Manual of Vibration Exercise and Vibration Therapy

Jörn Rittweger
Editor

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Preface

After two decades of research, and after one decade of ample clinical application, vibration exercise and vibration therapy have conquered their positions, both in the local gym and in highly specialized centres for rehabilitation medicine. Physically, vibration exercise differs from most other types of exercise because it transfers mechanical energy into the human body and also because it induces movements that are much faster, and also smaller than with other types of exercise. Moreover, vibration can be combined with many other types of traditional exercise. Realistically, the proven effects by the vibration are often not superior, or at least not much superior, than could be achieved with more traditional forms of exercise. In many cases, however, addition of vibration leads to faster and easier achievement of the therapeutic target (see Chap. 13 on warming up).

Thus, vibration has established itself as an option for people who do not want to do other types of physical exercise. Alternatively, vibration can yield additional therapeutic benefits that would be difficult to reap in other ways. This is foremost the case where the patients' compliance is limited, because of physical or behavioural limitations, and where 'passive' types of exercise are needed. For example, introduction of vibration into paediatric rehabilitation (see Chap. 21) has been a tremendous success. This is because it helps children, who can normally not move, to expose their bodily systems to challenges that would normally only arise when children run or play. Metaphorically speaking, action and reaction is reversed in these rehabilitated children, as the vibration machines are working 'on the children'. Likewise patients with depression (see Chap. 21) can benefit from such a reversal, highlighting the former tenet. Another, much more speculative field where vibration could have unique benefits would be to exploit the neurophysiological effects (Chaps. 6 and 8) in order to pre-condition for training or performance optimization (Chap. 14)—readers are invited to study these chapters and to come up with their own ideas and trials!

However, general euphoria is out of place. Firstly, the evidence in support of vibration is still feeble in many areas. This is because many studies have been rather small, have tested only few endpoints that have not always been clinically relevant, and because of a lack of well-defined control groups in many studies. The reason for this lack of high-class studies is not only a lack of funding, but also a lack of knowledge of the widespread effects of vibration on the human organism certainly has also played a role. The primary aim of this book, therefore, is to provide an overarching platform of information for those who work with vibration. Thus, the book combines physical and biological principles of vibration with physiology and clinical application. Moreover, there is a specific chapter on the mechanical design principles of vibration exercisers (Chap. 3), which may help the reader understand what is possible in terms of machine design, and also what is available on the market. Unfortunately, though, the representative of only one company has accepted the invitation to contribute to Chap. 3, although I have made quite an effort to also involve other key manufacturers on the market.

The second aim of the book is to sensitize readers to the importance of the physical parameters of vibration therapy, such as vibration frequency and amplitude, duration, *etc*. Although many studies have demonstrated effectiveness of vibration interventions, we are still ignorant of exact dose-response relationships. It is hoped, therefore, that the next generation of vibration studies will establish such dose-response relationships, and thereby increase the effectiveness of the physical intervention.

Thirdly, safety aspects have to date been only sporadically considered in the field of vibration exercise and vibration therapy. Although there are only extremely few reports on adverse events in the published literature, it must be suspected that some events have gone unreported. Hence, this book is also meant to encourage the awareness of safety aspects. Indeed, it is here proposed to proactively collect information on occurrence and non-occurrence of adverse events.

I would like to end by saying thank you to all authors of this book, who have been extremely helpful and good to work with. Finally, I am also grateful for the unconditional support that I have received from my wonderful wife, Natia, and from my children whilst working on this book.

Cologne, Germany — Jörn Rittweger
February 2020

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Part I

The Fundamentals

1 The Physics of Vibration

Jörn Rittweger and Redha Taiar

1.1 Introduction

Vibrations are mechanical oscillations, which are closely linked to the concept of waves [1]. For whatever reason, standard textbooks of biomechanics are devoid of chapters on oscillation, vibration or waves [2, 3], and so are text books of physiotherapy. Hence, we anticipate that a good fraction of the readership will not be very familiar with the concept of oscillations. However, understanding them is very useful for practically working in vibration exercise and vibration therapy. Hence, we will be starting the chapter with a more intuitive outline of the questions and concepts, and we will be arriving at a more 'mathematical' level toward the end of this foundation chapter.

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1.2 How Oscillations Emerge

Periodic movements are very common. Think, for example, of your legs during walking, a leaf shaking in the wind, or a child on a swing. Physicists refer to such periodic movements by the wider term of ‘oscillation’. When discussing how they emerge, we have to distinguish two different kinds of oscillations. Firstly, something can start oscillating by itself. This is called a natural oscillation, and a typical example would be a tuning fork (Fig. 1.1 left). Secondly, one thing can be driven to oscillate by another thing. This is then called a ‘driven oscillation’, and a typical example would be a playground swing (Fig. 1.1 right).

Natural oscillations emerge from an energy transferal that excites the oscillating system so that it starts to move. Within the oscillating system, there is a continuous transformation from one type of energy into another. In the case of the tuning fork, this elastic energy is periodically transferred to kinetic energy and vice versa. The rate of energy transferal, which is determined by the physical properties of the oscillator, defines its natural frequency, which is also called the eigenfrequency. Other typical examples of natural oscillations can be found in musical instruments. For string instruments, the energy transferal can be either by a single impulse as in picking a guitar string, or it can be continuous as when a violin string is touched with a bow. Of course, a violin string can also be excited in picking (*pizzicato*), and it will produce a tone with the same pitch in either case. Some more examples of oscillations that occur during daily life are given in Table 1.1.

The situation is very different for driven oscillations: here, the frequency is imposed from an actuator onto a dynamic system. Often, the actuator is an engine, such as a car engine, or indeed a vibration platform. Whilst a vibration platform is purposefully built to operate at a given frequency, the vibration of a car engine is a by-product of its design. In the old days cars were much noisier, and truck seats were vibrating heavily until the 1980s to an extent that was even detrimental to

Fig. 1.1 Natural oscillation vs. driven oscillation. Mechanically speaking, the tuning fork (left) is excited once by a finger snap (= energy transferal). The two tines of the fork then naturally start oscillating to produce a specific tone, the pitch of which is defined by the structural properties of the tines. By contrast, the oscillation of the swing (right) is driven by the human ‘operator’. When the operator repeatedly agitates the swing at the right time points (= phase), the excursions augment with each cycle, and the energy stored within the swing system can accumulate. Of note, the swing oscillates at a specific frequency only, and it is in this sense physically similar to the tuning fork

Table 1.1 Typical real-world examples of oscillators in our daily life

Real-world example	Physical principle	Important properties
Tuning fork	Spring pendulum	Stiffness and mass
String of a musical instrument	Spring pendulum	Stiffness and mass
Metronome	Torsion pendulum	Stiffness and moment of inertia
Balance spring (e.g., in mechanical clocks)	Torsion pendulum	Stiffness and moment of inertia
Pan's pipe	Helmholtz-resonator	Air density and tube dimensions
Trumpet	Spring pendulum (lips) Helmholtz-resonator (pipe)	Air density and tube dimensions
Transistor radio	Oscillator circuit	Capacitance and inductance
Swing	Pendulum	Suspension length and gravity

spinal health (see Chaps. 4 and 20). Modern cars are much more comfortable, simply because they are designed to reduce vibrations. So, why do vibrations emerge in cars at all, and how is it possible to reduce them?

Within any complex mechanical structure, there will be some elements that behave in a way that is comparable to some kind of pendulum (Table 1.1). Thus, parts will start to oscillate when energy is transferred to them. Whenever the eigenfrequency of a given part matches the engine's pace, this will lead to the phenomenon of resonance.

Resonance is also the mechanism by which swings in children's playgrounds work (Fig. 1.1): to augment the excursions, the child has to invest energy, and this energy investment has to be in a certain temporal relationship. Physically speaking, the periodic action of the actuator (e.g., child) and the resonator (swing) occur in phase. In this way, energy storage within the system can accumulate over time. When car engineers aim at avoiding resonance, they have to shift the parts' eigenfrequencies away from the engine's actuation frequency. Musical instruments, on the other hand, are purposefully designed to amplify certain frequencies. This is beautifully exemplified in a trumpet, where the natural oscillations of the lips get amplified by the resonating pipe.

It is of particular note within the context of this book that most side-synchronous vibration platforms rely on the principle of resonance. Accordingly, these systems can struggle to maintain identical vibration frequency and amplitude for persons with different weight. Due to their make-up, most side-alternating systems do not encounter that problem.

1.3 How to Describe Oscillations

Since periodic movements, or oscillations, are somehow monotonous, one can simplify their description by a set of variables. The most useful descriptors are frequency, amplitude and phase (see Box 1.1).

Box 1.1

- The oscillation *frequency* (Fig. 1.2a) tells us how many cycles occur per unit time (a cycle being one full repetition of the movement). Sometimes, the periodicity or oscillation period is mentioned. It describes the time required for one cycle. Mathematically, it is therefore inversely related to the frequency. In other words, frequency and period convey the same information.
- The *amplitude* (Fig. 1.2b) tells us how large the movement is in each cycle. There is an important caveat: Whilst mathematically speaking the amplitude describes the movement from equilibrium to the maximal excursion, the so-called peak-to-peak amplitude describes the distance between the two maxima on either side of the equilibrium. Obviously, the distinction between amplitude and peak-to-peak amplitude is crucial. Unfortunately, this distinction is not always made, even not in the scientific literature. Therefore, one needs to be very explicit when reporting the amplitude of vibrations [4].
- The *phase* information defines the timing of the movement (Fig. 1.2c). Although phase is at least as important as frequency and amplitude information (or in some instances even more important [5]), it is often neglected. We will see further down how important phase information is, in particular when two oscillators interfere with each other.
- The shape of an oscillation is more difficult to define—it is more of an intuitive concept. The standard mathematical approach to oscillations is by so-called Fourier analysis, which regards sinus waves as basis of all oscillations. It is important to realize, therefore that Fourier analysiscan misinterpret the shape factor of an oscillation. Accordingly, when an oscillation's shape deviated significantly from a sine curve, we need to use more advanced techniques (e.g., wavelet analysis of pattern recognition algorithms) in order to adequately quantify frequency, amplitude and phase in our signals.

When engineers speak about oscillations, they usually imply sinusoidal oscillations. This is because sinusoidal oscillations are more convenient to produce in machines than other types of oscillations, and also because the mathematical concept of harmonic oscillation yields sine curves as a result. Moreover, sinusoidal functions are very convenient, as one can easily compute position, velocity and acceleration from each other when assuming a sinusoidal shape (Fig. 1.2). And, more complex wave forms can be generated, or simulated, by adding harmonics. These are oscillations with frequencies that are multiples of the fundamental frequency (Fig. 1.3d). However, there are many other different types of periodic movements and oscillations, in particular in biological systems. The heartbeat, hormonal cycles or nerve cell discharges may serve as well-known examples for this (see Fig. 1.2d). Still, we can describe such anharmonic oscillations in terms of frequency, amplitude and phase—it is just that they have a different shape.

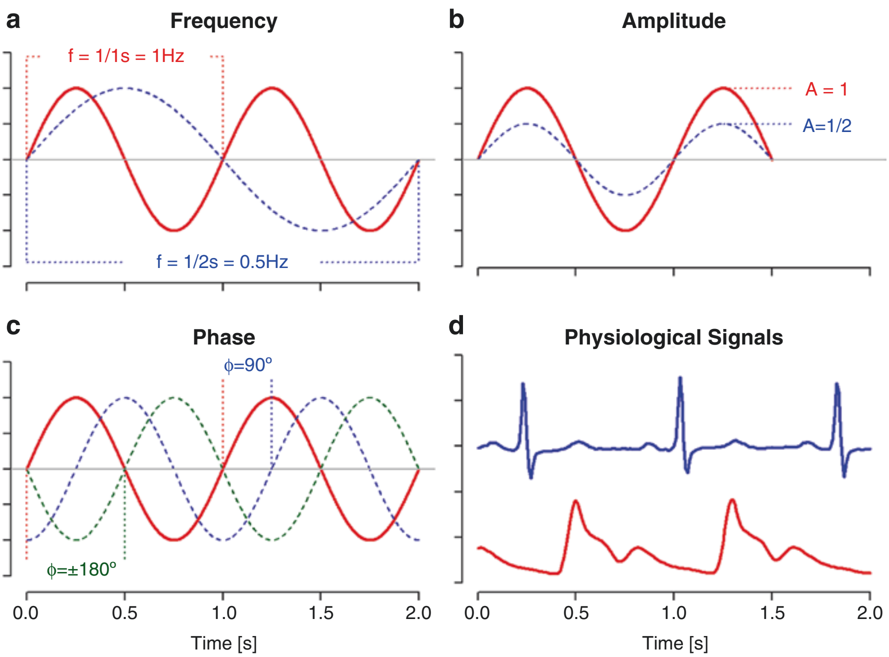

Fig. 1.2 Illustration of the concepts of frequency, amplitude, phase and shape in oscillations. Whilst curves in (**a**–**c**) are mathematically constructed sine curves, the curve in (**d**) depicts genuine physiological signals. (**a**) The red oscillation's period is 1 s, and its frequency thus 1/s or 1 Hz. The blue oscillation's frequency is half that of the red oscillation. (**b**) The blue oscillation's amplitude is half as large as the amplitude of the red oscillation. (**c**) The blue curve lags behind the red curve, and the green curve is antiphase to the red curve. Thus, the blue and green curves are said to be in phase relationship of $-\pi/2$ and - $\pi = -90°$ and 180°, respectively, with the red curve. (**d**) Arterial blood pressure (red) and electrocardiogram (blue) as physiological signals of oscillatory character

1.4 Interference of Oscillations

The superposition of two oscillators is called interference. When two oscillations have identical frequency and phase, their amplitudes will add (Fig. 1.3a). That is called constructive interference, and the constructive effect is the greatest when both oscillations are fully in phase. When they get out of phase, an opposite phenomenon may emerge: destructive interference (Table 1.2). Although both oscillations have identical frequency, the maxima of one oscillation coincide with the minima of another (Fig. 1.3b). They are antiphase and thus 'destroy' each other. When both oscillations have identical amplitudes, they can even cancel each other out entirely, which is the physical foundation of active noise cancellation.

Interesting phenomena may also arise when oscillations with different frequencies are superposed. For example, their frequency ratios are integer numbers, i.e., when one oscillation is 2, 3 or *n* times faster than the lowest frequency. This lowest frequency is then called the fundamental frequency, and the higher ones are called harmonics (sometimes also formants). Harmonic oscillations in musical instruments can emerge from simultaneous oscillations of strings at their full length and

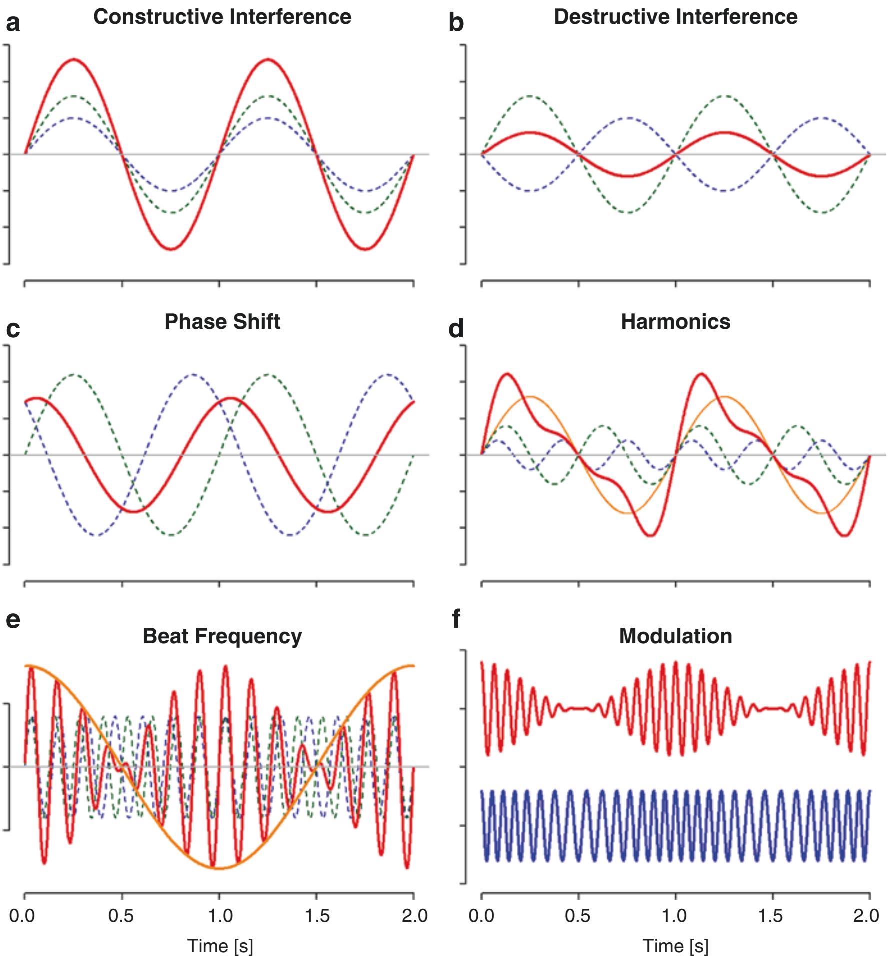

Fig. 1.3 Interference of oscillations. (**a**) Constructive interference: As the blue and green oscillations are in phase, the resulting red oscillation has greater amplitude then the red or green oscillation; (**b**) Destructive interference: The blue and green curves have been shifted so that they are antiphase. This is resulting in a substantial reduction of the red curve's amplitude; (**c**) Phase Shift: Phase lags between the blue and the green oscillations lead to a phase shift that results in the red oscillation; (**d**) Harmonics: Superposition of frequencies with integer ratio results in 'interesting' periodic oscillations. The red curve is, simply spoken, the sum of the first harmonic (also called mode or fundamental frequency, shown in yellow colour) and the 2nd and 3rd harmonics (yellow and blue, respectively). Note that the red and yellow curves are identical with regards to cycles per time, but obviously have a different shape. The more complex shape of the red curve almost resembles physiological signals such as blood pressure (see Fig. 1.2d); (**e**) Beat frequency: Superposition of two oscillations with a similar frequency results in the red curve. The blue and green oscillations are in-phase at 0, 1 and s, but antiphase at 0.5 and 1.5. This causes a waxing and waning of the resultant red oscillation. Such a variation in air pressure can be perceived by humans as a new tone with its own frequency (depicted by yellow line); (**f**) Modulation: Although the phenomenon of amplitude modulation resembles beat frequency, it is mathematically distinct. Frequency modulation (blue) is technically advantageous over amplitude modulation (red)

Table 1.2 Overview of different types of superpositions by two or several oscillators

Phenomenon	Frequency	Phase	Result
Constructive interference	Identical	Identical	Amplitude enhanced, phase unchanged
Destructive interference	Identical	Opposed	Amplitude reduced (up to cancellation), phase unchanged
Phase shift	Identical	Any other	Amplitude reduced, phase changed
Harmonic oscillation	Integer Relationship	Identical	Enrichment of information content
Beat frequency	Similar, but not identical	Variable	Emergence of a new oscillation

Note that the oscillators themselves do not interact (example: two instruments played in the same room), but that the resulting signal does

at ½, 1/3 or 1/n of their length (Fig. 1.3d). In music, harmonic oscillations are always more pleasant to hear than a pure sinus tone, and harmonics constitute the ‘acoustic color’ or ‘timbre’ of a given instrument. In human speech, harmonics or formants make up the difference between the different vowels and are thus an important source of information. Conversely, harmonics usually have undesirable effects in electric circuits, where they may emerge from some miss-behaving electrical devices.

A very interesting phenomenon is the so-called beat-frequency (Fig. 1.3e). It emerges from oscillations with similar but different frequencies. As a result, the phase relationship is variable, and constructive interference alternates with destructive interference. This results in two different frequencies that emerge from this, a carrier frequency that is defined by the mean of the two foundation frequency, and the beat frequency, which is defined by their difference. One can use this phenomenon, for example, when tuning an instrument: two tones have identical frequency when the beat frequency has disappeared. Note that although the beat frequency may resemble amplitude modulation of a signal, the two are mathematically not identical (Fig. 1.3f), and that they can be distinguished by spectral analysis.

1.5 Resonance and Damping

Whilst the previous section dealt with the interference as a mere superposition of oscillations, we now have to discuss interactions by which two oscillators affect the action of each other. Consider an oscillating actuator (e.g., a vibration platform) that drives a resonator. If the actuator’s excitation frequency matches the resonator’s eigenfrequency, and if the actuator and resonator are in phase, then this can lead to an accumulation of energy, even to an extent that is disruptive. This phenomenon is referred to as resonance catastrophe. To avoid this catastrophic event, soldiers (here: actuator) are required to march out-of-phase when crossing bridges (here: resonator). There are several ways to avoid resonance catastrophe. We have already discussed above that engineers can structurally design parts to

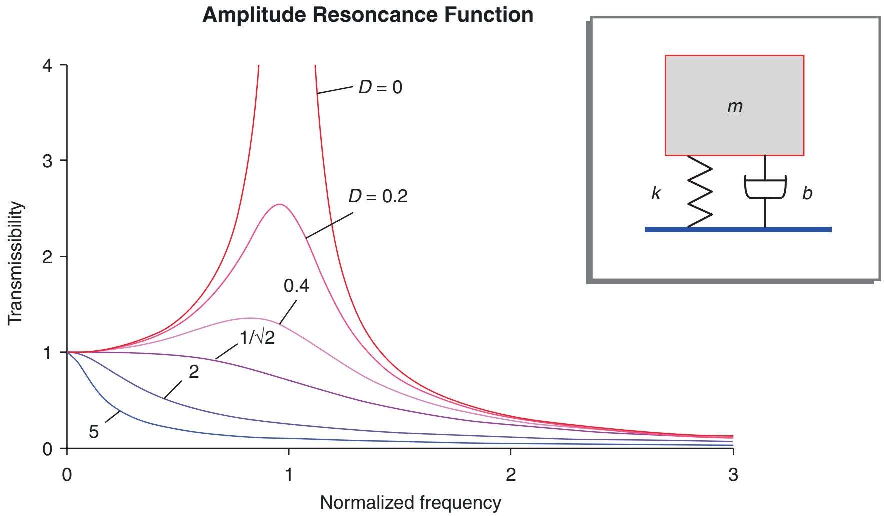

Fig. 1.4 Resonance in a damped mass-spring oscillator (see inlet). The resonance frequency is defined by mass *m*, stiffness *k* and friction *b*. Now imagine the blue plate in the inlet to be driven by an actuator at variable frequencies. Transmissibility is defined as the ratio of amplitudes in the resonator and in the actuator, and plotted against the frequency of the actuator, expressed in multiples of the resonance frequency (= normalilzed frequency). The damping coefficient D (see also Fig. 1.8) affects both transmissibility as well as resonance frequency. Amplitude amplification, i.e., transmissibility >1 occurs only when there is little damping. Figure reproduced from [6]

reduce or increase the resonator's eigenfrequency. An alternative way is to introduce damping elements. Dash-pots in the shock-absorbers of a car are an example (Fig. 1.4). Damping has two effects on the resonator: firstly, it withdraws a certain amount of energy from the oscillation. Second, damping reduces the eigenfrequency of the resonator. With regards to vibration exercise, it is important that muscles have such damping properties [7], and that they can act as shock absorbers in our body. However, any mechanical damping will lead to the absorption of energy and thus generate heat.

In order to practically assess whether resonance occurs in a given system, one can assess the presence of 'amplitude amplification'. This test makes use of the fact that resonance enhances movements within the resonator (example: swinging child). Thus, if any part of the system oscillates with greater amplitude, or with greater acceleration than the actuator, then this is indicative of resonance. Of course, such resonance phenomena occur only at certain actuation frequencies, so one usually has to test a range of different frequencies. To test for resonance of the human body during whole body vibration, for example, one can affix accelerometers to the platform and to the human body [8, 9]. Division of the acceleration signals (after subtracting Earth's gravity) will then yield the amount of amplitude amplification. However, most of the times, transmissibility of vibration signals is low, and amplitude amplification does not occur. It is thus apparent that amplitude amplification can only occur if there is little damping. Moreover, not all amplitude amplification causes resonance catastrophe, as this will happen only if the generated forces exceed the resonator's structural strength. Nevertheless, resonance should be prevented in vibration exercise, e.g., by alteration of muscle stiffness and thus ω_0 [7].

1.6 Waves

When parts of or body are vibrated, then the tissue deformations tend to spread out within our body. We therefore have to introduce the concept of waves. In physics there are three main categories of waves: gravitational waves, mechanical waves—such as swell, seismic waves or sound waves—and electromagnetic waves—such as light.

A wave is defined as a periodic movement, which can normally be described by a sinusoidal function (Fig. 1.2a and Eq. 1.1). However, the propagation of the wave is not equivalent to transport of matter. In fact, the wave per se does not transport any matter. Each wave is characterized by different quantities that are specific to it. According to these quantities, we can understand the nature of the wave, its properties and its consequences.

Transversal propagation: During the passing of the wave deformation, the different points of the environment move perpendicular to the direction of propagation, and the deformation is a transversal signal (Fig. 1.5a).

Longitudinal propagation: During the passing of the wave deformation, the different points of the environment move in the direction of propagation, and the deformation is a longitudinal signal (Fig. 1.5b). Transverse and longitudinal waves can have different velocities.

The wave length is one of the characteristics specific to each wave, whatever its nature. It is noted using the Greek letter lambda (λ). It represents the spatial periodicity of the oscillations, i.e., the distance between two maximum oscillations, for

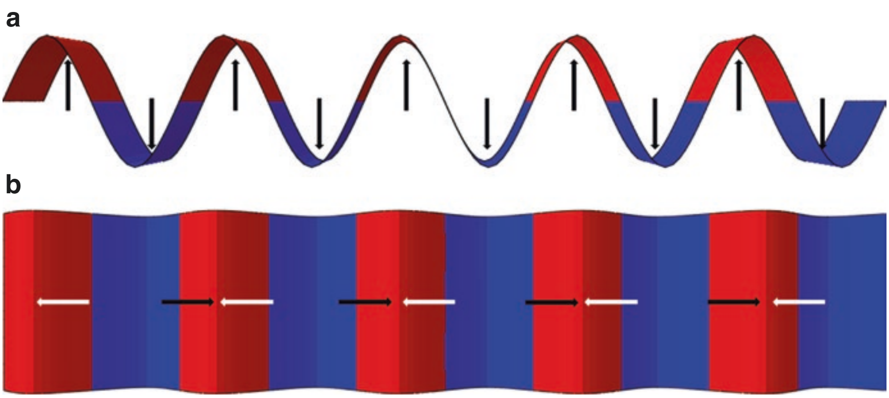

Fig. 1.5 (**a**) Transversal wave signal obtained when the different points move perpendicular to the direction of the propagation). In (**b**) a longitudinal wave signal results from the different points move in the direction of the propagation

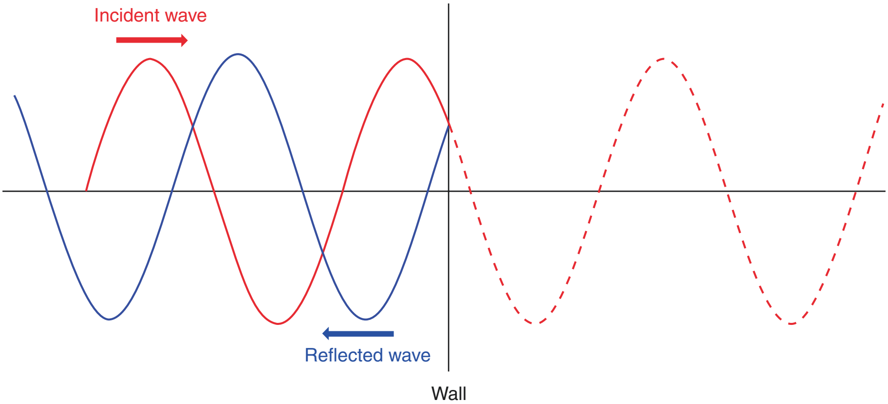

Fig. 1.6 Illustration of the reflection of the wave. The reverse reflected pulse is represented by the blue curve and after striking the wall

example. The wavelength is also the distance travelled by the wave during a period of oscillation. Thus, it is inversely proportional to frequency.

The wave length also depends on the speed at which the wave propagates in the environment. Thus, when a wave passes from one environment to another by changing velocity, its wave length will change, but the frequency remains the same. All this is described by the following relationship: $\lambda = v^* T_d = v/f$, where v corresponds to the wave velocity, T_d to the oscillation period and f to its frequency.

Reflection of waves occurs when the wave hits a fixed obstacle. After the collision, the wave propagates in the same environment, but in a different direction. A wave that strikes an object or an obstacle or shows discontinuity in the environment is partially reflected. For instance, we consider the case of a disturbance propagating along a rope. When the pulse reaches the end of the rope at its support point (Fig. 1.6), it exerts an upward force and the support opposes a downward force. The force exerted by the support creates the reverse reflected pulse. The pulse inversion corresponds to a 180° phase change. However, waves are not necessarily reflected, but can also be absorbed by an object.

1.7 Some Mathematical Background

Sinusoidal oscillations can naturally emerge, mathematically speaking, in cases that are described by 2nd-order differential equations. Such a situation is given in the suspended pendulum (Fig. 1.7), where the restoring force is opposite and proportional to the magnitude of the sideways deflection. Force is naturally related to acceleration, and acceleration is the 2nd derivative of deflection. Similar proportionalities can be found for other natural oscillators (see Table 1.3). It is this proportionality between deflection and its 2nd derivative that leads to the general solution by a sinusoidal function [1].

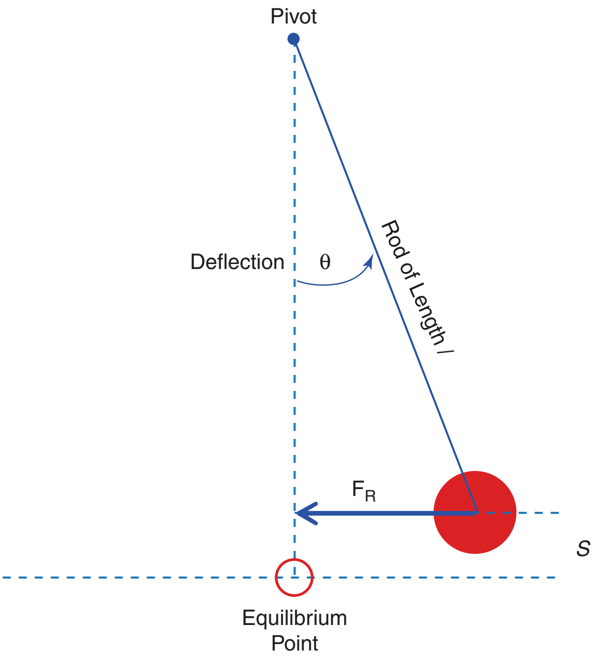

Fig. 1.7 Illustration of a suspended pendulum. Deflection of the pendulum away from the equilibrium by angle θ leads to vertical displacement s, and thus potential energy. If let loose, the mass (red bob) will have transformed all of its potential energy into kinetic energy at the equilibrium point, and then continue to swing to the other side until all of the kinetic energy is transformed into potential energy. This transferal of energy is affected by rod length l (the greater l, the slower the transfer), and by gravity (a pendulum will swing slower on the moon), but independent of the bob's mass. Mathematically speaking, the restoring force F_R is proportional to deflection angle θ, at least for small deflections. Therefore, the pendulum can be described by a 2nd order differential equation (for more information, see text books on physics)

Table 1.3 Eigenfrequency of some natural oscillators

	Eigenfrequency (f)	Variables
Pendulum	$f = \frac{1}{2\pi} \times \sqrt{\frac{g}{L}}$	π = circular number (3.1415) g = gravity (9.81 m/s on Earth) L = length of the string [m]
Spring-mass	$f = \frac{1}{2\pi} \times \sqrt{\frac{k}{m}}$	π = circular number (3.1415) k = stiffness of the spring [N/m] m = mass of the spring [kg]
Instrument string	$f_n = \frac{n}{2L} \times \sqrt{\frac{T}{\mu}}$	n = number of harmonic (e.g., 1st, 2nd, etc) T = tension of the string [N] μ = mass per unit length [kg/m] L = length of the string [m]

Note that these equations apply to idealized conditions, where there is complete conservation of energy. Note also that numerators (gravity, stiffness, tension) are positively associated with the eigenfrequency, whilst denominators (length, mass) are negatively associated. This is because the numerators foster the relative energy transferal, whilst denominators hamper it.

The basic equation for sinusoidal oscillations is

$$y(t) = A \times \sin(\varphi + t \times \omega) \tag{1.1}$$

Where y is the displacement, A is the amplitude, φ is phase, and t is time. These variables have been illustrated in Fig. 1.2. The circular frequency ω is given as

$$\omega = 2\pi f \tag{1.2}$$

And the peak-to-peak amplitude A_{p2p} is defined as

$$A_{p2p} = 2 \times A \tag{1.3}$$

It follows from Newton's second axiom that the maximal force exerted on a rigid body scales with the maximal acceleration (a_{max}), which can be collated as

$$a_{\max} = \omega^2 \times A \tag{1.4}$$

which is usually given in multiples of acceleration on Earth (g). The first derivative of the sine function in Eq. (1.1) is a cosine function

$$y'(t) = A \times \omega \times \cos(\varphi + t \times \omega) \tag{1.5}$$

and the sine function corresponds to the cosine function through a phase shift by π

$$\cos(t) = \sin(t \times \left(\omega + \left(\frac{\pi}{2}\right)\right) \tag{1.6}$$

Conversely, integration of a sine function yields a cosine function.

Finally, damped oscillations are described as

$$y(t) = A \times \sin(\varphi + t \times \omega) \times e^{-\delta \times t} \tag{1.7}$$

where e is Euler's number and δ is the damping constant. If the damping is constant, then it will only affect the amplitude of the oscillation. If the damping is proportional to velocity (also called viscous damping), then it reduces the amplitude and frequency. The damping constant can be graphically determined from the logarithmic decrement λ (Fig. 1.8), which is related to δ and the oscillation period T_d by

$$\lambda = \delta \times T_d \tag{1.8}$$

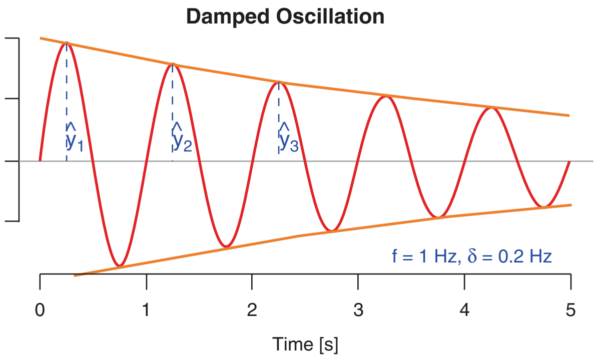

Fig. 1.8 In damped oscillations, the logarithmic decrement λ can be calculated by Eq. (1.8), or it can be graphically assessed as the ratio $\hat{y}_1 / \hat{y}_2$, or equally by $\hat{y}_2 / \hat{y}_3$, etc.

1.8 Analysis of Periodic Signals

There are several ways possible by which we can analyze the oscillatory components of signals with regards to their frequency, amplitude, phase and shape. Each of them has its specific strengths and weaknesses, and we can describe only a small selection here.

1.8.1 Spectral Analysis

This classical method is based on Fourier's theorem, which states that any periodic signal can be thought of as a composition of sine and cosine waves. When discussing the emergence of harmonics (Fig. 1.3d), we had already seen that superposition of sinusoidal waves can generate complex periodic patterns. The principle idea behind Fourier transforms is to back-trace harmonic superposition and to decompose empirical data into a hypothetical set of sinusoidal oscillations. Technically speaking, decomposition of N samples of a given time series yields N/2 frequency components as well as N/2 phase components. Thus, the entire information is conserved, which is a great strength of Fourier transforms. However, whilst interpretation of the amplitude information is straightforward (Fig. 1.9), humans typically struggle to comprehend the phase information, which is why this information is typically neglected. This can give rise to misinterpretations, namely when authors refer to 'higher frequencies' when in reality they speak of harmonics, i.e., the shape factors or formants. To avoid such confusion, the term 'frequency components' should be used (rather than 'higher frequencies'), and it should be understood that such higher frequency components typically result from deviations from the idealized sinusoidal curves, rather than by additional oscillations. For example, the vibration signals from riveting hammers and from other hand-held power tools are very rich in harmonics (Chap. 4), and they must surely not be confused with frequencies originating from other primary oscillations. Another example would be impacts that emerge from collisions with vibrating platforms, which can occur when affixment to the platform is insufficient (see Chap. 7). This is important, as higher frequency components are thought to be particularly provocative for vibration-related problems in occupational medicine (see Chap. 4).

Fourier transforms are not only useful for quantitative analysis of periodic signals, they also offer the mathematical foundation for frequency-selective filtering. This can often be useful in signal processing tasks.

1.8.2 Wavelet Transforms

To overcome the Fourier transform's limitations in assessing phase and shape information, wavelet analysis has been introduced in the early 1980s. The idea is here to *a* priori define the shape of the periodic oscillations, and to the approximate

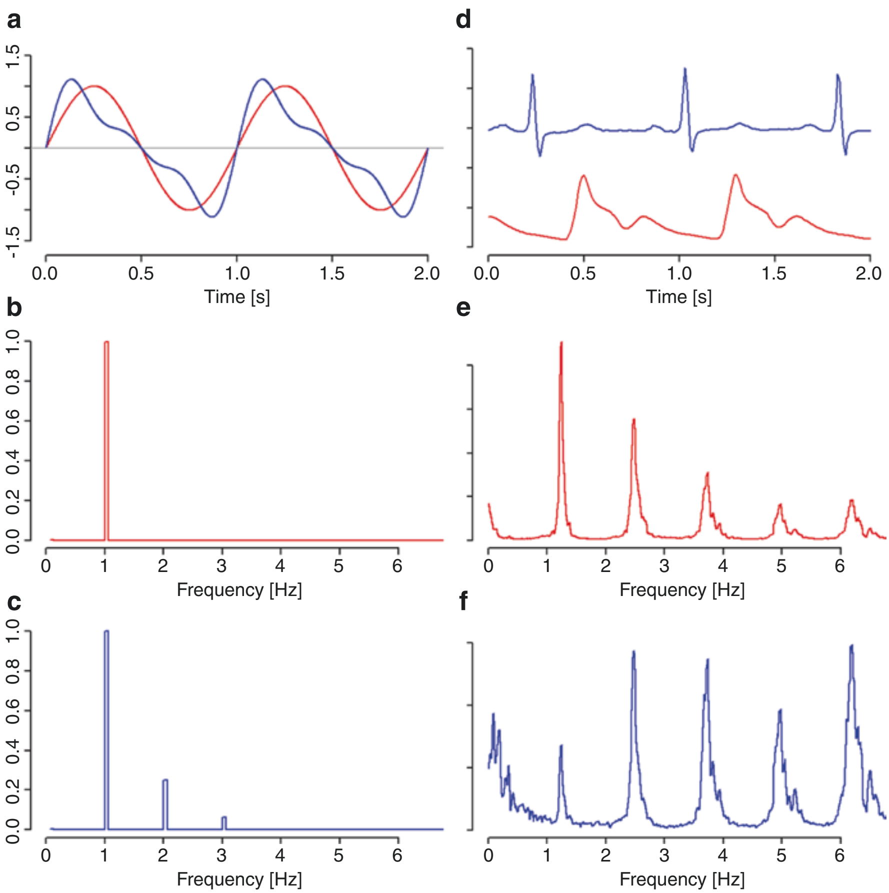

Fig. 1.9 Spectral Analysis of sinusoidal signals (left column) and of physiological signals (right column). (**a**) A pure sine wave (red curve) and an oscillation curve with 2nd and 3rd harmonic (blue curve, identical with Fig. 1.3d); (**b**) amplitude spectrogram of the red curve in A, showing that only one oscillation is present at 1 Hz; (**c**) amplitude spectrogram of the blue curve in A, showing peak at the fundamental frequency (1st harmonic, 1 Hz), as well as at the 2nd and 3rd harmonic (2 Hz and 3 Hz, respectively). (**d**) Blood pressure (red) and electrocardiogram (ECG, in blue) signals, which are identical with Fig. 1.2d; (**e**) amplitude spectrogram of the ECG in (**d**). Although the blood pressure curve looks quite similar to the red curve in (**a**), its harmonics have much greater amplitude. In the jargon of engineers, these are called 'higher frequency components', and they are often seen as shape factors. The greater the harmonic power, the 'edgier' is the oscillation; (**f**) amplitude spectrogram of the ECG signal. Here, the amplitude of the harmonics is even greater than the amplitude of the fundamental frequency. Note also that acceleration curves from riveting hammers (see Chap. 4) can look similar to an ECG

its occurrence in a given signal (time-frequency location). Mathematically, this works by generating a family of functions deduced from the same function (called mother wavelets) by translation and dilation operations (see Fig. 1.10). Thus, whilst Fourier transforms decompose a given signal into a set of sine waves that

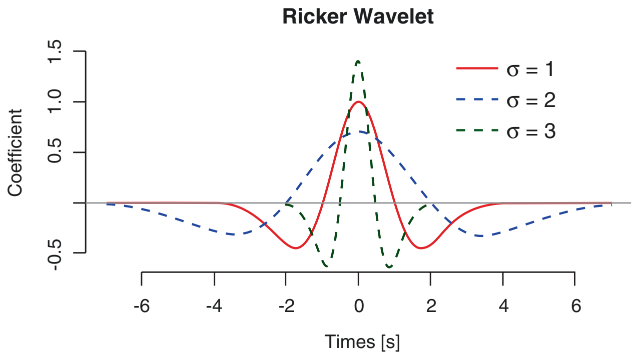

Fig. 1.10 The Ricker wavelet, also called 'Mexican hat' wavelet, is derived from the Gaussian function. It thus assumes a shape for which the frequency content scales with the parameter σ. As for the sine function, the curve oscillates around a mean value of 0. However, whilst the sine curve is unlimited, wavelets are limited in time.

extend over the entire signal, the wavelet approach is decomposing into wave elements that are limited in time. However, whilst the fundamental ideas behind wavelet transforms are promising, they have so far not become very popular among researchers.

1.8.3 Averaging Methods

Spectral analysis and wavelet analysis are extremely useful to analyze technical and physical signals. However, their strength is at decomposing signals, and not at recognizing patterns. Therefore, they are not so straightforward to use with physiological signals (see Fig. 1.9f). Hitherto, averaging methods provide an easy-to-use, intuitive alternative.

The principle idea is to analyze signal sweeps in relation to a time signal. Often, the time signal is an external stimulus, e.g., a light flash, a sound or an electric stimulus that is given to a test subject at regular (or irregular) intervals. That stimulus then serves as a timing event (E_T), and sweeps from another physiological signal (S) are overlayed and averaged. This approach is routinely used in clinical neurophysiology, e.g., for visually evoked potentials (E_T = light flash, S = electro-encephalogram (EEG)) or for brainstem auditory evoked potentials (BAEP, E_T = sound, S = electro-encephalogram (EEG)).

In neurophysiology, a related technique called peri-stimulus time histogram (PSTH) uses external stimuli and the discharge of a given neurone signal. Obviously, neuronal discharge is better modelled as an event than as a continuous signal. Hence, PSTH uses counts per time bin for its display, which requires some smart reasoning about the width of the time bin [10].

Using averaging methods in other fields of physiological data processing is straightforward. Triggering an ECG, for example, is as easy as triggering neural

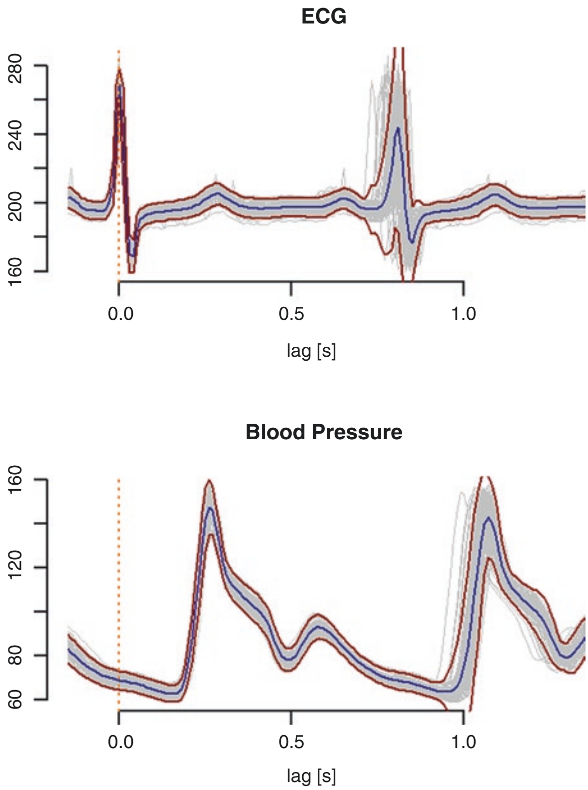

Fig. 1.11 Illustration of how averaging methods can help. Here, the ECG signal has been thresholded at a value of 240 to yield a series of timing events E_T. Next, sweeps of the blood pressure signal are overlayed such that they range from 0.15 s before (=negative lag) until 1.35 s after E_T (=positive lag). The individual sweep data are displayed as grey curves in the resulting peri-stimulus plot. In this plot, all ET coincides with lag = 0 (indicated by yellow line), and the blue curve denotes the averaged blood pressure over the cardiac cycle. In this example, the 95% confidence interval is indicated by red curves. Note from the upper figure that peri-stimulus plots can also be used to quickly judge the accuracy of the triggering process: Accuracies in the triggering reveal themselves by grey curves that do not follow the averaged curve

discharge (see Fig. 1.11). This can be used to get an averaged blood pressure, to check the accuracy of the ECG-triggering, and also to look at relationships between the cardiac rhythm and other oscillatory processes in the body. As illustrated by Fig. 1.11, the approach is very powerful in assessing the shape of an oscillatory process when the physiological signal does not follow any analytical mathematical function.

Averaging methods are also straightforward for the analysis of human vibration exercise. Either the position of the vibration platform or an accelerometric signal can be used for E_T, and S could consist in signals as varied as perfusion, joint angle or muscle fascicle length [11].

1.9 How to Quantify Signal Amplitude and Magnitude

Finally, we need to shortly discuss the concept of amplitude in some more detail. This is important, as the different measures of amplitude are frequently confused in the literature [4]. All is simple if we are to deal with sine curves. Then the positive peak amplitude A_{Peak} is given by the displacement between $\phi = 0°$ and $\phi = 0°$ (see Eq. 1.1 and Fig. 1.12a). As the sine wave is symmetric, the peak-to-peak amplitude

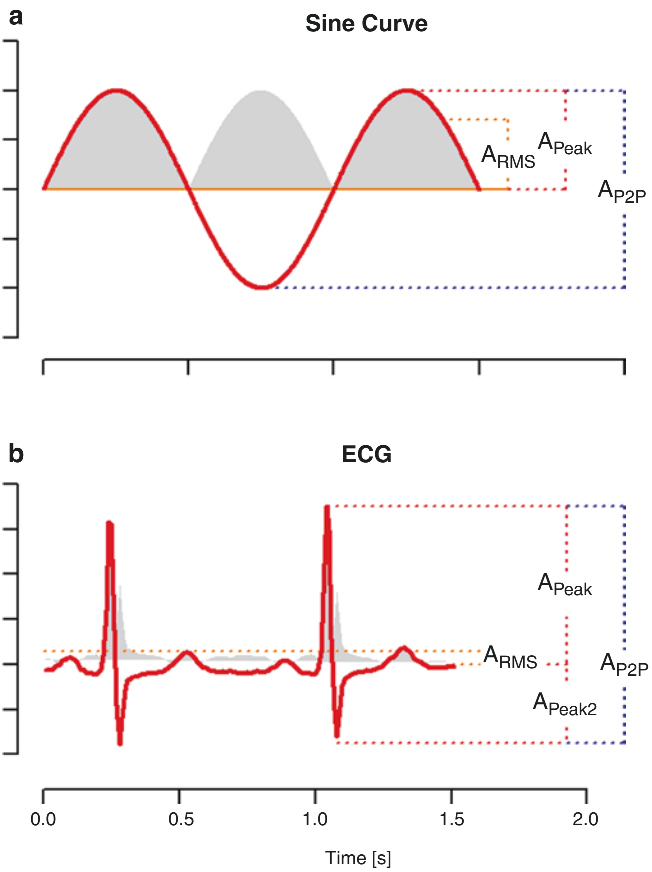

Fig. 1.12 Illustration of the different measures for signal amplitude. (**a**) sine curve. Peak amplitude is defined as the difference between mean value and the extreme value, both positive as well as negative. In the case of the sine function, the excursions are symmetrical, and A_{P2P} is simply 2 × A_{Peak}. The sinus function's absolute value is displayed as grey area, and its average is referred to as A_{RMS} (indicated in yellow), where *RMS* stands for root-mean-square ($RMS = \sqrt{mean\left(x^2\right)}$). *RMS* is mathematically equivalent to *(mean(|x|))*. This value is quite important, as it is directly related to the mechanical power of the vibration. (**b**) ECG signal. Because of the asymmetry of the signal, the positive and negative A_{Peak} have different extent, and A_{P2P} cannot simply be calculated, but has to be processed from the data. For similar reasons, A_{RMS} gets relatively smaller in relation to A_{P2P} for 'edgy' signals such as ECG

A_{P2P} is simply $2 \times A_{Peak}$ (Eq. 1.3). In addition, the averaged absolute amplitude A_{RMS} can be calculated for sinusoidal functions as $A_{Peak} / \sqrt{2}$. Thus, as long as we know at least one of the three ($A_{Peak,}$ A_{P2P} or A_{RMS}), the other two can be calculated in the specific case of sinusoidal functions.

This changes dramatically when we deviate from sinusoidal oscillations and turn to real-world data. As can be seen from Fig. 1.12b, the negative and positive A_{Peak} may have different magnitude. As a result, we cannot simply compute $A_{P2P,}$ or A_{RMS} from A_{Peak}, but rather have to assess those empirically. This can have a strong bearing on comparisons between different vibration devices. For example, if one of the systems produces relatively more higher frequency components than the other, then it also has, for the same A_{RMS}, a greater A_{P2P}. Thus, the comparison of vibration amplitudes is not as straightforward as it may seem.

Another term that is often used in the field of vibration exercise is the so-called vibration magnitude [12], which is defined as the peak acceleration a_{max}. For sinusoidal functions, it can be easily calculated (Eq. 1.4), and its importance consists in the fact that acceleration scales with the force that the body is exposed to. However, as for A_{RMS}, a_{max} strongly depends on the oscillation's shape, and one can normally not rely on calculations from the vibration frequency and the targeted A_{Peak}.

In summary, the different descriptors $A_{Peak,}$ $A_{P2P,}$ A_{RMS} and a_{max} must not be used interchangeably. Moreover, each of them has its specific implications for vibration exercise and therapy. Whilst A_{Peak} and A_{P2P} indicate the range of motion, A_{RMS} scales with the mechanical power, and a_{Peak} is related to the peak force. Given that many vibration exercise devices generate vibrations that deviate substantially from the sinusoidal shape, it seems mandatory for scientific and medical publications to report at least $A_{P2P,}$ A_{RMS} and a_{max}.

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