15. Identification of vibration components of ride vehicle caused by road roughness

The road unevenness determines the ride comfort, possible damage to goods, and vehicle wear and safety on one hand, and pavement damage and environmental noise and vibrations on the other hand. The study of traveling vehicle is the case of multiple sources of vibration interacting on vehicle and transfer into driver and passengers. In order to examine vibration related phenomena occurring in a moving vehicle or a stopped one with its engine in operation, identification of vibration sources should be done in the first place. The sources of vibration in a vehicle are dynamic forces but also free vibrations as well as forced, self-induced, parametrical, non-parametrical, random and stationary ones, all generated by the driving unit, the power transmission system and the road [41].

For the purpose of analysis of exposure to WHV and vibration absorption or isolation to the vehicle cabin the identification of different vibration sources should be performed. Thus the dedicated systems can be developed for vehicle vibration control and minimisation. The chapter presents simple method for identification vibration components caused by interior sources, i.e. engine and power transmission system and external sources as forces excited by the ground unevenness.

15.1. Ride vehicle vibration generated by the ground unevenness

Ride vehicle vibration results from interaction of a vehicle with: road roughness, aerodynamic forces, engine and driveline dynamics and tire/wheel assembly imbalance dynamics. All of these sources can induce vehicle body vibration and noise. The suspension system has conflicting demands, as isolation of the car-body from the forces generated by the ground unevenness and control of tire normal forces on the ground, thus the tires will have traction and lateral control (road holding).

The road roughness is the term used for deviations in a road surface compared to a real plane, which affect vehicle movement, ride quality, dynamic loads, drainage and winter maintenance. IRI is the most common metric to describe road roughness. It has become recognized as a general purpose roughness index and is strongly correlated to most kinds of vehicle responses that are of interest. The key importance of IRI is that road profiler users have shared experiences measuring IRI. Roughness is measured as the accumulated suspension stroke normalized by the total travelled distance. IRI is usually presented in engineering units such as mm/m, m/km or inc/mile. It is highly correlated with acceleration of vehicle passengers (ride quality) and tyre load (vehicle controllability). Roads may have different names and visual characteristics around the world but researchers can compare vibration analyses results for roads with similar IRIs [146, 168].

Thus the ground excitation is very important. The description of road surface profile can be very helpful. The wave number of the road γ, is a measure of the rate of change with respect to distance or length. In space, we relate wave number γ, to wavelength, λ:

$$\lambda = \frac{2\pi}{\gamma}. \tag{15.1}$$

The spatial cycle of wave length λ, is traversed by a vehicle with constant velocity v during a period T, given by:

$$T = \frac{\lambda}{v}. \tag{15.2}$$

If we use the relation between period T and frequency ω, we can write:

$$\omega = \left[\frac{2\pi}{\lambda}\right] v = \gamma v \Rightarrow v = f\lambda. \tag{15.3}$$

Thus the relation between frequency and forward vehicle velocity allows to calculate the frequency using the wavenumber, based description of a road profile, and velocity of the vehicle.

To consider the vehicle ride dynamics in terms of vibration the 3-directional movement has to be defined. Thus we can separate the roll (around the X – longitudinal axis), pith (around the Y – lateral axis) and bounce (in the Z – vertical axis) motions of the car and especially car-body. Understanding pitch and bounce dynamics can provide insight into how the vehicle responds to a road profile. Bounce motion can be excited when the road has a wavelength equal to wheelbase (WB) and for much longer multiples and shorter with integer multiples. Pitch motion can be excited by wavelengths that are twice the WB, and by shorter wavelengths that are odd integer multiples of this value.

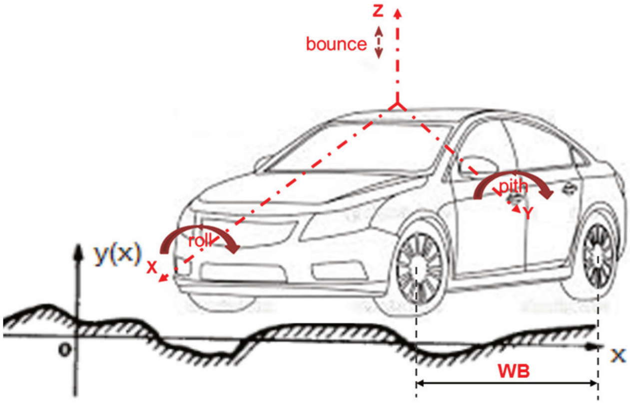


Fig. 15.1. Ride vehicle movement generated by the ground unevenness

15.2. Method of identification of vibration components of riding vehicle caused by the road roughness

The identification and separation of vibration components of riding vehicle caused by the powertrain system and road roughness requires large scope of the research included tests in laboratory and on the road. The same conditions of engine rotational speed and gear ratio of gearbox have to be conducted during each road test and laboratory research. For the elimination of the weather conditions the road tests were conducted in a tunnel. Thus allows to eliminate the wind forces from analysis. The section of the road was without any turns and equal rise level with angle between start and end of the road section ca. zero degree. Thus the lateral inertia forces and rolling resistance caused by hills have been minimalized.

For the purpose of proper identification of vibration transferred to car-body from road roughness it is necessary to provide measurement in multiple points located on vehicle construction. Human vibration perception depends on area and place of contact of human organism and vibrating machine. It depends also on dynamics of the vibration and exposure time. The identification of vibration transfer from road roughness to car-body in driving car was performed as the analysis of transformation of signals in time and frequency domains. This method of vibration signal processing allows to observe changes of the energy in selected frequency bands and correlate it with time.

15.3. Identification of vibration components caused by the powertrain system and road roughness

Due to the number of vibration sources affecting on motion of vehicle the method of comparison analysis have to be conducted. The scope of the research allows to assume that the dynamic responses of car-body are results of vibration sources i.e.: engine and powertrain system, road roughness impact on moving vehicle and aerodynamics resistances without wind forces.

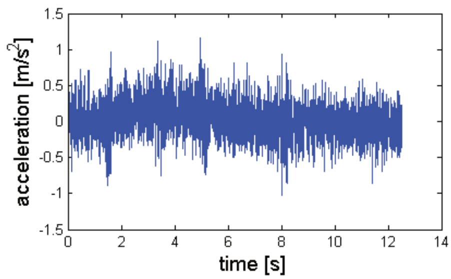
First the comparison of time realization of vibration was collected in Figs. 15.2-15.4. It enables observation of vibration energy changes for the vehicle moving at 50 km/h (Gear No. 3/2500 rpm) and 70 km/h speed (Gear No. 5/2300 rpm) versus vehicle under laboratory test with the same gear number and engine rotational speed.

The chapter presents results of directional distribution of vibration of floor panel in location of driver feet as major WBV penetration surface into driver.

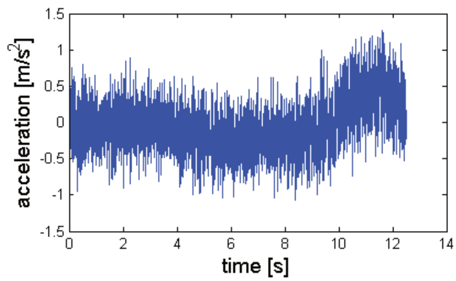
Basing on the analysis of directional distribution of vibration it was assumed that impact of aerodynamics resistances is much less important than road roughness in terms of generation of vibration in dynamic response. Thus it was assumed that it may be negligible. The dynamic components caused by the ride on the road roughness can be identified by the comparison of spectrums and differential spectrums of moving vehicle and laboratory tested vehicle at the same gear ratio and engine rotational speed, expressed from equation:

$$F_d(\omega) = \left|F_r(\omega) - F_g(\omega)\right|, \tag{15.4}$$

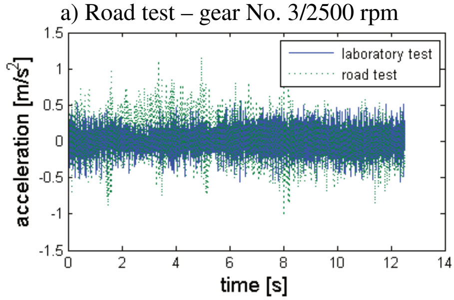
where: $F_r(\omega)$ – Fourier transform of vibration of riding vehicle, $F_g(\omega)$ – Fourier transform of running gear vibration.



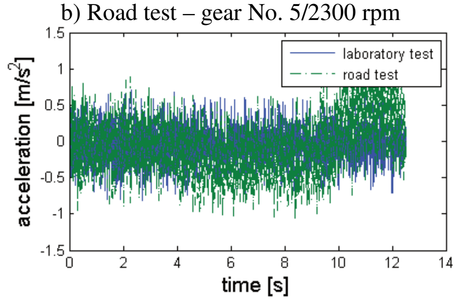
a) Road test – gear No. 3/2500 rpm



b) Road test – gear No. 5/2300 rpm

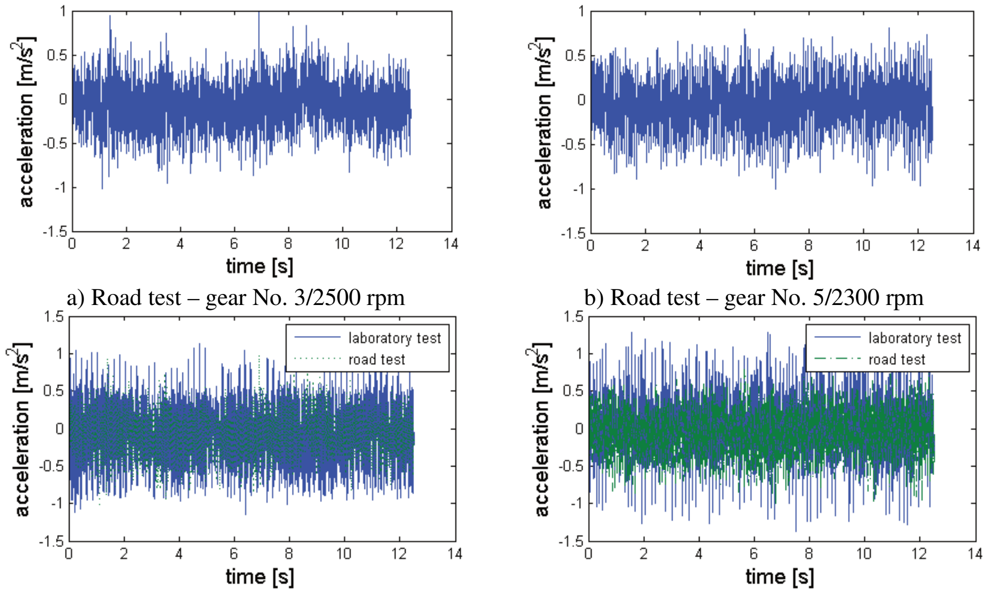


c) Laboratory test vs. road test – gear No. 3/2500 rpm



d) Laboratory test vs. road test – gear No. 5/2300 rpm

Fig. 15.2. The comparison of longitudinal vibration of vehicle moving at 50 km/h and 70 km/h speed versus laboratory tested vehicle at the same gear ratio and engine rotational speed (floor panel in location of driver feet)



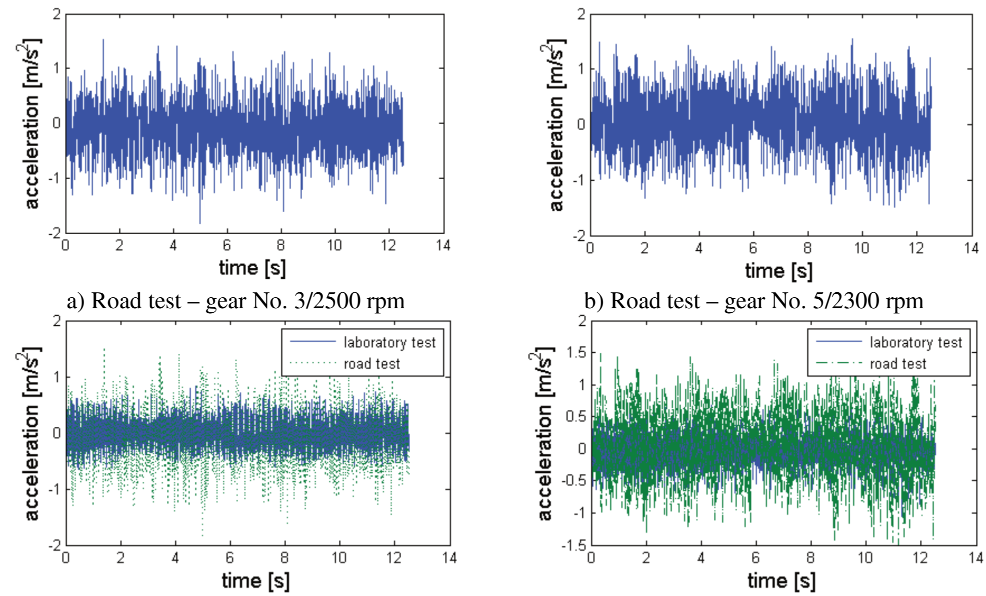
a) Road test – gear No. 3/2500 rpm

b) Road test – gear No. 5/2300 rpm

c) Laboratory test vs. road test – gear No. 3/2500 rpm

d) Laboratory test vs. road test – gear No. 5/2300 rpm

Fig. 15.3. The comparison of lateral vibration of vehicle moving at 50 km/h and 70 km/h speed versus laboratory tested vehicle at the same gear ratio and engine rotational speed (floor panel in location of driver feet)



a) Road test – gear No. 3/2500 rpm

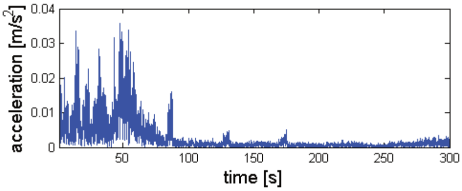
b) Road test – gear No. 5/2300 rpm

c) Laboratory test vs. road test – gear No. 3/2500 rpm

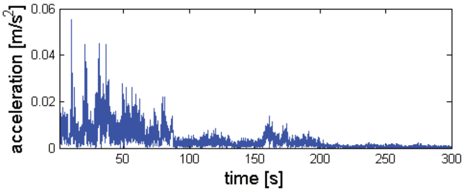
d) Laboratory test vs. road test – gear No. 5/2300 rpm

Fig. 15.4. The comparison of vertical vibration of vehicle moving at 50 km/h and 70 km/h speed versus laboratory tested vehicle at the same gear ratio and engine rotational speed (floor panel in location of driver feet)

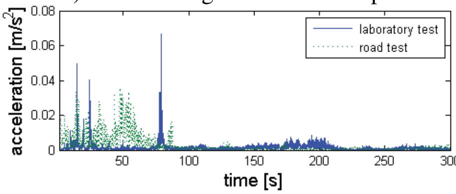
For the analysis of structure of vibration the TFR of the signals of moving vehicle and laboratory tested vehicle at the same gear ratio and engine rotational speed are presented in Figs. 15.8-15.10.



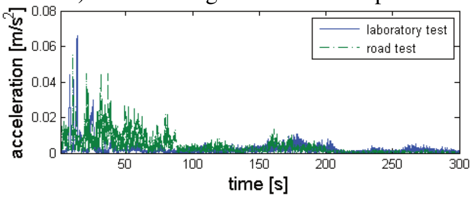
a) Road test – gear No. 3/2500 rpm



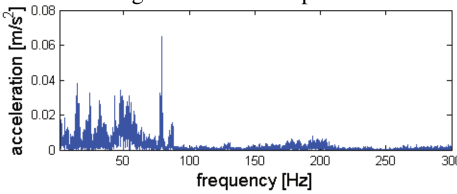
b) Road test – gear No. 5/2300 rpm



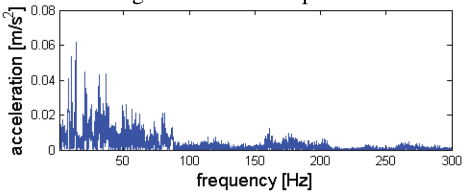
c) Laboratory test vs. road test – gear No. 3/2500 rpm



d) Laboratory test vs. road test – gear No. 5/2300 rpm

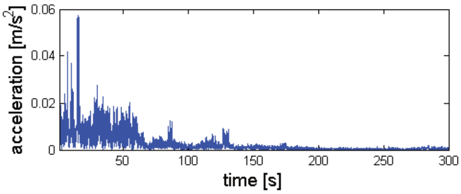


e) Differential spectrum of laboratory test and road test – gear No. 3/2500 rpm

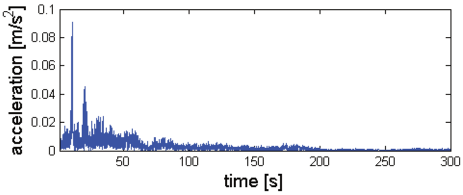


f) Differential spectrum of laboratory test and road test – gear No. 5/2300 rpm

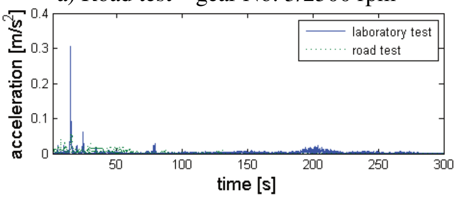
Fig. 15.5. The comparison of spectrums and differential spectrums of longitudinal vibration of vehicle moving at 50km/h and 70km/h speed versus laboratory tested vehicle at the same gear ratio and engine rotational speed (floor panel in location of driver feet)



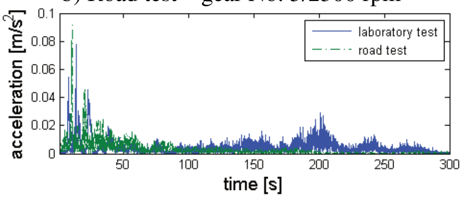
a) Road test – gear No. 3/2500 rpm



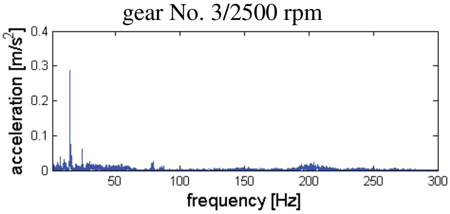
b) Road test – gear No. 5/2300 rpm



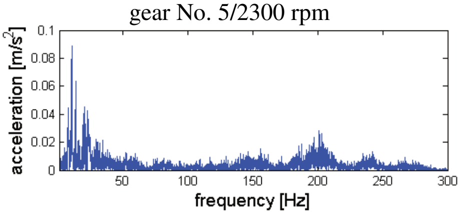
c) Laboratory test vs. road test – gear No. 3/2500 rpm



d) Laboratory test vs. road test – gear No. 5/2300 rpm

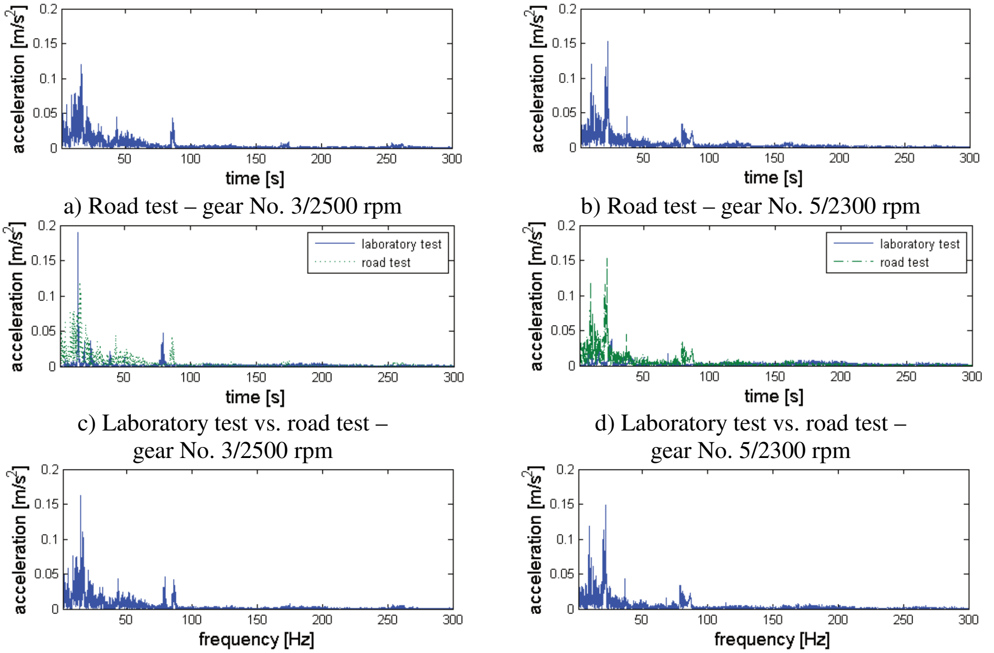


e) Differential spectrum of laboratory test and road test – gear No. 3/2500 rpm



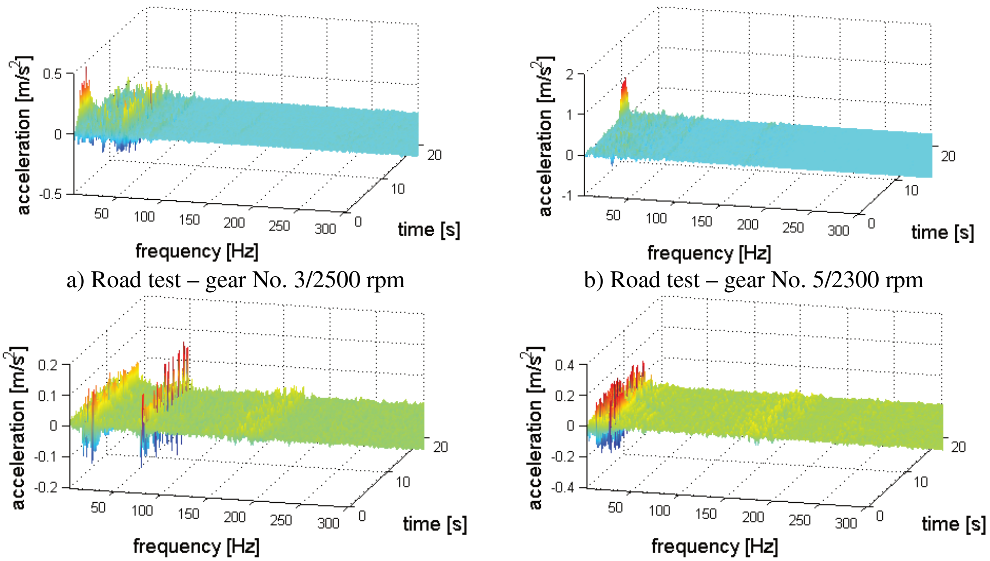
f) Differential spectrum of laboratory test and road test – gear No. 5/2300 rpm

Fig. 15.6. The comparison of spectrums and differential spectrums of lateral vibration of vehicle moving at 50 km/h and 70 km/h speed versus laboratory tested vehicle at the same gear ratio and engine rotational speed (floor panel in location of driver feet)



a) Road test – gear No. 3/2500 rpm
b) Road test – gear No. 5/2300 rpm
c) Laboratory test vs. road test – gear No. 3/2500 rpm
d) Laboratory test vs. road test – gear No. 5/2300 rpm
e) Differential spectrum of laboratory test and road test – gear No. 3/2500 rpm
f) Differential spectrum of laboratory test and road test – gear No. 5/2300 rpm

Fig. 15.7. The comparison of spectrums and differential spectrums of vertical vibration of vehicle moving at 50 km/h and 70 km/h speed versus laboratory tested vehicle at the same gear ratio and engine rotational speed (floor panel in location of driver feet)

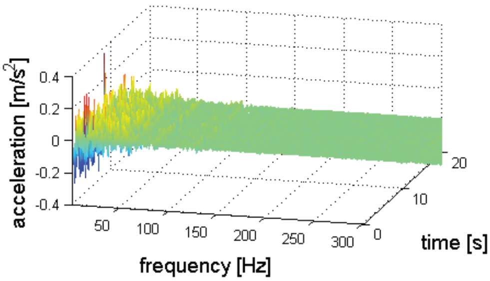


a) Road test – gear No. 3/2500 rpm
b) Road test – gear No. 5/2300 rpm
c) Laboratory test – gear No. 3/2500 rpm
d) Laboratory test – gear No. 5/2300 rpm

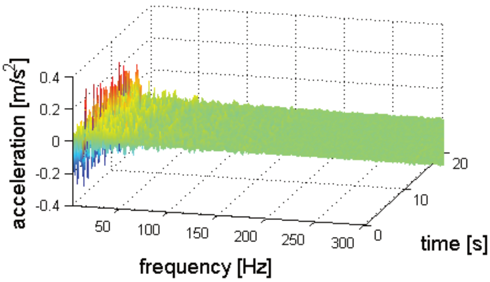
Fig. 15.8. The comparison of TFR of longitudinal vibration of vehicle moving at 50 km/h and 70 km/h speed versus laboratory tested vehicle at the same gear ratio and engine rotational speed (floor panel in location of driver feet)

Analysis of distributions of vibration in time, frequency domains and its TFR allows to identify all components of the vibration caused by the road roughness and powertrain system. These presentations enable observing the time of excitation on defined frequencies. For the comparison of total energy of vibration transferred into the human organism the distribution of estimators defined in previous chapters are collected in Fig. 15.11.

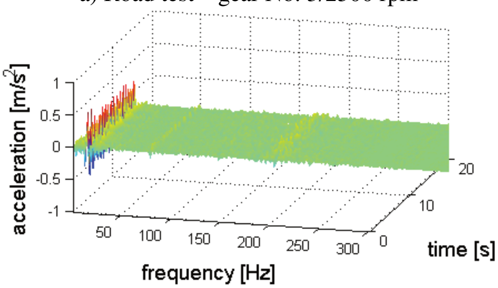
The chapter presents some results of identification of structure and directional distribution of vibration transferred to car-body from road roughness.



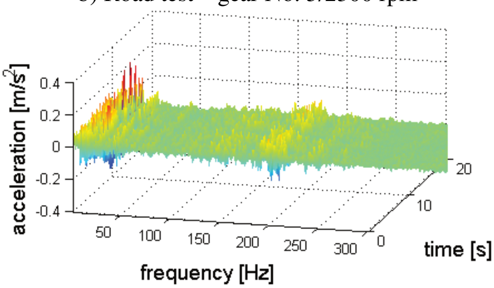
a) Road test – gear No. 3/2500 rpm



b) Road test – gear No. 5/2300 rpm

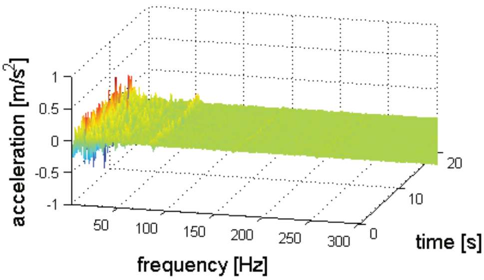


c) Laboratory test – gear No. 3/2500 rpm

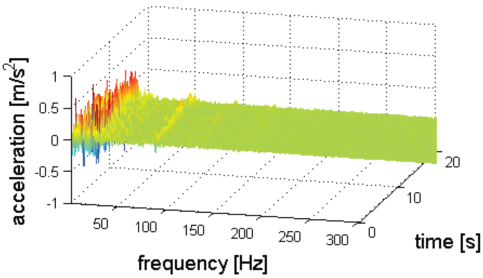


d) Laboratory test – gear No. 5/2300 rpm

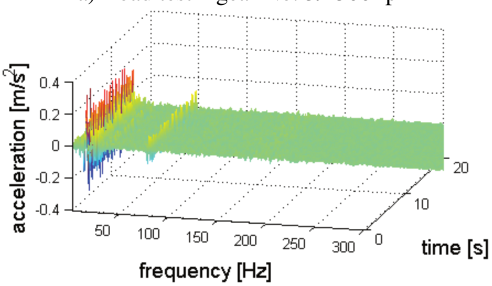
Fig. 15.9. The comparison of TFR of lateral vibration of vehicle moving at 50 km/h and 70 km/h speed versus laboratory tested vehicle at the same gear ratio and engine rotational speed (floor panel in location of driver feet)



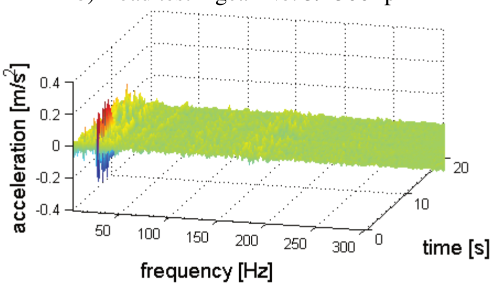
a) Road test – gear No. 3/2500 rpm



b) Road test – gear No. 5/2300 rpm

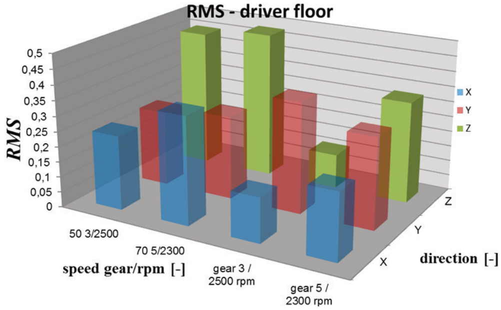


c) Laboratory test – gear No. 3/2500 rpm

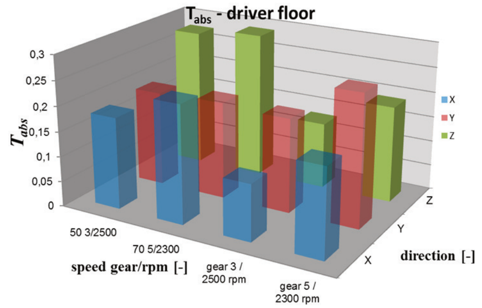


d) Laboratory test – gear No. 5/2300 rpm

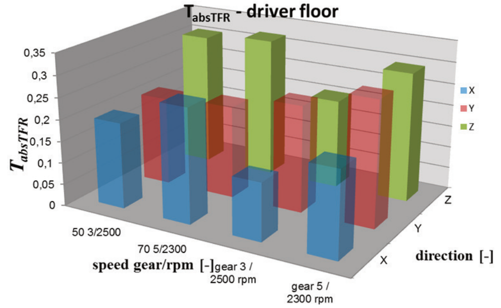
Fig. 15.10. The comparison of TFR of vertical vibration of vehicle moving at 50 km/h and 70 km/h speed versus laboratory tested vehicle at the same gear ratio and engine rotational speed (floor panel in location of driver feet)



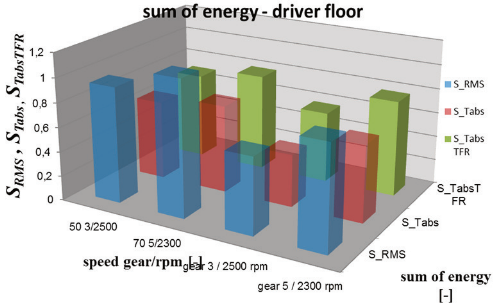
a) RMS



b) T_{abs}



c) T_{absTFR}



d) Sum of energy

Fig. 15.11. The comparison of energy estimators of vibration of vehicle moving at 50 km/h and 70 km/h speed versus laboratory tested vehicle at the same gear ratio and engine rotational speed (floor panel in location of driver feet)

The method proposed for identification of components of road irregularity induced vibrations for a moving vehicle may be brought down to comprehensive laboratory and road tests of the same vehicle while maintaining identical engine and power transmission operating parameters. It can be achieved by isolating components correlated with the signals obtained in the course of laboratory tests of a motionless car, excited to vibrate by an engine operating at a constant rotational speed and with the given transmission ratio, from the recorded signals of directional vibration propagation of a moving vehicle's load bearing structure. The foregoing is most evident in the difference spectrum function defined, one which represents the frequency distribution of absolute values based on the difference of vibration spectra obtained in road and laboratory tests.

By application of the TFR analysis a conclusion of the inferior stability of time distributions for predominant frequency components can be drawn, and hence the superior non-stationary characteristic of vibration signals of a moving vehicle, which only confirms the need for the TFR method to be applied to assess the human exposure to vibrations in transport.

A comparison of estimator distributions reveals the predominant share of vertical vibration components for a moving car. As for the laboratory tests, which was explicitly laid down in the previous sections as well, a considerable share in the directional distribution of vibrations can also be attributed to transverse vibration components. Hence one can deduce that the difference in question results from the stability difference between a car placed on a test rig (with brackets lifting the car) and a car tested on the road. For the manner in which the car is set on a foundation in laboratory studies, it may display higher propensity for side tilts due to being excited to vibrate. Irrespective of the foregoing, in each case analysed, both for directional and total estimators, the vibration energy of a moving vehicle was larger. Having analysed the differences between these measures, the volume of energy of the vibrations caused by road irregularities and aerodynamic resistances of a moving vehicle can be estimated.