

Extensive teaching of physics for students of technical specialties with the help of experimental units and computer simulation software

Alexander Semenov^{1*}, *Yuriy Bebikhov*¹, *Pavel Tatarinov*¹, *Pavel Zakharov*², and *Elena Korznikova*³

¹North-Eastern Federal University, Polytechnic Institute (branch) in Mirny, 678170 Mirny, Russia

²Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia

³Ufa University of Science and Technology, 450076 Ufa, Russia

Abstract. The paper studies the issues of the extensive teaching of physics for the students of technical specialties with the help of experimental units and computer simulation software. The authors proposed and experimentally tested a pedagogical method for increasing the students' interest in mastering the study material in physics. The article presents the experimental units developed by the authors and patented as utility models for the study of dielectric hysteresis and the tunnel effect, developed by the authors and patented as useful models. Computer models for calculating the current in an electrical circuit and for calculating the interaction potential of particles created by the authors and patented as computer programs are shown. The methods of performing work by students on experimental units and with the help of computer simulation software are described. In conclusion, an increase in the interest and involvement of students in project and research work after the introduction of experimental units and computer models into the educational process, and as a result, an increase in motivation for learning in general and in-depth study of physics in particular, was noted.

1 Introduction

The process of shaping a student's personality in the course of his/her becoming a qualified specialist is naturally interconnected with the process of learning [1]. The success of training is associated with multiple factors, which include: the general level of intellectual development, special knowledge and abilities, interests, reasoning, character traits, temperament, personality orientation, self-awareness and self-esteem of the individual, etc. [2]. Clearly, even from the point of view of common sense, a high level of general intellectual development and the presence of more or less specialized knowledge and skills (for freshmen they are indicated by a high level of unified state exam scores (in Russia)) should directly correlate with the training success [3]. However, experience shows that this direct obvious

* Corresponding author: as.semenov@s-vfu.ru

interconnection is not traced in all the cases. Other components of success are not so obvious, and quite frequently, we being the teachers miss a lot of our pedagogical opportunities paying very little attention to these “implicit” components of student learning success [4]. Nevertheless, it is necessary not only to focus on some of these factors, but also to influence them for activating the cognitive activity of students in mastering basic disciplines, such as physics [5]. In the future, the extensive study of physics will definitely help to successfully master the specialized disciplines, in particular, for students studying in technical knowledge areas that the Mirny Polytechnic Institute, a branch of The Ammosov North-Eastern Federal University (NEFU), offers: Mining, Oil and Gas Business and Electric Power and Electrical Engineering [6].

The research work [7] proposed and experimentally tested a pedagogical method that contributes to increasing student interest in the assimilation of study material in physics. It is proved how important it is to shape a consistent self-motivation of students in the development of educational material in physics; it is shown that a simple reformulation of the conditions of problems solved by students at workshops may influence their motivation. Thus, it is demonstrated how to form stable self-motivation in students by reformulating the problem conditions in the framework of their future professional interests.

However, this is not enough. Another condition which is also very important for the fulfillment of a person abilities is one’s activity which relates to training as well. It is possible to facilitate this activity by organizing conditions for students where they may focus on a certain type of activity. In other words, we can ultimately use the student values and goals which are especially important for the one having ambitions and aimed at self-development as effective activators of the most consistent self-motivation in educational activities. The following were proposed as the tools of such activity fostering in the research work [8]: organization of student project activities, students' project activities in scientific circles. When organizing the work of scientific and technical student circles where students are engaged in the project and research activities, two pedagogical approaches are implemented at once: updating the knowledge already acquired in the course of training by their application for their activities; boosting the cognitive activity of students by the need to acquire new knowledge for the project implementation by means of self-education. While introducing the second approach the authors suggest using of experimental units and computer simulation software for teaching certain sections of physics.

2 Purpose, objectives and research methods

The purpose of this research work is to familiarize, by means of experimental units and computer simulation software, with the methods of physical measurements used in the relevant sections of physics, and to contribute to the extensive acquisition of knowledge by students at all forms of study in specialized disciplines studied in technical areas of training.

Such sections of physics as “Electricity and Magnetism”, “Quantum Physics” and “Solid State Physics” are considered, which occupy a special place in the physics course and are very difficult to master. The works on quantum physics and solid state physics have their own well-known specific features due to the nature of the quantum phenomena under study. To observe them, rather complex experimental equipment is necessary, and to explain them one shall address the quantum theory. Thus, computer simulation tools greatly simplify this task.

Simulation is a complex process, the purpose of which is to develop a notion of the system behavior with variable parameters [9]. Simulation in practice is understood as a relevant replacement of the technical device or process studied with an appropriate model and its subsequent study with known methods [10]. Indeed, the model is not an exact copy of an object or system, and simulation implies neglecting any processes occurring in reality [11].

However, simulation is widely applied to study basic processes. In addition, replacing a real object with its model provides great advantages for research [12].

Today there are many programs on the software market for technical systems simulation [13]. Some of them emerged not so long ago, and some of them are well-known and popular among users. These programs can be used to simulate any technical systems, but there are also programs that have a narrow specialization in any subject area [14]. The so-called “conventional” software, such as Mathematica, Maple, MathCAD, are well adapted to performing calculations in the disciplines of the natural sciences, when the model is set in an analytical form [15]. In these cases, programming consists in writing relatively small programs in terms of volume comprising mainly macro-operators only. Component simulation software are almost entirely focused on numerical experiments [16]. Now they are mostly used in the design processes of technical facilities and systems. The MatLab software package can be attributed to the number of universal simulation software that are not focused on specific applied areas of technical system simulation [17].

Thus, in the research work, the authors show the results of the development of experimental units and computer models that allow simulating and studying physical processes and operating modes.

3 Research results

3.1 Experimental setup for the study of dielectric hysteresis

The dielectric hysteresis method is widely used to study the polarization of ferroelectrics. Therefore, within the laboratory class the study of the characteristics of ferroelectrics is conducted using dielectric hysteresis loops at the frequency of 50 Hz. It is possible to obtain and observe a dielectric hysteresis loop using an electrical circuit proposed by Sawyer-Tower [18].

Two capacitors C_1 and C_2 are connected in series; further, they are connected to an adjustable AC voltage source. The capacitor C_2 is filled with an ordinary “linear” dielectric with constant permeability and is a reference capacitor, and the capacitor C_1 is a ferroelectric under study. Both of them are connected to an alternating voltage source (as a rule, 50-60 Hz). Under the condition $C_2 \gg C_1$, almost all of the applied voltage decreases on the sample. Two resistors are connected in parallel to these capacitors. The resistor R_1 has an equivalent ohmic resistance of the ferroelectric under study, and the resistor R_2 serves for selecting the phase equality of the voltages fed to the oscilloscope input to avoid “circuit” phase distortions. The capacitance of the capacitor C_1 and the electric field strength E inside the ferroelectric are calculated by the formulas:

$$C_1 = \frac{\varepsilon_0 \cdot \varepsilon \cdot S}{d}, E = \frac{U_{C1}}{d}, \quad (1)$$

where ε is the dielectric constant, S is the area of the plates, d is the distance between them, U_{C1} is the voltage between the plates. Since the capacitors are connected in series, the charges on their plates will be the same: $Q_1 = C_1 \cdot U_{C1} = C_2 \cdot U_{C2}$. Thus, $U_{C1} = (C_2/C_1) \cdot U_{C2}$, or, given (1), we get:

$$E = U_{C2} \cdot \frac{C_2}{\varepsilon_0 \cdot \varepsilon \cdot S}. \quad (2)$$

Taking into account that for a ferroelectric $\varepsilon \gg 1$, it follows: $E = P/(\varepsilon_0 \cdot \varepsilon)$, and further:

$$\frac{P}{\varepsilon_0 \cdot \varepsilon} = U_{C2} \cdot \frac{C_2}{\varepsilon_0 \cdot \varepsilon \cdot S'} \quad (3)$$

from which it follows that:

$$U_{C2} = \frac{S}{C_2} \cdot P = U_y, \quad (4)$$

i.e., the voltage on the capacitor C_2 is proportionate to the ferroelectric polarization. This voltage is applied to the input Y of the oscilloscope.

Thus, it is clear that given the voltage U_{C2} is applied to the input of the vertical sweep of the oscilloscope (Y), and the voltage U_{R2} is applied to the input of the horizontal sweep (X), the electron beam along the Y axis will deviate in proportion to the polarization P of the ferroelectric, and along the X axis – in proportion to the strength of the external electric field E. Over one period of the sinusoidal voltage change, the electron beam displayed will make a complete hysteresis loop, and for each subsequent period it will repeat it exactly. Therefore, a fixed loop will be observed on the display.

This paper adopted a bridge version of the Sawyer-Tower circuit to study the properties of ferroelectrics. The schematic diagram of the unit is shown in Fig. 1 (a), and its external appearance is outlined in Fig. 1 (b). It includes a step-down transformer TV, a potentiometer R_P , C_1 – a capacitor with an insulator made of the studied ferroelectric, C_2 – a reference capacitor with an insulator made of a conventional linear dielectric, R_1 , R_2 – voltage divider resistances, R – resistance for indirect current measurement, R_ϕ – variable resistance for phase shift adjustment, S – switch, PZ – two-channel digital oscilloscope TDS2012B. If necessary, it can be measured with multimeters.

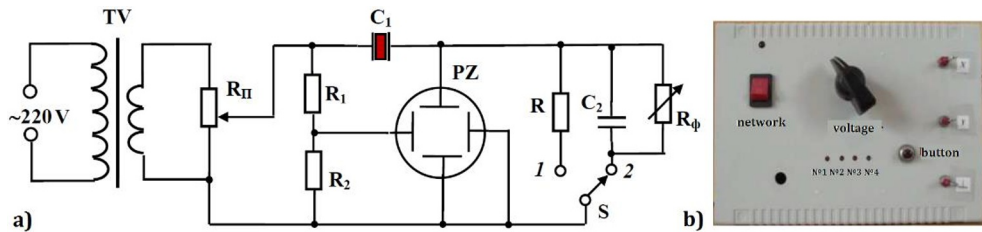


Fig. 1. Schematic electrical bridge circuit (a) and external appearance (b) of the experimental unit “Ferroelectric”.

The unit has four samples of ferroelectrics in the form of a capacity of M10 25 V N90 (No. 1), ceramic piezoelectric emitters from Panasonic telephones and other models (No. 2 and No. 3), varicond VK2-BSh (No. 4). In addition, a digital electronic load switch has been developed using the MOS3043 optocoupler for alternating connection of four studied of ferromaterial samples.

As a result of the research work, students shall conduct the following actions:

1. Familiarize with the schematic diagram of the device “Ferroelectric” shown in Fig. 1.
2. Before turning on the Ferroelectric, turn the voltage potentiometer knob to the leftmost position.
3. Turn on the oscilloscope. Have the device and the oscilloscope warmed up for 2-3 minutes.
4. Rotating the potentiometer knob clockwise get a saturated hysteresis loop on the oscilloscope display.
5. Using the knobs marked on the oscilloscope as “ \leftrightarrow ” and “ \updownarrow ”, place the hysteresis limit loop in such a way that it is symmetrical to the center of the coordinate grid.

6. Write down the division value of the coordinate grid along the x-axis K_1 and along the y-axis K_2 in the table.

7. Measure the coordinates of the five characteristic points of the loop on the coordinate scale of the oscilloscope screen. Enter the measurement results in the table.

8. Draw the hysteresis loop, take a picture or write it to a USB stick.

An approximate view of the hysteresis loop and the oscillograms of polarization and electric field strength that students should observe is shown in Fig. 2.

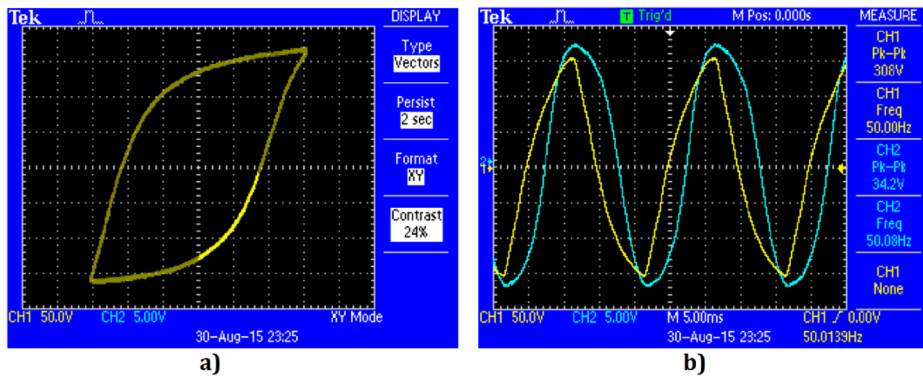


Fig. 2. A loop of dielectric hysteresis (a) and an oscillogram of the polarization and electric field strength E (b) of sample No. 3.

3.2 Experimental unit for the study of the tunnel effect

Electron tunneling and other quantum particles through a potential barrier underlies many phenomena of atomic and nuclear physics, solid state physics and superconductors, for example, α -decay, thermonuclear reactions, autoelectronic emission of electrons from metal, tunneling breakdown of the p-n junction, etc. [19, 20].

Today the tunneling effect is used to build a new element base of micro-, submicro- and nanoelectronics (in the nanostructures such as a field-effect transistor based on a quantum dot), various types of active semiconductor elements are being developed using thin-film technology where quantum effects are manifested along with tunneling [21, 22]. It is known that the tunneling effect can be studied by examining the current-voltage characteristic (CVC) of a degenerate p-n junction of a tunnel diode.

The proposed analog electrical schematic diagram of the unit consists of three functionally independent circuits: a sawtooth voltage generator, a push-pull emitter follower on a complementary pair of transistors and measuring amplifiers. A stabilized ± 12 V power supply has been assembled. In addition, any standard oscilloscope is required. In our case, the Tektronix TDS 2012B oscilloscope is used.

The frequency of the sawtooth signal at the generator output is determined by the formula (5):

$$f = 0.7 \cdot R_3 / (2C_1 \cdot R_6 \cdot (R_4 + R_5)), \quad (5)$$

where f is frequency, Hz; R_3 , R_6 , R_4 , R_5 are resistances, Ohm; C_1 is the capacitance, Farads.

The diode CVC is measured using two differential amplifiers, which are assembled on precision amplifiers K140UD17. One amplifier is used to measure the current through the diode, determined by the voltage drop at the reference resistance. The second amplifier is

designed to measure the voltage on the diode. To prevent the measuring probes from introducing noticeable parasitic inductance and capacitance, the voltages from the tunnel diode and current resistance are measured by difference amplifiers. Since such amplifiers have a large input resistance, the pickups from the output do not penetrate into the measuring circuit with a tunnel diode. In addition, it contributes to an increase in the signal-to-noise ratio. Although one end of the diode is connected to the ground, a difference amplifier is used instead of a single input amplifier. It allows significantly reducing the error. The gain of the current amplifier is 51, and the gain of the second amplifier equals 5.

The unit contains a Tunnel Effect device and an oscilloscope (Fig. 3). The device is placed in a plastic case 180x120x70 mm and weighs no more than 400 g.

As a result of the work on observing the CVC tunnel diode in the dynamic mode, students shall perform the following:

1. Familiarize with the schematic diagram of the “Tunnel Effect” device.
2. Plug the power cord of the device into the mains voltage of 220 V, 50 Hz, and turn it on by pressing the “Network” switch on the front panel.
3. Turn on the oscilloscope. Have the device and the oscilloscope warmed up for 2-3 minutes.
4. Connect the probe of channel K₁ to terminal “X” to the device, the probe of channel K₂ to terminal “Y”, the external synchronization cable of the oscilloscope to terminal “SI” of the device.
5. Smoothly rotating the potentiometer knob of the device clockwise to get the CVC of the tunnel diode on the oscilloscope display.
6. Write the CVC to a removable media (USB flash drive).
7. At the end of operation, turn off the device and the oscilloscope.

An approximate view of the current-voltage characteristic of the tunnel diode, which students should observe, is shown in Fig. 4.

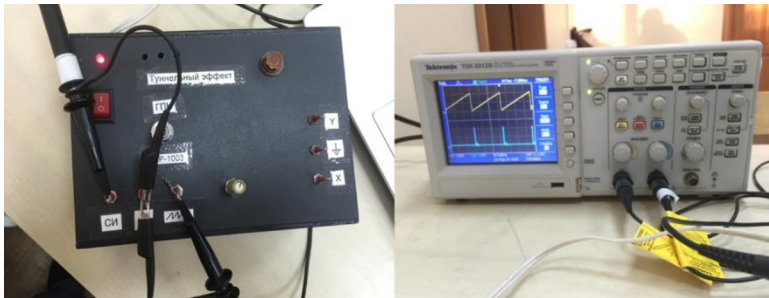


Fig. 3. Unit for measuring the current-voltage characteristic of a tunnel diode.

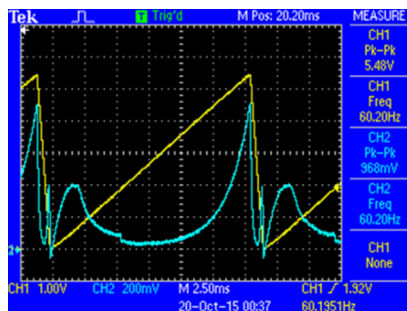


Fig. 4. Oscillogram of the voltage characteristic of the gallium arsenide tunnel diode Al306K: the voltage on the diode is a yellow beam ($K_1=5$), the current is a blue beam ($R=1.5$ Ohm, $K_2=51$).

3.3 Computer model for calculating the current in the electrical circuit

The purpose of calculating a DC electrical circuit is to determine some parameters based on the initial data from the problem condition. In practice, several methods of calculating simple circuits are used. One of them is based on the use of equivalent transformations that simplify the chain. But if the electrical circuit is relatively complex, such a method is no longer applicable [23].

During the calculation of a complex circuit, it is necessary to determine some electrical parameters (primarily currents and voltages on the elements) based on the initial values specified in the problem condition. In practice, several methods of calculating such circuits are used. To determine the branch currents, you can use: a method based on the direct application of Kirchhoff's circuit laws, the method of contour currents, the method of nodal potentials [24].

The circuit of the DC electrical circuit requiring calculation is shown in Fig. 5 (a). Simplify the DC circuit diagram: the current source, whose value is 0, is not depicted in the design diagram; the equivalent EMF in the branch with the current source is defined as $E_{i3} = E_i \pm J_i \cdot R_i$, where i is the branch number, and the “-“ sign is selected when the current direction and EMF do not match; equivalent resistances, depending on the connection type, are defined as sums for serial connection and as the ratio of the product to the sum – for parallel, i.e. a $R_i = R_{i'} + R_{i''}$; $R_j = \frac{R_{j'}R_{j''}}{R_{j'}+R_{j''}}$. A simplified design circuit design commonly called an equivalent circuit is shown in Fig. 5 (b).

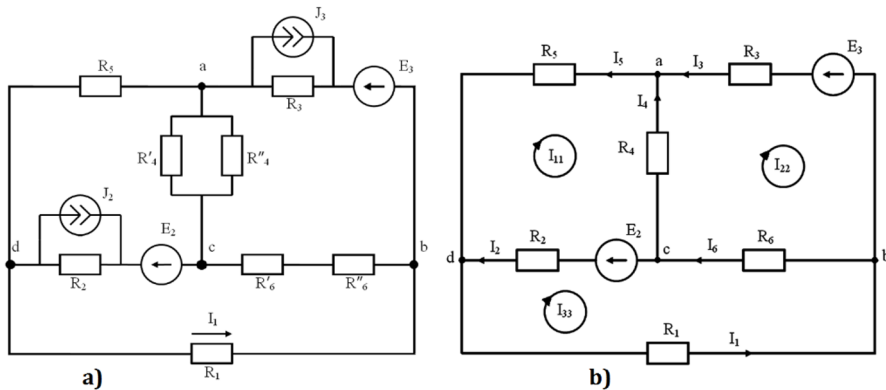


Fig. 5. DC electrical circuit (a) and its equivalent circuit (b).

Further calculation of the electrical circuit and the compilation of its equations is carried out according to Kirchhoff's laws according to the following rules: $N_{eq}^{1K} = n_{dot} - 1$; $N_{eq}^{2K} = n_{br} - (n_{dot} - 1)$. Choose the circuit traversal clockwise. Further, indicate the directions of the branch currents (in branches with EMF sources in the direction of the source arrow). We obtain the following equations for a given electrical circuit:

- according to Kirchhoff's first law:

$$(a) I_3 + I_4 - I_5 = 0;$$

$$(b) I_1 - I_3 - I_6 = 0;$$

$$(c) I_6 - I_2 - I_4 = 0;$$

- according to Kirchhoff's second law:

$$(1k) E_2 = I_2 \cdot R_2 - I_5 \cdot R_5 - I_4 \cdot R_4;$$

$$(2k) -E_3 = -I_3 \cdot R_3 + I_4 \cdot R_4 + I_6 \cdot R_6;$$

$$(3k) -E_2 = -I_2 \cdot R_2 - I_6 \cdot R_6 - I_1 \cdot R_1.$$

Further, conduct the calculation of branch currents by the method of circuit currents. To do this, we make up a system of equations, calculate the constant equation coefficients, namely, the inherent and mutual resistances of the circuits, EMF circuit, calculate the determinants, obtain the circuit currents and, finally, determine the currents in the branches [25]. All these calculations take a lot of time and are greatly simplified with a computer model.

The model is being developed in the MatLab software package using the Simulink block library, which includes the SimElectronics and SimPowerSystems subdirectories [26]. A computer model simulating a DC electrical circuit (Fig. 5) is shown in Fig. 6.

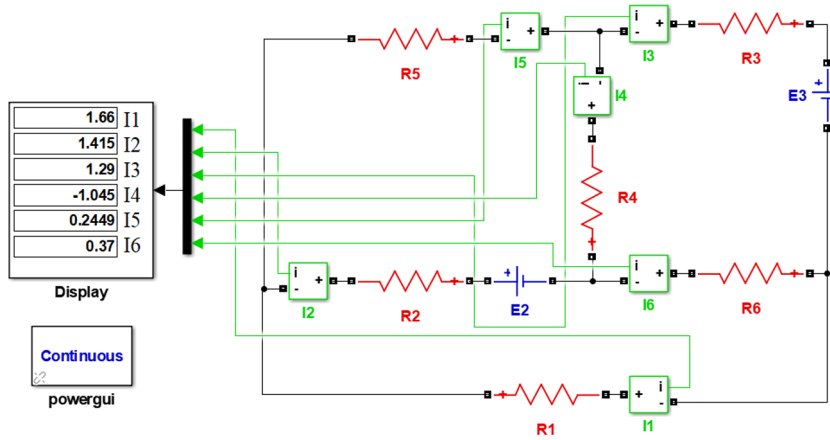


Fig. 6. Computer model of a DC electrical circuit.

The model contains EMF sources E_2 and E_3 , resistances R_1 - R_6 , current meters I_1 - I_6 . The Display block displays the values of currents in the branches, which completely coincide with the calculated values [27].

3.4 Computer model for calculating the interaction potential of particles

One of the important branches of crystal physics is the study of crystal lattice vibrations, since they determine such important properties as thermal conductivity, heat capacity, thermal expansion and many others [28].

Along with experimental methods for studying the nonlinear dynamics of the crystal lattice, effective computer modeling methods, such as first-principle modeling and the method of molecular dynamics, are widely used [29]. The method of mathematical modeling is used to a lesser extent, since the calculation error can reach 10% during its application. At the same time, it is the least expensive in computation terms. Currently, mathematical modeling is considered as a powerful tool for theoretical research of nonlinear problems in physics [30].

The computer model consists of a system of differential equations, their difference analog, the potential of interatomic interaction, specifically defined initial and boundary conditions.

Simulation was conducted in a three-dimensional (3D) space, the gradient was taken in three directions. The transformation of potential $U(r(t))$ into $U(x(t), y(t), z(t))$ was conducted according to the formula (6):

$$\vec{r}_{3D} = x\vec{i} + y\vec{j} + z\vec{k}. \quad (6)$$

125 atoms (N) with the dimensions of the crystal lattice (cell) $L \times W \times H = 5 \times 5 \times 5$ were selected as the initial data for 3D modeling. The main initial data for modeling also include: T_k – the end time of calculations; d_t – the time step; r – the distance between the centers of particles, ε – the depth of the potential “pit”, σ – the distance at which the interaction energy goes down to zero. The parameters ε and σ are the atomic characteristics of the corresponding substance that can be obtained through the Joule-Thomson coefficient, or by comparing the experimental value of the viscosity coefficient with the value obtained from the formula for potential energy. To expedite the calculations, we will cut off the Lennard-Jones potential at a distance $r_c = 2.5 \cdot \sigma$. This choice is due to the fact that at this distance the value of the interaction energy is only ≈ 0.0163 of the depth of the pit ε .

The software was developed and saved in the m-file of the MatLab software package. Fig. 7 shows the program code with the source data and two cycles for 3D modeling.

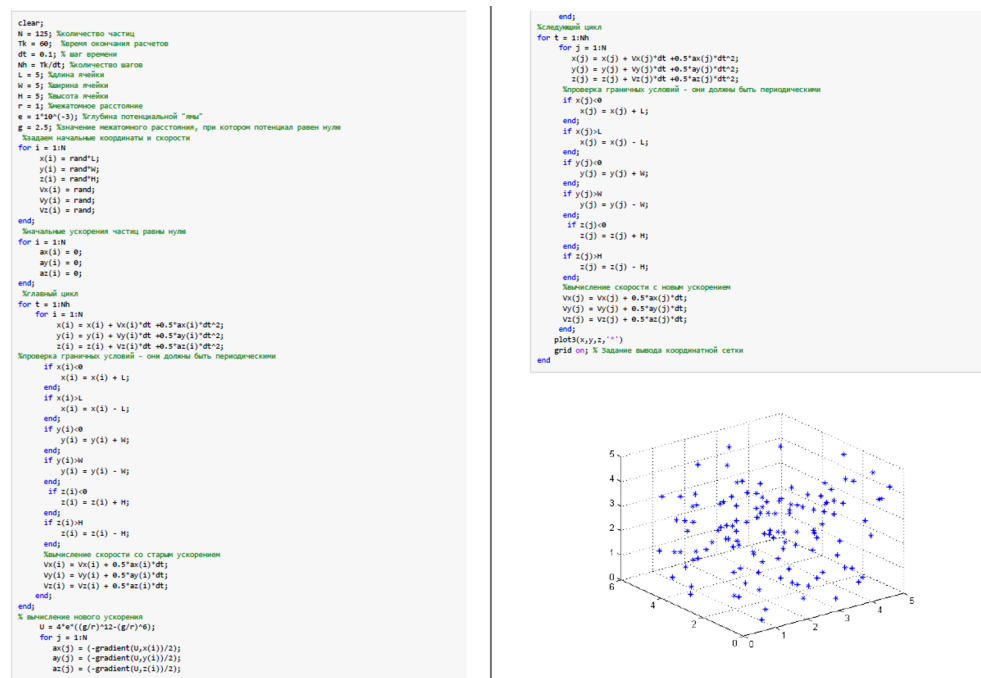


Fig. 7. Downloading the program code from the editor window of the MatLab software package.

As a result of the simulation, we obtained a three-dimensional coordinate system (x, y, z) with the final coordinates of atomic displacements with chaotic oscillations at the end of the simulation. We determine the sample average value of the particle interaction potential by the formula (7):

$$\bar{U} = \frac{\sum_{i=1}^n U_i}{n} \quad (7)$$

where n is the sample size, U_i is the i -th element of the sample. If the potential has a positive value, then this indicates strong repulsive forces of atoms as a result of chaotic motion.

4 Conclusion

In conclusion, it is worth noting that after the introduction of experimental units and computer models into the educational process, the interest and involvement of students in project and research work increased. After the survey, it turned out that students who are not involved in project and research activities, have pressure and debt as the prevailing motivating factors for study (71%), while the students actively involved in project and research activities have the reverse pattern: in the structure of their motivation to study the prevailing factor is the motivation related to cognitive need and the content and process of learning (62%).

The developed experimental units and computer models were patented (RU 172271 U1, RU 188630 U1, RU 2021615775, RU 2022662820) and introduced into the educational process of extensive physics training for students of technical specialties at the Mirny Polytechnic Institute, a branch of The Ammosov North-Eastern Federal University (NEFU).

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