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O. KUZMENKO, V. FOMENKO

LABORATORY WORKSHOP FOR THE GENERAL PHYSICS COURSE

Tutorial for cadets/students

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The tutorial prepared by the authors:

Kuzmenko O. – introduction; chapter 1; chapter 2; M-1; M-2; M-3; M-4; T-1; E-1; E-3; K-1; O-2; O-5; A-2.

Fomenko V. – introduction; chapter 1; chapter 2; M-1; M-2; M-3; M-4; T-1; E-1; E-3; K-1; O-2; O-5; A-2.

Reviewers:

1. **Sadovyi M. I.** – Doctor of Pedagogical Sciences, Professor, Head of the Department of Theory and Methodology of Technological Training, Occupational Safety and Life Safety of Volodymyr Vynnychenko Central Ukrainian State Pedagogical University.
2. **Slipukhina I. A.** – Doctor of Pedagogical Sciences, Professor, Leading Researcher of the Department of Creation of Educational-Thematic Knowledge Systems of the National Center «Junior Academy of Sciences of Ukraine».
3. **Strizhak O. E.** – Doctor of Technical Sciences, Deputy Director for Research of the National Center «Junior Academy of Sciences of Ukraine».
4. **Radul S. H.** – Ph.D. in Pedagogics, Associate Professor at the Department of Foreign Languages, Flight Academy of the National Aviation University.

Навчальний посібник призначений для курсантів та студентів Льотної академії НАУ як основне керівництво у процесі підготовки та виконання робіт фізичного практикуму із загального курсу фізики. Навчальний посібник включає: необхідну теоретичну інформацію та інструкції для виконання лабораторних робіт, завдання для проведення експериментів, хід виконання кожної з робіт, контрольні запитання для самоперевірки курсантів/студентів, рекомендовану літературу для поглибленого вивчення теоретичного матеріалу.

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This manual is allotted cadets and students of FA NAU as the main guide in the preparation and implementation of laboratory works of the general physics course. The manual includes the necessary theoretical information and instructions for performing laboratory works, tasks for making experiments, the progress of each of the works, control questions for self-examination, recommended references for an in-depth study of theoretical material.

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CONTENT

INTRODUCTION

Aviation equipment at the current stage of social, scientific and technological progress is booming and improving. Today, the requirements for an aviation specialist are becoming higher. The air specialist must possess the appropriate qualifications for the operational solution of any problems arising in his professional activity. Physics is one of the basic disciplines necessary for the profound mastery of the corresponding special knowledge. Physics studying the world around with all its phenomena, patterns and laws, is based on certain model ideas. The physics-training course cannot be fully successfully mastered without visual experimental work, which is reflected in a physical laboratory practice.

The developed laboratory workshop is allotted cadets of the Flight Academy of the National Aviation University (FA NAU) and should be considered as the main guide in preparing for the implementation of laboratory work under the program for the general physics course.

The first chapter is devoted to acquaintance with the procedure and rules for conducting a laboratory workshop and preparing a report on laboratory work.

The second chapter is devoted to the basics of measurement theory and the rules for calculating measurement errors.

The third chapter describes the works of the laboratory physical workshop.

Methodical recommendations are intended to cadets and students of FA NAU.

CHAPTER 1

INTRODUCTION TO LABORATORY PRACTICE IN PHYSICS

1. The subject and tasks of the physical laboratory works

A laboratory works in the course of general physics pursues three main goals: 1) an experimental illustration of the basic theoretical principles of physics; 2) familiarization of cadets with instruments and equipment that are used for measurements; 3) cadets gaining experience in planning and conducting of experiments.

The main task of the laboratory workshop is to learn:

1) to plan the experiment so that the accuracy of the measurements is consistent with the goal;
2) to take into account the possibility of systematic errors and to take measures to eliminate them;
3) to analyze the results of the experiment and to make the right conclusions;
4) to evaluate the accuracy of the result;
5) to keep a record of measurements and calculations neatly, clearly and concisely.

In preparing for the laboratory work, the following requirements should adhered to:

a) do not start laboratory work until you understand your purpose, method and plan for making measurements;
b) preparation for the work should be carried out the day before it. For preparation it is necessary:
a) to read the tutorial for the work, find out what physical laws are used to solve the problem and what patterns are the basis of the calculation formulas, get acquainted with the list of recommended literature. The description of each work in this tutorial contains theoretical information necessary for

the work and understanding of its essence, a description of the measuring instruments and measurement methods, a description of the process of the work and the results required.

b) to work out the recommended additional literature, with particular attention to the conditions in which the physical laws and calculation formulas are valid;

c) to derive formulas that are used for calculations in the work independently or with the help of textbooks,

In preparation for the work, the cadet must:

a) prepare summary of the theoretical information containing the name of the work and its index, the purpose of the work, a list of the devices used, the basic and working installation schemes, calculation formulas and formulas for calculating measurement errors in the laboratory notebook;

b) separately prepare the report form in which the measurement data are being reflected when executing work, their mathematical processing is carried out, graphs are built and the corresponding conclusions are formulated.

A full report on laboratory work should contain:

1) number (index) and name of the work;
2) calculation formulas;
3) installation schemes;
4) tables with the results of measurements and principal calculations, the necessary graphs;
5) examples of calculations of the sought quantities;
6) formulas for calculating measurement values and their errors;
7) the final measurement result indicating the resulting error. Items 1, 2, 3, 6 of the report form for the laboratory lesson should be prepared at home. The other items should be made in the laboratory.

The report is signed by the teacher after checking the result and setting the final grade for this work.

CHAPTER 2

PHYSICAL MEASUREMENTS AND BASES OF THE THEORY OF ERRORS OF MEASUREMENTS

2.1 Measurements, measurements units. Measurements' errors

The basis of any laboratory work on the course of physics is the measurement of physical quantities.

The measurement of a physical quantity means its comparison with the same type of quantity accepted as a unit of measurement. For example, the mass of a body equals to 5 kg means that this mass is 5 times greater than the mass of 1 kg, taken as a unit of measurement of the mass value. Because physical quantities are functionally interconnected, units of measurement for each of them cannot be arbitrarily set. In physics, units are arbitrarily set for only a few quantities, which are called **basic units**. The International System of Units (SI system) uses the following basic units:

Mass (M) - 1 kilogram (kg);
Length (L) - 1 meter (m);
Time (T) - 1 second (s);
Electric current strength (I) - 1 ampere (A);
Thermodynamic (absolute) temperature (θ) - 1 Kelvin (K);
Amount of substance (N) - 1 mol (mol);
Light power (J) - 1 candela (cd).

Units of other quantities are derived on the basis of physical formulas that relate these quantities to basic quantities. Such units are called **derived units**. For example, the speed of a body is defined in the simplest case as the ratio of the path length to the passing time of this path. Therefore, the unit of speed is equal to the ratio of unit of length to unit of time:

$$[v] = [L] / [T] = m/s.$$

As practice shows, measurements cannot be made with absolute accuracy; some inaccuracies always occur, which are called **measurement errors**. The causes of errors are the imperfection of measuring instruments and methods of physical quantities measuring; problems associated with taking into account all the factors that accompany the phenomenon under study, the limited capabilities of our senses, and so on. The magnitude of the error influences the acceptability of the result. With a significant error, for example, it may be necessary to improve the measurement procedure, use measuring equipment, that are more accurate etc.

Measurement processing involves obtaining the result of this measurement in conjunction with its error in the form

$$a = a_0 \pm \Delta a, \tag{1}$$

where a_0 is the **result of this measurement**, Δa is its **absolute error**.

The **absolute measurement error** of a quantity is a value that indicates the limits between which the true meaning of this quantity is located. For example, the result of measuring the length l of a certain segment is written in the form $l = (7.6 \pm 0.1)$ cm. In this expression, the value 7.6 cm is called the measurement result, and the value 0.1 cm is called the absolute measurement error. This means that the true value of the measured quantity l is in the range (7.5 - 7.7) cm.

The relative error ε is the ratio of the absolute error of the measured quantity to the result of this measurement:

$$\varepsilon = \frac{\Delta a}{a_0}. \tag{2}$$

For the previous example, $\varepsilon = 0.1/7.6 \approx 0.013$ or 1.3%. It is the relative error that characterizes the **accuracy of the measurement**. For example, if, when measuring the length of the table, the result is (125.0 ± 0.5) cm, and when measuring the length of the bar, the result is (12.5 ± 0.5) mm, then the absolute error of 0.5 cm made when measuring the table length, significantly more than the absolute error of measuring the length of the rod 0.5 mm. However, the relative error of measuring the length of the rod is $\varepsilon_1 = 0.5/12.5 = 0.04$ (4%), and the relative error of measuring the length of the table is $\varepsilon_2 = 0.5/125 = 0.004$ (0.4%). This means that the length of the table is measured 10 times more accurately than the length of the rod.

Measurements are divided into **direct** and **indirect**.

Direct measurements are made directly by measuring instruments. For example, the measurement of length is carried out directly with a ruler (caliper, micrometer), the measurement of time with a stopwatch, the measurement of mass with weighing a body on a scale, etc.

Indirect measurements are made by some mathematical actions with the results of direct measurements. So, for example, the result of measuring the area of *ab* the rectangle S is obtained by the formula $S = ab$, when the length a and width b of this rectangle are measured directly (for example, using a ruler).

By their nature, errors of **direct measurements** of physical quantities are divided into **systematic**, **random**, and **misses**.

Systematic errors have always a certain sign, i.e. the measured value of the quantity at each measurement will be either greater or less than the true value of this quantity. For example, «hurrying» or, conversely, «lagging» watches have a systematic error. Another example is the zero-point error of the scale of the measuring device (ammeter, voltmeter, etc.). For example, an ammeter, the readings of which in the absence of current is 0.2 A, during measurements will give overestimated readings, and the measurement results will have a systematic error of +0.2 A. It can be eliminated by setting the instrument arrow to zero mark. In general, systematic errors due to:

a) improper manufacture or incorrect setup of measuring instruments;
b) imperfections of the chosen measurement method, in which some factors affecting the measurement results are not taken into account.

To eliminate (or at least significantly reduce) systematic errors, correctly tuned instruments and correct measurement methods should be used.

Random errors are the errors that, with different measurements of the same value, can change their meaning and sign without any apparent regularity. Random errors represent the total effect of the influence on the measurement process of many factors, each of which, independently of the others, makes its own error in the measurement result.

Random errors due to:

a) insufficient sensitivity and insufficient accuracy of measuring instruments;
b) imperfection of the sensory organs of the experimenter (mainly vision and hearing);
c) influence of the environment on the measurement process (vibration, air currents, temperature changes, etc.).

Properties of random errors:

a) the larger is the value of the random error, the less its probability, that is, the less often it occurs;
b) random errors of the same magnitude, but opposite in sign are equally probable, that is, they occur equally often;
c) arithmetic average of magnitudes of random measurement errors of the same value tends to zero with an unlimited increase in the number of measurements.

It is impossible principally to eliminate random errors. To increase accuracy, the process of some value measuring **is carried out several times**, and the arithmetic average of the results obtained is used as the **measurement result**. An important point of the theory of errors is the statement: the arithmetic average of the results of several measurements of the same value is more reliable than the result of each individual measurement.

Misses are measurement results that stand out sharply from a series of analogues results of the same type of measurement. They caused by a sudden malfunction of the measuring device, violation of the rules of its operation, incorrect reading of readings, illegible recordings of the measurement result, etc. Such error results are not taken into account when processing the measurement results (often a repeated (control) measurement is performed).

2.2 Calculation of measurement errors

Calculation of errors of direct measurements. Let, as a result of several measurements of some physical quantity *a*, we obtain a sequence of values: a_1, $a_{2,}$ ...., a_n Then the arithmetic average value of this quantity is determined by the formula $a_0 = \frac{1}{n}\sum_{i=1}^{n} a_i$. The absolute errors of individual measurements Δa_i are equal to the absolute value of the difference between the average value a_0 and the results of individual measurements a_i: $\Delta a_1 = |a_0 - a_1|$, $\Delta a_2 = |a_0 - a_2|$, ..., $\Delta a_n = |a_0 - a_n|$.

The value $\Delta a = \frac{1}{n}\sum_{i=1}^{n} \Delta a_i$ is called the **average absolute measurement error** (or simply **absolute error of the measurement)**.

Therefore, the measured meaning of this value is in the range:

$$a_0 - \Delta a \le a \le a_0 + \Delta a.$$

The final measurement result is usually written in the following form:

$$a = a_0 \pm \Delta a. \tag{3}$$

When determining the average absolute error Δa of a measured physical value, one should take into account such possible cases:

1. If, as a result of several measurements, the obtained identical meanings of the measured value (that is, $\Delta a = 0$) or the calculated error is less than the **instrumental own error**, then this instrumental error should be taken as the absolute error of the measured value. This rule also applies to cases where only one measurement of a physical value is performed.
2. Instrumental error is usually indicated in the passport or description of the device. On the scales of many electrical measuring instruments (ammeters, voltmeters, etc.), the instrumental error is indicated as the value of the **accuracy class** of this device. The value of the accuracy class is equal to the absolute instrumental error of the device, expressed as a percentage of the maximum meaning of the measured value on the scale of the device. For example, the maximum current strength measured by an ammeter is 10 A, and accuracy class is 0.5. That means that the absolute error in measuring the current with this device is $10 \cdot 0.5/100 = 0.05$ (A).
3. If the instrumental error of the device is unknown, then half of the scale graduation value of the device is usually taken as its value. In the case when the instrumental error is very small, it is not taken into account.
4. Constant error values are considered equal to zero. When using tabular meanings of physical quantities determined with high accuracy, the absolute errors of these values can be neglected if other values are measured in the experiment with less accuracy.

To fully characterize the accuracy of direct measurements, in addition to the **absolute error** Δa, calculate the **relative error** ε:

$$\varepsilon = \frac{\Delta a}{a_0}, \text{ or in percent: } \varepsilon = \frac{\Delta a}{a_0} \cdot 100\%.$$

When performing calculations, one should adhere to the rules of operations on approximate numbers.

Calculation of errors of indirect measurements. In indirect measurements, the desired physical value and its error are calculated based on the results of direct measurements of the values whose function it is. Let, for simplicity, the desired value of C is a function of only two variables a and b measured directly (their average absolute errors are respectively Δa and Δb). The absolute and relative errors of a value C depending on the type of function $C = f(a, b)$ are calculated according to certain rules. Some formulas for calculating errors of indirect measurements are presented in Table 1.

Table 1

Formulas for finding absolute and relative errors

№	Algebraic expression	Absolute error value	Value of relative error
1	$a+b$	$\Delta a+\Delta b$	$\frac{\Delta a+\Delta b}{a+b}$
2	$a-b$	$\Delta a+\Delta b$	$\frac{\Delta a+\Delta b}{a-b}$
3	$c\cdot a$ ($c = const$)	$c\cdot\Delta a$	$\frac{\Delta a}{a}$
4	$\frac{a}{c}$ ($c = const$)	$\frac{\Delta a}{c}$	$\frac{\Delta a}{a}$
5	$a\cdot b$	$a\Delta b+b\Delta a$	$\frac{\Delta a}{a}+\frac{\Delta b}{b}$
6	$\frac{a}{b}$	$\frac{a\Delta b+b\Delta a}{b^2}$	$\frac{\Delta a}{a}+\frac{\Delta b}{b}$

7	a^2	$2a\Delta a$	$2\frac{\Delta a}{a}$
8	a^3	$3a^2\Delta a$	$3\frac{\Delta a}{a}$
9	$\sqrt{a}$	$\frac{\Delta a}{2\sqrt{a}}$	$\frac{\Delta a}{2a}$
10	$\sqrt[3]{a}$	$\frac{\Delta a}{3\sqrt[3]{a^2}}$	$\frac{\Delta a}{3a}$
11	$ca^n b^m$ ($c = const$)	$c(\|n\|\frac{\Delta a}{a} + \|m\|\frac{\Delta b}{b})\cdot a^n b^m$	$\|n\|\frac{\Delta a}{a} + \|m\|\frac{\Delta b}{b}$

2.3 Graphical representation of the experiment results

In experimental physics, measurement results are often presented in a visual form, convenient for use and processing. For example, in order to illustrate the relationship between the quantities, a graph is plotted for the experimentally measured meanings of these values. In this case, the functional dependencies become apparent, and the measurement results are visual. When building graphs, you should follow the basic rules:

1. Graphs are performed on the graph (millimeter) paper on which the coordinate axes are applied. On the horizontal axis (abscissa axis) the value of the independent variable (argument) is plotted, on the vertical (ordinate axis) the value of the determined value (function) is plotted.
2. It is necessary to choose the scale and the range of values when marking the axes. The scale should be simple: one division of the scale should correspond to a unit value multiple of 10 (for example, 0.1; 1; 10, etc.), or multiple of 2 (for example, 0.2; 2; 4 etc.) or a multiple of 5 (2.5 and 4 are also acceptable), or the same numbers multiplied by $10^{\pm n}$ (n is an integer). The amount of divisions with numbers on each axis is usually from 4 to 10.

3. On the axes of the graph, the symbol of the deferred value and its dimension should be indicated. Usually, the scale order of this value ($10^{\pm n}$) is also written there.
4. The scale must be chosen so that the curve occupies the entire sheet, and the absolute measurement error corresponds to one or two small divisions of the scale. At the same time, it is not necessary to start counting the values laid down along the coordinate axes from zero. Sometimes it is more convenient to choose a certain initial nonzero meaning of the value as a reference point and thus increase the scale, but the error should still be one or two small divisions.
5. Experimental data are plotted with well-defined points. If several curves are built, various icons are used: crosses, circles, etc. Then the most suitable smooth curve is applied with the least number of bends, passing as close as possible to the plotted points. On the graph, the points should be approximately equal on both sides of this curve.
6. It is convenient to process the results if the curve is close to a straight line, inclined at an angle approximately equal to 45° to the abscissa axis. To do this, not the quantities themselves, but some of their functions (logarithms, reciprocal values, etc.) can be laid off on the graph axes so that the resulting graph to be close to a straight line.

Test questions

1. What is called measurement of a physical quantity?
2. What is called absolute measurement error? Relative error?
3. Which of the errors (absolute or relative) determine the accuracy of the measurement and why?
4. What measurements are called direct? Indirect?
5. How are the errors of direct measurements divided?
6. What is the cause of random errors, systematic errors, and misses?
7. Formulate an algorithm for calculating the errors of direct measurements.
8. Formulate an algorithm for calculating the errors of indirect measurements.
9. How are the instrumental errors of measuring instruments calculated?

CHAPTER 3

LABORATORY WORKS

3.1 *Laboratory work M-1* Study of the Laws of Dynamics on an Atwood Machine

Objective: to study the regularities of uniformly accelerated motion.

Equipment: Atwood machine, set of overloads, stopwatch.

Brief Theoretical Information

The motion of bodies (particles) obeys *Newton's second law*: the rate of change of the momentum of the body is equal to the vector sum of all the forces acting on this body.

$$\frac{d(m\vec{v})}{dt} = \sum \vec{F}. \tag{1}$$

Taking into account that in Newtonian mechanics m = const, and using the concept of acceleration, for Newton's second law we have:

$$m\vec{a} = \sum \vec{F}. \tag{2}$$

To study the laws of motion, a device called Atwood machine may be used. The Atwood Machine (see Figure 1) has a vertical graduated rule 1. At the upper end of the ruler, block 2 is installed, rotating with little friction.

A thread with weights 3 and 4 of equal mass is thrown over the block. In the initial position, the load 3 is on the platform 7 and is fixed by hand.

If the load 4 is put with extra load 5 and released, then the loads will begin to move. At the same time, you should turn on the stopwatch. If load 4 falls on the receiving table 6, the stopwatch Figure 1 time for movement of the loads recorded. Thus, the stopwatch registers the time of movement of the loads from the beginning

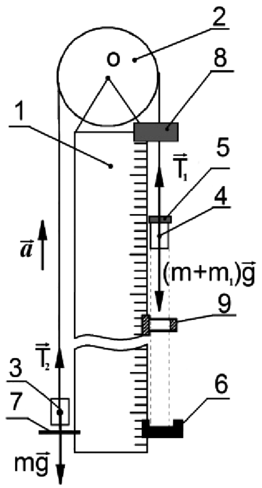


Figure 1

of this movement to the arrival of the load 4 on the receiving table 6. The receiving table can be fixed at various positions on the scale using a clamping screw.

Acceleration of loads is determined by the formula:

$$a = \frac{2L}{t^2} \tag{3}$$

where L is the distance from the lower end of the load 4 to the plane of the receiving table 6; t is the time recorded by the stopwatch.

Assuming the thread to be inextensible and weightless, we will compose equations describing the motion of the system. For load 3, the Newton's second law (2) in the projection on the direction of movement of this load gives:

$$T_2 - mg = ma, \tag{4}$$

where T_2 is the tension force of the left side of the thread;
m - weight of cargo 3;
g - acceleration of free fall;
a - module (magnitude) of the acceleration of load movement.
Similarly, the equation for the movement of load 4 with the overload 5 is:

$$(m+m_1)g - T_1 = (m+m_1)a, \tag{5}$$

where m_1 is the mass of the overload 5;

T_1 is the tension force on the right side of the thread.

The difference in the tension of the thread to the right and left of the ruler is due to the existence of mass of the block 2, its rotation and the presence of friction in the axis of the block.

The equation of the law of the dynamics of the rotational motion of a block has the form:

$$T_1 \cdot R - T_2 \cdot R = I \cdot \varepsilon + M_{fr}, \tag{6}$$

where R is the radius of the block;

I - moment of inertia of the block;

$\varepsilon = a/R$ - angular acceleration of the block rotation;

M_{fr} is the moment of the frictional force on the block axis.

Solving the system of equations (4-6), we obtain:

$$a = \frac{m_1 g - (M_{fr}/R)}{2m + m_1 + (I/R^2)}. \tag{7}$$

Considering that $m_1 << 2m + (I/R^2)$, we finally get:

$$a = \frac{m_1 g - (M_{fr}/R)}{2m + (I/R^2)} \tag{8}$$

Working Process

Checking the Laws of Uniformly Accelerated Motion

1. Place the receiving table 6 so that the distance that the load 4 will pass from the start of the drive to the stop on the receiving table is L = 20 sm. Transfer the load 3 to the platform 7 and hold it with your hand.
2. Put some overload on the load 4. Release load 3 and simultaneously turn on the stopwatch. The system of loads begins to move. When the load 4 reaches the table 6, turn off the stopwatch. The time interval measured by

stopwatch should be recorded in Table 1. The experience to repeat at least 3 times.

3. Repeat item 2 for $L = 40$ cm and $L = 60$ cm and calculate for each value of L the acceleration a (equation (3)). Calculate the error of the acceleration measurement Δa for each case. The results should be recorded in Table 1.

Table 1

L, cm	20	40	60
t_1, s			
t_2, s			
t_3, s			
$t_{ср.}$, s			
Δt, s			
a, cm/s^2			
Δa, cm/s^2			

4. Make conclusions.

Checking Newton's Second Law.

1. Repeat item 2 of the previous experiment at the value $L = 60$ cm for three different masses of overloads m_1, m_2, m_3.
2. Calculate the acceleration a_i ($i = 1, 2, 3$) for each case by the formula (3). Calculate the error of measurement of the acceleration Δa_i for each case. The results should be recorded in Table 2.

Table 2

m_i, g			
t_1, s			
t_2, s			
t_3, s			
$t_{cp.}$, s			
Δt, s			
a, m/s^2			
Δa, m/s^2			

3. Graph $a = f(m_i \cdot g)$, where m_i is the overload mass. Check the linearity of this dependence (Newton's second law).
4. Make conclusions. Make a report on the work.

Test questions

1. Formulate and write down the second and third Newton's laws.
2. Write the formulas of the kinematics of uniform and uniformly accelerated motions.
3. Record the equation of the Newton's second law for a load without overload and a load with overload in an experiment on checking the law of uniformly accelerated motion.
4. Derive the formulas (3) and (8).

3.2 *Laboratory work M-2* Study the Laws of Rotational Motion by the Oberbeck Swing

Objective: to study the laws of the rotational motion of a solid body, to measure the moment of inertia of the body.

Equipment: 1) Oberbeck's Swing; 2) a set of loads; 3) stopwatch; 4) a large-scale ruler; 5) caliper.

Before starting work, you should study the material of Lectures 5 and 6.

Brief Theoretical Information

The motion of a solid body is rotational if all the points of this body move in circles whose centers lie on one straight line, called the rotation axis.

The *law of the dynamics of rotational motion in general case* is expressed by the formula:

$$\frac{d\vec{L}}{dt} = \sum \vec{M}, \tag{1}$$

where $\vec{L}$ is the vector of the moment of momentum of a rotating body, $\sum \vec{M}$ is the vector sum of the moments of forces acting on this body.

If the body rotates about some fixed axis *z*, we have the *law of dynamics of the rotational motion of the body relative to the fixed axis*:

$$I_z \varepsilon = \sum M_z, \tag{2}$$

where $\sum M_z$ is the sum of projections the moments of all forces acting on the body on the axis of rotation *z*, I_z is the moment of inertia of the body relative to the z -axis.

It follows from formula (2) that the basic dynamic concepts used in describing of the body rotation are the concepts of *moment of inertia* of the body and the *moment of force* acting on the body.

The *moment of inertia of a material point* of mass *m*, moving along a circle of radius *r* about the *z*-axis, is determined by the formula:

$$I_z = mr^2 \, (\text{kg} \cdot \text{m}^2). \tag{3}$$

The *moment of inertia of a body* (as a *system of material points*) is defined as the sum of the moments of inertia of all these material points relative to an axis of rotation:

$$I_z = \sum_{i=1}^{n} m_i r_i^2 \quad (4)$$

Taking into account the continuous distribution of masses inside the body, the summation in formula (4) turns into integration over the volume of the body:

$$I_z = \int r^2 dm. \quad (5)$$

The physical meaning of the moment of inertia is that it is a **measure of the inertia of a body** when it rotates about some axis.

Using formula (5), one can get expressions for the moments of inertia of some bodies of regular geometric shape:

– solid homogeneous **cylinder** (**disk**) relative to the axis of symmetry:

$$I = \frac{mR^2}{2}, \quad (6)$$

(m is the mass of the cylinder; R is its radius);

– solid homogeneous **rod** about the axis, which passes through the middle of the rod perpendicular to its length:

$$I = \frac{1}{12} ml^2, \quad (7)$$

(m is the mass of the rod; l is its length);

– solid homogeneous **ball** relative to the axis, which passes through its center:

$$I = \frac{2}{5} mR^2, \quad (8)$$

(m is the mass of the ball; R is its radius).

In the case when the axis of rotation does not pass through the center of mass of the body, the moment of inertia of the body can be found using the Steiner's formula:

$$I = I_0 + m \cdot a^2, \tag{9}$$

where I is the moment of inertia of the body relative to some axis, I_0 is the moment of inertia of this body relative to the parallel axis passing through its center of mass, m is the mass of the body, a is the distance between these axes.

The *moment of force* relative to the axis of rotation z is the quantity M_z (see Figure 1) which is determined by the formula

$$M_z = \pm \left| \vec{F}_\perp \right| \cdot d, \tag{10}$$

where $\left|\vec{F}_\perp\right|$ is the force component perpendicular to the rotation axis z, $d = \left| \vec{r} \right| \cdot sin\alpha$ is the arm of the force.

In formula (10), the sign «+» is taken in the case when the direction of the vector $\vec{M}_z$ coincides with the direction of the vector of the angular velocity of the body's rotation ù⃗ (the force «helps» the rotation of the body in this direction). Otherwise, the «-» sign is taken. As follows from formula (10) and Figure 1

$$M_z = \left| \vec{r} \right| \cdot \left| \vec{F}_\perp \right| \cdot sin\alpha. \tag{11}$$

The physical meaning of the momentum of force relative to this axis M_z is that it is a *measure of the rotational effect* of force on the body when it rotates about this z-axis.

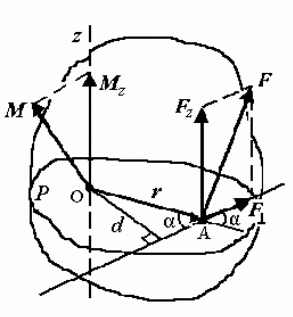


Figure 1 Moment of force

Installation Description

The experimental installation, which is used in this work, has historically received the name «Oberbeck Swing». The scheme is depicted in Figure 2.

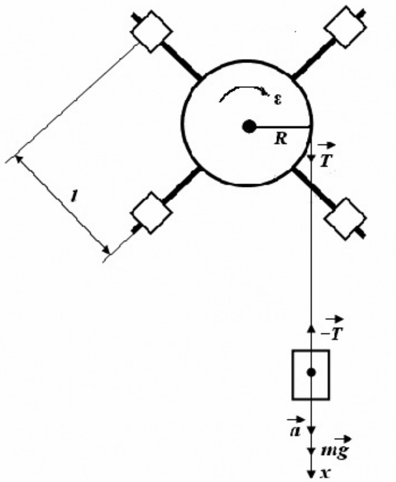


Figure 2 Oberbeck Swing

The installation consists of four spokes fixed on a rotating drum perpendicular to each other. The equal weights are fixed on the spokes on equal distances l from the rotation axis. The drum is winded with a thread, the end of which is attached a small load. This load, descending down with some constant acceleration $\vec{a}$, untwists the drum with angular acceleration

$$\varepsilon = \frac{a}{R}, \tag{12}$$

where R is the drum radius.

Let us analyze the motion of the Oberbeck's Swing on the basis of the laws of dynamics. The load on the thread moves down uniformly accelerated under the action of the gravity force $m\vec{g}$ (m is the mass of the load) and the force of the thread tension $\vec{T}$. The equation of Newton's second law for the movement of this load in projections on the vertical axis x is:

$$m \cdot a = m \cdot g - T\,. \tag{13}$$

From here, we find the tension force of the thread:

$$T = m(g - a)\,. \tag{14}$$

The magnitude of the acceleration *a*, with which the load is descending, can be determined by measuring the path *h* and the time of its movement *t*. Since the initial velocity of the load is zero, we have:

$$a = \frac{2h}{t^2}\,. \tag{15}$$

Substituting relation (15) into formula (14), we obtain for the tension force of the thread:

$$T = m\left(g - \frac{2h}{t^2}\right). \tag{16}$$

This force is applied tangentially to the surface of the drum and creates a moment of force $M = T\ R$, which spins the drum:

$$M = mR\left(g - \frac{2h}{t^2}\right). \tag{17}$$

The angular acceleration of the rotation of the drum ε is determined from formulas (12) and (15):

$$\varepsilon = \frac{2h}{Rt^2}\,. \tag{18}$$

Using the law of the dynamics of rotational motion in the form (2) and neglecting the friction forces in the axis of the drum, we obtain for the moment of inertia of the drum with spokes and weights:

$$I = \frac{M}{\varepsilon} = mR^2 \left(\frac{gt^2}{2h} - 1\right). \quad (19)$$

Working Process

1. Measure the diameter of the drum with a caliper, determine its radius and the absolute error of its measurement. The result is written in the form $R = R_0 \pm \Delta R$. Attach the weights on the spokes on the label indicated by the teacher.
2. Attach a weight of mass m = 100 g by the end of the thread, record the value of mass to the table.
3. Release the load; it begins descending. Use the stopwatch to determine the time t for descending the load from the height h. Repeat the experience for at least 3 times. Calculate the average value of the time of movement of the cargo t_{av} and the error Δt_{av}. Record the results to the table.
4. Using formulas (17) and (18), calculate the values of the moment of force M and the angular acceleration ε. Estimate the absolute measurement errors ΔM and $\Delta\varepsilon$. Record the results to the Table.

Table 1

m of load	№ *of test*	t	t_{av}	Δt_{av}	M	ΔM	ε	$\Delta\varepsilon$	I	I_{av}	ΔI_{av}
	1 2 3										

5. According to the formula (19) calculate the moment of inertia of the system I and the error of its measurement ΔI. Put the calculation result to the Table 1.
6. Make a report on the work.

Test questions

1. What is the moment of force relative to the axis of rotation? How can its value be determined?

2. Write the formulas of the law of the dynamics of rotational motion in general form and of this law when the body rotates about a fixed axis.

3. What is the moment of inertia of the body? How to calculate the moments of inertia of simple symmetrical bodies (a disk, a ball, a rod)?

4. Write down Steiner's formula. What is the meaning of this formula?

5. How can you determine the moment of inertia of a body of an arbitrary geometric shape?

3.3 *Laboratory work M-3* Measurement of the Moment of Inertia of a Physical Pendulum

Objective: to study the oscillations of a physical pendulum, measure the moment of inertia of a physical pendulum.

Equipment: 1) physical pendulum (plane symmetrical metal figure), 2) a holder, 3) stopwatch, 4) ruler.

Brief Theoretical Information and Installation Description

The moment of inertia of a rigid body about a certain axis is a **physical quantity characterizing the inert properties of the body when it rotates on this axis.** Theoretically, the moment of inertia of the body is determined by the formula

$$I = \sum_i \Delta m_i r_i^2 \ (\text{kg}\cdot\text{m}^2), \quad (1)$$

where the summation is taken over all particles that make up the body, Δm_i is the mass of the particle, r_i is the distance from this particle to the rotation axis of the body.

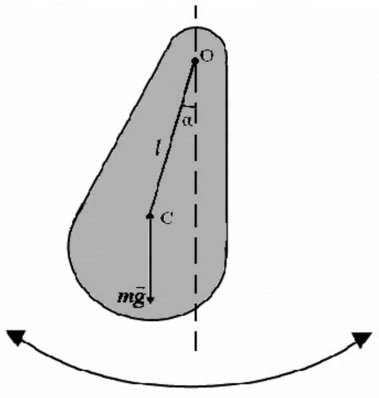


Figure 1 Physical pendulum

In the limit, when the masses of particles into which the body is mentally divided tend to be infinitely small ($\Delta m \rightarrow dm$), and their number tends to infinity, the summation in formula (1) goes to integration over the body volume V

$$I = \int_V r^2 dm. \tag{2}$$

The moment of inertia of bodies can also be measured experimentally. One of the methods of this measurement is the use of a body, the moment of inertia of which must be determined as a physical pendulum.

A **physical pendulum** is called a solid body, which undergoes the mechanical oscillations influenced by gravity force around a fixed point O, which does not coincide with the mass centre of the body C (Figure 1).

Mechanical oscillations are body motions in which its space position and the characteristics of the movement are repeated in regular intervals. An important characteristic of a physical pendulum is its oscillation period.

The oscillation period of a pendulum is the time interval during which one complete oscillation takes place. As a theoretical analysis shows, the period T of oscillations of a physical pendulum is determined by the formula:

$$T = 2\pi\sqrt{\frac{I}{mgl}}, \tag{3}$$

where I is the moment of inertia of the pendulum relative to the horizontal axis passing through point O, m is the mass of the pendulum, l is the distance from the axis of rotation to the mass center of the pendulum, $g \approx 9.81$ m/s^2 is the free fall acceleration.

It follows from formula (3) that the moment of inertia of the pendulum I is equal to:

$$I = \frac{T^2}{2\pi} mgl. \tag{4}$$

This formula is the basis of the method of determining the moment of inertia of the pendulum used in this paper. To use it, it is necessary to know the mass of the pendulum m, which is indicated on it, the distance l between points O and C (see Figure 1), which can be measured by a ruler, and the period of oscillations T.

The oscillation period of the pendulum can be determined by measuring (by the stopwatch) the time interval t during which the pendulum performs a certain number of oscillations N. Then

$$T = \frac{t}{N}. \tag{5}$$

Substituting formula (5) into equation (4), we obtain the **working formula** for determining the moment of inertia of the pendulum:

$$I = \frac{t^2}{2\pi N^2} mgl \cdot \quad (6)$$

Working Process

1. Record the mass of the pendulum in the form: $m = m_0 \pm \Delta m$ in the report on the work. The mass is indicated on the pendulum.
2. Measure with a ruler the distance l between the suspension point of the pendulum O and its center of mass C (see Figure 1). Record the result in the report in the form: $l = l0 \pm \Delta l$.
3. Hang the pendulum on the holder. Deflect the pendulum from the vertical to a small angle and release. Having skipped 1-2 oscillations, start the stopwatch. Having counted N = 15-20 full oscillations, turn off the stopwatch. Report the number of oscillations N and the stopwatch readings in the report in the form: $t = t_0 \pm \Delta t$.
4. Calculate the moment of inertia of the pendulum, using formula (6), as well as its absolute and relative errors. The result is written as $I = I_0 \pm \Delta I$, $\varepsilon = \Delta I/I_0 = \ldots.$
5. Make a report on the work.

Test Questions

1. What is called the moment of inertia of a body over a given axis? What formulas does it determine? What is its physical sense?
2. What motions are called mechanical oscillations? Give examples of oscillatory motions.
3. What is called a physical pendulum? What other pendulums exist?
4. What is called an oscillation period? Write down the formula for the oscillation period of the physical pendulum.
5. Derive the working formula for this work.

3.4 *Laboratory work M-4* Determination of the Viscosity Coefficient by the Stokes Method

Objective: to study the phenomenon of internal friction and the method of measuring the coefficient of dynamic viscosity by the Stokes method, the measurements using this method.

Equipment: 1) installation for determining the viscosity by the Stokes method; 2) balls; 3) micrometer; 4) stopwatch; 5) ruler.

Brief Theoretical Information

All real liquids and gases have **viscosity** (or **internal friction**).

Viscosity (internal friction) is a property of real continuous media (liquids and gases) to resist the movement of one part of the medium relative to another.

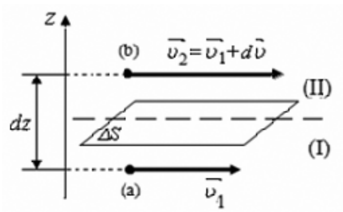


Figure 1 To the Newton's equation for viscosity

The phenomenon of viscosity in liquids and gases can be described as follows. Let two layers of liquid or gas (layers (I) and (II) in Figure1) have different speeds $\vec{\upsilon}1$ and $\vec{\upsilon}2 = \vec{\upsilon}1 + d\vec{\upsilon}$. The distance between the points (a) and (b) at which these velocities are measured is equal to *dz* (these points are situated in different layers).

From the layer that moves faster, an accelerating force acts on a layer that moves more slowly. Accordingly, a braking force acts on the fast layer from the slow layer. These forces, directed tangentially to the surface of the layer, are called **internal friction forces.** They are larger, the larger the area of the contacting layers, and depend on the difference in the flow rates of the liquid (gas).

The internal friction force between the fluid layers is determined by the formula:

$$F = -\eta \frac{dv}{dz} \Delta S, \tag{1}$$

where the quantity $\frac{dv}{dz}$ is called the **velocity gradient**, it shows how rapidly the velocity of the medium changes during the transition from layer to layer in the z direction, perpendicular to the direction of the velocities of the layers. In formula (1), ΔS is the area of the site, mentally distinguished on the surface of contact between the layers, on which the internal friction force determined by this formula accounts; η is the **coefficient of dynamic viscosity** of the medium (liquid or gas).

Expression (1) is called **the Newton's equation for viscosity**. The unit of the coefficient of dynamic viscosity in the system of units of SI is Pascal-second (Pa·s). The viscosity coefficient generally depends on the nature of the liquid or gas, as well as on temperature. In this regard, as the temperature rises, the viscosity of the gases increases, while that of liquids decreases.

When a body moves in a viscous medium, **resistance forces** arise. At low speeds of body motion in the medium, at which turbulence does not form behind the body (i.e., the flow of the medium past the body is **laminar**), the resistance force of the medium is determined only by its **viscosity**.

According to Stokes' law, when a spherical body (ball) moves in a viscous medium at low speed, the resistance force acting on the body from the medium is:

$$\vec{F}_C = -6\pi R\eta\vec{v}, \tag{2}$$

where R is the radius of the ball, v is its velocity, and η is the coefficient of dynamic viscosity of the fluid. The sign «-» indicates that Stokes force is directed against the speed of the ball.

The method of measuring the coefficient of dynamic viscosity, called the Stokes method, is based on using this formula. A ball falling in a viscous fluid is affected by three forces (Figure 2): a downward **force of gravity** F_g, a **buoyancy force** (or **Archimedes force**) F_A upward and a **resistance force** (or **Stokes force**) F_S directed against the motion, that is, also upwards.

If you put the ball into the liquid, it will first move rapidly. With an increase in the speed of the ball, the Stokes force will grow in accordance with formula (2) until this force combined with the Archimedes force balances the force of gravity and the movement of the ball becomes uniform. With a uniform movement of the ball, the condition of balance of forces is fulfilled. In the projection on the direction of movement of the ball, it has the

$$F_g - F_A - F_S = 0. \qquad (3)$$

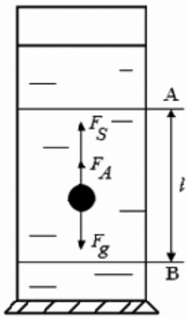


Figure 2 Forces, acting on a ball in a fluid

The magnitude of the force of gravity F_g can be determined by knowing the density of the material of the ball ρ_b and the radius of the ball R, according to the formula:

$$F_g = mg = \rho_b Vg = \frac{4}{3}\pi R^3 \rho_b g. \qquad (4)$$

The magnitude of the force of Archimedes determined by knowing the density of the liquid ρ_l:

$$F_A = \rho_l gV = \frac{4}{3}\pi R^3 \rho_l g \qquad (5)$$

Substituting in (3) the expressions (2), (4), (5) we get:

$$\frac{4}{3}\pi R^3 \rho_b g - \frac{4}{3}\pi R^3 \rho_l g - 6\pi\eta R\upsilon = 0 \qquad (6)$$

From equation (6) for the coefficient of dynamic viscosity of the liquid η we get:

$$\eta = \frac{2R^2 g(\rho_b - \rho_l)}{9\upsilon}. \qquad (7)$$

The speed of the ball in the liquid (assuming this motion is uniform) can be determined by measuring the time *t* of the ball passing a certain distance *l*:

$$\upsilon = \frac{l}{t}. \qquad (8)$$

Substituting expression (8) into formula (7), taking into account the fact that $R = \frac{d}{2}$ (where *d* is the ball diameter), we obtain the calculating formula for determining the coefficient of dynamic viscosity of a liquid:

$$\eta = \frac{d^2 g(\rho_b - \rho_l)t}{18l}. \qquad (9)$$

Installation Description and Working Process

To determine the viscosity by the Stokes method, a high cylindrical vessel is used and it is filled with the test liquid (liquid oil, see Fig. 2). There are two ring marks A and B on the vessel. Label A approximately corresponds to the height where the forces acting on the ball balance each other and the its movement becomes uniform. The bottom mark B is applied for easy timing. The work should be carried out in the following sequence:

1. Measure the diameter *d* of the ball with a micrometer three times.
2. Calculate the average diameter d_{av} of the ball and its absolute error Δd.
3. Measure the distance *l* between the marks. Estimate the value of Δl.
4. Throw the ball into the vessel with liquid. Measure the time *t* of the passing the distance between marks A and B by the ball. Estimate the absolute measurement error Δt.
5. Calculate the viscosity η of a liquid using formula (9).
6. Repeat similar measurements with other balls. Find the average value of the coefficient of viscosity η_{av} and the absolute error $\Delta\eta$.
7. The results of measurements and calculations recorded in table 1.

Table 1

№ of ball	d_1, m	d_2, m	d_3, m	d_{av} m	Δd m	t, s	Δt, s	l, m	Δl, m	η, $Pa\times s$	η_{av}, $Pa\times s$	$\Delta\eta_i$, $Pa\times s$	$\Delta\eta$, $Pa\times s$
1													
2													
3													
4													

8. Make a report on the work.

Test Questions

1. To define the force of internal friction.
2. Write the Newton's equation for internal friction in a viscous medium.
3. How does the viscosity of liquids and gases depend on temperature?
4. To derive a formula for determining the coefficient of dynamic viscosity of a liquid according to the Stokes method.
5. What is the dimension of the coefficient of dynamic viscosity in the system of SI units?

3.5 *Laboratory work T-1* Determination of Poisson's Index of Air By the Clement and Desorm Method

Objective: to determine the Poisson's index γ of atmospheric air, i.e. the ratio of the molar heat capacity of air at constant pressure C_P to its molar heat capacity at constant volume C_V ($\gamma = C_P / C_V$).

Equipment: glass balloon with a liquid manometer, pump, hydrostatic valve, tap, connecting tubes.

Brief Theoretical Information

The heat capacity of a substance is called a physical quantity numerically equal to the amount of heat required to heat a substance by one degree 1°C (or 1 K). The heat capacity of a substance is determined by the formula:

$$C = \frac{dQ}{dT}\left(\frac{\text{J}}{\text{K}}\right), \tag{1}$$

where dQ is infinitely small amount of heat received by the substance, dT is infinitely small change in its temperature.

The heat capacity depends on the mass of the heated body. The heat capacity of 1 kg of the substance is called its **specific heat capacity** c_y:

$$c_y = \frac{C}{m} = \frac{dQ}{m \cdot dT}\left(\frac{\text{J}}{\text{kg} \cdot \text{K}}\right). \tag{2}$$

The specific heat is numerically equal to the amount of heat that must be delivered to a unit mass of a substance in order to increase its temperature by 1 K (or by 1°C).

The heat capacity of unit mole of a substance is called its **molar heat capacity** $C\mu$:

$$C_\mu = \frac{\mu \cdot dQ}{m \cdot dT}\left(\frac{\text{J}}{\text{mol} \cdot \text{K}}\right), \tag{3}$$

where μ is molar mass of the substance.

The molar heat capacity is numerically equal to the amount of heat required to heat one mole of a substance by one degree.

From relations (2) and (3), it is possible to determine the amount of heat ΔQ received or given away by the body when its temperature changes by ΔT:

$$\Delta Q = c_{\text{y}} \cdot m \cdot \Delta T = C_{\mu} \cdot \frac{m}{\mu} \Delta T. \tag{4}$$

With an increase in body temperature ($\Delta T > 0$), this body receives heat from external bodies ($\Delta Q > 0$), with a decrease in body temperature ($\Delta \mathrm{T} < 0$), the body gives off heat to external bodies ($\Delta Q < 0$).

The relationship of molar and specific heat is determined by the formula:

$$C_{\mu} = \mu \cdot c_{\text{y}}, \tag{5}$$

An important equation used for the physical description of gases (as well as other thermodynamic systems) is the **first law of thermodynamics.** With a small change in the state of the system (gas), it has the form:

$$dQ = dU + dA, \tag{6}$$

The amount of heat dQ received by the system is spent on increasing its internal energy dU and on this system performing work dA on external bodies (against external forces).

For the finitesimal (not small) change in the state of the system:

$$Q = U + A\,. \tag{7}$$

The amount of heat received by the gas during any process, and, therefore, its heat capacity, defined by formulas (2) and (3), significantly depend on the heating conditions, i.e. on the type of process occurring in the gas.

In gases, two heat capacities are distinguished: the heat capacity in a process with a constant volume i.e. **isochoric heat capacity** (C_V – molar, c_V – specific) and the heat capacity in the process at constant pressure or **isobaric heat capacity** (C_P – molar, c_P– specific).

The value of C_V is determined by the formula:

$$C_V = \frac{i}{2} R, \tag{8}$$

Where R = 8,31 J/(mol·K) is the universal gas constant, i is the number of freedom degrees of the gas molecules.

For **monatomic** molecules (He, Ar, etc.) $i = 3$, for **diatomic** molecules (O_2, CO, HCl, etc.) $i = 5$, for other (**polyatomic**) molecules (CH_4, CO_2, etc.) $i = 6$.

The molar heat capacity of gas at constant pressure can be determined from the equation of R. Mayer:

$$C_P = C_V + R, \tag{9}$$

whence, taking into account the formula (8):

$$C_P = \frac{i+2}{2} R. \tag{10}$$

The ratio of heat capacities

$$\gamma = \frac{C_P}{C_V} \tag{11}$$

is called the **adiabatic index** or **Poisson's coefficient** of the gas. From formulas (8), (10) and (11), we obtain:

$$\gamma = \frac{i+2}{i}. \tag{12}$$

Thus, for monatomic gases, $\gamma \approx 1.67$, for diatomic (and, in particular, for air) $\gamma = 1.4$, for polyatomic gases $\gamma \approx 1.33$.

The Poisson's coefficient γ is very important for the description of **adiabatic processes** in gases. An adiabatic process is a process that occurs without heat transfer of a given system (gas) with surrounding bodies, i.e., under the condition of overall thermal insulation of the system. This means that in the equation of the first law of thermodynamics (6) $dQ = 0$, and this equation for the adiabatic process takes the form:

$$dA = -dU. \tag{13}$$

From the first law of thermodynamics it follows that in an adiabatic process the work of gas on external bodies is accomplished by reducing its internal energy. For example, if the volume of gas increases (gas expands and does work on external bodies), then the internal energy of the gas decreases, i.e., its temperature decreases. On the contrary, with gas compression, its temperature rises.

The pressure P and the gas volume V during the adiabatic process are related by the **Poisson equation**:

$$PV^{\gamma} = const, \tag{14}$$

where γ is the adiabatic index determined by equations (11) and (12).

Installation Description

To determine the numerical value of the Poisson's index of air in this paper, we use the method proposed by the French physicists N. Clement and C. Desorm in 1819. The installation for performing the work consists of a glass bulb C (Figure 1) connected to a liquid (water) pressure gauge G and pump P. Bulb C is connected to the atmosphere through tap K.

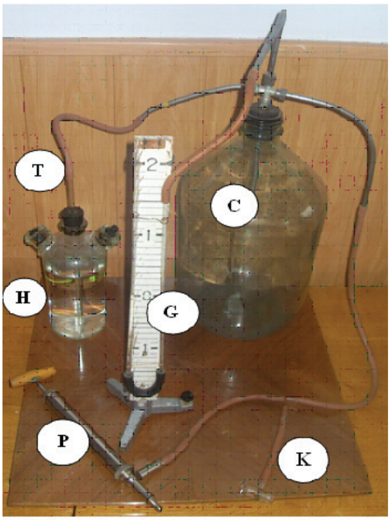


Figure 1 Laboratory setup

Pouring out water from the pressure gauge in the process of pumping air into the bulb is prevented with the hydrostatic valve T in the form of a vessel with water, into which the end of the tube H is put down. Let the end of the tube H is at a depth h. Then when the pressure in the bulb exceeds atmospheric pressure by the value of $\rho_w gh$ (where ρ_w is the density of water); air will displace water from the immersed part of the tube H and will exit through the lower end of this tube; and the pressure increase in the bulb will stop.

At the beginning of operation, the tap K is open, the pressure P_0 and the air temperature T_0 in the bulb are equal to atmospheric pressure and the temperature in the laboratory room.

Then the valve closes, and air is pumped into the bulb using a pump P. Manometer G fixes the pressure increase in the bulb. The air in the bulb should be inflated until the difference in water levels in the elbows of the pressure gauge becomes equal to 15-20 sm. The process of compressing air in the bulb because of pumping additional air, due to its short duration, can be considered as **adiabatic compression**. As a result of this process, the air temperature in the bulb will increase slightly.

After pumping, the valve closes again, and then there is a slight decrease in air pressure in the bulb. It is fixed by a decrease of the difference in levels at the manometer elbows and is associated with the bulb air cooling to a temperature in the laboratory. When the air temperature becomes equal to the temperature in the laboratory, the level difference in the manometer elbows will stop decreasing and will reach a certain value h_1. The pressure in the bulb in this state is (State 1):

$$P_1 = P_0 + \rho_w g h_1. \tag{15}$$

After this, the next part of the experiment is performed; it is the adiabatic expansion of the gas in the bulb. To do this, the tap K opens and the gas sharply leaves the bulb, because of which the level difference in the elbows of the manometer drops to zero quickly. That means the pressure in the bulb becomes equal to the atmospheric pressure in the laboratory P_0. Because of this process, the air temperature in the bulb decreases and becomes lower than the temperature in the laboratory (State 2).

After the tap K is closed, the air in the bulb will warm up to the temperature in the laboratory, while the pressure in the bulb rises, which is fixed by the occurrence and increase of the difference in levels in the elbows of the manometer. After the completion of heating the air in the bulb, the level difference will cease to increase and will become equal to h_2. In this state, the pressure in the bulb will be equal to (State 3):

$$P_2 = P_0 + \rho_w g h_2. \tag{16}$$

To derive a formula for determining the Poisson's index γ, we mentally select a certain mass of air in the bulb; and we assume that this mass does not change during all the described processes, but only changes its volume, pressure, and temperature. We consider three consecutive states of this mass.

State 1 – after pumping air into the bulb and cooling it until the moment when the tap K is opened:
V_1 – volume,
$P_1 = P_0 + \rho_w g h_1$ – pressure,
T_0 – temperature (equal to the temperature in the laboratory).

State 2 – immediately after adiabatic expansion of the air in the bulb:
V_2 – volume,
P_0 – pressure (equal to atmospheric pressure in the laboratory),
T_2 – temperature ($T_2 < T_0$).

State 3 – after the temperature in the bulb equals the temperature in the laboratory:
V_2 – volume,
$P_2 = P_0 + \rho_w g h_2$ – pressure,
T_0 – temperature (equal to the temperature in the laboratory).

In State 1 and State 3 the gas has the same temperature, and these States can be related by the Boyle-Mariotte law:

$$P_1 V_1 = P_2 V_2. \tag{17}$$

The transition from State 1 to State 2 is an adiabatic process, and the Poisson equation (14) is applicable to it in the form:

$$P_1 V_1^{\gamma} = P_0 V_2^{\gamma}. \tag{18}$$

Raising both sides of formula (17) to the power γ and dividing it term by term by formula (18), after the transformations we obtain:

$$\frac{P_1}{P_0} = \left(\frac{P_1}{P_2}\right)^{\gamma}. \tag{19}$$

Having log-transform of both sides of this equation, taking into account the mathematical properties of the logarithms, we have for the quantity γ:

$$\gamma = \frac{lnP_1 - lnP_0}{lnP_1 - lnP_2}. \tag{20}$$

Changes in bulb pressure during the experiment are much less than atmospheric pressure:

$$\rho_w g h_1 << P_0,\ \rho_w g h_2 << P_0, \tag{21}$$

therefore, the pressures P_1 and P_2 determined from formulas (15) and (16) are close to each other and close to atmospheric pressure P_0. From the properties of natural logarithms it follows that the ratio of the differences of the logarithms of close quantities can be approximately replaced by the ratio of the differences of the quantities themselves. Using that, from formula (20) we obtain:

$$\gamma \approx \frac{P_1 - P_0}{P_1 - P_2}. \tag{22}$$

Then, taking into account formulas (15) and (16), we obtain a working formula for determining the Poisson's index of air:

$$\gamma = \frac{h_1}{h_1 - h_2}. \tag{23}$$

Working Process
Attention: do not apply big efforts when turning the tap K!

1. With the tap K closed, pump a certain amount of air into the bulb so that the level difference in the pressure gauge is 350–400 mm.
2. After waiting for a while (1-2 minutes), when the difference in fluid levels in the elbows of the manometer stops changing, record this level difference as h_1 in Table 1.
3. Open the tap K, which communicates the bulb with outside air, for a short time (1-2 seconds), necessary for the levels in the pressure gauge to level out, and close it immediately.
4. After closing the tap, the difference in liquid levels in the manometer begins to slowly increase, and after a while (0.5-1 minute), an invariable difference in the levels of h_2 is established. Record the value of h_2.
5. Calculate the Poisson's index g by formula (23).
6. Repeat measurements at least 5 times.
7. Calculate the average value of g_{av}, the absolute error Δg_{av} and the relative error $e = \Delta g_{av} / g_{av}$.
8. The measurement results are recorded in the Table.

Table 1

№ of measure-ment	h_1, mm	h_2, mm	g	g_{av}	D g	Δg_{av}	e
1							
...							
5							

9. Make a report on the work.

Test Questions

1. To formulate a definition of the concepts of specific and molar heat capacities of a substance.
2. Write the equation of R. Mayer.

3. What model is used for air in this work? Write the Mendeleev-Clapeyron equation.
4. Formulate and write down the first law of thermodynamics.
5. What process is called adiabatic? Write the equation of the first law of thermodynamics for the adiabatic process.
6. Write down the Poisson equation for the adiabatic process.
7. What is called the Poisson's index? How does it depend on the number of degrees of freedom of gas molecules?
8. How does the gas temperature change during adiabatic expansion/ compression?
9. Explain the principle of operation of the hydrostatic valve T (see Figure 1).

3.6 *Laboratory work E-1* Measuring of an Ohmic Resistance with the Bridge of Direct Current

Objective: to study the method of measuring of resistance using bridge circuits; measure the unknown resistances by the Whitsone direct current bridge (DC Bridge); check the rules for addition of resistances by means of making their series and parallel connections.

Equipment: DC Bridge of the type MO-62 (or some other type), a set of unknown resistances (R_{x1} and R_{x2}), connecting wires.

Brief Theoretical Information

You can measure the resistance by using a voltmeter and amperemeter, or by comparison method. Comparison methods using bridge circuits are widely used to measure the parameters of electrical circuits in measuring equipment. These methods have a significant advantage because of opportunity to measure resistance with high accuracy. At the same time, such measuring devices as a voltmeter and amperemeter are not needed, which simplifies the electrical circuit and eliminates the error that these measuring instruments introduce.

To measure the resistance by the method of comparison direct current bridges are used, in this work, it is the Whitsone DC Bridge. The scheme of this bridge is shown in Figure 1.

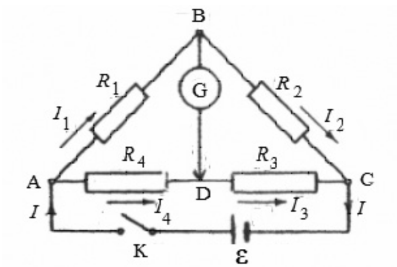


Figure 1 Direct current bridge scheme

Calculations of currents and voltages in complex electrical circuits (including DC Bridges) can be carried out by various methods, for example, on the basis of **Kirchhoff's rules.** Let us have a brief look at these rules.

Any electric circuit can be represented as a set of **nodes** and **contours**.

The **node** is the point of the circuit, in which more than two conductors converge (Figure 2(a)). Since the charge can not accumulate at the node, the *algebraic sum of currents converging in any node of the circuit is zero*: $\sum_k I_k = 0$ (**the first Kirchhoff's rule**). In this case, the currents flowing to the node are considered positive, and the currents that flow from it are negative. For example, for a node depicted in Figure 2(a), this formula looks like: $I_1 - I_2 + I_3 = 0$, or $I_1 + I_3 = I_2$.The **contour** is called any closed chain, each section of which is the site of this circuit considered (Figure 2 (b)). For each section of the chain from the formula of the Ohm's law follows: $I_{ij} (R_{ij} + r_{ij}) = (\varphi_i - \varphi_j) + \varepsilon_{ij}$, where the indices *i* and *j* denote the numbers of the nodes of the chain between which this section is located. Adding these equations to all sections of the chain and taking into account that the sum of potential difference is zero (since the chain is closed), we obtain $\sum I_{ij}(R_{ij} + r_{ij}) = \sum \varepsilon_{ij}$(**the second Kirchhoff's rule**).

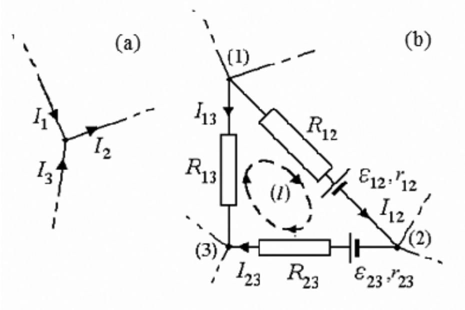


Figure 2 To the formulation of the Kirchoff's rules

The algebraic sum of the voltages on the resistances entering the closed chain (taking into account the internal resistance of the current sources r_{ij}) equals the algebraic sum of the electromotive forces in this chain.

In this formula, the current in this site is positive when it flows in the direction that coincides with the direction of bypass of the circuit (*l*). Otherwise, the current is negative.

Similarly, the value of the electromotive force ε_{12} is positive when it contributes to the flow of current in the direction that coincides with the direction of the contour bypass. Otherwise, this value is negative. For example, for the contour in figure 2 (b) we have: $I_{12} (R_{12} + r_{12}) + I_{23} (R_{23} + r_{23}) - I_{13} R_{13} = \varepsilon_{23} - \varepsilon_{12}$.

Let us return to the bridge scheme in Fig. 1. In this circuit, R_1, R_2, R_3 and R_4 are the resistances that are called the arms of the bridge; ε - current source; K - key; G - null-galvanometer, which is an indicator of the absence of current in the BD site during measurements.

By selecting resistances R_1, R_2, R_3 and R_4, it is possible to ensure that the potential difference between nodes B and D is zero, i.e. the potentials of points B and D will be the same ($\varphi_B = \varphi_D$), which means that the current in the BD site will be zero. In this case, the bridge is **in equilibrium** (the bridge is **balanced**).

With a balanced bridge, you can find any unknown resistance, for example, R_1, knowing the remaining R_2, R_3 and R_4. Let us write the first Kirchhoff's rule for nodes A, B, C (see Figure 1)

$$\begin{aligned} &A: I - I_1 - I_4 = 0 \\ &B: I_1 - I_2 = 0 \\ &C: I_2 + I_3 - I = 0 \end{aligned} \tag{1}$$

The directions of the currents are shown in Figure 1. From these equations, it follows that: $I_1 = I_2$, and $I_3 = I_4$.

Let us write the second Kirchhoff's rule for the contours:

$$\left.\begin{aligned} &ABDA: I_1R_1 - I_4R_4 = 0 \Rightarrow or\ I_1R_1 = I_4R_4 \\ &BCDB: I_2R_2 - I_3R_3 = 0 \Rightarrow or\ I_2R_2 = I_3R_3 \end{aligned}\right\} \tag{2}$$

We took into account that for a balanced bridge the current through the galvanometer is zero. The directions of bypassing of all the indicated contours are selected clockwise. From relations (2), taking into account the fact that $I_1 = I_2$, $I_3 = I_4$, it follows:

$$\frac{R_1}{R_2} = \frac{R_4}{R_3} \tag{3}$$

This formula for the ratios of resistance of the arms of the bridge expresses the **condition of equilibrium of the bridge**.

Using the relation (3), one can determine any of the four resistances, if the others are known. For example,

$$R_1 = R_2 \frac{R_4}{R_3} \quad (4)$$

Installation Description and Working Process

In practice, all parts of the DC Bridge are installed in a single device containing a power supply, resistance box, null-galvanometer, connecting wires, etc. Separately allocated terminals for connecting the resistance to be measured. In our work, the DC Bridge MO-62 is used.

Measurement of resistances from 10 to 10^6 ohms.

1. The measured resistance is connected to the terminals $П_1$ and $П_2$.
2. Switch of the bridge «ПС» is set to position «23».
3. The power switch of the bridge «ПП» is set to position 36 В.
4. The switch of the arms «N» is set to the selected multiplier (see Table 1).

Table 1

№	measured resistance, Ohm	*N*
1	$10, 10^2$	1
2	$10^2, 10^3$	1
3	$10^3, 10^4$	10
4	$10^4, 10^5$	100
5	$10^5, 10^6$	1000

5. When the «ГРУБО» button is pressed, by turning the knobs of the selector «×100», «×10», «×1», «×0.1», «×0.01» set the galvanometer to zero.
6. With the «ТОЧНО» button pressed, by turning the knobs of the selector «×1», «×0,1», «×0,01» set the galvanometer to zero again.

7. Record the readings of the knobs and calculate of the comparison resistance value R_{com} as the sum of these readings, taking into account the corresponding coefficients «×100», «×10», «×1», «×0.1», «×0.01».
8. Calculate the unknown resistance R_{x1} by the formula (5):

$$R_{x1} = R_{com} \times N \tag{5}$$

which is identical to formula (4).
9. Repeat for three times experience in measuring the value of R_{x1}. Calculate the average value of the measurement results and the absolute error ΔR_{x1}. Record the calculation results to Table 2.
10. Repeat points 1 - 9 are for another resistance R_{x2}.
11. Connect both resistances in series and repeat points 1-9. Make a conclusion about the accordance of the measurement result with the theoretical formula

$$R_{Xser} = R_{X1} + R_{X2} \tag{6}$$

12. Connect both resistances in parallel and repeat points 1-9. Make a conclusion about the accordance of the measurement result with the theoretical formula

$$R_{Xpar} = \frac{R_{X1} \cdot R_{X2}}{R_{X1} + R_{X2}} \tag{7}$$

Table 2

№	R_{X1}	ΔR_{X1}	R_{X2}	ΔR_{X2}	Connection in series		Connection in parallel	
					R_{ser}	ΔR_{ser}	R_{par}	ΔR_{par}
1								
2								
3								
Average value								

13. Make a report on the work.

Test Questions

1. How are formulated the Ohm's laws for a homogeneous site of circuit and for a full circuit?
2. What is the total resistance of conductors connected in series ?, in parallel?
3. How are formulated the Kirchhoff's first and second laws?
4. What are the advantages of determining the resistance by the bridge method in comparison with the method of amperemeter and voltmeter?
5. What are the equilibrium conditions of the bridge?
6. What is the purpose of the null-galvanometer in the DC Bridge circuit?

3.7 *Laboratory work E-3*
Determination of the Horizontal Component of the Strength of the Magnetic Field of the Earth Using a Tangent-Compass

Objective: to study the main parameters of the Earth's magnetic field, to determine the horizontal component of the Earth's magnetic field induction and the magnetic field strength.

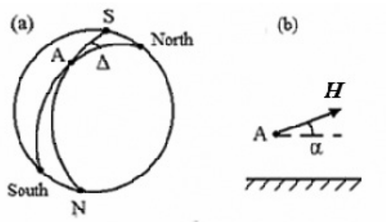
Equipment: 1) tangent-compass; 2) a direct current source; 3) switch; 4) ammeter; 5) connecting wires.

Brief Theoretical Information

The Earth is a natural magnet, the poles of which are located close (~ 300 km) to geographic poles.

The magnetic pole of the Earth, which is located in the north (near Canada), is the **South magnetic pole (S)**, the other, respectively, in the south (in Antarctica) is the **North magnetic pole (N)**.

Through each point A on the surface of the Earth, one can draw **a magnetic meridian** and a **geographical meridian**. A magnetic meridian is an arc of a large circle passing through this point and the magnetic poles of the Earth (S – N line in Figure 1). A geographical meridian is an arc of a large circle passing through this point and geographical poles (North – South line in Figure 1). The angle between the directions of the geographical and magnetic meridians is called the **angle of magnetic declination** Δ (Figure 1(a)). **The angle of magnetic inclination** is the angle between the direction of the vector of magnetic field strength $\boldsymbol{H}$ at a given point and the horizontal plane (Figure 1(b)).



(a) - magnetic declination (b) - magnetic inclination

Figure 1 Characteristics of the magnetic field of the Earth

These angles (declination and inclination) are called **elements of Earthly magnetism**.

Thus, in the general case, the magnetic strength at a given point is inclined, i.e. has horizontal H_h and vertical H_v components. A magnetic arrow (for example, a compass arrow) that rotates freely on a fixed vertical axis is placed in the plane of the magnetic meridian under the influence of the horizontal component of the Earth's magnetic field $\boldsymbol{H}_h$.

If using a circular electric current to create another magnetic field near the arrow, the arrow will be established in the direction of the resultant strength of both magnetic fields $\boldsymbol{H}$ (Fig. 2). Since the circular current field is easy to calculate, knowing the magnitude (strength) of the current, the horizontal component of the earth's magnetic field can be determined from the angle of deflection of the arrow and the current field strength.

Determination of the horizontal component of the magnetic field of the Earth can be made using an instrument called a **tangent-compass** or a **tangent-galvanometer**. The tangent-compass has a flat vertical bobbin of radius r with a certain number of conducting turns N. In the center of the bobbin, there is a small magnetic arrow (compass). With a sufficiently large bobbin radius, we can assume that the magnetic arrow is in a uniform magnetic field.

The magnetic arrow of the compass in the absence of current in the turns will be oriented along the magnetic meridian. By turning the turns on the vertical axis, it is possible to achieve alignment of the bobbin plane with the plane of the magnetic meridian.

When current I passes through the turns, the magnetic field H_I generated by this current in the center of the bobbin can be determined by the formula (see formula (16.11) in Lecture 16 and take into account that $H = B/\mu\mu_0$):

$$H_I = \frac{I}{2r} N \tag{1}$$

where I is the current in amperes, r is the turn radius in meters, N is the number of turns.

After installing the bobbin in the plane of the magnetic meridian of the Earth and passing the current throw the turns, the horizontal component of the magnetic field of the Earth H_h and the field strength induced by the current in the turns H_I in the center of the bobbin will be perpendicular to each other (Fig. 2). As can be seen from Fig. 2, the compass arrow at the same time will turn through an angle ϕ, which is determined by the formula

$$\text{tg}\,\varphi = \frac{H_I}{H_h} \tag{2}$$

from where

$$H_h = \frac{H_I}{\text{tg}\varphi}. \tag{3}$$

Substituting formula (1) into (3), we obtain a **calculating formula** for determining the horizontal component of the Earth's magnetic field:

$$H_h = \frac{I}{2r \cdot tg\varphi} N. \tag{4}$$

Installation Description

The laboratory setup (Figure 2) consists of: 1) tangent compass G; 2) ammeter A; 3) a direct current source DCS; 4) rheostat R (in reality it is mounted inside the DCS); 5) switch K.

Course of the work

1. Assemble the electrical circuit in accordance with the scheme shown in Figure 2.
2. Set the plane of the tangent-compass bobbin in the plane of the magnetic meridian. In this case, the compass arrow should be set to zero scale.
3. Using a rheostat, set the value of the current in the circuit equals to 0.5 A, and record the angle of rotation ϕ of the arrow of tangent compass.
4. Repeat the measurement for different current values.
5. Using the calculator to find the values of tg ϕ.
6. Using formula (4), calculate the horizontal component of the Earth's magnetic field H_h. Record the results into the Table 1.
7. Calculate the average value of H_h (in A/m).
8. Determine the absolute (D H_h) and relative ε (%) errors of the measurement.

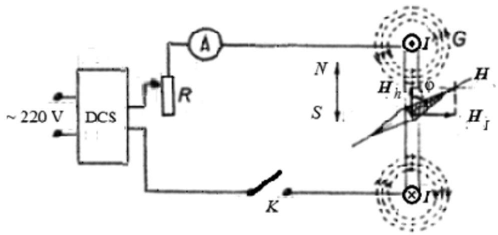


Figure 2 Scheme of the laboratory setup

Table 1

№ п/п	strength of a current *I*, A	angle of rotation of the arrow φ (degrees)	tg φ	number of turns *N*	radius of the turns *r*, m	H_h, A/m	D H_h, A/m	ε (%)
1.	0,5							X X X X X X X X
2.	0,6							
3.	0,7							
4.	0,8							
5.	0,9							
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx					average values			

Test Questions

1. How the magnetic induction and the magnetic field strength are related. In what units are they measured?
2. What is the magnetic meridian?
3. What angle is the angle of magnetic declination?
4. What angle is the angle of magnetic inclination?
5. Formulate and write down the law of Biot-Savart-Laplace.
6. Write the formulas of intensity and induction of the magnetic field created by a circular turn with a current in its center.
7. Derive the calculating formula for determining the horizontal component of the Earth's magnetic field of this work.

3.8 *Laboratory work K-1* Study of Free Mechanical Oscillations

Objectives: to measure the deviation from the position of the equilibrium of the oscillating system, the period and amplitude of mechanical oscillations; calculate the coefficient and the logarithmic decrement of damping the oscillation; calculate measurement errors in this work.

Equipment: laboratory installation - a spring pendulum (vertical spring with a weight of fixed mass), a ruler, a stopwatch.

Brief Theoretical Information

Oscillations are called processes that are periodically repeated over time.

Main kinds of oscillations are **mechanical oscillations** (oscillatory movements) and **electromagnetic oscillations** (oscillations of electric and magnetic quantities in the corresponding systems).

Free oscillations are called the oscillations that arise in an oscillatory system under the action of a single external influence (initial shock or initial deviation of the system from the state of its stable equilibrium).

Forced oscillations are the oscillations occurring in an oscillatory system exposed to periodic external influences.

In this laboratory work, **free mechanical oscillations of a spring pendulum** are studied.

The laws of free oscillations are described using two models of oscillating systems – the model of a **perfect oscillator** and a model of a **damped oscillator**.

The perfect oscillator is a model of the oscillatory system, which neglects the loss of energy in the process of oscillation and, therefore, in which the oscillations are not damped over time. The oscillations of the ideal oscillator are made according to the law of harmonic oscillations

$$x(t) = Asin(\omega_0 t + \varphi_0) \quad (1a)$$

or

$$x(t) = Acos(\omega_0 t + \varphi_0). \quad (1b)$$

In these formulas:

$x(t)$ is the **oscillating value** i. e. the **current deviation of the oscillating value from its equilibrium meaning**. For a spring pendulum, $x(t)$ is the current deviation of the weight from its equilibrium position during the process of its oscillations;

A is the **oscillation amplitude** – the maximum deviation of the oscillating value from its equilibrium meaning. The dimension of the amplitude coincides with the dimension of the oscillating value;

$(\omega_0 t + \varphi_0)$ is the **phase of oscillation**, it characterizes the current state of the oscillatory system, the value φ_0 is the initial phase. The phase and the initial phase are measured in radians (rad) in the system of SI units;

ω_0 is the **circular (cyclic) frequency** of oscillation, it characterizes the rapidity of the oscillation. In the system of units SI $[\omega_0] = 1/\text{s}$. For each oscillatory system, ω_0 has a certain value, for example, for a spring pendulum

$$\omega_0 = \sqrt{\frac{k}{m}}, \qquad (2)$$

where k is the rigidity coefficient of the spring, m is the mass of the weight.

In addition to the circular frequency ω_0, other characteristics of the rapidity of oscillations are their **period** and **frequency**. The period of oscillation T is the time interval over which one complete oscillation takes place. During one oscillation period, the phase of this oscillation increases by 2π, i.e. $(\omega_0(t + T) + \varphi_0) - (\omega_0 t + \varphi_0) = 2\pi$, so $T = 2\pi/\omega_0$. For a spring pendulum, as follows from formula (2),

$$T = 2\pi\sqrt{\frac{m}{k}}. \qquad (3)$$

The oscillation frequency ν is the number of oscillations performed in 1 s. Obviously, $\nu = 1 / T = \omega_0 / 2\pi$. The dimension of the frequency $[\nu] = 1 / \text{s} = \text{Hz}$ (hertz). For example, the frequency of oscillations of alternating current in the household electrical network in Ukraine is 50 Hz. This means that 50 oscillations of the value of current occur in a time interval equal to 1 s.

The values of A, ω_0, φ_0, T, and ν within the framework of the perfect oscillator model do not change during the oscillation process and are called the **characteristics of harmonic oscillations**.

The graph of harmonic oscillations is presented in Figure 1.

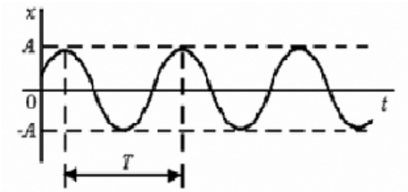


Figure 1 Graph of harmonic oscillations

A **damped oscillator** is a model of an oscillating system that takes into account energy losses due to the presence of friction forces in the system (mechanical oscillations) or the presence of electrical resistance (in electrical circuits in which electromagnetic oscillations occur). The law of damped oscillations is

$$x(t) = A_0 e^{-\beta t} \, sin(\omega t + \varphi_0) \quad (4a)$$

or

$$x(t) = A_0 e^{-\beta t} \, cos(\omega t + \varphi_0). \quad (4b)$$

In these formulas:

A_0 is the **initial amplitude** of oscillation (i.e., the amplitude at the time $t = 0$);

e = 2,718281 is the basis of natural logarithms; β – oscillations **damping factor**, [β] = 1/s in the system of units SI; ω is the **circular frequency of damped oscillations**. As the calculation shows

$$\omega = \sqrt{\omega_0^2 - \beta^2}. \quad (5)$$

This means that with an increase in the damping factor, the rapidity of damped oscillations decreases, and the period of them $T = \frac{2\pi}{\sqrt{\omega_0^2 - \beta^2}}$ increases.

As follows from formula (5), damped oscillations can exist in an oscillatory system only for $\omega_0 > \beta$.

As follows from formulas (4), the amplitude of damped oscillations decreases with time according to the law

$$A(t) = A_0 e^{-\beta t}. \quad (6)$$

The graph of damped oscillations is shown in Figure 2.

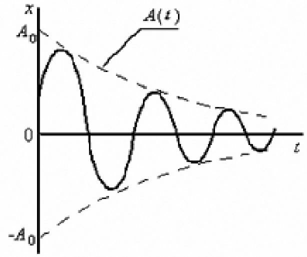


Fig. 2 The graph of damped oscillations

In addition to the oscillation damping factor β, there is a dimensionless damping characteristic, which is called a **logarithmic decrement of damping** λ. It is determined by the formula

$$\lambda = \beta T. \tag{7}$$

For oscillatory contours in radio engineering systems, the quality factor $Q = \pi / \lambda$ is used as a damping characteristic. The slow damping corresponds to $Q >> 1$, fast damping means $Q \sim 1$.

Working Process

1. Measure the coefficient of elasticity of the spring. To do this, the weight of the known mass m (the mass value is not stamped on the bottom of the weight) is suspended to the spring and its elongation x_0 is determined. The coefficient of elasticity of the spring will be determined by the formula

$$k = \frac{mg}{x_0}.$$

The absolute measurement error of the value of k is estimated from the ratio

$$\frac{\Delta k}{k} = \frac{\Delta x_0}{x_0}.$$

The result of measuring the value of the coefficient of elasticity of the spring is written in the form: $k = k_0 \pm \Delta k$.

2. Measure the period of oscillation of the weight on the spring T. For this, oscillations are excited and the time t of $n = 5$ oscillations is measured. The period of oscillation is determined by the formula $T = t / n$. The experiment is repeated 5 times, the average value of the period T_{av} is calculated, the absolute error of each individual measurement ΔT and the absolute error and its average value ΔT_{av} are determined. The results are represented in Table 1.

Table 1

№ of experiment (i)	1	2	3	4	5	T_{av}	ΔT_{av}
t_i							
$T_i = t_i/n$							
$\Delta T_i = \|T_i - T_{av}\|$							

3. Measure the damping factor of the oscillations β. For this, oscillations are excited and, having missed 2-3 oscillations, determine the amplitudes of the subsequent oscillations. Amplitudes are measured on one side of the equilibrium position after every 3 oscillations, the number of measured amplitudes should be at least three. The first measured amplitude is denoted by A_0, the remaining A_3, A_6, A_9. From formula (6), taking into account the fact that $t = nT$ (n = 3, 6, 9 is the amplitude number) for the damping factor β, we have:

$$\beta = \frac{1}{nT} ln \frac{A_0}{A_n}.$$

Using the thus obtained for different n values of the damping coefficient β_3, β_6, β_9, calculate the average value of β_{av}, the absolute errors of each individual measurement $\Delta\beta_3$, $\Delta\beta_6$, $\Delta\beta_9$ and the average value of the measurement error $\Delta\beta_{av}$. The results are represented in Table 2:

Table 2

	A_0	A_3	A_6	A_9	β_{av}	$\Delta\beta_{av}$
A_n (sm)						
β_n (c^{-1})						
$\Delta\beta_n = \mid \beta_n - \beta_{av} \mid$						

4. Using formula (7) and the results of item 2 and item 3, determine the value of λ_0 and the absolute error $\Delta\lambda$ of the logarithmic decrement of damping. The result is written as $\lambda = \lambda_0 \pm \Delta\lambda$.
5. Make a report on the work.

Test Questions

1. Write the equation of harmonic oscillations. What model of the oscillatory system is described by this equation?
2. Give definitions of amplitude, frequency, phase, circular frequency and oscillation period.
3. Write the equation of damped oscillations. What model of the oscillatory system is described by this equation? Under what condition in the oscillatory system are damped oscillations?
4. How does the amplitude of damped oscillations change over time?
5. To define the logarithmic decrement of oscillation damping. What is the physical dimension of this quantity in the SI system of units?

3.9 *Laboratory work O-2*
Determination of the Lens Focal Length by Bessel Method

Objective: to learn the main parameters of lenses: to determine the focal length of the convergent lens by the Bessel method; calculate the measurement errors in this work.

Equipment: lens (objective), screen, lighter.

Brief Theoretical Information

The section of optics, in which the laws of light propagation are considered based conception of light rays, is called **geometric optics**. Light rays are the lines along which a stream of light energy spreads in space. Geometrical optics allows us to consider the main phenomena associated with the passage of light rays through optical systems.

The lenses are transparent bodies bounded by two spherical surfaces (one of them can be flat, that is, a sphere of infinitely large radius), which refract light rays and can form the optical images of objects. The materials for the lenses are glass, quartz, transparent crystals, plastics, etc.

A lens is called thin if its thickness (the distance between the bounding surfaces) is significantly less than the radii of curvature of these surfaces. The lens, which has a middle thicker than the edges, is called **convergent** (or positive). In Figure 1 these are lenses 1, 2, 5. If the edges of the lens are thicker than its middle, it is called **divergent** (or negative), in Figure 1 these are lenses 3, 4, 6. The straight line passing through the centers of curvature of the lens surfaces C_1 and C_2 is called its **main optical axis** (Figure 2). For any lens there is a point (in Figure 2 it is a point O), called the **optical center of the lens**, which lies on the main optical axis and has the property that the rays passing through the lens at this point is not refracted.

Based on the law of refraction of light, you can get a formula that is called **a thin lens formula**. It looks like:

$$(n-1)\left(\frac{1}{R_1}+\frac{1}{R_2}\right)=\frac{1}{a}+\frac{1}{b}, \qquad (1)$$

where n is the relative refractive index of the lens material relative to the medium in which it is located, that is, $n = n_{len}/n_{med}$; R_1 and R_2 are the radii of curvature of the surfaces of the lens, and the radius of curvature R is considered positive if the surface it limits is convex and negative if this surface is concave; a is the distance from the object to the lens; b is the distance from the lens to the image.

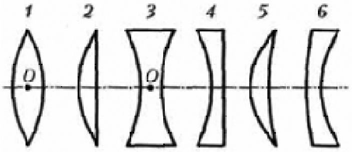


Figure 1 Types of lenses

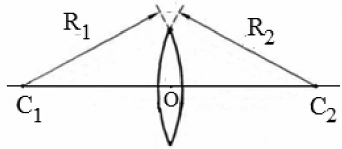


Figure 2 Main optical axis

If $a = \infty$, i.e. light rays fall on a convergent lens in a parallel beam (Figure 3), then from formula (1) we get:

$$\frac{1}{b} = (n-1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right). \quad (2)$$

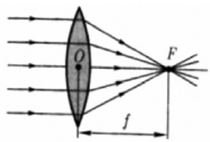


Figure 3 Lens focus F and focal length f

The corresponding distance is called the **focal length** of the lens. From the formula (2) it follows that the focal length of the lens is determined by the formula:

$$f = \frac{1}{(n-1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)}. \quad (3)$$

Thus, the focal length of the lens depends on its relative refractive index and the radii of curvature of its surfaces.

The point located on the main optical axis of the lens at a distance equal to the focal length from its center is called the **focus of the lens**. The focus is the point at which rays being parallel to its main optical axis, intersect after refraction in the lens. (see Figure 3).

The value $D = \frac{1}{f}$ is called the **optical strength** of the lens. It is measured in **diopters** (d). Diopter - the optical power of the lens with a focal length of 1 m: 1 d = 1/m. The optical strength of the lens is calculated by the formula:

$$D = \frac{1}{f} = (n - 1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right). \tag{4}$$

Lenses for which $D > 0$ are convergent, and for which $D < 0$ are divergent. Unlike the convergent lenses, the divergent ones has an **imaginary focus**. In the imaginary focus, imaginary continuations of the rays incident on the divergent lens parallel to the main optical axis intersect (Figure 4).

Given formula (4), the lens formula (1) can be written as

$$\frac{1}{a} \pm \frac{1}{b} = \pm \frac{1}{f} \tag{5}$$

For a divergent lens, the magnitude and should be considered negative.

Images of an object formed by a lens are created as a set of images of each point of this object. The imaging of a point by a collecting lens is carried out using two rays emanating from this point. For such rays are usually used (see point B in Figures 5(a), and 5(b)):

1) the ray emanating from this point and passing through the optical center of the lens. This beam is not refracted by the lens and does not change its direction;
2) a ray emanating from this point and being parallel to the main optical axis, after refraction in the lens this beam passes through its focus.

The image of the point is obtained at the intersection of these rays after passing through the lens. For example, the creation of images in a convergent lens is given (see Figure 5(a), 5(b)).

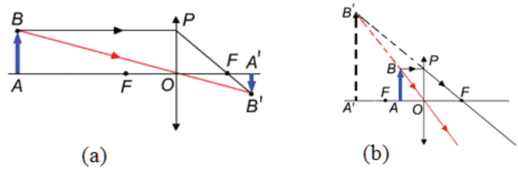


Figure 5 Creation of images in a convergent lens

a) **Creation of the image of the object AB, located behind the focus of the lens** (Figure 5(a)). In this case, the image A'B' is **inverted** and **real** (this means that you can actually get it on the screen). The distances from the object to the lens and from the lens to the image (i.e., to the screen) are related by formula (5), and in all cases the signs «+» are taken. Figure 5(a) shows the case when the lens gives a **reduced** image, i.e. **linear magnification** of the lens, defined by the formula

$$k = \frac{A'B'}{AB}, \tag{6}$$

satisfies the condition $k < 1$.

This is how an objective of a camera works, creating a little image of an object being photographed on a photosensitive matrix or on photographic film. However, it is also possible that the collecting lens will give a real **enlarged** image ($k > 1$). This case is implemented in various kinds of projectors, projecting the image of a small frame on a large screen with a significant increase (cinema).

b) **Creation of an image of an object located between the focus and the lens** (Figure 5(b)). There is no real image in this case, but if you place the observer's eye to the right of the lens and look at the AB object through it, then at the intersection point of the ray extensions the eye (more precisely, the brain) will see point B', that is the seeming image of point B of the object. The same is true for all other points of the object. As a result, a seeming image of the entire object A'B' is formed in the brain of the observer. This image will be **direct** (not inverted), **magnified** and cannot be obtained on the screen. The connection of distances from the object to the lens and from the image to the lens is given by formula (5), in which the sign «-» is used in front of the 1/b value in its left part. Figure 5 (b) corresponds to the **magnifying glass** (**loupe**).

Consider an example of creating an image in a divergent lens (Figure 6). The image created by the divergent lens is **direct**, **imaginary (seeming)**, **reduced**. In formula (5) for this case, both signs «-» are used.

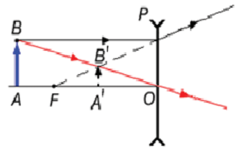


Figure 6 Creation of the image in a divergent lens

The combination of convergent and divergent lenses (objective) is used in optical devices to solve various practical and scientific problems.

Installation Description

Laboratory work uses an objective that is optically equivalent to a convergent lens, a light source, and a screen.

The aim of the work is to determine the focal length of a given objective, regarded as a single lens. In principle, the focal length of the lens could be determined from formula (5) by measuring the distance from the object to the optical center of the lens *a* and the distance from the optical center of the lens to the image *b*.

However, the values *a* and *b* cannot directly be determined precisely because in this case the position of the optical center O of the objective (which plays the role accurately the Bessel method may be used.

From formula (5) it is clear that the values *a* and *b* can be interchanged, and the formula does not change its appearance. This can be done in practice by moving the lens L along the line connecting the object and the screen. In this case, two images of the object AE can be obtained on the screen (at two positions of the lens): an enlarged A_1E_1 and a reduced A_2E_2 (Figure 7).

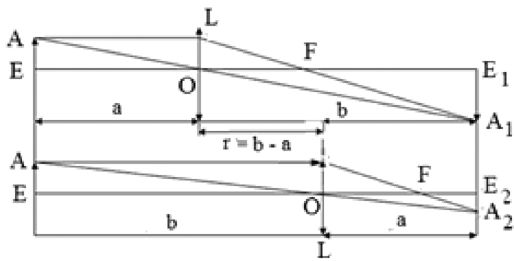


Figure 7 To the laboratory work

To laboratory work.

Let us denote the value by which the optical center of the lens O was shifted in by r; The value of *r* can be associated with the movement of any point of the lens, since during its movement the position of the optical center inside the lens does not change. Denote $B = b + a$ is the distance from the object to the screen (it does not change during operation), $r = b - a$ is the distance that the lens was moved to obtain the second image. From here, we have:

$$a = \frac{B + r}{2};\ b = \frac{B - r}{2}. \qquad (7)$$

Substituting these formulas for a and b into formula (5) and solving the resulting equation with respect to the focal length *f*, we get:

$$f = \frac{B^2 - r^2}{4B}. \qquad (8)$$

Formula (7) is the formula of the Bessel method, and that is the **working formula** of this work and is used to determine the focal length of the lens (objective).

Working Process

1. Install the screen on one side of the table, and the light source on the other side.
2. Install the lens (objective) between the screen and the light source.
3. Turn on the light source.
4. By moving the lens, a sharp enlarged image of the source on the screen is obtained and the position of the lens pointer (N') is fixed on a scale. The measurements are repeated three times, moving the lens off and again seeking a sharp image on the screen. Calculate the average value of N'_{av}.
5. Move the lens to get the second (reduced) image of the source. Fix the position of the lens pointer (N"). Measurements are also repeated three times and found (N''_{av}).
6. Calculate the distance r, equal to $r = N''_{av} - N'_{av}$.
7. The position of the source N_1 and the position of the screen N_2 count on a scale. Calculate the distance $B = N_2 - N_1$ and the error of its measurement ΔB.
8. Calculate the focal length of the objective *f* by formula (7).

Table 1

№	N', (mm)	N'', (mm)	r, (mm)	Δr, (mm)	N_1, (mm)	N_2, (mm)	B, (mm)	ΔB, (mm)	*f*, (mm)	Δf, (mm)	ε, (%)
Av.					xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx						

9. Calculate the error of measurement of the focal length. Represent the results in Table 1.

Test Questions

1. Give a definition of the concept of a lens and its focus and focal length.
2. What types of lenses do you know?
3. Build an image of the object in the convergent (divergent) lens.
4. Write the lens formula.
5. Give the definition of the optical strength of the lens. In which units is it measured? What does it depend on?
6. What determines the focal length of the convergent lens?
7. Derive the working formula of the Bessel method.
8. What are the advantages of the Bessel method in comparison with other methods for measuring the focal length of a lens?

3.10 *Laboratory work O-5* Determination of the Light Wavelength Using Diffraction Grating

Objective: to learn how to determine the length of the light wave using a diffraction grating, to calculate the measurement errors in this work.

Equipment: light source; diffraction grating; ruler with diffraction grating holder; screen with a vertical slit and scale.

Brief Theoretical Information

Diffraction of light is a combination of phenomena caused by the wave nature of light, which is observed when it propagates in media with pronounced inhomogeneities (for example, near the borders of bodies, through small holes in screens, etc.). Diffraction, in particular, is the **light wave bending around obstacles** and the **penetration of light into the region of a geometric shadow**. Diffraction is most clearly observed if the dimensions of the obstacles or holes are comparable with the wavelength of light.

The phenomenon of diffraction underlies the operation of one of the most important optical devices - the **diffraction grating**, which is a system consisting of a large number of identical slits located at equal distances from each other. The simplest diffraction grating is a glass plate on which using a precise dividing machine with a diamond cutter parallel strokes are made (opaque to light), between which narrow transparent areas remain. The sum of the distance between the strokes and the width of the stroke is called the **grating constant** or **grating period** d (Figure 1).

The main purpose of diffraction gratings is the spatial decomposition of light radiation by wavelength (i.e., by color), in order to obtain a **spectrum** of this radiation. This is used in practice for **spectral analysis** of radiation emanating from a particular source in order to determine its chemical composition.

If a beam of monochromatic light with a wavelength λ is directed to a diffraction grating R (Figure 1), then, in accordance with the Huygens-Fresnel principle, each point of transparent slits will be a source of secondary waves propagating in all directions. The different direction of propagation of light waves in Figure 1 are shown as rays.

Let us select the rays that go from different grating slits at the same angle ϕ to the optical axis of the system. This angle is called the **angle of diffraction**. If a convergent lens is installed behind the diffraction grating, it will collect parallel rays into one point A on screen E located in the focal plane of the lens (i.e., in a plane located from the lens at a distance equal to its focal length F).

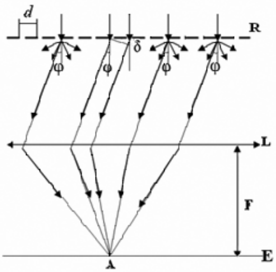


Figure 1 Interference of waves at the diffraction angle φ

At the same time, at point A, the interference of waves from all the slits occurs, as a result of which the intensity of the resulting light intensity decreases or increases, depending on the difference of the optical paths of the neighboring rays. This is also true for waves emanating from the grating slits at different diffraction angles. Thus, at each point of screen E there will be interference of waves emanating from the slits at the corresponding diffraction angle φ (Figure 1).

An increase in the intensity during the interference of waves from different slits is observed when the optical path difference of waves from neighboring slits δ is equal to an integer number of wavelengths:

$$\delta = d\sin\varphi = \pm k\lambda, \tag{1}$$

where k is an integer (named **the order of the spectrum**), d is the grating constant; φ is the diffraction angle.

In accordance with condition (1), we write the **main maxima condition** for the diffraction of light on a diffraction grating:

$$d\sin\varphi = \pm k\lambda. \tag{2}$$

Installation Description

To determine the wavelength using a diffraction grating at one end of the optical bench (Figure 2) a light source1 and a screen 2 with a vertical slit and a scale are installed, the diffraction grating 3 is located at the other end of the optical bench.

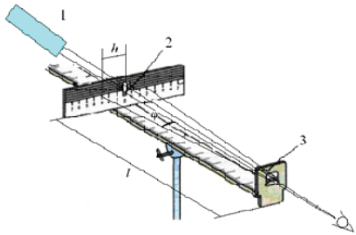


Figure 2 The laboratory setup

The spectrum is observed with the observer's eye located behind the grating, against the background of the scale. The role of the lens is performed by the lens of the eye (L), which focuses parallel beams of rays from the slits of the diffraction grating on the eye's retina (E), as on a screen (see Figure1).

If l is the distance from the diffraction grating to the scale, and h is the distance from the slit in the scale to the visible spectral line of a given color in the spectrum of some order, we have:

$$tg\varphi \approx sin\varphi \approx \frac{h}{l}. \tag{3}$$

Substituting (3) into (2), we obtain the **working formula** for determining the wavelengths of the spectral lines:

$$\lambda = \frac{hd}{kl}. \tag{4}$$

Working Process

1. Place the optical bench horizontally and install the light source. Place the diffraction grating and the scale with a slit on the optical bench as shown in Figure 2.
2. Switch the light source on and by a slight rotation of the diffraction grating around the vertical axis to achieve the location of the side spectral lines at

approximately equal distances from the slit. Select a line of a certain color (as instructed by the teacher).

3. Measure the distance from the slit to the first order ($k = 1$) of red ($\lambda = \lambda_1$) line on the scale, and then to the next order of that line ($k = 2$), denoting them with the letter $h`$ on one side of the slit and $h``$ on the other. Calculate the average of these values of h. The measurement results are recorded in Table 1.
4. Repeat item 3 for the blue ($\lambda = \lambda_2$) line of the spectrum.
5. Measure the distance l from the scale with a slit to the grating.

Table 1

Wave-length	d, (mm^{-1})	$k = 1$				$k = 2$				λ_{av} (nm)	$\Delta\lambda$ (nm)
		$h`$	$h``$	h	λ	$h`$	$h``$	h	λ		
λ_1 (red)	0,01										
λ_2 (blue)		$h`$	$h``$	h	λ	$h`$	$h``$	h	λ		

6. Calculate the wavelengths by the formula (4).
7. Record the results into the Table 1.
8. Make a report on the work.

Test Questions

1. What is called a diffraction of light?
2. What light is called monochromatic light? Is sunlight monochromatic?
3. What is called a diffraction grating? What is the main characteristic of the grating?
4. Record the main maxima condition for the diffraction of light on a diffraction grating.
5. What characteristic of light reaches its maximum when condition (2) is fulfilled?
6. What is called the angle of diffraction?
7. Derive the working formula of this work.
8. What is the practical purpose of the diffraction grating?
9. Explain why the diffraction grating decomposes white light into a spectrum.

3.11 *Laboratory work A-2* Study of Line Spectra and Determination of the Rydberg Constant

Objective: to experimentally determine the wavelengths of light emission lines; calculate Rydberg constant and its error.

Equipment: spectroscope, gas discharge tubes of gases (helium (He)), hydrogen (H), etc.), tube power supply.

Brief Theoretical Information

The composition of the electromagnetic radiation of a body is called its **emission spectrum**. The emission spectra are divided into three types: **continuous**, **striped** and **line**. Continuous spectra are emitted by heating solid and liquid bodies. Striped spectra arise when light is emitted by excited gas molecules. Line spectra are formed if the radiation source is atoms of chemical elements in a gaseous state at low pressure.

Each chemical element has a typical line spectrum for it, i.e. a specific set of wavelengths. Measurements of the wavelengths of the spectral lines showed that these wavelengths correspond to certain laws that were initially established empirically. Their theoretical calculation should be based on the equations of quantum physics. However, for the initial acquaintance with these problems in this paper, we restrict ourselves to considering a model of the simplest atom – the **hydrogen (H) atom**. The model of hydrogen atom was created by the Danish physicist N. Bohr in 1913. According to this model, electrons revolve around the atomic nucleus in orbits that can be considered circular. The number of electrons is equal to the number of protons in the atomic nucleus and is equal to the ordinal number of this element in the periodic table. The hydrogen atom has a number equal to 1, and, accordingly, contains **one electron** only. Bohr's theory of a hydrogen atom is based on the following postulates:

1. An electron in a hydrogen atom can rotate around a nucleus only in orbits with certain radii, which are called **stationary orbits**. For those orbits, the orbital angular momentum of an electron should be equal to an integer number multiplied by a value of $\frac{h}{2\pi}$, i.e.

$$m v_n r_n = n \frac{h}{2\pi}, \qquad (1)$$

where $m = 9{,}1 \cdot 10^{-31}$ kg – electron mass; v – linear velocity of an electron in the n-th orbit; r_n – radius of the n-th orbit; $n = 1,2,3....$ – main quantum number indicating the number of the stationary orbit; $h = 6{,}62 \cdot 10^{-34}$ J·s – Planck's constant; $m v_n r_n$ – the orbital angular momentum of the electron in the n-th orbit.

Thus, in a hydrogen (H) atom for a single electron, many different stationary orbits are possible. Being in a stationary orbit, **the electron does not radiate and does not absorb energy**.

2. An atom radiates or absorbs energy in the form of a **quantum of electromagnetic radiation** (**photon**) only when the electron transfers from one stationary orbit to another, in accordance with the formula:

$$h\nu = E_1 - E_2 \qquad (2)$$

where $h\nu$ – quantum (photon) energy (ν – radiation frequency), E_1 – electron energy in the initial orbit, E_2 - electron energy in the final orbit. When $E_1 > E_2$, electromagnetic radiation occurs by an atom of one photon with a frequency

$$\nu = \frac{E_1 - E_2}{h}. \qquad (3)$$

When $E_1 < E_2$, photon is absorbed by the atom.

The total energy of electrons in various stationary orbits is determined by the formula: $E = T + \Pi$, where $T = \frac{mv^2}{2}$ is the kinetic energy; $\Pi = -\frac{e^2}{4\pi\varepsilon_0 r}$ – potential energy of interaction of an electron with the nucleus, $e = 1{,}6 \cdot 10^{-19}$ C – elementary electric charge, $\varepsilon_0 = 8{,}85 \cdot 10^{-12}$ Ф/m – electric constant of the SI unit system.

According to the theory developed by N. Bohr, the electron total energy in a stationary orbit in a hydrogen atom is determined by the formula

$$E_n = -\frac{me^4}{8h^2\varepsilon_0} \frac{1}{n^2} \qquad (4)$$

Then, taking into account formula (3), the frequency of the quantum emitted during the transition of an electron from orbit with number *k* to orbit with number *i* can be determined as follows:

$$\nu_{\kappa i} = \frac{E_{\kappa} - E_{i}}{h} = \frac{me^4}{8\varepsilon_0^2 h^3 c}\left(\frac{1}{i^2} - \frac{1}{k^2}\right) \qquad (5)$$

The value (where $c = 3{\cdot}10^8$ m/s is the speed of light in vacuum) is called the **Rydberg constant**. Using the value of R, formula (5) can be rewritten in the form:

$$\nu_{\kappa i} = Rc\left(\frac{1}{i^2} - \frac{1}{k^2}\right) \qquad (6)$$

By the formula (6), one can also calculate the energy necessary for the **excitation** of an atom, i.e. to transfer an electron in an atom to an orbit more distant from the nucleus. The greatest energy will be required to remove an electron from the first orbit to infinity (for **ionization** of an atom). To calculate this energy in the formula (6) take the values $i = 1$, $k = \infty$. Then the ionization energy is calculated by the formula:

$$E_{ion} = hRc \approx 13{,}6 \text{ eV}, \qquad (7)$$

where 1 eV (**electronvolt**) – the off-system unit of energy used in atomic physics and equal to$1{,}6{\cdot}10^{-19}$ J.

Given the relationship between the frequency and wavelength of the radiation, expression (6) can be rewritten in the form:

$$\frac{1}{\lambda_{ki}} = R\left(\frac{1}{i^2} - \frac{1}{k^2}\right) \qquad (8)$$

The wavelength λ_{ki} and frequency ν_{ki} determine the **spectral line** of electromagnetic (light) radiation. When considering the radiation of a hydrogen atom, the spectral lines are combined in a series according to the numbers of energy levels included in formula (8). During electron transitions from various stationary orbits to the first ($n_i = 1$, $n_k = 2, 3, \ldots$), lines are generated that form the **Lyman series** located in the ultraviolet region. For $n_i = 2$, $n_k = 3, 4, 5, 6 \ldots$, which corresponds to transitions of an electron to the second orbit, the atom emits the frequencies of visible (first four lines) and ultraviolet radiation (subsequent lines), combined into the **Balmer series**. In transitions of an electron from more distant to the third, fourth, and fifth orbits, the Paschen, Brecket, and Pfuntd series are formed, located in the infrared region.

Radiation wavelengths for the Balmer series are:

$$\frac{1}{\lambda_{ki}} = R\left(\frac{1}{4} - \frac{1}{k^2}\right),\ k = 3, 4, 5, 6, \ldots \qquad (9)$$

The most bright are: the red line (H_α, for it $k = 3$); blue (H_β, for it $k = 4$); blue (H_γ, for it $k = 5$); violet (H_δ, for it $k = 6$). The corresponding wavelengths are denoted: λ_α, λ_β, λ_γ, λ_δ.

Installation Description

To obtain the spectra in this work, gas-discharge tubes with the studied gases are used, in which, when current flows in the gas, electromagnetic radiation arises.

The study of the spectra of substances is carried out using **spectroscopes**. A spectroscope is a device that serves for spatial separation of radiation in accordance with the wavelengths, of which this radiation consists, i.e. for **decomposition of radiation into a spectrum**. Observation of the resulting spectrum as a whole or individual spectral lines is carried out visually, as well as by photographing or recording with instruments.

The work of a prism spectroscope is based on the phenomenon of **dispersion, i.e., the dependence of the refractive index of light on its wavelength**. The optical scheme of the simplest spectroscope is shown in Figure 1.

The main part of the spectroscope is the glass prism P, which decomposes into the spectrum a parallel beam of non-monochromatic light incident on it after the collimator. The collimator tube consists of a narrow gap S, which is located in the focal plane of the lens, which forms a parallel beam of light incident on the prism.

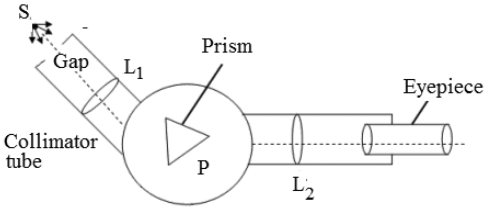


Figure 1 Spectroscope scheme

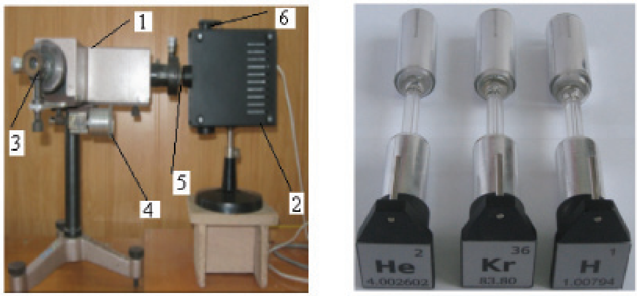
Since light rays with different wavelengths are refracted by the prism at different angles, parallel beams of different wavelengths (i.e. light beams of different colors) emerge from the prism at different angles. Using a lens, these beams are collected at various points on the focal plane of the lens, forming the spectrum of this radiation. This spectrum is visually observed using an eyepiece.

When the prism P is rotated with the help of a calibrated drum, the spectrum will move in the field of view of the eyepiece and the arrow located in the middle of it will indicate one or another line having a certain color and corresponding to a certain light wavelength. A graph giving the dependence of the light wavelength on the position of the drum is called the **calibration curve** or (**calibration graph**) of this spectroscope.

To build a calibration curve requires some known spectrum. Coinciding in series the lines of this spectrum with the arrow in the field of view of the eyepiece and fixing these wavelengths with the position of the drum according to the divisions plotted on it, we can obtain a calibration curve. In the present work, helium (He) is used as a reference gas.

Working Process

1. Assemble the laboratory setup (Figure 2).
2. Coincide the vertical slit of the power source for gas discharge tubes with the slit of the collimator tube.
3. Turn on the power of the device for gas discharge tubes and set the spectroscope drum to the middle of the scale.



a) *b*)

Figure 2 a) Apparatus for laboratory work: 1 – spectroscope, 2 – tube power supply, 3 – eyepiece, 4 – drum, 5 – gap, 6 – hole for insertion of gas-discharge tubes; b) gas discharge tubes: helium (He), krypton (Kr), hydrogen (H).

4. Insert a gas discharge tube with neon (Ne) and then with krypton (Kr) into the case of the tube power supply and the spectra of these gases are observed. Compare the spectra and be convinced of their difference.
5. Insert a tube of helium (He) into the power supply case.
   Attention! The total operating time of the helium tube (He) is about 45 minutes, so you must turn on the power only during the experiment.
6. Measure the position of all visible lines of the spectrum of helium (He) on the scale of the drum and enter their values in Table 1.
7. Build a calibration graph of the dependence of the wavelength on the value of the scale division of the drum (on millimeter paper), using helium (He) as a reference gas.
8. Remove the tube with helium (He) from the power supply case and insert the tube with hydrogen (H) in its place. Measure the position of all visible hydrogen lines on a drum scale.
9. Using the calibration graph, determine the wavelengths and frequencies of the lines of visible light in the hydrogen spectrum.
10. According to the measurements of the wavelengths of the hydrogen spectrum, using the relation (9) for each wavelength, the value of Rydberg constant R is calculated.

Table 1

The spectrum of the helium atom

Line number	Color	Wavelength (Å)	Drum division
1	Red	6678,2	
2	Yellow	5875,6	
3	Green	5015,7	
4	Green	4921,9	
5	Blue	4713,1	
6	Dark blue	4471,5	

<u>Note</u>: **Angstrom** (Å) is an off-system unit used in atomic physics, 1 Å = 10^{-10} m.

11. Calculate the average value and determine the absolute and relative errors. The measurement results are recorded in Table 2.

Table 2

The spectrum of the hydrogen atom

Line number	Designation of the line	Drum division	Wave-length (Å)	Frequency (10^{15} Hz)	R	R_{av}	ΔR
1							
2							
3							
4							

12. Make a report on the work.

Test Questions

1. What types of spectra exist, what is the condition for their occurrence?
2. To formulate Bohr's postulates.
3. What is a spectral series and how does its formation occur?
4. What is the ionization energy? What is its numerical value for a hydrogen atom?
5. What is the essence of the phenomenon of dispersion of light?
6. Explain the scheme and principle of operation of the spectroscope.
7. Why should the collimator gap be as thin as possible for accurate measurements with a spectroscope?

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