EVALUATION OF THE USEFULNESS OF MULTIDIMENSIONAL METHODS OF NON-STATIONARY SIGNALS' ANALYSIS IN THE DIAGNOSTICS OF SHOCK ABSORBERS ENCASED IN PASSENGER VEHICLES

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Summary

The paper discusses the possibilities of applying vibroacoustic methods to identify the loss of fluid in shock absorbers encased in passenger cars. Three methods of analysis are presented (STFT, WVD, WT). A diagnostic method based on a wavelet analysis has been proposed.

Keywords: vibroacoustic (VA) diagnostics, multidimensional analysis of non-stationary signals, telescopic shock absorbers.

OCENA PRZYDATNOŚCI WIELOWYMIAROWYCH METOD ANALIZY SYGNAŁÓW NIESTACJONARNYCH W DIAGNOSTYCE AMORTYZATORÓW SAMOCHODÓW OSOBOWYCH ZABUDOWANYCH W POJEŹDZIE

Streszczenie

W pracy omówiono możliwości zastosowania metod wibroakustycznych do identyfikacji ubytku płynu w amortyzatorach samochodów osobowych zabudowanych w pojeździe. Porównano trzy metody analizy (STFT, WVD, WT). Zaproponowano metodę diagnozowania opartą na analizie falkowej.

Słowa kluczowe: diagnostyka WA, analiza wielowymiarowa sygnałów niestacjonarnych, amortyzatory teleskopowe.

1. INTRODUCTION

For testing shock absorbers encased in cars, kinematic systems inducing vibration in unsprung and sprung masses are commonly applied. They are tuneable mechanical vibration exciters, where a platform onto which the car runs with a wheel with the tested shock absorber is the element inducing force. The excitation cycle during the tests consists of 3 stages. The first stage consists of accelerating the inducing platform, with the induction frequency varying in a range from 0 to ca. 21 Hz in time of ca. 10 seconds. At the second stage lasting approximately 20 second, the platform excites the car at a constant frequency of ca. 21 Hz. At the third stage, after switching off the inducing platform's propulsion system, vibration of the platform takes place for 10 seconds. It is a period of free vibration, when transition of the vehicle's unsprung and sprung masses through resonance occurs. The unsprung masses are the wheels together with tyres and elements leading the wheel (rocking levers, bars, etc.). The sprung masses include the bodywork with the equipment, connected with unsprung masses by means of springing and dampening elements. The springing elements in modern passenger cars are coil springs with non-linear characteristics, and the dampening elements are telescopic shock absorbers with asymmetrical, strongly non-linear dampening characteristics. In consequence, the vehicle tested on a vibration exciter can be regarded as a vibrating, non-linear and non-stationary mechanical system. To diagnose a system of this type, the methods of non-stationary randomized signal analysis can be applied.

2. RESEARCH OBJECT AND METHODOLOGY

The object of the research was the front suspension of Skoda Fabia 1,4, whose constructional solution is presented in Fig. 1.

The front suspension of Fabia 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 the 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.

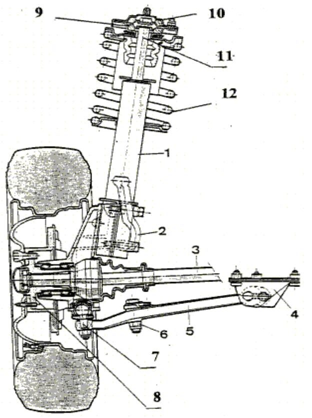


Fig. 1. McPherson's front suspension [10]: 1 – shock absorber; 2 – steering knuckle arm; 3 – drive shaft, 4 – support of articulated mounting of the lower rocking lever (screwed to the bodywork cross-bar); 5 – lower rocking lever; 6 – lower rocking lever pivot; 7 – ball-and-socket joint of the rocking lever; 8 – steering knuckle; 9 – elastic column-to-bodywork mounting; 10 – upper spring plate; 11 – shock absorber piston rod; 12 – suspension spring

The method of making measurements was as follows: The car (with the engine off, idle running, with a released auxiliary brake) was placed with its wheel with the tested shock absorber on the central part of the exciter platform. Next, a full 3-stage excitation cycle was activated. The measured parameters were accelerations in the vibrations of unsprung parts (rocking-lever and wheel) and sprung parts (bodywork) to be processed, for which acceleration converters, ADXL 105 and ADXL 250 of Analog Devices, were applied. The places where converters were mounted were as follows: lower – near the place of mounting the shock absorber casing; upper – on the seating of the shock absorber mandrel in bodywork. The converters' axes converged with the direction of the shock absorber dampening force. The HAD-1200 measuring module was applied for measurements. It is a 16-bit computer card. The modul is equipped with a 12-bit A/C converter and an analogue multiplexer enabling making measurements with the use of maximum 8 channels in a differential mode or 16 channels when working with common mass. The measuring procedure consisted in recording the wheel and bodywork vibration acceleration signal at a sampling frequency of 500 [Hz]. The database containing vibration accelerations over time was created in the computer mass memory. Example of the obtained relative vibration accelerations is presented in Fig. 2.

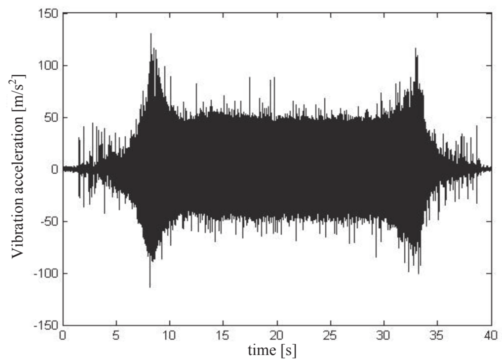


Fig. 2. Course of relative vibration accelerations

In the tests on the car, new shock absorbers and ones with programmed damage were subsequently mounted. Their dampening characteristics were identified on an indicator unit. The damage consisted in losses of the shock absorber fluid, thus simulating operational leaks. That type of damage in the tested shock absorbers was modelled with the degree of their fill-up with the fluid. For this purpose, the fluid volume defined in percent of nominal volume (100%) of new absorbers was decreased in the shock absorbers specially prepared for the tests. Shock absorbers with fluid volumes from 100% down to 60%, with differences every 5% (i.e., 95%, 90 and so on) were tested. After identification of their dampening characteristics on the indicator unit, the so prepared shock absorbers were encased in the suspension of the tested car which was then subject to testing on a vibration exciter. The obtained non-stationary signals were subjected to the below specified multidimensional analyses:

- short-time Fourier transform,
- Wigner-Ville transform,
- continuous wavelet transform,

thus obtaining spatial images of spectrum changes as a function of time.

The purpose of the above-mentioned analyses was to determine which of them would be the most suitable in diagnosing shock absorbers with fluid loss encased in a vehicle and the identification of percent degree of such loss. A comparison was made in time and frequency windows corresponding to the resonance of unsprung masses (suspension) and sprung masses (bodywork). For comparative purposes, from among a number of estimators, one was chosen constituting a sum of maximum values of the transform coefficients in resonance bands of the unsprung and sprung components, and defined as follows:

where:

$$E_{max} = W_z + W_n \qquad (1)$$

W_z – maximum value of transform coefficients in the resonance frequency band of unsprung masses,

W_n – maximum value of transform coefficients in the resonance frequency band of sprung masses.

3. MULTIDIMENSIONAL ANALYSES OF SIGNALS

3.1. The short-time Fourier transform - STFT

The results of the STFT analysis are the coefficients described by the dependence:

$$S(\omega,b) = \int_{-\infty}^{+\infty} x(t)\cdot w_{\omega,b}(t)dt = \int_{-\infty}^{+\infty} x(t)\cdot g(t-b)e^{-i\omega t}dt \qquad (2)$$

where: ω – analysing frequency, b – window shift, *g(t - b)=const* – constant width of the subsequently analysed window.

A rectangular window was applied for the analysis. To improve the frequency resolution, in a single FFT analysis, a method of completing with zeros was applied, bearing in mind the law of decreasing profits. An example of the analysis results is presented in Fig. 3 and the estimator's distributions as a function of shock absorber filling level are shown in Fig. 4.

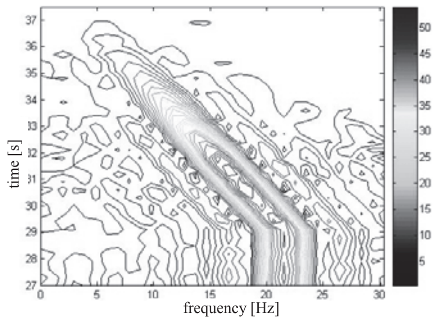
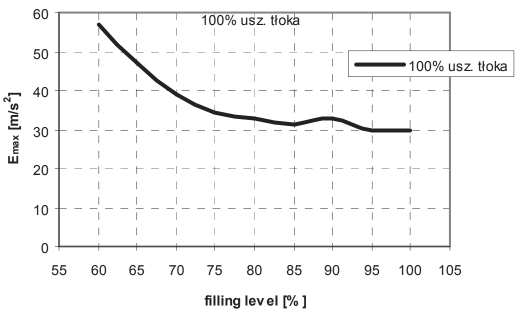


Fig. 3. Distribution of signal amplitudes for relative vibration accelerations after STFT



Rys. 4. Wykres zbiorczy wartości estymatora E_{max} (STFT)

3.2. Wigner-Ville transform

The Wigner-Ville time-frequency spectrum can be presented in the following form:

$$WVD(\theta,\tau) = \int x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})e^{-j2\pi\theta t}e^{-\left(\frac{\theta\tau}{\sigma}\right)^2}dt \qquad (3)$$

where:
WVD (θ, τ) – Wigner-Ville pseudo-transformation,
x(t)* – combined signal coupled with x(t),
τ – shift in time domain,
θ – shift in frequency domain.

In order to improve resolution in the analysis domains, the Wigner-Ville transform was applied. The disadvantageous phenomenon of spectrum leakage was reduced via filtering. Based on analytical experiments and data from specialist literature, an analysis window was used to this end as the Choi-Williams tapering function in a form:

$$\phi(\theta,\tau) = \exp(-\theta^2\tau^2/\sigma^2) \qquad (4)$$

where:
σ – parameter proportional to the spectrum leakage amplitude

As a result of the experiment, a dampening parameter was assumed for the calculation in the Choi-Williams analysis window, *σ=0.05.*

The result of the Wigner-Ville transform of the signal of relative vibration accelerations is presented as a distribution of WVD coefficients in Fig. 5 and the estimator distribution as a function of shock absorber filling level, in Fig. 6.

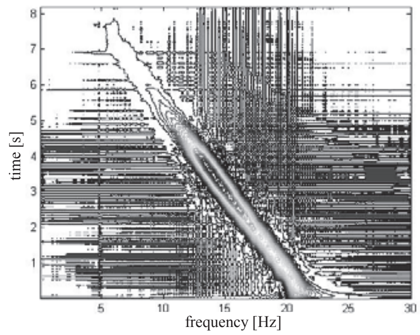
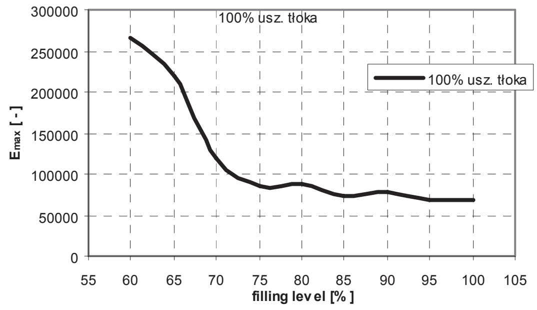


Fig. 5. Distribution of WV coefficients of relative vibration accelerations signal



Rys. 6. Wykres zbiorczy wartości estymatora E_{max} (WVD)

3.3. Signal transformation by means of the continuous wavelet transform - CWT

The Morlet wavelet was selected for the analysis, described by the dependence:

$$\psi(t) = C\cdot e^{\frac{-t^2}{2}}\cos(5t) \qquad (5)$$

where:
C – standardising constant.

The wavelet serves to construct a family of defined analysing wavelets:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \cdot \psi(\frac{t-b}{a}) \quad (6)$$

where:

b – shift in time - $b \in R$,

a>0 – the so-called narrowing-broadening coefficient responsible for the frequency and time related range of the analysis.

The coefficients representing the realised signal in the time-scale domain are described by the dependence:

$$WT(a,b) = (x(t) * \psi_{a,b}) = \int_{-\infty}^{+\infty} x(t) \cdot \psi_{a,b}(t)dt = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi(\frac{t-b}{a})dt \quad (7)$$

Such dependence is equivalent to the convolution of the analysed signal x(t) with athe analysing wavelet $\psi_{a,b}(t)$.

An example of the CWT result of the measured signal is shown in Fig. 7 and changes in the value of the estimator assumed, in Fig. 8

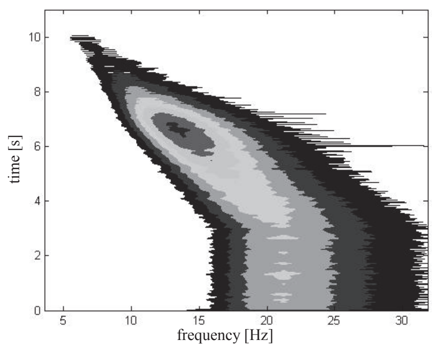
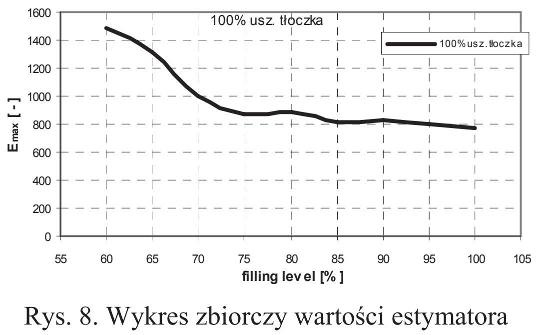


Fig. 7. Distribution of wavelet transform coefficients



Rys. 8. Wykres zbiorczy wartości estymatora E_{max} (CWT)

4. SUMMARY AND CONCLUSIONS

While analysing the collective diagrams of the estimator assumed for comparative purposes, we can conclude that all the multidimensional analysis methods applied are suitable for diagnosing shock absorbers encased in cars to identify a single fault, i.e. leakage of the shock absorber fluid. In the range from 0 to 20% of loss, changes in the assumed estimator are insignificant. Only for larger losses, its values increase, thus increasing the equivalence of identification. Therefore, it is the defects that must determine the possibility of applying one of the three transforms in the diagnostics. The short-time Fourier transform, STFT, introduced by Gabor uses a constant time window for averaging, which is shifted after the time specified. This reduces the accuracy of the analysis as the frequency grows. The Wigner Ville transform, WVD , is based on Fourier double transform. To avoid aliasing, it requires sampling of a continuous signal with at least double frequency in relation to that specified by Nyquist criterion. Application of initial signal filtering reduces the spectrum leakage. A major drawback of this method is long duration of the analysis and high equipment requirements.

Advantages of both the methods described above are combined in a wavelet analysis. As opposed to STFT, the rules of constucting a family of analysing functions are different. In the wavelet analysis, the number of wavelet oscillations is constant and the frequency variation is accompanied by a proportional change of the wavelet time range. An analysis of non-stationary spectral properties of a signal requires the utilisation of windows which automatically narrow at high frequencies and broaden when analysing low frequencies. Analysis of this type is not much slower than STFT and outclasses the latter in terms of accuracy. Therfore, from among the three above-mentioned transforms, the wavelet transform is the most suitable for diagnosing a single defect of shock absorbers.

CONCLUSION

The proposed method of diagnosing shock absorbers encased in a vehicle based on a wavelet analysis can be used in practice. The kinematic excitation units existing in vehicle testing stations can be used for the measurements. The method enables an explicit qualitative and quantitative identification of fluid losses in shock absorbers. It is characterised by simplicity, since it is based on a computer analysis of vibration accelerations measured on the bodywork and rocking-lever by means of cheap volume converters. An automatic shock absorber diagnostics system is relatively easy to be developed.

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