The Wavelet as the Evaluation Tool of Vehicles' Seat Suspension System

Sebastian GLOWINSKI, Andrzej BLAZEJEWSKI
Koszalin Technical University, Faculty of Mechanical Engineering,
Sniadeckich 2, 75-453 Koszalin
sebastian.glowinski@tu.koszalin.pl, andrzej.blazejewski@tu.koszalin.pl

Abstract

In this paper, an innovative active seat suspension system for vehicles is presented. This seat suspension prototype is built with a shear guidance mechanism, an air spring, a hydraulic shock absorber and end-stop buffers. The acceleration particular signals are measured by using Inertial Measurement Units (IMUs) placed on the seat and the human head. As the excitation, the horizontal vibrations are applied. As an alternative to the classical Fourier approach, the Wavelet Transfer Function (WTF) is introduced to describe the effectiveness of particular seat suspension. In both of the system cases, the human head reaction is investigated by using the Matlab package.

Keywords: Inertial Measurement Units, Frequency modulation, Active seat suspension, Multidimensional signal processing

1. Introduction

Much research is being on drivers' ride comfort. It is believed that the vibration transferred to the human body is one of the leading factors influencing drivers' comfort and health. Therefore, it becomes essential to study this phenomenon in case of vehicles, trucks, machines or aircraft and investigate their influences on the human body [1,2]. The studies of this problem have been of academic and industrial interest for a long time. There are three main types of seat suspension: passive, semi-active and active. At first, the passive seat suspension has been developed and investigated [3,4]. The conventional passive suspension systems do not provide the driver comfort and vehicle handling against the road disturbances in a wide range. The passive suspension system stores energy by a spring and disperses it by using a damper. The conventional passive seat suspension simply consists of elastic parts, such as springs and damping parts, such as shock absorbers. That kind of system may consider as simple mass-spring-damper setup. Passive seats can both decrease and increase vibration. Generally speaking, less spring stiffness may lead to good driver ride comfort but causes large suspension deflection and an increase in the vibration transmitted at low frequency. Deflections can sometimes reach the limit of movement. To tackle the problem, the semi-active and active suspension systems are commonly used in vehicle seats [5]. Semi-active seat suspension using the electrorheological (ER) fluid damper and the magnetorheological (MR) fluid damper has been proposed [6]. On the other hand, it is widely accepted that an active suspension is the most effective way to improve ride comfort and for this reason, it has attracted attention in recent years. The main purpose of this kind of system is to reduce vertical acceleration, which affects the driver comfort. Typically, a vehicle seat moves up and down in response to the road surface and pitch around an axis perpendicular to the direction of motion. But in case of trucks or have machines, the horizontal excitations become significant. It is important, when they are used in rough terrain or going off-road.

The driver of the earth-moving machinery is mostly exposed to low-frequency vibration. Therefore, the system can amplify the vibration amplitudes at eigenfrequencies i.e. resonance frequencies, especially at their low range. The parameters of this kind of system are fixed. It means that they are selected and compromise between the inequality of the road or terrain and driver-operator comfort. The passive suspension system was investigated by using WTF in work [7]. The WTF calculated in this case showed that examined seat suspension system may amplify vibrations in the wider frequency range, exceeding resonance range for the same periods in time signal history. The essential feature, and in the same way lack of passive systems, is observed when WTF is calculated in case of the driver's head. Therefore, low-frequency vibration can be periodically amplified in the human head. The active systems are employed to reduce these limitations [8,9]. The typical active suspension system consists of a dedicated actuator. This one is implemented in the form of additional, usually pneumatic system. It stores and dissipates energy outside the system, mainly as heat [10,11].

The remainder of the paper is organised as follows; Section 2 presents the experimental stand for seat suspension systems examination, Section 3 discussed the measurement and analysis, the platform-seat suspension system is presented in Section 4. In Section 5 platform-head suspension system is discussed, whereas Section 6 Analysis of the results and systems effectiveness is presented. Conclusions summarize this article.

2. Experimental stand for seat suspension systems examination

The main parts of experimental stand consist of a shear guidance mechanism, an air spring, a hydraulic shock absorber and end-stop buffers. It is a simple passive system, which can accelerate some vibration in the frequency range 0–2 Hz. This one was examined previously [7]. In this article, the vibration affecting a human driver was surveyed. The reaction of the driver's head was considered especially in the passive seat system. The results obtained showed the human body as a system possessing a damping feature is the considerably sharp frequency range of 10–15 Hz. The amplification occurred periodically. It generated an impulse effect on the human head. In the range below 10 Hz, the vibrations were relatively bigger than excitation in the passive system one. The investigated seat suspension system, shown in Fig.1(a) consists of a shear-guidance mechanism together with (like passive one): a pneumatic spring 3 and a hydraulic shock absorber 2. Additionally, this active system is extended to controlled airflow. It is done employing two proportional valves: inflating 5 and exhausting 6 implemented in pneumatic spring. The control signal is transmitted to valves and worked out by the controller 4 with a dedicated algorithm. The air pressure inside the air spring is properly changed by the airflow adjusted to the load, generated by a mass 1. It creates an active force in the suspension system. The equation of motion of this seat suspension has been explored in the previous papers [10,12]. Three 6-DOF sensors (ProMove Mini) are fixed on the vibration platform (I), seat (II), and driver head (III) as shown in Fig. 1(b). Sensors are mounted by using rubber straps, which allows holding them really tight. The vibration accelerations are stored on the IMUs memory and by using the software Inertia Technology analyzed on the personal computer.

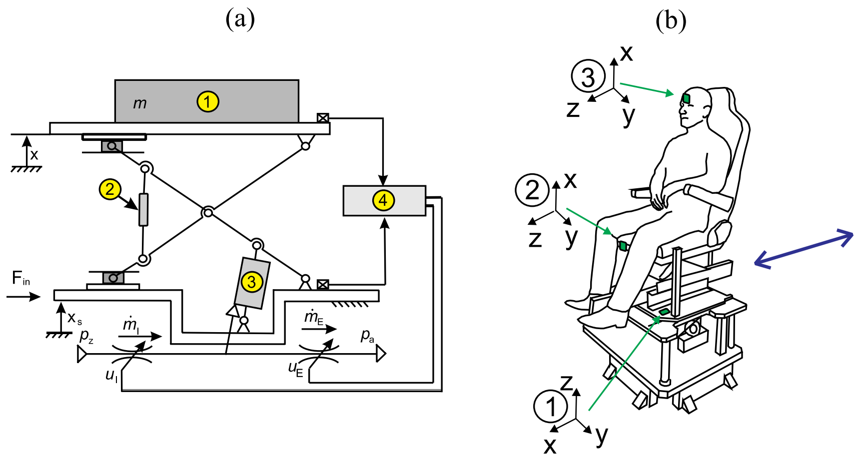

Figure 1. (a) Side view of active seat suspension system: 1 – mass, load comes from driver's body, 2 - hydraulic shock absorber, 3 - pneumatic spring, 4 - control system, 5 - inflating valve, 6 - exhausting valve; (b) (I-III) Numbering of Inertial Measurement Unit (IMU) location and (*x*, *y*, *z*) axes orientation.

3. Measurement and Analysis

Detailed measurement methodology and experiment procedure are introduced and presented in details in the paper [7]. In this work, the same methodology and procedure are applied in case of active suspension to compare both systems. The horizontal excitation is realized by proper force, acting on the platform. It is the force F_{in} (Fig. 1a), that frequency spectrum is white noise. It has a constant power spectral density up to 20 Hz. This excitation force is subsequently representing by the acceleration signal measured by IMU (I) on the platform (Fig. 1b). Further analysis is conducted by using other accelerometers (II, III) signals. IMU devices located on the experimental stand are shown in (Fig. 1b) as well. The measuring path (Fig. 2) during the experiment was configured. The measured signals components $S_X(t)$, $S_Y(t)$ and $S_Z(t)$ are transferred from the stand level with high-speed wireless network by Basic Inertia Gateway (Fig. 2a). The Gateway is connected with a computer by the USB. In the analysis level, the package Matlab with Wavelet Toolbox is used (Fig. 2b).

All signals values are recalculated as modulus (absolute values) of acceleration vectors according to the formula:

$$S(t) = \sqrt{[S_X(t)]^2 + [S_Y(t)]^2 + [S_Z(t)]^2} \tag{1}$$

where the $S(t)$ signal's values represent general device or human part action-reaction.

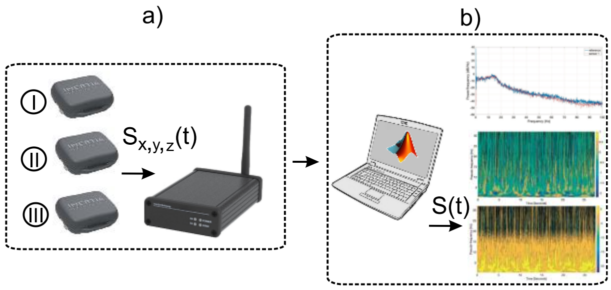

Figure 2. Measuring path: (a) ProMove-mini sensors with Inertia Gateway (measuring hub), (b) analysis level - Matlab Wavelet Toolbox and WT and WTF results

The seat suspension systems are frequently analyzed using power spectral density function (PSD). It means that these analyses introduce Fourier's transform (FT), which is best suited to analyze stationary periodic signals $S(t)$. This transform represents the spectrum for whole signal. Mathematically, it represents the integral:

$$F(\omega) = (2\pi)^{-1/2} \int_{-\infty}^{\infty} S(t) e^{-j\omega t} \mathrm{d}t \tag{2}$$

where F is Fourier transform function and ω symbolizes angular frequency and finally analysis frequency domain. While in case of stationary signals it may work, for non-stationary is not reliable especially, when these kinds of signals are used to evaluate a whole process, device or system. Therefore, when a harmonic or linear combination of harmonic signals excite a driver seat, the Fourier transforms and power spectral density function, in the same way is adequate. It falls in case of non-stationary excitations. Some solution provides a short-time Fourier transform (STFT). This transform is the Fourier transform of the signal $S(t)$, examined through some time-limited window, the uniform function $w(t)$ centered on t. These transforms appear by sliding the examination window along with in time with τ step. Mathematically, it is noted as:

$$\hat{F}_w(\omega, \tau) = \int_{-\infty}^{\infty} S(t) w(t - \tau) e^{-j\omega t} \mathrm{d}t \tag{3}$$

where $\hat{F}$ is short-time Fourier transform function in time and angular frequency domains. In comparison to FT, in case of the STFT some information about time localization of the frequency spectrum of the particular part of the signal (in a centre of window $w(t)$) is shown. The problem arises when the sliding window $w(t)$ is a simple uniform and FT reaches the end or enters the windowed part of signal $S(t)$. They are commonly known in the form of a sharp change in the power spectrum. It is encounter as a discontinuity, while transform is calculating when it enters or leaves the window. Simply, it results in a lack of sensitivity to the position (in the time domain) of the discontinuity within the window. In the frequency domain, the problem is a spectral leakage. It occurs when the windowed component of the signal $S(t)$ has a cycle time which is not an integer divisor of the window width, the transform exhibits false response at many frequencies. It is improved by applying special function $w(t)$ (windowing function), which attenuating this part of the examined signal inside the window, that away from the centre of the window. This property has very common Gaussian function (it creates a so-called Gabor transform with the formula (3)). It results from formula (3), the Gaussian and the other windows modulate exponential function with parameter ω. Because the function $w(t)$ is the same i.e. does not change in the time domain, while the parameter ω changes the following problems-features occur (according to Heisenberg's uncertainty principle):

- at high frequencies the number of waves in a window is high. It results in good accuracy in frequency measurement, on the other hand, the finite window width prevents good localization of signal discontinuities or other properties such as impulses;
- at low frequencies, the number of waves in a window is low (in critical case the window span does not contain wavelength). It results in the worse accuracy in frequency measurement and simultaneously more precise time-localization of discontinuities or other properties;
- the frequencies correspond to wavelengths longer than window span could not be measured.

The transformation mechanism represents by (2) and (3), in case of wavelet transform is the same. It is an inner product of a signal and a tasting function i.e. wavelet. The wavelet function $\psi[(t-b)/a]$ is shifting with parameter b in time and scaling with parameter a in the frequency domain [13], [14]. Eventually, wavelet transform (WT) $S_\psi(a,b)$ of signal $S(t)$ measured in time and scale, is calculating as follows:

$$S_\psi(a,b) = |a|^{-1/2} \int_{-\infty}^{\infty} S(t)[(t-b)/a]dt \tag{4}$$

When the argument equals $[(t-b)/a]$ and $p = 2\pi$ Morlet wavelets oscillation period equals a. Among many known wavelets, the Morlet wavelet is chosen. Mathematically, following formula represents mother wavelet:

$$\psi(t) = e^{jpt}\left[e^{\frac{-t^2}{2\pi^2}} - \sqrt{2}e^{\frac{-t^2}{\sigma^2}} \cdot e^{\frac{-p^2\sigma^2}{4}}\right] \tag{5}$$

where p is a frequency modulated parameter, σ is decay parameter. The exponential factor introduces oscillations. The mother wavelets have the same general properties [13]. In order to analyze both suspension systems, one chosen Morlet wavelet is used.

Generally, the particular value of $S_{\psi}(a,b)$ represent the signal $S(t)$ and wavelet $\psi[(t-b)/a]$ correlation. They are expressed as the number-wavelet coefficients. The values of these coefficients are shown in form of bar-scales, presented on the right side of each figure. Following, the parameters a and b are related to the pseudo-frequency (Y-axis) and time domain (X-axis) respectively. In Fig. 3 the wavelet transforms (WT) of the horizontal excitations (for chosen periods - 30s) are shown. These signals are considered as input $S_{in}(t)$. As it is presented in the figure, the excitations imposed are in the same manner (white noise) on both, passive and active seat suspensions.

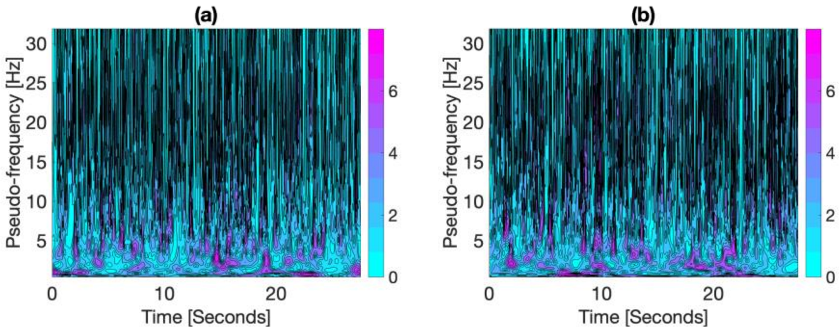

Figure 3. Wavelet transform WT of the excitation signal in case of: (a) passive and (b) active seat suspension, obtained using Morlet wavelet with parameter 4

The analyze is conducted on two levels. First one, evaluate the suspension system itself and describes vibrations transfer from the platform $S_{in}(t)$ on the driver's seat $\left(S_{out}^{S}(t)\right)$. In real situations it is action, which is came from the road and is imposed on the driver body as the main source of vibrations (besides hands and foots). The second one, includes the analysis of the vibrations transfer from the platform $S_{in}(t)$, considering specific seat suspension, to the important human body part i.e. head $\left(S_{out}^{H}(t)\right)$. The wavelet transfer function (WTF) is calculated according to following formula [7]:

$$W_{\psi}(a,b) = \frac{S_{out}(a,b) - S_{in}(a,b)}{max_a[S_{out}(a,b) - S_{in}(a,b)]} \tag{6}$$

WTF introduces arithmetical dependence, which is the difference between the respective wavelets' coefficient values of the output and input signals, concerning maximal values of difference in each scale. It results that, the maximal values of WTF presented on left hand side scales, is equal to 1. In this case the system passed vibrations without any damping. Anyway, in case of the negative values of WTF the vibrations are reduced. An application of a time-frequency signal analysis technique for modal parameters identification and specific dynamical systems description were also presented by [15-17]. The wavelet filtering procedures, which allowed estimate mechanical parameters for systems with non-constant parameters, had been shown. The wavelets were used to detect natural frequency of the system and transform system time response into the time-scale domain.

4. The Platform-Seat Suspension System

The wavelet transforms of vibration signals $S_{out}^{S}(t)$, measured in the proper frequency range by IMU II (mounted on the seat), are shown in Fig. 4. The passive and active system signal transforms are presented separately. In the case of further analyses, Morlet wavelet with parameter 4 is used.

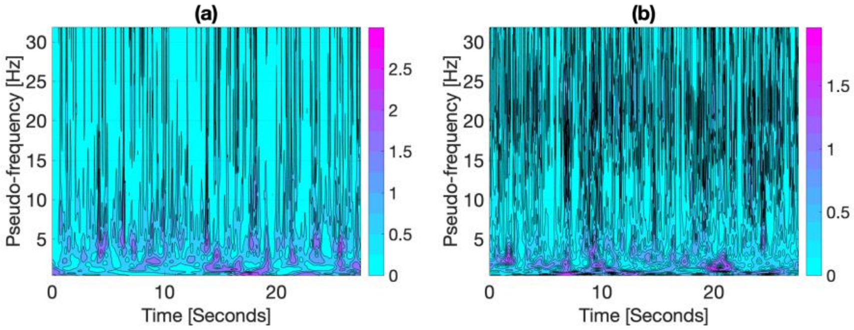

Figure 4. Wavelets transform WT of the seat signal in case of: (a) passive, (b) active seat suspension - the Morlet wavelet parameter 4

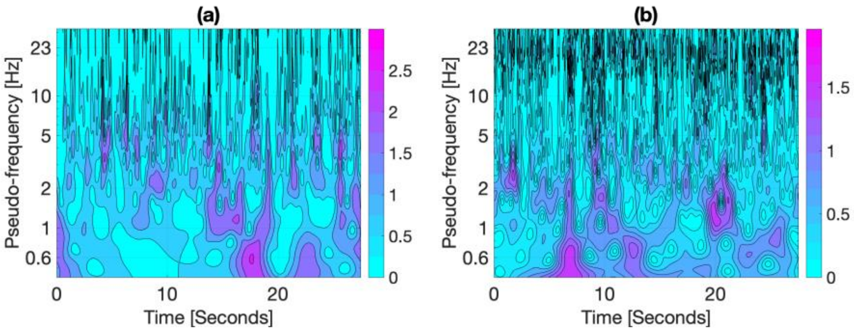

Figure 5. Wavelets transform WT of the seat signal in case of: (a) passive, (b) active seat suspension, the logarithmic frequency scale introduced - the Morlet wavelet parameter 4

In order to focus on the lowest frequency range (the strongest reaction is converged), the scale is changed from linear to logarithmic (Fig. 5). The logarithmic scale allows more precisely to indicate the frequency limit of vibrations reduction.

The transfer functions, calculated according to formula (6), where $S_{out}(t) = S^{S}_{out}(t)$ in the case of passive and active systems are presented in Fig. 6a, b, respectively. Here, to calculate WTF, wavelet parameter 3 is used and different colours.

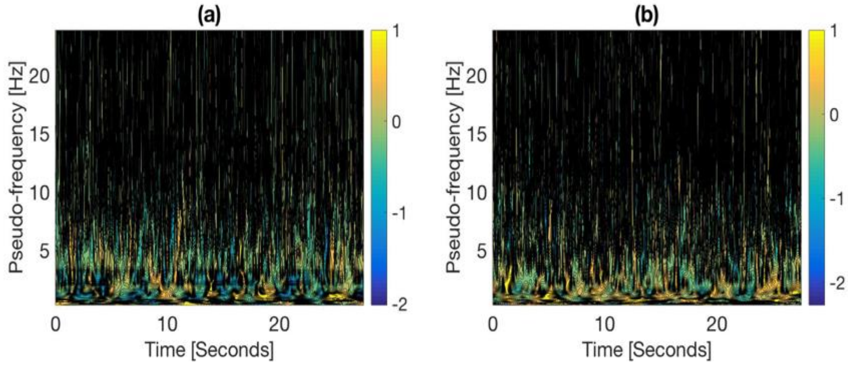

Figure 6. Wavelet transfer function WTF platform - driver's seat in case of:
(a) passive, (b) active seat suspension - the Morlet wavelet parameter 3

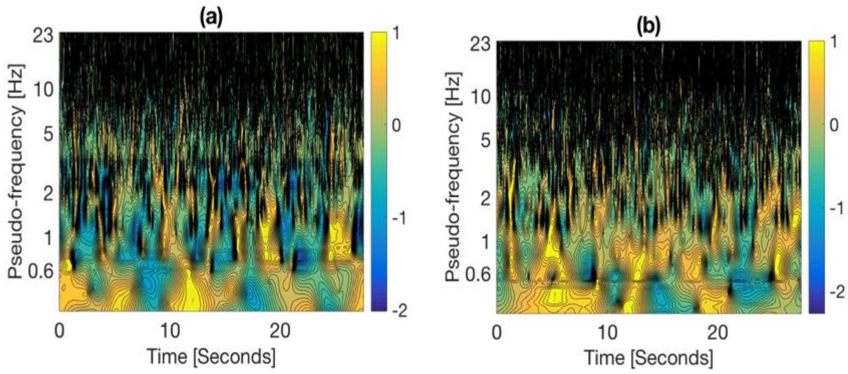

Figure 7. Wavelet transfer function WTF platform - driver's seat in case of:
(a) passive, (b) active seat suspension, the frequency logarithmic scale introduced - the Morlet wavelet parameter 3

It seems to be no significant differences shown by WFT (Fig. 7a and Fig. 7b). To distinguish the areas, where WTF are positive, the following figures are generated additionally (Fig. 8).

It shows, where the system reduces or not, the vibrations come from platform to the seat. As can be seen in these figures, the improvement is not significant, comparing both systems. One has to be aware that the active system was designed to reduce or damped mainly the vertical vibrations. Comparing the figures Fig. 8a-b, some improvement is reached above 3 Hz. It is more visible in the figures with linear frequency scale (Fig. 6). In Fig. 6a the frequency 3Hz can be easily identified and referred to Fig. 6b. In the case of the active system, the areas with positive WTF values are smaller than in the passive one, above this frequency. The most important „behavioral" characteristics of the system are expected in the low-frequency range and the figures logarithmic scale emphasizes them. This kind of scale is used in the further analysis.

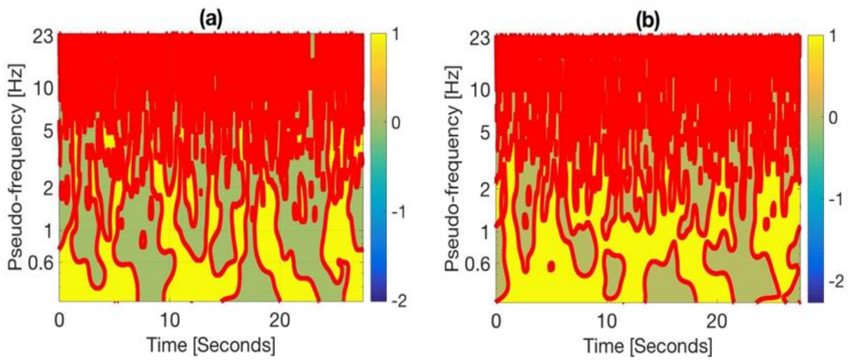

Figure 8. The positive values of wavelet transfer function
WTF (platform - driver's seat), indicated by yellow areas:
(a) passive, (b) active seat suspension - the Morlet wavelet parameter 3

5. The Suspension Platform-Head System

The wavelet transforms of vibration signals $S_{out}^{H}(t)$ measured by device III (placed on the driver's head) are shown in the proper frequency range in Fig. 9. The results in the case of passive and active systems are distinguished. Here the wavelet parameter 4 is used again.

In Fig. 10a (passive system) the WFT shows that values above zero dominate in frequencies range to 5 Hz. The Fig. 10b and subsequently Fig. 11b (by contrast), show that the active system gives more driver's head protection against vibrations in this frequency range. To calculate and show WTF the wavelet parameter 3 is used together with a different colour scale.

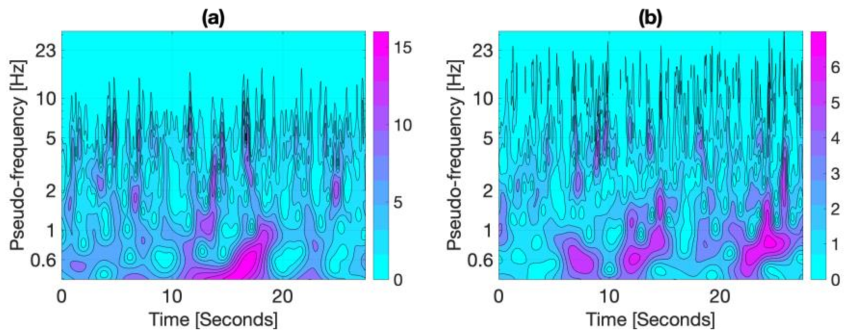

Figure 9. Wavelets transform WT of the signal measured on the driver's head, in case of: (a) passive seat suspension and (b) active seat suspension, the frequency logarithmic scale introduced - the Morlet wavelet parameter 4

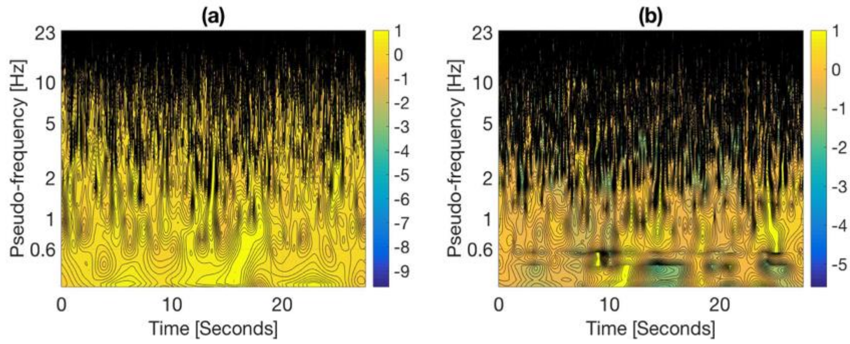

Figure 10. Wavelet transfer function WTF platform - driver head in case of: (a) passive and (b) active seat suspension - the Morlet wavelet parameter 3

The orange areas in these figures confirm vibro-isolation rather than damping in the system. The damping feature is represented by negative values i.e. mainly from green to blue colours of right-side bars-scales in figures. Red lines mainly in higher frequencies cover these areas.

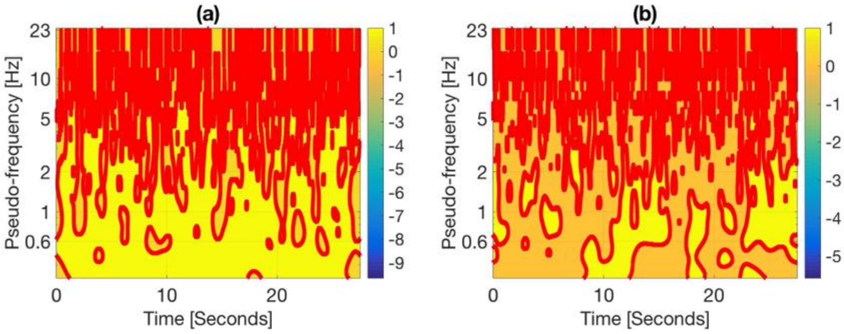

Figure 11. The positive values of wavelet transfer function
WTF (platform - driver's head), indicated by yellow areas:
(a) passive, (b) active seat suspension - the Morlet wavelet parameter 3

6. Analysis of results and system effectiveness

The suspension systems are examined in the case of horizontal excitation. The results present in this work shown, that this kind of vibrations may not be significantly reduced in some cases, even an active seat suspension system is applied. The experimental examinations are conducted on two levels. The results obtained are analyzed introducing the wavelets analysis, using Morlet wavelet with parameter 4 and 3. The parameter 3 allows to focus the analysis on the frequency up to 25 Hz, whereas the parameter 4 up to 30 Hz. The first is analysis and evaluation, which show how the vibration passes through both seat suspension systems (platform-driver's seat). The second level of evaluation reveals, how the vibrations act on one of the most important human organs - the driver's head. On the first level of examination, analyses are conducted using WT analysis, in linear pseudo-frequency range (Fig. 4). In this case of real excitation (0-20 Hz), the low-frequency vibrations are registered as passed, whereas the higher frequencies are reduced. It is seen, in the case of the excitation signal wavelet transforms in Fig. 3 is compared to wavelet transform in Fig. 4. The coefficient values of WT reach 7 (left-hand side bar-scales), in case of both system excitations (Fig. 3a-passive and Fig .3b-active). In the case of seat-analyzed signals, these values are below this level (Fig. 4 a-b). Passive system reduced the wavelet coefficients to 3 and active to 2. It is confirmed by the previous research, which are conducted on and evaluated using similar suspension systems [10], [12]. The vibrations are not significantly reduced in the low range of frequency (up to 5 - 7 Hz), but in some cases, they may be amplified due to system resonance. The passive systems show this feature, but in the case of the horizontal excitation, the active one seems not to improve it significantly. In Fig. 5 the logarithmic pseudo-frequency scales focus on the potential resonances, induce in both systems. In Fig. 5 the coefficients increase the adequate values in Fig. 3, where the resonances occur. In the case of the passive one, it is approx. 7 Hz and for active it is 5 Hz.

The wavelet transfer function WTF let's combine both, the system input i.e. the excitation and the system output i.e. the driver's seat reaction. These analyses, shown in Fig. 6, 7 and 8, underline two aspects of system evaluation. First two figures (Fig. 6, 7), the WTF in linear and logarithmic scales point out a general feature of systems. Three stripes around pseudo-frequencies 0.6 Hz, 2 Hz and 3 Hz are seen in Fig. 6a and in particularly in Fig. 7a, in the case of the passive system. Whereas, one strip is seen around 0.6 Hz in case of an active one, presented in Fig. 6b and 7b. These strips occur because of the driver presence during the measurements. As it is mentioned initially, the same person is the object i.e. simulated a driver. Therefore, the active system seems to be more robust to the driver's mass influences. Simultaneously, the yellow areas represent the WTF values exceeding zero coefficients value and green one below zero (Fig. 8). It means, that the first areas represent the moments and frequencies, where the system passes the vibrations and the second one shows the damping feature of the system. The significant differences are not noticed between systems (Fig. 8a vs. 8b). In the case of the platform - driver's head WTF the different situation occurs if the same evaluation criteria are applied. The Fig.9 i.e. WT shows that the wavelet coefficients get significantly high values in case of the passive system, in comparison to the active one. More than two times maximal coefficient values occur in Fig. 9a-passive vs. Fig. 9b - active one. The most convenient is WTF analysis that results are shown in Fig. 10 and subsequently in Fig. 11. The driver more gently receives the vibration, in case of an active system in comparison to a passive one. The yellow areas (Fig. 11b) are significantly smaller than in Fig. 11a. The reason for not significantly different vibro-isolation and damping feature of the passive and active system (platform-driver's seat) is identified. In the case of the active one, the control criterion is a relative displacement of the platform and driver's seat. It is measured in direction x (Fig.1), which is minimized using a dedicated algorithm. This configuration is dedicated to the reduction of vertical vibrations. Whereas, the WFT includes the signals, which are the absolute values (modulus) of acceleration (1) and the direction is not considered. The wavelet analysis, considered the components of the signals x, y and z separately, shows that this active system reduced horizontal (acts in the same direction as excitation) components worse, than the rest. These vertical components are reduced better in the active system than the passive one. The passive system produces better horizontal vibration components reduction and the worse the vertical. It is visible comparing Fig.8a vs. Fig. 8b. Yellow areas in active system case are a little greater than in passive one. The resultants give comparable feature in the case of platform-seat both systems. Simultaneously, the human body has the ability that compensates the resultant seat vibration much better in case of the active system, which is seen comparing Fig. 11a and Fig. 11b.

7. Conclusions

Three analysis approaches are mentioned in this work. They can be used to examine dynamical systems such as truck (heavy machine) seat together with a driver (operator). Comparing formulas (2), (3) and (4) one can notice similarities. All transforms are based on the inner product of the signal S(t) and specific functions. In the case of (2), it is pure harmonic, in case of (3) it is window modulating harmonic and for wavelets transform it is „mother wavelet". First one the FT provides sharp frequencies localization in the signal measured in the system. It is not enough to trustworthy analyze the system. The STFT improves the FT, introducing time-frequency localization. But because of window function w(t) a lack of time adjusting with frequency properties generates uncertainties in same cases mentioned above. It is solved in wavelet transform WT, where special functions Ψ are used, which „adjust themselves" in time and frequency simultaneously, during the signal transformation. Due to their capability to localize in time, wavelet transforms readily lend themselves to non-stationary signal analysis. Our intent in this paper was to present the basic concept of the wavelet transform of the active seat suspension systems. The suitability of the Morlet wavelet for active seat vibration decomposition is discussed. Acceleration signal decomposition strategy has been presented where a seat vibration signal is iteratively decomposed into vertical and horizontal components, which are non-stationary signal.

Due to their capability to localize in time, wavelet transforms readily lend themselves to non-stationary signal analysis. Our intent in this paper was to present the basic concept of the wavelet transform of the active seat suspension systems. The suitability of the Morlet wavelet for active seat vibration decomposition is discussed. Acceleration signal decomposition strategy has been presented where a seat vibration signal is iteratively decomposed into vertical and horizontal components, which are non-stationary signal.

Finally, the wavelets transfer function WFT is proposed, which combines input and output signals in analyzed dynamical systems, such as seat suspension system including the driver. The results presented in this work to be aimed at WTF ability in the area of particular, chosen seat suspension systems comparison and the results visualization. In the work, there are references to the already obtained and known researches conducted in the area of seat suspensions systems. It is obvious that the work is limited to specific excitation, one driver case and prespecified type of suspension system, but the potential of the proposed tool is the main intention.

The active systems are constantly improved, because of long-term exposure to whole-body vibration, which can be dangerous and oppressive. The main purpose of these systems implementation is the elimination of the vibration in the most possible widest range. The majority of the tests are carried out using the mannequins or weights. Our research was carried out using the human body. The previous experiments indicated there is a difference between results using mannequins and humans. The conducted experiments and wavelet analysis in the form of WTF indicate the following statements:

- the active and passive seat suspensions can suppress equally the vibration acceleration in the high-frequency range, especially above 5 Hz;

- the WFT allows to show systems momentary adverse reaction (maximal acceleration), unlike commonly used power density function (PSD);

- the WFT analysis within measurements on driver body express, that passive and active system in case of the horizontal excitations on the seat not improve vibro-reduction or vibro-isolation.

- the active system is far safer and more comfortable when the driver's head is particularly considered.

The active seat suspension can significantly improve driver comfort (in comparison to the passive one) and should be constantly extended. It can be done including more and more factors, such as the influence of driver or operator body mass. Some systems may be armed with the magnetorheological dampers, which can be more sensitive in responses to vibrations. There should be important to identify the most endangered organs and body parts response on predicted frequency range and consider it in systems action. The next part of experiments will be focused on analyzing the vertical vibrations and their influence on the part of the human body as a torso (stomach and lung areas).

References

1. S. Glowinski, T. Krzyzynski, *Modelling of the ejection process in a symmetrical flight*, Journal of Theoretical and Applied Mechanics 51 (2013) 775-785.
2. T.R. Eger, M.S. Contratto., J.P. Dickey, *Influence of driving speed, terrain, seat performance and ride control on predicted health risk based on ISO 2631-1 and EU Directive 2002/44/EC*, Journal of Low Frequency Noise, Vibration & Active Control 30 (4) (2011) 291-312.
3. D. Karnopp, *Analytical results for optimum actively damped suspensions under random excitation*. ASME Journal of Vibration, Acoustics, Stress, and Reliability in Design 111 (1989) 278-83.
4. R.M. Goodall, W. Kortuoam, *Active control in ground transportation - review of the state-of-the-art and future potential*, Vehicle System Dynamics 12 (1983) 225-57.
5. GJ. Stein, *Results of investigation of an electro-pneumatic active vibration control system*, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 209 (1995) 227-34.
6. A. Blazejewski, S. Glowinski, I. Maciejewski, *The wavelet transfer function of a human body-seat system*, Journal of Low Frequency Noise, Vibration & Active Control (2018) 1-9, DOI: 10.1177/1461348417747180.
7. D. Ning, S. Sun, J. Zhang, H. Du, W. Li, X. Wang, *An active seat suspension design for vibration control of heavy-duty vehicles*, Journal of Low Frequency Noise, Vibration & Active Control 35 4 (2016) 264-278.
8. M. Gohari, M. Tahmasebi, *Active off-road seat suspension system using intelligent active force control*. Journal of Low Frequency Noise, Vibration & Active Control, 34 (4) (2015) 475-490.
9. I. Maciejewski, S. Glowinski, T. Krzyzynski, *Active control of a seat suspension with the system adaptation to varying load mass*, Mechatronics 24 (2014) 1242-1253.

10. I. Fialho, G.J. Balas, *Road adaptive active suspension design using linear parameter-varying gain-scheduling*, IEEE Transactions on Control Systems Technology 10 (1) (2002) 43-54.
11. I. Maciejewski, L. Meyer, T. Krzyzynski, *Modelling and multi-criteria optimisation of passive seat suspension vibro-isolating properties*, Journal of Sound and Vibration 324 (2009) 520-38.
12. I. Daubechies, *Ten lectures on wavelets*. CBMS-NSF Regional Conference Series in Applied Mathematics 61 (1992) 1-350.
13. G.P. Nason, T. Sapatinas, *Wavelet packet transfer function modelling of nonstationary time series*, Statistics and Computing 12 (1) (2002) 45-56.
14. A. Blazejewski, P. Koziol, M. Luczak, *Acoustical analysis of enclosure as initial approach to vehicle induced noise analysis comparatevely using stft and wavelets*, Archives of Acoustics 39 (2014) 385-394.
15. T. Uhl, A. Klepka, *Application of wavelet transform to identification of modal parameters of nonstationary systems*, Journal of Theoretical and Applied Mechanics 43 (2) (2005) 277-296.
16. Z. Hryniewicz, P. Koziol, *Wavelet-based solution for vibrations of a beam on a nonlinear viscoelastic foundation due to moving load*, Journal of Theoretical and Applied Mechanics 51 (1) (2013) 215-224.