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PISTON MOVEMENT ANALYSIS FOR THE PURPOSES OF GAS IMPULSATOR DIAGNOSTICS

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Abstract
The article describes the results of the tests carried out for the purposes of diagnostics of the control and dynamics of the piston movement, which is a component of the gas pulser. The aim of the work is to obtain knowledge about physical phenomena and processes occurring during the operation of the device. This allows to determine the causes of accelerated wear of the piston and its seals. The task of gas pulsers is to support the transport of bulk materials. These are pneumatic devices controlled by pneumatic valves. They are used in places where transported materials that create overhangs are stored (e.g., coal, bran, sand, glass). A pulse of compressed air directed from gas container trough outlet pipe into the tank causes the remaining material to peel off from the walls, which restores the free flow of the raw material.

Keywords: compressed air pulser, pneumatic control, piston valve, piston valve diagnostics.

1. INTRODUCTION

1.1. Pneumatic pulser system application

Known methods of cleaning the interior of tanks, transfers, and bunkers storing bulk materials involve the use of systems that generate vibrations of the walls of objects (vibrators, impact hammers) and systems that blow air or inert gas i.e. nitrogen into the interior of the structure (air-nitrogen cannons) [15] or pulsers shown on Fig. 1 and Fig. 2.

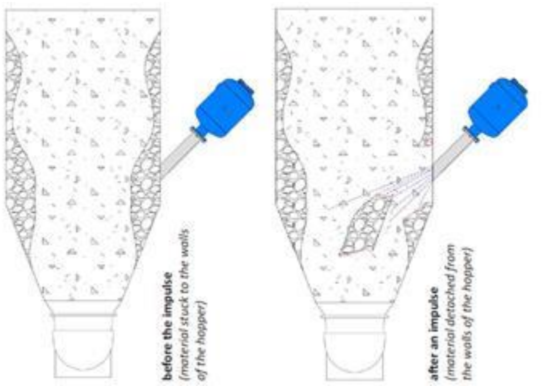

Fig. 1. The idea of using a gas pulser

Failure of the cleaning system results in the need to mechanically or manually remove overhangs (renovation teams providing mountaineering services), often stopping the production process and consequently stopping the raw material supply chain.

The operational process of treatment systems shows their insufficient reliability. This means failure-free operation during technological processes, i.e., the period from the scheduled inspection (during downtime of the production plant) to the next scheduled service inspection of the installed system. In the case of gas pulsers, the manufacturer guarantees failure-free operation for 1,000 cycles. It is assumed that four cycles will be launched in one day, which gives 35 weeks of operation. The remaining 17 weeks of the year are allocated to servicing equipment during the plant's production downtime.

The increased failure rate of the gas pulser creates the problem of unpredictability of the failure-free operation time of the system for clearing overhangs from facilities storing raw materials. This causes disruption of the continuity of technological processes in plants where bulk materials are transported [14].

This type of process is used by coal-fired power plants, grain plants, cement plants, glassworks, and mines. In mines, high equipment reliability, ensuring the operation of strategic industrial facilities, is especially expected.

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Fig. 2. Pulser system - application example

There are close connections between the operation of these facilities aimed at ensuring sufficient production efficiency, i.e., ensuring continuity of supply of electricity, heat energy or raw materials in the event of downtime, or failure of one of the plants of a given network.

1.2. Piston valve operation

The primary mechanism by which gas pulsers achieve their function (infusing gas to tank) is the piston's movement. Gas infusion happens when piston moves away from position at which it seals outlet pipe. The piston valve's operation resembles that of a pneumatic actuator. The advantages of this solution are high speed, low production cost, easy maintenance, and, above all, the availability of compressed air in plant installations [2,13].

The valve operates by supplying compressed air to the piston chamber (Fig. 3).

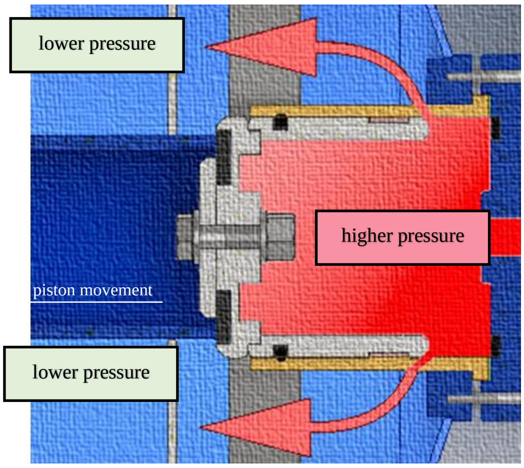

Fig. 3. 1st stable piston position: container charging

This causes the piston to move and expose the holes in the cylinder. The holes in the cylinder are intended to bring air into the pressure vessel. The piston closes the exhaust nozzle, and the pressure in the tank increases until it reaches a set value.

When the pressure in the tank is the same as the pressure in the piston chamber, the quick-release valve causes a pressure drop in the cylinder, which causes the piston to move and gas to be released through the exhaust nozzle. (Fig. 4).

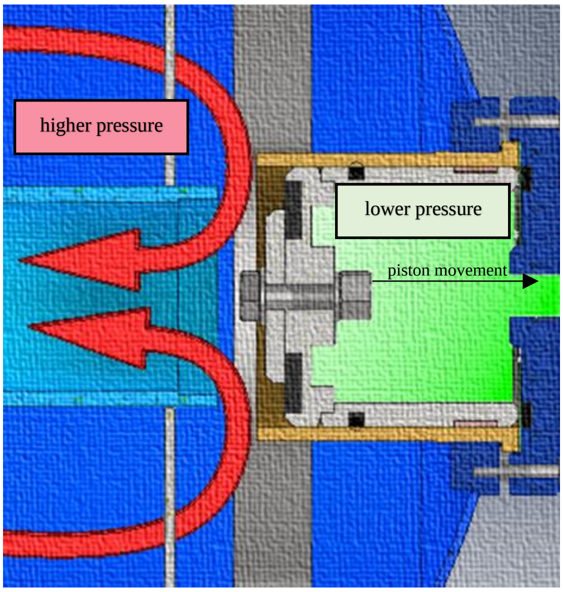

Fig. 4. 2nd stable piston position: container air discharge

Thus, the piston makes sliding movements in the same direction over a distance of 0.02m but in opposite directions.

1.3. Exploitation problems

1.3.1. Destruction of seals

The most common cause of failure of the gas pulser system is damage to the front and side seals (Fig. 5) resulting from friction and transferred forces caused by the stick-slip phenomenon [5]. A damaged seal causes air leaks from the pulser's tank and exhaust nozzle. In the described situation, the gas pulser exposes the plant to the costs associated with the production of compressed air.

Fig. 5. Damaged front seal

1.3.2. Piston cracking and deformation

It happens that only one of the seals, which is also the piston bumper, is damaged. In such a situation, the piston without cushioning breaks, causing a severe failure of the pulser as shown on (Fig. 6).

Fig. 6. Piston after 2000 cycles of work.
Damages marked by white paint

1.3.3. Thread damage of the nut

The service work carried out includes the need to thread holes and replace the impulse screws. During the operation of the device, the threaded connections are weakened (Fig 7). Under the influence of vibrations, the screws tended to loosen, which forced the manufacturer to use screws with drilled heads through which the wire was inserted.

The wire ties two adjacent screws together to prevent them from coming loose. The technical documentation also provides for periodic inspection of the tightening of screws when the devices are attached to the walls of tanks, silos, and bunkers with threaded connections.

Fig. 7. Damaged threads of the main nut

1.3.4. Damages of silo walls

Gas impulses are attached to the steel walls of the tanks through a relatively heavy welded nozzle. This assembly is over 0.8 m long, which causes stress in the area of welded joints. This intensifies the vibrations caused by the piston movement, causing damage to welded joints and deformation of silo sheets (Fig. 8).

The threaded connections by which the pulser is connected to the exhaust nozzle are also weakened and destroyed.

Therefore, the installation of the devices requires the use of reinforcing supports and protection in the form of a steel cable, protecting the pulser against a possible fall from a height. Welded joints require inspections and repairs.

If a leak occurs, there is a risk of material spilling out from inside the tank. For plants storing flammable and explosive materials, it is unacceptable for light to enter the tank due to the fire sensors used. There is a risk that this light will be identified as a potential fire.

Fig. 8. Weld repair and support installation

Summarizing, there are there are four major problems during pulser operation (see Fig. 9 for reference):

1. Vibrations and pulser structure and fixtures of pulser to tank/container superstructure,
2. Damages of the piston during settling in both stable positions for charging and discharging positions. Piston damage is caused by inertial forces acting on the piston during position change.
3. Side sealing damage caused by friction force and gasodynamic forces.
4. Frontal sealing damage caused by overload caused inertial force in transition to 1st stable position excretes by gas pressure change.

The listed above components of the gas impulser piston valve are shown in the cross-sectional drawing (Fig. 9).

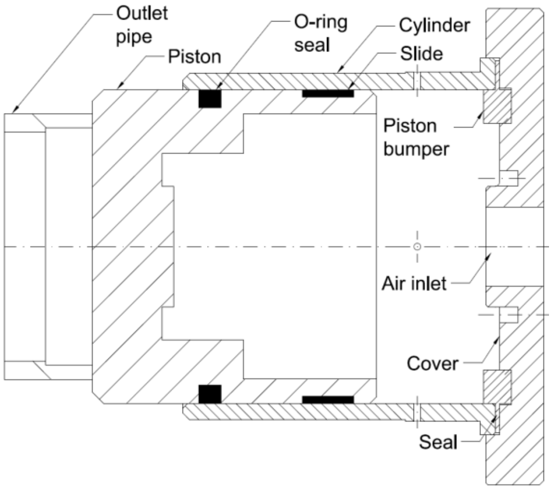

Fig. 9. Cross section of the piston in the
cylinder and discharge pipe

Supposedly these wears are generated mainly by piston's uncontrolled movement inducted by pneumatic forces. It resulting in violent piston's mass displacement and after that sudden stopping during sealing and unsealing of outlet pipe. Piston hits the objects at the end of its travel (i.e. front seals and pistons bottom). Moreover during transition and sudden halt the variable piston alignment to the cylinder creates wear on side seals and cylinder surface.

The problem here lays in piston dynamic understanding and piston movement controllability verification. This concerns this featured piston design and concerns steering by using only pneumatically inducted forces.

Moreover such investigations were not found in literature, so this research will extend the knowledge about such systems.

2. RESEARCH OBJECTIVES

In this investigation, we will concentrate on piston movement dynamics because it influences, as we believe, all phenomena related to exploitation problems. Moreover, the determination of piston [11] movement dynamics will lead to the following:

1. Diagnostic of gas pressure in piston – cylinder volume for assure proper pulser operation.
2. Control of piston movement and further - reduction of destructive phenomenon.
3. Extension of time of operation of pulser and its overall reliability.

In particular, we will focus on the piston movement during its transition from the 2nd to the 1st stable position. Piston in this position seals the discharge pipe (Fig. 8) and after sealing it completely charges the pulser's container with pressurized air from under pressure 408 kPa to 612 kPa, according to the user's decision.

Three experiments were designed:

1. The first one is intended to determine the pressure at which the piston is in equilibrium i.e. all forces acting on it are cancelling.
2. The second one serves the purpose of investigating the influence of the seal as well as its lack of piston movement and impact vibrations.
3. The third one is intended to check the piston for behaviour for different air flow rates.

The experiments courses are intended to gain the knowledge about the following suspects:

1. What influences the acceleration of the piston in the movement phase when it transits from 1st to second stable positions.
2. Are there any indicators of piston acceleration or movement in the cylinder as well as of its reaching one of the stable positions.
3. Is the speed and position of the piston controllable in order to reduce impact vibration and pulser elements damage.

3. TESTS

3.1. Test Stand

A dedicated research stand (Fig. 10) was developed to ensure the ability to perform measurements while maintaining the most common operating parameters of the device. This is a particularly important achievement because the measurement is performed directly on the described device, so the results obtained are reflected in reality.

a)

b)

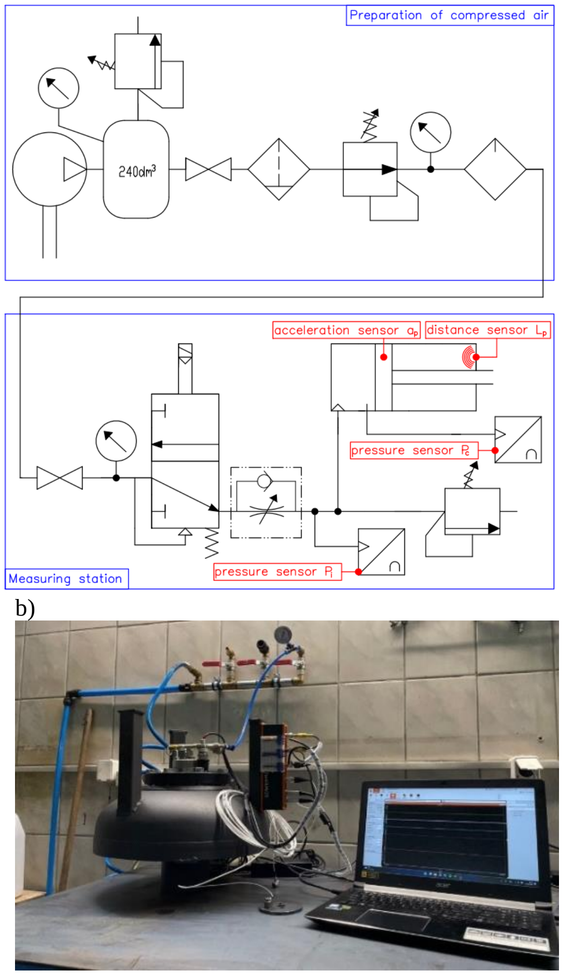

Fig. 10. Diagram of the pneumatic system and the measurement setup (a) and photo of the measurement station (b)

The airflow characteristics of the throttle valve are shown in Fig. 11.

The test stand is equipped with devices, which supplying dehydrated air with a maximum pressure of 600 kPa [9]. The pneumatic installation was designed in way to ensure safe operation for people in the near of the station. Pressure gauges and safety valves were installed for this purpose.

3.2. Measurement system

The measurement equipment includes the air pressure sensors shown in Fig. 13, an accelerometer, an optical distance sensor, and a device recording data obtained from the sensors.

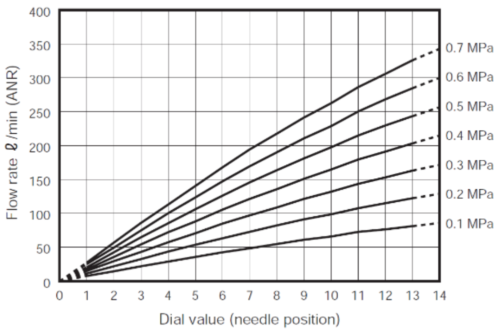

Fig. 11. Flow characteristics of proportional valve depicted earlier in Fig 10a

The accelerometer is mounted directly on the piston bottom, the optical distance sensor is mounted above the piston, and the pressure sensors are installed in the pneumatic bus supplying compressed air directly into the piston chamber.

The data recorder is equipped with four analog input channels of the following types: voltage, IEPE (ADC 24-bit delta-sigma with anti-aliasing filter). The measurement is performed simultaneously on all channels.

The detailed parameters of the sensors used are listed in Table 1, and the diagram and connection method are shown in Fig. 12.

Table 1. Sensor parameters

Data logger parameters	
Input accuracy:	±0.03 % of reading ±0.02 % of range ±0.2 mV
Gain Drift:	Typical 10 ppm/K, max. 20 ppm/K
Offset Drift:	Typical 0.5 µV/K + 1 ppm of range/K, max 2 µV/K + 3 ppm of range/K
Distance sensor parameters	
Range:	100-1500 [mm]
Frequence:	60 [Hz]
Tolerance:	± 0.2 [mm]
Pressure sensor parameters	
Range:	0~1600 [kPa]
Measurement accuracy:	0.5 [%]
Response time:	< 2.0 [ms]
Acceleration sensor parameters	
Range:	4905 [m/s^2]
Sensitivity:	1 [mV/m/s^2] ± 5 [%]
Frequency response:	1-5000 [Hz] ± 10 [%]
Frequency response:	1-10000 [Hz] ± 10 [%]
Resonant frequency:	> 36 [kHz]
Broad band resolution:	0.023 [m/s^2]
Maximum shock:	49050 [m/s^2 pk]

What is important is that the pneumatic sensors and steering elements are grouped as in [6] in the so-called measuring station.

In the future, valve control will be implemented using the PWM control method [1]. The measurement system is installed on a specially prepared part of the gas pulser (Fig. 10b).

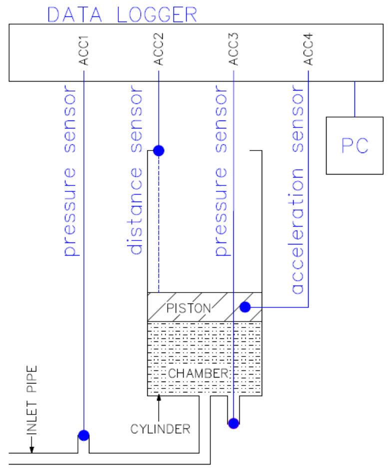

Fig. 12. Diagram of the measurement system

It is designed so that the distance between constituent elements are the shortest as possible. The control and regulation process is carried out using a pressure reducer, throttle valve, and electromagnetic or manual release valve [9].

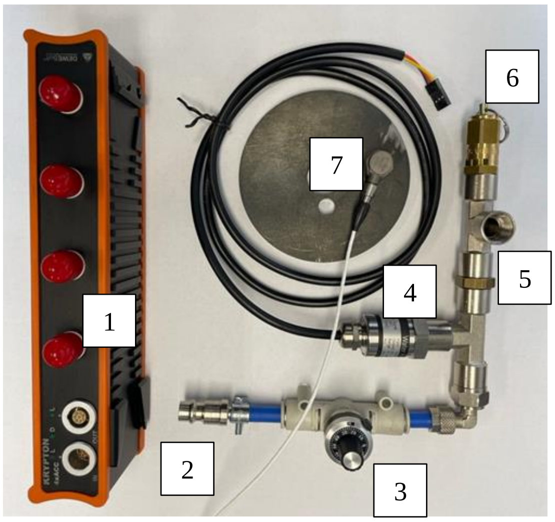

Fig. 13. Components of the measurement system (1 - Data logger, 2 - Air supply, 3 - Throttle valve, 4 - Pressure sensor, 5 – Air supply to the air chamber, 6 - Safety valve, 7 - Accelerometer)

3.3. Experiments Course

The experiment involved examining the parameters accompanying the operation of the piston valve of the gas pulser on a specially prepared measurement station.

The tests were carried out using two control methods. The first one was a reproduction of the control used during standard operation of the gas pulser, i.e., supplying air with a pressure of 0.6 MPa to the piston chamber, which was equipped with seals. It was assumed that the impact of seals and the stick-slip phenomenon on the device's control capabilities and the generated accelerations and forces [7] would be investigated. The second control method involved measuring the air pressure that would cause the piston to rise and examining the possibility of controlling its position.

The following parameters were measured: piston acceleration, piston position relative to the outlet pipe, air pressure in its chamber, air pressure in the pneumatic conduit supplying the laboratory station.

The input parameters were a supply pressure of 612 kPa and a mounting distance of the position sensor relative to the piston of 120 mm.

In the first stage of the experiment, the piston was in the position where h2 = 0 mm (Fig. 14). The pressure in the supply system was equal to atmospheric pressure. The measurement system was launched, the sensors were calibrated, and then the pressure in the supply line was increased to 0.6 MPa using a valve. Due to the increase in air pressure in its chamber, the piston moved to the position h1 = 0 mm (Fig. 14).

Data from the sensors were recorded, synchronized, and analyzed.

The obtained acceleration values were transformed according to formula (1) to obtain the value of velocity v and distance s (2).

$$v = \int_0^+ a dt \tag{1}$$

$$s = \int_0^+ v dt \tag{2}$$

The data recorded as a result of the measurement activities carried out were synchronized with each other using the tools offered by the recorder software. It allows you to mark those results that show a sudden and dynamic change in their values by inserting the same marker in the measurement of each sensor. The user independently determines the value of the result that will be treated by the system as a marker of the recorded event in time. In the case of the described experiment, the signal from the distance sensor (piston movement) was taken into account.

The measurement process starts at the same time for each sensor, and the data is recorded at a frequency of 100 Hz.

The safety of conducting the experiment on the pressure device was ensured by the use of a safety valve and a pressure gauge. Compressed air was supplied remotely from a safe distance for the system user.

4. RESULTS

4.1. Piston equilibrium

4.1.1. Piston without side seals and guidance ring

In this experiment, the piston without side seal and guide ring was held as steady as possible with speed and acceleration almost equal zero.

During the experiment, the operator tied achieve situation, which can be described by the formula:

$$Fp - Fg = 0 \tag{3}$$

where:

F_p – propulsion force generated by air pressure,

F_g – gravitational force related to mass of piston.

It was kept in the middle between two stable position ca. 1cm below the second stable position. The proportional valve was used to control the piston position marked as h_1 in Fig. 14, and forces equilibrium state at v=0. The pressure in cylinder was measured at least 1024 times with 0.01s interval and for all of the data were mean value as well as standard deviation were calculated. This procedure was repeated 15 times. After that, the experiment results were compared to calculations and summarized in Table 2 to assess the discrepancy.

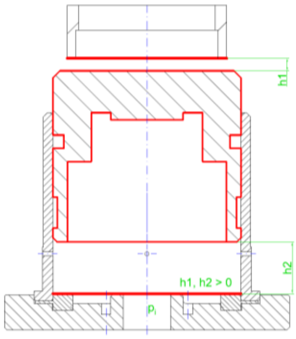

Fig. 14. Piston position during equilibrium experiment

At first, it was noticed that there was a 0.6 kPa pressure difference between sensors output. This situation happens only if nonzero and measurable air flow is passing through the pipes.

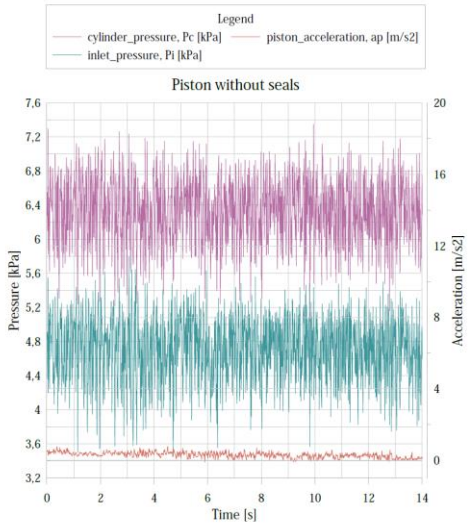

Fig. 15. The piston in equilibrium. Fourth repetition of the experiment

Moreover, the pressure difference is then greater as the airflow becomes greater. This is also vivid in the next experiments. This observation can be utilized for diagnostic rules formulation when air flow indication and diagnostics is needed and for air-tightness of pulser.

The calculated pressure needed (Table 2) for the piston to be in a stable position was ca. 0.5 kPa higher than the mean value measured in experiments. It still places itself in the range of sensors uncertainty. More, there was never exactly a=0 in the experiment. Rather, the acceleration varied from -0.1 m/s^2 to $0.2 m/s^2$ (when noise was filtered out as in [4,8]).

Table 2. Comparison of experiment results and calculations

Source	p	Uncertainty
Experiment	4.87 kPa	±0.46 kPa
Calc	5.39 kPa	±0.01 kPa

It is important to mention that pressure sensor uncertainty is ±0.843 kPa, and both pressure sensors mean value deviation under the same pressure in range from 0 to 612 kPa) was no greater than 1.102 kPa.

The main conclusion from that experiment are measured pressure is close, but not exactly as foreseen by calculations, but still remains in sensors uncertainty.

Higher pressure than 5.39 kPa and a=0 will indicate the presence of additional forces (for example, some frictional from guide rings and side seals). These forces must be considered in the balance of forces equation.

Higher pressure than 5.39 kPa and a<>0 (only in that experiment) will indicate propulsion of the piston by compressed air pressure mitigated only by inertial force from mass piston and gravitation.

4.1.2. Piston with side seals and guidance ring

This time, the piston was equipped with a side seal and guide ring. Because of friction forces involved, and because they are usually velocity dependent, the pressure was slowly increased until the sudden movement of the piston occurred. The last pressure value at which the piston was stationary is considered as the highest one which keeps the piston steady. Any greater force results in piston movement. The balance of the forces for that system describing (4).

$$Fp - Fg - Fs - Fgr = 0 \tag{4}$$

where: F_p – propulsion force generated by air pressure, F_g – gravitational force related to the mass of the piston, F_s – friction force of side seal, F_{gr} – friction force of guidance ring.

As suspected, the pressure at which the piston begins to move is higher than for piston without friction generating elements. The value p_p=58.17 kPa were measured as mean of 15 trials. This is almost 10 times greater figure than in case of piston pressure without seals.

The static friction forces sum of side seal and guidance ring were calculated as in (5).

$$Fp - Fg = Fs + Fgr \tag{5}$$

where: F_p – propulsion force generated by air pressure, F_g – gravitational force related to the mass of the piston, F_s – friction force of side seal, F_{gr} – friction force of guidance ring.

Finally, the static friction forces total is F_s+F_{gr}=537.3N, which is almost 10 times greater than the gravitational force generated by pistons mass.

Unfortunately, there is a stick and sleep phenomenon, and during piston movement, the friction decreases.

4.2. Piston movement controllability

To reduce piston impacts and superstructure vibrations a control over piston movement must be achieved. To do this, there must be at least two opposite forces which allow to keep piston forces in balance, accelerate and decelerate it in the range of its movement according to the direction to the second stable point [3, 10].

One of the force must be steered. This is the pneumatic one – the F_p. In fact, the steering is realized by a change of air pressure beneath the piston [3]. And it is known from earlier experiment that pressure greater than 58 kPa brings the piston to the move. If the piston is in the move, then immediately the F_s and F_{gr} forces reduce its values according to [2] by 15% and so it is assumed in this case. That means the pressure reduction after setting the piston in the move must be greater than the 15 percent to invoke deceleration of the piston. In the case of that pneumatic system, it must be reduced to 49.3 kPa.

According to performed experiments for different air inflows, the pressure drops only to 51 kPa (Fig. 16).

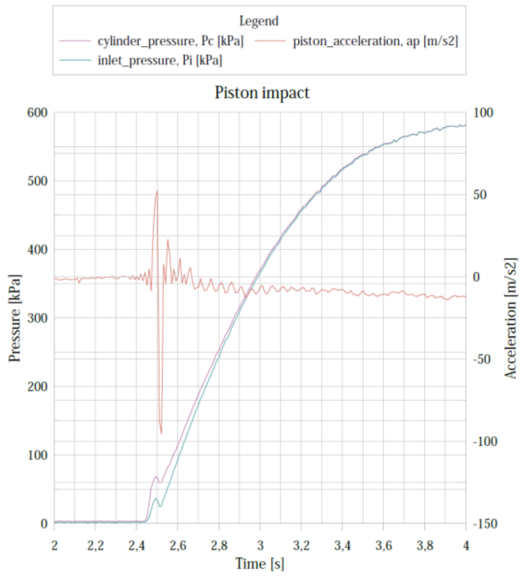

Fig. 16. Characteristics of the acceleration value upon piston impact

Therefore, no matter what airflow is set and no matter what max pressure before the proportional valve is applied (in the pragmatic range from 4 to 6 bar), there will be no piston braking because of stick and slip phenomenon. The piston will accelerate all the way to the 2-nd stable point and create a substantial impact of up to 150 m/s^2 and invoke some vibration.

5. CONCLUSIONS

The following main conclusions can be made:

1. There is no control possible of piston movement between stable points in the actual applied control method because of the lower kinematic friction coefficient, the impossibility of sufficient

pressure drop in time 0.02s, and ten times greater friction forces than needed for piston lift.
2. The lower kinematic friction coefficient influence can be reduced by careful selection of guiding ring and side sealing material.
3. There is a difference in pressure during air inflow, which can be utilized for pulser air tightness diagnostic and monitoring damaged seals and piston bottom.

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