# 4. Advanced signal processing methods in research on vibration propagation in vehicle structure

The requirements to the passenger car become very broad. As the result we can observe constant development in automotive industries in numerous engineering directions. Designers and engineers are working on alternative engine, combustion, electrical, hybrid or light constructions and increase of passive and active safety. There are a lot of efforts put in environmental issues. Thus the safety and minimization of environmental impact become regular factors ensured by the homologation requirements. For the customers the most important issues are quality and comfort [35, 48, 58].

Human vibration perception in transport is strongly correlated with comfort and safety. The chapter presents possibilities of advanced signal processing methods in research on vehicle vibration. Depending on the characteristics of the vibration signal or even its periods different mathematical transformations can be made. It enables elaborating of dedicated signal processing method for research on vibration in many terms.

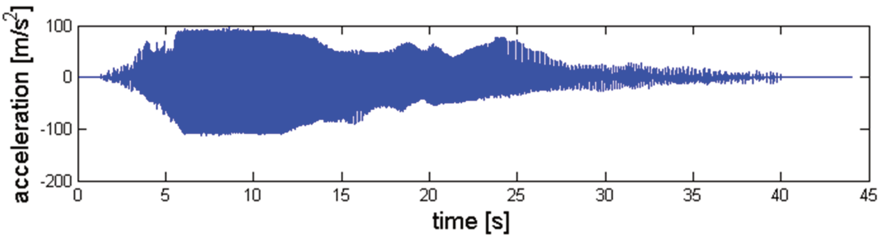
The methodology was tested on results of research of vibration of passenger car forced to vibration by the special kinematic excitation machine. The signals were registered in chosen location of the vehicle for purpose of analysis path of propagation from source to the location when vibration penetrate to the driver and passengers via feet. The vibration sensors were placed in: exciter plate (source), suspension arm, upper mounting of shock absorber, floor panel in 4 locations for feet of driver and passengers. The location of the sensors are shown in Fig. 6.1.

## 4.1. Vehicle vibration signal processing methods

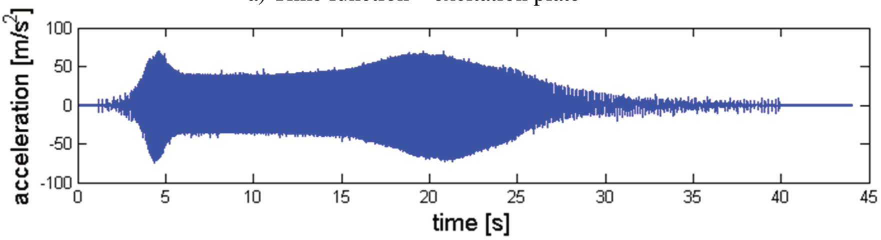
Analysis of the vibration propagation and influence on human body is difficult. It is important to observe the changes of the values and dynamics of the signal. The result obtained are signals with splot of stationary and non-stationary vibrations (Figs. 4.1-4.4).

The resonance is well noticed as the local amplitude of vibration increase, both in time and frequency domains. The quantity of vibration isolation by suspension system was presents as comparison of FFT spectrums between suspension arm (blue line) and upper mounting of shock absorber (green line) registered signals. As it can be calculated the energy of the vibration in unsprung masses resonance band (ca. 12-15 Hz) is more than 10 times lower in upper mounting than in suspension arm signal. The results are shown in Fig. 4.5.

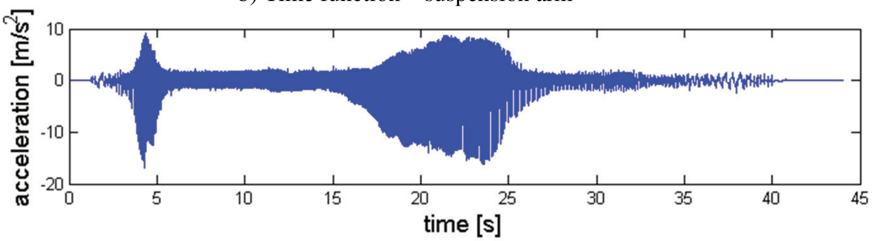
The analysis of the dynamics of the vibration penetrating into the human body by the floor panel are presented in Fig. 4.6, as comparison of the spectrum of the vibration registered on floor panel. The analysis of the dominant frequency bands are shown in Fig. 4.7.




a) Time function – excitation plate

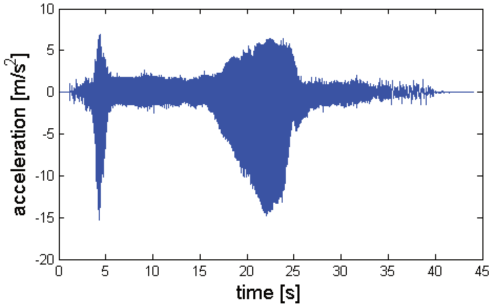



b) Time function – suspension arm

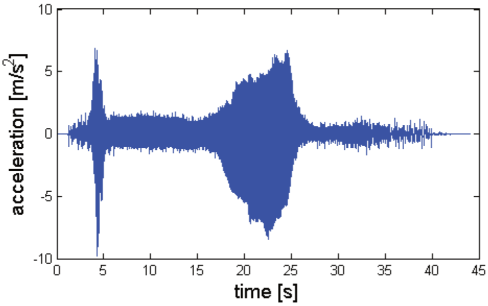



c) Time function – upper mounting of shock absorber

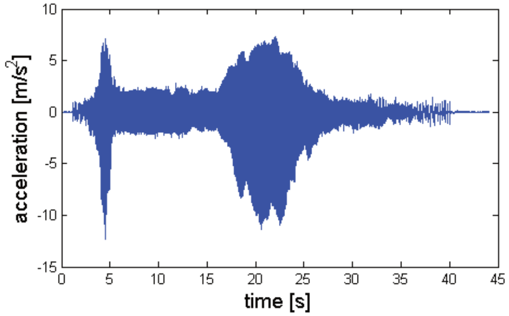
**Fig. 4.1.** Signals recorded



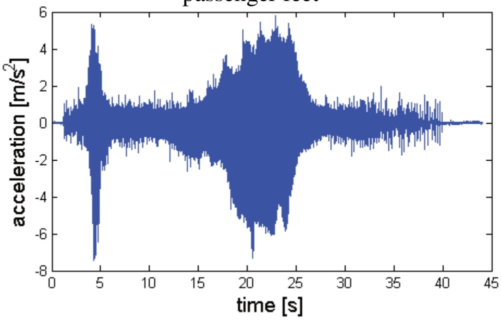

a) Time function – floor pan under the driver feet




b) Time function – floor pan under the front passenger feet

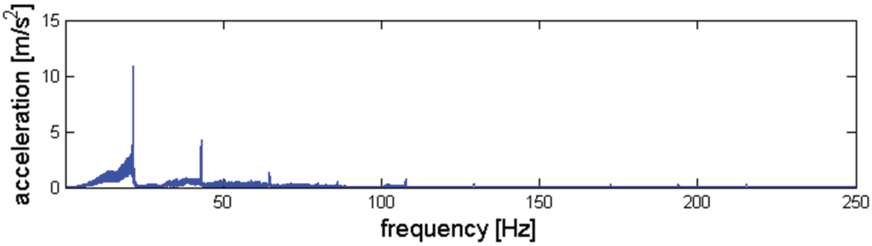



c) Time function – floor pan under the rear left passenger feet

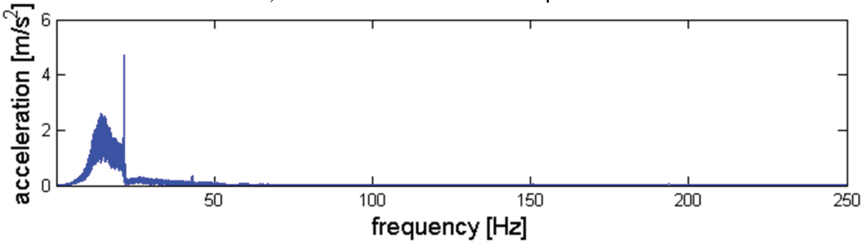



d) Time function – floor pan under the rear right passenger feet

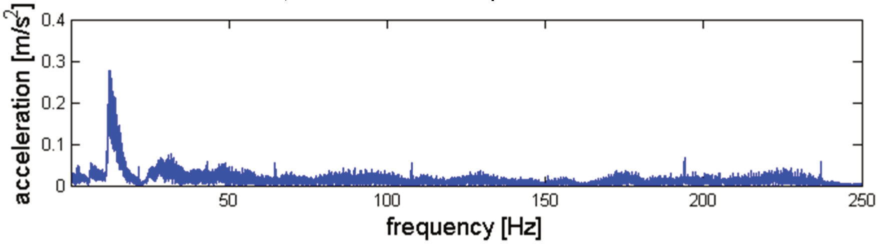
**Fig. 4.2.** Signals recorded




a) Time function – excitation plate

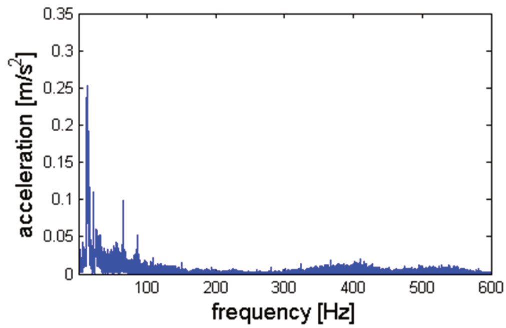



b) Time function – suspension arm

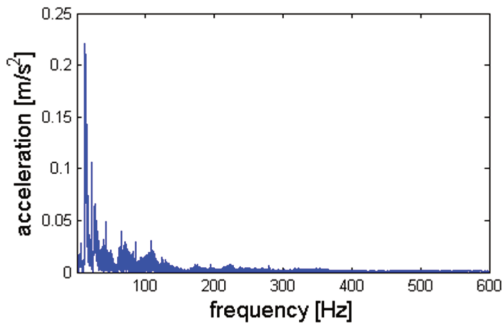



c) Time function – upper mounting of shock absorber

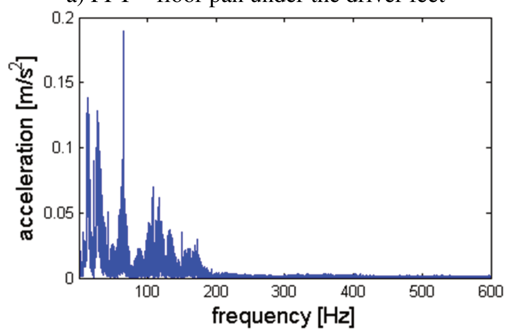
**Fig. 4.3.** Spectrum of the signals recorded – FFT



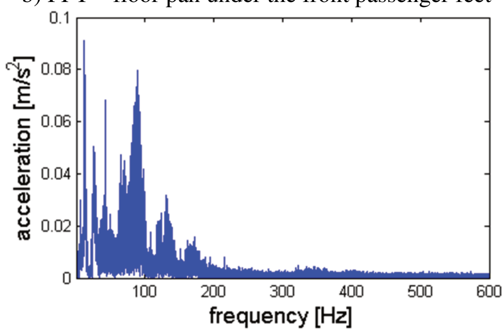

a) FFT – floor pan under the driver feet




b) FFT – floor pan under the front passenger feet




c) FFT – floor pan under the rear left passenger feet




d) FFT – floor pan under the rear right passenger feet

**Fig. 4.4.** Spectrum of the signals recorded – FFT

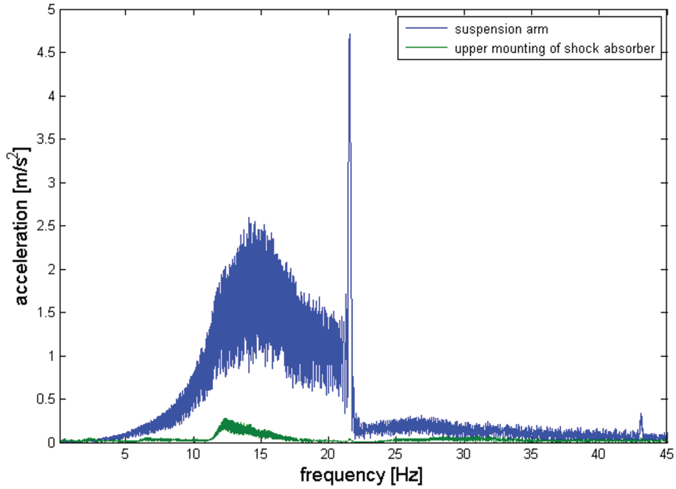



**Fig. 4.5.** Vibration isolation by suspension system

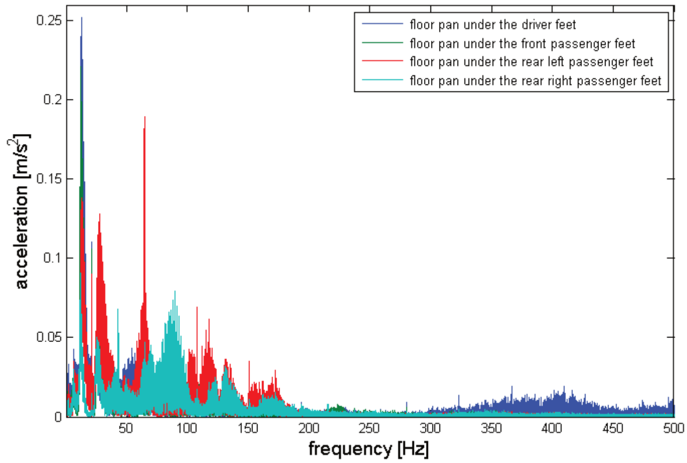



**Fig. 4.6.** Dynamics of the vibration penetrate into the human body by the floor panel

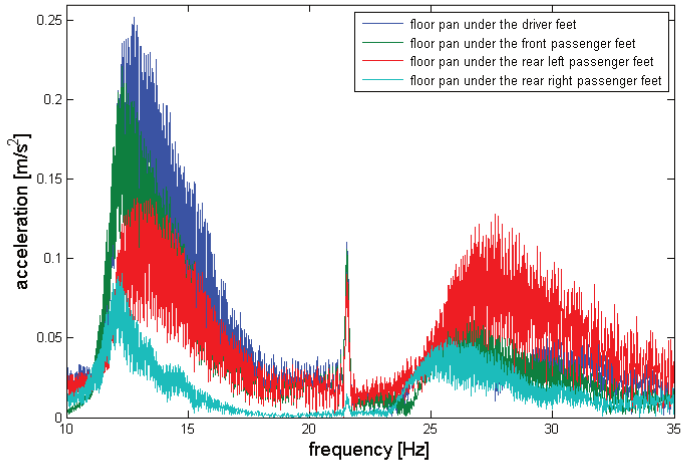
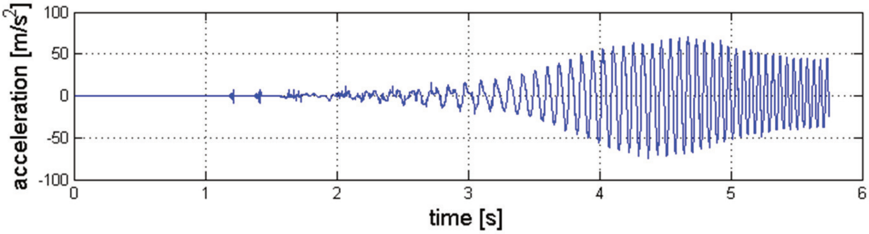
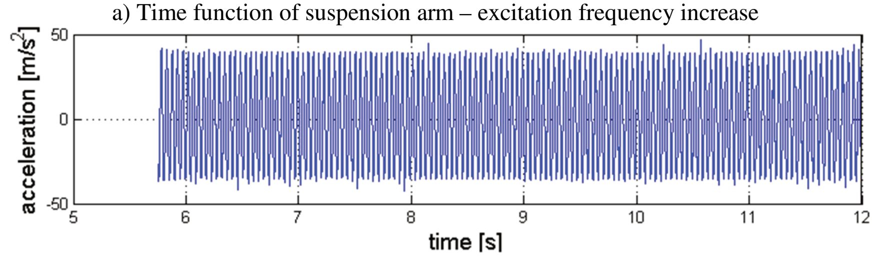



**Fig. 4.7.** Dominant frequency bands of the floor panel vibrations

Vehicles vibrations are random processes as results of vide range of possibilities forces and nonlinear characteristics of suspensions elements of the vehicles construction. The stationary and non-stationary signals require the use of different transformation for signal processing. For the proper analysis the distribution of the signal has to be made. The author developed the algorithm of the signal distribution by the stationary and non-stationary conditions. The mathematical algorithm prepared and programmed enables analysis and separation of the vibration signals in accordance with the stationary and non-stationary states. It is based on core of the frequency comparison to localize the signal with constant frequency as the main condition for stationary signal. Simultaneous the changes of the mean values of the signal in processed window are compared. Those operations allow dividing of the signal for windows with stationary and non-stationary part of the recorded signal. The markers of frequency comparison based on STFT transformation were used. The main reason of choosing this transformation was short realization time. The STFT transformation enables signal observation in time-frequency domains. It is possible to choose the constant frequency band and observe in time realization of the signal. Based on time function it can be identifying algorithm of frequency comparison. Elaborated algorithm is based on comparison of next value of analyzed frequency band (“analysis of edge”) around set parameters. The divided signals are presented in Figs. 4.8 and 4.9.




a) Time function of suspension arm – excitation frequency increase




b) Time function of suspension arm – excitation with constatnt frequency

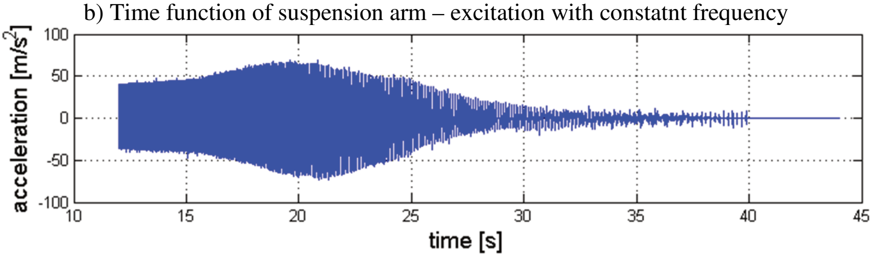
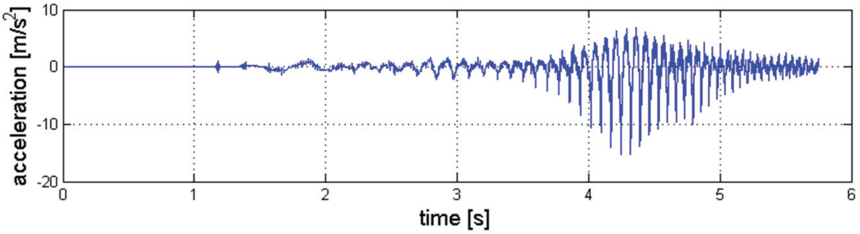
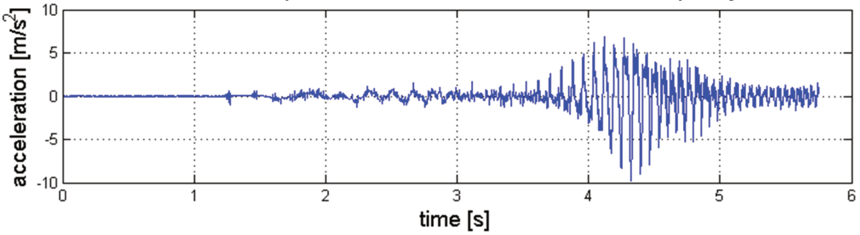



**Fig. 4.8.** Suspension arm vibration signal distribution by the stationary and non-stationary conditions

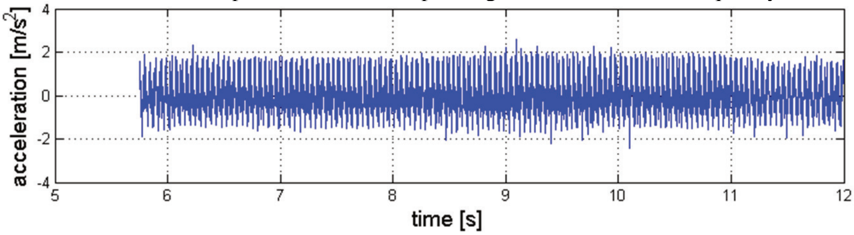
This methodology allows analysis of the signal with proper transformation. For the increase and decrease of the frequency the signal is non-stationary. The analysis spectrum is very difficult because frequency components are blurry. For the constant frequency the signal is stationary and frequency component are strongly isolated. Some of the results are shown in Figs. 4.10 and 4.11. The comparison of the spectrums of the stationary signals of vibration in suspension arm (unsprung masses), upper mounting of shock absorber, floor panel (sprung masses) are presented in Fig. 4.12. It can be observed that stationary signal of unsprung masses is typical harmonic signals without any polyharmonics components. The signals of sprung masses have got many polyharmonics components.



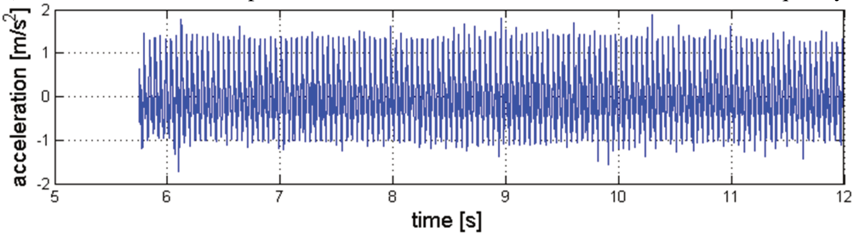

a) Time function of floor pan under the driver feet – excitation frequency increase



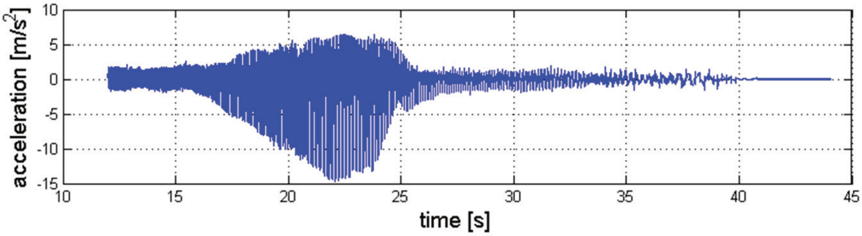

b) Time function of floor pan under the front passenger feet – excitation frequency increase



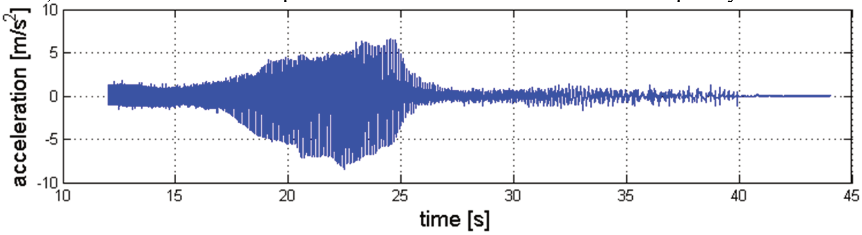

c) Time function of floor pan under the driver feet – excitation with constatnt frequency




d) Time function of floor pan under the front passenger feet – excitation with constatnt frequency

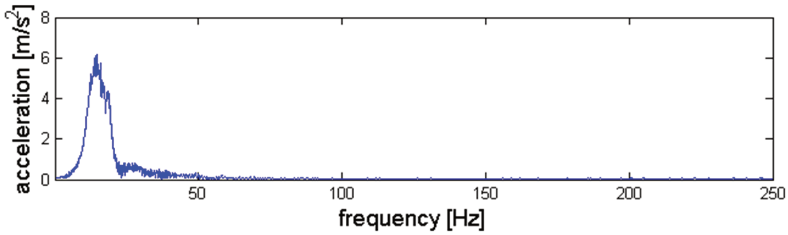



e) Time function of floor pan under the driver feet – excitation frequency decrease

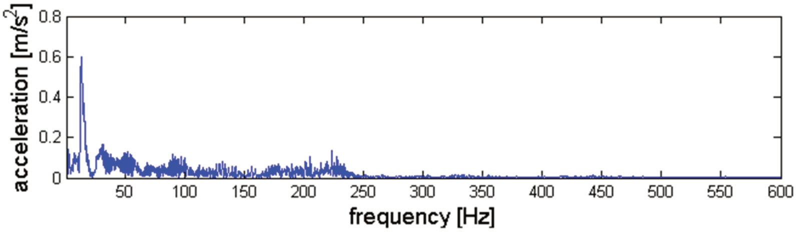



f) Time function of floor pan under the front passenger feet – excitation frequency decrease

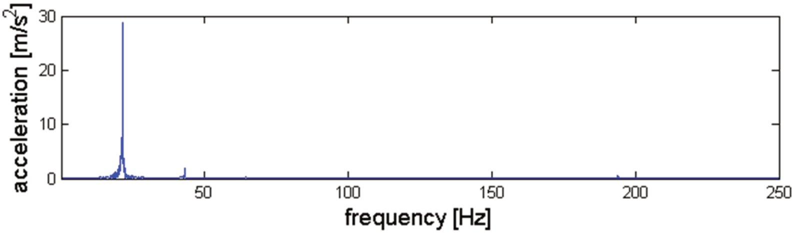
**Fig. 4.9.** Vibration signal distribution by the stationary and non-stationary conditions



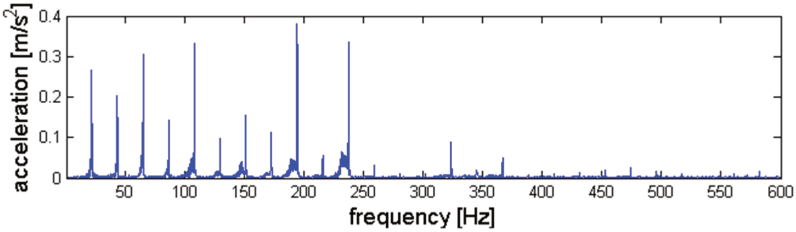

a) FFT excitation frequency increase – suspension arm



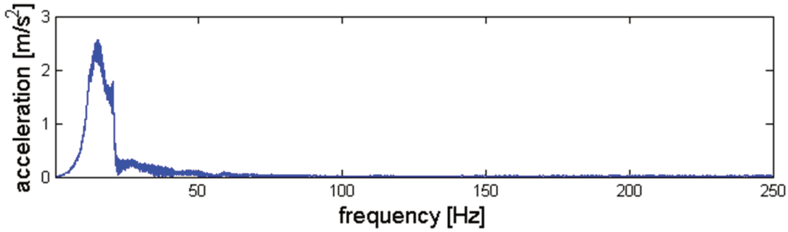

b) FFT excitation frequency increase – upper mounting of shock absorber



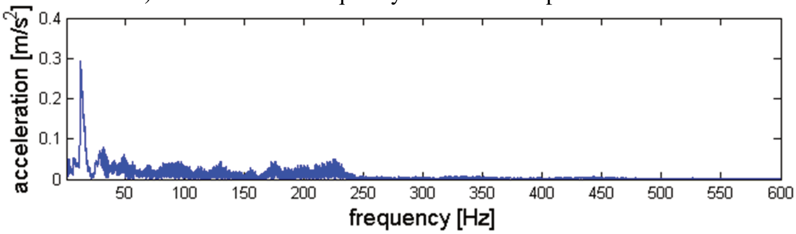

c) FFT excitation with constant frequency – suspension arm




d) FFT excitation with constant frequency – upper mounting of shock absorber

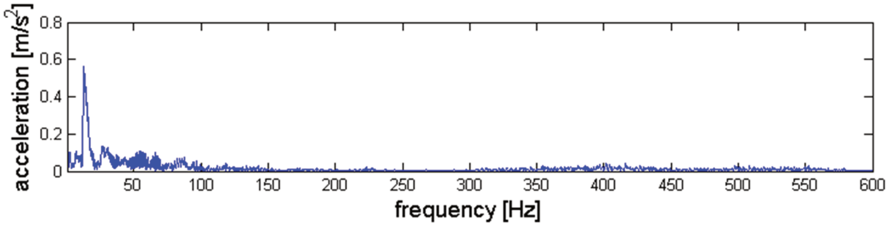



e) FFT excitation frequency decrease – suspension arm

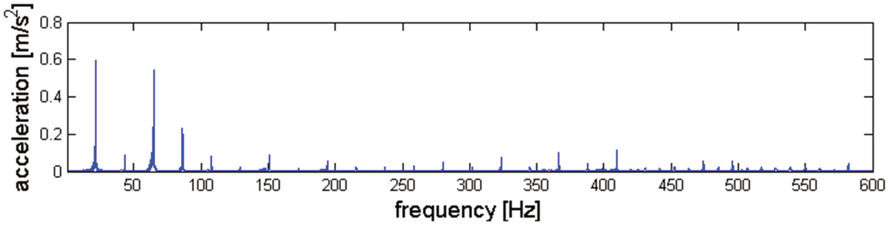



f) FFT excitation frequency decrease – upper mounting of shock absorber

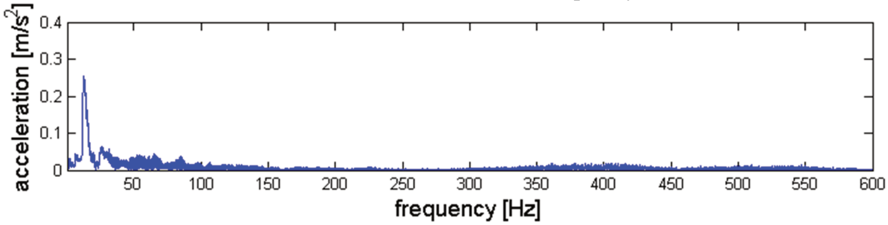
**Fig. 4.10.** Spectrums of the divided signal by the stationary and non-stationary conditions




FFT excitation frequency increase

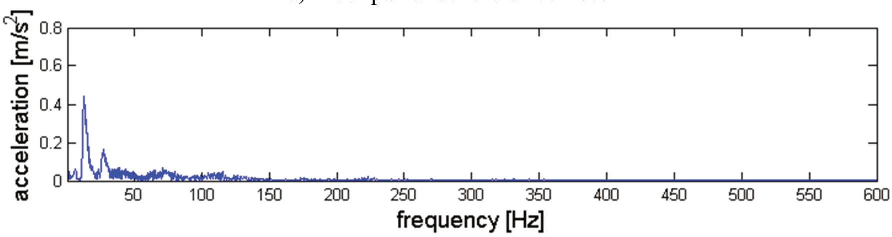



FFT excitation with constant frequency

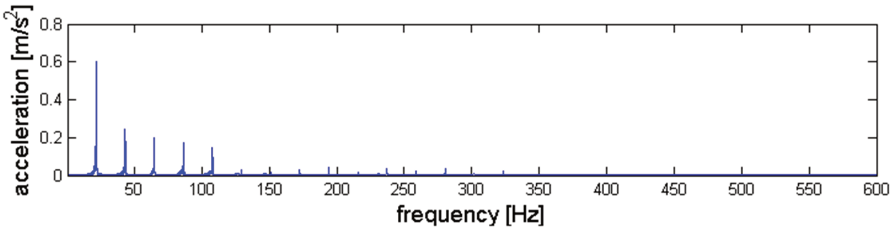



FFT excitation frequency decrease

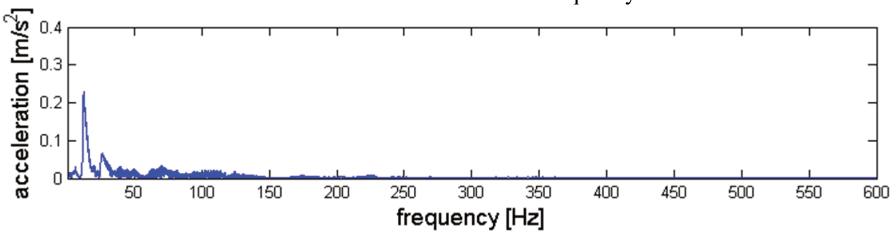
a) Floor pan under the driver feet




FFT excitation frequency increase

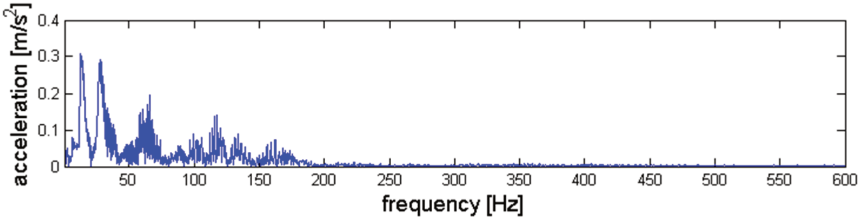



FFT excitation with constant frequency

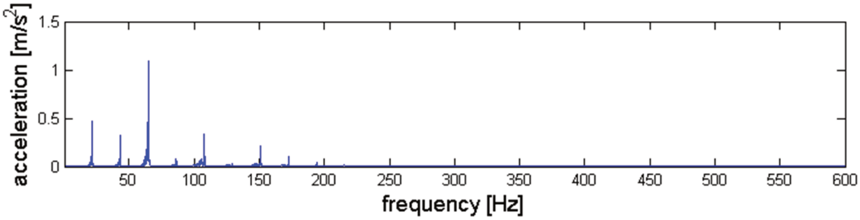



FFT excitation frequency decrease

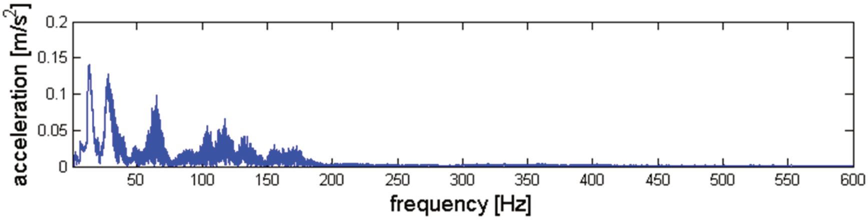
b) Floor pan under the front passenger feet




FFT excitation frequency increase

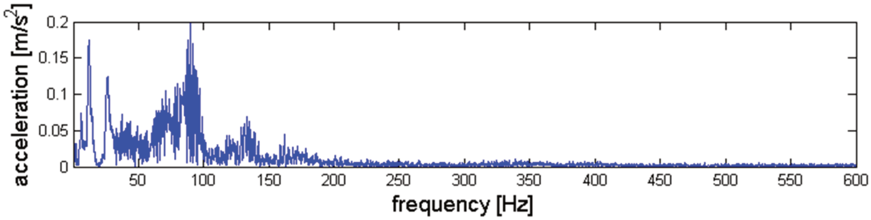



FFT excitation with constant frequency

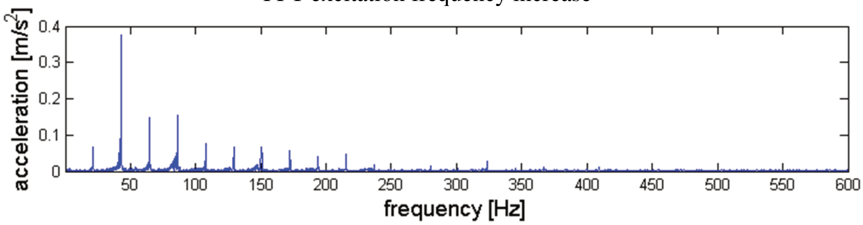



FFT excitation frequency decrease

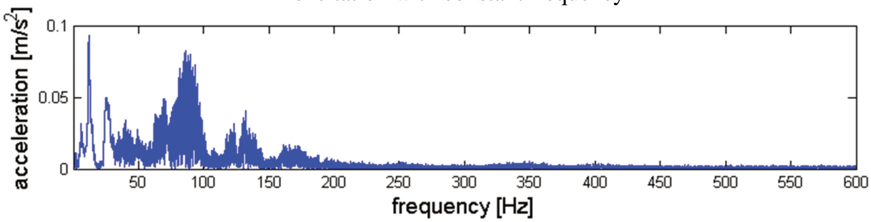
c) Floor pan under the rear left passenger feet




FFT excitation frequency increase



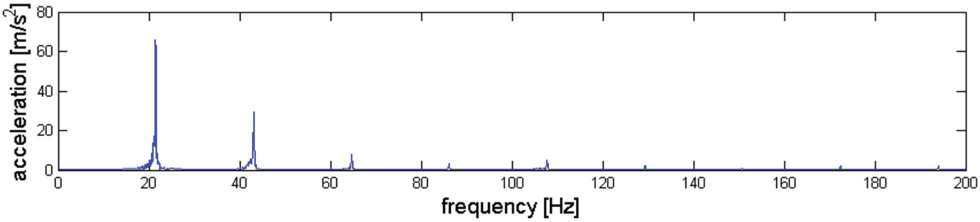

FFT excitation with constant frequency



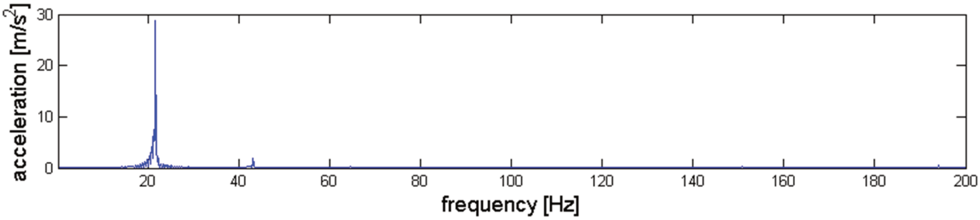

FFT excitation frequency decrease

d) Floor pan under the rear right passenger feet

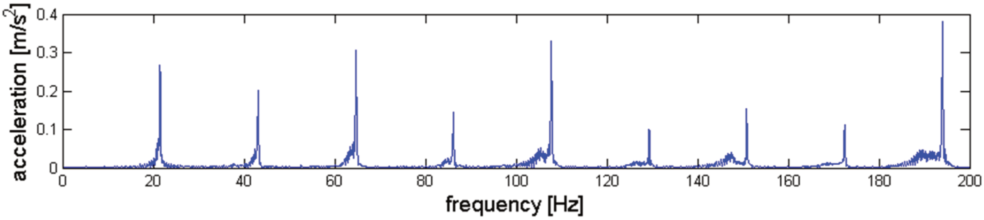
**Fig. 4.11.** Spectrums of the divided floor panel vibration signal by the stationary and non-stationary conditions



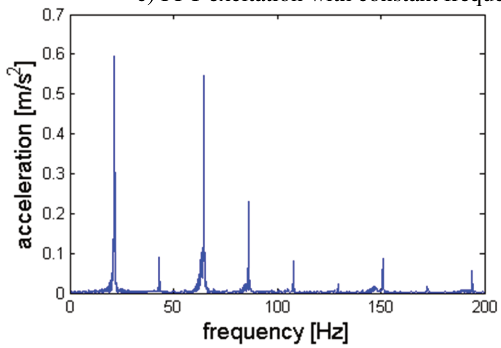

a) FFT excitation with constant frequency – excitation plate



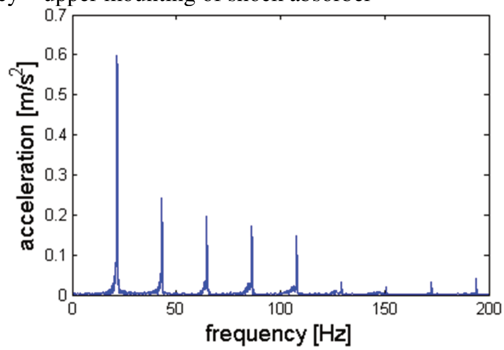

b) FFT excitation with constant frequency – suspension arm



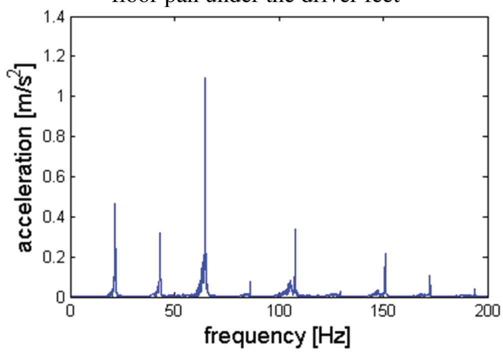

c) FFT excitation with constant frequency – upper mounting of shock absorber



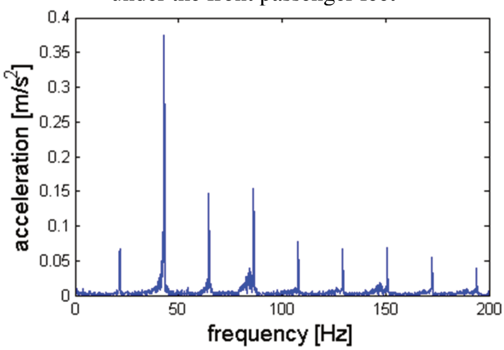

d) FFT excitation with constant frequency – floor pan under the driver feet




e) FFT excitation with constant frequency – under the front passenger feet




f) FFT excitation with constant frequency – under the rear left passenger feet




g) FFT excitation with constant frequency – under the rear right passenger feet

**Fig. 4.12.** Comparison of the spectrums of the stationary periods of vibration signals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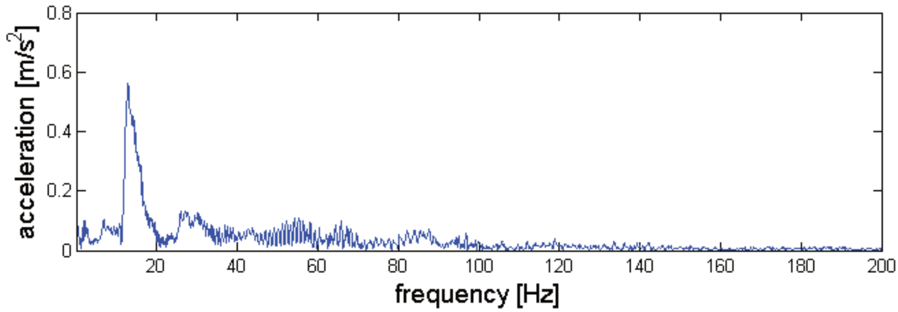
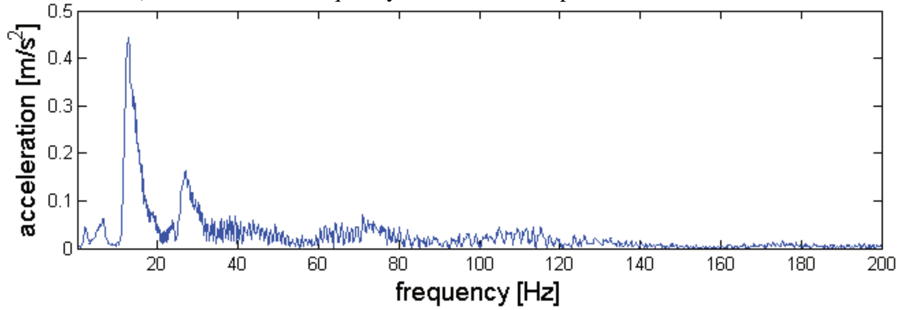
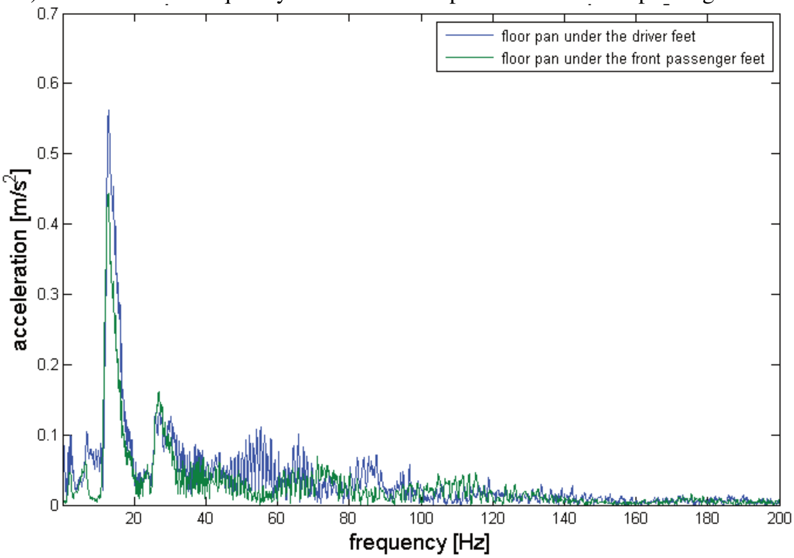



a) FFT excitation frequency increase – floor pan under the driver feet




b) FFT excitation frequency increase – floor pan under the front passenger feet

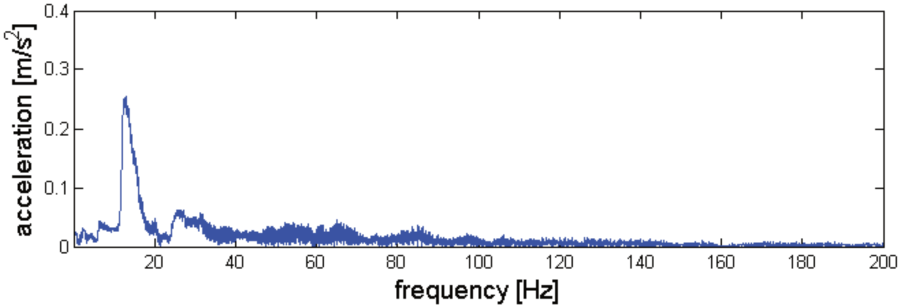



c) Comparison of FFT excitation frequency increase –
floor pan under the driver feet vs under the front passenger feet

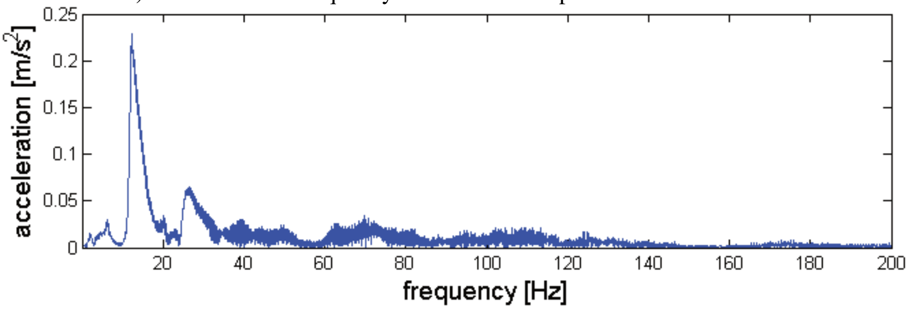
**Fig. 4.13.** The correlation of the non-stationary periods of vibration signals dynamics of the front floor panel during the excitation frequency increase

The correlation of the non-stationary periods of vibration signals dynamics of the front floor panel are presented in Figures 4.13 and 4.14. The signals registered during increase and decrease of excitation frequencies were compared. It can be observed that vibration registered under the feet of driver and front passenger are strongly correlated, especially for unsprung masses resonance (12-15 Hz). Thorough analysis of the spectrums allow observing the resonance of sprung masses. The amplitudes in 1-2 Hz band are higher. Comparison of the sprung and unsprung masses resonances shows that energy of the signal for unsprung masses resonances is more than 5 times higher.

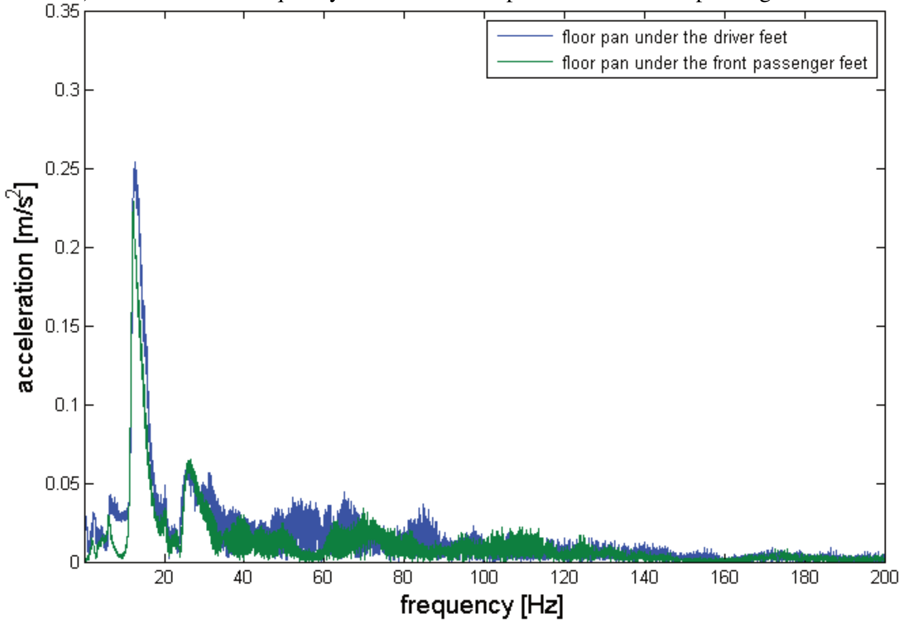
For the proper analysis of non-stationary signals the time-frequency methods should be used. Simultaneous extraction of information concerning the time-frequency structure of a signal being analysed is possible owing to a Short Time Fourier Transform (STFT). Application of this method allows identifying with good precision the time of the resonance occurs. The Figs. 4.15 and 4.16 present some exemplary results of STFT transformation of the vibration registered during the increase frequencies of the excitation in whole vehicle structure.




a) FFT excitation frequency decrease – floor pan under the driver feet

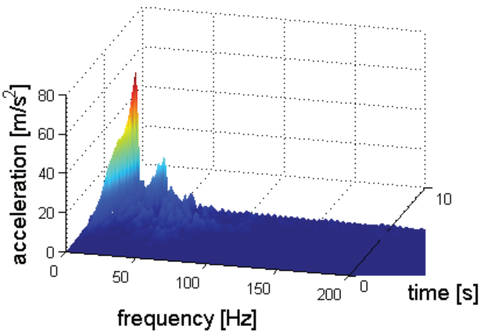



b) FFT excitation frequency decrease – floor pan under the front passenger feet

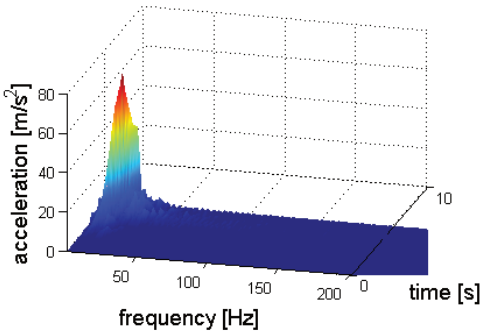



c) Comparison of FFT excitation frequency decrease –
floor pan under the driver feet vs under the front passenger feet

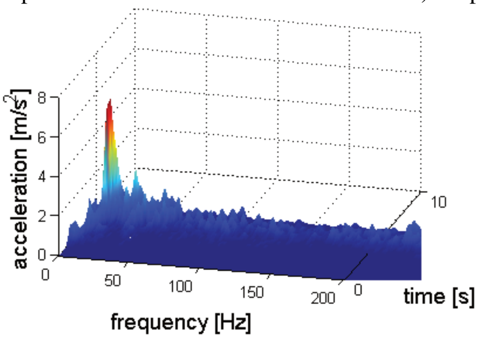
**Fig. 4.14.** The correlation of the non-stationary periods of vibration signals dynamics of the front floor panel during the excitation frequency decrease



a) Excitation plate

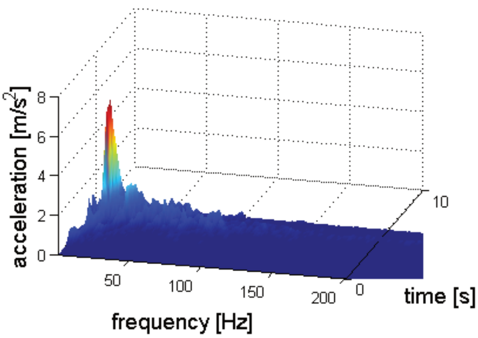


b) Suspension arm

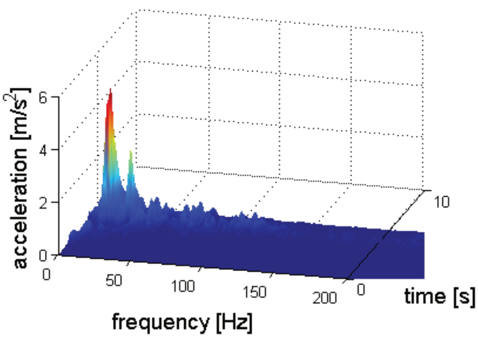


c) Upper mounting of shock absorber

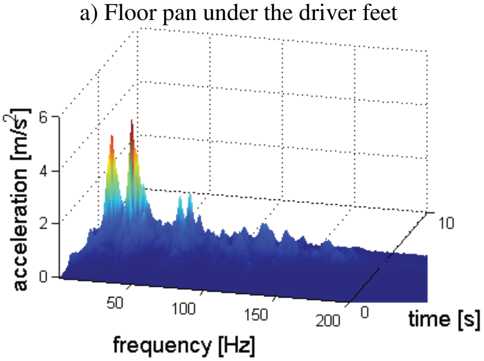
**Fig. 4.15.** The STFT transformations of vibration registered during the increase frequencies of the excitation in vehicle suspension (time window 0.25 s, resolution 0.4884 Hz)



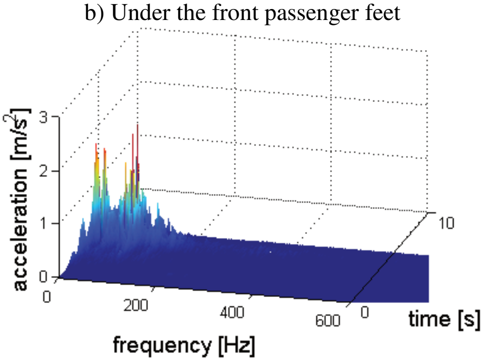
a) Floor pan under the driver feet



b) Under the front passenger feet



c) Under the rear left passenger feet



d) Under the right passenger feet

**Fig. 4.16.** The STFT transformations of vibration registered during the increase frequencies of the excitation on the floor panel (time window 0.25 s, resolution 0.4884 Hz)

The chapter presents proposition of methodology on advanced signal processing for research on vibration propagation in vehicle construction. To evaluate the vibration research for the human vibration perception in vehicle it is necessary to analyse the structure of vibration signals in chosen elements of suspension and car body of the means of transport. For the human exposure to vibration the signals registered in places where vibrations are penetrating into the body can be analyzed. The scope of the research allows analysis of vibration isolation quantity by suspension system and distribution of the vibration penetrating into human body by feet. The algorithm of the signal distribution by the stationary and non-stationary conditions allows proper analysis of the signals separately as the stationary and non-stationary signal.