CAMBRIDGE
Cambridge University Press
978-1-108-83495-7 — Vibration Protection Systems
Chang-Myung Lee, Vladimir Nicholas Goverdovskiy
Excerpt
More Information

1 Vibrations Destroying Human–Machine Systems Inside and Outside

1.1 Introduction

All vibrations, more or less important to human safety and comfort, are in the frequency spectra, which can be symbolically divided into the ranges close to 0 Hz, <10 Hz, and 10–100 Hz. This paradigm exists due to the human body that remains mostly invariable and, at the same time, due to variability and huge trend to a certain miniaturization of the machine mechanisms and other aids generating and transmitting the vibrations to humans. This is determined with the dimensions, shape, other specifics of elastic and dissipative elements, and spatial location of a human vibration protection system (VPS) inside or outside the machine.

The above ranges become critically important, as new objects appear that require high quality of the infra-low vibration protection in the first place, such as in bioengineering and medical research, in micro- and nanoelectronics, and in transport vehicles such as high-speed trains, helicopters, nanosats, and other modern and next-generation machines. This is clear when considering a key parameter of a VPS, namely, its natural frequency spectra, which are changed as the VPS structure and geometry features and other characteristics are changed. For instance, the natural frequency of a single-degree-of-freedom (1DOF) VPS is

$$f_0 = (2\pi)^{-1}\sqrt{n_g g z_0^{-1}} \tag{1.1}$$

where f_0 is the natural frequency of undamped VPS, $n_g \in (0;\ 1]$ is the coefficient of gravitation, $g \approx 9.81$ (m/s^2), and z_0 (m) is the parameter determining the system travel in a direction of vibration motion (see Table 1.1).

In Table 1.1, a VPS we symbolically consider as the “macro” if relative displacements and deformations of its elements are measured in dozens or hundreds of millimeters. For instance, a VPS like “suspended vehicle – track” can be considered as “macro,” and human biomechanism is also a “macro-VPS.” If the displacements and deformations are within the limits of few millimeters, then we deal with a “mini-VPS.” This concerns mechanical, pneumatic, hydraulic, gas, or electromagnetic mechanisms used in a vehicle. And a system refers to a “micro/nano-VPS” if the displacements and deformations are measured in micrometers or hundreds of nanometers. Finally, the human life support systems are interrelated “mini and micro/nano” VPSs.

Table 1.1. The VPSs and their frequency spectra of vibrations

Type of a VPS	System parameter: Travel z_0 (m)	System parameter: Natural frequency f_0 (Hz)	Forced frequency f (Hz)	Samples of vibrating machines and mechanisms inside/outside affecting human VPSs
"Macro"	(0.05–1)	0.5–2.5	2–40 and over	Transport or automotive technological machines: land passenger vehicles and trucks, railroad rolling stock and infrastructural objects, subsonic vehicles, helicopters, construction equipment, etc.
"Mini"	$(1–10) \cdot 10^{-3}$	5–16	5–70 and over	Aids of the vehicles and equipment, the engine units and elements
"Micro"	$(1–10) \cdot 10^{-7}$	50–160	100–400	Movable joints (bearings), MEMS, multilayer structures, and coatings
"Nano"	$(3–10) \cdot 10^{-11}$	500–900	$<1,000$	Micro/nanoelectronic elements of machines, mechanisms, and structures

There are indefinite number of the models to describe a certain vibration motion of human body and parts depending on the purpose and objectives. Figure 1.1 illustrates such models. In Figure 1.1a, the natural frequencies of the human biomechanism and life systems envelop the range of $f_0 = 2-100$ Hz. There are an infinite number of literature regarding the effects of the low-frequency vibrations on the whole human body (see one of these many, e.g., [1]).

As seen, the main resonant frequencies of human VPSs are located in the range of $f_0 = 2-20$ Hz. Besides, some human systems vibration and noise-related complaints account for 35 percent or over of all environment-related ones since human biosystems can very sensitive to the perturbation in the bandwidth close to zero values, namely, $f_0 = 0.04-0.40$ Hz [2]. This problem is ubiquitous regardless of age and residence region. The impacts increase direct health-related effects such as performance issues, sleep disturbance, and annoyance, as well as indirect ones such as dysfunction of the autonomic nervous and cardiovascular systems. Obviously, these effects will increase as the transportation distance and time increase.

Furthermore, a composite spectrum of a land vehicle "macro"-VPS includes three typical bandwidths of natural frequencies. These are vibrations of sprung mass ($f_0 = 2-4$ Hz) and unsprung mass ($f_0 = 10-20$ Hz) and the structure-borne vibrations (usually, $f_0 = 40-60$ Hz) of the vehicle body and its structural elements (Figure 1.1b). A sprung mass of a car includes the masses of chassis (or body), engine, exhaust system, transmission parts (e.g., differential gear), as well as the masses of a human operator, passengers, and/or cargo. While an unsprung mass consists of the tires, elements of function-generating mechanisms, control arms, braking systems, and so on.

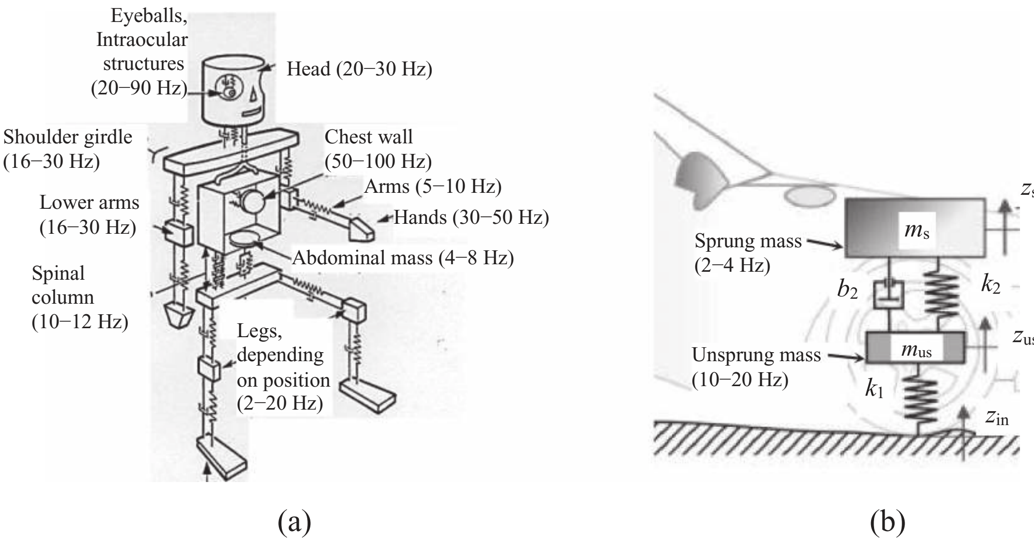

Figure 1.1 Simplest models of “macro-VPSs.” Natural frequencies of (a) human biomechanism and (b) a two-mass system of a land vehicle “carbody–1/4-car suspension−road.”

Excitation in a “mini”-VPS is generated by the vibrations in the numerous movable joints (bearings, guiderails, etc.) of the mechanisms and other aids or due to vibration of unbalanced elements of operating engines depending on the driving mode as sampled, for example, in Chapter 10 (see Figure 10.8) [3]. The relative displacements in the joints are small in comparison with the overall dimensions of the mechanisms and units. The natural frequency spectra of these “mini”-VPSs are from $f_0 = 5-70\,\text{Hz}$, however, the resonances are distributed in a range from $f_0 = 1.5-2.5\,\text{Hz}$ to hundreds of Hz due to relative displacements and deformations of individual joints and drivetrains (kinematic chains joined). We will discuss these aspects in Chapters 8–10 in more detail.

It would seem that there is little in common in the vibration dynamics of a “mini/nano”-VPS like conventional widespread rolling bearings and unmanned aircraft such as nanosats (especially at the starting, i.e., least reliable, flight phase).

The nanosats took advantages of smart telephony and other widespread technology based on the MEMS and NEMS. They provide the most cost-effective way of using the space. However, in terms of the vibration spectrum generated by both VPSs, they have a common feature. Namely, the most intense vibrations in different types of rollers and sliding bearings are generated at the low- and medium-frequency spectra (an envelope spectrum) from $f_0 = 18-125\,\text{Hz}$ [4]. While, a variety of micro/nanoelectronics elements inside the nanosats orbital modules and other cutting-edge technologies are under intensive low-frequency vibrations in the frequency range from almost zero to 125–150 Hz, as well as intense linear accelerations (the crest factor is 4 and over), when risking being destroyed long before the start of orbital work. However, the nanosats suffer infant mortality. The environment vibration and shock impacts affect the mission failure. For instance, 80 percent of the deployable mechanisms and chips have failures [5].

A comparison of the natural frequency spectra f_{0k}, $k = 1, 2, n, \ldots$ of the VPSs sampled above and forced frequencies $f \subseteq (0, 100)$Hz of vibration excitation shows that humans using machines are permanently under broadband resonance vibrations. Most of these vibrations occupy the spectra up to 100 Hz and the most intensive at $f_0 = 1{-}40$ Hz. These are the infra-low-frequency vibrations, which are most harmful and dangerous for human health and work activity. These vibrations are most harmful and dangerous for many types of machine as well.

Below we selected several types of transport vehicles that are most widespread in a human–machine system and whose vibration activity is most harmful and dangerous to humans. We focus on such types of vehicles since their vibrations affect humans most intensively and harmfully just in the infra-low-frequency range due to dramatic coincidence of the natural frequency spectra of the human VPS and external sources of forced vibrations acting on these systems. Next, we will try to theoretically and practically show how to break this "vicious circle" that worsens human health and activity, as well as the productivity of human–machine systems both operating and most promising.

1.2 Vibrations and Vibration Protection in High-Speed Train Systems

1.2.1 The Limits of Transport Infra-frequency Vibrations: Quality Criteria for Vibration Protection Systems

The transport vibrations affect passengers and crewmembers and have even greater impact on factory and office workers and residential areas [6]. Therefore, the vibrations are strictly limited by general health and industrial standards [7, 8]. The standards are used to compare the limits and intensity of vibrations in the infra-low-frequency range. The standards define a frequency-weighted vibration acceleration (m/s^2):

$$a_{\mathrm{w}} = \left(T^{-1} \int_0^T a_i^2(t)\mathrm{d}t \right)^{0.5} \tag{1.2}$$

where a_i is a root-mean-square value (RMS) measured in the x, y, or z direction of vibration motion within a time T(s) and filtered at ith frequency.

The weighted curves are displayed in the frequency domain. If the frequency domain vibration analysis is the method of measurement, then the RMS of accelerations at the central frequencies in the range given are defined in absolute (m/s^2) or relative (dB) units as

$$\tilde{a} = \sqrt{\frac{1}{t_{\text{int}}}\int_0^t a_i^2(t)\,\mathrm{d}t} \tag{1.3a}$$

$$L_{\text{a}} = 20\lg \tilde{a}/a_0 \tag{1.3b}$$

where t_{int} is the total integration time of the accelerations a_i, $a_0 \approx 3.16 \cdot 10^{-5}$ m/s^2 is the limit value of the acceleration. The time measurement is, for example, $t_{\text{int}} \leq 10$ s in steady-state vibration motion, and, for example, $t_{\text{int}} \geq 30$ s in a transient [9].

Most transport vibrations are random. Therefore, a fast Fourier transform (FFT) can be a more efficient algorithm of the vibration analysis both in lab and field conditions [10, 11]. The power spectral densities (PSD) are used to characterize random vibrations as well. A PSD is computed by multiplying each frequency bin in an FFT by its complex conjugate, which results in the only real spectrum of amplitude measured in g^2 units. The key aspect of a PSD, which makes it more useful for random vibration analysis, is that this amplitude is then normalized to the frequency bin width to get units of g^2/Hz. By normalizing the result, one can get rid of the dependency on bin width so that we can compare vibration levels in signals of different lengths.

Based on the measurement data, one may define nondimensional measures of VPS efficiency. The transmissibility T and crest factor F_{d} are among the parameters of the system efficiency [12]:

$$0 < T(D, \eta) = \sqrt{\frac{1 + 4D^2\eta^2}{(1-\eta^2)^2 + 4D^2\eta^2}} < 1 \tag{1.4}$$

where $D = 0.5Q^{-1}$ is the damping ratio informing that a VPS can be undamped $D = 0$, underdamped $D < 1$, critically damped $D = 1$, or overdamped $D > 1$; here Q is the system Q-factor, and $\eta = f/f_0$ is the frequency ratio.

The vibration transmissibility is a criterion of the VPS quality in steady-state vibration motion. This is used to evaluate the mechanical Q-factor in a certain range of stiffness and damping control.

The crest factor is the criterion to estimate the quality of a VPS under impulsive excitation:

$$F_{\text{d}} = [a_i(t)]_{\max}/\tilde{a} \tag{1.5}$$

where $[a_i(t)]_{\max}$ is a peak value of the frequency-weighted accelerations.

The T and F_{d} measured values shall not exceed the vibration limits by recommendations of ISO 2631 in assessing the human exposed to whole-body vibration and shock [7]. These data are used to compare them with the limits, as well as compare the quality of different types of VPSs.

The above measured data are then used to evaluate the ride comfort by nondimensional parameter, for example,

$$N_{\text{MV}} \approx 6\left(\tilde{a}_{\text{wx}}^2 + \tilde{a}_{\text{wy}}^2 + \tilde{a}_{\text{wz}}^2\right)^{0.5} \tag{1.6}$$

Vibration-induced health conditions progress slowly. In the beginning, people are tired of the vibrations, leading to distractibility, wrong decision-making under stress, and so on. As the vibration exposure continues, pain appears, and then the pain develops into an injury or disease. The pain is the first health condition that is noticed and should be addressed in order to stop the injury. A special parameter is introduced to evaluate the harmful and dangerous effects of vibration and, accordingly, to interrupt this harmful process for humans in a timely manner. This is the vibration dose value (m/s^2):

$$a_{\mathrm{VDV}} = \left(\int_0^{T_e} a_i^4 \mathrm{d}t \right)^{0.25}, \tag{1.7}$$

which is used to define the vibration impact for a certain exposure time T_e (hr) [7].

Figure 1.2a illustrates the vibration limits for all categories of humans (whole-body) if vibration exposure times are 2.5 to 24 hr [7]. By using these data, one can estimate discomfort experienced inside a moving train and the efficiency of the VPSs of rolling stock. For instance, for passengers and crew of a train, the vibrations are limited to the levels of $a_{w1} \leq 0.56 \sim 0.71$ m/s^2 (measured by using 1/3-octave filters), if exposure time is $T_{e1} \leq 2.5{-}4$ hr. This limitation concerns short-distance railroad lines. Evidently, the levels must be limited to $a_{w2(\max)} = a_{w1}\sqrt{T_{e1}/T_{e2}} \leq 0.23 \sim 0.39$ m/s^2 for a long distance, since the exposure time would be increased $T_{e2} = 8{-}24$ hr.

The limits of vibrations affecting different categories of people within a workday or a 24-hr period are shown in Figure 1.2b. By using these limits, one can estimate efficiency of the VPSs designed to protect, for example, railroad infrastructural objects (tracks, bays, depots, tunnels, bridges, etc.) from ground-borne vibration and thus the human environment outside a passing train. For workplaces and residential areas surrounding the railroad, the vibration limits are stricter: $a_w \leq 0.04 \sim 0.13$ m/s^2 [8].

1.2.2 Vibration Exposure Affecting Humans Inside and Outside a High-Speed Train

1.2.2.1 Actual Levels of Railroad Vibrations

High-speed railroad systems are under intensive development. They became dominant in some domestic transportation and are expected to produce long-distance intercontinental passenger traffic and freight service [13, 14]. This developmental trend requires a new strategy to improve vibration protection inside and outside moving trains, especially in the infra-low-frequency range, $f = 1{-}40$ Hz, which is the most harmful for human health and work activity [15].

The rail transport generates complex vibrations [15–18], some of which are increased at higher speeds of a moving train. Figure 1.3 shows the data measured on the ground within a radius of 7.5 m from ballasted track when a train passed at speeds of 70 and 200 kph [18]. Thus, actual levels of vibrations outside the train can

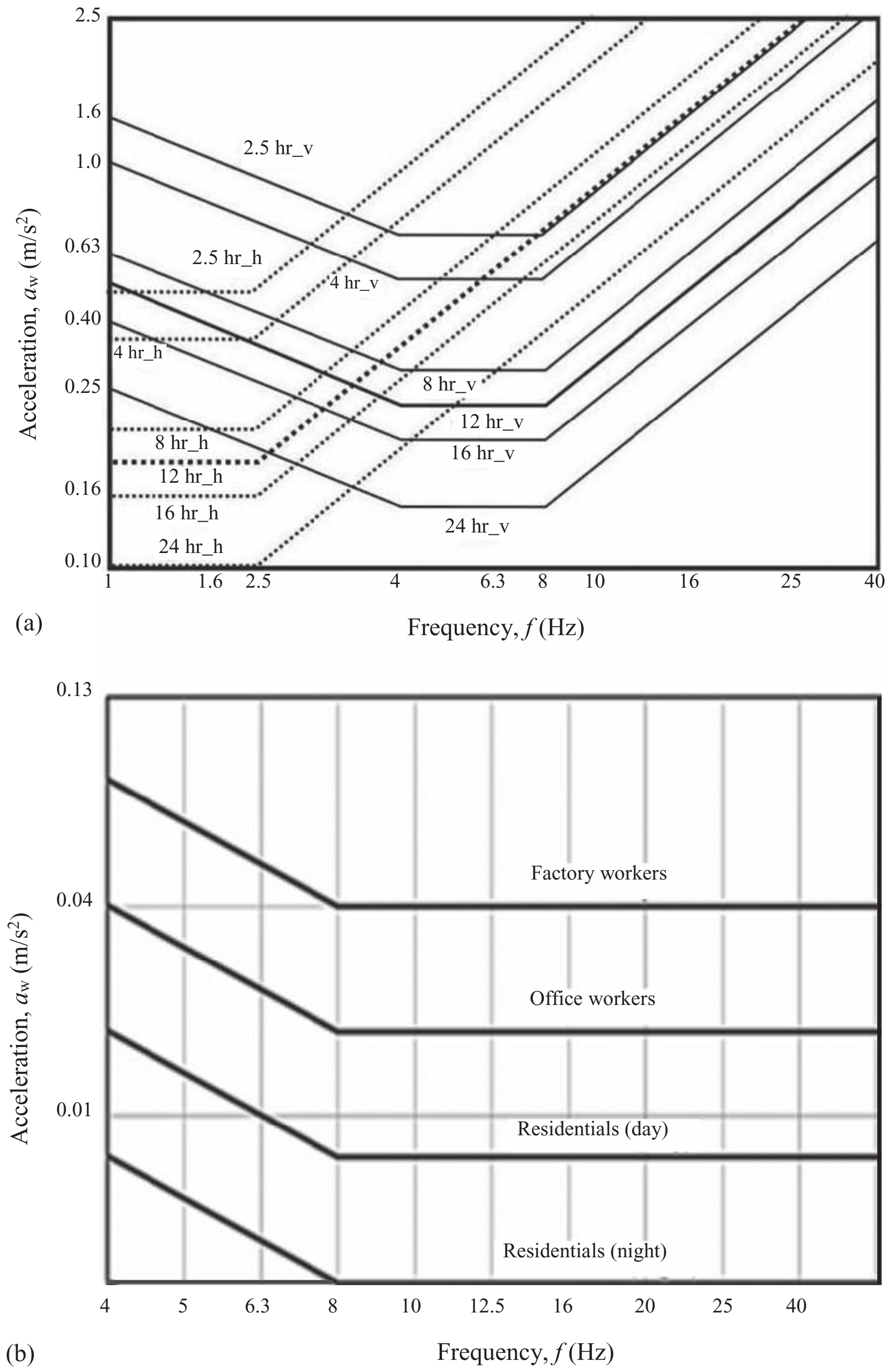

Figure 1.2 Vibration limits by general and industrial standards for human safety and comfort. Shown are the limits for vertical (solid line) and horizontal (dashed line) vibrations with reference to railroad transport (a) inside a moving train for different exposure time and (b) outside the train.

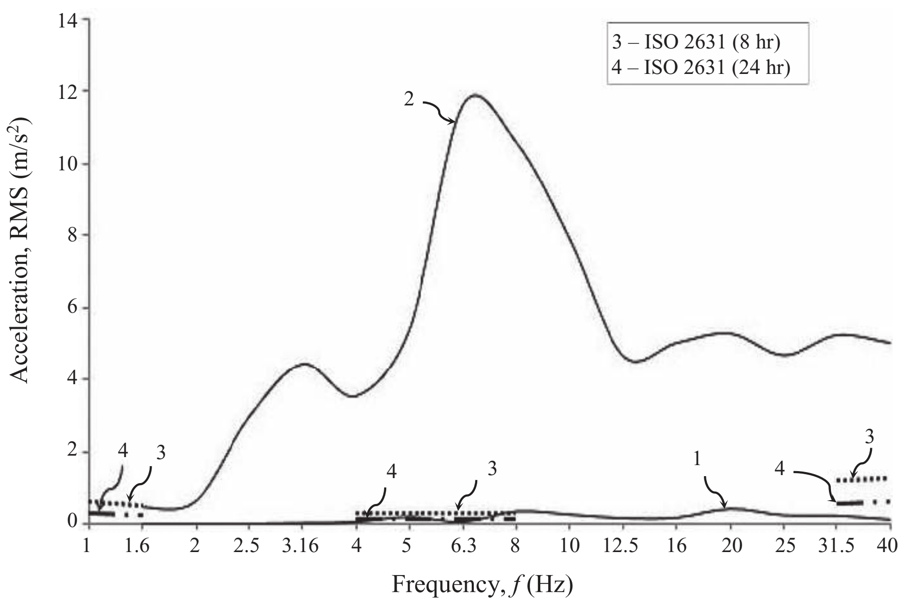

Figure 1.3 Infra-low-frequency vibrations generated by a moving high-speed train: actual vibration levels in comparison with vibration limits outside the train (on the ground), where 1 and 2 are the levels at the speed of 70 and 200 kph.

reach $a_w \geq 0.1-12$ m/s^2, which exceed the limits by 250 percent and more. This is a serious issue for humans living and/or working near a high-speed railroad.

Furthermore, in work [18] the data of simulating the motion of a passenger high-speed train carbody under vibrations in the frequency range $f = 1-30$ Hz are presented. From analysis of these data, one can conclude that the passengers and crew are in comfortable conditions if the train speed is less than 200−250 kph. However, train speeds already reach 350–600 kph and faster.

Discomfort appears and increases as the speed increases. Since the parameter of ride comfort calculated by Eq. (1.3) reaches $N_{MV} \geq 2.5$. Perhaps, the conditions inside the train that are considered as comfortable on short lines would become uncomfortable as the distance and time of transportation increases. Thus, a long distance of high-speed railroad passenger traffic is another issue for humans inside the train due to increased speed (see Figure 1.4).

The speed increase results in drastic differences between actual levels of the infra-low-frequency vibrations and the limits set by health standards. These high vibrations affect humans inside and outside of a high-speed train. The rolling stock and infrastructure of high-speed rail systems for a long-distance from 1,000–2,000 to 14,000 km are planned for an intensive development in the foreseeable future (see, e.g., [13]). Apparently, duration of a leg of a route of a passenger high-speed train will increase from 10–20 min to 2–4 hr. Then the issue of infra-low-frequency vibrations will sharply aggravate, and by Eq. (1.4), their harmful effects on humans will increase in proportion to the dose of vibration,

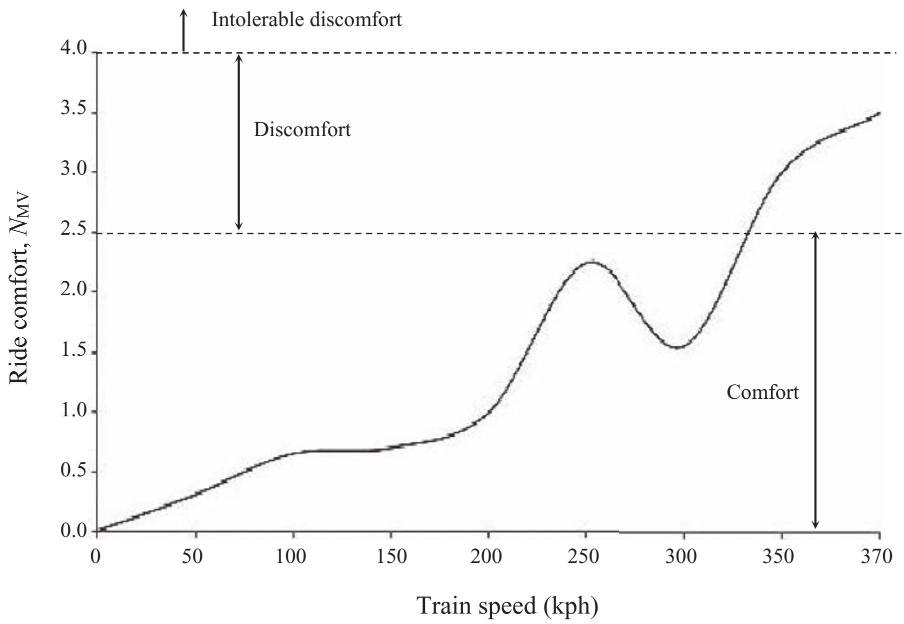

Figure 1.4 Infra-low-frequency vibrations generated by a moving high-speed train: actual vibration levels and their gain inside the train as the speed increases.

$VDV_L = VDV_S(T_L/T_S)^{0.5}$, where T_L и T_S are the vibration exposure time for long and short distances. In this case, the up-to-date railroad VPSs will become ineffective for protecting the passengers and crew. Apparently, fundamentally new railroad VPSs will be required, which must be much more effective especially in the infra-frequency range, $f = 0.5–10$ Hz.

1.2.2.2 Trends in Improvement of the Existing Railroad VPSs

Many types of VPSs for railroad rolling stock and infrastructural objects have been created and are continuously improved to increase ride comfort of crewman and passengers as well as protect people in residential and industrial areas located near railroad systems.

In general, a railroad VPS is multicascade. Not all the cascades are effective enough, especially in the infra- and low-frequency ranges, which are the most critical for human health and work activities as previously mentioned. However, one can (quite conventionally) focus three cascades that make a major contribution for reducing the most harmful and dangerous vibrations affecting humans inside a moving train and outside the train at a distance of some meters to several tens of meters from the train. These VPS cascades include the engineer or passenger seat suspensions (it could be conventionally cascade 1), a car or locomotive bogie suspensions (cascade 2), and a set of track bed elements (cascade 3).

As to cascade 1 (seat suspensions), Figures 1.5 and 1.6 illustrate the vibrations affecting humans inside a regular fast train. These vibrations are most intensive in the

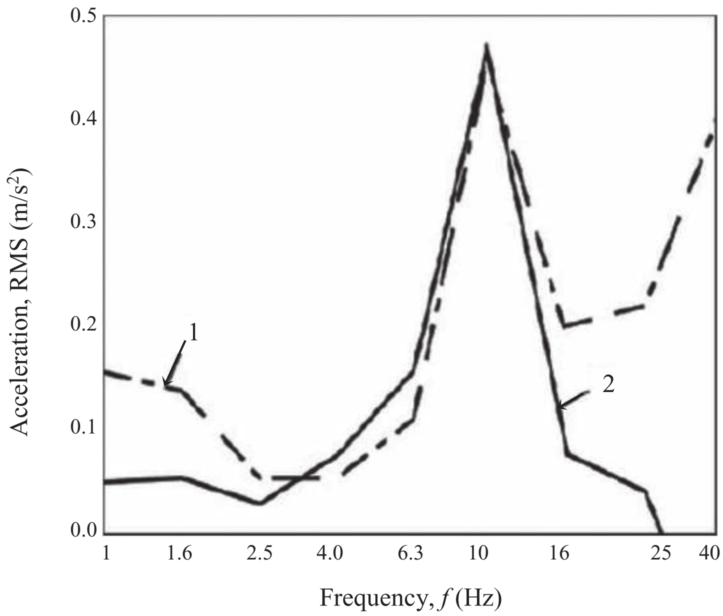

Figure 1.5 Actual levels and the limits of the infra-low-frequency vibrations on the stage 1 (engineman seat) of railroad VPSs in a regular passenger fast train, where 1 and 2 are the vibrations on the cab floor and seat cushion at the train speed of 120 kph.

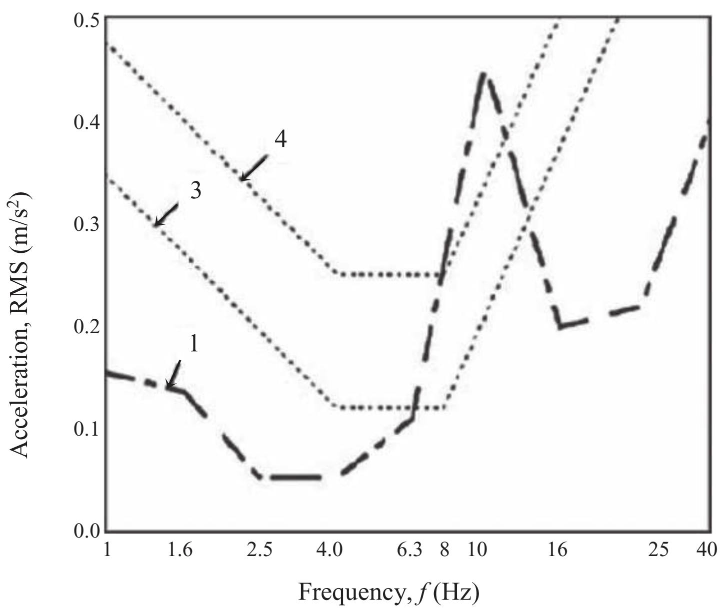

Figure 1.6 Actual levels and the limits of the infra-low-frequency vibrations on the stage 2 (carbody) of railroad VPSs in a regular passenger fast train, where 1 are the vibrations on the cab floor at the train speed of 120 kph and 3 and 4 are the limits for exposure times of 12 hr and 8 hr.