2. Vibration effects on the transport system

2.1. General information on vehicle vibration

The effects caused by transport should be examined in a breakdown into desirable and undesirable as well as external and internal ones. The desirable effects of transport are related to its function of purpose, namely moving and increasing of mobility. The undesirable ones involve a negative impact on the surrounding. The division into external and internal effects stems from the influence exerted on the components of a system which do not take part in the transport process as well as those directly related to the process. The internal effects are of a feedback nature and they influence the efficiency of transport processes. An example of undesirable transport effects of both external and internal relevance is vibration. Representing phenomena generated and propagated into the environment, vibrations may cause damage to the transport infrastructure and other surrounding elements. Vibrations perceived as internal phenomena reduce the efficiency of transport processes as well as transport safety and comfort [67, 197]. Sudden or intensifying vibration phenomena of local nature may compromise safety. A man operating a mean of transport subjected to local vibrations may lose control over the vehicle. Also general vibrations are very significant in this respect, as they influence the feeling of discomfort to a considerable extent. It is more and more common that vibrations, being undesirable residual phenomena, are used in machinery monitoring and diagnostics [37, 61, 72, 94, 126, 130, 148-151, 160, 192, 193, 201].

Studying vibration phenomena in automotive vehicles should primarily pertain to their effects on men and the chosen structural elements of a vehicle. In the scope of the impact on structural elements, one should perceive vibrations in terms of destructive factors. Consequences of the human exposure to vibrations include various harmful changes occurring in the organism. They have a direct or indirect influence on comfort and safety [2, 33, 83, 84, 121, 134, 143, 152]. The scope and the procedure of handling them depend on a considerable extent on the location where they penetrate the organism. Mechanical vibrations occurring in a working environment may be classified as general vibrations, i.e. those affecting the human organism via lower extremities, the pelvis and the back. The second category comprises local vibrations affecting the human organism through upper limbs. It allows to describe the vibration affecting on the human as Hand-Arm Vibration (HAV) and Whole-Body Vibration (WBV) (Fig. 2.1). For the HAV the standards of measurement and evaluation have been collected in ISO 5349:2001 – Measurement and evaluation of Human Exposure to Hand Transmitted Vibration. For the WBV the main standards are described in ISO 2631 – Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration [103-105]. Directives and guidelines based on measurement standards define allowable exposure limits for HAV and WBV.

Vehicle vibrations are classified into two general types of the rigid body vibration of sprung and unsprung mass and stiffness vibration. Stiffness vibration is determined by mass, stiffness and damping forces which are contained in suspension component parts. Some interesting investigation on vibration energy according to type and structure of the tire have been presented in [131]. In many papers the main goal of investigation on vehicle tires are noise. Interaction between tire and road is recognised as the main source of interior and exterior noise for velocities over the 40 km/h. In the paper [166] a three-dimensional elemental approach has been adopted to predict the stochastic tire vibration and hence the interior and exterior noise due to this kind of excitation.

Drive comfort depends on many parameters, such as the mass of the vehicle, tire pressure [147, 174], shock absorber quality, the type of seat and the elasticity characteristics of the tires. The methods of investigation on the role of tires on the whole body vibration (WBV) of the operator have been presented in [69].

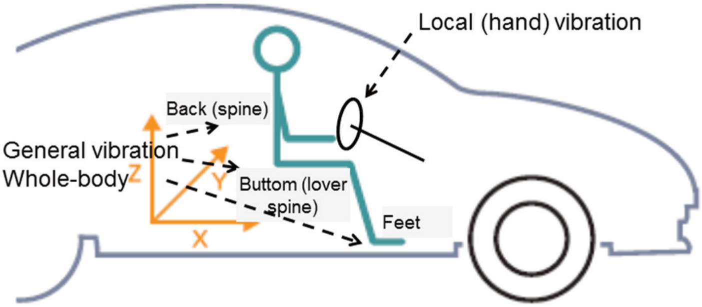

Fig. 2.1. Classification of vibration in term of exposure on human in passenger car

The characteristic of the spring and shock-absorber in the vehicle suspension system as well as other vehicle elastic elements are nonlinear. Therefore, vehicle nonlinear oscillatory models are used in oscillatory behavior analyses [25, 28]. The paper [173] presents results of the investigation on influence of air spring and hydraulic shock absorber of the bus driver's seat on driver comfort. Vibrations are transmitted from the bus floor via the driver seat suspension system to the driver's body. Effects of vibrations on the bus driver oscillatory comfort depend on the spring stiffness and the shock-absorber damping. The results presented show changes in the driver's vertical acceleration for various values of the spring stiffness and various values of the shock-absorber damping of the driver's seat.

The procedure as regulated by the international ISO 2631-1 standard [102] prescribes the vibration total value of weighted root mean square accelerations as a reference quantity for the assessment of vibration effects on the comfort. Many more estimators for the assessment of vibration effects on the comfort have been presented in [88, 89, 198], especially for the child seat.

The state of the art review indicate that main stream of investigation on vehicle vibration comfort is focused on research on vibration of the seat. Thus author decided to conduct the research on vibration of the floor panel in location when vibration are penetrate into the human organism via feet.

Vibrations are also a very ample source of information on the technical condition, and hence they are commonly used in diagnostic systems [49, 50, 52, 55, 60, 85, 108, 190-192]. Bearing in mind such extensive fields of influence and application of vibrations, it is highly recommendable that the impact exerted by selected parameters on the form of vibrations recorded as well as their distribution in the vehicle structure should be studied. One should also strive to verify the influence of material parameters and invasive repair methods on propagation of vibrations in structural elements [27, 36, 119, 196] with the many analysis on influence of some parameters on physical and chemical properties. Car manufacturers use more often lighter materials in the design of vehicles to reduce energy consumption. This loss in mass combined with the design of increasingly powerful vehicles lead to car frames more vulnerable to the propagation of vibration and the generation of noise [25].

2.2. Vibration effects on the human

A very large group of people exposed to general vibrations comprises car drivers, passengers, tram drivers or building and road machinery operators. Occupations that require driving long distances or operating heavy equipment expose workers daily to low-frequency vibrations generally less than 100 Hz. Exposure to these vibrations can cause serious physical problems ranging from chronic back pain to nerve damage. Whole-body vibration is caused by twisted sitting postures combined with vibration. The combination increases stress and load on the neck, shoulder and lower back. Vibrations propagate into the human organism through vehicle seats via the pelvis, the back and lateral parts of the body as well as through the vehicle floor panel via feet. As vibration is transmitted to the body, the effect of the vibration can be amplified by factors such as body posture, type of seating and frequency of the vibration. Individual human body parts have their own resonant frequencies. The vibrations most harmful to people are those whose input frequency is close to the natural vibration pulsatance of human organs. For a vibration frequency lower than 2 Hz, the human body behaves as a uniform mass. The first resonant frequency for a person remaining in a sitting position is 4 Hz or 6 Hz. The human vibration perception depends on human body position, as standing, sitting and lying positions. The natural vibration frequency of an automotive vehicle's sprung masses is assumed to be contained within the range from 1 to 2.5 [Hz]. Such dynamics of vibration phenomena does not essentially exert any negative effects on passengers, since it corresponds to man's natural frequency of making steps (Fig. 2.2). Vibrations of the frequency below 1 [Hz] cause effects similar to seasickness in people, whereas those of the frequency exceeding 2.5 [Hz] bring prompt weariness and pain. The first resonant frequency for a man in a sitting position comes to ca. 4-6 [Hz] depending on individual body build features [14]. Input functions with the frequency of 3-4 [Hz] trigger strong vibrations in the abdominal cavity organs. The amplitude maximisation of the effects caused by these vibrations occurs at the frequency of 5-8 [Hz]. Close to these frequencies are those causing resonance in a human chest (i.e. 7-8 [Hz]). Organs of the head resonate in the band of 20-30 [Hz], whereas eyeballs at 60-90 [Hz]. However, it is the nervous as well as the cardiovascular system that are the most sensitive to the whole organism vibrations. The responses of these systems and their respective organs manifest themselves in their functions being disturbed, in poor physical and mental state, and even in certain forms of damage on higher amplitudes of effects and long exposure times. Health effects of excessive vibration for the HAV is the vascular and neuropathic effects and for the WBV are: low back pain, neck-shoulder disorders, digestive and circulatory disorders, cochleo-vestibular disorders and possible reproductive effects or vehicular safety hazards. The state of the art in scope of dynamics of the human vibration exposure on the sitting person via vehicle seats are published in numerous manuscripts [67, 92, 187, 200].

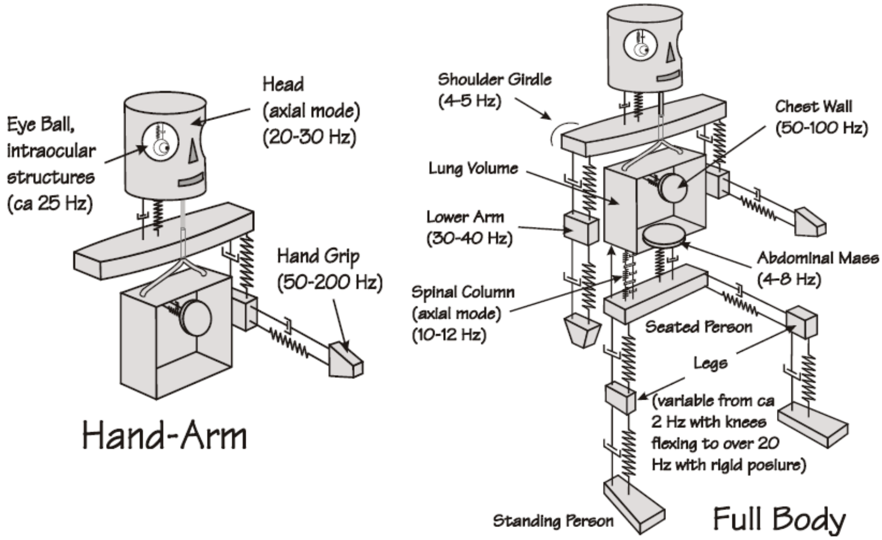

Fig. 2.2. Human body – resonant frequencies for the HAV and WBV [31]

Consequences of the human exposure to vibrations include various harmful changes occurring in the organism [67, 197, 121, 143, 88, 89, 200]. The scope and the procedure of handling them depend to a considerable extent on the location where they penetrate the organism.

The human organism may exhibit various responses to vibrations:
- subjective responses,
- psychosomatic responses,
- responses being functional disorders.

Short-term exposure vibration causes only small physiological effects such as a slight degree of hyperventilation and increased heart rate. Vibration also causes increased muscle tension from voluntary and involuntary muscle contraction. Muscles become tense in order to dampen the vibration. The adverse health effects may also include reduced motion control, blurred vision, or impairment of the ability of free communication, memory processes, or perception. The issue of the influence of vibrations on adult people's bodies has been relatively well described, which is reflected in numerous normative acts. Low-frequency vibrations of moderate intensity can induce sleep. Higher frequencies have the opposite effect. Vision can also become blurred because of the movement of the image on the retina.

Intervertebral discs serve as shock absorbers and become susceptible to injury over prolonged periods. The research result [200] asserts that constant exposure to vibrations represents the ultimate cumulative trauma. The authors [197] also found that prolonged exposure to whole-body vibration can lead to bulging or herniated discs. The vibration sensitivity of organs has been depicted in Fig. 2.3.

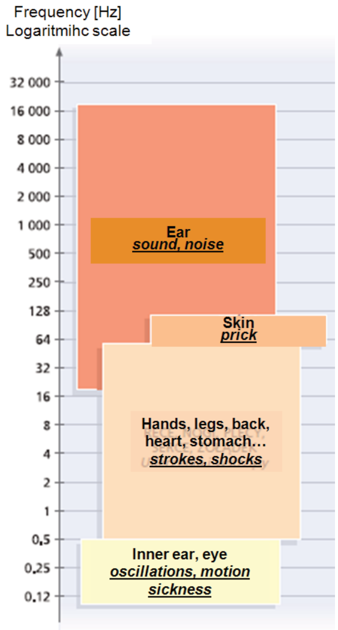

Fig. 2.3. Vibration sensitivity of chosen human organs

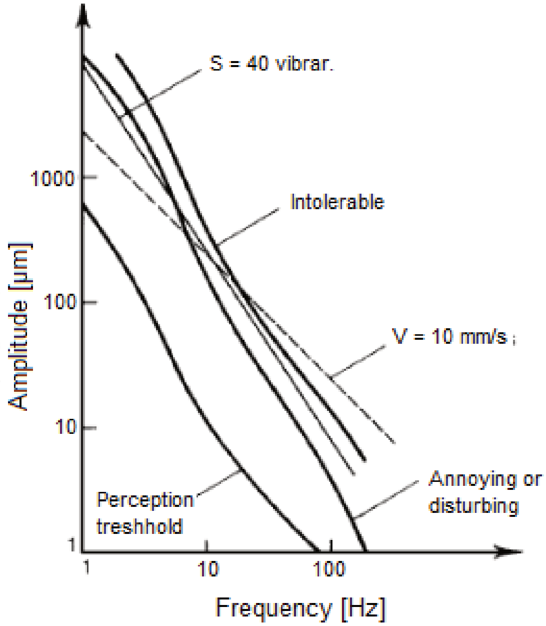

Fig. 2.4. Human response to vibration [23]

Human perception of vibration is very good. A human organism may then be perceived as a complex spring-mass system of a large number of degrees of freedom and diversified properties characterising elasticity, damping, masses, frequency of natural vibrations of individual components and human organs. The division of human perception of vibrations determines the subjective and psychosomatic responses as well as disturbances in the system functioning. As regards the location where vibrations penetrate the human organism, one may speak of general and local vibrations. General vibrations are transferred into the human organism via feet in a standing position or via the pelvis, the back and feet in a sitting or lying position. Local vibrations affect the human organism through upper limbs. Perception of the impact of wave related phenomena, such as noise and vibrations, on a human being is a complex matter, also in terms of the very nature of the said phenomena. The vibration energy affecting the human organism originates in the direct penetration area exclusively, therefore, what matters for the vibration perception is the energy affecting a unit of surface area in a unit of time. It is a real challenge in structural design to ensure that the perception threshold level is not exceeded. An indication of the likely human response to vertical vibration is shown in Fig. 2.4.

It shows harmonic vibration amplitude as a function of frequency. As it is presented the lines for constant velocity have smaller slopes than lines for constant vibration intensity. Therefore standards based on constant velocity give increased weight to lower frequency vibrations which are more likely to induce structural resonance and damage than frequencies above 50 Hz.

2.3. Perception of vibrations in automotive vehicles

The scientific problems of vehicle's vibration in many aspects, especially in term of biodynamic response of the human body to the whole-body vibration, are main goal of many years investigation of Professor Michael Griffin from Southampton. Number of biodynamical models, vibration transmissibility concepts, and human biodynamic responses are considered in [91]. His research show the goal and way of investigation for many researchers [29, 67, 111, 186, 127, 128].

In order to examine vibration related phenomena occurring in a moving vehicle or a stationary one with its engine on, one should start with identification of vibration sources. Vibration sources in a vehicle are dynamic forces. The natural vibrations can be consider 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.

The vibrations experienced during vehicle ride may cause a variety of pathological symptoms arising in people such as alimentary system disorders, pains in the lumbosacral region and in the cervical spine section, or the occurrence of kyphosis and lordosis, joint and muscular pains, labyrinth disorders (travel sickness), or headaches [197].

The papers [88-92] present results of research on effects of vibration exposure on human organism. For this purpose are commonly used frequency analysis and spectrum's estimators. The transmission of vibration to the occupant of a car seat has been studied using the multiple vibration inputs to the seat [92, 158]. The vibration experienced when riding in a vehicle may be greatly affected by the manner in which the vibration is attenuated or amplified by the suspension system and the seat [67, 120, 202]. The results discussed in [67] indicated that fore-aft vibration on the seat pan and the backrest were induced not only by fore-aft vibration at the car floor but also by vertical floor vibration, partly due to the inclination of the seat pan and backrest. Due to rotational motions and non-rigidity of the car floor, the vibration may not be identical at the four corners by which a car seat is normally secured to the car floor.

Due to the properties of vibration related phenomena, they may be analysed from the perspective of diagnostics, degradation and impact on men. A human organism may then be perceived as a complex spring-mass system of a large number of degrees of freedom and diversified properties characterising elasticity, damping, masses, frequency of natural vibrations of individual components and human organs. The division of human perception of vibrations determines the subjective and psychosomatic responses as well as disturbances in the system functioning. As regards the location where vibrations penetrate the human organism, one may speak of general and local vibrations. General vibrations are transferred into the human organism via feet in a standing position or via the pelvis, the back and feet in a sitting or lying position. Local vibrations affect the human organism through upper limbs. Perception of the impact of wave related phenomena, such as noise and vibrations, on a human being is a complex matter, also in terms of the very nature of the said phenomena.

The vibration energy affecting the human organism originates in the direct penetration area exclusively, therefore, what matters for the vibration perception is the energy affecting a unit of surface area in a unit of time. A quantity determined as wave power designated as P divided by surface S which the energy penetrates is referred to as wave intensity. It is defined according to the following dependence:

$$I = \frac{P}{S} \text{ [W/m}^2\text{]}. \tag{2.1}$$

In order to assess this perception, one applies multiple argument functions. An example in this respect may be a corrected measure of quantity of the energy transferred defined as follows:

$$Q = ISt, \tag{2.2}$$

which entails vibration intensity I, vibration time t and surface S of the direct contact between a man and the vibrating object.

To recapitulate the above consideration, the perception of vibrations occurring in automotive vehicles depends on physical characteristics and the current state of the man, the location and the area of the vibration penetration into the organism, the time-frequency structure of the penetrating vibrations which enables assessment of the exposure time for vibrations of specific frequencies.

The perception of vibrations occurring in automotive vehicles depends on physical characteristics and the current state of the man, the location and the area of the vibration penetration into the organism, the time-frequency structure of the penetrating vibrations which enables assessment of the exposure time for vibrations of specific frequencies.

Vertical vibration limits from ride and vibration data manual (SAE) and “Janeway’s comfort criterion” – based on sinusoidal vibration (single frequency) have been depicted in Fig. 2.5.

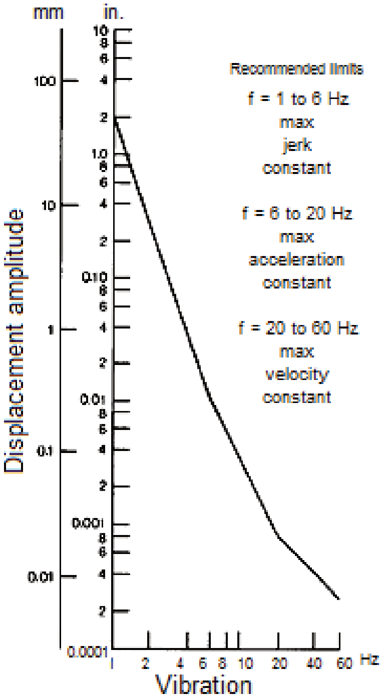

Fig. 2.5. Vertical vibration limits from ride and vibration [202]

The dynamics model of vehicle should permit for analysis of response function of the vehicle or human (occupant) on chosen excitation. The state of the art shows many publications on different approach to vehicle dynamics modeling. The paper [127] presents the three degrees of freedom (3-DOF) Human-Vehicle-Road (HVR) model, comprising a quarter-car and a biomechanical representation of the driver. The model used the Kelvin element as viscoelastic representation for modeling vehicle suspension systems and human muscular-skeletal structures. Differential equations are provided to describe the motions of various masses under the influence of a harmonic road excitation. The paper [127] formulates the optimization problem in terms of the requirements stipulated by ISO 2631 standards and utilizes a quarter-car model coupled with the biodynamical model of the driver. The model has been depicted in Fig. 2.6 in which M_3 denotes the driver's mass, M_2 stands for the mass of the vehicle body, and M_1 signifies the unsprung masses of the suspension. The model has been excited by a ground vertical motion, $u(t) = Ae^{j\omega t}$, with an amplitude A and a frequency ω. The z_i represents time-depending deflection. The C_i are the viscous damping coefficients and K_i are spring rates.

The differential equations of the motion for the 3-DOF are given by:

$$M_1\ddot{z}_1 + C_1\dot{z}_1 + K_1 z_1 + C_2\dot{z}_1 + K_2 z_1 - C_2\dot{z}_2 + K_2 z_2 = C_1\dot{u}(t) + K_1 u(t), \tag{2.3}$$

$$M_2\ddot{z}_2 + C_2\dot{z}_2 + K_2 z_2 - C_2\dot{z}_1 - K_2 z_1 - C_3\dot{z}_3 + C_3\dot{z}_2 - K_3 z_3 + K_3 z_2 = 0, \tag{2.4}$$

$$M_3\ddot{z}_3 + C_3\dot{z}_3 + K_3 z_3 - C_3\dot{z}_2 - K_3 z_2. \tag{2.5}$$

The equations can be expressed in a matrix form (detailed solution have been presented in [127]) it allows to obtain the expressions for the motions and accelerations of the masses M_1, M_2 and M_3 as equations as follows:

$$\begin{aligned} a_1(t) &\\ = -\omega^2 &\frac{(K_1 + jC_1\omega)(\omega^2 K_3 M_2 - j\omega C_2 K_3 + \omega^2 K_3 M_3 + \omega^2 K_2 M_3 - j\omega K_2 C_3 - K_2 K_3)}{\delta} Ae^{j\omega t} \\ - \omega^2 &\frac{(K_1 + jC_1\omega)(-\omega^4 M_2 M_3 + j\omega^3 C_3 M_2 + j\omega^3 C_2 M_3 + \omega^2 C_2 C_3 + j\omega^3 C_3 M_3)}{\delta} Ae^{j\omega t}, \end{aligned} \tag{2.6}$$

$$a_2(t) = -\omega^2 \frac{(K_1 + jC_1\omega)(K_2 + j\omega C_2)(\omega^2 M_3 - j\omega C_3 - K_2)}{\delta} Ae^{j\omega t}, \tag{2.7}$$

$$a_3(t) = \omega^2 \frac{(K_1 + jC_1\omega)(K_2 + j\omega C_2)(K_3 + j\omega C_3)}{\delta} Ae^{j\omega t}. \tag{2.8}$$

A generalized nonlinear two-degrees-of-freedom (2-DOF) model has been formulated in [29] for the dynamic analysis of suspension seats with passive, semi-active and active dampers. These model has been depicted in Fig. 2.7. The model incorporates Coulomb friction F_f due to suspension linkages and bushings, forces arising from interactions with the elastic limit stops, a linear suspension spring and nonlinear damping force for passive, semi-active and active dampers, while the contribution due to biodynamics of the human operator is considered to be negligible. The model masses m_c and m_{ss} represent the masses due to occupant upon neglecting its biodynamic interactions and the seat, respectively. The cushion is characterized by linear stiffness K_c and viscous damping coefficient C_c. The suspension is represented by its linear stiffness K_{ss}, a clearance spring K_{st}, dry friction force (Columb) F_f and a viscous damping coefficient C_{ss} in the case of a passive suspension seat. The z_c and z_{ss} represent the vertical movement of the occupant mass m_c and the suspension seat mass, respectively. The suspension force F_d may be either F_a for the active. The forces due to the passive components of the suspension are derived from the algorithm where z_{sp} represents the displacement excitation at the base of the seat.

The equations of the motion for the 2-DOF suspension seat are given by:

$$m_c\ddot{z}_c = -F_c, \;\; m_{ss}\ddot{z}_{ss} = F_c - F_{sp}, \tag{2.9}$$

$$F_c = K_c(z_c - z_{ss}) + C_c(\dot{z}_c - \dot{z}_{ss}), \tag{2.10}$$

$$F_{sp} = F_{ss} + F_f + F_{st} + F_d, \tag{2.11}$$

$$F_{ss} = K_{ss}(z_{ss} - z_{sp}) + C_{ss}(\dot{z}_{ss} - \dot{z}_{sp}), \tag{2.12}$$

$$F_f = F_f \frac{\|(\dot{z}_{ss} - \dot{z}_{sp})\|}{(\dot{z}_{ss} - \dot{z}_{sp})}, \;\; F_a = g\dot{z}_{ss}, \tag{2.13}$$

$$F_{st} = K_{st}\left(\left(z_{ss} - z_{sp}\right) - \frac{d}{2}\right). \tag{2.14}$$

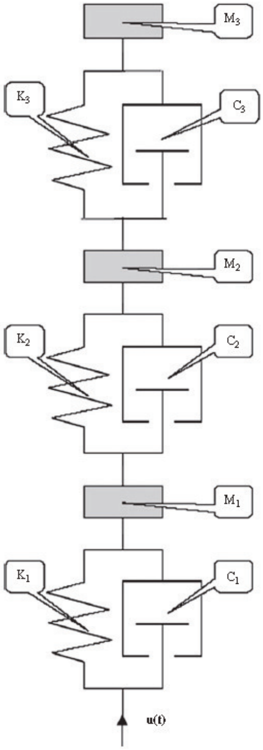

Fig. 2.6. 3-DOF HVR model of the motion [127]

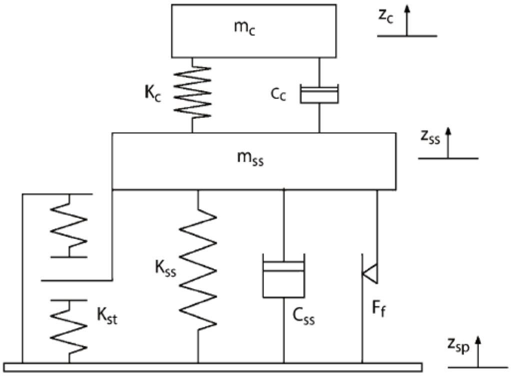

Fig. 2.7. Analytical 2-DOF model of the seat suspension of the motion [29]

New approach to system modeling based on possibilities of Finite Element or Neural Network methods allows to develop models dedicated to realize specific functions [154, 211].

2.4. Environmental impact of transport

Some documents indicate the cost to society caused by the vibration. Heavily regulated in EU ca. ~25 % of workforce is exposed to the vibration.

Traffic induced vibrations are a common source of environmental nuisance as they may cause malfunctioning of sensitive equipment, discomfort to people and damage to buildings and historical monuments [2, 66, 129, 195]. During the last few years, the interaction problem between moving vehicles and buildings has drawn much attention. Noise and vibrations from road and rail traffic through residential areas are ones of major concern, because nearby buildings and residential areas need to be protected from them. Like most vibration problems, road and rail traffic vibrations can be characterized by a source-path-receiver scenario. Vehicle contact with irregularities of the road and rail surface induce dynamic loads that generate stress waves, which propagate in the soil, eventually reaching the foundations of adjacent buildings and causing them to vibrate. Road traffic vibrations are caused by heavy vehicles such as buses and trucks. Passenger cars and light trucks rarely induce vibrations that are perceptive in buildings. Road traffic tends to produce vibrations in the range from 5 to 25 Hz. Rail traffic vibrations are produced in a similar way by vehicle contact with irregularities in the rail surface. The produced vibrations in this case are in the range from 60 to 100 Hz, according with [98, 156].

The problem of vibration caused by underground traffic is discussed in [99, 207, 208]. Other aspects of the vibration analysis of bridges under moving vehicles and trains can be found in [9]. The environmental problems of vibrations, caused by train/traffic, construction activities and factory operation, and other man-made sources are investigated in [184].

The group of technical objects most considerably exposed to the impact of vibrations includes railway transport lines, vehicle transport roads, airfields and ports. The vibrations generated by means of transport, analysed from the perspective of their environmental impact, are to be classified as elastic foundation vibrations generating paraseismic waves. With regard to the impact surface, one can distinguish between surface waves and body waves. Surface waves propagate on boundaries of two media, e.g. on the ground surface. Body waves propagate in all directions [26, 179, 180]. Depending on the propagation direction, paraseismic waves can be divided into primary and secondary waves. The propagation velocity of longitudinal waves is about two times higher than that of transverse waves. Having reached the medium boundary, e.g. the ground surface, these waves keep propagating as surface waves of either the Rayleigh or the Love type. The energy dissipation of surface waves is far smaller than that of body waves. Moreover, surface waves are characterised by a lower frequency and a higher amplitude. For all these reasons, they constitute a greater hazard to the environment and the infrastructure [122].

What matters particularly from the scientific and engineering perspective of the analysis of environmental impacts of transport is the phenomena emerging at the point of contact between a running wheel and the road pavement. They constitute sources of kinematic input functions transferred to the road pavement, propagating as paraseismic vibrations to the surrounding infrastructure. The most crucial source of vibrations of a running car is the road irregularity, and the highest dynamic input functions occur as a consequence of running on considerable irregularities, such as a hole, a kerb, tracks, manholes etc [3, 4, 122, 123, 145, 179, 180]. All of these issues affects on human exposure to vibration in transport [65, 77, 78, 144].

An integrated approach to the analysis of vibration impacts in transport should entail both the vehicle-man and the vehicle-road-environment systems.