Oscillations and Waves

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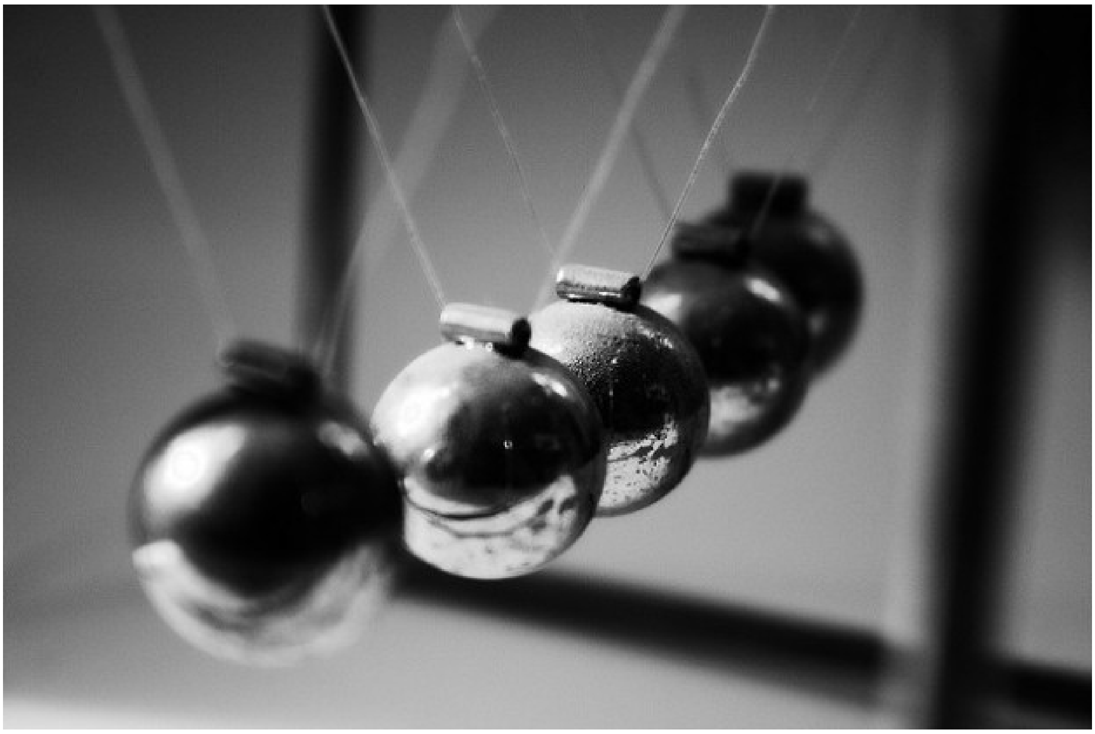
In diagnostic sonography, the so-called Doppler effect is used for the determination of blood flow velocity. This is done by measuring the frequency of the sound reflected by detected blood cells. The sound is reflected by the blood cells. What exactly is sound, which vibration modes exist and how do they react on interfaces—all of this will be addressed in the following article.



Oscillation

Oscillations are **processes in which a physical quantity changes periodically in dependence of time**. These include movements that occur periodically around an idle position.

The most significant vibration form is the harmonic vibration; this periodic change of physical quantity is sinusoidal. All other vibration modes are not harmonious.

Basic Concepts of Oscillations and Waves

- A complete back and forth movement of the oscillating body is called a **period**.
- The **amplitude** is the extent of a wave measured from the highest peak down to the zero position.
- The **period duration T** is the time needed for an oscillating body to move

back and forth, i.e., to fulfill one period. It is often referred to as just **period**.

- **Frequency** is the quotient of the number of periods and the time required for it.
- **Elongation** is defined as the current distance from the zero position.
- **Circular frequency** is the angular velocity of a circular movement whose projection on a straight line results in a harmonic oscillation.
- The **phase** is specified by the two oscillation parameters elongation and time and is indicative for the current state of oscillation.
- The **damped oscillation** is an oscillation in which the amplitude of the oscillating quantity decreases with time due to frictional forces.
- **Undamped oscillations** have constant amplitudes. However, it is necessary that the energy supplied to the vibrating system is maintained. In the case of constant small energy losses, a sustained undamped oscillation, in reality, is only approximately possible. If one wants to create a real undamped oscillation, the energy losses that occur must be compensated by regular energy supply.

Undamped Harmonic Oscillation

Harmonic oscillations are also referred to as sine oscillations. The reason for this is that its elongation is a sinusoidal function of time.

The harmonic oscillation is an irregular accelerated motion. Its acceleration is a function of time. Find out more in the articles “Mechanics Part I” and “Mechanics Part II.”

At any given time of harmonic oscillation, a force acts in the direction of acceleration that wants to bring the oscillating body to its center position. This force is known as the **restoring force**. This restoring force is proportional to the elongation.

The base equation of dynamics for mechanical oscillation is as follows:

$$\text{restoring force} = \text{mass} \times \text{acceleration of gravity}$$

$$Fr = m \times a$$

From this principle, the **equation of the undamped harmonic oscillation** can be derived:

$$\ddot{y} + y \times \omega^2 = 0$$

$y \Rightarrow$ Elongation
$\omega \Rightarrow$ Angular frequency

Forced Oscillations

Whenever an oscillatory system is displaced and released from its zero position, it will begin to oscillate. If no more external forces are applied, it is a **free oscillation**. The frequency of the **free oscillation** is called natural frequency, or eigenfrequency.

If, however, an external periodical driving force is imposed on the oscillating system to keep it going, then one speaks of **forced oscillation**. There are **three forces** acting on the oscillating system:

1. Conservation force
2. Damping force

3. Excitation force.

Resonance

Resonance occurs when the excitation frequency matches the natural frequency of the oscillation. In small damping, the amplitude decreases greatly. In everyday life—and in technology—resonance plays a very important role.

As most mechanical structures are subject to an oscillating force, they can be stimulated by external periodic forces. **In the case of resonance this would result in an increase of amplitude followed by the destruction of the structure.**

In order to prevent such a “resonance catastrophe,” one has to avoid any periodic forces or maintain large margins between the natural frequency and the excitation frequency, provide damping options and allow a resonance frequency only for a short period of time which is less than the build-up time. **For rotary movements, the resonance frequency is referred to as a critical rotational speed.**

Superposition of Oscillations

Each oscillating system can execute several oscillations simultaneously. The individual oscillations overlap and form a resultant oscillation. In conclusion: **If the oscillating bodies excite to several oscillations, they then superpose themselves without interfering with each other.**

A distinction is made between **oscillations that possess the same oscillating directions and oscillations whose directions of oscillation are perpendicular to each other**.

If two harmonic vibrations with the same direction and same frequency are superposed, it results in a harmonic oscillation of the same frequency, whose amplitude depends on the individual amplitudes. The phases of the initial oscillations also affect the amplitude of the resulting oscillations.

When two oscillations with the same direction, but not the same frequency, are superposed, the result is a non-harmonic oscillation.

Waves

An oscillation process in an extended medium is called an oscillating wave. An extended medium consists of a vast amount of oscillating particles, all of which are interconnected. If one of these particles receives an oscillation impulse, it then becomes the center of a propagating wave movement.

A **wave** is a spatial and temporary periodic process, where energy—but no matter—is transported. The direction of energy propagation is called the **wave ray**. Perpendicular to the wave ray runs the **wavefront**. A wavefront is the geometric location of all the particles that belong to the same phase.

The distance between two successive wavefronts is called the **wavelength**. The distance between two neighboring particles of the same oscillation phase is the **wave propagation**. It is independent of location and time. The wave propagation can be analyzed according to **Huygens’ principle** of wavelets.

Huygens' principle: Every point of a medium covered by a wave motion can be regarded as the starting point of a new wave—a so-called wavelet. Each wavefront conforms to the envelope of wavelets. Huygens' principle applies to all types of waves, even to electromagnetic waves.

Wave Types

- **Longitudinal waves**: The particles oscillate back and forth in the direction of propagation. If the particles oscillate in the direction of travel of the wave, an overpressure (compression) occurs. If they oscillate opposite to the direction of wave travel, a vacuum (rarefaction) occurs. Compressions and rarefactions alternate among each other.
- **Transverse waves**: The particles oscillate perpendicular to the direction of travel of the wave. Transverse waves have troughs and crests which alternate.
- **Plane waves** are one-dimensional waves. They travel only in one direction.
- **Surface waves** are two-dimensional waves. Their propagation possibility is an expanding surface.
- **Sky waves** are three-dimensional waves. Their travel possibility takes the form of an expanding sphere.

When surface waves have a punctiform excitation center, the wavefronts are circles. When sky waves have a punctiform excitation center, the wavefronts are spherical shells.

The **velocity of wave propagation** is equal to the product of its frequency f, with which each particle of the wave oscillates, and its wavelength λ:

$$c = f \times \lambda$$

The following regularities have validity for the velocity of wave propagation:

Elastic transverse wave in solids:

$$c = \sqrt{\left(\frac{F}{(pA)}\right)}$$

Elastic longitudinal wave in solids:

$$c = \sqrt{\left(\frac{E}{p}\right)}$$

Longitudinal wave in liquids:

$$c = \sqrt{\left(\frac{K}{p}\right)}$$

c ⇒ propagation velocity
F ⇒ tensioning force
A ⇒ cross-sectional area
ρ ⇒ density of the medium
E ⇒ modulus of elasticity
K ⇒ bulk modulus

If two waves superpose and coincide in amplitude, frequency, and wavelength, but run in the opposite direction, a so-called **standing wave** occurs. In a standing wave, the spatial image does not travel any further. Locations at which the amplitude is maximum (**antinodes**) and locations with amplitude minimum or equal to zero (**nodes**) remain in a constant position.

Standing waves can occur with the reflection on a thinner or a denser medium. **A standing wave occurs most frequently when a plane wave superposes with itself after a reflection.**

Reflection

When a wave strikes the boundary of its medium onto another medium, it is completely or partially reflected. This process is called reflection. The **law of reflection** is as follows:

angle of incidence = angle of reflection

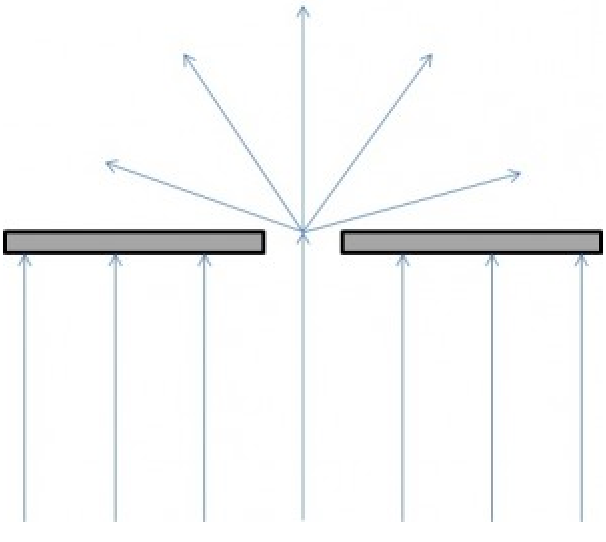
$$\alpha = \beta$$

A wave ray is refracted during the transition between two media, and the propagation direction, as well as the propagation speed, change. For the propagation velocities, the **law of refraction** applies:

$$\frac{\sin\alpha}{\sin\beta} = \frac{c1}{c2}$$

Diffraction

A further change in the propagation velocity of the wave can be found **at the edge of an obstacle**, such as a slit. The obstacle does not cast sharp shadows. The phenomenon of diffraction can be explained by the Huygens’ principle.



The energy of the wave-particle diffracted through the opening slit of the wall is distributed in individual directions after diffraction so that the energy parts decrease with increasing diffraction angle. The **diffraction angle** is the **angle between the original wave direction and the new wave directions**.

Electromagnetic Spectrum

The electromagnetic wave **is caused by the oscillation of electric and magnetic fields, which are coupled together**. They are dependent on the frequency.

Electromagnetic waves **can propagate both in free space and in a vacuum**. They do not need a carrier medium. In the vacuum, these waves propagate with the speed of light. The speed of light in a vacuum is according to current measurements c = (299792.5 + / – 0.9) km/s.

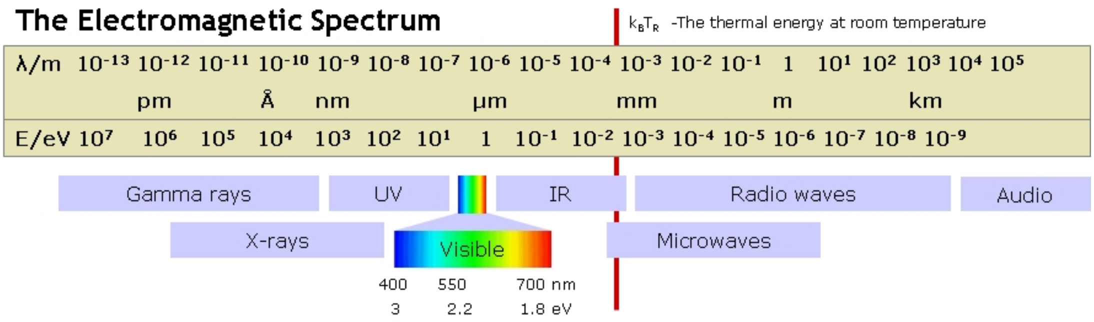
Infrared Light

The white light of an arc lamp or light bulb provides **invisible radiation that can be found in the visible spectrum next to red**. It is referred to as infrared radiation and results in the infrared light.

Ultraviolet Light

Outside the violet range of the visible color spectrum is the ultraviolet color range. The irritation and tanning of the skin under the sun are due to the ultraviolet light component. Mercury vapor lamps, which are used as artificial tanning lamps, also send out ultraviolet light.

The different impressions of color are projected to our eye by different frequencies of the visible spectrum:



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Gamma radiation

Apart from the nuclear components such as the protons, the neutrons, and the electrons, today there are more than 200 other **elementary particles** known. A lot of them are the result of the interactions between the terrestrial atmosphere and cosmic radiation or the product of nuclear disintegrations supported by particle accelerators. The elementary particles are **classified into the following groups**:

- **Leptons**: light particles
- **Mesons**: medium heavy particles
- **Baryons**: heavy particles

Most elementary particles exist with an antipole electric charge and a reversed magnetic momentum—so-called **antiparticles**. If a particle meets with its antiparticle, the result is **annihilation**. Its energy is released as gamma radiation.
Higher and Lower Frequencies
Photons

Sound Waves

Sound waves are **mechanical longitudinal waves**. They have their origin in the sound source, a vibrating body, and propagate in solids, liquids, and gases in the form of compression waves.

Example: The human ear is able to hear frequencies from 16 Hz to 20,000 Hz. Frequencies lower than 16 Hz are called **infrasound**. Frequencies higher than 20,000 Hz are called **ultrasound**.
In acoustics, a distinction is made in the following **types**:

- **Tone**: The pure tone is graphically displayed as a sinusoidal wave. The pitch of the tone is specified by the frequency. The ratio between the two tones is called the interval. In musical intervals, the lowest note is called the root – the fundamental tone. The higher note is the octave, the perfect fifth, the perfect fourth, etc. The musical interval of two tones, which can be detected by the sense of hearing, is defined by the quotient of their frequencies.
- **Sound**: Several sinusoidal oscillations superpose to a non-sinusoidal vibration. The pitch is determined by the root; the other sounds convey the timbre.
- **Noise**: A variety of many sounds with rapid changing frequencies and strength.
- **Bang**: A sudden loud noise lasting for a very brief moment.

Sound

Everything perceived with the human ear is called sound. We distinguish between tones and noises. The way we perceive a sound event depends on its volume, pitch, and timbre.

The sound comes from a **sound generator**—which is an oscillatory body.

In order for sound to reach our ears, **it must be transmitted by a sound carrier**. The propagation of sound requires solid, liquid or gaseous bodies as a sound carrier. Sound cannot be transmitted in a vacuum. A **sound source** generates progressive longitudinal waves in the sound carrier. The perception of sound occurs when these longitudinal waves reach our ears (sound receivers).

Speed of Sound

The speed of sound **specifies how fast the sound propagates in a certain sound carrier**. It is independent of frequency. In the air, for example, the speed of sound is 340 meters per second, and in water, it is 1440 meters per second.

When sound waves hit another medium, they are reflected at the transition boundary.

Example: In a sonographic measurement, frequencies of a certain size, transmitted by a sound source, are reflected at an interface (e.g., tissue or blood components in the Doppler method) and picked up with a measuring probe in a changed frequency. The distance covered can be calculated from the required time, given a known sound propagation speed (or known initial frequencies).

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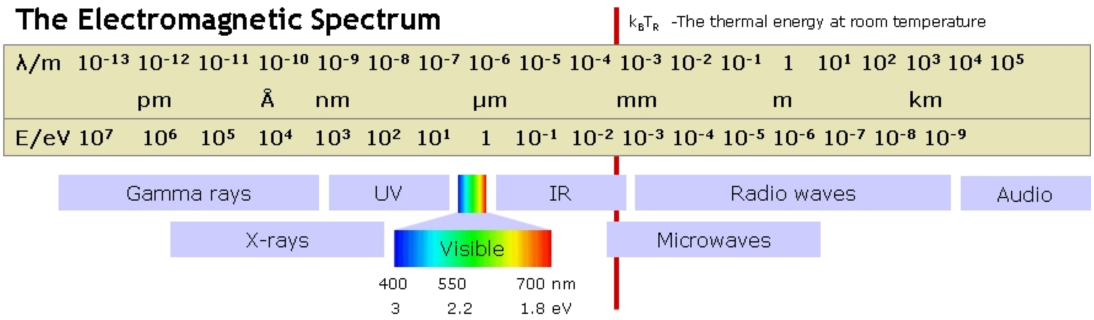

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Popular Exam Questions on Oscillations and Waves

The solutions can be found below the references.

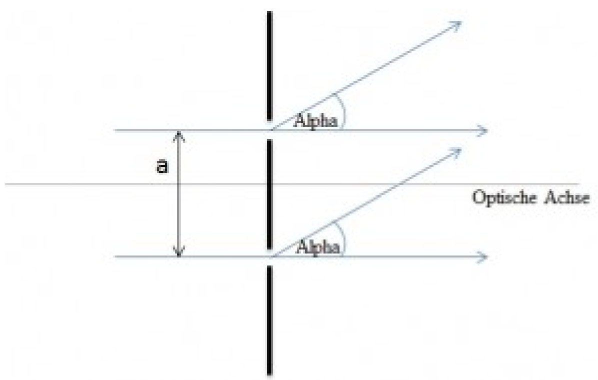
1. Longitudinal waves can be polarized just as transverse waves can be (statement 1) because (link) both longitudinal and transverse waves can be bent (statement 2). Which parts of this sentence are true?

A. Statement 1: correct, statement 2: correct, link: correct
B. Statement 1: correct, statement 2: correct, link: wrong
C. Statement 1: correct, statement 2: wrong, link: –
D. Statement 1: wrong, statement 2: correct, link: –
E. Statement 1: wrong, statement 2: wrong, link: –

2. Due to interference, two transverse wave trains should completely annihilate. What requirement has to be fulfilled hereto?

A. The path difference between the two wave trains is equal to zero.
B. The wave trains have the same amplitude.
C. The wave trains oscillate on the same plane.
D. The wave trains possess the same frequency.
E. The wave trains have a fixed phase difference equal to an odd multiple of π.

3. In a double-slit onto which light of the wavelength λ impinges, the first interference minimum can be observed for the radiation, which is diffracted by the angle α = 30° against the horizontal axis. How big is the slit distance a?



A. λ
B. 2 λ
C. λ / s
D. 0.86 λ
E. λ / 0.86

References

Staudt, Experimentalphysik, Bd. 1, Verlag Carl Grossmann.
Bünte, Das Spektrum der Medizin, Schattauer Verlag.

Correct answers: 1D, 2A, 3A

Notes