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Module 4

Oscillations and Waves

Manual

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Having joined in with Bologna process, Ukraine requires creating new books on physics (in English in particular). The book is developed for all forms of studying physics at the higher school Credit-based Modular System basis.

"Physics. Module 4. Oscillations and Waves" presents the essential principles of mechanical and electromagnetic oscillations and waves. It contains Study Units which include theoretical information, test questions, sample problems, laboratory works and individual home tasks.

It is designed for students of engineering specialities.

У той час, коли Україна приєднується до Болонського процесу та вступає до «Європи знань», видання англомовних навчальних посібників є вкрай необхідним. Даний посібник розроблено для використання на всіх формах занять з курсу загальної фізики в умовах кредитно-модульної системи.

Модуль 4 «Коливання і хвилі» складається з навчальних елементів, які містять теоретичне ядро, задачі для аудиторної та індивідуальної роботи, а також лабораторний практикум. Розглянуто програмні питання з основ механічних та електромагнітних коливань і хвиль.

Для студентів інженерно-технічних спеціальностей вищих технічних навчальних закладів.

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PREFACE

Foreword to Module M 4 “Oscillations and Waves”

This book is the forth module of the discipline "Physics". It helps to elucidate essential principles of oscillatory and wave processes.

As a result of studying this module, students must ***know*** the definitions of such concepts as oscillatory and wave processes, harmonic oscillations and monochromatic waves, basic regularities of propagation of mechanical and electromagnetic waves.

Students must get ***skills*** to research and apply theoretical methods of oscillations and waves, plot graphs, estimate errors of physical measurements, and use theoretical knowledge for solving practical problems.

It is necessary to ***understand***, that mechanical and electric oscillations have different nature, but their description can apply the same mathematical tools.

The differential and integral calculus is widely used in the module but for first year students’ level.

The module "Oscillations and Waves" consists of the following **Study Units** (**SU**):

Preliminary SU — Brief physical data, Glossary;
SU 1 — Mechanical oscillations;
SU 2 — Electric oscillations;
SU 3 — Elastic waves;
SU 4 — Electromagnetic waves;
SU 5 — Laboratory works;
SU 6 — Individual home tasks;
Supplementary SU — Key words, Help tables.

The Preliminary unit contains the basic concepts and laws of mechanics, molecular physics and thermodynamics, electricity and magnetism that are necessary to study efficiently this module and a glossary with explanations of in mathematics and physics terminology.

“Study Units 1–4” include theoretical material, test questions, sample problems, as well as problems for work in class. “Study Unit 5” gives instructions on how to perform laboratory works. “Study unit 6” contains problems to be solved by students on their own. “Supplementary Units” are aimed at facilitating the module study.

For effectiveness, we advise using self-check questions. Each question is provided with information as to where to find an answer on it. Concepts, which are studied in the module, are basic for all engineering fields of study; they are used in theoretical mechanics, aerodynamics, technical electrodynamics etc.

Preliminary Study Unit

The aim of this Study Unit is to elucidate some concepts of mechanics, molecular physics and thermodynamics in order to alleviate students studying electricity and magnetism.

It is advisable to start with answering questions for self-control. If you succeed in giving correct answers, you can pass on to studying SU 1. If you fail, it is necessary to revise corresponding sections all over again.

1. Self-control questions

1. What is the physical meaning of an instantaneous velocity vector? How is it directed?
2. What does acceleration characterize?
3. What is a momentum, how to find its direction?
4. Newton's second law. In what formulas is it possible to express the law?
5. Newton's third law. Why do not forces counterbalance each other according to this law?
6. What is an elementary work in mechanics?
7. What is the concept of power? Give definitions of the average power and instantaneous power.
8. What is the physical sense of efficiency? What practical values does it have?
9. Energy. What kinds of energy in mechanics do you know?
10. What is the equation for the kinetic energy of a system of bodies?
11. Give the common definition of the concept "potential energy". Does the potential energy of a body depend on a choice of zero position of the body?
12. What is the essence of the momentum conservation law?
13. The law of conservation of mechanical energy. What restrictions exist for this law in comparison with the law of momentum conservation?
14. What is the gradient of a scalar quantity? Where does it point to?
15. What relationship is there between the macroparameters of an ideal gas? The equation of state of an ideal gas.
16. Isoprocesses in an ideal gas. Adiabatic process.
17. What is electric field? Electric field intensity.

18. What is electric current? Ohm's law in integral form.

19. What is a source of a magnetic field? How does a magnetic field effect?

20. What is the process called "displacement current" by Maxwell? Note the system of Maxwell equations in integral and differential form. What magnitudes are parts of these equations?

2. Brief physical data

Instantaneous velocity (or ***velocity*****),** that is the limit, to which the ratio of the position-vector $\Delta\vec{r}$ to the time interval Δt tends when $\Delta t \to 0$:

$$\vec{v} = \lim_{\Delta t \to 0} \frac{\Delta \vec{r}}{\Delta t} = \frac{d\vec{r}}{dt}.$$

As, when $\Delta t \to 0$, $|d\vec{r}| = ds$ (ds is an elementary distance), instantaneous velocity may be found as $v = \dfrac{ds}{dt}$.

A velocity vector $\vec{v}$ is directed along the tangent to the trajectory.

Let us consider the case when the equations of motion are given in a coordinate form. Derivatives from these expressions with respect to time will give the projections of velocity vectors on the corresponding coordinate axes:

$$v_x = \frac{dx}{dt}; \qquad v_y = \frac{dy}{dt}; \qquad v_z = \frac{dz}{dt}.$$

Then, for the velocity vector, we will have:

$$\vec{v} = v_x \vec{i} + v_y \vec{j} + v_z \vec{k},$$

and for its module:

$$v = \sqrt{v_x^2 + v_y^2 + v_z^2}.$$

Acceleration is a physical quantity that characterizes the change of velocity along with time and is equal to the first derivative of velocity vector with respect to time:

$$\vec{a} = \frac{d\vec{v}}{dt}.$$

Acceleration may be also defined as the second derivative of the position-vector with respect to time:

$$\vec{a} = \frac{d^2\vec{r}}{dt^2}.$$

The acceleration vector can also be written by its projections a_x, a_y, a_z on coordinate axes:

$$\vec{a} = a_x\vec{i} + a_y\vec{j} + a_z\vec{k}; \qquad a = \sqrt{a_x^2 + a_y^2 + a_z^2}.$$

Momentum $\vec{p}$ of a material point in classical mechanics is equal to the product of a material point mass to its velocity:

$$\vec{p} = m\vec{v}.$$

The direction of a momentum vector $\vec{p}$ coincides with the direction of a velocity vector $\vec{v}$. Momentum unit in SI is kg·m/s.

NEWTON'S SECOND LAW (the main law of dynamics): **acceleration of a body (material point) is directly proportional to the force acting on the body, coincides with the force direction and inversely proportional to the mass of the body:**

$$\vec{a} = \frac{\vec{F}}{m}.$$

Whence, $\vec{F} = m\vec{a}$, or, in view of the definition of acceleration,

$$m\frac{d^2\vec{r}}{dt^2} = \vec{F}.$$

As $\vec{a} = \frac{d\vec{v}}{dt}$, we obtain $\vec{F} = m\frac{d\vec{v}}{dt} = \frac{d\left(m\vec{v}\right)}{dt}$.

Taking into account that $m\vec{v} = \vec{p}$, we finally get

$$\vec{F} = \frac{d\vec{p}}{dt}.$$

NEWTON'S THIRD LAW: **two bodies act on each other with forces, which are equal by module and have opposite directions**

$$\vec{F}_{21} = -\vec{F}_{12}.$$

Mind that forces act on different bodies; therefore, they never counterbalance one another (that is to say, it is impossible to determine their resultant force).

The scalar product of the force $\vec{F}$ and elementary displacement $d\vec{r}$ is called ***elementary work***:

$$dA = \left(\vec{F}\, d\vec{r}\right),$$

or

$$dA = F\left|d\vec{r}\right|\cos\alpha,$$

where α is the angle between vectors $\vec{F}$ and $d\vec{r}$.

As $F\cos\alpha = F_\tau$, that is a projection of the force $\vec{F}$ to the tangent $\vec{\tau}$ at a given point of the trajectory and $\left|d\vec{r}\right| = ds$, the expression for elementary work can be written as $dA = F_\tau ds$.

If a body moves rectilinearly under the action of a constant force (F = const, cosα = const), for this particular case, we receive:

$$A = \int_0^s Fds\cos\alpha = F\cos\alpha\int_0^s ds = Fs\cos\alpha.$$

Time does not play any role as for work conception. However, it is very essential to know how much time is spent for some work to be performed. We may find the answer on this question using such a notion as power. ***Instantaneous power*** (or ***power***) is the ratio of an elementary work dA to the time dt, this work was done by:

$$N = \frac{dA}{dt}.$$

Efficiency (η) is the characteristics of some technical devices quality. Efficiency can be defined through different physical values, depending on the concrete task, but it is always a ratio of «useful results» to «consumption». One can express it in mechanics as follows:

$$\eta = \frac{A_{useful}}{A_{cons}}; \qquad \eta = \frac{N_{useful}}{N_{cons}}.$$

Kinetic energy $W_к$ is the energy of a moving body. Kinetic energy for a body (material point) at the *translational motion* is: $W_к = \frac{mv^2}{2}$.

Kinetic energy is the additive quantity. It means that we can find kinetic energy of a system as the sum of kinetic energies of the system separate elements: $W_к = \sum_{i=1}^{N} W_{кi}$.

If a body under the action of a force changes its velocity from v_1 to v_2 during translational motion, then the performed work is:

$$A = \Delta W_к = \int_{v_1}^{v_2} dW_к = \int_{v_1}^{v_2} mv\,dv = \frac{mv_2^2}{2} - \frac{mv_1^2}{2}.$$

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