

Physics Formula Sheet

402-0023-01L Physics

2023/ 2024

Constants

Constant	Symbol	Value
Speed of light	c	3.00×10^8 m/s
Gravitational constant	G	6.674×10^{-11} N(m/kg) ²
Planck's constant	h	6.626×10^{-34} J.s
Mass of the electron	m_e	9.10939×10^{-31} kg
Mass of the proton	m_p	1.67262×10^{-27} kg
Charge of the electron	$-e$	-1.60218×10^{-19} C
Permittivity of free space	ϵ_0	8.85419×10^{-12} C ² /J m
Permeability of free space	μ_0	$4\pi \times 10^{-7}$ T m / A
Boltzmann constant	k_B	1.38066×10^{-23} J/ K
Avogadro's constant	N_A	6.022×10^{23} 1/mol

Oscillations

- **Natural Frequency:** $\sqrt{\frac{k}{m}}$

- **Damping Ratio (ζ):**

$$\zeta = \frac{b}{b_c}$$

where $b_c = 2\sqrt{mk}$

Quality Factor (Q factor)

The Q factor is a dimensionless parameter that describes the damping of an oscillator. It represents the energy stored to energy dissipated ratio.

$$Q = \frac{1}{2\zeta} = \frac{\omega_0}{\Delta\omega} = 2\pi f \times \frac{\text{energy stored}}{\text{power loss}}$$

where $\Delta\omega$ is the bandwidth over which the energy is stored.

Types of Oscillations

- **Critically Damped** ($\zeta = 1$): The system returns to equilibrium as quickly as possible without oscillating.
- **Overdamped** ($\zeta > 1$): The system returns to equilibrium without oscillating but slower than the critically damped case.
- **Underdamped** ($\zeta < 1$): The system oscillates about the equilibrium position with a frequency ω_d given by:

$$\omega_d = \omega_0 \sqrt{1 - \zeta^2}$$

1

Electrostatics and dynamics

$$\mathbf{F} = \sum_{i=1}^N \frac{q_0 q_i (\mathbf{r} - \mathbf{r}_i)}{4\pi\epsilon_0 |\mathbf{r} - \mathbf{r}_i|^3}$$

Torque: $\tau = \mathbf{p} \times \mathbf{E}$

Energy of a dipole: $U(\theta) = -\mathbf{p} \cdot \mathbf{E}$

Gauss' law: $\phi = \oint_S \mathbf{E} \cdot d\mathbf{A}$

Potential: $\Delta V \equiv \frac{\Delta U}{q} = -\int_C \mathbf{E} \cdot d\mathbf{l}$

Energy of a capacitor: $U = \frac{Q^2}{2C}$

Current: $I = \dot{Q}$

Potential: $V_b - V_a = -\int_a^b \mathbf{E} \cdot d\mathbf{l}$

Kirchhoff's rules: 1. $\sum_{j,\text{loop}} \Delta V_j = 0$ 2. $\sum_j I_{j,\text{into node}} = 0$

Magnetic force: $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$

Cyclotron radius: $r = \frac{mv}{qB}$

Biot-Savart: $\mathbf{B} = \frac{\mu_0}{4\pi} \frac{q\mathbf{v} \times \mathbf{r}}{r^2}$

Faraday's Law: $\mathcal{E} = -\frac{d\Phi_m}{dt}$

Self-inductance of a solenoid: $L = \mu_0 n^2 A l$

Mutual inductance: $\frac{\Phi_{M1}}{N_1} = \frac{\Phi_{M2}}{N_2}$

Impedance: $Z_R = R$, $Z_C = \frac{1}{i\omega C}$, $Z_L = i\omega L$

Waves

$$\oint_S \mathbf{E} \cdot d\mathbf{A} = \frac{Q_{enc}}{\epsilon_0} \quad (\text{Gauss's Law for Electricity}) \quad (1)$$

$$\oint_S \mathbf{B} \cdot d\mathbf{A} = 0 \quad (\text{Gauss's Law for Magnetism}) \quad (2)$$

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt} \quad (\text{Faraday's Law}) \quad (3)$$

$$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_{enc} + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt} \quad (\text{Ampère's Law with Maxwell's addition}) \quad (4)$$

In electromagnetic waves, the ratio $B_0 = \frac{E_0}{c}$ holds.

Wavenumber: $\omega = vk$

Compton wavelength: $\lambda_c = \frac{h}{m_e c}$

De Broglie wavelength: $\lambda_{dB} = \frac{h}{p}$

Heisenberg uncertainty relation: $\Delta x \Delta p \geq \frac{h}{4\pi}$

Energy of a particle in a 1D box: $E_n = \frac{h^2 n^2}{8L^2 m}$

3

General Solution

For a driven damped harmonic oscillator, the general solution can be expressed as:

$$x(t) = e^{-\zeta\omega_0 t} (A \cos(\omega_d t) + B \sin(\omega_d t))$$

where A and B are constants determined by initial conditions.

Moments of Inertia

Object	Axis	Moment of Inertia (I)
Thin cylindrical shell	Diameter through centre	$\frac{1}{2}mr^2 + \frac{1}{12}ml^2$
Thin cylindrical shell	Axis	mr^2
Thin rod	End	$\frac{1}{3}ml^2$
Thin rod	Centre	$\frac{1}{12}ml^2$
Spherical shell	Centre	$\frac{2}{3}mr^2$
Solid sphere	Centre	$\frac{2}{5}mr^2$
Solid cylinder	Axis	$\frac{1}{2}mr^2$
Solid cylinder	Diameter through the centre	$\frac{1}{2}mr^2 + \frac{1}{12}ml^2$
Hollow cylinder	Axis	$\frac{1}{2}m(r_1^2 + r_2^2)$
Hollow cylinder	Diameter through centre	$\frac{1}{2}m(r_1^2 + r_2^2) + \frac{1}{12}ml^2$
Rectangular parallelepiped	Through centre, perpendicular to sides	$\frac{1}{12}m(h^2 + w^2)$

Thermodynamics

0th law: If two objects are in thermal equilibrium with a third object, then all three objects are in thermal equilibrium with each other.

1st law: For any process concerning a given system, the change in internal energy ΔU of that system is equal to the sum of the heat Q transferred to that system and the work W performed on that system.

2nd law:

- **Carnot:** Wherever there exists a difference in temperature, motive power can be produced.
- **Kelvin:** It is impossible for a self-acting machine to convey heat from a colder body to a hotter one.
- **Clausius:** Heat cannot flow from a colder to a hotter body without another process occurring, connected therewith, simultaneously.

$$T = \left(\frac{\partial U}{\partial S} \right)_{V,N}$$

Energy per mode: $\langle E_{mode} \rangle = \frac{3}{2}k_B T$

$$Q = C\Delta T, \quad Q = \int_{T_1}^{T_2} C(T) dT$$

$$L = \frac{Q_{latent}}{m}, \quad \gamma = \frac{C_P}{C_V}, \quad dS = \frac{\delta Q_{rev}}{T}$$

2

Quantum Mechanics

Time-dependent Schrodinger's Equation : $i\hbar \frac{\partial}{\partial t} \psi(\vec{r}, t) = \left[-\frac{\hbar^2}{2m} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) + V(x) \right]$

Special relativity

Postulates of relativity and inertial reference frames:

- 1: Absolute uniform motion cannot be detected.
- 2: The speed of light in a vacuum is independent of the motion of the source.

Doppler Shift

Non-relativistic Doppler Shift:

$$f' = f \left(\frac{c \pm v_{\text{observer}}}{c \pm v_{\text{source}}} \right) \quad (\text{for sound or slow-moving sources}) \quad (5)$$

Relativistic Doppler Shift:

$$f' = f \sqrt{\frac{1 + \beta}{1 - \beta}} \quad (\text{for motion towards the observer}) \quad (6)$$

$$f' = f \sqrt{\frac{1 - \beta}{1 + \beta}} \quad (\text{for motion away from the observer}) \quad (7)$$

where $\beta = \frac{v_{\text{source}}}{c}$.

Velocity Transformations in Special Relativity

For two observers in relative motion with velocity v along the x-axis:

$$u'_x = \frac{u_x + v}{1 + \frac{vu_x}{c^2}} \quad (8)$$

$$u'_y = \frac{u_y}{\gamma(1 + \frac{vu_x}{c^2})} \quad (9)$$

$$u'_z = \frac{u_z}{\gamma(1 + \frac{vu_x}{c^2})} \quad (10)$$

where $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$ is the Lorentz factor.

Energy

$$E_{\text{total}} = \gamma mc^2 = \sqrt{p^2 c^2 + m^2 c^4}, E_{\text{rest}} = mc^2$$

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