3. Analysis of vibration propagation into vehicle‘s structure

3.1. Propagation of vibration in transport system

The analysis of the way in which the structure responds to the forcing, and in particular the way the vibration propagates from a source into distant parts of the system allow to research on vibration phenomena in means of transport. There is more than one approach to the theory of structural vibration, and it is useful at the outset to recognise a basic division into three general classes. These can be characterised as the ‘waves’, ‘modes’ and ‘rays/wavepackets’ approaches. All three have advantages for particular types of problem [11, 73, 97].

Transport system consists of infrastructure and suprastructure elements. As the sources of vibration the suprastructure elements, as means of transport, have to be considered. Means of transport generate the vibration which are propagating into the humans, buildings and environment via structure, air and combination of both (Fig. 3.1).

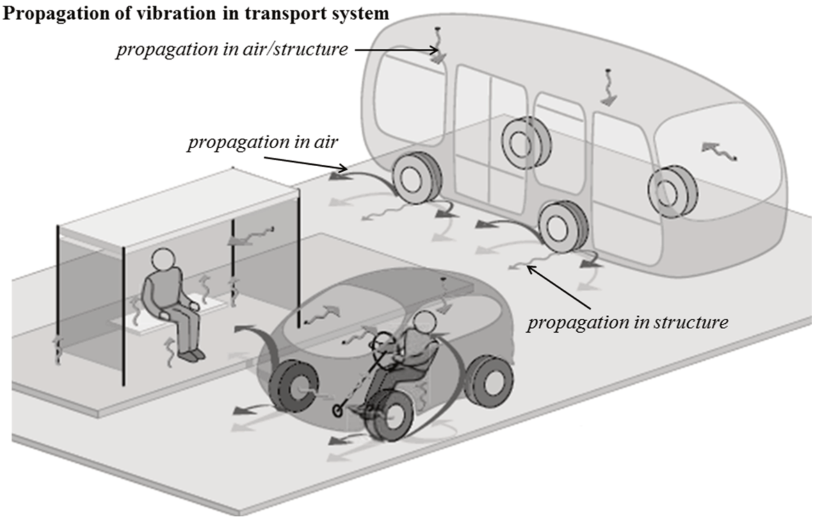

Fig. 3.1. Propagation of vibration in transport system

When the frequency of force usually acting on a vehicle matches or exceeds its natural oscillations, a vibration resonance is caused and the amplitude is increased, resulting frequent failures of the suspension and other elements of vehicle. During the drive it can cause wheels lose grip with the ground in effect vehicle becomes uncontrolled. Thus the vibration transfer from the road to the occupants can be illustrated as transmittance by multi-filter element. The excitation is given by the wheel movement caused by the road roughness. First filtering of vibration occurs as result of stiffness and damping properties of tire. Second and third will be results of stiffness and damping properties of suspension and car-body. The last filter is biodynamics properties of human body. These path of propagation determined the human exposure to vibration and feeling of discomfort (Fig. 3.2).

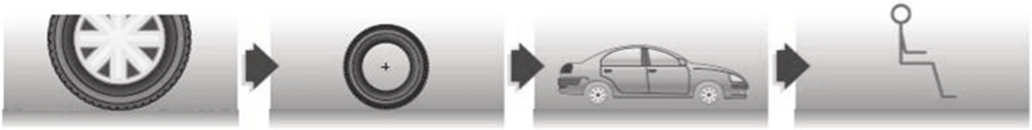

Fig. 3.2. Vibration transfer from road into the human in vehicle

3.2. Vibration – stochastic wave propagation

Vibration related phenomena, like all physical phenomena, should always be considered as random processes, even in deterministic models. Hence the identification and quantitative characterisation require that randomness should be taken into account each time. For the sake of proper analysis and description of random phenomena, one recognises the relevant regularities in order to complete a mathematical notation. In mechanics and material sciences, such an approach enables supplementation of imperfect equations and mathematical functions which then make it possible to model real phenomena. Direct outcomes of this methodology include such notions as entropy (defined by L. Boltzmann in 1866), statistical mechanics and Gibbs distributions (1903), a probabilistic model of Brownian motions (Einstein-Smoluchowski, years 1905-1906) and Langevin equations (formulated as early as in 1908) entailing random noise, constituting the origins of the entire contemporary stochastic dynamics. A true breakthrough in the analysis of random phenomena, regardless of the field of application, was Kolmogorov's theory of probability developed in 1933 to describe regularity in the scope of random phenomena. Numerous methods have been formulated for the sake of examination of random phenomena changing in time (theory of stochastic processes) and in space (random field theory and stochastic geometry), and recommendations have been provided with regard to the manner of extracting and analysing information contained in numerical data from observations and empirical tests (mathematical statistics) [177].

The necessity to complement real studies and modelling with stochastic methods in mechanics is particularly important in the analysis of dynamic processes. The foregoing is mainly due to the fact that a decided majority of external input functions affecting machines is characterised by an irregular and random course in time. An example of such input functions is the impact of road surface irregularities on structures of automotive vehicles. Bearing in mind other vibration sources affecting a moving vehicle, such as the engine, the power transmission system or aerodynamic phenomena, it occurs that correct analysis and modelling of vehicle vibrations is a problem of largely stochastic nature. It requires application of the theory of stochastic processes as well as the stochastic wave and vibration theory. In terms of modelling and optimisation of vehicle design, one must take random impacts of input functions into consideration. The mathematical and numerical methods applied in engineering practice should be based on stochastic differential equations describing the way a structure behaves.

An overall mathematical model of technical systems subject to random input functions changing in time is a system of stochastic equations which may be represented in the following vector form:

$$\frac{dX(t)}{dt} = F(X,t) + G(X,t)h(t,g), \tag{3.1}$$

$$X(t_0) = X_0(g). \tag{3.2}$$

In the Eq. 3.1 the $X(t) = [X_1(t), \ldots, X_n(t)]$ characterises the state of the system at instant t, $F(X,t)$ is a regular motion component, whereas $G(X,t)h(t,g)$ models random fluctuations, and $h(t,g)$ is a suitable stochastic process characterising a random external or internal impact. Symbol g implies that the suitable quantity is random.

A stochastic dynamics problem thus defined consists in formulating equations of dynamics $dX(t)/dt$ relevant to the given phenomenon being studied, assigning appropriate stochastic

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process $h(t, g)$ characterising the random input functions and estimating its characteristics based on empirical data.

Modelling of vehicle structure vibrations requires that all linear and non-linear phenomena should be taken into consideration, both in the analysis of external impact and of internal relationships (e.g. suspension characteristics) [13, 15, 75, 113, 165, 182, 183].

The contemporary stochastic approach extends as far as to the observation of the structure and properties of various material media and structural materials. Assuming a homogeneous material continuum, providing grounds for classical material theories (e.g. theories of elasticity, plasticity etc.), does not reflect the complexity and inhomogeneity of real media and materials. Models and solutions based on classical theories are too simplified as regards the complexity of the deformation process for a number of real media. Depending on the thermomechanical working process, macroscopic mechanical properties may differ. A major scientific issue at the moment is an attempt to characterise and describe in mathematical terms complex and random material microstructures. In order to find the relevant solution, one needs both synthesis and integration in the spheres of random field theory, stochastic geometry and geometrical (spatial) statistics.

Since the loads affecting a vehicle structure essentially change in time, also stresses are of variable nature, which causes progressive changes in the material structure, i.e. degradation. Its effect is a system's decreasing capacity to transfer the loads assumed. As for vibrating systems, one mainly speaks of degradation in terms of rigidity of structural components caused by accumulation of fatigue failure. Therefore, a model should entail the system dynamics in the function of its internal degradation. Such a model will comprise a correlation between stochastic dynamics and the degradation occurring in time and caused by vibrations [176, 178].

A confirmation of how significant random dynamics of loads is from the perspective of technical degradation may be sought in the known case of buckling of an ideally rectilinear pole. For static load, the prerequisite of buckling is satisfied after Euler's critical load is exceeded. However, if the load contains components variable in time, then the buckling may occur even though the total load does not exceed Euler's static critical load at any time during the impact.

3.3. Propagation of vibrations and vibroacoustic diagnostics

Analysis of vibration related phenomena is a solution commonly applied in Structural Health Monitoring (SHM) systems. One may distinguish between two major approaches to detection and positioning of defects in SHM systems, i.e. global [191] and local [161] methods. The global methods rely on measurements of a structure and are mainly based on vibrations up to 1 kHz. The local ones consist in inducing phenomena sensitive to selected defects, primarily within small predefined areas (systems). The input functions used for the sake of these analyses are predominantly of high-frequency nature [190]. Among the methods mentioned, one may also speak of those based on elastic wave propagation. It makes it possible to analyse a broad band of ultrasonic frequencies, i.e. from 0.2 to 30 MHz and higher. Standard ultrasonic techniques are based on application of two kinds of input functions: resonant and pulse ones [5, 19]. The resonant techniques make use of narrow band input functions, whereas the pulse techniques are characterised by broad band inputs functions [8, 12, 14]. Grounds for this methodology are provided by the phenomenon of ultrasonic pulse propagation in the structure as well as its interactions with a potential defect. The ultrasonic wave frequency and length is determined as follows:

$$\lambda = \frac{c}{f}, \tag{3.3}$$

where: λ is the wave length and c is the wave velocity in the material.

If wave velocity is constant, wave length will decrease as frequency increases, which implies that the capacity to detect a defect of small dimensions increases as the frequency increases. On the other hand, one of the phenomena occurring in materials is that wave amplitude changes along with the distance from the point of its generation. It declines in the course of propagation caused by damping. Ultrasonic wave damping is a function of frequency, i.e. if wave frequency increases, its propagation distance declines. On frequencies with wave lengths equalling the structure grain dimensions, there is an additional phenomenon of wave scattering occurring at the grain boundary. Contemporary techniques enable structure testing at frequencies exceeding 50 MHz. It makes it possible to detect defects of diameters smaller than 0.1 mm. Unfortunately, in certain cases it is impossible to observe such high frequencies, just to mention an example of materials of high attenuation or those of large grain diameter (e.g. stainless steel) [6].

Two kinds of waves may propagate inside an elastic body, namely the transverse and longitudinal ones. Combining longitudinal and transverse vibrations make the vibrating point perform trajectories described by the Lissajous curves. Elastic waves propagating in solid bodies are channelled through boundaries of the medium in which they propagate. When applying the concept based on propagation of elastic waves, one strives to solve a wave equation for an elastic linear wave having assumed appropriate boundary conditions representing the geometry of the object studied. It is a classical problem of seeking eigenvalues.

While solving the wave equation for displacements in directions x and z, one obtains the following [181]:

$$\xi = A_x F_x(z) e^{i(t\omega - kx)}, \tag{3.4}$$

$$\xi = A_z F_{zx}(z) e^{i(t\omega - kx)}. \tag{3.5}$$

The foregoing equations describe the phenomenon of wave propagation in direction x for wave length of $2\pi/k$ and frequency of $\omega/2\pi$. The displacement is a function of variables x, z and t.

The main assumption made when taking advantage of the wave phenomenon to detect defects by means of surface waves is the fact that a wave introduced into a structure will change its parameters (e.g. velocity, amplitude) after it encounters an obstacle (diffraction).

Measures of defect detection in the function of time are the time of flight (TOF) and the energy dissipation factor. If it is not possible to measure a model signal (input function), one must apply reverse algorithms (time reversal) based on spectral transformations and the transfer function [113, 163, 164].

One of examples of a low-frequency method is a modal filter. It is used to decompose a system's response signal into components connected with individual forms of natural vibrations.

Vibroacoustic diagnostics, based on the analysis of vibration or acoustic signals perceived as residual processes of non-invasive nature, is becoming more and more important in this respect. The scope of its application as well as the applicability of methods in numerous diagnostic systems also results from the capabilities of advanced methods of signal analysis and identification of numerous characteristics of technical condition [44, 57, 60, 62, 81, 86, 108, 118].

3.4. Analysis and comparison of the vibration dynamics for the chosen points in the vehicle structure

As the first experimental investigation on vibration propagation into the vehicle's structure the research on dynamics of vibration distribution in different location in vehicle suspension, car-body and floor panel have been conducted. The first stage of the result analysis envisaged that dynamics of the vehicle vibration phenomena occurring in points of the structure where vibrations penetrated the human organism should be assessed. The section provides results of an analysis of general vibrations recorded on the floor panel in locations where passengers rest their feet. For the sake of the signal transformation, the FFT (Fast Fourier Transform) was applied, as it enabled determination of the Fourier spectra of signals.

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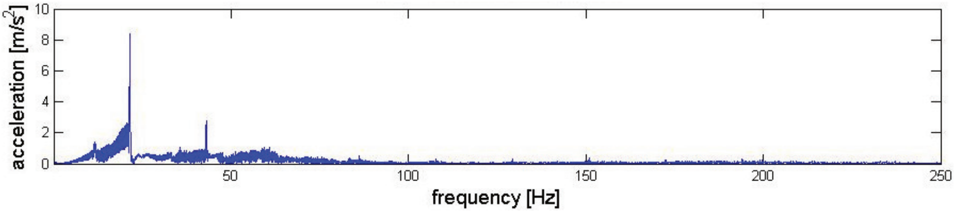
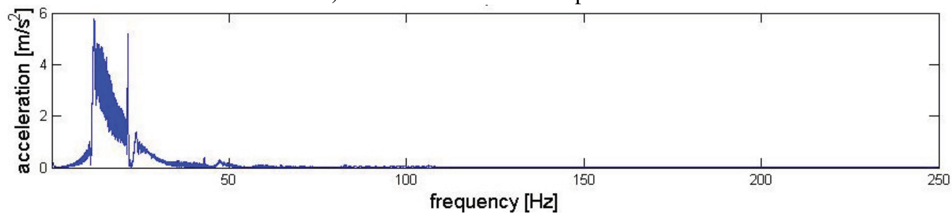
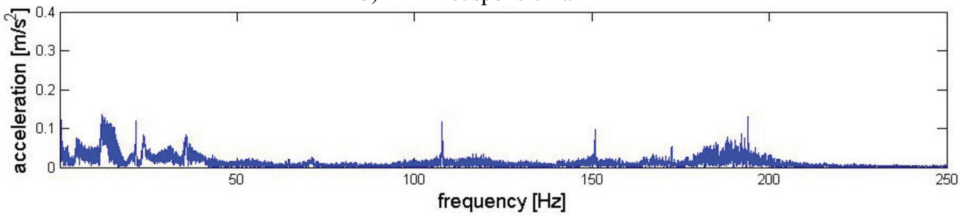


a) FFT – vibration exciter plate

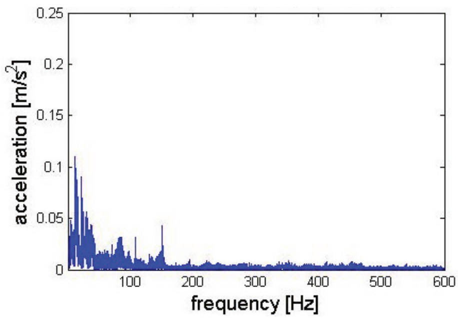


b) FFT – suspension arm

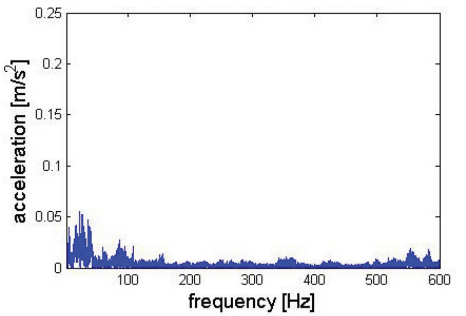


c) FFT – upper mounting of shock absorber

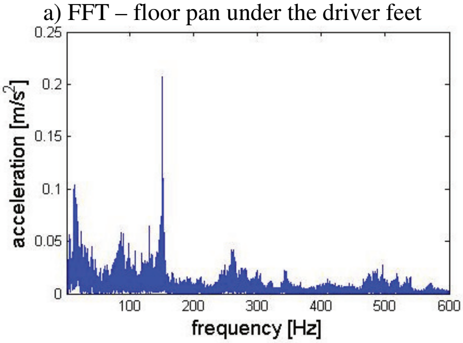
Fig. 3.3. Spectrums of the vibration signals recorded on exciter plate and suspension elements

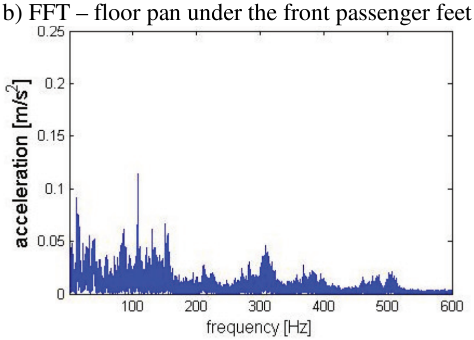


a) FFT – floor pan under the driver feet



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. 3.4. Spectrums of the vibration signals recorded on the floor panel

The comparison of the vibration dynamics for the chosen points in the vehicle structure enables evaluation of the dominant frequency components. It can be observed that for those locations in the vehicle structure there are different frequency components carrying most vibration energy values. Sample spectra of the signals recorded are presented in Figs. 3.3 and 3.4.

Basing on the vibration spectrum of the exciter plate, suspension arm and upper mounting of shock absorber analysis and comparison the evaluation of the damping properties can be done. The best results of the evaluation can be obtained by the analysis of the resonance of the unsprung masses (ca. 10-12 Hz). The presentation of the analysis is presented in upper chart in Fig. 3.5.

The evaluation of the differences in the vibration dynamics for chosen locations in the vehicle structure at the floor panel were conducted from an analysis of the signals spectrum for next frequency bands (Figs. 3.6-3.9).

This brief of result presentation shows the propagation of the vibration from unsprung masses excited by the wheel movement into sprung masses, i.e. car-body and floor panel. The comparison and propagation properties are illustrated in terms of vibration dynamics changes as spectrums of the signals recorded in chosen location of vehicle.

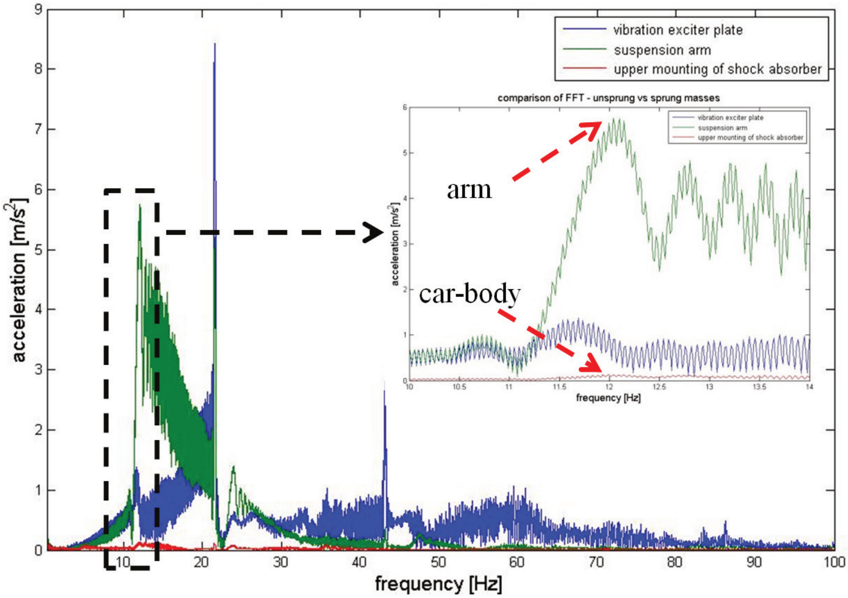


Fig. 3.5. Comparison of spectrums of unsprung and sprung masses (evaluation of the damping properties)

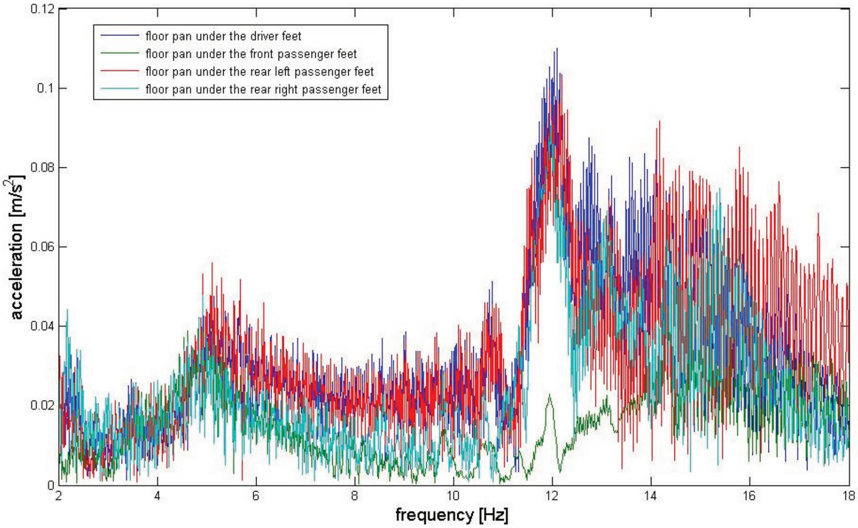


Fig. 3.6. Comparison of floor panel vibration dynamics, frequency band 2-18 Hz

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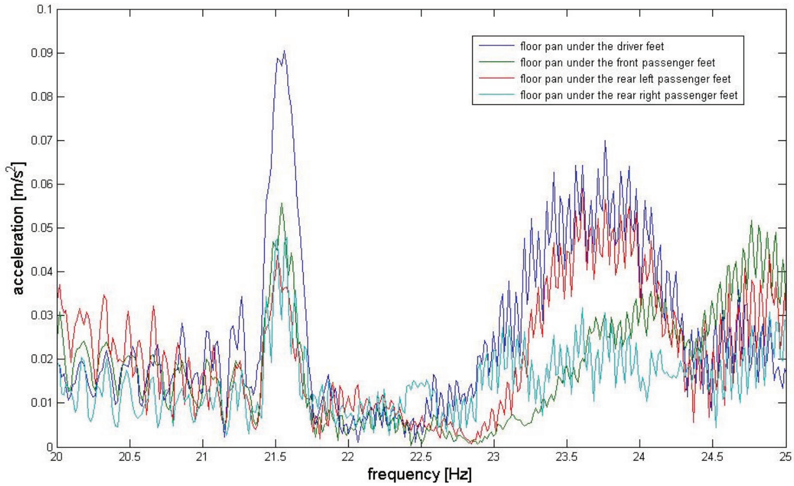

Fig. 3.7. Comparison of floor panel vibration dynamics, frequency band 20-25 Hz

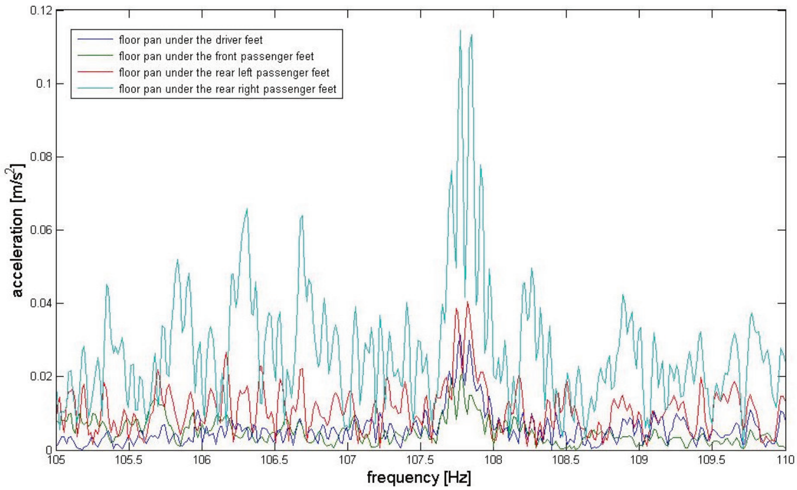

Fig. 3.8. Comparison of floor panel vibration dynamics, frequency band 105-110 Hz

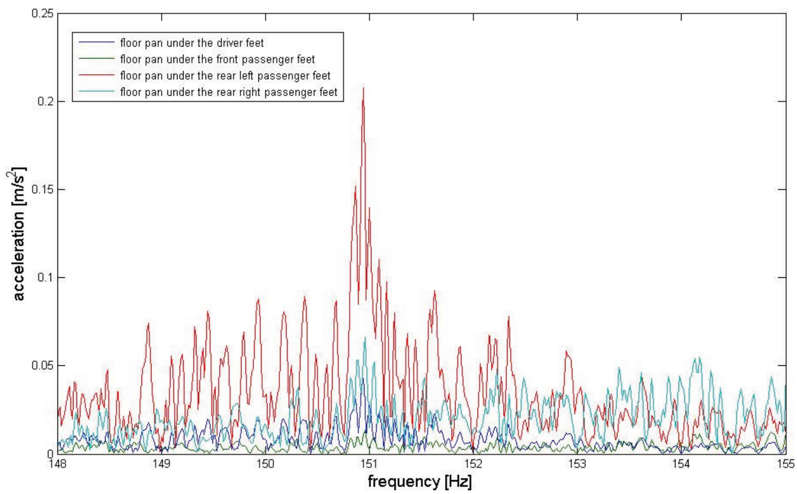

Fig. 3.9. Comparison of floor panel vibration dynamics, frequency band 148-155 Hz