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ANALYSIS OF THE CONDITION OF CAR DAMPERS ON THE BASIS OF IDENTIFICATION OF THE PARAMETERS OF FFT SPECTRUMS

Summary. Analysis of the frequency spectrum of technical objects enables the accurate identification of damages of many technical objects and recognition of their source. The article presents the assessment of the possibility of applying frequency spectra for the purpose of analysing the technical condition of car dampers within the frequency range 0÷1,2 kHz (with the method of direct examination on the production line). The paper presents the constraints resulting from the restrictions of the industrial quality control systems and the proposal of measurement methods in the industrial conditions. Analysis of the usability of the method of classifying the damages of damper base valve has been performed on the basis of frequency spectra.

ANALIZA STANU AMORTYZATORA SAMOCHODOWEGO NA PODSTAWIE IDENTYFIKACJI PARAMETRÓW WIDM FFT

Streszczenie. Analiza widma częstotliwości obiektów technicznych pozwala na bezpośrednią identyfikację uszkodzeń wielu obiektów technicznych oraz jednoznacznego określenia ich źródła. W artykule przedstawiono ocenę możliwości zastosowania widm częstotliwości do analizy stanu technicznego amortyzatorów samochodowych w zakresie częstotliwości 0÷1,2 kHz (metodą bezpośredniego badania na linii produkcyjnej). Przedstawiono założenia ograniczające, wynikające z restrykcji przemysłowych procesów kontroli jakości oraz propozycję pomiaru w warunkach przemysłowych. Przeprowadzono także analizę przydatności metody klasyfikacji uszkodzeń zaworu podstawy amortyzatora na podstawie widm częstotliwości.

1. Introduction

Tests involving car dampers are usually carried out with servo-hydraulic testers. Such tests lead to obtaining characteristics of damper operation and are the basis for wear tests in the operational phase [1,7÷10].

For the case considered in this article, the main element is the application of the method of characteristic frequency identification [2÷4] combined with the observation of amplitude values, for the purposes of identifying the damages of a damper base valve. The tests require accurate identification of the irregularities in the performance within one movement of the piston rod.

The constraints adopted for the purposes of evaluating the condition result from the requirements of the quality control process on the line. The main constraints are the following: inspection time – dependent on the production line tact time, it has been allowed that one measurement may be taken without the possibility of forcing another movement (pushing the piston rod of a damper is performed with the pneumatic actuator and the extending is free – extending time of the tested series of dampers varies from three to twelve seconds); coefficient of measurement accuracy certainty – overestimation of the number of damaged products influences the increase of PPM factor (Parts Per Million), which decreases the efficiency of the plant and generates losses; simplification of the measurement method and operation procedure – due to reduction in the number of errors made by the production staff.

The adopted constraint regarding the possibility of taking one measurement eliminated the factor of hydraulic fluid heating and related adverse phenomena such as aeration or cavitation.

Aeration may lead to changes in the bulk modulus of the fluid which entails changes in damper characteristics in the range of higher frequencies. Cavitation, on the other hand, causes irregularities in the performance, which, with the adopted method of failure identification, influences the spectra of characteristic frequencies of a damper.

2. Identification and justification of the test method selection

The value of the response to forcing the movement generated by the hydraulic damper may be noted using the following equation [11÷13]:

$$F_{HD} = p_r \cdot A_r + p_0 \cdot A_{rd} - p_c \cdot A_c + F_f \tag{1}$$

where:

A_{rd}, A_c, A_r - piston rod surface, surface of the compression and expansion sides respectively [m^2],

p_c, p_r - pressure in the compression and expansion chambers [Pa],

p_0 - atmospheric pressure [Pa],

F_f - dry friction force between the piston rod and the internal tube.

Friction force F_f between the piston and the tube may be determined with the following formula [11÷13]:

$$F_f = F_{f\_max} \cdot \tanh\left(\frac{v_t - v_r}{v_{ref}}\right) \tag{2}$$

where:

F_{f_max} – maximum friction force (determined experimentally by measuring the hydraulic damper with removed valves and the reference speed) [N],

v_t – speed of the external damper tube [m/s],

v_r – speed of the damper piston rod [m/s],

v_{ref} – reference speed [m/s].

The identified force of the damper's response depends on many factors, such as the following: damping fluid parameters – density, temperature, capacity; geometric dimensions of the damper; parameters and characteristics of the damper base valve [2,5].

The application of diagnostic concluding based on the methods with mathematical models of dampers is a complex issue due to the necessity of considering model components dependent on the equations of force balance, pressure losses on the valves [5,6], as well as mass and emulsion balance (taking into account the priming of air effect).

Given the stability of geometric parameters and hydraulic fluid properties the main element in determining failures of the shock absorber is the valve disk condition that affects performance characteristics.

Due to the complexity of phenomena occurring in the examined element and high production variability (the necessity of developing a new parametric model) the model-based feature identification method has been rejected. The adopted test method is based on the knowledge of production line quality inspectors, combined with testing the dampers acquired straight from the production line.

3. Identification of damper damage within the scope of experimental tests

Table 1 presents the basic types of car damper damages that lead to irregularities in performance presented in figure 1. The damage connected with operation (such as broken springs or wear of McPherson strut bearings) have been disregarded due to their classification to the group of operating damage. On the basis of the presented damages, a graph of damages propagation of car dampers has been prepared (Fig. 1).

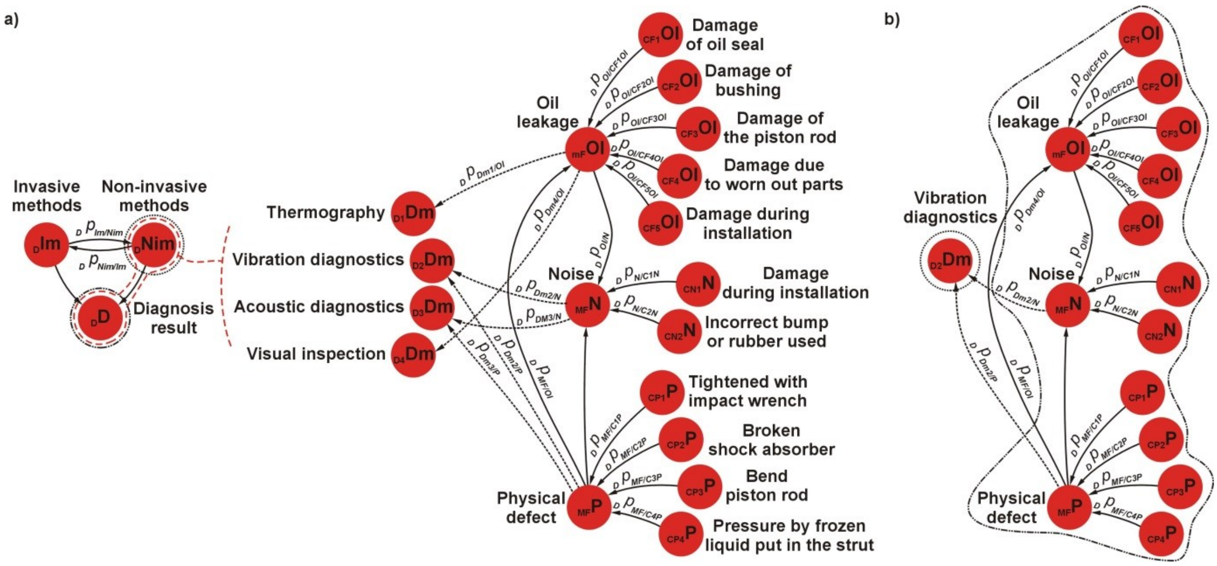

Fig. 1. Cause and effect graph of the damages and irregularities and their path of development for the case of the damper base valve unit: a) complete graph, b) graph after reduction

Table 1

Basic causes of car damper damages [9,10,11], where: E – operating or assembly damage outside the production plant, A – damage on the production line, D_C – damage category

General cause/ symptom	Details	D_C
Piston rod leakage/ Oil leakage	Seal wear	E
	Dust protection damage	E, A
	Piston rod mechanical damage	E, A
	Piston rod seal damage	E, A
	Guide bush damage	E, A
	Piston rod damage	E, A
	Damage as a result of wear	A
	Body damage	E
Cracks and corrosion spots on the piston rod/ Physical damage	Dust protection damage	E
	No dust protection	E
	Scratches at the assembly stage	A
Uneven wear of the protection layer on the piston rod/ Physical damage	Incorrect assembly in the car or on the production line	E,A
Piston rod bending/ Physical damage	Incorrect operation, storage or assembly	E,A
Piston rod bolt shear or strip/ Physical damage	Incorrect assembly in the car (chamfering or too high tightening torque)	E
Valve unit damage/ Physical damage	Mechanical damage of the valve base (material loss as a result of the fall or impact)	E, A
	Pressure by frozen liquid put in the strut	A
	Bumper damages	E, A
	Wrong selection of a damper spring	E
Loosening of the valve nut (using the impact wrench)/ Noise	Incorrect assembly	E
	Bumper damages	E
	Wrong selection of a damper spring	E
Material and assembly damages/ Noise	Material fatigue	E
	Frequent overload	E
	Strains at the assembly	E
	Worn spring elements	E
	Damaged accessories (stabilizer, connecting bars, rubber bearings)	E
	Worn elements of vehicle chassis and steering	E
	Foreign particles in oil	E, A
	Damaged valves of the valve disc	A
	Assembly with too strong clamping force	A

The identified graph constitutes the formal notation of the error development path. However, the main task is the identification of the peak corresponding to the current condition of the examined unit. The selected mechanical subsystem enables the identification of damage on the basis of the frequency spectra analysis.

The effects of damage include inter alia: deterioration of performance quality, safety hazard, deterioration of product quality, blocking the piston rod, increased risk of piston rod rupture, unstable operation, complete destruction of the damper

4. Results of the test at workbenches

Damaged products have been divided into two independent series due to their cyclic occurrence. Dampers classified as damage-free products have been randomly chosen for tests straight from the production line in the time of completing the set of damaged pieces, and then subject to tests.

Table 2

Characteristic peak acceleration values in the dominant frequencies for the dampers with and without defects (sensor VS01)

<table>
<tr><th rowspan="2">No.</th><th colspan="6">Peak values P [mg]</th><th rowspan="2">P_{SD} [mg]</th><th colspan="4">Frequencies of peak values $P_{1\div4}$ [Hz]</th></tr>
<tr><th>P_1</th><th>P_2</th><th>P_3</th><th>P_4</th><th>P_{MIN}</th><th>P_{AV}</th><th>f_1</th><th>f_2</th><th>f_3</th><th>f_4</th></tr>
<tr><td colspan="12">The 1st measurement series – shock absorbers with failures (sensor VS01)</td></tr>
<tr><td>1</td><td>4,32</td><td>4,06</td><td>-</td><td>-</td><td>0,09</td><td>0,40</td><td>0,27</td><td rowspan="5">648,50</td><td rowspan="5">720,21</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>4,43</td><td>3,78</td><td>-</td><td>-</td><td>0,11</td><td>0,41</td><td>0,27</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>4,50</td><td>4,30</td><td>-</td><td>-</td><td>0,15</td><td>0,41</td><td>0,28</td><td>-</td><td>-</td></tr>
<tr><td>4</td><td>4,61</td><td>4,21</td><td>-</td><td>-</td><td>0,10</td><td>0,41</td><td>0,27</td><td>-</td><td>-</td></tr>
<tr><td>5</td><td>4,47</td><td>4,20</td><td>-</td><td>-</td><td>0,10</td><td>0,43</td><td>0,29</td><td>-</td><td>-</td></tr>
<tr><td colspan="12">The 2nd measurement series – shock absorbers with failures (sensor VS01)</td></tr>
<tr><td>1</td><td>4,43</td><td>3,68</td><td>-</td><td>-</td><td>0,09</td><td>0,41</td><td>0,26</td><td rowspan="5">648,50</td><td>732,42</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>4,62</td><td>3,57</td><td>-</td><td>-</td><td>0,14</td><td>0,42</td><td>0,26</td><td rowspan="4">730,90</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>4,55</td><td>4,15</td><td>-</td><td>-</td><td>0,11</td><td>0,40</td><td>0,27</td><td>-</td><td>-</td></tr>
<tr><td>4</td><td>4,82</td><td>4,08</td><td>-</td><td>-</td><td>0,10</td><td>0,40</td><td>0,28</td><td>-</td><td>-</td></tr>
<tr><td>5</td><td>4,43</td><td>4,08</td><td>-</td><td>-</td><td>0,12</td><td>0,40</td><td>0,25</td><td>-</td><td>-</td></tr>
<tr><td colspan="12">The 1st measurement series – shock absorbers without failures (sensor VS01)</td></tr>
<tr><td>1</td><td>4,42</td><td>3,97</td><td>-</td><td>-</td><td>0,13</td><td>0,41</td><td>0,26</td><td rowspan="5">648,50</td><td rowspan="3">711,06</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>4,48</td><td>3,66</td><td>-</td><td>-</td><td>0,13</td><td>0,49</td><td>0,33</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>4,67</td><td>3,66</td><td>-</td><td>-</td><td>0,09</td><td>0,41</td><td>0,27</td><td>-</td><td>-</td></tr>
<tr><td>4</td><td>4,32</td><td>3,87</td><td>-</td><td>-</td><td>0,11</td><td>0,45</td><td>0,29</td><td rowspan="2">709,53</td><td>-</td><td>-</td></tr>
<tr><td>5</td><td>4,23</td><td>3,58</td><td>-</td><td>-</td><td>0,17</td><td>0,47</td><td>0,28</td><td>-</td><td>-</td></tr>
</table>

In order to minimize the possibility of the influence of random disruptions, the following procedures have been followed to enable maintaining the reproducibility of measurements at the stage of preparing the damper for tests: constant value of ambient temperature (in the phase of testing particular groups of dampers); damper storing conditions; excitation parameters (constant value of pressure, pneumatic cylinder start-up and excitation time); method of manipulating the tested object; reproducibility of mounting the measurement sensors and configuration settings for measurement unit parameters.

The presented results have been obtained with: one-time damper excitation (no cyclic repeated measurements) with registering the characteristics (FFT spectra, peak acceleration values and effective speed values); the graphs have been developed as a result of averaging the measurements in each measurement series, and the analysis have been carried out on the averaged spectrum (in order to minimize fluctuation of the transition processes).

Table 3

Characteristic peak acceleration values in the dominant frequencies for the dampers with and without defects (sensor VS02)

<table>
<tr><th rowspan="2">No.</th><th colspan="6">Peak values P [mg]</th><th rowspan="2">P_{SD} [mg]</th><th colspan="4">Frequencies of peak values $P_{1÷4}$ [Hz]</th></tr>
<tr><th>P_1</th><th>P_2</th><th>P_3</th><th>P_4</th><th>P_{MIN}</th><th>P_{AV}</th><th>f_1</th><th>f_2</th><th>f_3</th><th>f_4</th></tr>
<tr><td colspan="12">The 1st measurement series – shock absorbers with failures (sensor VS02)</td></tr>
<tr><td>1</td><td>4,76</td><td>3,69</td><td>1,83</td><td>2,83</td><td>0,20</td><td>0,49</td><td>0,28</td><td rowspan="5">648,5</td><td rowspan="5">720,21</td><td>988,77</td><td>1126,10</td></tr>
<tr><td>2</td><td>4,32</td><td>3,67</td><td>1,81</td><td>2,23</td><td>0,14</td><td>0,48</td><td>0,27</td><td rowspan="2">990,30</td><td>1124,57</td></tr>
<tr><td>3</td><td>4,47</td><td>3,55</td><td>1,95</td><td>2,70</td><td>0,17</td><td>0,49</td><td>0,27</td><td>1126,10</td></tr>
<tr><td>4</td><td>4,42</td><td>4,03</td><td>2,15</td><td>2,65</td><td>0,16</td><td>0,50</td><td>0,27</td><td>991,82</td><td>1124,57</td></tr>
<tr><td>5</td><td>4,00</td><td>3,79</td><td>2,87</td><td>2,81</td><td>0,20</td><td>0,74</td><td>0,43</td><td>988,77</td><td>1126,10</td></tr>
<tr><td colspan="12">The 2nd measurement series – shock absorbers with failures (sensor VS02)</td></tr>
<tr><td>1</td><td>4,40</td><td>3,65</td><td>1,92</td><td>2,71</td><td>0,21</td><td>0,52</td><td>0,27</td><td rowspan="5">648,5</td><td rowspan="5">730,90</td><td>1002,50</td><td>1116,94</td></tr>
<tr><td>2</td><td>4,40</td><td>3,98</td><td>1,69</td><td>2,48</td><td>0,19</td><td>0,50</td><td>0,27</td><td>1000,98</td><td rowspan="4">1118,47</td></tr>
<tr><td>3</td><td>4,39</td><td>3,57</td><td>1,98</td><td>2,47</td><td>0,16</td><td>0,49</td><td>0,27</td><td rowspan="2">999,45</td></tr>
<tr><td>4</td><td>4,69</td><td>3,53</td><td>1,63</td><td>2,31</td><td>0,23</td><td>0,54</td><td>0,26</td></tr>
<tr><td>5</td><td>4,61</td><td>3,85</td><td>1,66</td><td>2,37</td><td>0,23</td><td>0,55</td><td>0,28</td><td>1000,98</td></tr>
<tr><td colspan="12">The 1st measurement series – shock absorbers without failures (sensor VS02)</td></tr>
<tr><td>1</td><td>4,32</td><td>3,85</td><td>2,11</td><td>2,37</td><td>0,12</td><td>0,54</td><td>0,28</td><td rowspan="5">648,5</td><td rowspan="3">709,53</td><td>1008,61</td><td>1112,37</td></tr>
<tr><td>2</td><td>4,56</td><td>3,96</td><td>1,82</td><td>2,68</td><td>0,13</td><td>0,49</td><td>0,27</td><td rowspan="3">1007,08</td><td>1113,89</td></tr>
<tr><td>3</td><td>4,60</td><td>3,36</td><td>1,37</td><td>2,49</td><td>0,19</td><td>0,50</td><td>0,26</td><td>1115,42</td></tr>
<tr><td>4</td><td>4,70</td><td>3,57</td><td>1,50</td><td>2,70</td><td>0,16</td><td>0,48</td><td>0,27</td><td>708,01</td><td>1113,89</td></tr>
<tr><td>5</td><td>4,55</td><td>3,60</td><td>2,34</td><td>2,67</td><td>0,24</td><td>0,70</td><td>0,36</td><td>709,53</td><td></td><td>1112,37</td></tr>
</table>

Sensor VS01 has been mounted on the piston rod of the pneumatic cylinder (vertically) in order to control the frequencies originated from the system forcing the movement of damper's moving parts and constant components of the FFT spectrum. Sensor VS02 has been mounted on the cylindrical surface of the damper tube (bipolar magnet).

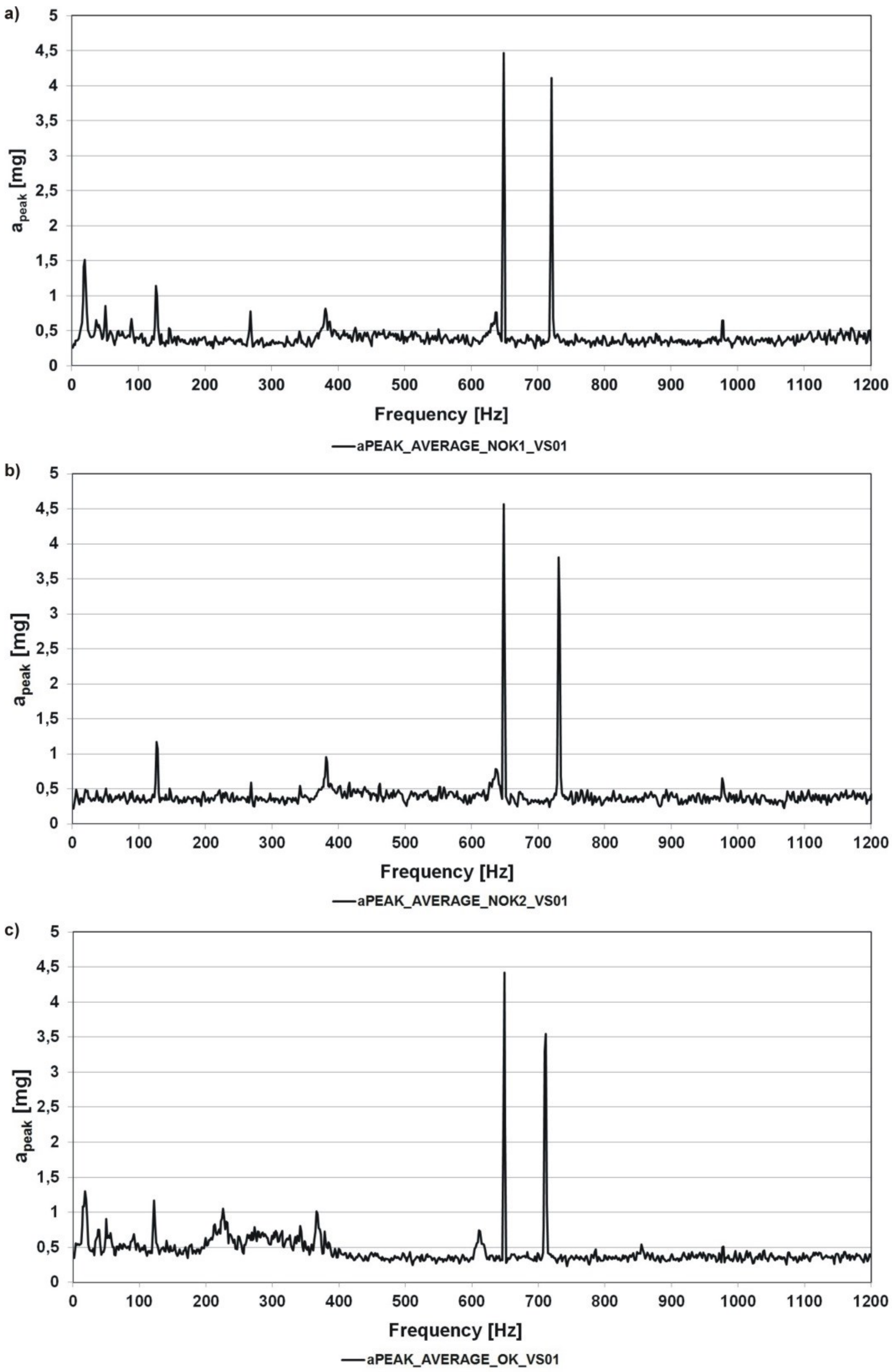

Fig. 2. Differential frequency spectrums of acceleration from two independent measurement series measured by the sensor VS01 for the dampers: a) with defects (the first measurement series), b) with defects (the second measurement series), c) fully functional (the summary result from the two measurement series)

Despite maintaining the reproducibility conditions of measurements and controlling the values of parameters that might influence the result in one of the measurement series, a significant deformation of frequency spectrum has been observed that results from the incorrect mounting of the damper in the housing.

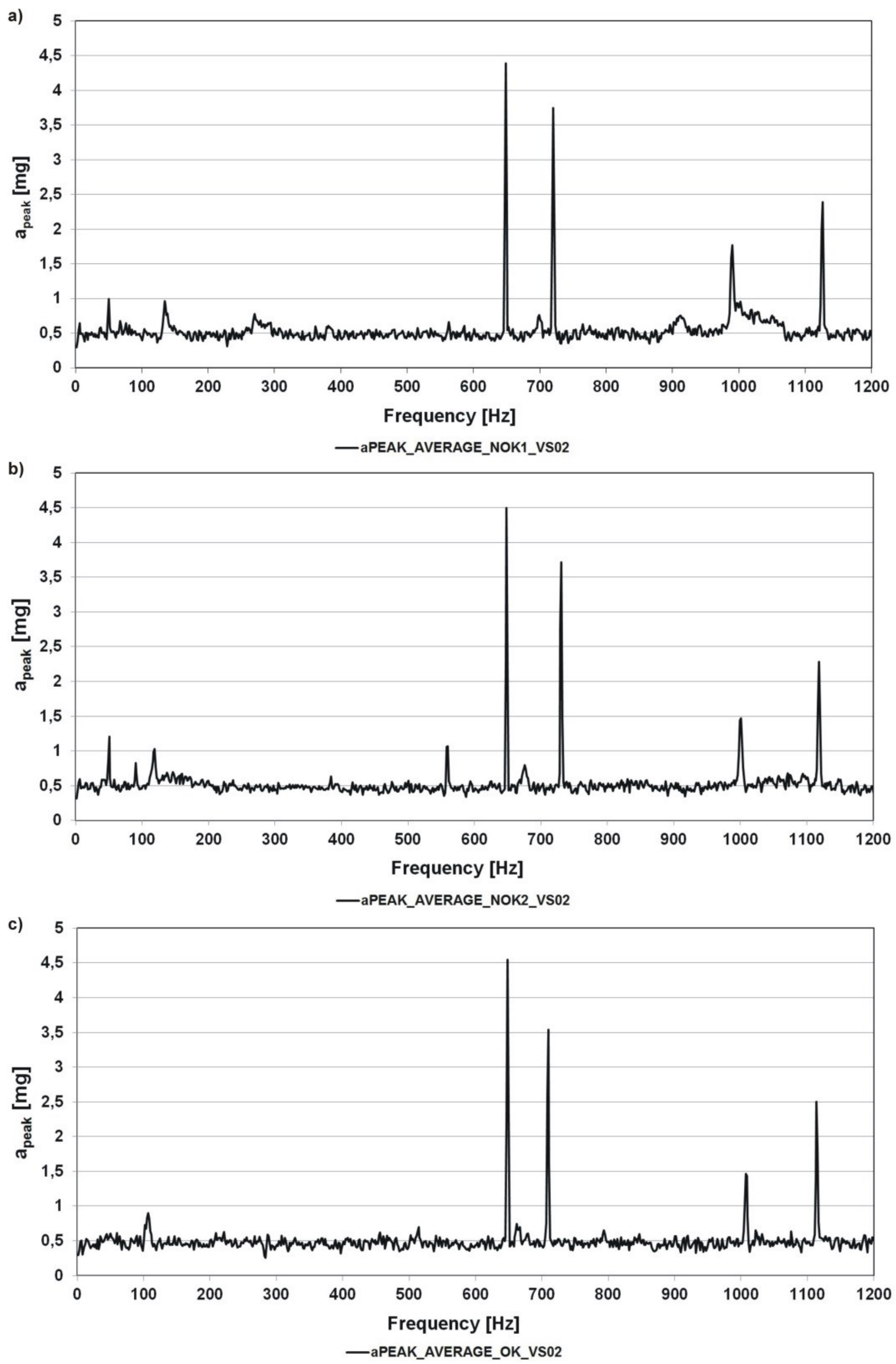

Fig. 3. Differential frequency spectrums of acceleration from two independent measurement series measured by the sensor VS02 for the dampers: a) with defects (the first measurement series), b) with defects (the second measurement series), c) fully functional (the summary result from the two measurement series)

In the spectra of measurement series for the defective disc valves obtained on the base, the following characteristic elements may be observed:

- measurements with sensor VS01 (Tab. 2):
  - in the spectra one may see clear harmonics with dominant peak value and constant frequency of 648,5Hz,
  - second harmonic of the defective pieces changes the characteristic frequencies within the range 720,21÷732,42Hz (ten times larger value of sampling resolution),
  - in case of the piece with no identified irregularities there is a shift of second dominant harmonic to higher frequencies with a value within the range 19,84÷22,89Hz,
  - lack of 3 and 4 dominant harmonics,
- measurements with sensor VS02 (Tab. 3):
  - in the spectra one may observe clear harmonics with dominant peak value and constant frequency of 648,5Hz,
  - the second harmonic is positioned in two different frequency values (the difference is a single value of sampling resolution),
  - second harmonic of the defective pieces takes two values of characteristic frequencies occurring at an interval of 10,68Hz (nine times larger value of sampling resolution),
  - in case of the pieces with no identified irregularities there is a shift of the second dominant harmonic to higher frequencies with a value within the range 21,36÷22,89Hz,
  - the third dominant component changes its position within the frequency range 988,77÷1002,5Hz,
  - the fourth dominant component changes its position within the frequency range 1116,94÷1126,1Hz.

The flow of hydraulic fluid through the valve constraints, uneven opening of disc valves, changes of the temperature of hydraulic fluid in operation and variable position of dirt particles cause significant changes in FFT characteristics (in the form of noise in the frequency broad band).

Tested shock absorber has been treated as a black box. To assess states the author did not use the mathematical model but only method of real object parameter identification and comparison of the measured values with the thresholds (a comparison of defectively and correctly assembled system).

Measurements were repeated with maintaining values for crucial parameters (forcing conditions, environmental parameters and levels of external disturbances). A strong influence on the measurement results is connected with the hydraulic fluid foaming. Multiple forcing of shock absorbers reveals a lack of reproducibility of the measurements, which significantly impedes a condition evaluation.

The adopted classifier (based on the FFT spectrum) can be obtained as a formula:

$$C_{OS} = \langle H_D, \left(a_{Peak\_Val}, w_{Wdith\_Val}, f_{Central\_Val}\right), \langle a_{Peak_{f3/4}}, w_{Wdith_{f3/4}}, f_{Central_{f3/4}}\rangle, f_C\rangle \quad (3)$$

where:

H_D – tested hydraulic damper,

a_{Peak_h} – peak values of acceleration amplitudes (3-rd and 4-th harmonics) [mg],

w_{Width_h} – frequency range widths (3-rd and 4-th harmonics) [Hz],

$f_{Central\_h}$ – central frequencies (3-rd and 4-th harmonics) [Hz].

The decision function f_C may be presented as a formula:

$$f_c = \begin{cases} a_{peak\_min\_f3} < a_{peak\_f3} < a_{peak\_max\_f3}, \\ w_{width\_f3} = f_{Central\_f3} \pm C_1\%, \\ a_{peak\_min\_f4} < a_{peak\_f4} < a_{peak\_max\_f4}, \\ w_{width\_f4} = f_{Central\_f4} \pm C_2\%. \end{cases} \quad (4)$$

where:

$a_{peak\_min\_f3/f4}$, $a_{peak\_max\_f3/f4}$ – respectively minimum and maximum values of average acceleration amplitudes of hydraulic dampers without failures [mg],

$a_{peak\_f3/f4}$ – measured values [mg],

$f_{Central\_f3/f4}$ – mean value of 3-rd and 4-th harmonics related to fully functional shock absorbers (determined on the basis of the tuning algorithm),

C_1, C_2 – coefficients related to specific batch (determined on the basis of the tuning algorithm).

5. Conclusions

The measurement of parameters of car damper vibration is to be perceived as a method with a high degree of complexity. Geometric measurements or correct assembly inspection require specialist knowledge aided by modern measurement tools.

The basic problems occurring in the undertaken process of evaluating the condition of dampers are as follows:

- random occurrence of damage symptoms – foreign particles in damper's hydraulic oil constantly travel,
- foreign particles may cause blocking valve discs of the base and influence the angle of opening in the phase of oil flow (pressure may, however, cause tearing off of particles and free flow in the fluid, without coming into contact with the surface of valve elements),
- hydraulic oil foaming inside the cylinder – taking a few measurements in a series results in obtaining different frequency characteristics.

The above mentioned features lead to the lack of reproducibility of the spectra shapes within the defined measurement range. Even in case of the repeated tests on the same piece, there still is a high dispersion of amplitude values of the registered vibration parameters and shifts of the harmonics on the frequency axis.

The main problem of the method application for industrial purposes may be the selectivity of vibration signal. Vibration originated from the drive components of other machines may strongly influence the shape of vibration spectra and peak values. The obtained results led to the decision about narrowing the range of frequency measurements, at the same time increasing the measurement resolution.

Furthermore, the lack of defined relationships between specific types of failures or detuning, identified in relation to the characteristics of the selected frequency range significantly hamper the analysis of the spectrum.

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