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The application of a linear decimation procedure in the diagnostics of shock absorbers in passenger vehicles

K e y - w o r d s

Shock absorber diagnostics, suspension of passenger vehicles, telescopic shock absorbers, VA test methods for shock absorbers.

S ł o w a k l u c z o w e

Diagnostyka amortyzatorów, zawieszenia samochodów osobowych, amortyzatory teleskopowe, metody badań WA amortyzatorów.

S u m m a r y

The paper presents diagnostic methods for shock absorbers encased in passenger vehicles. This includes: the EUSAMA method commonly used in Vehicle Testing Stations, and multidimensional methods of vibroacoustic analysis of non-stationary signals. The presented method based on LDP (linear decimation procedure) is an innovative method for the diagnostics of shock absorbers. Obtain results confirm the justified use of the linear decimation procedure for non-stationary signals. LDP, apart from the decrease in sampling speed, also transforms the signal, which enables the application of fast Fourier transform in signal description.

1. Introduction

Periodic vehicle tests for diagnosing their further usability on public roads are a compulsory part of motor vehicle use. This refers particularly to units determining the safety of the vehicle. Vehicle suspension is one of these units. Diagnostics of loose in suspension, in the joints of couplers, torsion bars and

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bearings is relatively simple and applies equipment with induced force, popularly known as play testers. The wear of springing elements is identified by organoleptic tests and by the test of static spring deflections. However, the diagnostics of dampers (shock absorbers) encased in the vehicle is difficult because the nature of the damping of currently applied telescopic shock absorbers is strongly non-linear and asymmetric. This hinders diagnostic conclusions and the identification of individual damage.

There are many resonant frequencies characteristic for a vehicle including, but not limited to, the resonance of:

– sprung mass (1–3 Hz),
– unsprung mass (8–18 Hz).

Band 1–3 Hz is more important for passengers' comfort, and band 8–18 Hz is important for driving safety.

Some research methods for testing the technical condition of shock absorbers are:

– indicator tests of shock absorbers not encased,
– tests of shock absorbers encased in the vehicle.

Owing to the time required for measurements, the second mentioned research method is in common use.

2. EUSAMA method for testing shock absorbers encased in the vehicle

The European Shock Absorber Manufacturers Association EUSAMA has developed a method for the evaluation of damping efficiency. The method measures the value of contact force, expressed in percent, between the tyre and the support member on which the tyre associated with the damper to be tested is disposed. The evaluation of the damping efficiency of the shock absorber is defined by the EUSAMA ratio (ER) described by the correlation:
where:

$$ER = \frac{W_{\min}}{W_{st}} \cdot 100\% \tag{1}$$

W_{min} – minimum measured dynamic tyre-to-support contact force,
W_{st} – static tyre-to-support contact force (static weight).

During the test the vehicle wheel rests on a static platform of the unit which induces force (vibration exciter). In these circumstances the static measurement is performed (W_{st}) and the ER value is 100%. After that the force inducing system is actuated. The platform attains vibrations of amplitude 4–8 mm at the frequency of 25 Hz. After the shut-down of the drive system at a frequency of ca. 16 Hz the minimum dynamic tyre-to-platform contact force (W_{min}) is measured. If at that frequency the tyre remains in contact with the platform, the ER

value is 0%. This measurement approach is clear and logical. The aforesaid method requires no database.

However, the drawback of this testing method is its susceptibility to tyre stiffness and static load. Tyre stiffness is determined e.g. by pressure in the tyre. Low pressure increases and high pressure decreases the value of the EUSAMA ratio. Conversely, high static load increases and low load decreases the value of the ratio.

The evaluation criteria are the following:

a) ER = 0–20% poor technical condition of shock absorbers (insufficient value of damping force),
b) ER = 21–40% fair damping value – the shock absorber requires inspection after removing it from the vehicle at the indicator station,
c) ER = 41–60% good damping value,
d) ER>60–100% excellent damping value.

Ratios obtained in tests performed by the EUSAMA method do not indicate particular damage. The database of results provides a possibility to observe a trend in technical condition during use. The constant resonant frequency (16 Hz) creates the usability limit of this method. The same ER values, e.g. 60% can be attained by individual tyres, but they may be attained at different resonant frequencies in individual tyres. Such differences influence the safety of driving. Therefore, the results of tests performed by this method should be considered as approximate. The four-stage evaluation of the technical condition of the shock absorber based on such tests in fact differentiates two states (efficient – inefficient) and by its nature does not allow the identification of damage.

3. Methods of vibration analysis as a diagnostic measure for shock absorbers in passenger vehicles

The exciters used for testing shock absorbers encased in the vehicle induce vibration in unsprung and sprung masses connected to the shock absorber. Therefore, it is a mechanical system generating a vibroacoustic signal, which after processing is a non-stationary randomized process. The vibrations of the vehicle are induced during the measurements by the exciter. The induction process is complex and consists of the following stages:

– start-up and swinging of the inducing platform,
– period of platform induction at a constant frequency ca. 25 Hz,
– decay of platform vibration after unit shut-down.

The measured parameters are accelerations in the vibrations of sprung and unsprung masses. One converter is mounted on the rocking-lever near the bottom mounting of the diagnosed shock absorber, and the second one is mounted on the bodywork near the upper shock absorber mounting. The vibrations processed into signals are recorded at all stages of the exciter’s work. These types of

non-stationary signals are analysed predominantly by two-dimensional analytical methods in the time and frequency domain.

These include the following methods:

– short-time Fourier transforms,
– Wigner-Ville transforms,
– wavelet transforms.

The aforementioned analytical methods are time consuming and not suitable for real-time diagnostic systems. For the above reason a new method was proposed based on linear decimation, and enabling the demonstration of a non-stationary signal in stationary form and its application in FFT analysis.

4. Linear Decimation Procedure (LDP)

The procedure for the calculation of the effective signal number representing an individual series, and therefore the decreased sampling frequency, is defined as signal decimation. The rules of decimation are demonstrated in Figure 1.

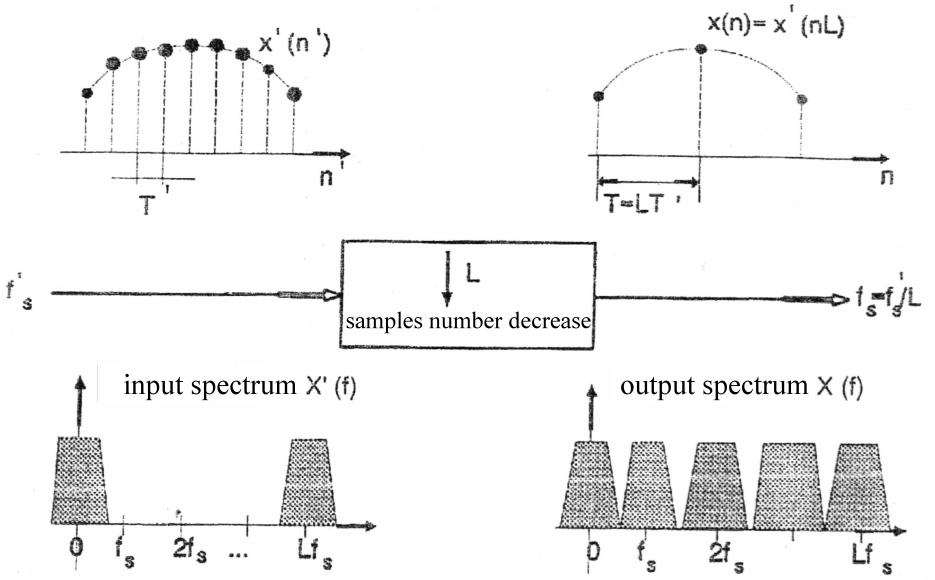

Fig. 1. Signal decimation in the time and frequency domain
Rys. 1. Decymacja sygnału w dziedzinie czasu i częstotliwości

For the case demonstrated in the Figure, the record of output signal after decimation is the following:

$$X(n) = X_{zred}(n) = X'(nL) \tag{2}$$

After the change of sampling time from T into LT the signal spectrum also changes.

$$X(f) = X_{zred}(f) = \frac{1}{L}\sum_{m=0}^{L-1} X'(f - mf_S^{'}) \tag{3}$$

A comparison of correlation indicates that the non-periodical spectrum changes into periodical. So, a system for the a digital decimation procedure can be developed (Fig. 2).

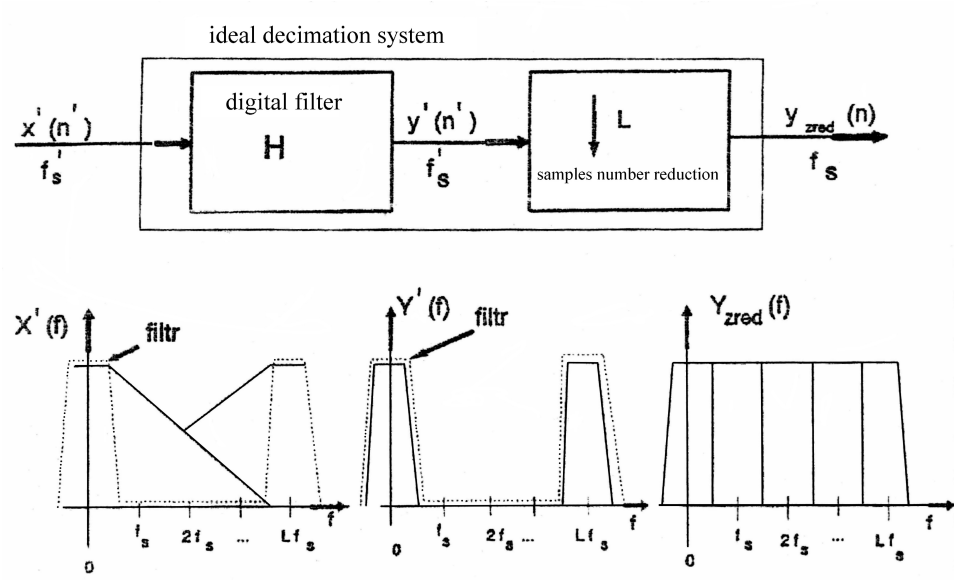

Fig. 2. Ideal digital signal decimator in frequency domain [3]
Rys. 2. Idealny cyfrowy decymator sygnału w dziedzinie częstotliwości [3]

By filtering with a low-pass filter (H) impulse responses are obtained.

One of standard time windows, e.g. the Kaiser window, can be applied with a limited length of pulse response. A primary time series after decimation can be described as:

$$Y_{zred}(n) = (nL) = \sum_{m'=0}^{N-1} h(m')X'(nL - m') \tag{4}$$

After transformation a periodic spectrum is obtained:

$$Y_{zred}(f) = \frac{1}{L}\sum_{m=0}^{L-1} Y'(f - mf_S) \tag{5}$$

In the analysis of non-stationary processes the estimators using the averaging of an *m*-dimensional data file require an increase in N number in the proportion of $N = n^m$. The object of averaging shall be a synchronized set of *n* realizations of the non-stationary process (e.g. undefined).

The low-pass filter used in the decimation procedure eliminates spectrum components higher than a half of the new sampling frequency.

The linear decimation procedure (LDP), which is a variable-step dynamic decimation, was proposed in the papers of Jan Adamczyk, Piotr Krzyworzeka and later Witold Cioch, staff of the AGH University of Science and Technology in Kraków.

It consists in dynamic signal sampling in the form of linear step increments, according to frequency increments.

This procedure enables us to remove a set of samples in proportion to the cycle increment, and leaves a constant number of samples per cycle.

The procedure in which a secondary vector is obtained after the LDP procedure from a primary vector is demonstrated in Figure 3.

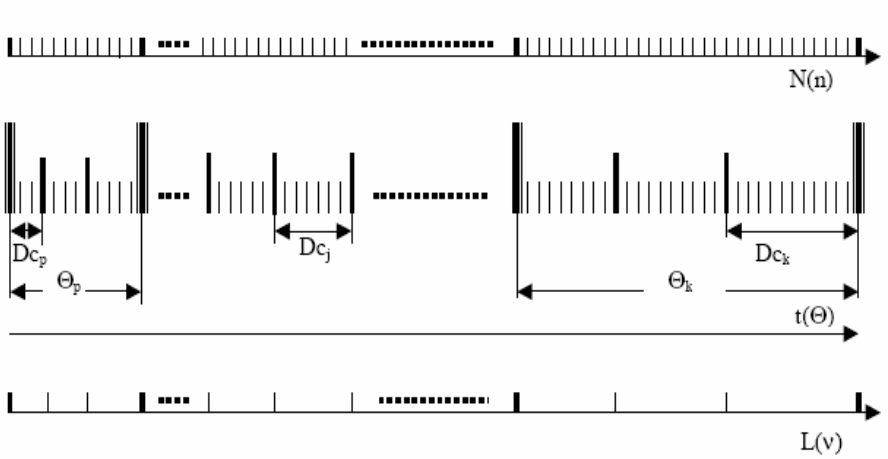

Fig. 3. Linear decimation procedure [8]: Θ – cycle time, t(Θ) – observation time, N(n) – primary set of samples in the observation window, L(v) – secondary set of samples in the observation window after LDP, Dc_p – initial decimation ratio, Dc_k – final decimation ratio

Rys. 3. Procedura liniowej decymacji [8]: Θ – czas cyklu, t(Θ) – czas obserwacji, N(n) – pierwotny zbiór próbek w oknie obserwacji, L(v) – wtórny zbiór próbek w oknie obserwacji po PLD, Dc_p – początkowy współczynnik decymacji, Dc_k – końcowy współczynnik decymacji

During the observation time for the observation window t(Θ), the record of a signal is defined as N samples of a sequence, sampled uniformly in t_h moments.

$$h = t_h - t_{h-1} = const \tag{6}$$

where:

t_h – sampling time.

The sampling frequency is defined by the Kotielnikov-Shannon sampling theorem. During decimation this frequency shall amount to:

$$f_s > 2 f_{\max} Dc \tag{7}$$

where:

f_s – sampling frequency,

$f_{\max}$ – upper frequency of analysed band for the signal limited by low-pass filter for frequency $f < f_{\max}$,

Dc – value of decimation ratio.

Number of samples for the observation window amounts to:

$$N = \frac{f_s}{r} \tag{8}$$

where:

r – required spectral resolution.

For the correct operation of FFT the number of N samples being a power of 2^k shall comply with the relation:

$$N = 2^k \geq \frac{f_s}{r}, k \in C \tag{9}$$

The decimation step by which the signal is sampled is connected with the cycle change (e.g. swinging, breaking). It is described by the *Dc* decimation ratio. *Dc* is determined in the way presented in Figure 4.

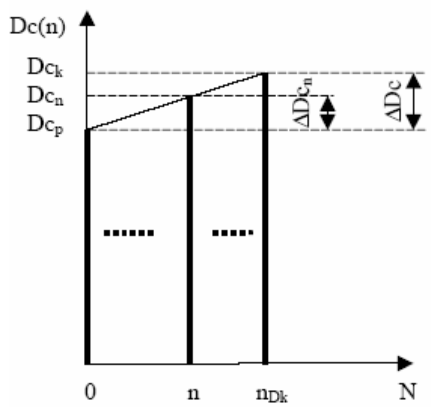

Fig. 4. Determination of the decimation ratio depending on the sample number of a primary vector [8]: Dc_k – assumed final decimation ratio, Dc_P – initial decimation ratio, Dc_n – decimation ratio for n-number of primary vector sample, n – sample number, n_{Dk} – number of a sample enabling the completion of LDP

Rys. 4. Wyznaczanie współczynnika decymacji w zależności od numeru próbki wektora pierwotnego [8]: Dc_k – założony końcowy współczynnik decymacji, Dc_P – początkowy współczynnik decymacji, Dc_n – współczynnik decymacji dla n – numeru próbki wektora pierwotnego, n – numer próbki, n_{Dk} – numer próbki umożliwiającej zakończenie PLD

Dc_k ratio when assumed allows us to transform the signal into a stationary form in the observation window for the last cycle.

By determining:

$L_{\Theta k}$ – number of samples of the last cycle observation window for a newly created vector,

$N_{\Theta k}$ – number of samples of the last cycle observation window for a primary signal.

The following is obtained:

$$L_{\Theta k} = \frac{N_{\Theta k}}{Dc_k} \tag{10}$$

For the stationary process the number of samples per cycle has to be constant, i.e.:

$$L_{\Theta j} = L_{\Theta k} = L_{\Theta p} = const \tag{11}$$

where:

$L_{\Theta j}$ – number of samples in *j*-th vector sampling cycle.

The decimation ratio has to be an integral number. It is essential for the selection of the subsequent sample number from the primary vector. If the decimation ratio is not an integral number, it can be replaced by a new vector obtained from the linear interpolation of values between the samples of the primary vector, which brings this method closer to sampling compliant with the temporary frequency value (Fig. 4).

5. Experimental studies

LDP for damage identification was performed by diagnostic experiments on a real passenger vehicle. The tested vehicle had a typical McPherson assembly of columns with coil springs, transverse triangular rocking-levers and anti-roll bars. Double-tube hydraulic shock absorbers were encased in columns.

The carrying element of the front suspension was a three-part supportive frame made of welded steel sheet drawpieces.

The steering knuckle was made as a complex casting connected with a hub and damping unit.

The diagnostic experiment consisted in testing the dynamics of the vehicle to which new shock absorbers and ones with programmed damage where subsequently mounted. Tests were performed on a group of telescopic shock absorbers in technical condition programmed and identified on the indicator unit. The influence of the most common kind of damage, i.e. oil leak from shock absorb-

ers, was analysed. The functioning of the remaining suspension elements was defined as correct after the test.

The system which induced vibrations in the sprung and unsprung elements of the tested vehicle was a mechanical exciter of harmonic vibrations within the range of 0–21 [Hz].

The relative accelerations in the vibration of the shock absorber piston towards the casing were measured and processed from averaged signals produced by two converters. The bottom converter was mounted on a rocking-lever, and the upper one on the socket of the shock absorber on the bodywork. The digital recording of signals was performed in a full 3-stage induction cycle. Example results are demonstrated in Figs. 5, 6, 7, 8.

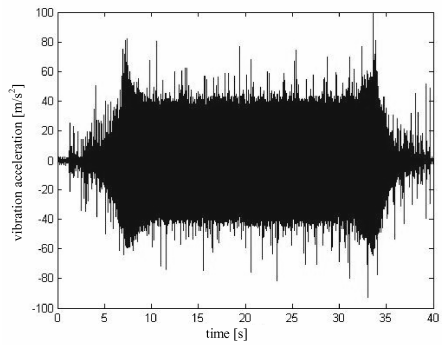

Fig. 5. Accelerations of tyre vibrations (new shock absorber)
Rys. 5. Przyśpieszenia drgań koła (amortyzator nowy)

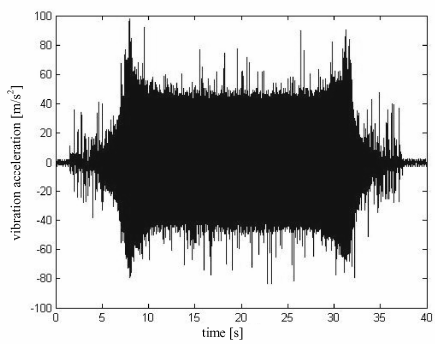

Fig. 6. Accelerations of tyre vibrations (shock absorber with 80% of liquid volume)
Rys.6. Przyśpieszenia drgań koła (amortyzator z 80% objętości płynu)

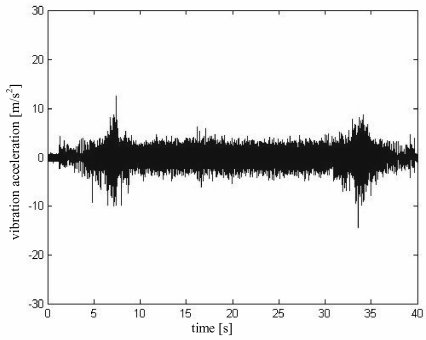

Fig. 7. Accelerations of bodywork vibrations (new shock absorber)
Rys. 7. Przyśpieszenia drgań nadwozia (amortyzator nowy)

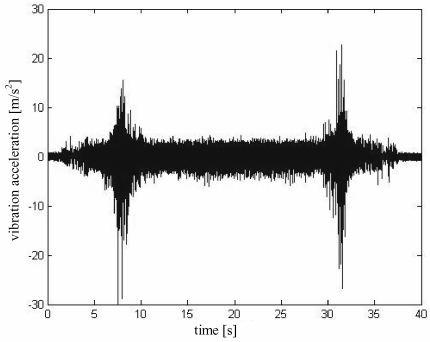

Fig. 8. Accelerations of bodywork vibrations (shock absorber with 80% of liquid volume)
Rys. 8. Przyśpieszenia drgań nadwozia (amortyzator z 80% objętości płynu)

Identification of racing end and coasting start enables us to divide signals into three time windows.

In the first window the signal increases according to a continuous increment of induction frequency and is decimated by a linear procedure. Assuming that, based on the number of observation samples in the last period, the final decimation ratio is Dc_k, we can calculate the subsequent decimation ratios Dc_n, ending with n_{Dk} sample.
where:

$$Dc_n = Dc_k \left[\frac{N_{\Theta p}}{N_{\Theta k}} + \frac{n}{n_{Dk}} (1 - \frac{N_{\Theta p}}{N_{\Theta k}}) \right] \tag{12}$$

$N_{\Theta p}$ – number of samples from the first cycle observation window for a primary signal,
$N_{\Theta k}$ – number of samples of the last cycle observation window for a primary signal.
n – sample number,
n_{Dk} – number of sample enabling the completion of LDP.

$$n_{Dk} = n_k - Dc_k \tag{13}$$

where:
n_k – number of the last sample of observation window (for racing: n_k = i1).

Signal decimation requires the previous use of low-pass filtering, which helps to avoid aliasing after decimation. The linear decimation procedure requires the designing of a filter with a variable barrier limit. The research applied a filter with an inverse ratio of variable value of frequency limit to the variable decimation ratio.

The decimation ratio $Dc_n = const$ is constant during the decimation of the signal observation window with a constant induction frequency. Therefore, the filter also has constant features.

Signal amplitudes decrease during coasting simultaneously with the steady decrease in induction frequency. The decimation of this time window is performed the same as for racing, taking linear decrease into account instead of frequency increase.

As a result of LDP a reduced number of signal samples is obtained. The primary signal consists of 19,999 samples, and after LDP the signal consists of 1,048 samples. Similarly, the number of spectrum samples for this signal considerably decreases, and informational readability is improved. The signal obtained from LDP was processed by the FFT procedure, which provided spectra of relative frequency acceleration values for programmed damage (liquid leak) in shock absorbers. Example results of analysis are demonstrated in Figs. 9, 10, 11.

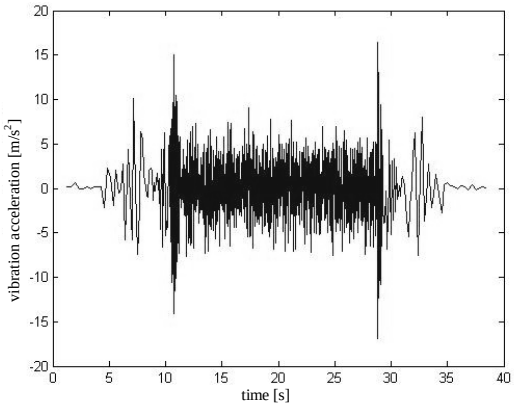

Fig. 9. Decimated structure over time
Rys. 9. Przebieg czasowy zdecymowanego sygnału

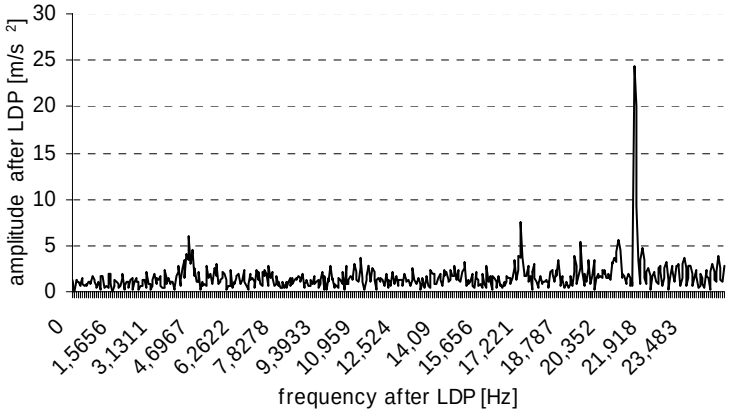

Fig. 10. Signal spectrum after LDP (shock absorber: 90% oil)
Rys. 10. Widmo sygnału po PLD (amortyzator: 90% oleju)

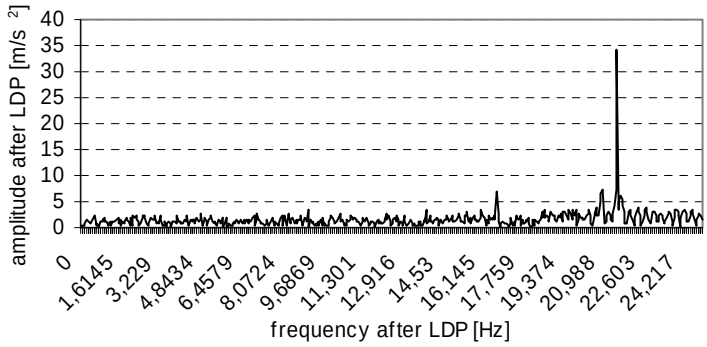

Fig. 11. Signal spectrum after LDP (shock absorber: 96% piston sealing and 90% oil)
Rys. 11. Widmo sygnału po PLD (amortyzator: 96% uszczelnienia tłoka i 90% oleju)

6. Conclusions

Results confirm the justified use of the linear decimation procedure for non-stationary signals. LDP, apart from the decrease in sampling speed, also transforms the signal, which enables the application of fast Fourier transform in signal description.

The predominant amplitude for the frequency of ca. 21 Hz corresponds the component of the induction system, which at the operational stage of constant induction corresponds with a frequency of 21 Hz. The linear decimation procedure of vibration signal recorded during the racing and coasting of the machine provided a possibility to separate spectrum amplitudes at resonant frequencies of the system.

Damage in the form of a leak from shock absorbers influence the value of amplitudes at the resonant frequency of unsprung elements (ca. 16 Hz).

The increased loss in sealing of the shock absorber piston results in the decrease of FFT amplitude for the resonant frequency of sprung elements (ca. 4 Hz). For the value of this damage exceeding 4% loss in sealing the amplitude decreased below the level of measurement noise.

Therefore, the linear decimation procedure has features allowing the identification of damage during the testing of shock absorbers encased in vehicles.

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Zastosowanie procedury decymacji liniowej w diagnostyce amortyzatorów samochodów osobowych

S t r e s z c z e n i e

Praca przedstawia metody badań amortyzatorów samochodów osobowych zabudowanych w pojeździe. Są to metody: EUSAMA stosowana powszechnie na Stacjach Kontroli Pojazdów i metody wielowymiarowe analiz wibroakustycznych sygnałów nieustalonych. Nowatorską w diagnostyce amortyzatorów jest zaprezentowana metoda oparta na procedurze liniowej decymacji (PLD).