18. Application of vibroacoustic methods for monitoring of vibration propagation and comfort in vehicles

18.1. Impact of vibration on vehicle's comfort and safety

The compromise between comfort and safety of the vehicle driving is very difficult to achieve. For the driving safety it is extremely important to provide constant contact of vehicle wheels to the road surface. It determines the high damping coefficient. For the comfort of the passengers it is important to minimize the vibration perception. It can be achieved by the gradual and smooth vibration absorbing [124, 125, 175]. The driver and passengers are exposed to whole-body vibration of the vehicle. It can affect from short-term body discomfort and inefficient performance to longterm physiological damage. The vibrations of the vehicle body are main problem in ride comfort. Ride comfort is extremely difficult to determine because of the variations in individual sensitivity to vibration.

The vibration exposure of the car depends on road roughness, speed, engine and powertrain parameters. To provide the best vibration isolation for the passengers the damping properties of the suspension have to be changeable to the drive condition. At the present the numerous automotive companies offer adaptive shock absorbers or active suspensions. It contains many of mechatronics systems and elements which are perfect to adjust the damping parameters of the suspension to the drive condition. The control system proper information on safety or comfort is required. The chapter presents the possibilities of application of vibroacoustic methods and signal processing algorithms for those purpose.

Analysis and evaluation of the vibration phenomena in car vehicles are very difficult and it requires using proper methods and mathematics algorithms. The number of physics and chemical phenomena occurring during working of many systems of vehicles which are affecting on propagation of energy in different forms. Thus research on this kind of phenomena has to be conducted and the results and developed methods should be analysed for different parameters of mechanical systems working. The chapter presents method verified for different exploitation parameters of the vehicle. As the results of observing and acquisition of vibration phenomena signals of displacement, velocity or acceleration of vibration are received. A vibration signal is a carrier of information on the state, the changes or the process to which the given physical or technical system is subject. Vibroacoustic signals are characterised by the largest information carrying capacity and they enable observation of changes occurring in a broad frequency band.

18.2. Methods of vibration signal analysis

Numerous measuring problems may be considered on a general level of a signal, perceiving the signal as an entirety in the course of observation. It may be examined in the domains of amplitudes, time and frequency. As far as random vibration phenomena are concerned, the signals recorded are of non-stationary nature which requires that the signal distribution is observed in the domains of time and frequency simultaneously.

One of the mathematical instruments enabling separation of non-stationary signal components is a wavelet transformation which consists in distinguishing a part of the $f(t)$ signal being similar to a present template, i.e. the part which corresponds to the determined component. The template role is performed by basic wavelet $\psi(t)$. The wavelet functions as a transformation kernel. A single wavelet is used in the given transformation, however, due to modification of scale coefficient a and modification coefficient b, it forms what is referred to as a wavelet family. A continuous wavelet transform in the domain of time and frequency is defined as follows:

$$\tilde{s}_{\Psi}(a,b)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{+\infty}s(t)\Psi\left(\frac{t-b}{a}\right)dt, \tag{18.1}$$

where: a – scale coefficient, b – modification coefficient, $s(t)$ – value of the signal examined in the function of time, $\tilde{s}_{\Psi}(a,b)$ – wavelet coefficient dependent on a and b, ψ – wavelet function, $\Psi((t-b)/a)$ – transformation kernel.

The value of wavelet coefficient $\tilde{s}_{\Psi}(a,b)$ established by means of the above formula is generally understood as a measure of similarity between the signal examined and the chosen wavelet.

Furthermore, due to dimensional estimates' sensitivity to the stationary nature of operating conditions, in the process of identification of signal characteristics, besides dimensional estimates, one applies quotients of these measures being dimensionless amplitude discriminants. They are obtained by dividing moments of various ranks by one another.

18.3. Method of multidimensional identification of signal characteristics in the analysis of vibration properties

For the sake of identification of signal characteristics in the analysis of vibration properties of an automotive vehicle's floor panel, a complex mathematical algorithm was developed to be subsequently implemented in the MatLab environment, and a user interface was created named WIBROCAR. The programme developed was named Vibroacoustic Signals Analyzer (WSA), and it was then extended with several modules dedicated to analysis, monitoring and diagnostics of selected vehicle systems and structural assemblies. It is a self-designed program for the signal processing with friendly-user interface. The communication with the user is based on the dialog windows programmed in Graphical User Interface Tools in MATLAB environment. Procedure of testing starts with vehicle data and research parameters entry (Fig. 18.1).

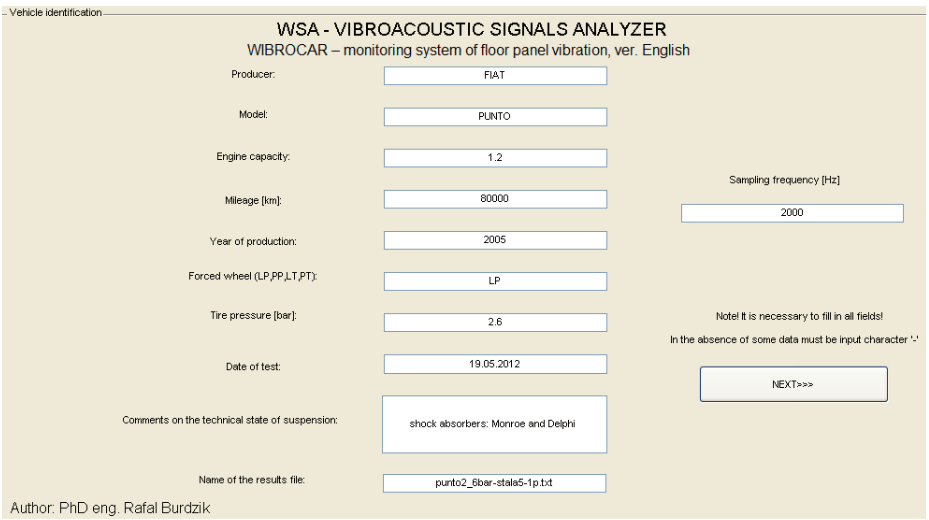

Fig. 18.1. First window of WSA program

It was assumed the utility properties of the software implementation of the WSA program. For this purpose it is very important to communicate with clear orders and information reports to user. The work in the WSA should be close to intuitive. Some examples of the communication windows are presented in Fig. 18.2.

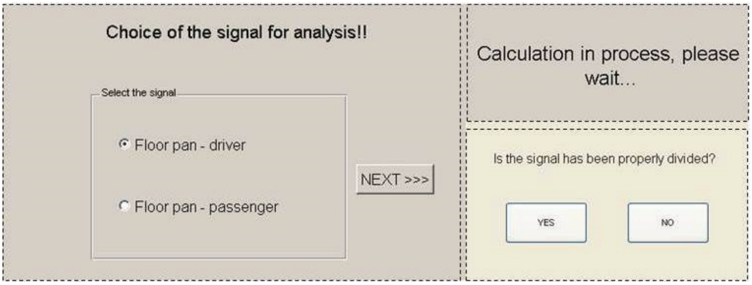

Fig. 18.2. User – WSA program communication windows

Due to the complexity resulting from nonlinear and random nature of vibration phenomena in automotive vehicles, the analysis in question is multidimensional. The property table being established consists of numerous measures and estimators, both dimensional and dimensionless ones, in the domains of amplitudes, time, frequency and time-frequency. In order to accurately identify signal characteristics, one needs appropriate analytical methods depending on the stationary and non-stationary nature of the signal. An automatic algorithm is developed for positioning of stationary and non-stationary signal cycles. For this purpose identification of next cycles of forced machine working there were next phases of vibration inductor working identification measure formulated. The markers of next cycles of forced machine working measures based on STFT (Short Time Fourier Transform) transformation is used. The main reason of choosing this transformation was short realization time. There was 21-22 Hz frequency band cut out from STFT spectrum for analysis. Based on time function of cut off frequency band identifying algorithm of end of stand run up and start of stand coasting time coordinates was created. Elaborated algorithm is based on comparing next value of analysed frequency band („analysis of edge") around set parameters. Locating of end of stand run up and start of stand coasting enables to divide signal on three time windows. First window for fragment of signal growing according to constant frequency increase of the forced system. Second window for signal with constant frequency and the third one for coasting stand – decrease of signal amplitudes according to constant frequency decrease of the forced system. This method and algorithm is presented in Fig. 18.3.

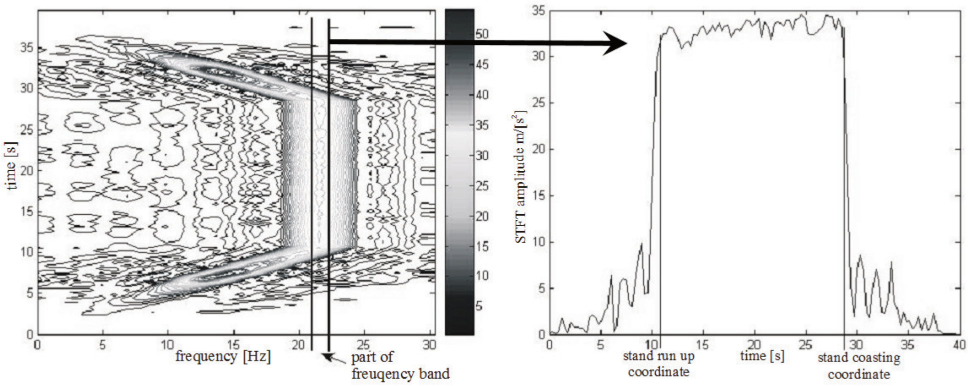

Fig. 18.3. Calculation and analysis of time function of STFT coefficients for identification of stationary and non-stationary parts of the signal

An example of such a division is presented in Fig. 18.4. It is the very first step towards identification of signal characteristics using dedicated methods in the analysis of stationary and non-stationary signals.

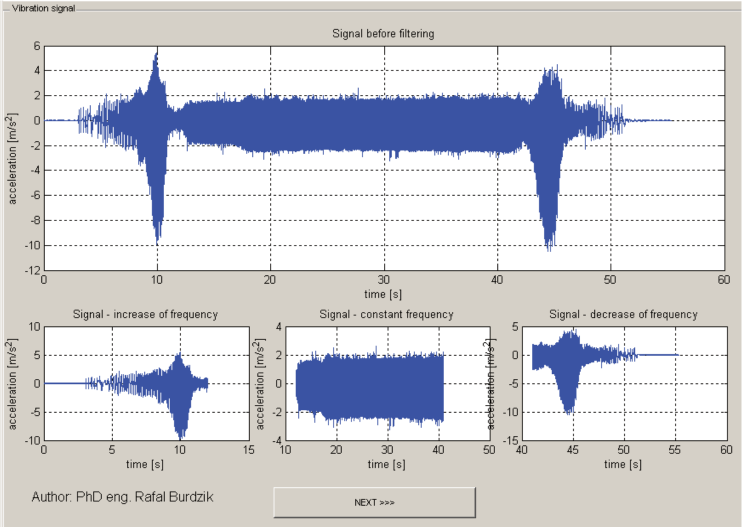

Fig. 18.4. Vibration of the floor panel - automatic algorithm for positioning of stationary and non-stationary signal cycles

For the purposes of analysis of the stationary signal part, an algorithm based on FFT was developed. The signal characteristics are then identified by amplitude based correlation of successive signal harmonics which were accurately separated from non-stationary signal components. Results of this algorithm are shown in Fig. 18.5. Preliminary tests of a car's floor panel proved various sensitivities to deviation of vibration damping parameters of successive harmonics from a constant input function.

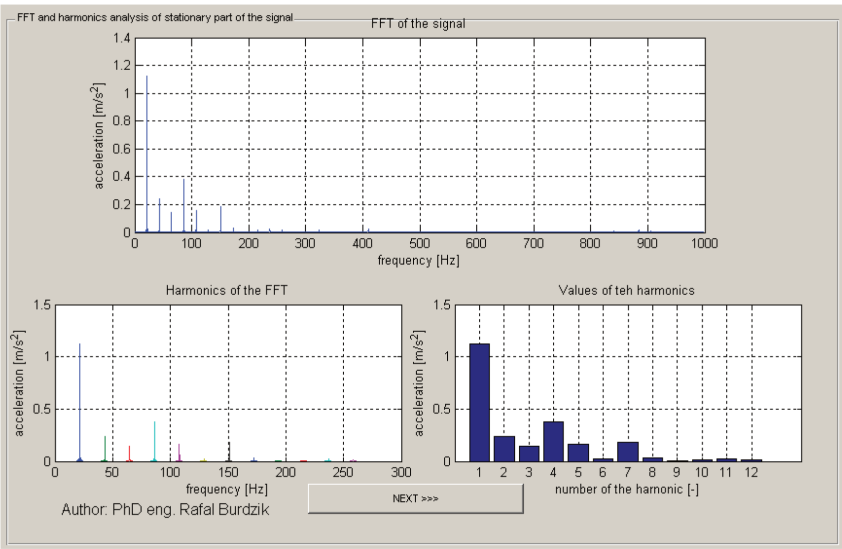

Fig. 18.5. Results of the FFT analysis for the stationary signal portion

In order to analyse predominant components of resonant frequencies of sprung and unsprung masses, a transformation algorithm was developed for the non-stationary signals recorded during a rundown of the vibration forcing station and once it was completely shut down. Finally, for the purposes of identification of the signal characteristics, a vehicle free vibration suppression window was chosen, where the vibrations of a system subject to free suppression were recorded. It enabled the system's free vibration frequency bands to be accurately observed and defined. The window used to analyse and define the range of resonant frequency bands for sprung and unsprung masses is presented in Fig. 18.6. The wavelet based time and frequency distribution of a signal enables accurate definition of resonant windows.

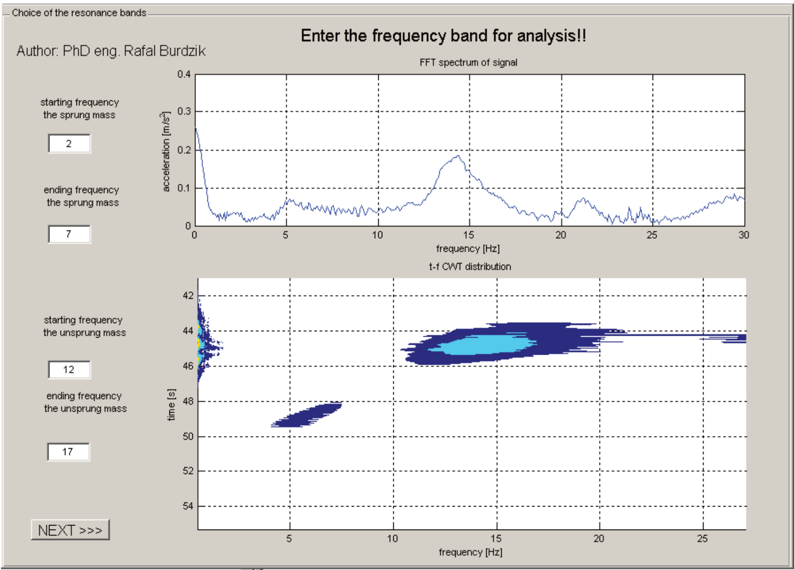

Fig. 18.6. Identification of resonance frequency bands – non-stationary signal portion

75-elemnents matrices of measures of signal characteristics were used as a multi-parameter measure of signal characteristics for an automotive vehicle's floor panel. They were established as estimators based on averaged time and frequency courses of resonant windows for sprung and unsprung masses (Fig. 18.7).

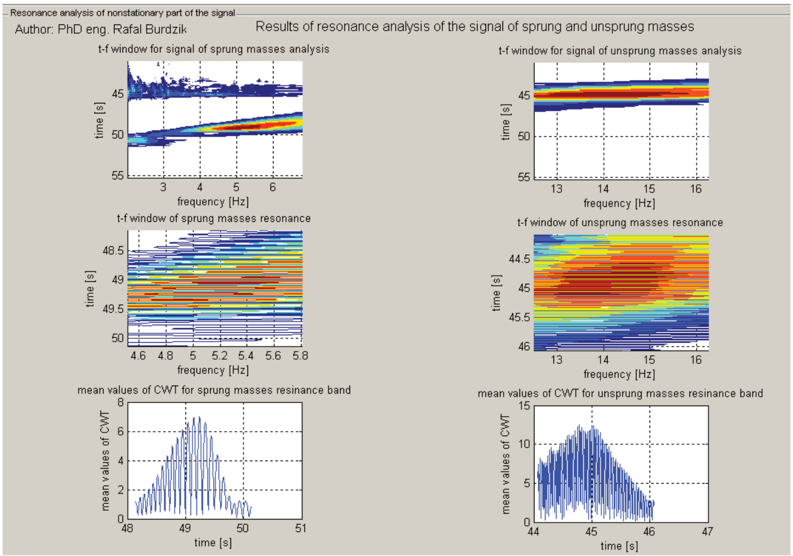

Fig. 18.7. Comparison of RMS directional dispersion factor of floor panel vibration for different engine rotational speed

The method of multidimensional identification of vibration signal characteristics, described in previous chapter, allows to determine table of properties of an automotive vehicle's floor panel. The complicated vibration phenomena and random character of excitation forces acting on car vehicle determine to use many estimators to define vibration occurring in the car. The method described enables determining measures of signal distribution in time, frequency and time-frequency in terms of stationary and non-stationary parts of the signal.

The tables below contain a collation of the chosen estimators of vibration characteristics of an automotive vehicle's floor panel featuring built-in shock absorbers filled with working medium in 50 %. These form of 75-elements table is measures of signal characteristics. From the time realization of acceleration of vibration registered during slowing of excitation, when the mechanical system goes by resonance frequencies bands of sprung and unsprung masses of the vehicle the 16 global estimators were determined (Table 18.1).

Table 18.1. Global estimators of time realization of vibration

Global estimators (amplitude, time) – resonance window					
Max	Skewness	Kurtosis	Play factor	Root amplitude	Standard deviation
2.951	–2.533	14.072	–30.490	0.004	1.157
Shape factor	P2p	Peak factor	Impulsivity factor	Rms	Momentum 1
–10.206	5.663	4.229	–43.166	1.339	0.000
Correlaction	Variance	covariance	Median		
1.000	1.339	1.339	0.002		

Basing on the preliminary experimental research of stationary part of the vibration signal, during excitation force with constant frequency, the sensitivity on changes of technical condition of car suspension were specified. Thus for the vibration properties table were added estimators calculated on spectrum of vibration as 12th next harmonics values. The values of those estimators for the same case study (shock absorbers filled with working medium in 50 %) are presented in Table 18.2.

Table 18.2. Spectrum of the vibration estimators (stationary signal)

FFT estimators					
1st harm.	2nd harm.	3rd harm.	4th harm.	5th harm.	6th harm.
1.121	0.242	0.142	0.378	0.159	0.019
7th harm.	8th harm.	9th harm.	10th harm.	11th harm.	12th harm.
0.186	0.034	0.007	0.017	0.027	0.016

Some extra „control" estimators of identification of resonance occurring in time and frequency domains for sprung and unsprung masses of vehicle have been added to the Table 18.3. The values can change for different technical parameters of the suspension system (masses, stiffness).

Table 18.3. Estimators of resonances location

Estimators of value and location of the resonances					
Sprung masses			Unsprung masses		
Max value	Time	Frequency	Max value	Time	Frequency
7.511	49.142	5.078	13.909	45.072	13.542

For the precise time-frequency characteristics of the resonance windows, according to the methodology described in Chapter 3, the estimators of CWT (Continuous Wavelet Transform) have been determined. Time and value of the exposure on resonance vibration were determined separately for sprung and unsprung masses. The Tables 18.4 and 18.5 contain a collation of the chosen estimators of vibration determined from resonance distribution of CWT. Those estimators were added to the table of properties of floor panel vibration.

Table 18.4. Collation of estimators of sprung masses resonance distribution of CWT

Estimators of resonance distribution of CWT – sprung masses window					
Max	Skewness	Kurtosis	Play factor	Root amplitude	Standard deviation
6.995	0.800	2.437	1.642	1.483	1.900
Shape factor	P2p	Peak factor	Impulsivity factor	Rms	Momentum 1
1.479	3.457	0.960	1.420	3.601	0.000
Correlaction	Variance	Covariance	Median	Integral of average cwt	Mean/max
1.000	3.610	3.610	1.703	4.883	0.698

Table 18.5. Collation of estimators of unsprung masses resonance distribution of CWT

Estimators of resonance distribution of CWT – unsprung masses window					
Max	Skewness	Kurtosis	Play factor	Root amplitude	Standard deviation
12.512	0.246	1.938	0.726	7.591	3.357
Shape factor	P2p	Peak factor	Impulsivity factor	Rms	Momentum 1
2.040	6.160	0.548	1.118	11.239	0.000
Correlaction	Variance	Covariance	Median	Integral of average cwt	Mean/max
1.000	11.267	11.267	5.283	11.048	0.883

Basing on the previous research some extra estimators were proposed to the table of properties of floor panel vibration. The relative (total) estimators of CWT distribution between resonances of sprung and unsprung masses are presented in Table 18.6. These are the relation representation's measurements of vibration characteristics of sprung and unsprung masses.

Table 18.6. Relative dimensionless estimators of the relation of CWT vibration characteristics of sprung and unsprung masses

Dimensionless relative estimators (CWT)				
C_w	L	E_{sr}	E_{max}	E_w
6.352	0.726	7.946	19.507	4.910

Those estimators are defined as below.

C_w – half of the sum of maximum values of amplitude of CWT of unsprung masses resonances (unsprung resonance P2P – scope range measurement):

$$C_w = \frac{Wz_{max} + Wz_{min}}{2} \tag{18.2}$$

where: Wz_{max} – maximum value of the average of CWT distribution for the unsprung masses resonance window, Wz_{min} – minimum value of the average of CWT distribution for the unsprung masses resonance window.

L – play factor of average of CWT distribution for the unsprung masses resonance window:

$$L = \frac{\overline{w}}{\left(\frac{1}{n}\sum|w_i|^{\frac{1}{2}}\right)^2}, \tag{18.3}$$

where: w_i – average of CWT distribution for the unsprung masses resonance window, n – number of samples of CWT distribution average values.

E_{sr} – sum of the average of CWT distribution for the sprung and unsprung masses resonance windows:

$$E_{sr} = Wz_{sr} + Wn_{sr}, \tag{18.4}$$

where: Wz_{sr} – mean value of CWT distribution for the unsprung masses resonance window, Wn_{sr} – mean value of CWT distribution for the sprung masses resonance window.

E_{max} – sum of maximum values of the average of CWT distribution for the sprung and unsprung masses resonance windows:

$$E_{max} = Wz_{max} + Wn_{max}, \tag{18.5}$$

where: Wz_{max} – maximum value of average of CWT distribution for the unsprung masses resonance window, Wn_{max} – maximum value of average of CWT distribution for the sprung masses resonance window.

E_w – concentration coefficient of the average of CWT distribution for the resonance windows:

$$E_w = \frac{E_{max}}{\frac{E_{sr}}{2}}. \tag{18.6}$$

To sum up the table of properties of floor panel vibration is collected from estimators determined from time realization of the vibration, spectrum and time-frequency distribution of the vibration. Exemplary structure of those table is presented in Table 18.7. It represents the vibration estimators calculated on the results of the research of the real object, as passenger car with shock absorbers filled with 50 % of fluid volume. The color of the next values represents the estimators presented in Tables 18.1-18.6.

Table 18.7. Table of properties of floor panel vibration

2.951	0.002	5.078	0.000	0.548
–2.533	1.121	13.909	1.000	1.118
14.072	0.242	45.072	3.610	11.239
–30.490	0.142	13.542	3.610	0.000
0.004	0.378	6.995	1.703	1.000
1.157	0.159	0.800	4.883	11.267
–10.206	0.019	2.437	0.698	11.267
5.663	0.186	1.642	12.512	5.283
4.229	0.034	1.483	0.246	11.048
–43.166	0.007	1.900	1.938	0.883
1.339	0.017	1.479	0.726	6.352
0.000	0.027	3.457	7.591	0.726
1.000	0.016	0.960	3.357	7.946
1.339	7.511	1.420	2.040	19.507
1.339	49.142	3.601	6.160	4.910

18.4. Prototype of systems of monitoring of vibration properties and propagation in vehicles

The prototype of the system for monitoring of vibration properties and propagation in vehicles is based on vibration signals analysis by use of the Vibroacoustic Signals Analyzer (WSA).

Application of the automatic developed algorithm for recognition of stationary and non-stationary states makes it possible to use the appropriate tools assuming the form of frequency as well as time and frequency transforms. Fig. 18.8 presents the programmable algorithm for „analysis of edge”. Application of the automatic developed algorithm for recognition of stationary and non-stationary states makes it possible to use the appropriate tools assuming the form of frequency as well as time and frequency transforms.

   ISSN 2351-5260

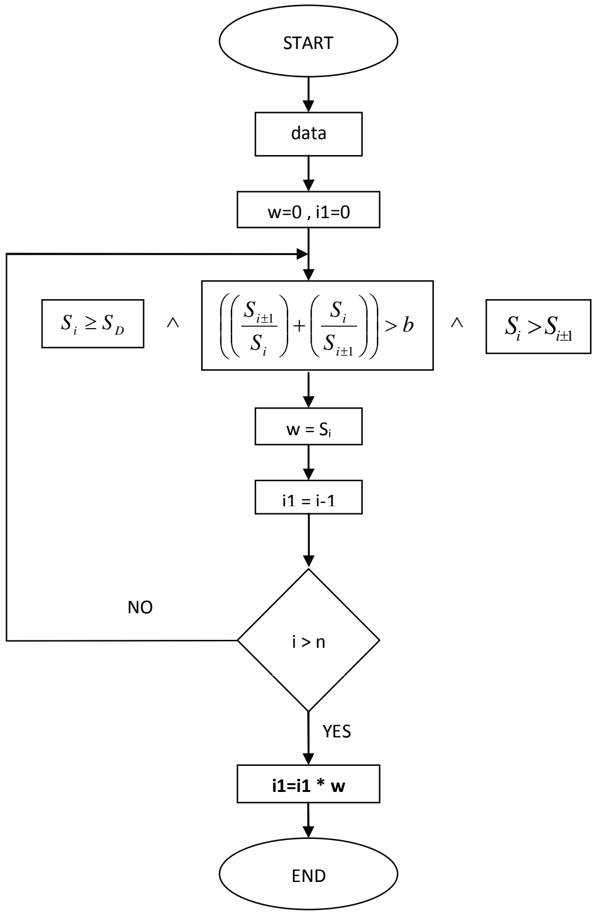

Fig. 18.8. The programmable „analysis of edge" algorithm

The WSA program was extended with several modules dedicated to analysis, monitoring and diagnostics of selected vehicle systems and structural assemblies. For the control system of damping properties the AMOR module was developed. For the system of comfort monitoring the FLOOR module was developed.

The AMOR allows monitoring and determining the parameters of vibroisolation quantity of suspension system by comparison of vibration registered on suspension arm (as unsprung mass) and upper mounting of shock absorber (as sprung mass). Transformations of the signal in frequency and time-frequency domains enable observing the energy of the vibration in resonances and as the results evaluation of the damping properties. Basing on those information the control signal to adaptive suspension mechatronic systems can be formed to adjust the damping characteristics of shock absorbers.

The FLOOR module was designed for monitoring of exposure to whole-body vibration of passengers of car. The signal processing methodology is similar to AMOR but the possibility of determining by the user the frequency bands for analysis allows evaluating the exposure to vibration in free vibration bands of chosen human organs. It is very useful tool for analysing of driving comfort [36, 44, 47].

Both prototype systems have been tested during the experimental research. The results have already been presented in [37, 54]. The scope of the experimental prototype researches included the tests of AMOR and FLOOR modules for the chosen damping properties parameters. There were researching on damping characteristics of shock absorbers, characteristics of suspension spring, pressure level in tires and value and location of extra load in the passenger cabin. The prototype of the system enables choosing of the vibration signal and frequency bands for the analysis. Some of the results are presented as the program's screens in Figs. 18.9 (AMOR) and 18.10 (FLOOR).

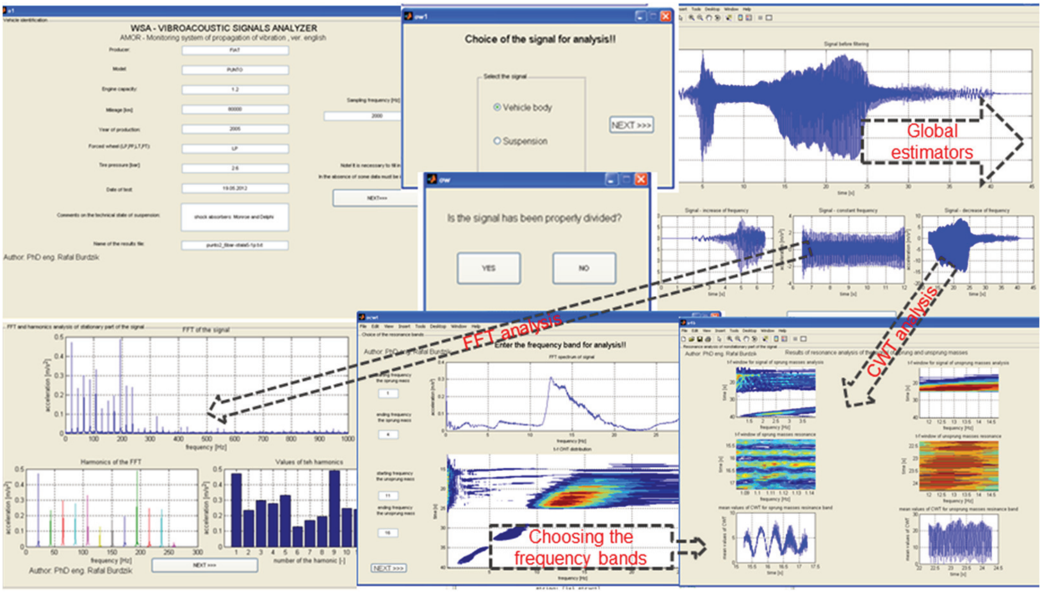

Fig. 18.9. Selected screens of the WSA program, module AMOR

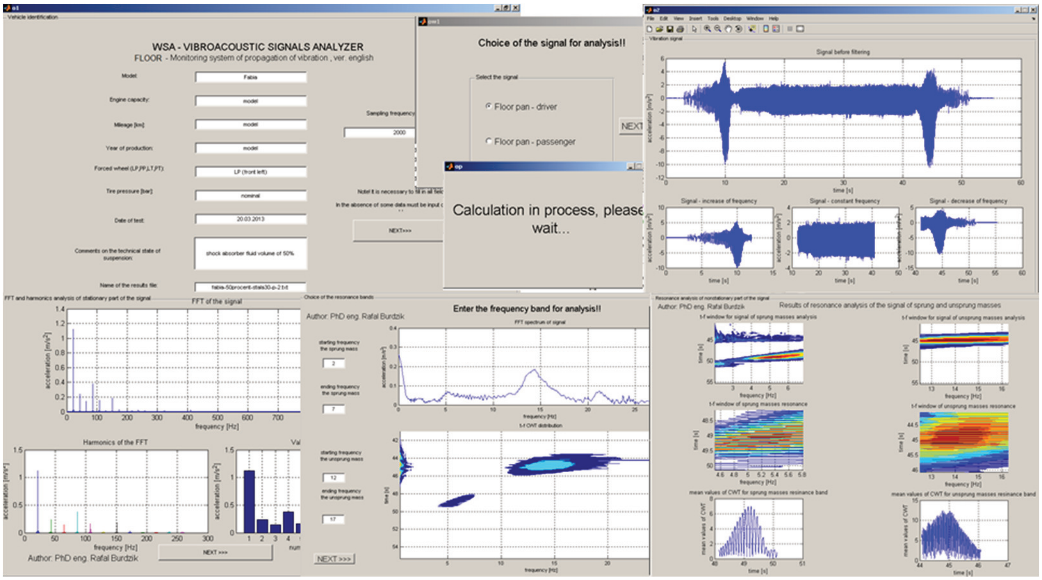

Fig. 18.10. Selected screens of the WSA program, module FLOOR

The results of WSA are vectors of estimators of resonances of unsprung and sprung masses or any others frequency bands defined by the user. Some of the example of the results are shown in Table 18.6. The proper conclusion basing on such large data collection is very difficult. Thus the papers [37, 59] present some application of neural networks as classifier or input module for the control system of vibration absorbing elements in vehicle structure. That choice was influenced by neural networks attributes such as: generalization of knowledge, approximation of functions and recognizing of patterns. The possibility of constant development of the basic knowledge by numerous examples and simple adaptation of a monitoring system is very significant as well. The neural classification system can be applied as a decision-making module in a control system [136].

The simulating test of application of neural network in abnormal tire pressure and shock absorber defect detection basing on vibration signals were conducted. The architectures of the network were designed and the transfer functions in the layers were programmed. The results obtained were satisfying. Fig. 18.11 presents the architectures of the example feed-forward network and training process.

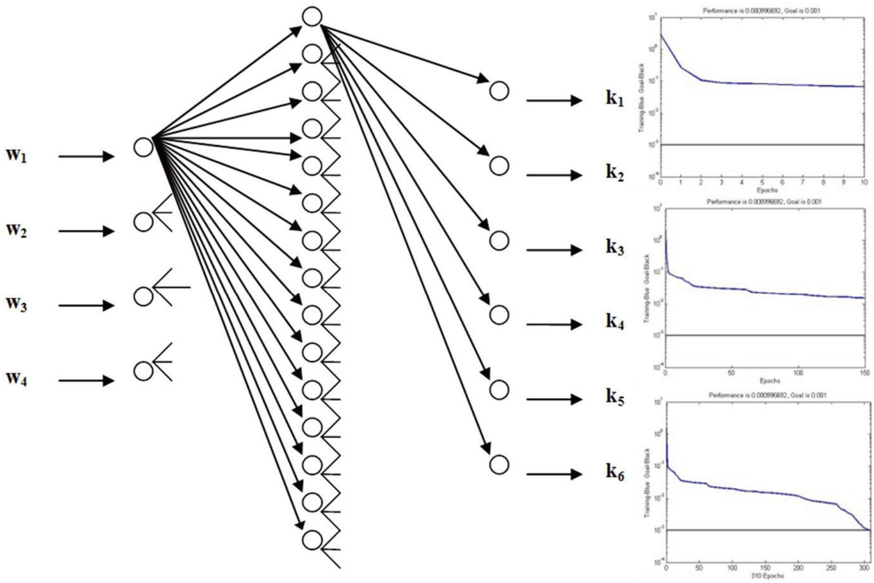

Fig. 18.11. Neural network classification module with training process graphs

The prototype of monitoring system is based on the assumption that vibrations can be recorded at any chosen structural points of a vehicle which enables the vibration propagation to be analysed. The monitoring system of vibration propagation in vehicles includes methods and algorithms for signals acquisition, pre-processing, transmission and data processing and storage. Consequently, the whole system consists of the following modules: data acquisition, stationary and non-stationary signal localization, WSA and neural classification system. It can be used as the input signal for the damping properties control system integrated with mechatronics system of vibration absorbing elements of suspension or engine and powertrain system mounting and springing elements.

18.5. Concept of on-board comfort and propagation of vibration monitoring system for vehicles

The conception of passenger cars comfort and safety monitoring and control system is based on prototype described in section above. The system has parameters for monitoring and control of the vibration. It is designed as 3-modular system integrated with WSA. First FLOOR module registers the floor panel vibration for surface and mapping of vibration transferred to human organism in multiple geometrical points distribution of vibrations. It can be consider as the comfort monitoring system. Second AMOR module monitors the damping properties of the suspension. It records the vibration of the suspension elements (sprung and unsprung). This module enables safety monitoring and controlling of the suspension elements. Basing on the previous research the system was expanded to third module. The last TIRES module is for the identification of pressure level in tires. It is very important exploitation parameter affecting on vibration transfer to car-body of the vehicle.

As the results of each module the defined estimators is reached. For the AMOR and TIRES some analytical experiment were conducted on application of neural network for the classification. For the comfort analysis the measures recommended in ISO 2631 and described in Chapter 16 for assessing exposure to vibrations of the overall impact on the human body are calculated. For the monitoring purpose those estimators are compared to some references values. Then system can generate the input function to the control unit of vibroisolation elements.

The architecture of the monitoring and control system of comfort and safety of passenger cars is shown in Fig. 18.12.

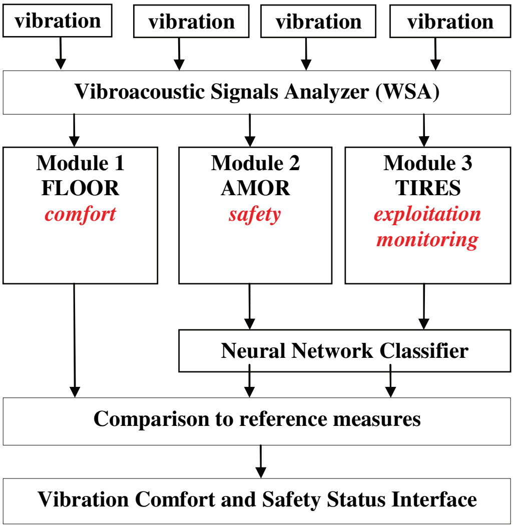

Fig. 18.12. Architectures of the monitoring and control system of comfort and safety of passenger cars

18.6. The potential practical application of the WSA

The method of multidimensional identification of signal characteristics in the analysis of vibration properties proposed and described in the chapter enables observation and separation of signal components in various domains. It also makes it possible to define signal measures depending on stationary and non-stationary characteristics as well as accurate time positioning of resonant frequencies. The measures applied in the table of signal characteristics determine a range of properties such a dynamics, amplification, scattering, concentration, attenuation, stability etc. The described software implementation of those method has the utilitarian character. WSA program is provided in friendly user interface. The results as table of properties of vehicle vibration could be adopted as mapping input signal to system of monitoring and control of vibration.

Vibroacoustic Signals Analyzer (WSA) was used for the signal processing. It is a self-designed program for the signal processing with friendly-user interface. Application of the automatic developed algorithm for recognition of stationary and nonstationary states makes it possible to use the appropriate tools assuming the form of frequency as well as time and frequency transforms. As the estimators of the vibration signals the measures calculated from time, frequency and time-frequency domains is used. The global measures are calculated from time realization of the signal. The stationary part of the signal allows calculating the measures of FFT harmonics. The nonstationary signal is transformed by Continuous Wavelet Transform so the time-frequency resonances windows can be determined. The WSA enables complex signal processing for the monitoring and comfort system application.

The preliminary prototype experimental research were successful. The scope of research presented in the chapter included the tests of AMOR and FLOOR modules for the chosen damping properties parameters. It enables developing the conception of the system for monitoring and control of comfort and safety of passenger cars is based on vibration signals analysis. The system based on Vibroacoustic Signals Analyzer (WSA). The WSA program is extended with several modules dedicated to analysis, monitoring and diagnostics of selected vehicle systems and structural assemblies. For the comfort monitoring system the module FLOOR was developed. For the safety control the AMOR can be used. The TIRE module enables monitoring of chosen exploitation parameters important for vibration transfer. As the results of each module are generated defined estimators. Monitoring of driving safety and comfort based on comparison to some references values. System can generate the input signal for the damping properties control system integrated with mechatronics system of vibration absorbing elements of suspension or engine and powertrain system mounting and springing elements.