5. Identification of floor panel vibration characteristics for a motor vehicle, empirical evaluation of distribution of natural vibrations

The ongoing development of the automotive industry is not only about improving vehicle subunits but also about using new structural materials manufactured by state-of-the-art metallurgical technologies and application of new technologies for joining vehicle components [93, 117]. Therefore the scope of studies of vehicle vibration dynamics has been extended by stationary empirical tests of oscillatory wave propagation in a vehicle structure as well as identification of natural vibrations. A detailed analysis of vibration related phenomena requires that other properties and mechanical phenomena take place in the course of degradation as well as the impact of external factors should be taken into consideration [10, 51].

The purpose of this chapter is to propose a method of empirical studies for identification of characteristics of vehicle structure vibrations which enable modelling of vibration distribution in a broad range of frequencies. The chapter also contains a proposal as to the manner of modelling of floor panel vibration surface estimates based on global measures of propagation of random vibrations.

5.1. Material vibration signal processing methods

The vibration signal can be very useful for research on properties of the materials, diagnosing of the materials defects or even for monitoring and testing on quality of the metallurgical technologies in production processes. Large capacity of the information in vibration signals allows to create many research methods and results analysis. Vibroacoustics is the science discipline which describes the possibilities of vibration and acoustics signals useful for diagnosing and research purpose.

There are a lot of publications showing original methods of vibration signal analysis for many applications [1, 40, 53, 155]. The publication of Batko and Majkut presents the purposefulness in controlling the phase images of the vibration signals as a useful tool for fault development process identification in the object monitored. The presented diagnostics method based on phase trajectories analysis determines displacement and velocity in arbitrary chosen point [21, 22].

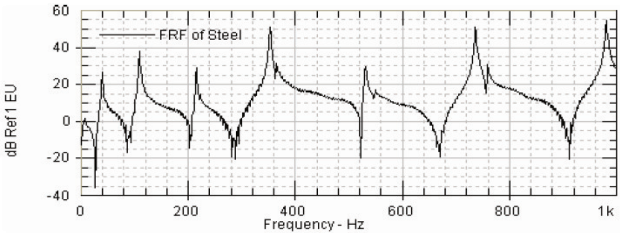
Interesting application of acoustic signal in structures defects research were presented in [9]. It shows application of the method of elastic wave propagation to detect defects in composite castings. It was proved that if a defect occurs, which is detected by the radiography, elastic wave propagation changes locally. Another example can be the photoacoustic transformation. In [141] the investigation of photoacoustic transformation in naturally-gyrotropic and magnetoactive crystals under internal stress by sound excitation in different modes by Bessel light beams was described.

Resonant is the main phenomenon useful in vibration research. Resonance vibration of materials is caused by an interaction between the inertial and elastic properties of the materials within a structure. Resonance vibration amplifies the vibration response more than the level of deflection, stress, and strain caused by static loading. Resonances are determined by the material properties, such as:

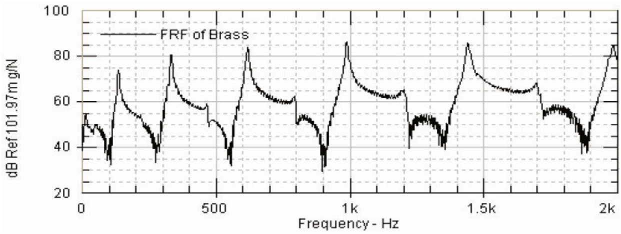
– mass,

– stiffness,
– damping properties,
– boundary conditions of the structure.

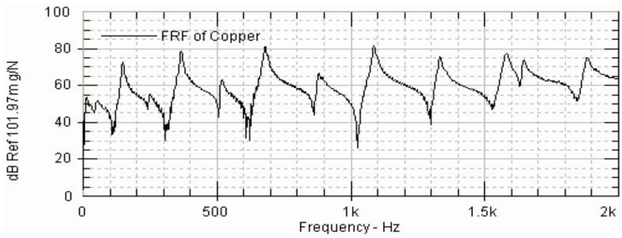
The modal research allows the frequency response function (FRF) to be determined. This describes the input-output relationship between two points on a structure as a function of frequency. Nowadays the modal testing is mean effective for identifying and simulating dynamic behavior and responses of structures. A very useful group of this research is experimental modal analysis (EMA) because this is an example of non-destructive testing. Modal research is based on vibration responses of the structures. New methods of the signal processing allows the vibrational response of the structures to the impact excitation (instrumented hammer impact excitation), which are measured, transformed into frequency response functions using Fast Fourier Transformation (FFT) [95, 157]. In the practical applications the modal parameters are required to avoid resonance in structures affected by external periodic dynamic loads. Modal analysis is a process of describing a structure in terms of its natural characteristics which are the frequency, damping and mode shapes.



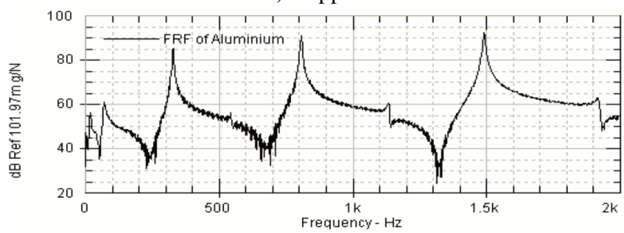
a) Steel



b) Brase



c) Copper



d) Aluminum

Fig. 5.1. Frequency response function [157]

D. J. Mead in [138] describes some methods developed at the University of Southampton to analyze and predict the free and forced wave motion in continuous periodic engineering structures. These kinds of methods are very commonly used in wide research. In the paper [112] the calculation of natural frequencies vibrational analysis of composite propeller shafts and decrease of weight was presented. The role of structural elements on the loss of total energy were investigated in [135].

The research on the nature of the wave dynamics in rod were presented in [109]. This investigation shows developed combination of finite element modeling and the transfer matrix method to solve the dynamics of the wave propagation of the periodic beam structures with defects.

Prasad and Seshu [157] investigated an experimental modal analysis of beams made with different materials such as Steel, Brass, Copper and Aluminum. The beams were excited using an impact hammer excitation technique. Some of their results are presented in Fig. 5.1.

By using SDOF (Single Degree of Freedom) and MDOF (Multiple Degree of Freedom) estimation algorithms, natural frequencies and damping ratio could be calculated. In SDOF and MDOF estimation the modal parameters are calculated using finite difference and quadrature methods. The research shows the differences between natural frequencies, damping ratio of the materials and shapes of modes (Tables 5.1-5.4).

Table 5.1. EMA natural frequencies calculated by SDOF estimation algorithm using finite difference method

Mode No.	Steel [Hz]	Brass [Hz]	Copper [Hz]	Aluminum [Hz]
1	40.27	40.00	24.43	70.71
2	110.34	105.52	45.21	170.29
3	216.50	224.83	150.78	329.16
4	353.72	333.61	250.108	548.42
5	532.22	469.46	367.85	808.60
6	533.75	619.46	518.46	1136.87

Table 5.2. EMA damping ratio calculated by SDOF estimation algorithm using finite difference method

Mode No.	Steel [%]	Brass [%]	Copper [%]	Aluminum [%]
1	2.02	14.43	39.21	6.12
2	0.78	1.78	17.44	1.48
3	0.33	1.02	1.96	0.51
4	0.18	0.70	1.28	0.31
5	0.13	0.56	1.01	0.22
6	0.10	0.47	1.71	0.24

Table 5.3. Modal shapes of steel beam

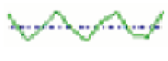
Mode No.	1	2	3	4
Mode shape				
Frequency	40.27 Hz	110.34 Hz	216.50 Hz	353.72 Hz

Table 5.4. Modal shapes of steel beam in SDOF (quadrature method)

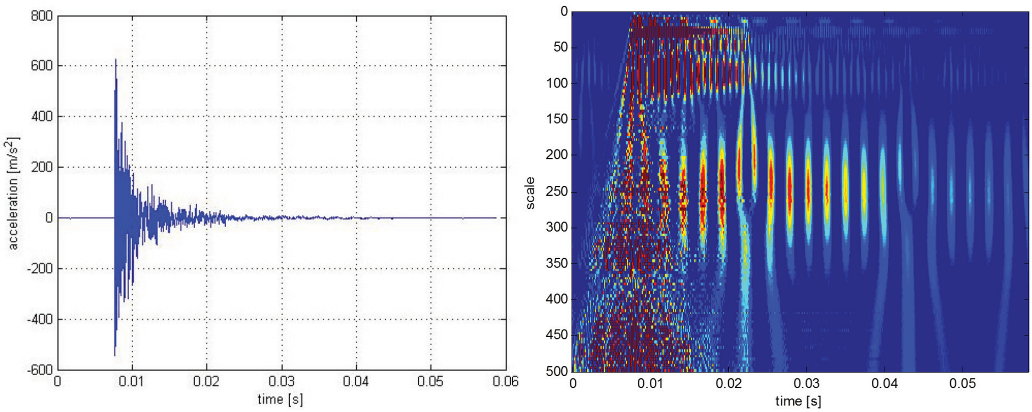
Mode No.	1	2	3	4
Mode shape				
Frequency	41.07 Hz	110.00 Hz	216.25 Hz	353.75 Hz

The paper [60] presents some preliminary research on possibilities of vibration signal application in research on materials. During the research the vibration accelerations in a direction parallel to the symmetry axis of disks in two selected points were measured. The vibrations in the disk material structure were excited by impacts in specific points.

The qualitative impact assessment for the structural material the disk was made of was performed by establishing the correlograms of time sections of the wavelet coefficient matrices (Fig. 5.2). The time sections applied in the analysis were chosen bearing in mind the natural vibration frequencies of the components examined. The autocorrelation function for the chosen wavelet sections were used for the analysis.

A random signal autocorrelation function characterises the general dependency between the signal value at a certain instant and the signal value at another instant. For any chosen execution $x(t)$ of the process in question, the autocorrelation function value estimator, linking values $x(t)$ at instants t and $t+\tau$ (where τ is the shift), can be obtained by calculating the product of these values and subsequently averaging it within the observation time range of T. When T is approaching the infinity, a precise value of the autocorrelation function is calculated. This function is always real and even, and its maximum is at the point corresponding to a zero shift and may assume both positive and negative values. A cross-corelation function established for various random signals is a measure of their mutual dependency. It is defined as follows:

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t)y(t+\tau)dt. \tag{5.1}$$



a) b)

Fig. 5.2. Results of the research: time course of vibration accelerations and distributions of wavelet coefficients [60]

This function constitutes an efficient tool for detection of predetermined processes (in the case of a random process, on high shift values, the autocorrelation function is approaching zero, whereas for a harmonic signal or other predetermined signals, the autocorrelation function does not fade as the shift value increases). When the aforementioned transformation is applied in the analysis of wavelet sections, the relevant function is as follows:

$$R_{A,B}(t_u) = \lim_{T\to\infty} \frac{1}{T} \int_0^T WT_A(t)WT_B(t+t_u)dt, \tag{5.2}$$

where: A, B – indices of the measuring sensors mounting points, $WT_x(t)$ – time sections of matrices of wavelet coefficients, t_u – time shift.

Fig. 5.3 presents a sample correlogram obtained for a steel disk excited to vibrate.

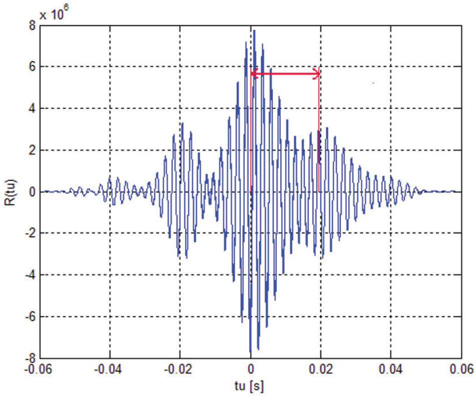


Fig. 5.3. Correlogram of wavelet sections with the time shift value marked on which the local maximum of the intercorrelation function occurs [60]

5.2. Experimental research method

Models of phenomena random in nature, defined on the grounds of the theory of probability, are also to be verified against the reality. For that purpose, one needs numerical data characterising the relevant properties of the phenomenon examined. Therefore, empirical data concerning the given phenomenon must be acquired and statistical conclusions drawn.

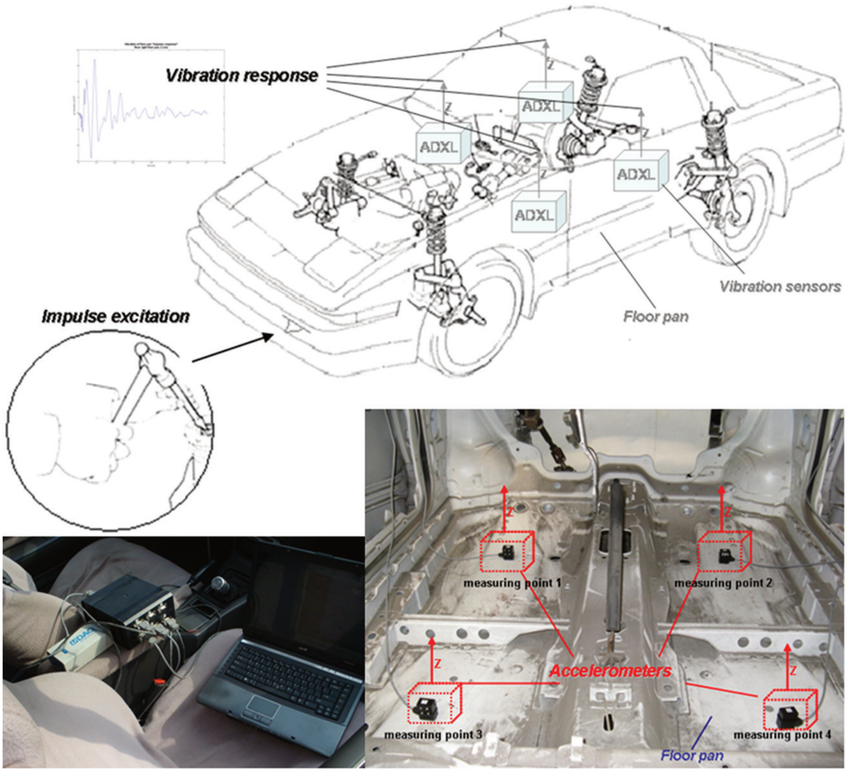


Fig. 5.4. Testing diagram and measurement chain

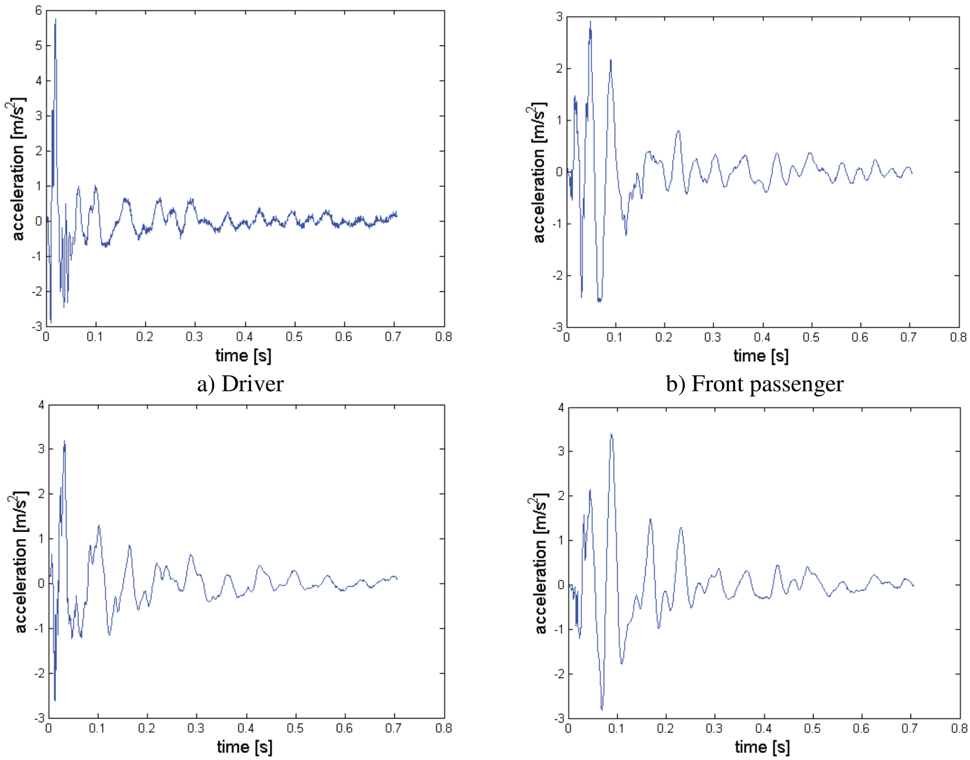
The experimental studies discussed in the chapter were conducted on an actual object, namely the Toyota Supra mk3 passenger car of the complete vehicle kerb weight of 1.540 kg. The purpose assumed for the studies was to identify natural vibrations of the vehicle floor panel as well as to determine their structure in geometrically arranged measuring points. It was to enable determination of signal characteristics and a geometrical distribution of vibrations on the surface of the floor panel. Natural vibrations are those which nature depends on physical properties of the vibrating system (inertia, damping and elasticity), and not on the manner in which the vibrations are induced.

The nature of the studies conducted was that of an experimental modal analysis which does not require recording of the course of the vibration input function. An impulse response of the vehicle structure was examined at selected points by application of forced input function assuming the form of an impact pulse. Vibrations of the floor panel were recorded at 4 points. In order to refer the results obtained to the analysis of the passenger exposure to vibrations, the measuring points were arranged at locations where the vibrations were transferred into the human organism, i.e. where feet rested.

The measurement chain consisted of the piezoelectric sensors, a measuring unit with data acquisition card and a computer featuring the software. Fig. 5.4 presents the testing diagram and a view of the measurement chain.

5.3. Propagation and structure of the floor panel‘s vibration

As a result of the tests conducted, time courses of acceleration changes for vibrations recorded in 3 orthogonal axes: X – horizontally along the vehicle axis, Y – horizontally crosswise the vehicle axis, and Z – vertically and perpendicularly towards plane XY were obtained. The chapter provides an analysis of the vertical vibrations that constitute the main cause of passenger exposure to vibrations. Courses of vertical vibration accelerations at structural points of the floor panel where passengers rest their feet are illustrated in Fig. 5.5.



a) Driver

b) Front passenger

c) Left back passenger (behind the driver)

d) Right back passenger

Fig. 5.5. Recorded courses of vertical vibrations accelerations in the floor panel at points where passengers rest their feet

In order to conduct a preliminary analysis of the frequency components of the signals recorded, their spectra with Fourier transforms application were established. Fig. 5.6 presents sample spectrum of floor panel vibrations.

Basing on the spectral analysis, it was found that the predominant energy content of the signals occurre in a band of up to 200 Hz. Fig. 5.7 illustrates the vibration spectra of the signals recorded.

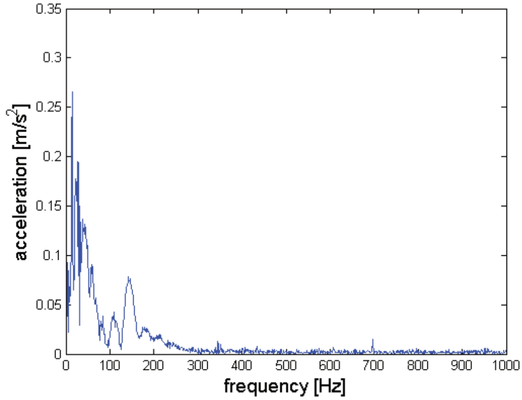
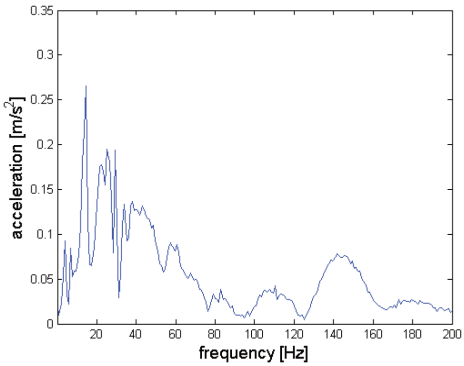
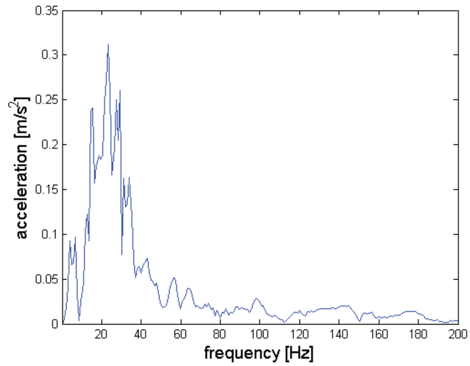


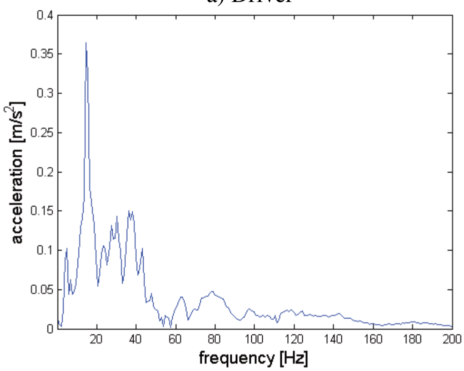
Fig. 5.6. Sample spectrum of floor panel vibrations



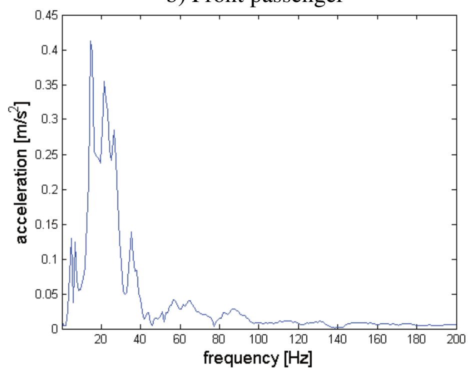
a) Driver



b) Front passenger



c) Left back passenger (behind the driver)



d) Right back passenger

Fig. 5.7. Spectrums of vertical vibrations accelerations in the floor panel at points where passengers rest their feet

Identification of distribution of natural vibration demands the relative phase of all measurement point determining. Fig. 5.8 show the phase shift of accelerations of vertical vibrations in the floor panel at points where passengers rest their feet. The data cursors indicated on left chart presents the time and amplitude of very first amplitude of response on impulse force. The Table 5.5 presents time of local maximum of vibration for measurement points and phase shift between next amplitudes and relative phase shift to the time of first maximum amplitude occurring.

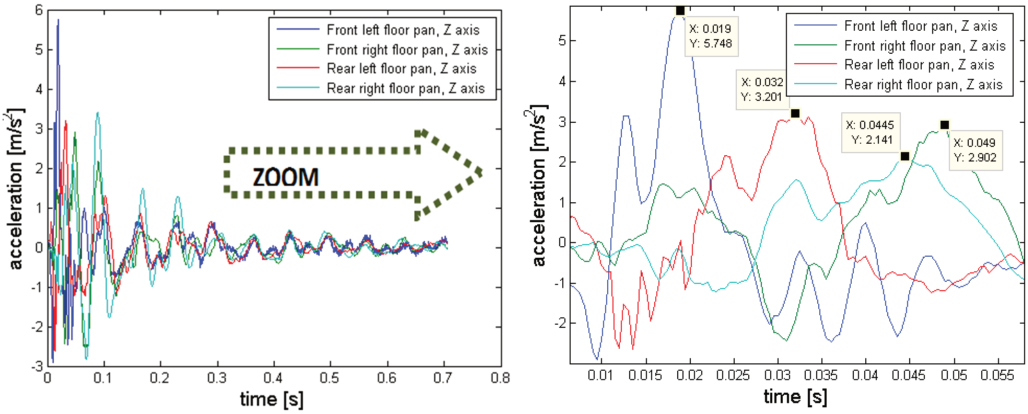
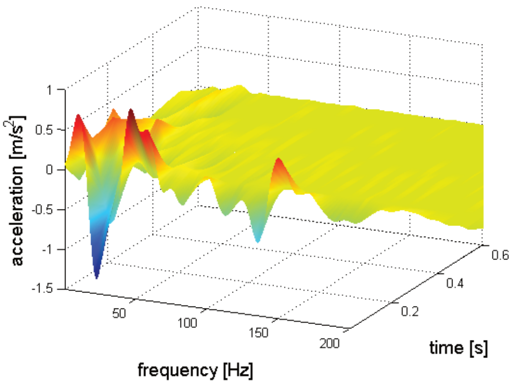
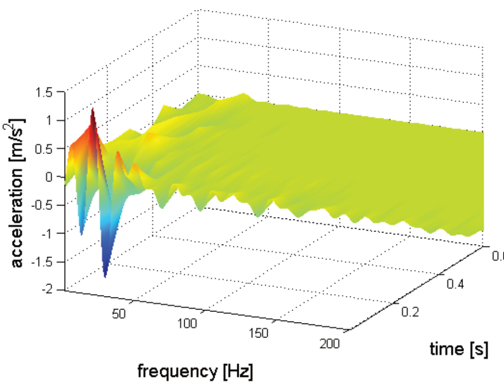


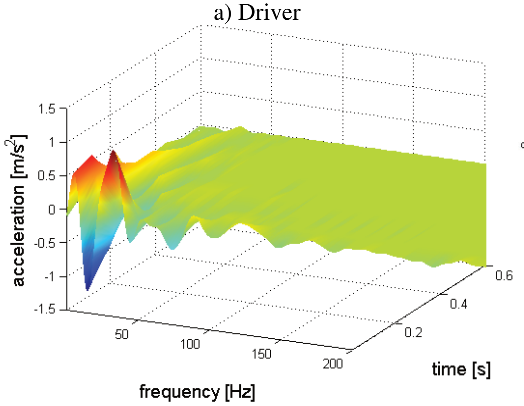
Fig. 5.8. Phase shift of accelerations of vertical vibrations in the floor panel at points where passengers rest their feet



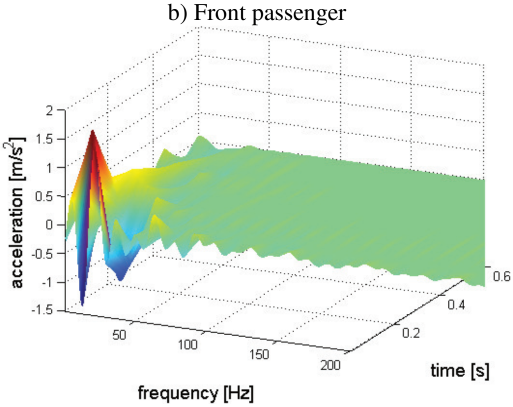
a) Driver



b) Front passenger



c) Left back passenger (behind the driver)



d) Right back passenger

Fig. 5.9. Time-frequency distribution of accelerations of vertical vibrations in the floor panel at points where passengers rest their feet

These vibrations are of non-stationary nature, and therefore, one should observe the distribution of component values of a signal in the domains of time and frequency simultaneously.

For that purpose, the signals were transformed by application of the Short-Time Fourier Transform. The relevant results have been provided in the form of a time and frequency surface of distribution of the vibration signal components at the measuring points examined in Fig. 5.9.

Table 5.5. Phase shift of vibration measured on floor pan

Measurement point	Front left	Front right	Rear left	Rear right
Time [s]	0.019	0.032	0.0445	0.049
Phase shift [s]		0.013	0.0125	0.0045
Relative phase shift [s]		0.013	0.0255	0.03

5.4. Discussion, estimates of the floor panel's natural vibration surface

The above transformations of vibration signals enable accurate analysis of the phenomena taking place. However, a representation of the said characteristics is a multi-element set assuming the form of vectors or matrices. It is for that fact that application of these measures in modelling becomes more difficult. Therefore, one should choose global measures of vibration signal characteristics. A measure commonly applied to determine the energy content of a signal is the root-mean-square value:

$$X_{RM} = \left[\frac{1}{T} \int_{0}^{T} x(t) dt \right]^{1/2} . \tag{5.3}$$

However, bearing the randomness and dynamism of vibrations in mind, it is still not an explicit representation of the signal characteristics. Therefore, it has been proposed for identification and evaluation of the surface of the vehicle floor panel vibrations should be developed basing on several statistical estimators of the vibration signal. It is assumed to enable representation of several signal characteristics in the form of a set of surfaces in a geometrical distribution of vibrations. The surface estimates provided were established basing on the following measures representing accordingly:

– measures of position – absolute mean value and peak-to-peak value,
– measures of dispersion – variance and standard deviation,
– measures of asymmetry and concentration – skewness and kurtosis,
– dimensionless measures – shape factor, peak factor, impulsivity factor and play factor.

Basing on the previous author's research those estimators show some sensitivity on changes of technical condition of suspension elements responding for vibration isolation and shock absorbing [40, 42, 56].

The methodology of determination of the surface estimates for characteristics of the vehicle floor panel vibrations entails determination of a set of global signal measures at specific geometrical points and determination of a surface approximating the distribution of these values on the floor panel. The vibration surfaces thus established are illustrated in Figs. 5.10-5.12.

Basing on the established analysis of the surfaces, one may conclude that assessment and identification of vibrations purely relying on the root-mean-square value, being the most uniform one, does not allow for defining the natural vibration surface in an appropriate manner. The changes observed in distributions of other values of the measures of position, dispersion and asymmetry imply considerable differences in the courses of vibrations at the measuring points analysed. The estimates of surfaces determined as functions of dimensionless coefficients show the changes occurring in the point distribution of floor panel vibrations.

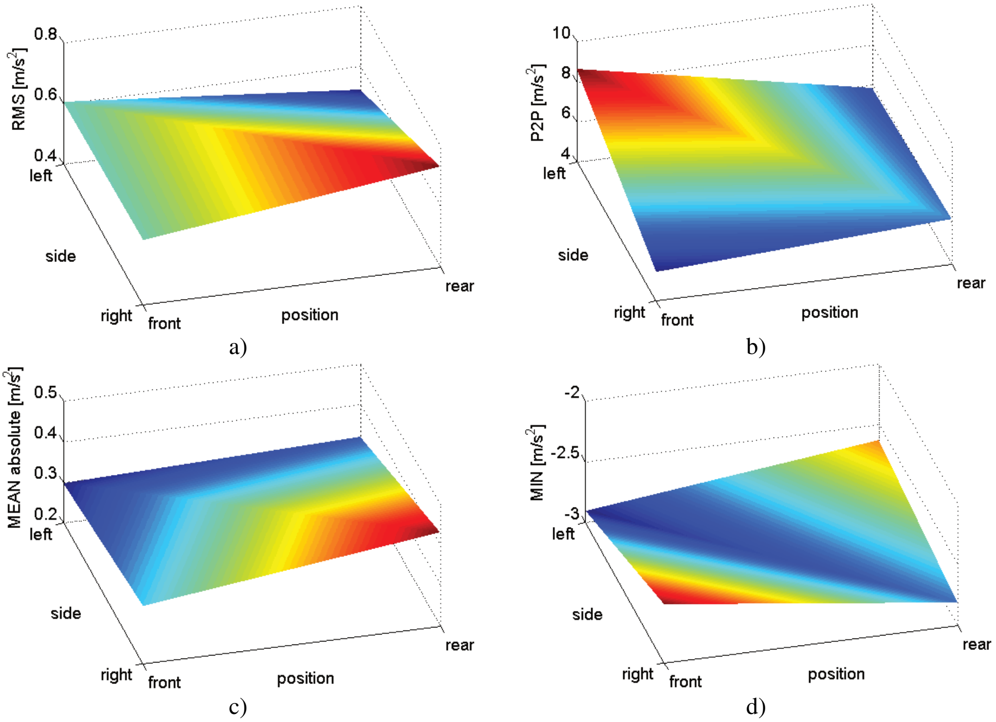


Fig. 5.10. Global vibration surface estimates as functions:
a) value of X_{RMS}, b) peak-to-peak value, c) absolute mean value, d) minimal value

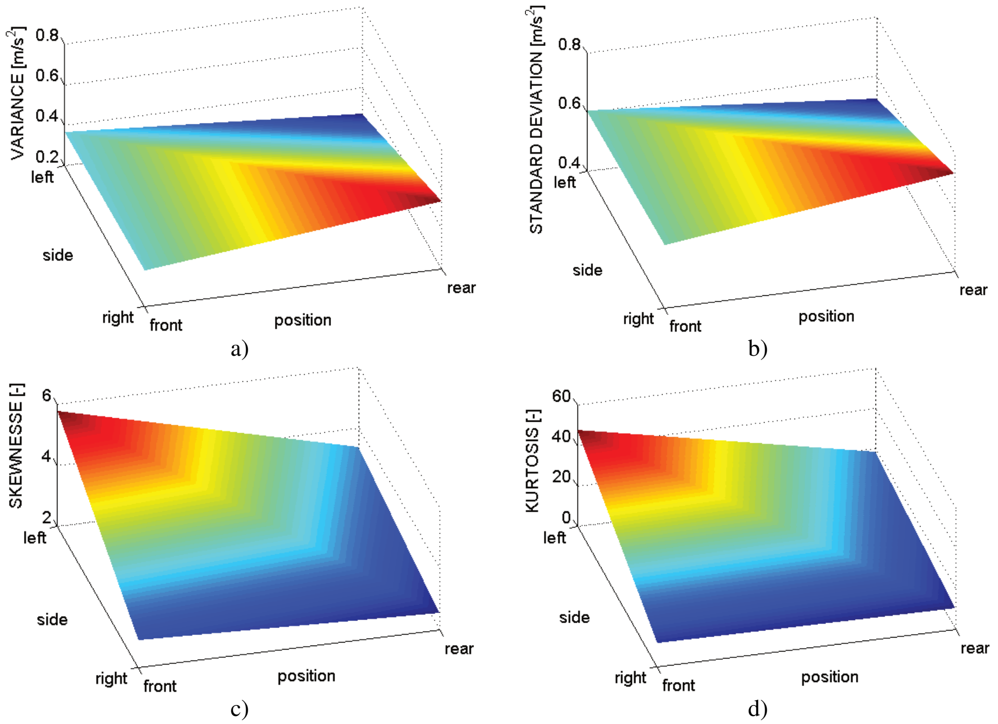


Fig. 5.11. Dispersion and surface asymmetry estimates as functions:
a) variance, b) standard deviation, c) skewness, d) kurtosis

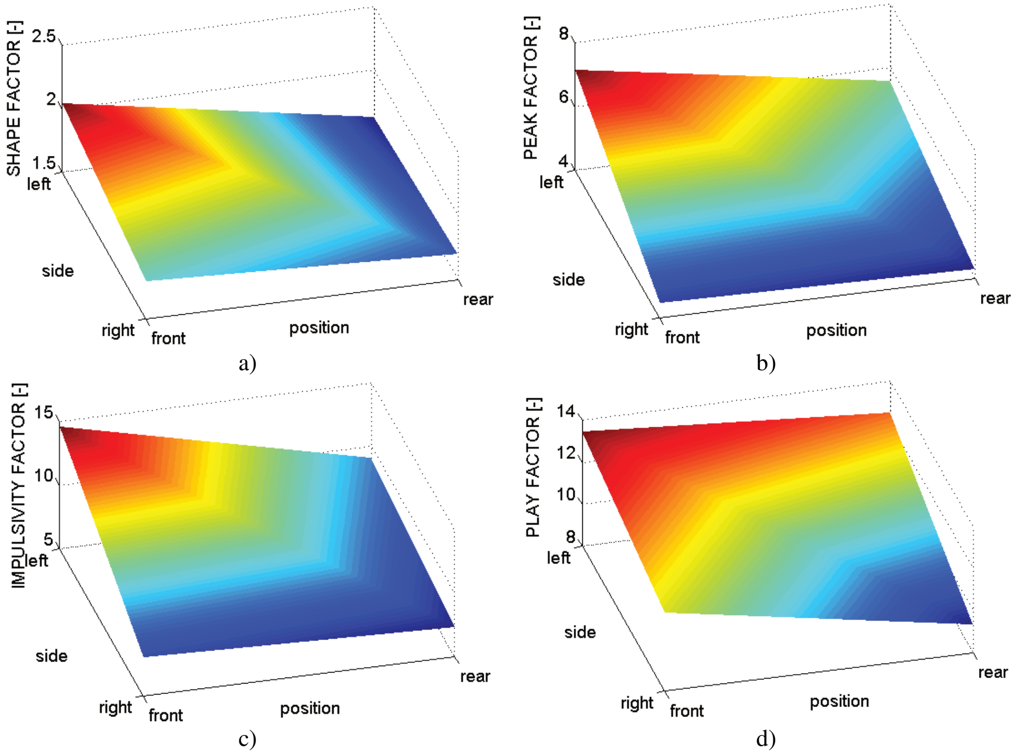


Fig. 5.12. Estimates as functions: a) shape factor, b) peak factor, c) impulsivity factor, d) play factor

The presented methods, based on stochastic nature of signals, allows to observe the single vibration signal (time realization) as series of distribution of some estimators of the vibration. This kind of approach allows to define the vibration phenomena as vector of many statistical estimators described series of vibration values changes in time. Furthermore, a statistical analysis of the vibration courses being recorded was conducted as well, leading to determination of empirical surface estimates for natural vibrations, which enabled the vibrations to be assessed with regard to the geometrical position on the floor panel.

The studies performed are essentially of preliminary nature, and hence they require supplementation and further verification.