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DIAGNOSIS OF PNEUMATIC CYLINDERS USING ACOUSTIC EMISSION METHODS

DIAGNOSTIKA PNEUMATICKÝCH VÁLCŮ METODOU AKUSTICKÉ EMISE

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KEYWORDS

Acoustic Emission (AE), Pneumatic cylinder, Detection Coefficient, Energy, Loading, Defect, Leakage.

KLÍČOVÁ SLOVA

Akustická emise (AE), pneumatický válec, koeficient detekce, energie, zatížení, defekt , únik.

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1. Introduction

This study tried effectively to apply real-time diagnostics to detect any malfunctions in automatic production lines and in the transport field, and looking for new ways to inspect and predict any defects. One option is the condition monitoring by acoustic emission method.

Non-destructive testing (NDT) is defined as the technical method to examine materials or components in ways that do not impair future usefulness and serviceability. NDT can be used to detect, locate, measure, and evaluate flaws; to assess integrity, properties, and composition. Each NDT technique has both advantages and disadvantages with regard to cost, speed, accuracy, and safety [1].

Acoustic emission testing is considered to be an important method of non-destructive testing (NDT) and condition monitoring. It can be conducted during operation and does not require any interruption of activity. Acoustic emission is the term given to transient elastic stress waves generated by the energy released when microstructural changes occur in a solid material or turbulence in the liquid. The main factors of the propagation velocity of the elastic stress wave are the wave type, the wave frequency, and the properties of the material. These waves are detected by sensors (transducers) attached to a specific place on the surface; the sensors convert the mechanical disturbance into voltage. Acoustic emission is usually divided into many applications such as: pressure vessel testing, diagnostics condition monitoring, leak detection etc. Leak detection includes detecting, locating and assessing leaks, and determining when the fluid flow becomes turbulent. Fundamental principles of AE leak detectors rely on the fact that escaping gas or liquid through a small breach creates a high-frequency sound wave that travels through the enveloping system via an acoustic leak path [2].

Pneumatic actuators convert fluid energy into straight line motion (linear actuators). During normal operation of a pneumatic actuator, a variety of defects can occur, which could lead to a catastrophic failure if left undetected. Therefore, it is crucial to detect even the minor problems and their sources as quickly and accurately as possible to ensure an uninterrupted safe operation. Defects may affect the function of the pneumatic cylinders and cause malfunctions [3].

The existence of the detection coefficient “D” facilitates the evaluation of defects, taking values that range from 1 to 10, with 10 being highly difficult to detect. The detection coefficient was taken from the method FMEA (Failure Mode and Effects Analysis) and was developed and classified using AE. The Coefficient "S" expresses the severity of a particular defect [4].

A number of undamaged pneumatic cylinders were tested with AE before artificial defects were made on the same cylinders and the results were compared. And undamaged and damaged cylinders were analysed using a frequency spectrum within a specified time and the results were compared. A set of defects was identified through this comparison, but the frequency spectrum, counts and events were not sufficient to identify all defects. The frequency spectrum was replaced later by the RMS, the average energy of acoustic emission signal RMS gives a clear picture of the different responses between damaged and undamaged pneumatic cylinders [5].

The cylinders were loaded gradually by different weights in a vertical direction. The effect of the defect occurs when the cylinder is loaded at the retreat and progress strokes. This defect affects the relationship between the applied load and the recorded signal of the sensors. The relationship between the RMS curve and loading is linear [6].

The main goal is to investigate the possibilities of implementing AE system for pneumatic cylinder leakages detection. The AE laboratory at the “*Institute of Machine and Industrial Design of Brno University of Technology*” has long focused on the use of AE for diagnostics of damage development in cyclically loaded materials and machine parts (standard fatigue, contact fatigue, bearings etc.). In addition to these relatively traditional applications, theses laboratory specialists implement other non-traditional possibilities of using acoustic emission method. This is possible by using a prototype of the newly developed diagnostic equipment.

2. State of the art and previous studies

2.1. Relationship between AE and leakage

The parameters analysis of AE signals in valves is a dominant method in the signal processing field. Compared with the full waveform analysis method, the parameters analysis has many advances, for example, fast recording and rapid processing. Many parameters, such as the rise time, ring down counts, amplitude, peak, duration and root mean square (RMS) value, and kurtosis, were analysed using this method. *Dickey et al.* found that the peak amplitude of AE signal in frequency domain was tightly related to transducer response or valve geometry [7]. The characteristic of AE signal in frequency domain and a relationship between the AE signal and the leakage rate were studied in a ball valve. *Jiang et al.* explored the function between the Reynolds number (Re) and the sound pressure level of gas leakage with AE technique. The mass of gas leakage in the flow field was calculated, which is the foundation for the detection of the valve leak [8]. *Gao et al.* presented the quantitative relationship between the valve leakage rate of coal-fired power plants and the AE_{rms}. Its precision was verified by the practice results. The experiment system which consists of the leakage system and the AE measurement system. For leakage system, valves are chosen to be the test subjects, which mainly are ball and globe balls because of their wide applications [9].

The correlation between the AE parameters and leakage rate are able to monitor the operating condition of critical valves. Some researchers tried made improvements of portable devices for leakage detection of valves based on the previous studies. The principle of measurement is that using a sensor to detect the leakage of valves this sensor converting the elastic wave to voltage by micro processing to the parameter of the AE signal. Simplifying the system and reducing the cost are depending on the accuracy. The devices are particularly inadequate for detecting the leakage of valves applied in engineering fields, because the devices that detect the leakage of valves with the AE technology are usually huge and inconvenient to move. [10].

Yang et al. applied the AE technique to identify the internal leaky modes of globe valve, which could be classified as the untight closing and crack. It was tested in the valves and the results showed it worked effectively [11]. *Wang et al.* proposed a method for detecting the actual working condition of a valve using the AE signal and the simulated valve motion. This method can easily distinguish the normal valve, valve flutter, and valve delayed closing conditions [12].

Pollock et al studied the characteristic of acoustic leak signals owing to the gas leakage through a ball valve in frequency domain. As a consequence, the correlation between the AE and the leakage rate was presented [13]. *Dickey et al* found that the peak amplitude of AE signal in frequency domain is independent of leak part or leakage rate but dependent on transducer response and valve geometry. However, they did not describe the relationship between AE parameters and valve leakage rate which is the primary basis for predicting leakage rate by AE method [7]. *Watit Kaewwaewnoi, Asa Prateepasen and Pakorn Kaewtrakulpong* present the relationship between AE parameters and the leakage rate of valve at various valve sizes and inlet pressures. The equation utilized to find out the leakage rate at different valve sizes and inlet pressures was also established. The basic mechanism generating AE signals in a leaking valve is the decay of turbulence resulting from the high pressure, high velocity of fluid flow [13]. *Gao et al.* presented the relationship between the AE parameters and the fluid filed and valves. It was found that the ring-down counts, energy, amplitude, or RMS of AE signals induced by leakage was directly proportional to the inlet pressure. However, the AE signal induced by the valve leakage is continuous. Two parameters are used to describe the leakage [14]. *Kaewwaewnoi et al.* found that a good correlation existed between the leakage rate and the ASL. An equation related to the valve leakage rate was achieved. Many literatures presented the average energy of AE signal (AE_{rms}) as a more sensitive parameter of valve. Chen et al. evaluated the various parameters of AE signals in terms of their capability of estimating the internal leakage rate of a water hydraulic cylinder. They have shown the RMS value was more suitable to interpret AE signals generated by internal leakage [15]. *Kaewwaewnoi et al.* also found the relationship between the AE_{rms} and the parameters such as inlet pressure levels, valve sizes, and valve types. The AE_{rms} could be used to predict the actual leakage rate qualitatively [16].*Sim et al.* employed AE signal to detect valve failure in reciprocating compressor. Any abnormalities of the valve motion could be detected effectively by analysing the RMS value. In their further study, the detection of other types of valve and the initiation of materials deformation in valves could be achieved [17]. *Yan, Jin, Y. Heng-Hu, Y. Hong, Z. Feng, L. Zhen, W. Ping and Y. Yan* studied the relation between valve and acoustic emission. A review of the applications of AE techniques for detecting the condition and faults of valves was presented. The popular parameters analysis methods were discussed. The parameter of AE_{rms} is proved to have a strong relationship with the fluid parameters and the valve parameters, such as the valve types and valve size, the leakage rate, the inlet pressure, and the types of fluid. The detection of leakage, condition monitoring of faults, cavitation detection of valves, and portable measurement device were proposed in this review [18]. *Bezn and Joon-Hyun Lee et al* suggested that AE_{rms} could be used to determinate the open and close positions of valves, such as relief and safety valves, and also to indicate aging and degradation of check valves in nuclear power plants. The RMS values of AE signal in different failure modes are shown in Figure 2.1 [19].

2.2. Location of leakage

Several researchers has studied The AE since 1980s. *Kupperman et al.* demonstrated that the leak detection in reactor components with acoustic emission with the minimum leak rate as 0.23 litter/hour in laboratory environment; however, the threshold to detect the leak rate depends on pipe geometry, material, internal pressure and measurement system selected [20]. *Miller et al.* designed a reference standard pipe to evaluate the AE equipment for leak detection. The fundamental advantage of the AE method is the capability to pinpoint the leak location in real time [21]. *Grabec* developed leak localization using cross correlation technique, which has limited success due to the influence of reflected waves and multiple wave modes. There are many studies since then to improve the location accuracy of continuous emissions [22]. *Gao et al.* also studied the effect of filtering on leak detection in plastic water pipelines [23]. *Fukuda and Mitsuoka* applied pre-whitening filter to AE waveforms to improve the leak detection and location through identifying a definite peak in the result of cross correlation of two waveforms [24]. *Wavelet* transformation is implemented to analyse complex leak signatures [25]. *Jiao et al.* used the dispersion curves of pipelines to identify the leak location with single sensor while the waveform can be influenced with reflections and multiple-sources in a realistic test. However, for any leak localization method, the dispersion (wave mode and frequency dependent velocity) and attenuation limit the minimum detectable leak rate and the maximum sensor spacing [26]. *Muggleton et al.* studied wave attenuation in plastic water pipes for frequencies less than 1 kHz. The attenuation factor depends on pipe material and geometry, surrounding medium and internal medium [27]. The leak detection and location in gas pipelines are more challenging than water pipelines because of smaller particle size of gas as compared to water that is the main source of AE through creating turbulence event at the leak location. Leak detection and location becomes more challenging for soil-buried pipelines as compared to on-ground pipelines or submerged pipelines. The reliable leak detection using the AE method requires understanding leak waveform characteristics as a function of pipe operational conditions and estimating the signal attenuation to define the discrete sensor spacing for pinpointing leak position spatially. The leak detection in gas pipelines using a continuous monitoring system can be used as an early diagnostic tool to prevent catastrophic failures [28].

Shama et al. simulated a section of underwater oil pipeline to study the possibility of using AE technology to monitor leakage in a submarine oil pipeline. The researchers set up various defects and leaks with different flow rates in the pipelines [29]. The results show that AE can monitor and identify leakage in underwater oil pipelines. To address the inconvenience of leak measurement in long-distance buried pipelines, *Xu et al.* designed a guide rod that can be inserted into the soil. This rod extends directly to the surface of the pipeline. The AE information transmitted by the guide rod is used to locate the damaged area [30]. For pipeline leakage with high-pressure gas, *Mostafa pour et al*. deduced the radial displacement of pipeline vibration in AE wave propagation and compared the measured signal spectrum with numerical simulation calculation, proving that the AE stress wave can theoretically be used in pipeline leakage detection. To solve two problems related to leakage monitoring in buried liquid-filled pipes. This study attempts to locate the AE sensors installed inside a pipeline to collect leakage signals and to verify the effectiveness of the method used. This provides a basis for subsequent built-in self- capacitive AE sensors to monitor the damage of fluid - filled pipelines. In addition, to identifying leakage types and locations. Moreover, the time-delay estimation method is employed to accurately locate the leakage source in the pipeline [31].

2.3.High frequency and pneumatic cylinders

Yan, Jin, Y. Heng-Hu, Y. Hong, Z. Feng, L. Zhen, W. Ping and Y. Yan studied Pneumatic cylinders are often used for various equipment. They are wearing down and it is an urgent problem to diagnose working conditions of pneumatic cylinders. The diagnostics of pneumatic cylinders is mostly based on pressure measurements and visual methods. The visual methods are simple and cheap, but inaccurate [32].

2.4.Cylinder and loading

T. Fujita, J. Jang, T. Kagawa and M. Takeuchi [33] studied that drive a pneumatic cylinder, meter-out circuit is used in many cases, since time to move the piston is constant even if the load is changed. That is, the meter-out restriction method realized velocity control. However, this principle of velocity control has not been explained sufficiently. The purpose of this study is to clarify the velocity control mechanism. Consequently, six parameters controlling the cylinder response are obtained. As a result, by drawing the block diagram of cylinder system, it is found that the compliance of a cylinder makes the feedback loop in cylinder velocity and the flow characteristics of retread in damping compensates the constant velocity for changing a load force.

M. Doll, R. Neumann and O. Sawodny [34] studied dimensioning pneumatic cylinders for motion tasks, considered the standard pneumatic cylinders with common directional control valves and exhaust flow throttles. The dimensioning of the cylinders for point-to-point motions is regarding energy efficiency. The proposed strategy is based on the Eigen frequency and considers similarity transformations.

3. Analysis and evaluation of references

Effectively applying acoustic detection methods requires full characterization of the particular leak signals, including the frequency spectrum, attenuation, and minimum leak rate detectable under given test conditions. Testing methods of leaks is rarely used to test the leak in cylinders. Our test was to reduce the noise by the filters, they tried to apply AE to detect leak and reduce the noises and to find the relation between the AE parameters and leak. All experiments had tried the frequency spectrum in the first [7 - 12]. Modelling an internal leak in a valve with unknown leak geometry is inherently difficult to detect and presenting relationship between AE parameters and the leakage rate. The flow is laminar when Reynolds number $Re < 2300$, transient when $2300 < Re < 4000$, turbulent when $Re > 4000$ at the orifice [13]. The power spectrum density of fresh water was greater than the compressed air because the acoustic impedance of water was closer to that of the valve material.

For continuous AE signal from both time and frequency domains, the most frequently used AE parameters are the average energy (AE_{rms}) and the Average Signal Level (ASL), The AErms increased with inlet pressure, which was similar to the relationship between the AErms and the leakage rate. The AErms was inversely proportional to the size of valve. The AErms was inversely proportional to the flow coefficient When the leak rate increases the amplitude of RMS increases with constant pressure and different valve size or in constant valve size and different pressure. All results have shown that the AE technique can work well in the field of valves [14 - 19].
Leakage may also be characterized by the effective diameter of leakage orifice. A method of indirect orifice diameter estimation using working pressure and flow rate pattern magnitude of initial cylinder operation phase was presented. Comparing with other leak detection techniques, acoustic emission methods give strong advantages in regard to leak location, continuous on-line surveillance, high sensitivity, quick response time, monitoring hard to-access locations, and potential estimation of leak rate. Typical AE is able to determine the location of defect in all last researches [20 - 31].
All defects are undesirable. The applications of new processing methods of AE signals including fast Fourier transform (FFT), wavelet transform, Hilbert-Huang transform (HHT), neural networks, and genetic algorithm in valves are presented. AE activities increases when there is leakage when the leak rate increases the amplitude of AE increases [32].
By using only, a restriction the meter-out circuit realizes velocity control. The load change does not affect much the piston velocity. It can be used to dimension systems with approximately constant speed, and it delivers interesting relations between all the system parameters. Furthermore, it can be used to increase energy efficiency by calculating a reduced, correct pressure level for existing [33,34].

4. Aim of the dissertation thesis

4.1. Objectives of the research

The aim of this work is to develop a new efficient diagnostic procedure for checking the function of pneumatic cylinders using acoustic emission.
This diagnostic procedure is able to detect distinctive differences that determine whether the cylinder is damaged or undamaged by finding a typical acoustic emission signal that associated with a particular type of damage, which it happens by select the necessary parameters of AE.

Determination of the relationship between parameters of AE and defects in the cylinders, precisely the relation between RMS of AE and the leakage that elucidates the rate and the location of leakage.

The possibility to determine the type of defects in the cylinders after production in order to change the damaged parts

The possibility to determine the quality of cylinders after production, and Predict the defect during actual operation of the cylinder (online checking) and determining the level of danger. Determination of the diagnostic criteria that evaluate the quality of the pneumatic cylinder and detect the defects, these diagnostic criteria are inserted later by MATLAB to make a program that is capable of evaluate the cylinders.

The novelty of the proposed solution lies in a very new concept for mobile diagnostic tool using AE methods with greater sensitivity of detection of defects. Simplified designing process of electronic equipment for data capture development and evaluation software.

4.2. Diagnostic criteria

1. The RMS was normalized, and the different responses between damaged and undamaged pneumatic cylinders were recognized by the time delay of the strokes.
2. The differences were identified by comparing the max RMS from the sensor fixed in the head cap of the cylinder and the max RMS from the sensor fixed in the rear cap of the cylinder for one cycle in the retreat stroke.
3. The damaged and undamaged cylinders were distinguished using the difference in energy values present in the signals from the two sensors in the retreat stroke.
4. The final evaluation of the cylinder was determined by the calculation of the total value of RMS.

4.3. Hypotheses and questions.

4.3.1. The problems (disadvantages)

1. The different behaviour of recorded signal in undamaged cylinders.
2. Assembly of sensors on the cylinder and the type of the cylinders.
3. The noise is in the signal.
4. The signal is mixture noise of mechanical movement and pressure air inlet and outlet.

4.3.2. Hypotheses

The changing of signal takes place when the cushion portion piston inserts to cushion seal causing the initiation of throttling or damping.
When the value of the leak usually increases the signal of AE increases.
The allowance of leakage value in the cylinder is no more than 6 pa/s.
The flow is laminar when Reynolds number $Re < 2300$, transient when $2300 < Re < 4000$, turbulent when $Re > 4000$ at the orifice.

Scientific questions

1. What is the relationship between pressure in the pneumatic cylinder and the AE?
2. What is the relationship between the kinematic energy in the cylinder and AE?
3. What is the relationship between the friction and AE?
4. What are the effects of the mixing defects in the cylinder to the AE?
5. What are the suitable conditions of testing the cylinder using AE?

4.4. Thesis layout

1. Finding the relationship between AE and the leakage using frequency spectrum.
2. Finding the relationship between typical acoustic emission signal and particular type of damage in the cylinder using RMS.
3. To find distinctive differences that determine whether the cylinder is damaged or undamaged.
4. The relationship between AE parameters and loaded cylinders.

5. Experiment, Measurement and Methods

5.1. Pneumatic actuator

All results of this work is depending on PS pneumatic cylinders as shown in figure 6.1.

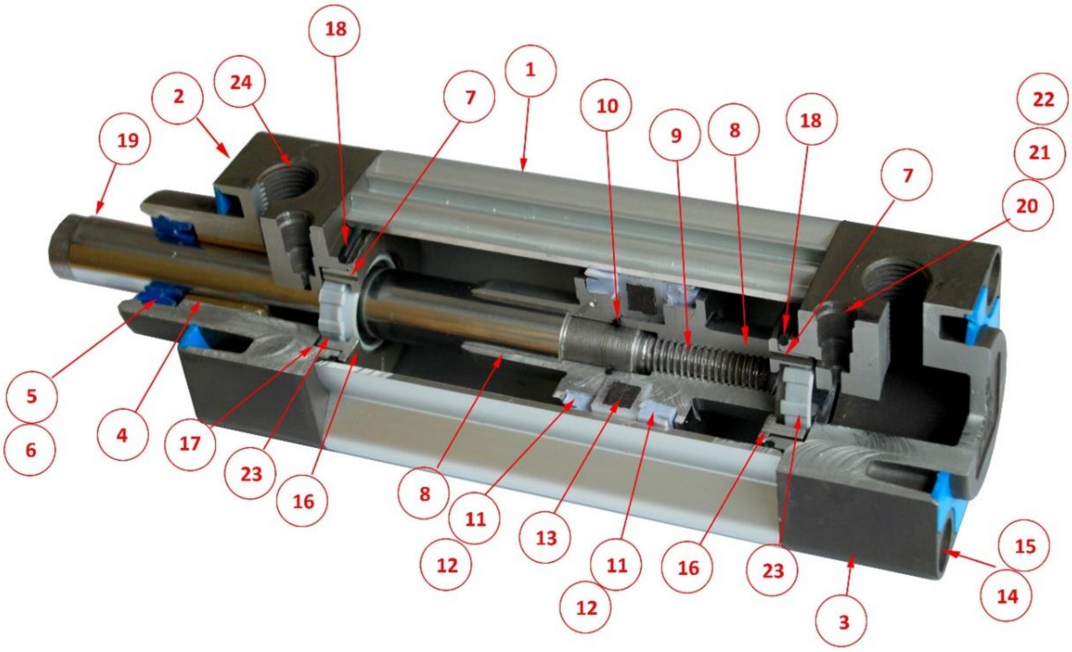


Figure 5.1 Parts of pneumatic cylinder PS.

(1) Cylinder body (barrel). (2) Head cap. (3) Rear cap. (4) Rod Bearing. (5) Rod wiper (Wiper Seal). (6) Rod Seal lip-seal. (7) Needle valve. (8) Head and rear Piston. (9) Piston fastener (Tie Rods). (10) O- ring seal piston fastener. (11) Piston seal lip-seal. (12) Piston seal bumper seal. (13) Magnetic ring. (14) Head cap fastener. (15) Rear Cap fastener. (16) Head cap cushion, rear cap cushion. (17) O- Ring seal needle valve. (18)O- Ring seal cap cushion. (19) Piston rod. (20) Throttle needle valve. (21) O- ring seal throttle needle valve. (22) Throttle knop. (23) Cushion check seal. (24) Porting.

The characterization of PS actuator: width 50mm, inside diameter 40mm, stroke 100mm, and diameter of rod 12mm port 6mm. The process of understanding of defects requires detailed knowledge of the different parts of the cylinder. The main parts are shown in figure 6.1.

5.2. Defects

Leakage, Leakage in motion, Galling, Mechanical defects.

5.3. Types of specific defects

All defects are undesirable. Defects may affect the function of the product and cause malfunctions. The defects were simulated and made artificially: leakage, leaks in motion, galling and mechanical defects. Three types of defects were chosen. All have a high value of detection coefficient

Unsealed O-ring thread Piston and leakage - NP08, PP03

Unsealed O-ring front and rear Piston and leakage - NP07

Mechanical defect M04

5.4. Equations

AE_{rms} can be defined as:

$$AErms = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} v^2(t)dt} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} v^2(n)} \qquad 5.1$$

Here, *v* is the voltage signal from an AE sensor, *t* the initial time, *T* the integration time of the signal, and *N* the number of discrete AE data within the interval *T*. Thus, we are attempting to highlight the parameter RMS.

Root Mean Square and Energy defined as:

$$RMS = \sqrt{(1/N)\sum_{1}^{N} u_i^2 \ \ [V]} \qquad 5.2$$

$$E = \sum \mathrm{U}_i^2 * \mathrm{dT} \quad [V^2 * s * ohm] \qquad 5.3$$

Where N discrete voltage values sampled over the measurement period, U is voltage, dT is the value of sampling (in our case 0.004s).

5.5. Stand of the experiment

Horizontal stands for pneumatic cylinder without load

The experiment platform contains testing devices including AE sensors, air pressure supply, pneumatic control system, linear potentiometer and an AE analyser, in addition to damaged and undamaged cylinders. Two sensors which are installed at different positions of the cylinder are referred to as (A) on the right and (B) on the left as shown in figure 6.2.

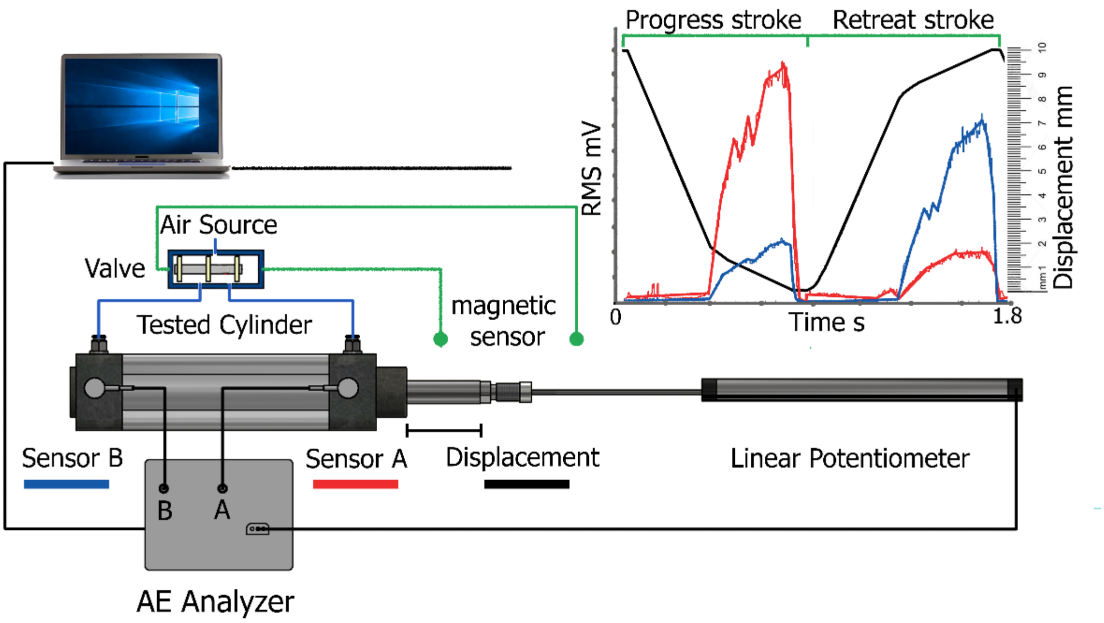
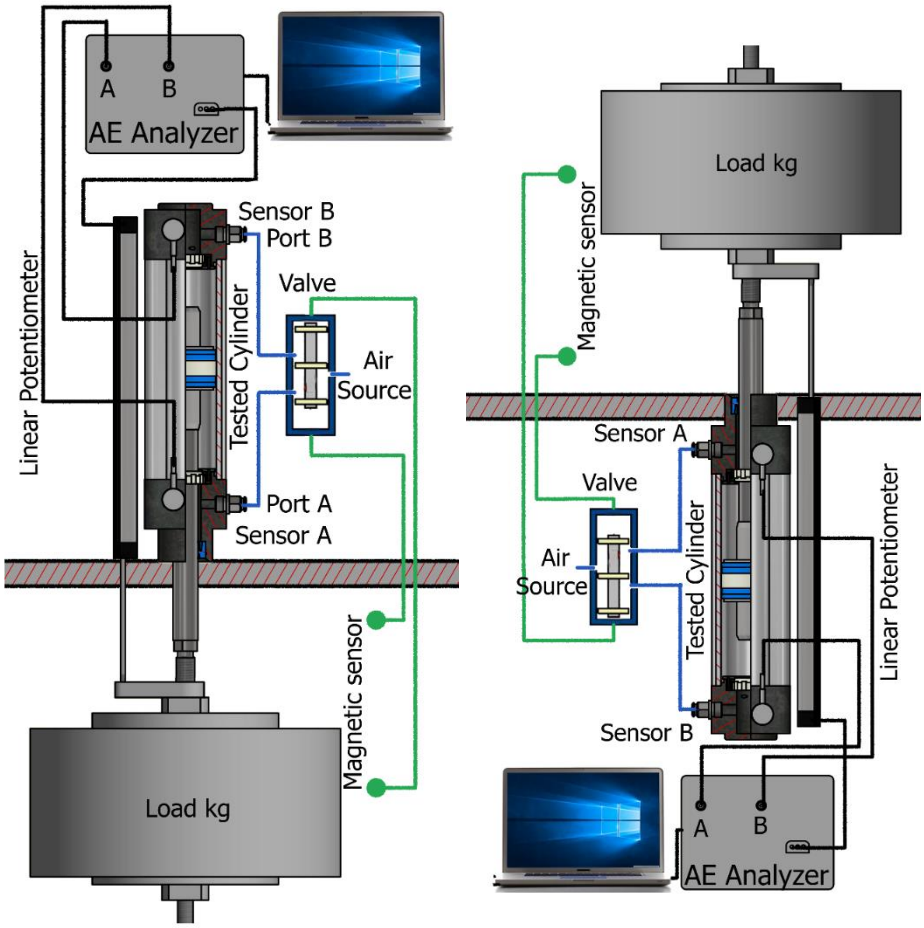


Figure 5.2 schematic drawing of the experiment.

Vertical stands for pneumatic cylinder with loads

The equipment used to conduct the experiment includes: tested cylinders PS ISO Piston diameter 40mm, Piston stroke 100mm, Thread M12x1.25, AE sensors IDK-14 Built-in preamplifier 35 dB, air pressure supply, pneumatic control system, linear potentiometer and the AE monitoring system with the analyser DAKEL-ZEDO with two channels and different weights. The cylinder is put in the vertical position with loading and the locations of AE sensors are on head cap A and rear cap B of the cylinder body as shown in figure 6.3.



a) Loading below the rod of cylinder b) Loading above the rod of cylinder

Figure 5.3 Schematic drawing of the experiment equipment in Vertical position.

5.6. Types of sensors of acoustic emission

Two types of sensors are used in our testing **Model IDK and Model IDK-14AS** [22].

5.7. Software and apparatus

Main application window ZDAEMON

MATLAB program

It is very important to use MS EXCEL and MATLAB to analyse the data because of the large amount of data recorded from our measuring.

This program is able to open text and excel files that are exported from ZDAEMON and calculate the RMS, Energy and differences. And determine whether the cylinder damaged or undamaged and this criterion is used in ZDAEMON and PNEU-ZEDO.

The code of parameters calculation in MATLAB programme is written in the appendix of the dissertation thesis.

6. Results and Discussion

6.1. Frequency spectrum of acoustic emission applied on pneumatic actuator

The main aim of this part is to find a typical acoustic emission signal associated with a particular type of damage in the cylinder. The acoustic emission signals that are obtained from the undamaged cylinders, are processed and analysed, after that different types of artificial defects are made in the same cylinders. A new parameter "DAE", which is developed, evaluates and classifies the level of damage detection on the basis of the recorded differences between undamaged and damaged cylinders.

Figure 6.1 Rate changes caused by that damage coefficient and Defection (DAE).

The frequency spectrum was replaced later by the parameter RMS during the monitoring of changes in the test results. This is possible by using a prototype of the newly developed diagnostic equipment.

6.2. Leakage analysis of pneumatic cylinders

This chapter discusses the relationship between Acoustic Emission (AE) and different types of defects in pneumatic cylinders, shedding light on a new approach to determining these types of defects and distinguishing between them through Acoustic Emission. Difficulties that face the defects detection process are related to the types of the defects, and the available methods for detection. A detection coefficient has been assigned to each cylinder by applying different methods of non-destructive testing, where a set of cylinders, which have defects that are difficult to detect, were determined. Two of those defects in the cylinders are artificially made, and it is difficult to discover the differences between undamaged and damaged cylinders in this set using current methods. Therefore, the necessary parameters for comparison have been selected after analysing the signals that were obtained from the tests. The average energy of Acoustic Emission signal RMS gives a clear picture of the different responses between damaged and undamaged pneumatic cylinders.

6.2.1. Kinematic scheme of intact cylinder

The signals which are recorded in each measurement of the intact cylinders have similar parameters as other cylinders. This kinematic scheme of an intact cylinder shows the progress and retreat stroke, and the response of AE_{rms} to this movement.

6.2.2. Undamaged Cylinders

Undamaged Cylinder No.2 after 101500 cycles without damping

Piston progress: the signal behaves smoothly from the initiation of throttling until the end of the progress stroke, where the piston then impacts the head cap cushion with a large amplitude of a hit in the signal. Piston retreat: the signal behaves smoothly from the initiation of throttling until the end of retreat stroke, where the piston then impacts the rear cap cushion with a small amplitude of a hit in the signal. As shown in figure 7.2.

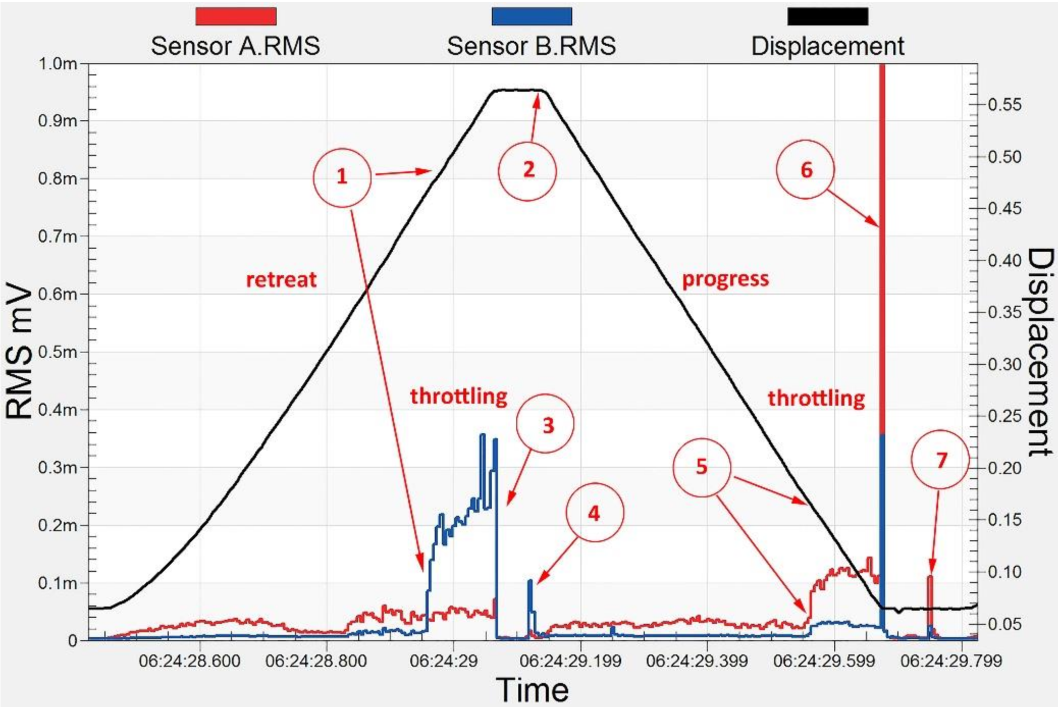


Figure 6.2 Undamaged cylinder No.2 after 101500 cycles without damping.

(1). Initiation of throttling (damping) in retreat stroke, (2). Stop time and return to progress stroke, (3). End of retreat stroke, (4). End of throttling in progress stroke, (5). Initiation of throttling (damping) in progress stroke, (6). End of progress stroke, (7). End of throttling in retreat stroke (also for next figures 6.3 and 6.4).

6.2.3. Damaged Cylinders

Damage type "unsealed piston and O-ring seal" was created in cylinder no. 8. The comparison between damaged cylinders without damping shows a significantly higher signal level in the area of the throttling process, including a higher hit at the start of the retreat stroke. In this case, it recorded leaks.

Damaged Cylinder No.8 after 51100 cycles without damping

Piston progress: the signal behaves differently from the initiation of throttling which increases and vibrates until the end of the progress stroke, and it ends when the piston impacts the head cap cushion. The black dotted circles determine the relation between the changes in the signal and possible leakage (PP03). Piston retreat: the signal behaves differently from the initiation of throttling which increases to maximum value then decreases, vibrates and ends when the piston impacts the rear cap cushion. The black dotted circles determine the relation between the changes in the signal and possible leakage (NP08). As shown in figure 6.3.

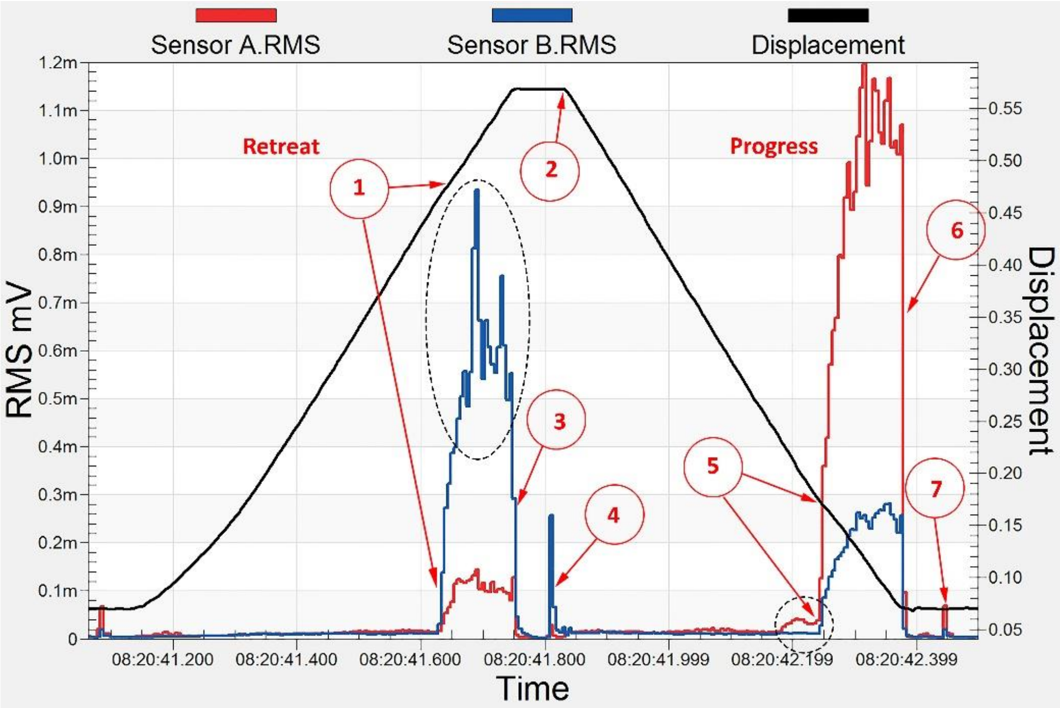


Figure 6.3 Damaged cylinder No.8 after 51100 cycles without damping.

Damaged Cylinder No.12 after 51100 cycles without damping

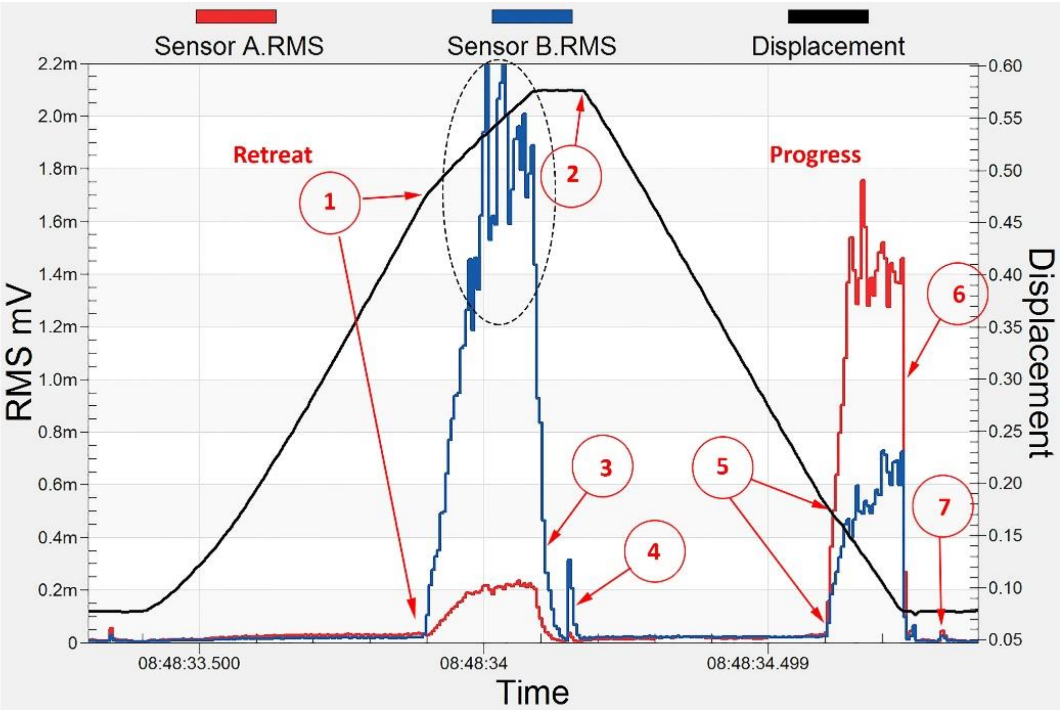


Figure 6.4 Damaged cylinder No.12 after 51100 cycles without damping.

Piston progress: the signal behaves differently from the initiation of throttling which increases and vibrates until the end of the progress stroke, where the piston then impacts the head cap cushion. There are no leaks. Piston retreat: the signal behaves differently from the initiation of throttling which increases to the maximum value, where it then decreases and increases and decreases gradually to the minimum value until the end of the retreat stroke, where the piston then impacts the rear cap cushion. The black dotted circles determine the relation between the changes in the signal and possible leakage (NP07). The amplitude of the RMS recorded from the head cap is bigger than from the rear cap. As shown in figure 6.4.

6.3.The criteria of acoustic emission testing for leakage

The study focuses on the relationship between root mean square (RMS) and defects in the cylinders. Undamaged and damaged cylinders were compared to find distinctive differences that determine whether the cylinder is damaged or undamaged. In this study several undamaged cylinders were tested by acoustic emission, before artificial defects were created in each one. The signals from the progress and retreat strokes were recorded and analysed into many parameters. The RMS was normalized, and the different responses between damaged and undamaged pneumatic cylinders were recognized by the time delay of the strokes. The signals were obtained by two sensors, one of them on the right (A) and the other on the left (B). The data was normalized and divided into A and B depending on the sensor. Because of the sensitivity of the sensor and the different responses of sensors and the contact condition between the sensors and the cylinders, the data was normalized to avoid the amplitude errors, in spite of implementing a pen test before each measurement to ensure that the sensors have the same amplitude. However, undamaged and damaged cylinders were compared according to the normalized data to find distinctive differences between them.

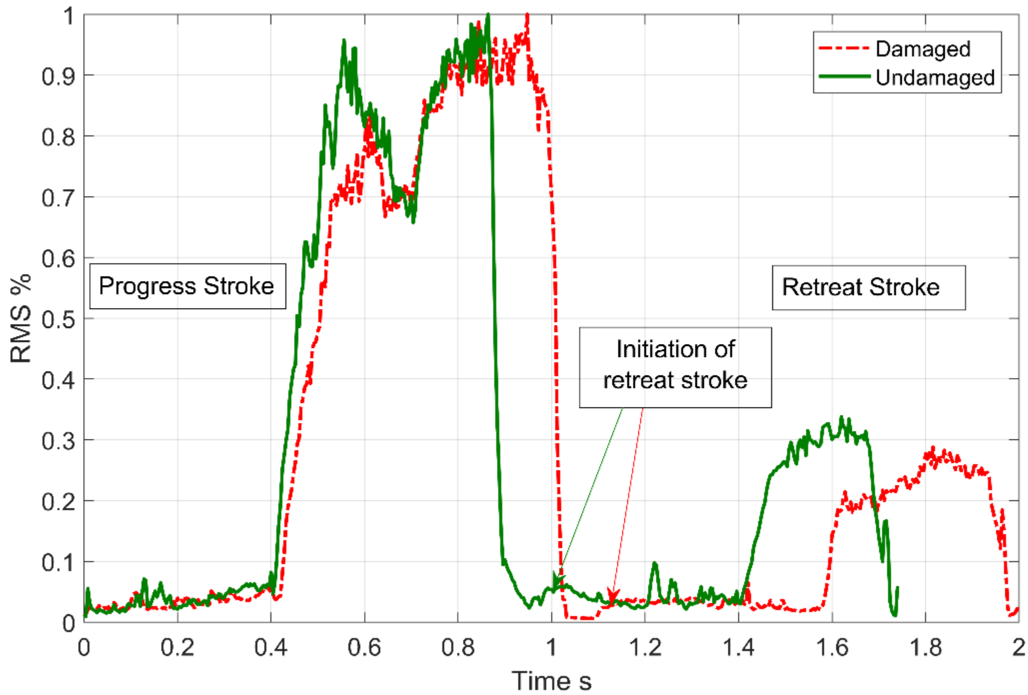


Figure 6.5 Comparing between damaged and undamaged cylinders No. 21, NP08, PP03 derived from the sensor A.

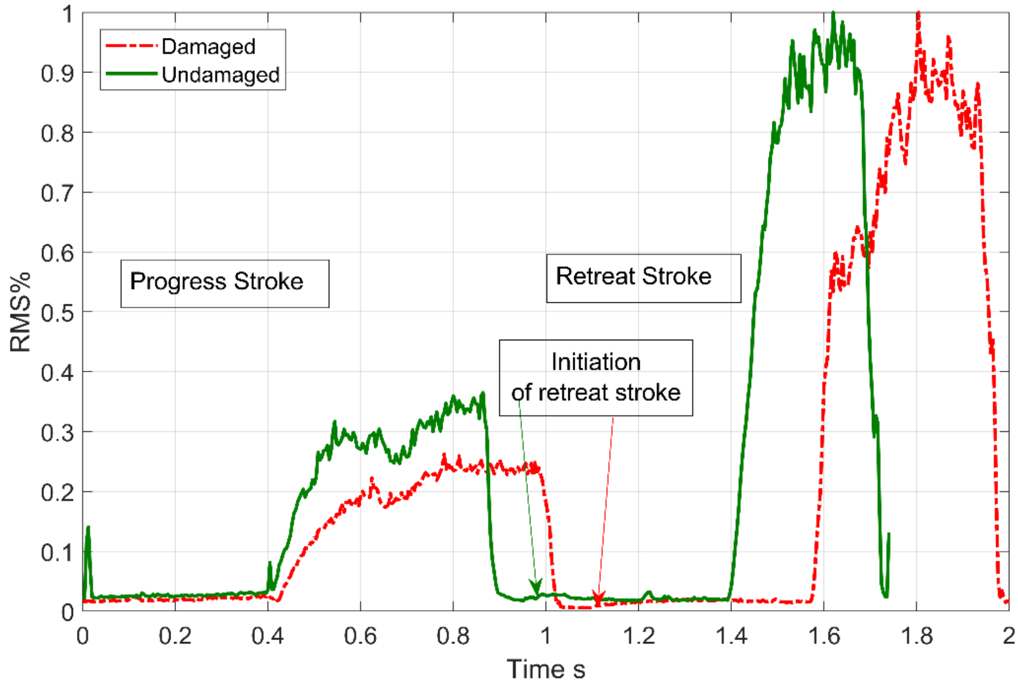


Figure 6.6 Comparing between damaged and undamaged cylinders No. 21, NP08, PP03 derived from the sensor B.

All cylinders had the same throttling adjustment before and after creating the artificial defect. When an artificial defect was made in the cylinder, the time of the stroke was extended. The stroke time should be the same but the defect in the cylinder causes this delay as shown in figures 6.5 and 6.6. The difference was recognized between an undamaged and damaged cylinder. After these distinctive differences were proved using acoustic emission, the goal of this research is to determine whether newly produced cylinders are acceptable or not.

The ratio between maximum RMS of Acoustic Emission from sensor B and the maximum RMS from sensor A in the retreat stroke is shown in figures 6.9 and 6.10.

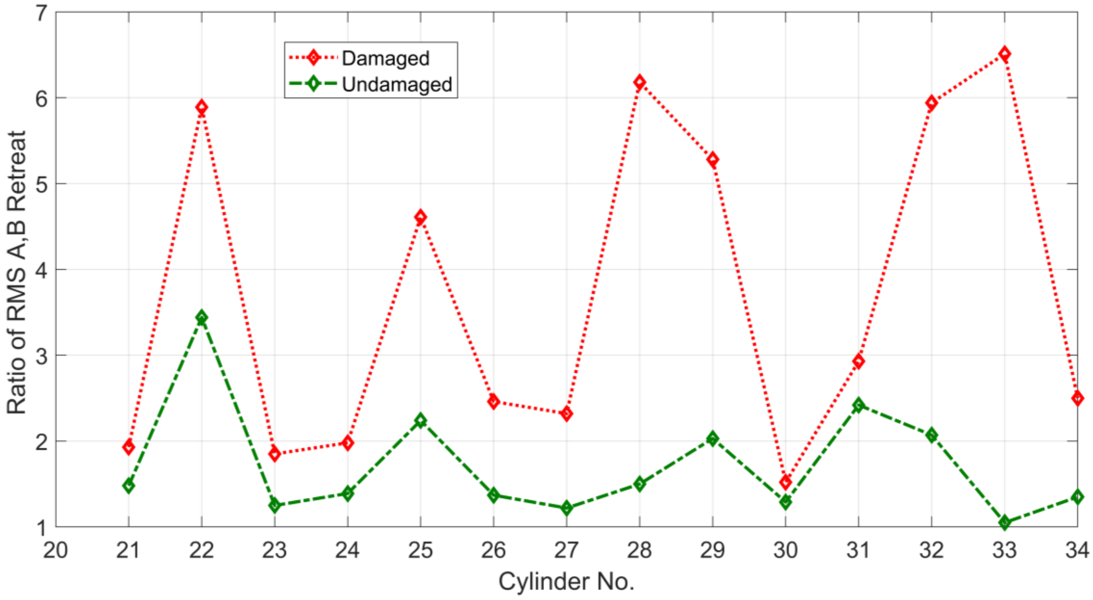


Figure 6.7 Comparing between damaged and undamaged cylinders according to the ratio of RMS values.

In the figure 6.7, there is an area, highlighted in the blue rectangle, where one criterion is not enough to determine the status of the cylinder. This rectangle represents a range of values that do not give a direct indication to whether the cylinder is damaged or undamaged. In this case, a new criterion should be considered.

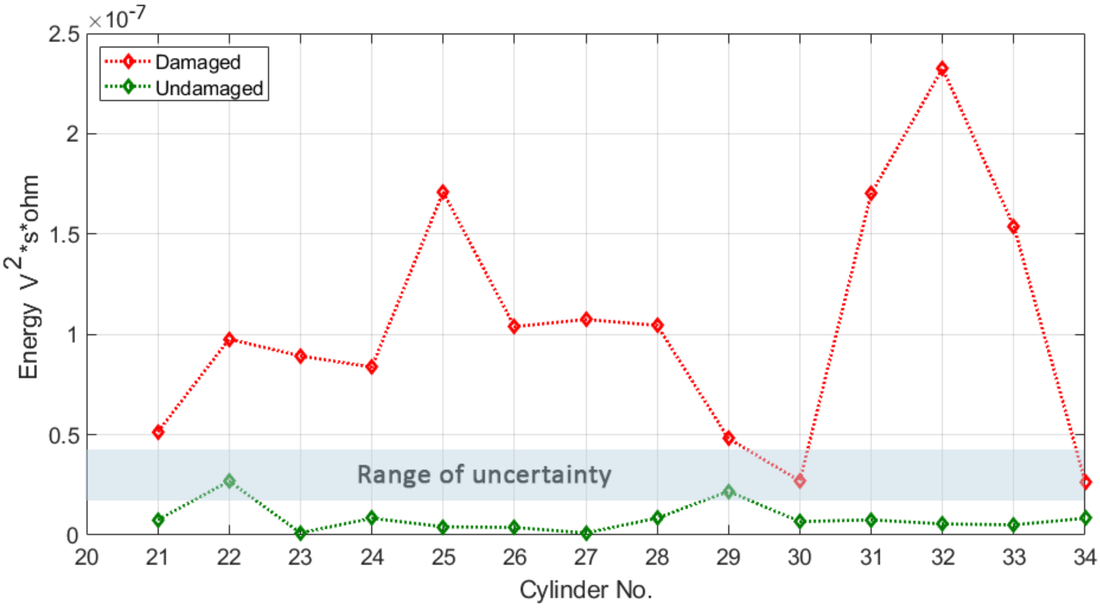


Figure 6.8 Comparing between damaged and undamaged cylinders according to the energy values.

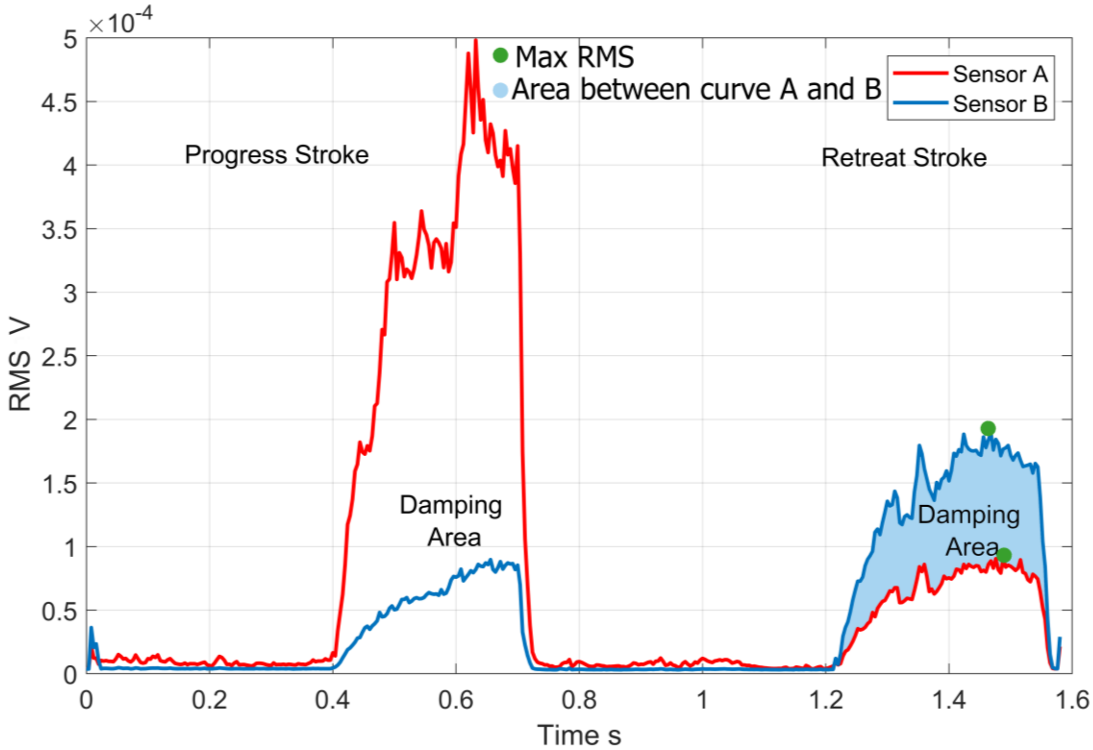


Figure 6.21 RMS dependency on time for undamaged cylinder No.32 with damping.

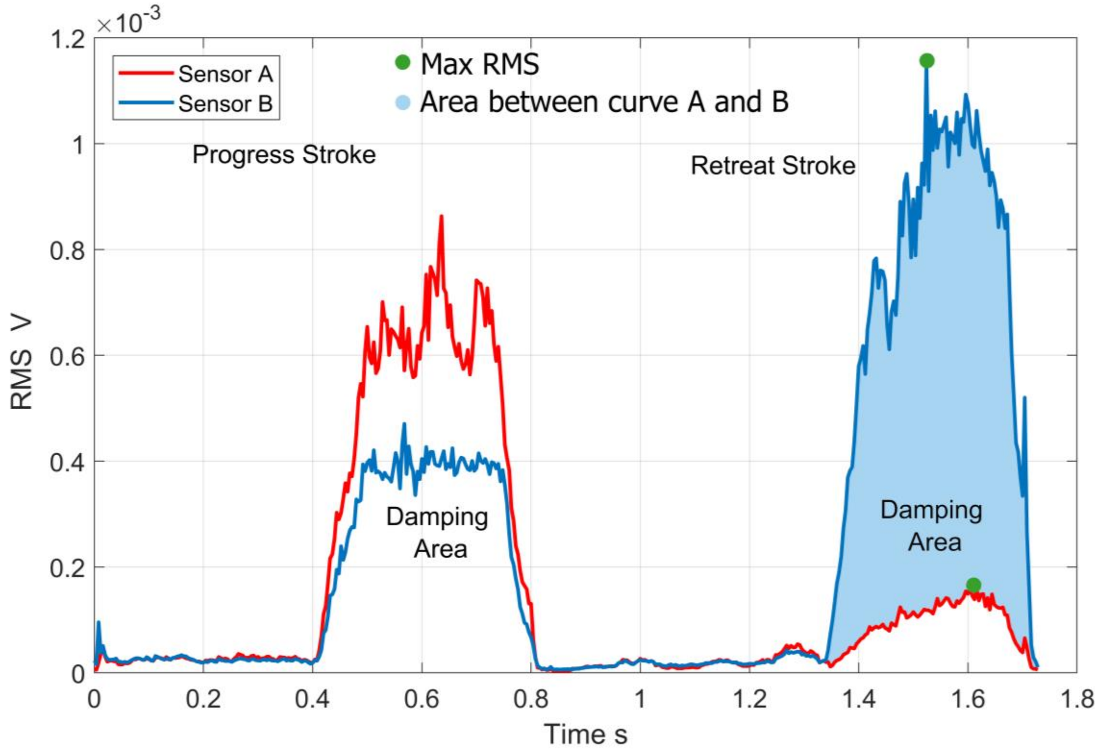


Figure 6.22 RMS dependency on time for damaged cylinder No.32 with damping.

Undamaged cylinders No. 22, 29 and damaged cylinders No. 30, 34, are in the blue rectangle in figure 6.8. The second criterion is applied as follows: The total value of RMS was calculated for each cylinder from the sensor B at one cycle according to the time.

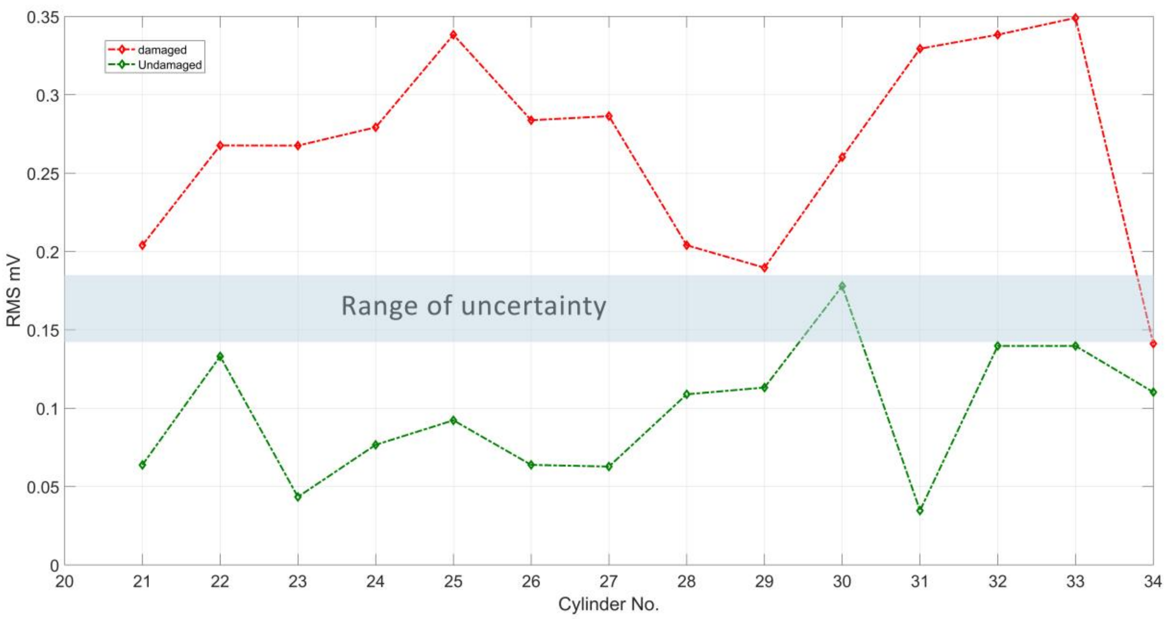
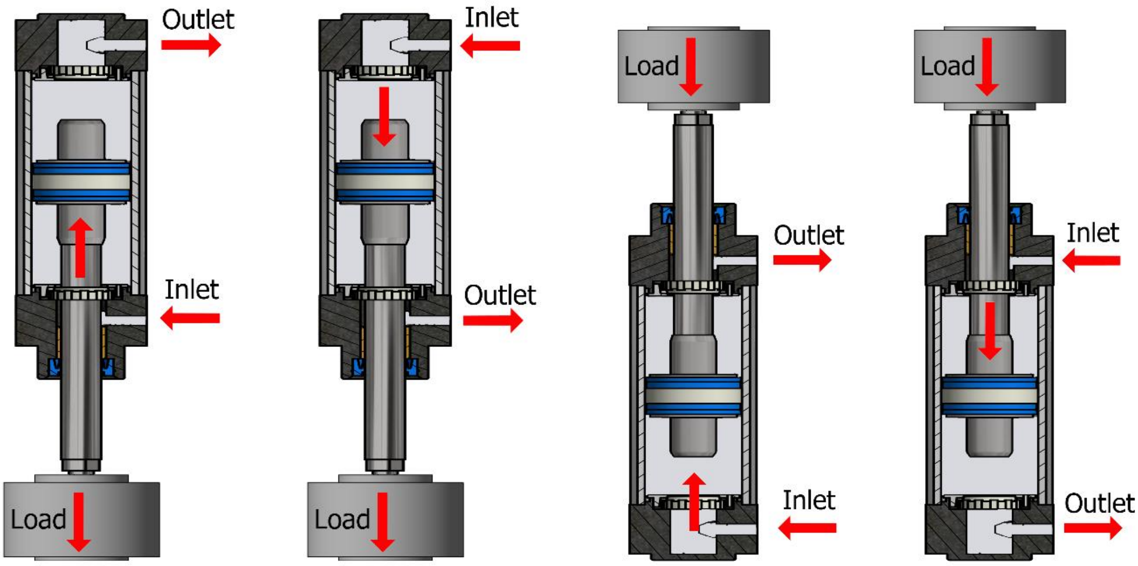


Figure 6.23 Comparing between damaged and undamaged cylinders NP08, PP03, NP07 according to the RMS values

The value of $\sum RMS$ from sensor B at one cycle can evaluate the quality of the cylinder, as observed; the smaller the value the better the quality as shown in figure 6.11.

6.4. Relationship between acoustic emission signal and loads on pneumatic cylinders

These results of this chapter were submitted in *"Non-destructive Testing and Evaluation journal impact factor in Taylor & Francis"*.



a) Retreat stroke b) Progress stroke c) Progress stroke d) Retreat stroke

Load is below piston Load is above piston

Figure 6.12 Position of load related to the cylinder.

The cylinders in our experiment were loaded gradually by different weights in a vertical direction. The effect of the defect occurs when the cylinder is loaded at the retreat and progress strokes. This defect affects the relationship between the applied load and the recorded signal of the sensors. The signals of the acoustic emission were recorded from the progress and retreat strokes and then analysed. The time delay is calculated between the digital input and the initiation of movement, and the time of the stroke. The energy and root mean square of the acoustic emission compare between the distinctive different responses in damaged and undamaged pneumatic cylinders, with and without loading. The energy and RMS were calculated for each cylinder with gradual loading. The results of the test showed a linear relationship between the RMS curve and loading.

Loads were applied to the cylinders during the test. The aim was to enlarge the amount of leakage. Two sensors were fixed on the head and rear cap of the cylinder. The cylinder was fixed under the table while the load was applied above the cylinder; the signal was recorded from the progress and retreat strokes. In another assembly the cylinder was fixed above the table while the loads were applied below the rod of the piston. The signals were recorded from the progress and retreat strokes as shown in Figure 6.12.

6.4.1. The load is below the piston of the undamaged cylinder

When a 1kg load is applied below the cylinder (figure 6.13).

In the progress stroke, the load and the pressure are in the same direction. After the valve is opened by the digital input, the air hits the piston and makes a peak in the signal. The time between the digital signal and the initiation of movement is 0.069 s. There are some effects on the signal at the beginning due to the air passing through the throttle nozzle; the piston vibrates at the beginning of its movement then the speed of its movement becomes steady until the initiation of the damping phase. The high amplitude of AE near sensor A is a result of the damping that happened in the head cap of the cylinder. When the head cushion piston impacts the head cushion cap, a small peak in the signal appears, and after that the air is expelled. The time of the stroke is 1.067s. In the retreat stroke, the load and the pressure are in different directions. After the valve is opened by digital input, the air impacts the piston and makes a peak in the signal. There is a delay in the movement and the signal at the beginning because it needs enough pressure to move the piston. This delay is 0.246 s. Following that, the speed of its movement becomes steady until the initiation of the damping phase. The high amplitude of AE near sensor B is a result of the damping that happens in the rear cap of the cylinder. When the rear cushion piston impacts the rear cushion cap, a small peak in the signal appears. After that air is expelled. The time of the stroke is 1.149s.

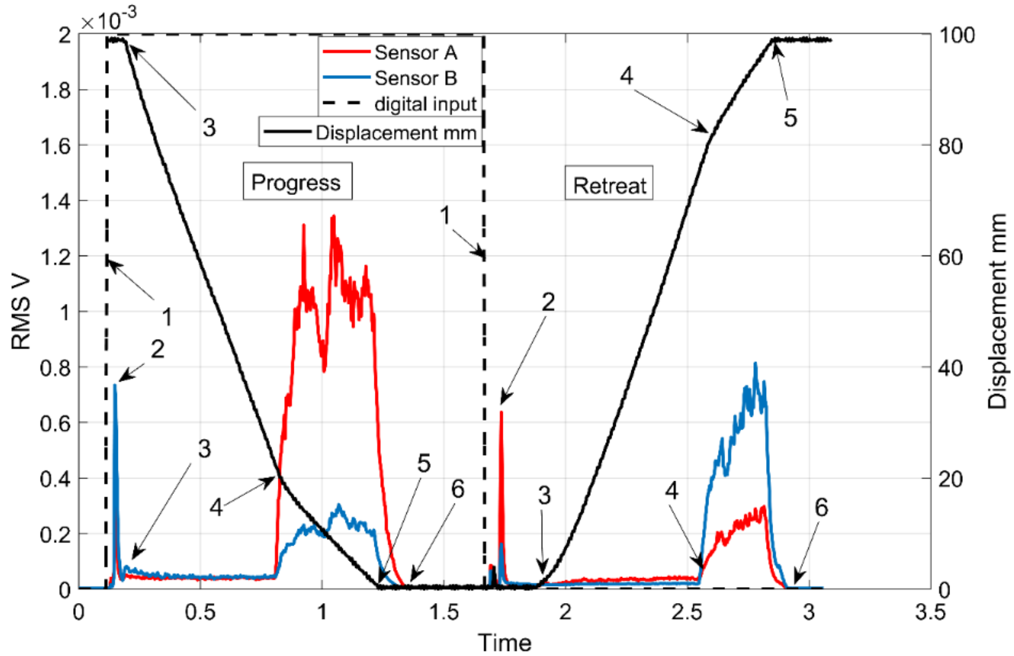


Figure 6.13 Load of 1 kg was applied below the undamaged cylinder.

(1) the valve is opened by the digital input to let the air pass through the port, (2) the impact of the air at the cushion piston, (3) the initiation of movement, (4) the initiation of the damping phase 21.7mm before the TDC, (5) when the cushion piston impacts the cushion cap, and stops, (6) the end of venting air and relaxing and the end of the stroke.

When a 21kg load is applied below the cylinder (figure 7.14)..
In the progress stroke, the load and the pressure are in the same direction. After the valve is opened by the digital input the air hits the piston and makes a peak in the signal. The time between the digital signal and the initiation of movement is 0.069 s. There are big effects on the signal at the beginning because of the air passing through the throttle nozzle and the load pushes the pressure forward. The piston vibrates at the beginning of its movement, and then the speed of its movement becomes steady until the initiation of the damping phase.
The high amplitude of AE near sensor A is a result of the damping that happens in the head cap of the cylinder. When the head cushion piston impacts the head cushion cap, a small peak in the signal appears, after that air is expelled. The time of the stroke is 0.952s.

In the retreat stroke, the load and the pressure are in different directions. After the valve is opened by the digital input, the air impacts the piston and makes a peak in the signal. There is a delay in the movement and the signal at the beginning because it needs enough pressure to move the piston. This delay is 0.49s, and then the speed of its movement becomes steady until the initiation of the damping phase.

The high amplitude of AE near sensor B is a result of the damping that happens in the rear cap of the cylinder. When the rear cushion piston impacts the rear cushion cap, a small peak in the signal appears, and after that air is expelled. The time of the stroke is 1.532s.

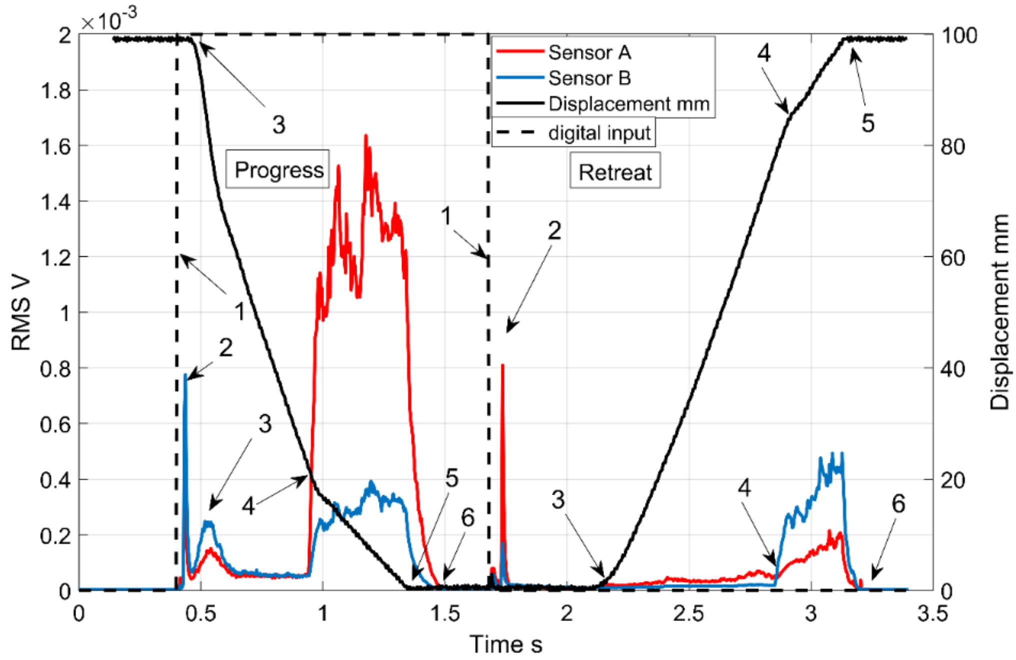


Figure 6.14 Load 21 kg was applied below the undamaged cylinder.

In the retreat stroke, the load and the pressure are in the same direction, and it also acts in the same way as the previous example. The time between the digital signal and the initiation of movement is 0.195 s, and the time of the stroke is 1.098s.

Table 6.1 Calculation of strokes time for undamaged cylinder the load is above and below.

Loads	Time	Time between digital input and initiation of movement		the time of the stroke	
	stroke	Progress	Retreat	Progress	Retreat
Loads below	1kg	0.069	0.246	1.067	1.149
	21kg	0.069	0.49	0.952	1.532
Loads above	1kg	0.07	0.195	1.101	1.098
	21kg	0.227	0.138	1.386	0.906

a) The relationship between RMS of AE and the loading is linear.
b) In the case of the load being above, when the load increases the RMS decreases in the progress stroke, and when the load increases the RMS increases in the retreat stroke.
c) In the case of the load being below, when the load increases the RMS increases in the progress
d) stroke, and when the load increases the RMS decreases in the retreat stroke.
e) The curve of energy and loading is very similar to that in figure 7.15.

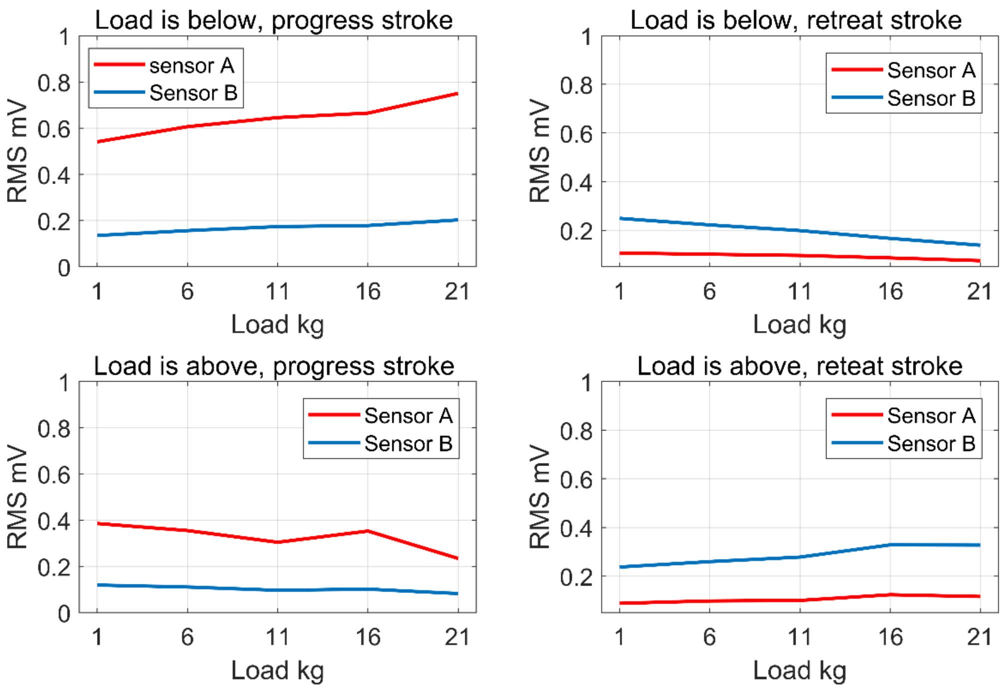


Figure 6.15 Relationship between RMS and loading on undamaged cylinder during one cycle.

6.4.2. The load is below the piston of the damaged cylinder

When the load is below the cylinder. In the progress stroke, the load and the piston movement are in the same direction; the leak is in port B and the air is expelled through port A, so there is a huge amplitude of RMS from sensor B, and there is a signal from sensor A. The leak continues flowing from port B after the piston stop, so the signal from sensor B is bigger than the signal from sensor A.

In the retreat stroke, the load and the piston movement are in different directions; the leak is from port A and the air is expelled through port B, so there is a huge amplitude of RMS from sensor A, and there is a signal from sensor B. The leak continues flowing from port A after the piston stops, so the signal from sensor A is bigger than the signal from sensor B.

6.4.3. The load is above the piston of the damaged cylinder

When the load is above the cylinder. In the progress stroke, the load and the piston movement are in different directions; the leak is in port B and the air is expelled through port A. The RMS from sensor A and the RMS from sensor B are in the same amplitude, and the leak continues flowing from port B after the piston stops, so the signal from sensor B is bigger than the signal from sensor A.

In the retreat stroke, the load and the piston movement are in the same direction, and the leak is from port A and the air is expelled through port B. The RMS from sensor A and the RMS from sensor B are in the same amplitude. The leak continues flowing from port A after the piston stops, so the signal from sensor A is bigger than the signal from sensor B.

The total RMS was calculated for each load for the progress and retreat strokes in two different positions of the cylinder - above and below.

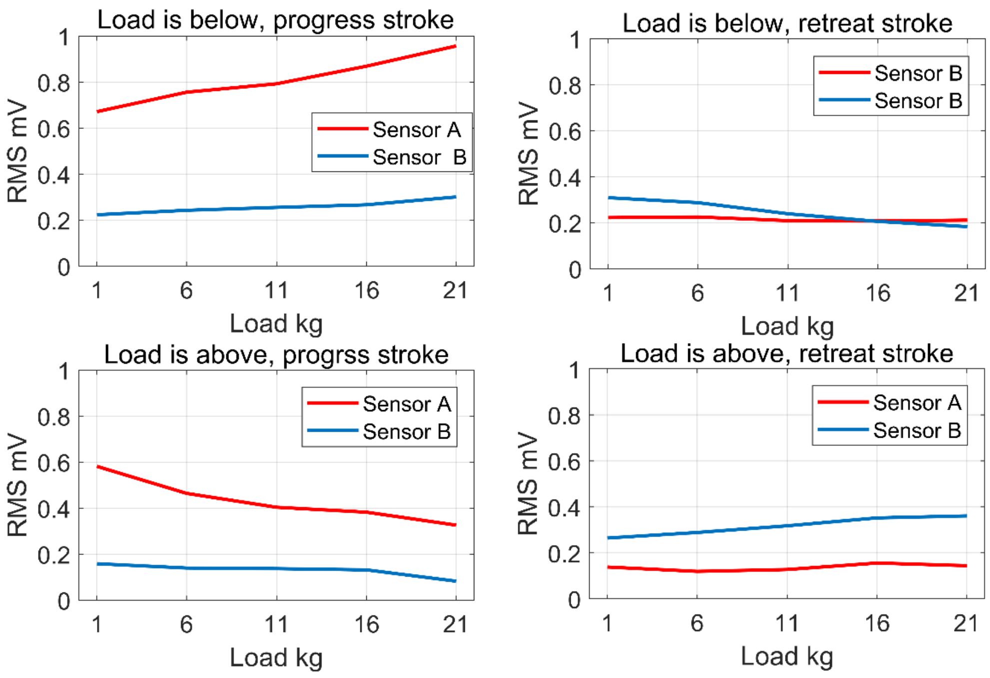


Figure 6.16 Relationship between RMS and loading during one cycle of the damaged cylinder.

When there is a leak in the porting (see figure 6.1) of the cylinder, the peak of the signal appears during the stroke, not only in the damping phase. The relationship between the RMS of AE and the loading is linear. In the case of the load being above, when the load increases the RMS decreases in the progress stroke, and when the load increases the RMS increases in the retreat stroke. In the case of the load being below, when the load increases the RMS increases in the progress stroke, and when the load increases the RMS decreases in the retreat stroke. The reason for the change in the results between the damaged and undamaged cylinder in the case where the load is below and the RMS from sensor A increases in the damaged cylinder and decreases in the undamaged cylinder in retreat stroke, is due to the leak near the port figure 6.16.

7. Conclusions

In this study, several undamaged cylinders were tested by acoustic emission, before artificial defects were created in each one. Undamaged and damaged cylinders were compared to find distinctive differences that determine whether the cylinder is damaged or undamaged.

Suitable acoustic emission signal parameters were selected based on the analysis of large data sets. These parameters can be used for more accurate diagnostics of condition monitoring for the development of pneumatic testing devices.

Current results show good conformity and repeatability, acoustic emission application in this domain of diagnostics brings higher quality results than currently used methods.

The frequency spectrum was used as a parameter to compare undamaged and damaged cylinders, which was replaced later by the parameter RMS.

Preliminary results of processed measurements confirm the assumption that the configuration that consists of two sensors located on the head and rear caps provides more detailed results than the configuration that uses only one sensor in the middle of the cylinder body.
The received signals are caused not only by defects, but also by mechanical movements, and inlet and outlet pressurized air.
Acoustic emission detectability of leakage depends on detection sensitivity, detection selectivity, differential pressure, and leak size.

The Acoustic emission can be applied to detect and locate leaks as long as there is enough pressure acting across the leak.

The determination of diagnostic criteria that evaluate the quality of the pneumatic cylinder and detect the defects. There are four criteria to evaluate the cylinder respectively:

- The RMS was normalized; the defect in the cylinder causes a delay in the stroke time, which causes an extension in the damping area. This delay distinguishes between undamaged and damaged cylinder.
- The specific ratio between maximum RMS from the sensor fixed in the head cap A of and the max RMS from the sensor fixed in the rear cap B the cylinder in the retreat stroke can identify whether the cylinder is damaged or undamaged.
  When the ratio is bigger than 3 the cylinder is damaged if the ratio is smaller than 1.7 the cylinder is undamaged.
- The damaged and undamaged cylinders were distinguished using the difference in energy values present in the signals from the two sensors in the retreat stroke. At signal energy $E_{B-A} > 0.000000027$ V2 *s*Ohm the cylinder is damaged, and at $E_{B-A} < 0.000000020$ V2 *s*Ohm it is undamaged.
- The final evaluation of the cylinder was determined by the calculation of the total value of RMS. The value of $\sum RMS$ from sensor B at one cycle can evaluate the quality of the cylinder, the smaller the value the better the quality. At $\sum RMS > 0.18$ mV the cylinder is damaged, and at $\sum RMS < 0.14$ mV it is undamaged.

The cylinders in the experiment were loaded gradually by different weights in a vertical direction. The defect affects the relationship between the applied load and the recorded signal of the sensors. The artificial defects were made in the cylinders and classified according to their severity and detectability.

- The relationship between RMS of AE and the loading is linear.

- Clear explanation of the actuator movement stages, where the certain similarities were found by comparing between the stages of the actuator movement and acoustic emission signals with the potentiometer curve.
- There is a delay in the time of movement and the signal at the beginning because enough pressure is needed to move the piston.
- When the loading and movement of the piston are in opposite directions, the time of the stroke is longer.
- When the loading and movement of the piston are in the same direction, the time of the stroke is shorter.

The load is above	progress stroke	when the load increases the RMS decreases
	retreat stroke	When the load increases the RMS increases
The load is below	progress stroke	when the loading increases the RMS increases
	retreat stroke	When the load increases the RMS decreases

It is confirmed that using acoustic emission method able to diagnose of the defects of pneumatic cylinders, and detect and predict the possible worst defects in the cylinder in practical work and determine the type of defects and its locations.

Future work

It is necessary to make other tests to apply the current criteria on other types of pneumatic cylinders and modify these criteria to be suitable for these cylinders under different conditions. In our laboratory, we test the cylinders in practice, especially when applied in the real-time function and during the loading. Above-mentioned criteria are applied practically on various types of cylinders that help in the opening door system in the buses. Our research continues in this area depending on our experiences during the first stage of this project.

This research will continue to improve a prototype of the newly developed diagnostic apparatus.

8. REFERENCES

[1] JACKSON, CH., CH. SHERLOCK and P. MOORE, *NDT Handbook: Third Edition: Volume 1, Leak Testing*, American Society for Non-destructive Testing, ISBN: 1-57117-071-5 Year: 1998

[2] MILLER, R.K. and E.VK. HILL: *Acoustic Emission Testing, NDT Handbook, Vol. 6, 3rd edition,* ASNT, Columbus, 2005. ISBN 1-57117-106-1.

[3] *The Pneu Book is produced by SMC Pneumatics (UK) [online]*

https://www.smc.eu/portal_ssl/WebContent/local/UK/Pneu_Book/pneubook.pdf

[4] MAZAL, P., F. VLASIC, H. MAHMOUD and M. JANA, The use of Acoustic Emission method for diagnosis of damage of pneumatic cylinders, *WCNDT, vol.19, pp. 2016.*

[5] MAHMOUD, H., F. VLAŠIC, P. MAZAL, L. NOHÁL and V. KRATOCHVÍLOVÁ, Analysis of Pneumatic Cylinder Damage by Acoustic Emission Method. *In Defektoskopie 2017 (NDE for Safety).* Brno, 2017. s. 151-161. ISBN: 978-80-214-5554-2.

[6] MAHMOUD, H., F. VLASIC, M. JANA, P. MAZAL, condition monitoring of pneumatic cylinders By Acoustic Emission, *14th International Conference of the Slovenian Society for Non-Destructive Testing, 4-6 September 2017.*

[7] J.Dickey, J.Dimmick, and P.M.Moore,“ Acoustic measurement of valve leakage rates,” Materials Evaluation, vol. 36, no. 1, pp. 67–77, 1978.

[8] Y. Jiang, Q.-C. Gong, Q. Ye, and C.-L. Liu, “The theoretical analysis and experiments of using ultrasonic to inspect the leak amount,” China Academic Journal Electronic Publishing House, no.1, 2005 (Chinese).

[9] Q.-X.Gao, L.-P.Li,H.-D.Rao, J.Yang, and Y.-J.Zhu, “Acoustic emission theory and testing technology for quantitative diagnosis of valve leakages,” Journal of Chinese Society of Power Engineering, vol.32, no.1, pp.42–46, 2012 (Chinese).

[10] R.Bayindir and H.Ates, “Low-cost and high sensitively microcontroller based control unit for a friction welding machine,” Journal of Materials Processing Technology, vol.189, no.1–3, pp. 126–131, 2007.

[11] J. Yang, L. Li, H. Rao, Y. Zhu, and G. Liu, “Diagnosis of valve leakage fault patterns based on acoustic emission detection,” Journal of Chinese Society of Power Engineering, vol. 33, no. 6, pp.455–483,2013.

[12] Y. Wang, C. Xue, X. Jia, and X. Peng, “Fault diagnosis of reciprocating compressor valve with the method integrating acoustic emission signal and simulated valve motion,” Mechanical Systems and Signal Processing, vol.56-57, pp.197–212,2015.

[13] A.A. Pollock and S.Y.S. Hsu, “Leak Detection Using Acoustic Emission”, Journal of Acoustic Emission, Vol. 1, No. 4, pp. 237-243, 1982.

[14] Q.Gao,L.Li,H.Rao,andJ.Yang, "Research on the relationship between internal fluid leakage through a valve and the acoustic emission features generated from the leakage," Journal of Engineering forThermal Energy and Power, vol.26, no.5, 2011.

[15] W. Kaewwaewnoi, A. Prateepasen, and P. Kaewtrakulpong, " Measurement of valve leakage rate using acoustic emission," in Proceedings of the International Conference on Electrical Engineering/Electronics, Computer, Telecommunications, and Information Technology (ECTI'05), pp.597–600, 2005.

[16] A. Prateepasen, W. Kaewwaewnoi, and P. Kaewtrakulpong, "Smart portable non-invasive instrument for detection of internal air leakage of a valve using acoustic emission signals," Measurement,vol.44,no.2,pp.378–384,2011.

[17] H. Y. Sim, R. Ramli, A. A. Saifizul, and M. A. K. Abdullah, "Empirical investigation of acoustic emission signals for valve failure identification by using statistical method," Measurement, vol.58, pp.165–174, 2014.

[18] YAN JIN, Y. HENG-HU, Y. HONG, Z. FENG, L. ZHEN, W. PING and Y. YAN. *Non-destructive Detection of Valves Using Acoustic Emission Technique*. DOI:10.1155/2015/749371. ISBN 10.1155/2015/749371.

http://www.hindawi.com/journals/amse/2015/749371/

[19] S.-H.Seong,S.Hur, J.-S.Kimetal., "Development of diagnosis algorithm for the check valve with spectral estimations and neural network models using acoustic signals," Annals of Nuclear Energy,vol.32, no.5, pp.479–492, 2005.

[20] Kupperman, D.S., Claytor, T.N. an Groenwald R. "Acoustic Leak Detection for Reactor Coolant S5stems," Nuclear Engineering and Design, Vol. 86, pp. 13-20, 1985.

[21] Miller, R.K., Pollock, A.A., Watts, D.J., Carlyle, J.M., Tafure, A.N. and Yezzi, J.J. "A Reference Standard for the Development of Acoustic Emission Pipeline Leak Detection Technique," NDT&E International, Vol. 32, pp. 1-8, 1999.

[22] Grabec, I. "Application of Cross Correlation Techniques for Localization of Acoustic Emission Sources," Ultrasonics, Vol. 41, pp. 111-115, 1978.

[23] Gao, Y., Brennan, M.J., Joseph, P.F., Muggleton, J.M. and Hunaidi, O. "A Model of the Correlation Function of Leak Noise in Buried Plastic Pipes," Journal of Sound and Vibration, Vol. 277, pp. 133-148, 2004.

[24] Fukuda, T. And Mitsuoka, T. "Applications of Computer Data Processing and Robotic Technology," Computers in Industry, Vol. 7, pp. 5-13, 1986.

[25] Ahadi, M. And Bakhtiar, M.S. "Leak Detection in Water-Filled Plastic Pipes through the Application of Tuned Wavelet Transforms to Acoustic Emission Signals," Applied Acoustics, Vol. 71, pp. 634-639, 2010.

[26] Jiao, J., He, C., Wu, B. And Fei, R. “A New Technique for Modal Acoustic Emission Pipeline Leak Location with One Sensor,” Insight, Vol. 46, No. 7, pp. 392-395, 2004.

[27] Muggleton, J.M., Brennan, M.J., Linford, P.W. “Axisymmetric Wave Propagation in Fluid-Filled Pipes: Wavenumber Measurements in in Vacuo and Buried Pipes,” Journal of Sound and Vibration, Vol. 270, pp. 171-190, 2004.

[28] Yang, J., Qingxin, Y. and Guanghai, L. “Leak Identification Method for Buried Gas Pipeline Based on Spatial-Temporal Data Fusion,” IEEE International Conference on Control and Automation, Guangzhou, China, pp. 774-777, 2007.

[29] Shama,A.;El-Shaib,M.; Sharara,A.; Nasser, D.Y. Experimental study for leakage detection in subsea pipeline by applying acoustic emission technique. In Proceedings of the International Congress of the International Maritime Association of the Mediterranean, Lisbon, Portugal, 9–11 October 2017.

[30] Xu, C.; Gong, P.; Xie, J.; Shi, H.; Chen, G.; Song, G. An acoustic emission based multi-level approach to buried gas pipeline leakage localization. J. Loss Prev. Process Ind. 2016, 44, 397–404. [CrossRef]

[31] Mostafapour, A.; Davoodi, S. Leakage locating in underground high pressure gas pipe by acoustic emission method. J. Nondestruct. Eval. 2013, 32, 113–123. [CrossRef]

[32] AUGUTIS AND SAUNORIS. *Investigation of High Frequency Vibrations of Pneumatic Cylinders.* ISSN 1392-2114 ULTRAGARSAS, Nr.2 (51). 2004.

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.561.8728&rep=rep1&type=pdf

[33] FUJITA, T., J. JANG, T. KAGAWA and M. TAKEUCHI, Dynamics of Pneumatic Cylinder Systems, *Japan*Department of Control & Systems Engineering, Faculty of Engineering Tohin University of Yokohama.*

[34] DOLL, M., R. NEUMANN and O. SAWODNY, Dimensioning of pneumatic cylinders for motion tasks, *Germany*; *Institute for System Dynamics, University of Stuttgart, Stuttgart, International Journal of Fluid Power, 2015, Vol. 16, No. 1, 11–24,* http://dx.doi.org/10.1080/14399776.2015.1012437

9. LIST OF MY PUBLICATIONS

Conferences

1. MAZAL, P., H. MAHMOUD, V. BUKÁČEK, F., VLAŠIC and M., JANA. Využití Metody Akustické Emise Pro Identifikaci Poškození Pneumatických Válců. *In Defektoskopie 2015 / Nde for Safety*. 2015. Brno: Vysoké Učení Technické V Brně, 2015. S. 81-90. ISBN: 978-80-214-5280- 0.

2. MAHMOUD, H.; F. VLAŠIC and P. MAZAL. Simulation of Operational Loading of Pressure Equipment by Means of Non- Destructive Testing. *by Metal 2015. 2015. Brno: Tanger Ltd., 2015. S. 321-327.* ISBN: 978-80-87294-58- 1.

3. MAHMOUD, H., F. VLAŠIC, P. MAZAL and M. JÁNA. Damage Identification of Pneumatic Components by Acoustic Emission. *In 32nd European Conference on Acoustic Emission Testing.* 1st Edition. Brno: Vutium Brno, Brno University of Technology, 2016. S. 315-322. ISBN: 978-80-214-5386- 9.

4. MAZAL, P., F. VLAŠIC, H. MAHMOUD and M., JANA. The Use of Acoustic Emission Method for Diagnosis of Damage of Pneumatic Cylinders. *In 19th WCNDT 2016 - World Conference on NDT. Munchen, Germany: German Society for NDT*, 2016. S. 1-10. ISBN: 978-3-940283-78- 8.

5. MAZAL, P., F. VLAŠIC and H. MAHMOUD. Use of Acoustic Emission Method for Diagnosis of Damage of Pneumatic Cylinders. *The E- Journal of Non-destructive Testing, 2016*, roč. 2016, č. 1, S. 1-10. ISSN: 1435-4934.

6. JÁNA, M., H. MAHMOUD, P. MAZAL and F. VLAŠIC. Stanovení Koeficientu Odhalení Poškození V Pneumatických Válcích Metodou Akustické Emise. *In Defektoskopie 2016, NDE for Safety*. první. Brno: Vysoké účení technické v Brně, ČNDT, 2016. S. 27-35. ISBN: 978-80-214-5422- 4.

7. MAHMOUD, H., F. VLAŠIC, P. MAZAL, L. NOHÁL and V. KRATOCHVÍLOVÁ. Analysis of Pneumatic Cylinder Damage by Acoustic Emission Method. *In Defektoskopie 2017 (NDE for Safety).* první. Brno: VUT v Brně ve spolupráci s ČNDT, 2017. S. 151-161. ISBN: 978-80-214-5554-2.

8. MAHMOUD, H., F. VLAŠIC and P. MAZAL. Application of Acoustic Emission Method to Diagnose Damage in Pneumatic Cylinders. *In First World Congress on Condition Monitoring. 1st. UK, Northampton: BINDT, 2017.* S. 858-868. ISBN: 9781510844759.

9. MAHMOUD, H., P. MAZAL and F. VLAŠIC. Condition Monitoring of Pneumatic Cylinders by Acoustic Emission. *In Application of Contemporary Non-Destructive Testing in Engineering. Ljubljana, Slovenija: University of Ljubljana, 2017.* S. 231-238. ISBN: 978-961-93537-3-8.

10. MAHMOUD, H., P. MAZAL, F. VLAŠIC and M. JÁNA. Damage Detection for Linear Pneumatic Actuators using Acoustic Emission. *In 33nd European Conference on Acoustic Emission Testing, Senlis, France, 2018.*

11. MAHMOUD, H.; MAZAL, P.; VLAŠIC, F. Метод акустической эмиссии для неразрушающего контроля пневматических цилиндров “Using Acoustic Emission Testing for Pneumatic Actuators Monitoring”. NDT world, 2018, roč. 21, č. 4, s. 64-67. ISSN: 1609-3178.

12. MAHMOUD, H.; MAZAL, P.; VLAŠIC, F.; NOHÁL, L. Leakage Detection for Pneumatic Circle of Bus Door Using Acoustic Emission and other NDT Methods. In Defektoskopie 2018 / NDE for Safety 2018. Brno: Vysoké učení technické v Brně ve spolupráci s Českou společností pro NDT, z.s., 2018. s. 67-77. ISBN: 978-80-214-5684-6.

13. RICHTER, V.; MAHMOUD, H.; MAZAL, P.; SKŘIVÁNKOVÁ, V. The Parameters of Acoustic Emission Signal Proposed to Identification of Damaged and Undamaged Cylinders. European Conference on Acoustic Emission (EWGAE) 2018. Senlis, France: CETIM, 2018. s. 1-13.

Impacted Journals

14. MAHMOUD, H., F. VLAŠIC, P. MAZAL and M. JÁNA. Leakage Analysis of Pneumatic Cylinders Using Acoustic Emission. *Insight BINDT, 2017*, roč. 59, č. 9, s. 500-505. ISSN: 1354-2575 (0.7).

15. MAHMOUD, H., P. MAZAL and F. VLAŠIC. Relationship Between Acoustic Emission Signal and Loads on Pneumatic Cylinders, *Non-destructive Testing and Evaluation, 2019, impacted journal (1.957) in Taylor & Francis.*

16. MAHMOUD, H., P. MAZAL, F. VLAŠIC. Detecting the Defects of Pneumatic Actuators Using Acoustic Emission Monitoring. *Insight BINDT, 2019*

CURRICULUM VITAE

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ABSTRACT

This work demonstrates the development of a new efficient diagnostic procedure for checking the function of pneumatic cylinders using acoustic emission. The aim of this work is to suggest and determine the diagnostic criteria that evaluate the quality of the pneumatic cylinder.

The first step is to find the typical acoustic emission signal that associated with a particular type of damage in the cylinder by the frequency spectrum. This parameter was replaced later by the parameter RMS during the monitoring of changes in the test results. The relationship between Acoustic Emission (AE) and different types of defects in pneumatic cylinders was discussed, shedding light on a new approach to determining these types of defects and distinguishing between them through Acoustic Emission.

The second step is to compare undamaged and damaged cylinders to find distinctive differences that determine whether the cylinder is damaged or undamaged. Several undamaged cylinders were tested by acoustic emission, before artificial defects were created in each one. The signals from the progress and retreat strokes were recorded and analysed into many parameters. The RMS was normalized, and the different responses between damaged and undamaged pneumatic cylinders were recognized by the time delay of the strokes. The differences were identified by the ratio of the max RMS from the sensor that fixed in the head cap of the cylinder and the max RMS from the sensor that fixed in the rear cap of the cylinder for one cycle in the retreat stroke. The damaged and undamaged cylinders were distinguished using the difference in energy values which present in the signals from the two sensors in the retreat stroke. The final evaluation of the cylinder was determined by the calculation of the total value of RMS.

In the third step in the experiment, the cylinders were loaded gradually by different weights in a vertical direction. The signals of the acoustic emission were recorded from the progress and retreat strokes and then analysed. The time delay is calculated between the digital input and the initiation of movement. The energy and root mean square of the acoustic emission compare between the different responses in damaged and undamaged pneumatic cylinders, with and without loading. The results of the test showed a linear relationship between the RMS curve and loading. The defect affects the relationship between the applied load and the recorded signal of the sensors.

ABSTRAKT

Tato práce se zabývá vývojem nového efektivního diagnostického postupu pro kontrolu funkce pneumatických válců pomocí metody akustické emise. Cílem práce bylo navrhnout a určit diagnostická kritéria pro hodnocení kvality vybraných typů pneumatických válců.

Prvním krokem bylo nalezení typického akustického emisního signálu, který je spojen s určitým typem poškození ve válci využitím frekvenčního spektra signálu. Později byl tento parametr nahrazen parametrem RMS během sledování změn v průběhu testů. Na konkrétních válcích byl sledován vztah mezi akustickou emisí a různými typy defektů a byl představen nový přístup k určování těchto typů vad a jejich odlišením v signálu akustické emise.

Druhý krok studie že neporušené a poškozené válce byly porovnávány tak, aby se zjistily výrazné rozdíly, které určují, zda je válec poškozen nebo nepoškozen. Několik nepoškozených válců bylo testováno akustickou emisí a následně v nich byly vytvořeny umělé vady. Signály z vysouvání a zasouvání pístu byly zaznamenány a analyzovány pomocí řady parametrů. Na základě časového zpoždění a normalizace RMS byly rozpoznány odezvy mezi poškozenými a nepoškozenými pneumatickými válci. Rozdíly byly zjištěny porovnáním maximální hodnoty RMS ze snímače upevněného na předním víku válce a snímače upevněného na zadním víku válce pro jeden cyklus. Poškozené a nepoškozené válce byly rozlišeny pomocí rozdílů energetických hodnot přítomných v signálech z obou snímačů v závislosti na zdvihu pístu. Konečné vyhodnocení válce bylo určeno výpočtem celkové hodnoty RMS.

Ve třetím kroku experimentu byly válce postupně zatěžovány různými závažími ve svislém směru. Signály akustické emise byly zaznamenány z vysouvání a zasouvání pístu a poté analyzovány. Časové zpoždění se vypočítává z digitálního vstupu a začátku pohybu pístu. Energie signálu a RMS akustické emise porovnávají různé reakce v poškozených a nepoškozených pneumatických válcích s a bez zatížení. Výsledky testu ukázaly lineární vztah mezi křivkou RMS a zatížením. Defekty ovlivňují vztah mezi aplikovaným zatížením a zaznamenaným signálem snímačů.