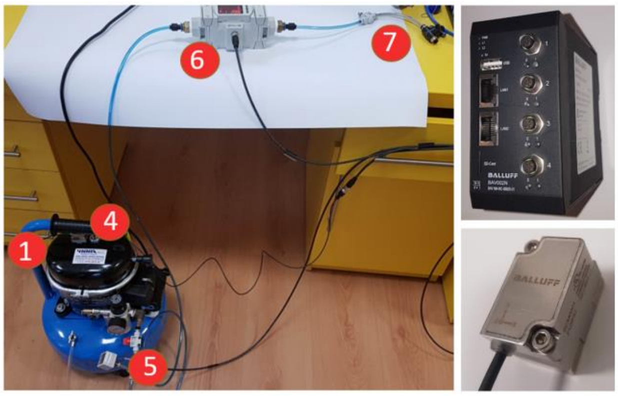


Figure 6. Measurement setup during the measurement

6 RESULTS

The measurements were performed in a laboratory environment on the premises of the Technical University of Kosice. The previous chapter described the measurement setup. During the measurements, a direct ethernet connection was used to view the actual measured data and later download them to a PC.

To evaluate the measured data the compressor was pressurized and discharged and during these cycles, the air pressure, flow rate, and vibrations were monitored. Based on these factors additional limitations and actions can be made, but it is not the goal of these experiments.

For comparison, the same type, but a different piece of the compressor was used. The comparison of the relevant parameters is shown in the following figures (Figs. 7-9).

The figures show the separated values for v-RMS, contact temperature, pressure, and flow and the relationship between the vibrations and pressure, where we can notice that during the pressurization the vibrations are rising with the rising pressure. The start and the end of this cycle come with the impulse vibration at levels approx. 22.5-24.5 mm/s. This was measured as the RMS value on Y-axis.

The second compressor while has similar mechanical characteristics as the first one shows significantly smaller values for the same process. The maximal vibration levels are approximately 12.5 mm/s, it was measured also as an RMS value on Y-axis.

The measured differences between the two compressors were caused by the worn out and not same operation times.

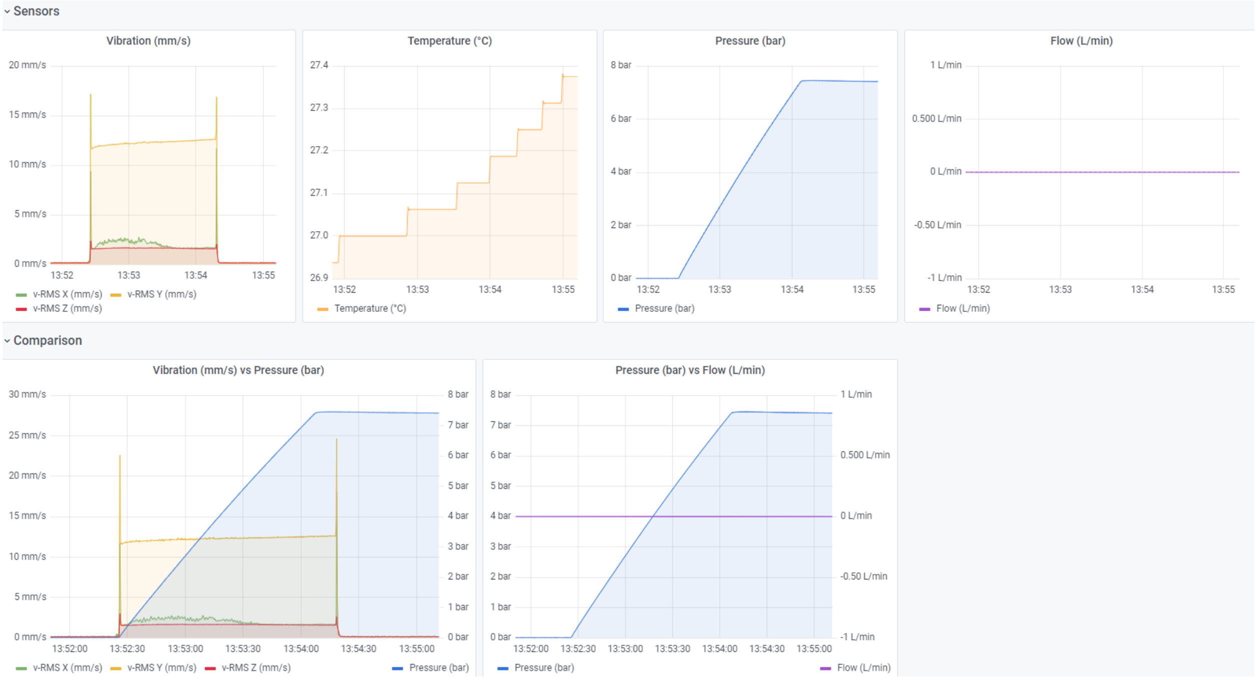


Figure 7. Measurement during pressurization

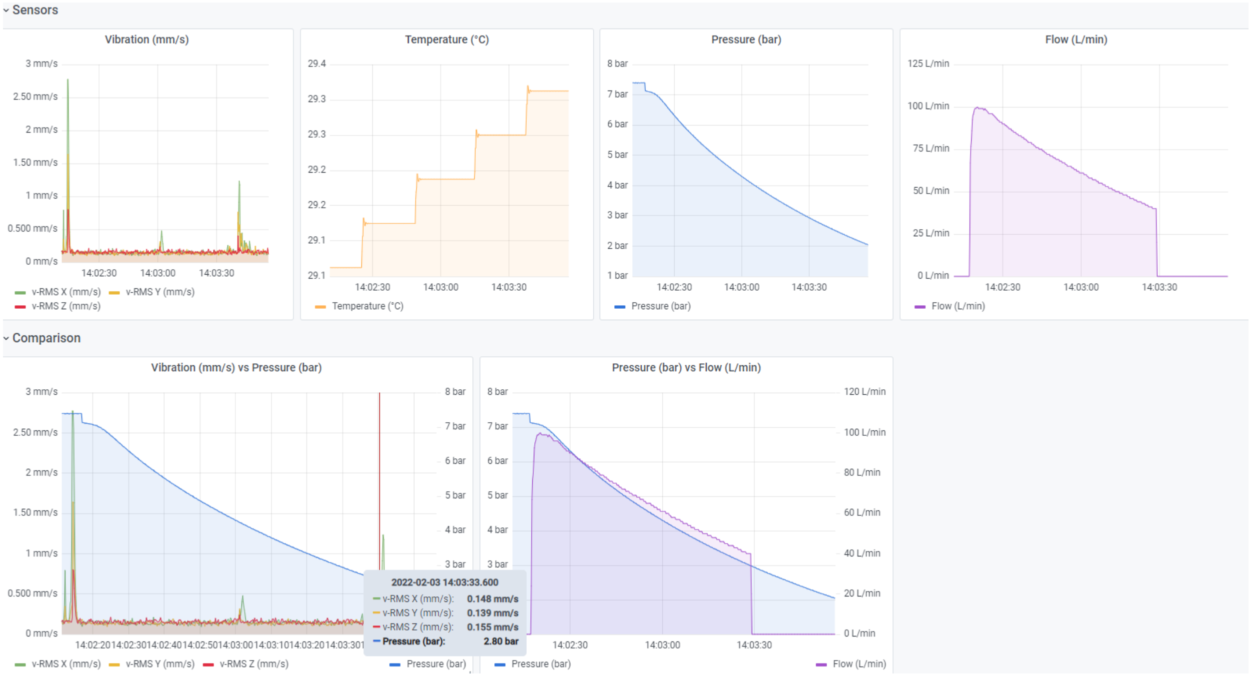
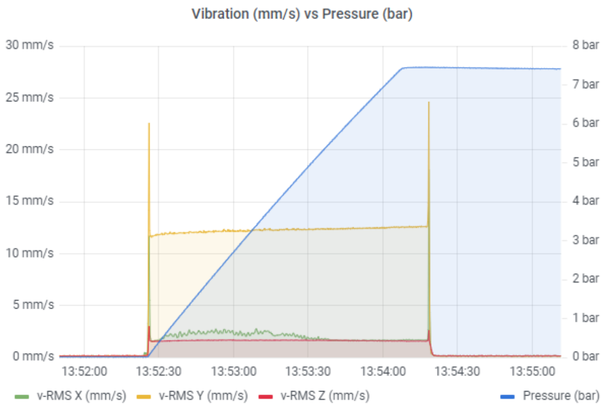


Figure 8. Measurement during discharge



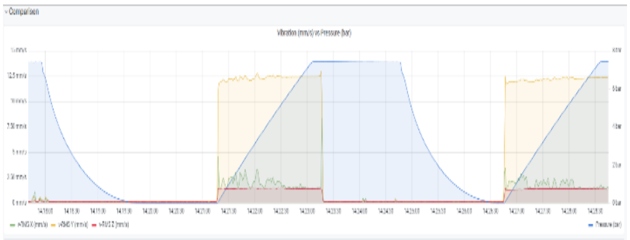


Figure 9. Measurements of two similar compressors

Additionally, the previous figures show that the graphical objects can be scaled for various time periods. The lower part of figure 9 also shows cycles of the pressure during pressurization and discharge. The values of the temperature were not relevant in this case, and also the contact surface wasn't chosen for that purpose. The measured temperature values indicate that the sensor itself functions on higher operation temperature. With increasing time the internal temperature wasn´t settled down during the measurements, and it wasn't part of the experiments, its purpose was to show the IO-Links additional advantages.

7 CONCLUSIONS

In this paper, an experimental condition monitoring system was introduced and tested using two similar compressors. The system of sensors and evaluation unit is suitable for automated production systems and their parts, where the operation shouldn't be interrupted. One of the biggest advantages of this kind of monitoring is that it's not needed to connect to the actual controller of the monitored process or machinery. We can work stand alone, by only using the BAV unit, without a network and supervisor device. The measured parameters can include various parameters of moving and stationary parts like vibrations, temperature, pressure, flow, and other characteristics which can describe or predict a future malfunction, wear out, and failure [Murcinkova 2013]. Based on the sensor data also different notifications and alarm conditions can be implemented, and if needed graphically monitored. In case of implementation to real machinery, the built-in guide and recommendations are useful. The main goal of the measurement setup was primary to test and prove the capabilities and advantages of this system. The IO-Link and MQTT communication channels are nowadays widely implemented. While the IO-Link-equipped devices produce additional data about their internal states, the MQTT provides easy machine-to-machine communication [Beniak 2018, Galajdova 2020 and 2021].

For testing purposes, vibration, pressure, and flow characteristics were measured. The result of the experiments has shown that by application of such a measurement setup even a device without any controller system can be measured. During the pressurization cycle of the compressor with rising pressure, the vibrations grow. The most critical levels were the beginning and the end of the cycle. The experiments also show that by comparison of two similar devices we can easily reveal a worn-out mechanical component or upcoming failure. Using the actual values of the sensors the maintenance can be significantly improved, and the system downtimes can be reduced.

Compared to other available condition monitoring systems the proposed solution offers advantages such as IO-Link connectivity, reconfigurability with various Node-Red-based applications, affordability, and reuse in other measurement tasks. Last but not least the created experimental setup provides a good basis for acquiring knowledge in the education of students in the field of machinery maintenance and measurement.

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CONTACTS:

MSc. Robert Rakay, PhD.
Prof. MSc. Alena Galajdova, PhD.
Assoc. Prof., MSc. Marek Vagas, PhD.
Technical University of Kosice, Faculty of Mechanical Engineering,
Department of Industrial Automation and Mechatronics, Park Komenskeho 8, 042 00 Kosice, Slovakia
robert.rakay@tuke.sk
alena.galajdova@tuke.sk
marek.vagas@tuke.sk