Investigation of high frequency vibrations of pneumatic cylinders

V. Augutis, M. Saunoris

Department of Electronics and Measurements Systems
Kaunas University of Technology

Introduction

Pneumatic cylinders are often used for automatization of 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. Another method is based on the comparison of dynamic air flow patterns in main supply line of a pneumatic installation [1, 2]. Also very often of the pressure in a pneumatic cylinder is measured [5, 6].

The proposed non-destructive method may be used for the diagnostics of working pneumatic cylinders. It is based on measurements of high frequency vibrations (HFV) (30 kHz – 200 kHz) on a pneumatic cylinder housing and inside the pneumatic cylinder and measurements of the force of pneumatic cylinder.

The large group of the methods of vibration measurements forms so called passive methods [4, 3]. In these cases HFV are generated inside the object under the investigation, when pneumatic cylinder works.

The measured HFV signal is a noise type non-stationary signal. The basic characteristics of the generated HFV are root mean square value, the envelope of root mean square values and the power spectrum density.

The measurement model of the pneumatic cylinder HFV

The measurement model of the pneumatic cylinder HFV was developed according to the assumption that the wear condition of the pneumatic cylinder may be investigated by measurement of the HFV on the pneumatic cylinder housing and inside it. According to this model experimental investigation was carried out.

The model of the HFV measurement of the pneumatic cylinder is given in Fig. 1. The airflow, which generates HFV, forms up because of the difference of pressures $p_1 - p_2$ and the leak *N* between the pneumatic cylinder housing and the piston. The intensity of the HFV is bigger in the lower pressure zone.

The wear of the pneumatic cylinder housing may be not the same along the axis *x*. When the piston is moving at the speed *v(t)*, the variable leak between the pneumatic cylinder housing and the piston will be

$$N(x) = N[\int v(t)dt], \qquad (1)$$

where $N(x)$ is the leak variable along the axis *x* situated between the pneumatic cylinder housing and the piston.

The voltage at the output of the measurement transducer due to the air flow inside the pneumatic cylinder may be described in the following way:

$$U_\phi = (p_1 - p_2)\cdot N(x)\cdot K_{\phi U}, \qquad (2)$$

where p_1 is the pressure in the higher pressure zone; p_2 is the pressure in the lower pressure zone; $(p_1 - p_2)\cdot N(x)$ is the air flow; $K_{\phi V}$ is the transfer function of the HFV generated by the flow; $K_{\phi U} = K_{\phi V}(\omega, x_\phi, \varphi_\phi, x_K, \varphi_K)\cdot K_K(\omega)$; x_ϕ, φ_ϕ are the cylindrical coordinates of the leak between the pneumatic cylinder housing and the piston; x_K, φ_K are the cylindrical coordinates of the transducer; $K_K(\omega)$ is the frequency response of the transducer.

If the cross-section area of the pneumatic cylinder is *S*, then

$$(p_1 - p_2)\cdot S = F + F_T, \qquad (3)$$

where the force *F* evaluates the resistance to the movement and the inertia.

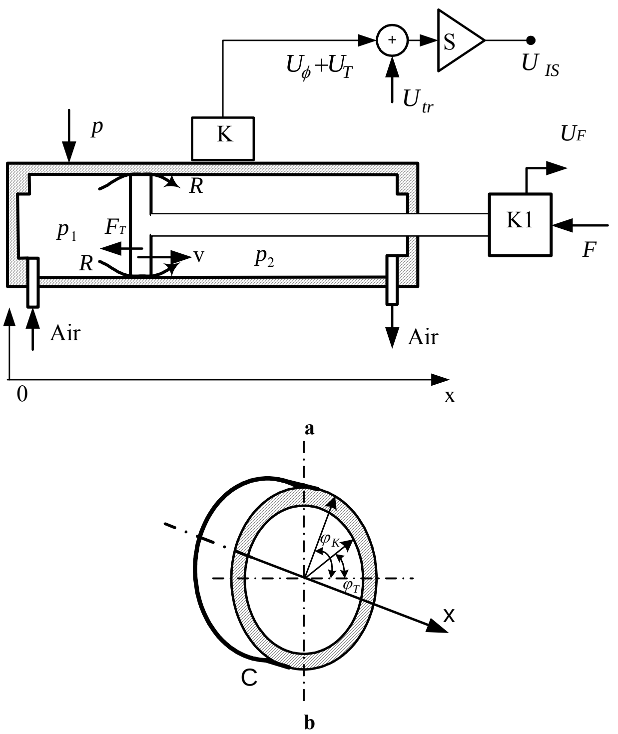


Fig. 1. **The measurement model of a pneumatic cylinder HFV (a) and cylindrical coordinates (b): K – HFV measurement transducer; K1 – force measurement transducer; p_1, p_2 - pressures; *R* – air flow between the pneumatic cylinder housing and the piston; *v* – speed; *F* – force of resistance to the movement; *p* – acoustic noise of environment; S – amplifier; U_{tr} – thermal and electrical noise; F_T - frictional force; U_F - signal of the force transducer; C – housing of the pneumatic cylinder**

The HFV in the pneumatic cylinder housing are generated by friction between the pneumatic cylinder housing and the piston. The intensity of the HFV is proportional to the frictional force and the piston speed. If the piston moves faster the higher frequencies are generated and the intensity of the HFV is increased. The voltage at the input of the amplifier due to friction will be [7]:

$$U_T = \left(\frac{dx}{dt}\right)^{\alpha} \cdot F_T^{\beta} \cdot K_{TU}, \qquad (4)$$

where α and β are coefficients that depends on the geometry and the material of the friction pair and lubrication; F_T is the force of the friction; $K_{TU} = K_{TV}(\omega, x_T, \varphi_T, x_K, \varphi_K) \cdot K_K(\omega)$; K_{TV} is the transfer function of the HFV generated by a friction; x_T, φ_T are the cylindrical coordinates of the friction zone.

The HFV generated by air flow propagate into the pneumatic cylinder indirectly, but the HFV generated by a friction propagate into the pneumatic cylinder directly. The distance from the place of the generated HFV to the measurement transducer K changes when the position of piston changes. Then the voltage at the output of the measurement transducer will change.

The HFV signal of the pneumatic cylinder is accompanied by an acoustic noise of the environment (*p*) and the thermal and the electrical noise (U_{tr}) of the measurement channel.

The noise type non-stationary signal at the output of amplifier is given by:

$$U_{IS} = K_S \cdot (U_{\phi} + U_T + U_{tr}), \qquad (5)$$

where U_{IS} is the voltage of the output of the amplifier; K_S is the gain of the amplifier; U_{ϕ} is the voltage due to the air flow inside pneumatic cylinder; U_T is the voltage due to the friction in the pneumatic cylinder; U_{tr} is the voltage caused by the acoustic noise of the environment, thermal and electrical noises.

The measurement channel of HFV of the pneumatic cylinder is presented in Fig. 2.

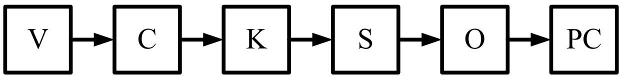


Fig. 2. **The block diagram of the HFV measurement channel in the pneumatic cylinder: V – high frequency vibrations; C – housing of the pneumatic cylinder; K – transducer; S – amplifier; O – oscilloscope; PC - computer**

Experimental investigation of the HFV

Two pneumatic cylinders (“Festo”): DNG-63-80-PPV-A and DNN-63-80-PPV-A were used for the experimental investigations. The both pneumatic cylinders possess the same parameters (the stroke – 80 mm, the piston diameter – 63 mm), but the first one is new and the second one is worn down (the leak is between the pneumatic cylinder housing and the piston). The measurement system used for experiments is presented in Fig. 3. Another pneumatic cylinder is used for the pneumatic cylinder under an investigation like a load (the pneumatic cylinder PC1 is a load for the pneumatic cylinder PC2, but they can be permuted). The pressured air (600 kPa) is fed from the compressor through the air valves SK1 and SK2. The air loads AP1 and AP2 are used to increase the pneumatic cylinders’ resistance. The HFV on the pneumatic cylinder housing and the force created by the pneumatic cylinder are measured using the transducers K1 and K2 (K1 is tensometer; K2 is the acoustic emission transducer in the frequency band (30…200) kHz developed in the Kaunas University of Technology). Then the signals are amplified and stored in the oscilloscope. Afterwards the signals are fed to a computer. The signals are measured using the Agilent Technologies digital oscilloscope 54622A with the sampling frequency 200 MHz and the 8 bit analog/digital converter. The Matlab programme was used for the data processing.

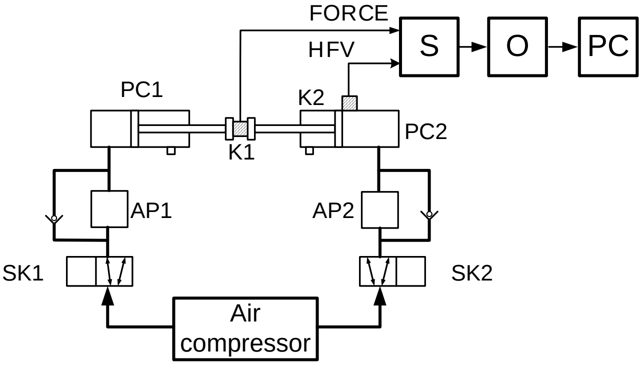


Fig. 3. **Experimental measurement system: SK1, SK2 – air valves; AP1, AP2 – air loads; PC1, PC2 – pneumatic cylinders; K1 – force measurement transducer; K2 – HFV measurement transducer; S – amplifier; O – oscilloscope; PC – computer**

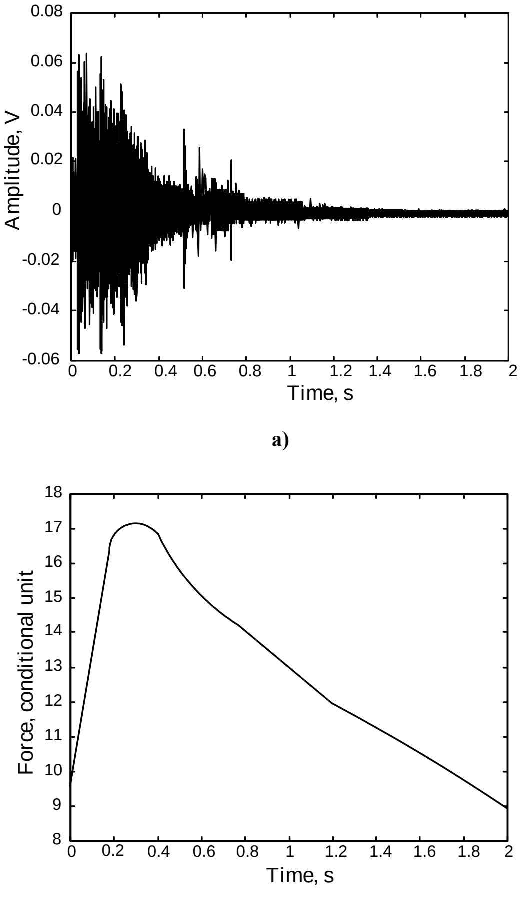
While the piston is moving the air flow and the friction are being formed between the pneumatic cylinder housing and the piston. The HFV are generated because of the air flow and the friction. The measurement transducer K2 measures the HFV. The measured HFV signals and the resistance force are presented in Fig. 4.

The investigation of the both pneumatic cylinders was performed with the same loads and under the same conditions. The differences have been noticed between the new and the worn pneumatic cylinders. The movement period of the piston in the new (“good”) pneumatic cylinder is shorter than in the worn one (Fig. 5). This happens because of the leak between the pneumatic cylinder housing and the piston thus creating a smaller force.

The generated HFV signal is a noise type non-stationary signal. It may be described by the root mean square value and the envelope of the root mean square values (In Fig. 5. the white lines are the envelopes of the root mean square values; T=2000000, M=1000). The envelope has the M segments of the root mean square values. The envelope of the root mean square values is calculated in the following way:

$$\bar{x}(n) = \sqrt{\frac{1}{M+1} \sum_{i=1}^{i+M} x_i^2}\ ; \qquad (6)$$

where $\bar{x}(n)$ is the root mean square n – segment value; $x_i = 1, 2 \dots \mathrm{T} - \mathrm{M} - 1$; x_i is i-th measurement point value; T is the number of measurement points.



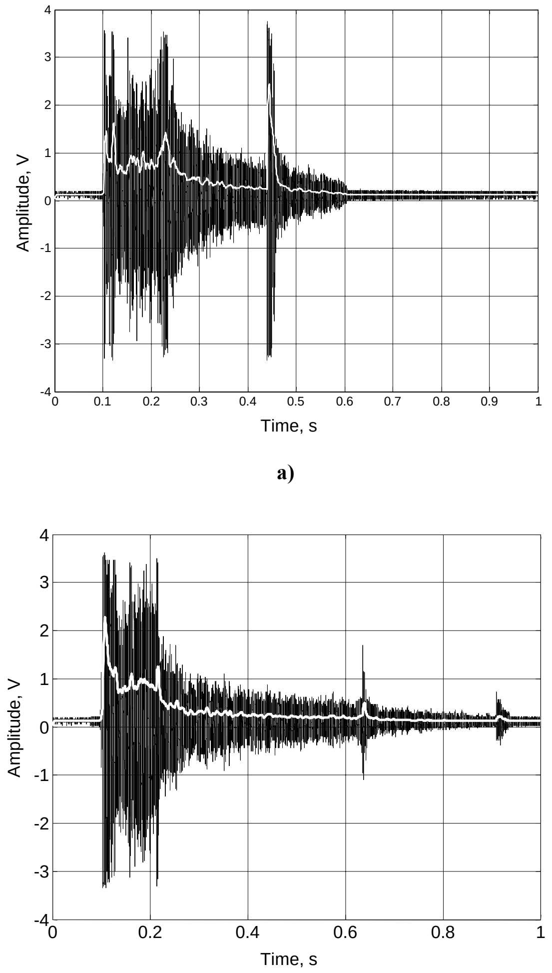
a)

b)

Fig. 4. **The voltage of the output of the K2 transducer (a) and the signal of the resistance force (b)**

For analysis of the HFV signals are important not only waveforms in the time domain, but also characteristics in the frequency domain. The calculated power spectral densities for both pneumatic cylinders are presented in Fig. 6 and Fig. 7. The process of the HFV can be analyzed according to the intensity and the distribution of the HFV in the frequency range. The intensity of the HFV in the new pneumatic cylinder (in the wide frequency range) is higher than the intensity of the HFV in the worn pneumatic cylinder (Fig. 6 and Fig. 7).

The differences between the new and the worn pneumatic cylinders may also be estimated when the piston is moving freely. The measurement process (Fig. 8) is analogous to the presented in Fig. 3. The both pneumatic cylinders are investigated in the same conditions. K2 measures the HFV on the pneumatic cylinder housing. The transducer K3 is isolated mechanically from the pneumatic cylinder housing and measures the HFV inside the pneumatic cylinder – in air.



a)

b)

Fig. 5. **The waveforms of the HFV of the pneumatic cylinders: a – the new pneumatic cylinder; b – the worn pneumatic cylinder (white lines marks the envelopes of the root mean square values)**

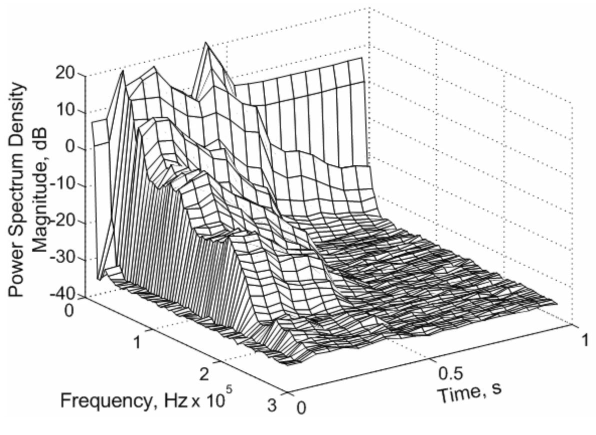


Fig. 6. **The power spectrum density of the HFV of the new pneumatic cylinder (Fig. 5. a) (dB re $\frac{1V^2}{Hz}$)**

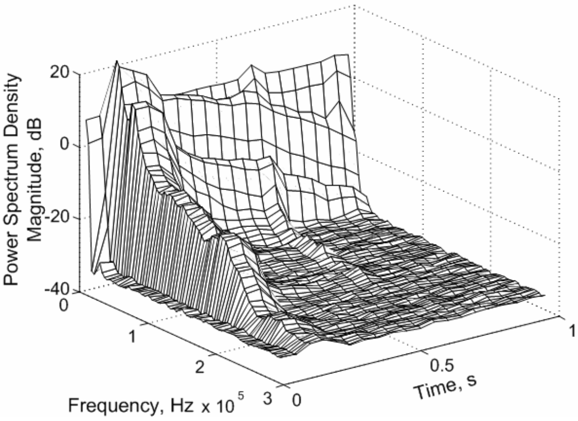


Fig. 7. **The power spectrum density of the HFV in the worn pneumatic cylinder (Fig. 5. b) (dB re $\frac{1V^2}{Hz}$)**

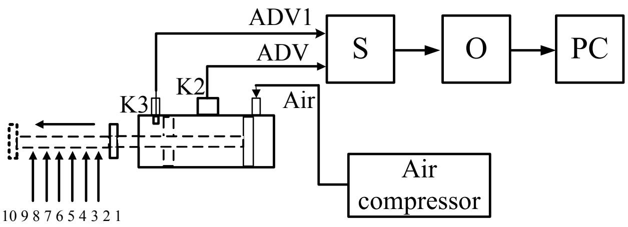


Fig. 8. **The block diagram of the experimental system: K3, K2 – HFV measurement transducers; ADV1 – signal from the first HFV measurement transducer; ADV – signal from the second HFV measurement transducer; numbers 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 mark the piston position points and ADV1, ADV the measurement moments; S – amplifier; O – oscilloscope; PC – computer**

The relationships between the measured (K2 transducer) intensities of the HFV and the position of the piston in both pneumatic cylinders are given in Fig. 9. The 600 kPa pressed air is being fed to the pneumatic cylinder. The piston is moving from 1 to 10 points and K2 measures the HFV. The interval between measurement points is 1 cm. If the pneumatic cylinder is new or worn equally along all piston length, the intensity of the HFV must be the same. It is because the conditions of HFV generation are the same. The position of the bigger root mean square value marks the place of the maximum leak (Fig. 9). The power spectrum densities of the HFV at various measurement points for both pneumatic cylinders are given in Fig. 10.

The HFV (Fig. 9) are formed due to the air leakage through the leak between the pneumatic cylinder housing and the piston and the friction.

In order to eliminate the friction, the HFV was measured at the measurement points when the piston is not moving (400 kPa-pressured air is fed in the pneumatic cylinder). K2 and K3 measurement transducers measure at the same time instant. In this case the intensities of the HFV are measured. The HFV are formed because of the air flow through the leak between the pneumatic cylinder housing and the piston.

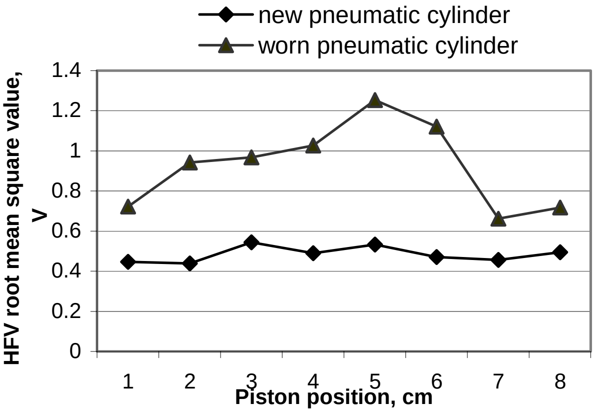
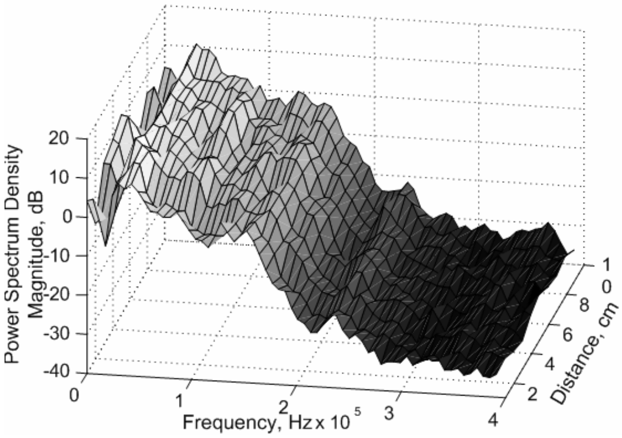
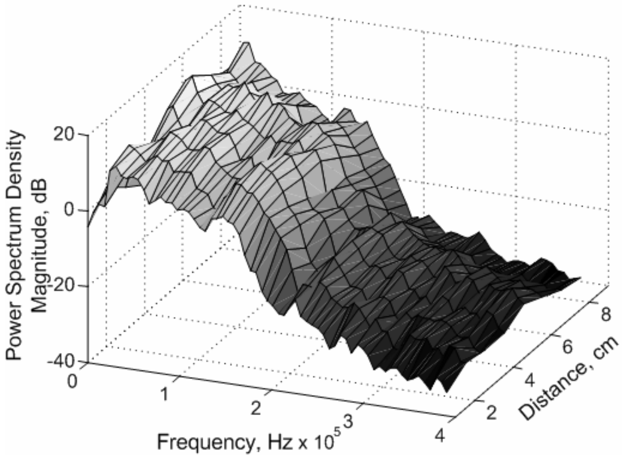


Fig. 9. **The relationships between the measured (*K2* transducer) intensities of the HFV and the position of the piston at both pneumatic cylinders**



a)



b)

Fig.10. **The power spectrum densities of the HFV at various measurement points: a) new pneumatic cylinder; b) worn pneumatic cylinder (dB re $\frac{1V^2}{Hz}$)**

The results (K2 measurement transducer) of the HFV measurements in the worn pneumatic cylinder are given in Fig. 11. The intensity of HFV is proportional to results in the Fig. 9 but is about 10 times lower. The HFV are measured also inside the pneumatic cylinder (in the air) by the K3 transducer (Fig.11). The measured intensity of the HFV is about 5 times lower than the intensity of the HFV on the pneumatic cylinder housing, but the dependence upon position is the same. The power spectrum densities of the HFV at various measurement points are given in Fig. 12.

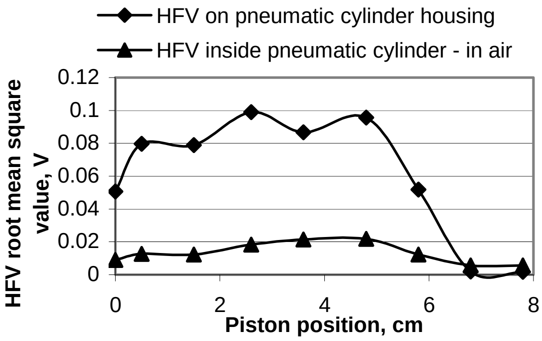
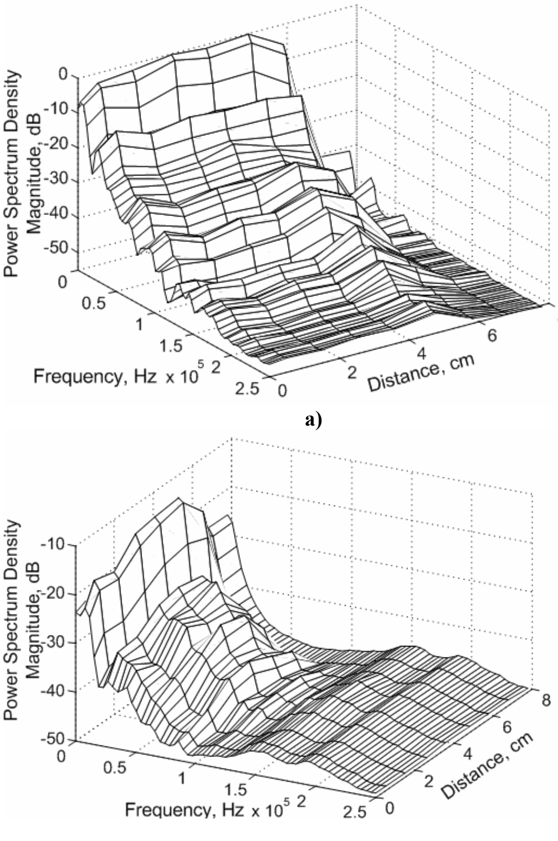


Fig. 11. **The relationships between the measured intensities of the HFV and the position of the piston**



a)

b)

Fig. 12. **The power spectrum densities of the HFV at various measurement points: a) HFV are measured on pneumatic cylinder housing; b) HFV are measured inside pneumatic cylinder – in the air (dB re $\frac{1V^2}{Hz}$)**

The results of measurements depend on the transfer function of the measurement channel (Fig. 2). The biggest influences have the transfer responses of the pneumatic cylinder housing and the transducer. These responses were estimated by the experimental set-up shown in Fig. 13. 2 μs duration and 62 V amplitude rectangular exciting impulses are fed from the impulse generator (IG) to the transducer K4. The transducer K4 is exciting an acoustic impulse in the pneumatic cylinder (the transducer K4 is attached every 1 cm along the pneumatic cylinder - 1, 2, 3,… points). The transducer K2 is used to measure the impulse response of the measurement channel. The measured impulse response at the point 2 of the worn pneumatic cylinder is given in Fig. 14. The signals at the output of the amplifier also show the transfer response of the transducer K2.

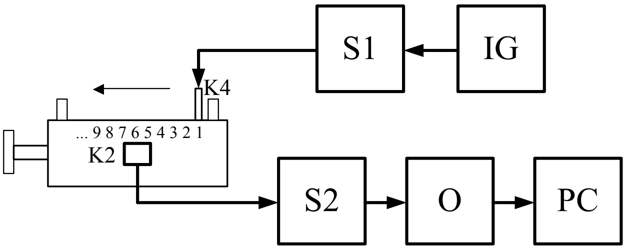


Fig. 13. **The experimental set-up for measurement of the transfer responses: K4, K2 – transducers; S1, S2 – amplifiers; O – oscilloscope; PC – computer; numbers 1, 2, 3, 4, 5, 6, 7, 8, 9 – mark the attachments points of the K4 transducer; IG – impulse generator**

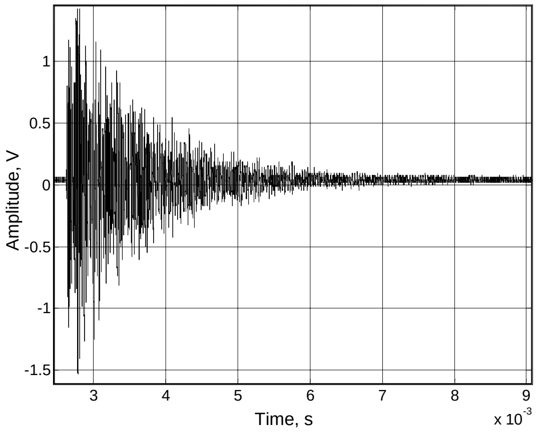
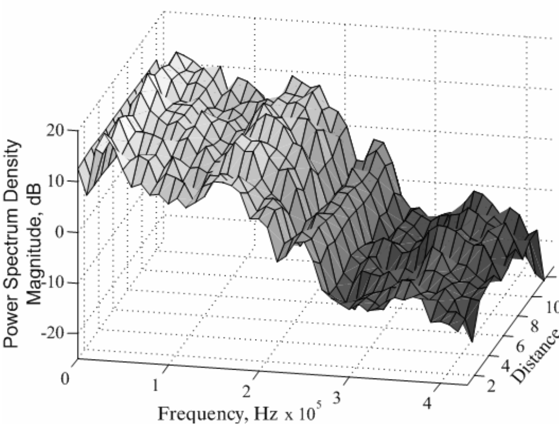


Fig. 14. **The measured impulse response at the point 2 of the worn pneumatic cylinder**

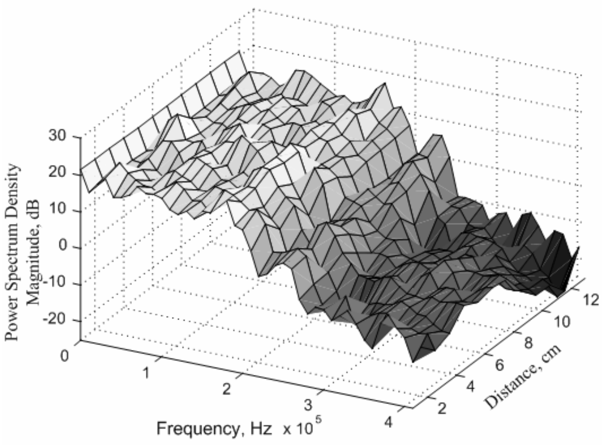
Fig. 15 shows the power spectrum densities of the impulse responses of the new and worn pneumatic cylinders at various points. It is obvious that the frequency responses up to 200 kHz do not depend on the place of impulse excitation. Hence it is possible to state that the HFV enable estimate the condition of the pneumatic cylinder.

Conclusions

1. While the pneumatic cylinder is working, the pneumatic cylinder housing is wearing down due to the piston repeatedly movement. This causes the leak between the piston and the pneumatic cylinder housing. It was found that the leak causes higher intensity of the.



a)



b)

Fig. 15**. The power spectrum densities of the impulse responses of the new (a) and worn (b) pneumatic cylinders at the various points (dB re $\frac{1V^2}{Hz}$)**

HFV. The parameters of the HFV may be used for the diagnostics of pneumatic cylinder

2. The HFV are generated inside the object under investigation while the pneumatic cylinder works. The generated HFV signal is the noise type non-stationary signal. The basic characteristics of the generated HFV, which are measured, are root mean square value, the envelope of the root mean square values and the power spectrum density.
3. The friction between the piston and pneumatic cylinder housing is a dominating factor in the formation of the HFV in the worn pneumatic cylinder. It was found that the influence of the friction is approximately 10 times bigger than the influence of the leak between the piston and the pneumatic cylinder. In the new pneumatic cylinder the HFV are generated just due to the friction between the piston and the pneumatic cylinder housing.
4. The intensity of the HFV on the worn pneumatic cylinder housing is about 5 times higher than the intensity of the HFV measured inside of the pneumatic cylinder in air.

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V. Augutis, M. Saunoris

Pneumatinių cilindrų aukštadažnių vibracijų tyrimas

Reziumė

Pasiūlytas neinvazinis metodas, kuriuo galima įvertinti pneumatinio cilindro darbą Metodas įgyvendinamas matuojant aukštojo dažnio virpesius - vibracijas (ADV) - ant pneumatinio cilindro ir jame bei jo sukuriamą jėgą. Pagrindinės pneumatinių cilindrų ADV signalo matuojamosios charakteristikos yra ADV signalo vidutinė kvadratinė vertė, laikinio signalo vidutinės kvadratinės vertės gaubtinė, ADV signalo galios spektrinis tankis. Nagrinėjamasis matavimo metodas gali būti taikomas pneumatinių cilindrų diagnostikai eksperimentiniais - tiriamaisiais tikslais.

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