11. Engine as the vibration source in vehicle

Road surface roughness often acts as a major source that excites the vibration of the vehicle running on the ground through the tire/wheel assembly and the suspension system [202, 205]. There are many different vibration sources in vehicles as well. The engine is primary vibration source along with external disturbance forces to the vehicle. Idle shake is one of the most important items to evaluate vehicle comfort [209]. A major comfort aspect is the transmission of engine-induced vibrations through powertrain mounts into the chassis.

The suspension system is very important for reduction of vibration transfer to car body. Before attempting to reduce the vibration levels in a machine or structure of the vehicles by increasing its damping, every effort should be made to reduce the vibration excitation at its source. Motor engine should be considered as one of the vibration generators. The vehicle engine mounting system, generally, consists of an engine, as vibration source and several mounts connected to the vehicle structure [210]. The engine mount is an efficient passive mean to isolate the car chassis structure from the engine vibration. The passive means for isolation is efficient only in the high frequency range. However the vibration disturbance generated by the engine occurs mainly in the low frequency range [206]. These vibrations result from fuel explosion in the cylinder and the rotation of the different parts of the engine.

11.1. Motor-engine as the source of vibration

The engine vibrations are strongly random processes because there are many different sources of vibration in engine. It has to be considered as dynamics responses which are most significantly dependent upon the nature of excitation forces and moments. They can have different mechanism of generation and different values and frequencies of vibration. The engine block mainly is characterised by the low coefficient of dumping. The vibrations of low and medium frequencies up to a few kHz are only slightly absorbed. Higher vibration absorbing effects appear only for frequencies of 10 kHz or more. Those parameters are determined by materials used in engine construction. There are a lot of novel materials used in engine with modern production technologies. Thus the optimal material parameters can be obtained.

Motor engine can be considered as one of the vibration generators in vehicles (Fig. 11.1). Rotating machinery such as motors can generate disturbing forces at several different frequencies such as the rotational speed and blade passing frequency. Reciprocating machinery such as compressors and engines can rarely be perfectly balanced, and an exciting force is produced at the rotational speed and at harmonics. There are two basic types of structural vibration: steady-state vibration caused by continually running machines such as engines, air-conditioning plants and generators either within the structure or situated in a neighbouring structure, and transient vibration caused by a short-duration disturbance such as a lorry or train passing over an expansion joint in a road or over a bridge.

The engine exciting force mainly composed of the internal force generated by the rotational reciprocated motion of the piston-cranshaft system and of the fluctuation of torque generated by the fluctuation of gas pressure [209]. It can be assumed that vibration and forces excitations due to the engine is a complex function of the gas pressure, firing, unbalance and operating parameters, such as engine rotational speed. The mechanism of vibration generation is the firing cycle from each cylinder and the moving masses resulting from the firing cycle impact dynamic forces and moments to the internal combustion engine block which are transmitted into frame and car body.

Many publications reported that the engine vibration response are directly related to variations in the gas pressure. The chapter reports results of investigation on engine vibration response relation to the rotational speed of engine unbalanced masses.

If considering whole engine as body with six degrees of freedom it should be continued by using Lagrange's equation as shown in the following expression:

$$\frac{d}{d_t}\left(\frac{\partial T}{\partial q_j}\right)-\frac{\partial T}{\partial q_j}+\frac{\partial V}{\partial q_j}=Q_j^{(n)}, \tag{11.1}$$

where: T – parameter of kinetic energy of the system, V – parameter of potential energy of the system, Q – is equal to both external forces and forces produced by damping objects.

Most models used to the engine vibration analysis, including the matrices with fixed components, i.e. mass matrix, M stiffness matrix K and damping matrix C. However, studying and optimizing such systems in terms of both free and forced vibrations require comprehensively accurate analysis as well as reliable input information [11]. It can be assumed that vibration amplitude of engine block is so small that structure is a linear vibration system. Thus the motion equation (vibration equation) which has a matrix form is expressed as:

$$M(t)\ddot{q}+C(t)\dot{q}+Kq=F(t), \tag{11.2}$$

where: M – global mass matrix, C – global damping matrix, K – global stiffness matrix, $\ddot{q}$, $\dot{q}$, q are vectors of acceleration, velocity and displacement.

In equation $F(t)$ above both forces caused by combustion in the cylinder chamber and external forces exerted on the engine. To determine the natural frequencies of the whole engine system, homogeneous solution ($F(t)=0$) is employed. Structural vibration responses depend on structural natural frequency, damping, stiffness and exciting condition [204].

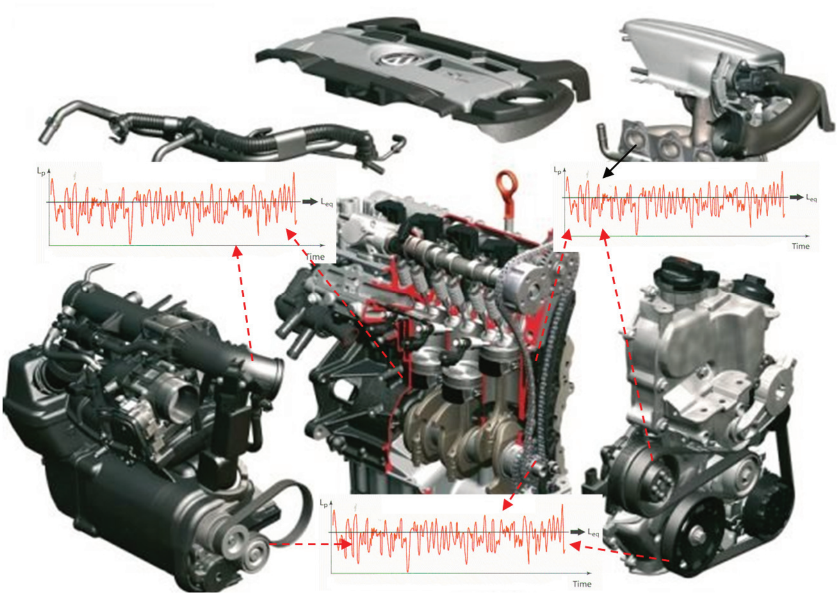


Fig. 11.1. Motor engine as the vibration generator

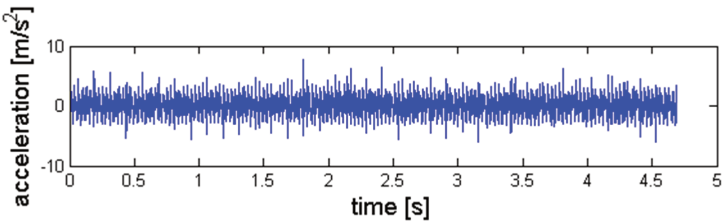
Considering the vibroacoustics analysis of an internal combustion engine it should be taken into account, that a high level of nominal vibrations is generated, resulting from the target function realisation. Internal combustion engine is an object under the influence of internal and external inputs. Among them there are mainly: burning pressure, the movement of the piston-crank mechanism, inputs from the timing gear system, inputs resulting from the work of the fittings of the engine, inputs transmitted from the motor-car body and the drive transmission system. One of the most important inputs during the work of the piston-crank mechanism are the impacts of the piston by the change of its work direction.

Vibration processes in combustion engine are unwanted effects but at the same time the can be very useful. This chapter take into account influence of the vibration as the detrimental effect on the safety and comfort in mean of transport. The human response to vibration depends on the values, frequencies and directions [46]. Perceptibility of the same frequencies and values of vibration in exposure in different directions can be diametrically different.

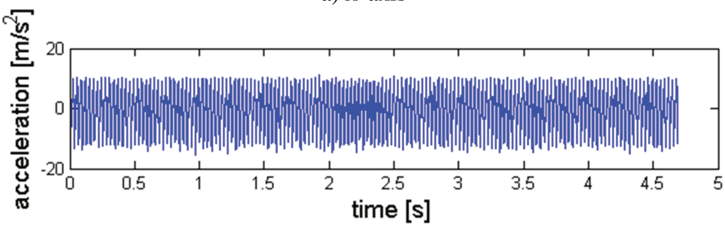
11.2. Identification of the vibration generated by the engine

The experimental research was conducted on directional distribution of vibrations generated by the combustion engine. The dual-axis accelerometer was used. Block of the combustion engine was studied. Active experiments were undertaken featuring measurements of vibration accelerations in three directions. The vibration in three orthogonal axes (X, Y, Z – Fig. 11.2) have been measured. The position and directions of measurements is presented in Fig. 11.3.

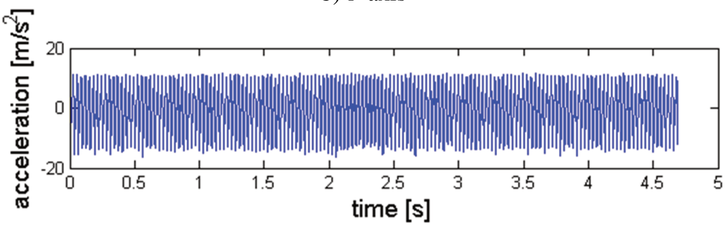
As a result the time functions of acceleration of vibration generated in the three orthogonal axes by the combustion engine were determined. Fig. 11.2 presents some exemplary distribution of vibration signals.



a) X axis



b) Y axis



c) Z axis

Fig. 11.2. Directional distribution of vibration signals of block of motor vehicle, 750 rpm

For the purpose of dynamics analysis of motor engine vibration the spectrums of the recorded signals in 3 axes were determined. For the identification of the frequency correlated to rpm (revolutions per minute) of the rotational speed of the engine the figures were analyzed separately with zoom window.

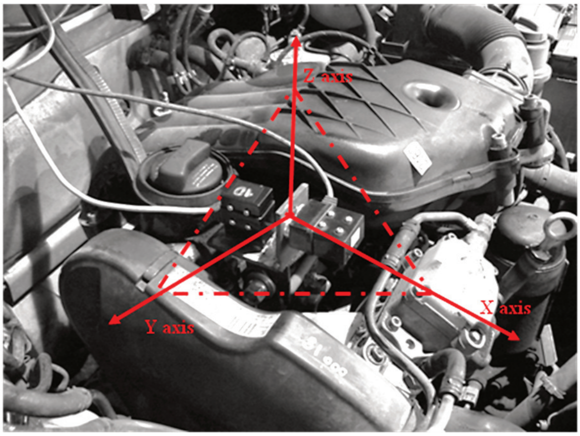
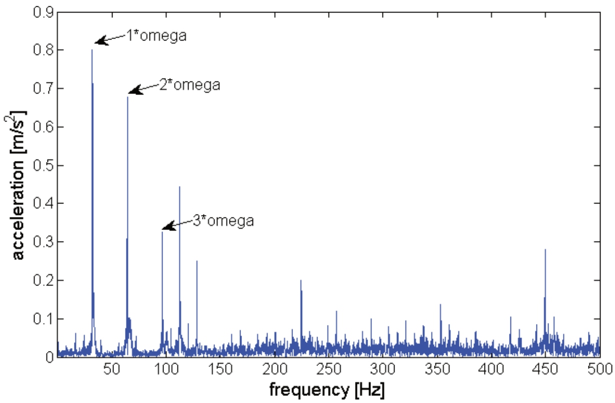
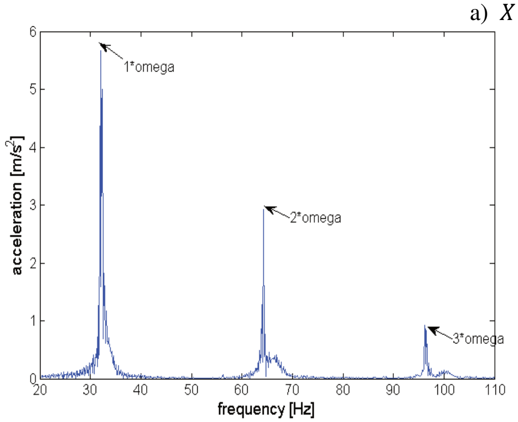


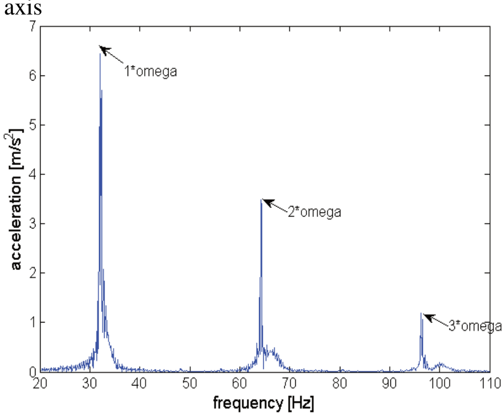
Fig. 11.3. The position and directions of measurement of the vibration of motor engine



a) X axis



b) Y axis



c) Z axis

Fig. 11.4. Spectrums of vibration of the motor engine in X, Y, Z axes, 750 rpm

Thus the frequency of unbalance disturbances is correlated to engine rotational speed (defined as rpm) and depends on the number of cylinders in the engine, the stroke number and the engine speed. For the four cylinders, four-stroke engine, which were investigated during research, the frequency of fundamental disturbances is at the second order of the engine speed. The frequency range is 20-200 Hz for an engine rotational speed range from 600 to 6000 rpm. Taking into consideration an eight-cylinder engine, the frequency of the disturbance torque is at the fourth orders of the engine rotational speed and the frequency range is 40-400 Hz for the same engine

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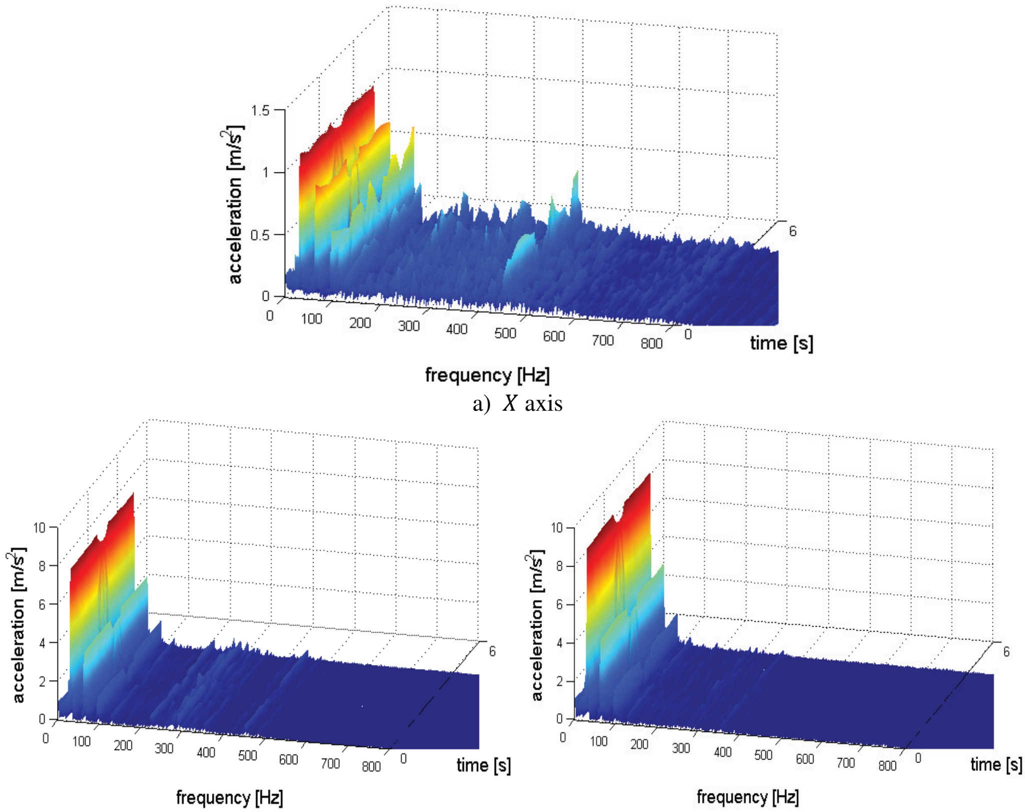
speeds. In general, at low engine speeds (near idle) the engine disturbance will result in an annoying shaking of the vehicle. At higher speeds, a booming sound is created inside the vehicle compartment when the engine disturbance force coincides with an acoustic resonance of the passenger compartment [210].

The main characteristics frequencies of the engine are marked on Fig. 11.4. Thus the analysis of different between amplitude of the harmonics vibration in axes X, Y and Z is possible.

In the spectrum of the signals the characteristics frequencies can be identified. In the presented results the ca. 32 Hz frequency is correlated with rotation velocity of the idle gear of the engine. The vertical vibrations have the largest amplitude but the signal is most stationary. The frequencies not correlated with rotation velocity of the idle gear of the engine (1-3 harmonics) are very low energy. The horizontal vibration have more frequencies, especially in the spectrum of the X axis vibration can be identified many of different frequencies. The directional distribution of vibration can be resulted from the elements and systems of the suspension and the mounting of engine. It can be resulted of the unbalance of the rotating elements of the engine or other defects.

The received signal is strongly interfered by various vibration sources and that is why there is a necessity to use advanced methods of signal selection and observation in time-frequency domains. The TFR of the signals propagated in three orthogonal axes is presented in Fig. 11.5. It shows the complex structure of vibration of motor engine.



a) X axis

b) Y axis

c) Z axis

Fig. 11.5. Time-frequency structure of vibration of the motor engine in X, Y, Z axes, 750 rpm (time 0.25 s, resolution 0.4884 Hz)

The transformations of the vibration signal into time-frequency representation enables analyzing of energy of vibration carrying by the defined frequency. Thus the periodic unstable of frequencies can be observed (Fig. 11.6).

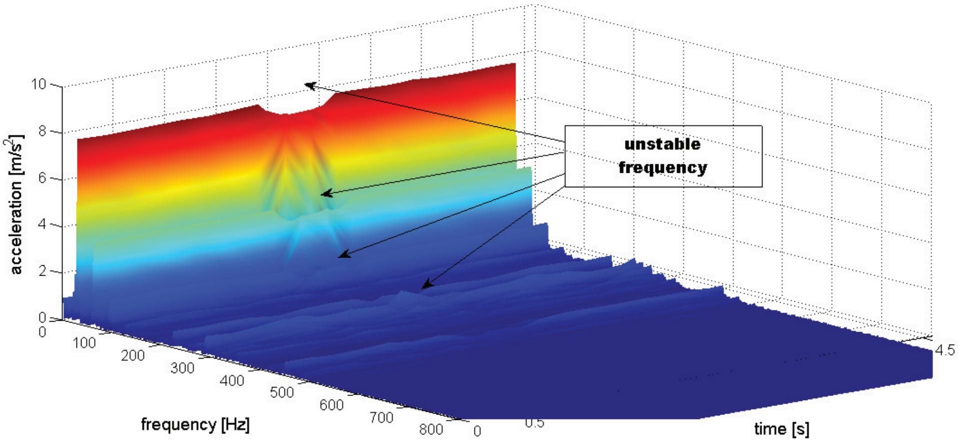


Fig. 11.6. Example of the unstable frequency (STFT of enfine block vibration, *Y* axis – time window 0.25 s, resolution 0.4884 Hz)

11.3. Influence of engine rotational speed on the vibration generation

To consider motor engine as vibration generator in vehicle investigation on influence of operating parameters and conditions of combustion engine were conducted. As most important condition of working engine the rotational speed expressed as revolutions per minute (rpm) was assumed.

The results of the investigation are presented in Fig. 11.7-11.9 as collection of charts presenting time and frequency functions of vibration generated for increasing rpm of engine.

For the purpose of analysis of rotational speed of engine influence on the vibration generation the RMS values were calculated. It shows changes in energy of vibration for different revolutions per minute of engine in orthogonal axes as direction of propagation. The distribution of RMS values were shown in Fig. 11.10.

Basing on the spectrums of the vibration the dominant dynamics component correlated with rotational speed of engine was identified. Those frequencies carry most of the energy of the vibration (a significant part of RMS). The Fig. 11.11 presents changes of the location of dominant frequency component for increasing of rotational speed of engine.

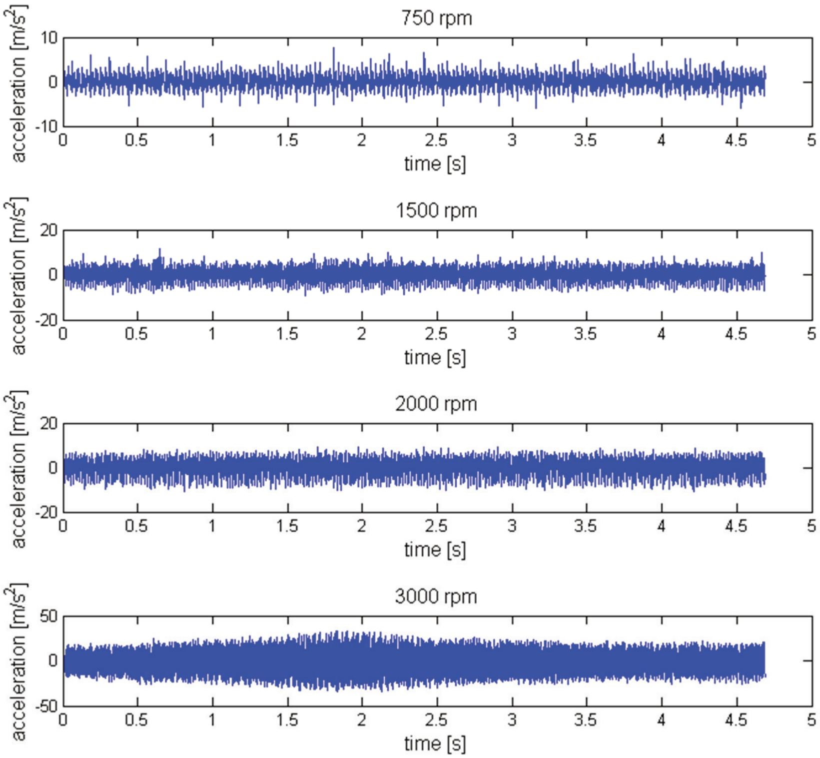
For the accurate identification of engine’s rotational speed impact on generated vibration the observation in time-frequency domains is necessary. The TFR of the signals enables analyzing of structure of the vibration and time of exposure to the defined frequencies.

The changes of the structure of vibration generated in different rotational speed of engine are presented in Fig. 11.12-11.14. Apart of analyzing of constant in dominant frequencies realization, the periodic excitation of different frequencies can be observed. The periodic changes in distribution of defined frequency vibration can’t be identified in regular spectrums obtained as Fourier transformation.

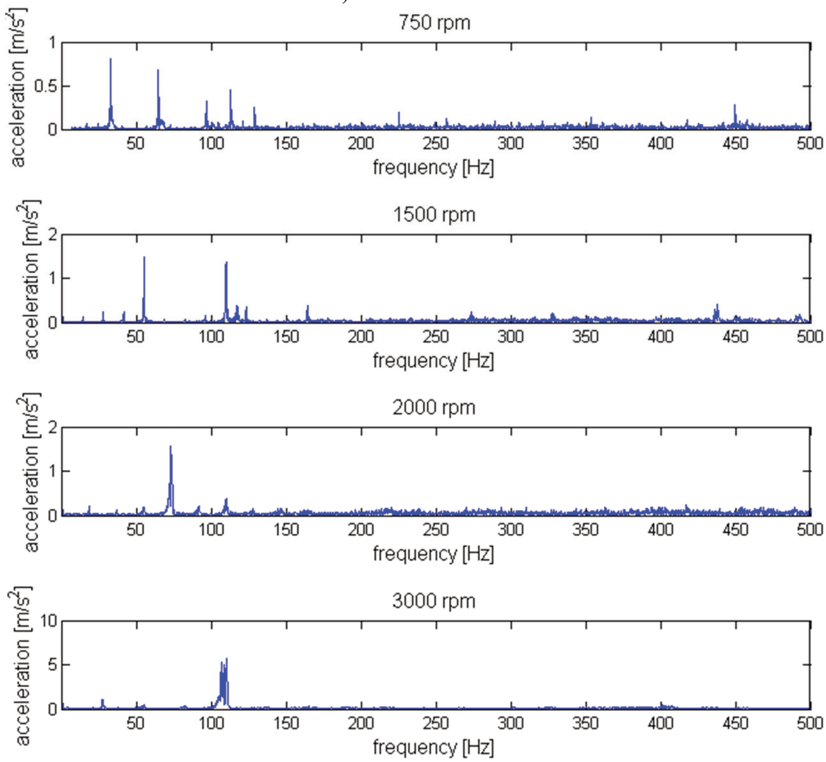
The higher values of vibration (RMS and amplitude of frequency component) can be a result of the variations in the gas pressure yield the principal force of disturbance at low engine rotational speeds, while the inertia forces may be considerable larger at higher speeds.

Spectrums of the vibration shows that the first order forces as identified from FFT are balanced and the second order forces carrying most of the vibration energy. These frequency components are result in an unbalance force. Apart from the magnitude of the unbalanced force, the frequency of dominant component of vibration depends on the engine rotational speed.

The transformations of the vibration signal into time-frequency representation show distribution and structure of vibration. This transformation enables identification of the periodic unstable of frequencies and evaluation of amplitude-time exposure to vibration in chosen frequencies bands.

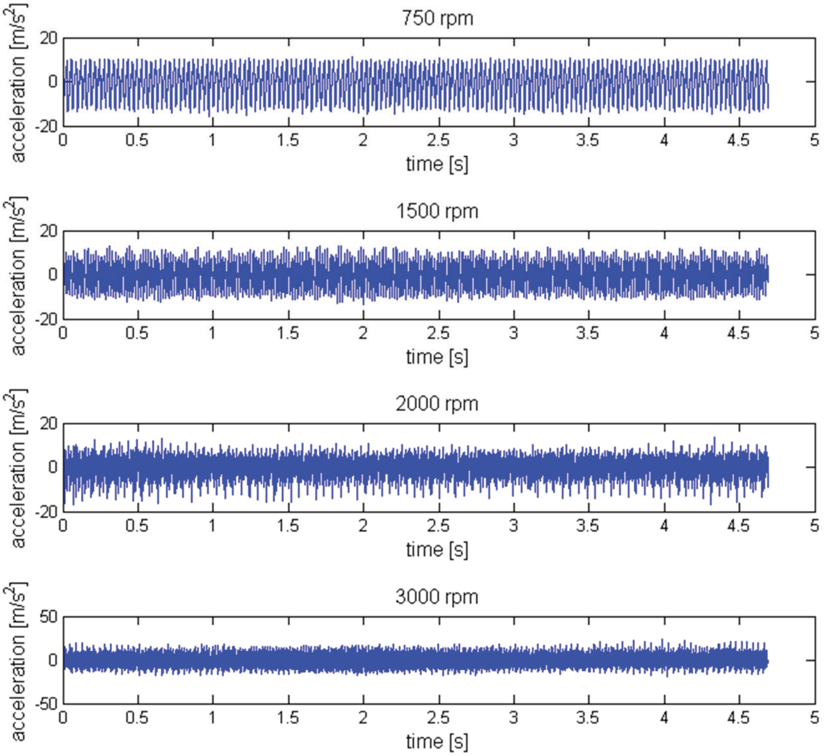


a) Time function

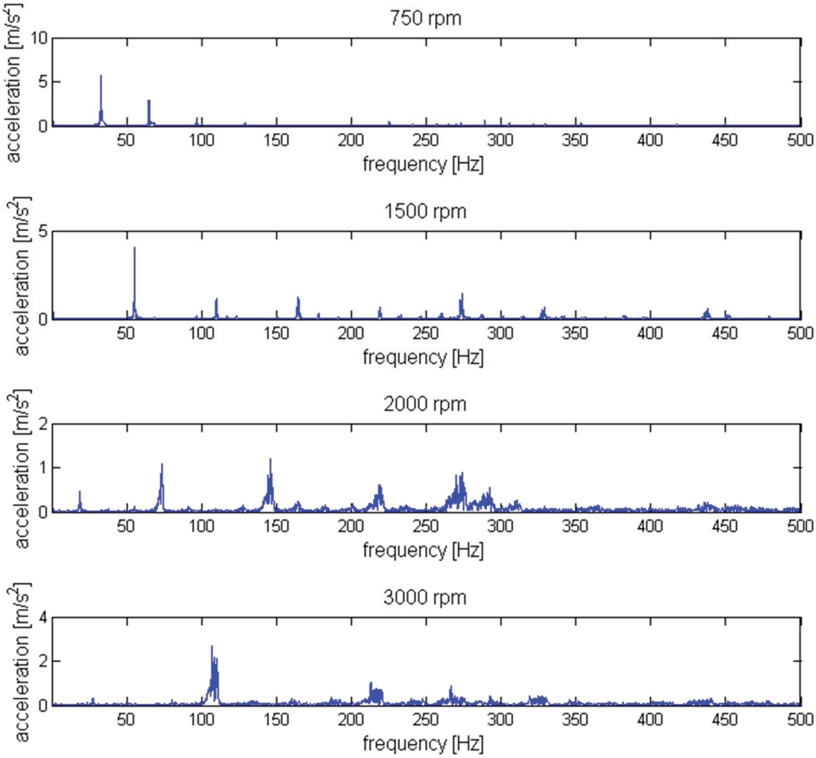


b) Frequency function

Fig. 11.7. The vibration of motor engine for increasing rpm value, X axis – longitudinal, 750 rpm

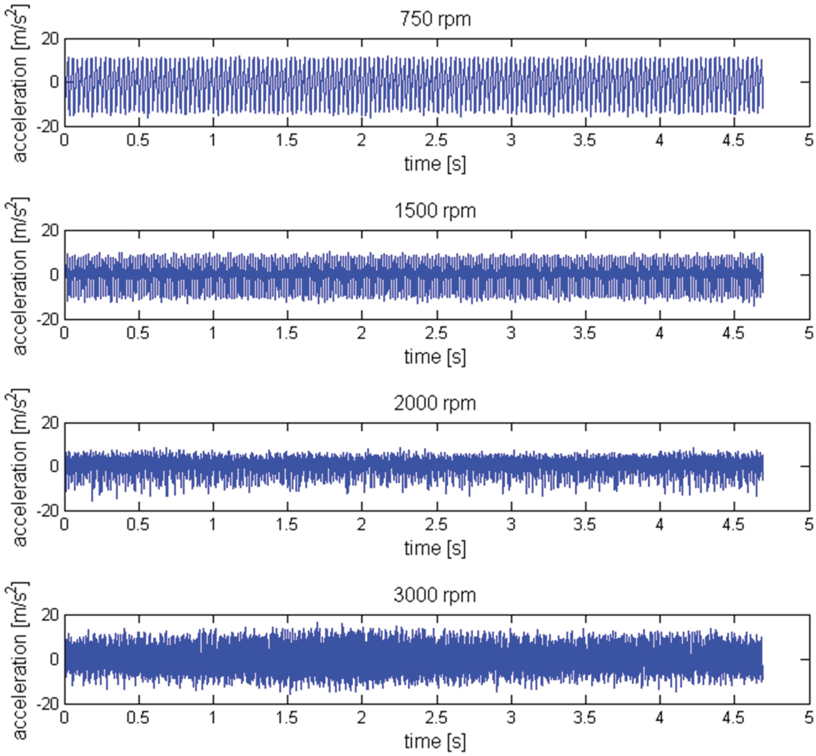


a) Time function

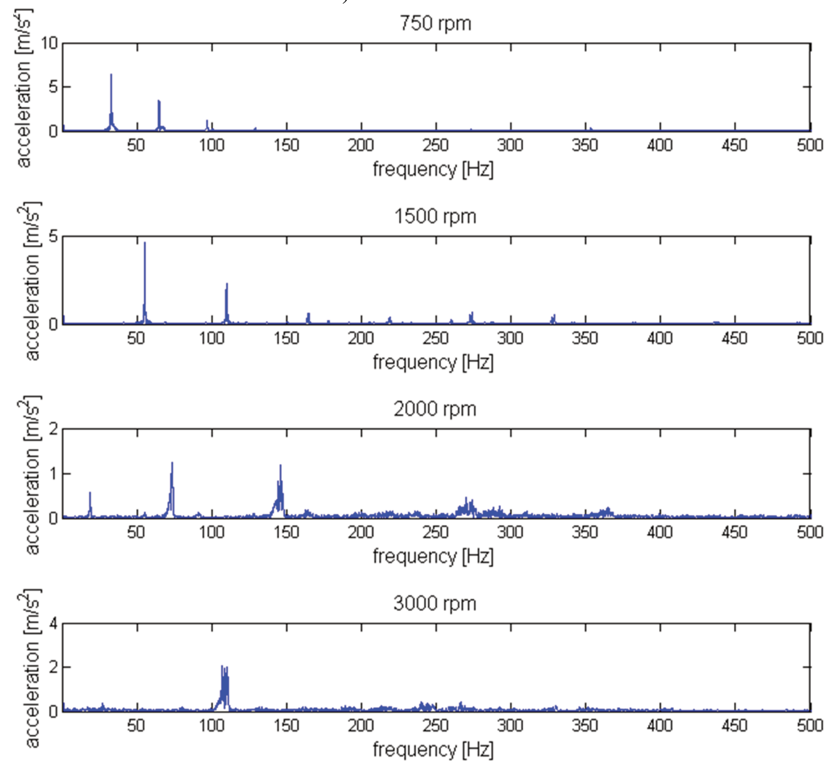


b) Frequency function

Fig. 11.8. The vibration of motor engine for increasing rpm value, Y axis – lateral

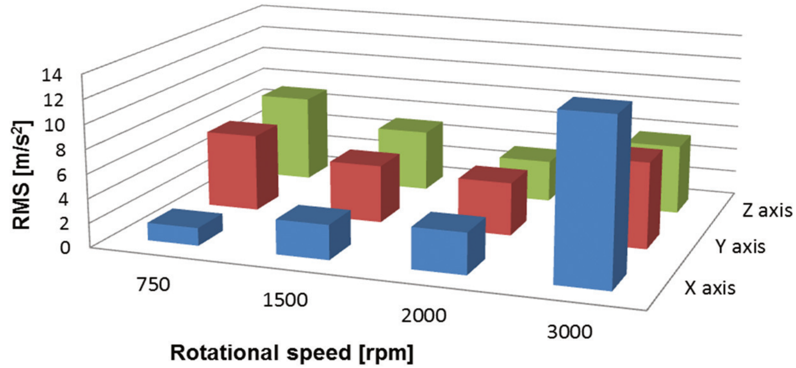


a) Time function



b) Frequency function

Fig. 11.9. The vibration of motor engine for increasing rpm value, Z axis – vertical



	750	1500	2000	3000
X axis	1.4615031	2.851705344	3.37566313	13.38934669
Y axis	6.391705216	4.788299865	4.368266727	7.073067795
Z axis	7.215869997	5.100786875	3.432679143	5.709143522

Fig. 11.10. The distribution of RMS of vibration for different rotational speed in 3 orthogonal axes

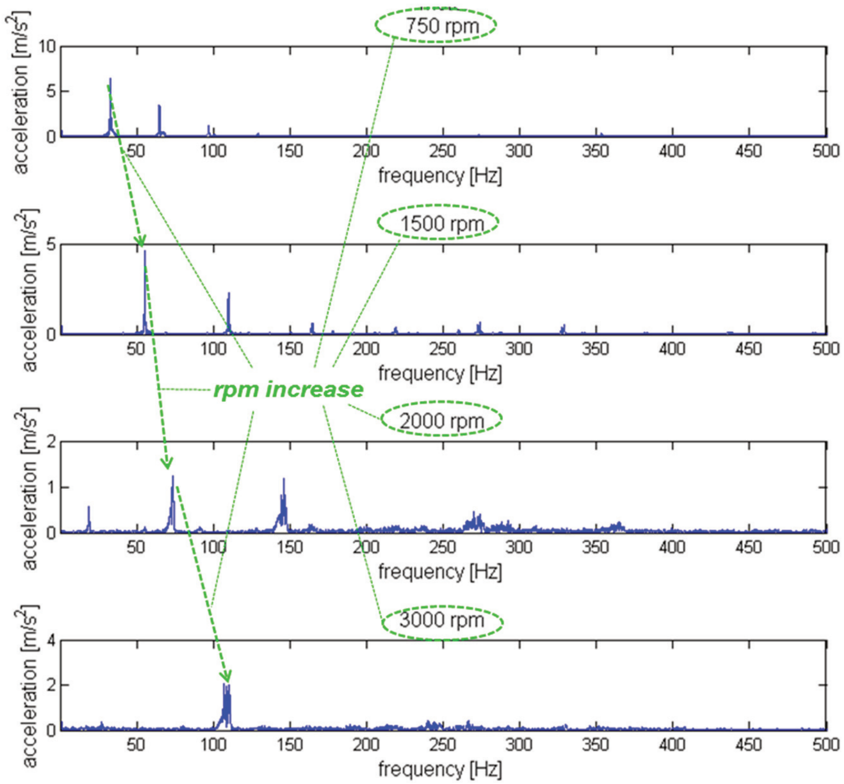


Fig. 11.11. Illustration of influence of rotational speed on dominant frequency component of vibration

Analysis of dynamics of vibration of 3000 [rpm] engine rotational speed shows concentration of vibration energy in narrow frequency band, close to frequency peak, especially for longitudinal and vertical directions of propagation.

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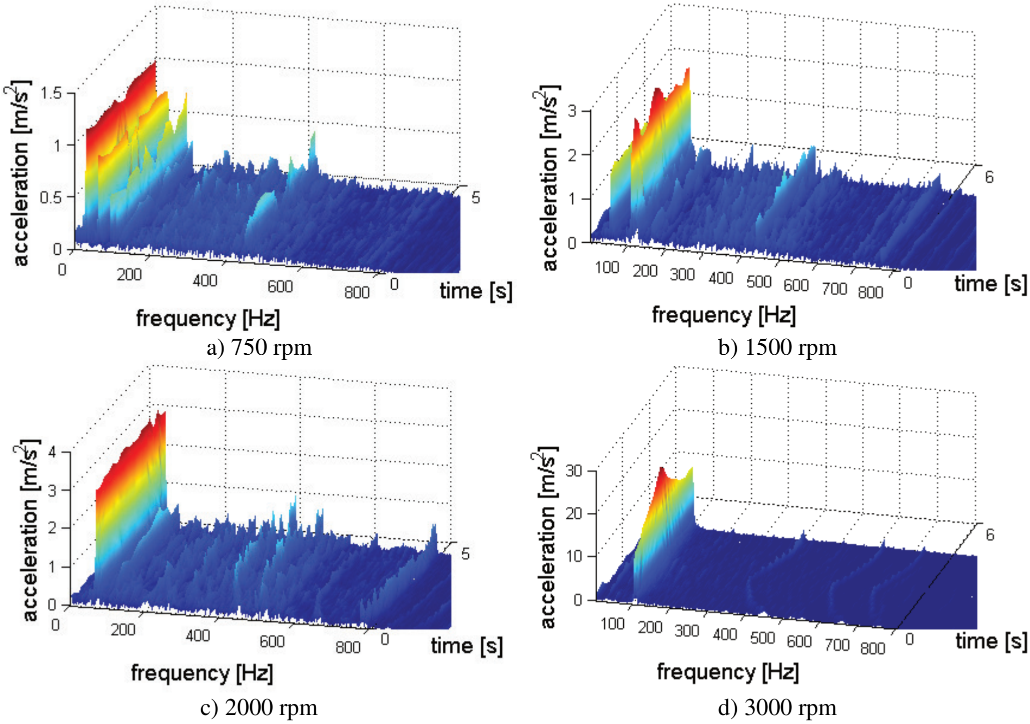
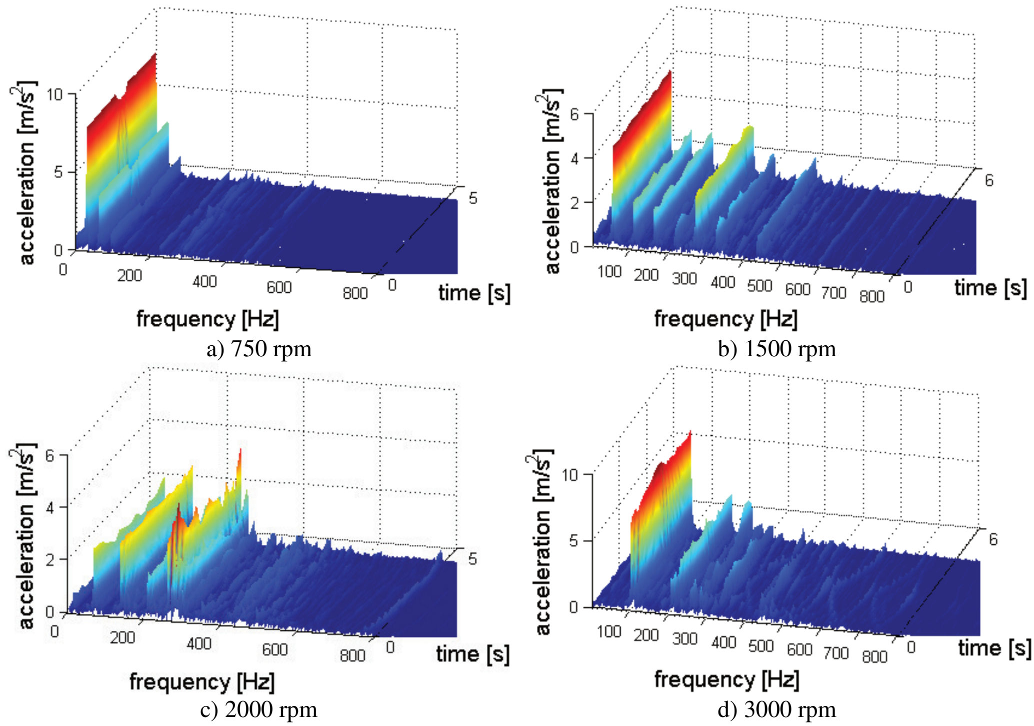


a) 750 rpm b) 1500 rpm

c) 2000 rpm d) 3000 rpm

Fig. 11.12. The structures of vibration for different of rotational speed of engine, *X* axis – longitudinal (time window 0.25 s, resolution 0.4884 Hz)



a) 750 rpm b) 1500 rpm

c) 2000 rpm d) 3000 rpm

Fig. 11.13. The structures of vibration for different of rotational speed of engine, *Y* axis – lateral (time window 0.25 s, resolution 0.4884 Hz)

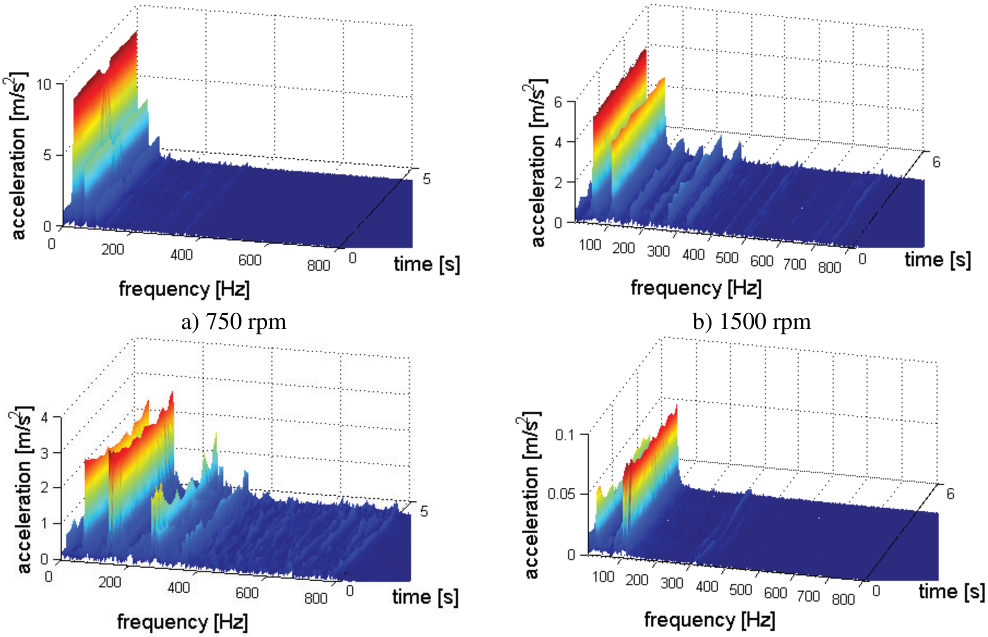


Fig. 11.14. The structures of vibration for different of rotational speed of engine, *Z* axis – vertical (time window 0.25 s, resolution 0.4884 Hz)