A Laboratory on Visualization of Electrostatic and Magnetic Fields

Kenzhekhan Kabylbekov, Khadisha Abdrakhmanova, Gaukhar Omashova, Pulat Saidakhmetov, Turlan Sultanbek, Nurzhamal Dausheyeva

M. Auezov South Kazakhstan state University, Tawek Khan Avenue, 5, 160012, Shymkent, Kazakhstan, e-mail: omashovag@mail.ru

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Abstract: This article presents calculations and visualization of an electric field of a point charge (equipotential lines) and systems of oppositely charged threads, of magnetic field lines of a thin long and straight current-carrying conductor, magnetic field lines inside a cylindrical conductor with evenly distributed current made using the MATLAB language. Calculations of an electric field and potential of a point charge as a function of a distance are provided as well as a potential of a system of oppositely charged threads, magnetic induction of a thin, long current-carrying conductor as a function of a distance and magnetic induction inside the cylindrical conductor are performed. The graphs of these dependencies are drawn.

Keywords: cylindrical conductor; electric field; equipotential lines; magnetic induction; point charge

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1 Introduction

At present practically all educational institutions of Kazakhstan are provided with computer hardware and software, interactive boards and internet. Almost all teachers have finished language and computer courses of professional development. So there are all conditions for using computer training programs and models for performing computer laboratory works. Over several years we conducted work on organizing physics usage in the computer laboratory utilizing theresources of the Fizikon Company [1] as well as the resources developed at Al-Farabi Kazakh National University [2]. This topic in general is extremely relevant in the area of modern research. In particular, the problem of the organization of performance of the laboratory work "Visualization of electrostatic and magnetic fields in MATLAB language" was partly covered in the survey of V. P. Dyakonov "MATLAB training course" [34], also in relevant works of H. K. Lam[35], R.-E. Precup[36], A. Ürmös, Z. Farkas[37], J. Saadat, P. Moallem [38], etc. The article is organically continuing the research line on the organization of laboratory works by the authors K. Kabylbekov, Kh. Abdrakhmanova, Zh. Abekova, R. Abdraimov, B. Ualikhanova, T. Tagaev, A. Bitemirova, M. Berdieva, etc. [3-33]. Some of worksheet templates for computer laboratory works are introduced in the educational process of our university and schools of Southern Kazakhstan [3-32]. Students of the specialties 5B060400 and 5B011000-physics are successfully mastering the discipline “Computer modeling of physical phenomena” which is the logical continuation of the disciplines “Information technologies in teaching physics” and “Use of electronic textbooks in teaching physics”. The aim of this discipline is to study and learn the program language of the MATLAB [33] system, to help the students get acquainted with its huge opportunities during the modeling and visualization of physical processes. So, the article is devoted to the methodology of organizing the given laboratory works “Calculation and visualization of an electric field of a point charge”, “Calculation and visualization of an electric field of a system of two oppositely charged threads”, “Calculation and visualization of a magnetic field of a thin and long current-carrying conductor” and “Calculation and visualization of a magnetic field of a cylindrical current-carrying conductor” in the MATLAB language.

2 Results and Discussion

2.1 Laboratory Work № 1. “Calculation and Visualization of an Electric Field of a Point Charge” in the MATLAB Programming Language

The aim of the work: to work out the program of calculation and visualization of an electric field of a point charge.

We will draw equipotential lines of ~~an~~ electric field of a point charge in three-dimensional space and in ~~p~~rojection on the XY plane.

The potential of electric field of a point charge is determined by the expression $\varphi = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$; Its electric field is determined by the expression $E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$;

where ε_0 is the electric constant, q is the quantity of a point charge, r is the distance from the charge to the point where the electric field is calculated.

Calculation and visualization program

```
>>x=-6:0.1:6; %input coordinate vectors

>>y=-6:0.1:6; %input coordinate vectors
```

```
>>q=9*10.^-9; %input a charge quantity
>>e0=8.85*10.^-12; %input an electric constant
>> [X,Y]=meshgrid(x,y); %setting of a grid at knots of which x иy coordinates are recorded
%(arrays X and Y).
>>a=0.5; %input a coordinate
>>r2 = ((X + a).^ 2 + Y.^ 2).^0.5; %calculation of a distance
>>r1 = ((X - a).^ 2 + Y.^ 2).^0.5; %calculation of a distance
>>r=sqrt(r1.^2+r2.^2); %calculation of a distance
>>Z=(q./(4*pi*e0*r)); %calculation of a potential
>>contour3(X,Y,Z,100); %drawing the lines of  levels
>>xlabel('X,m') %input the name of the axis
>>ylabel('Y,m') %input the name of the axis
>>title('lines of equal potential′) %input the name of the graph
```

The result of the program is shown in Figure 1.

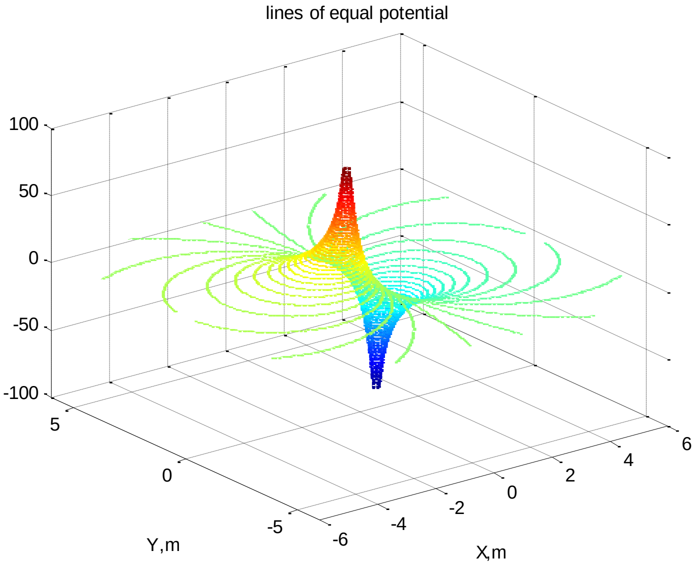

Figure 1

Equipotential lines of a point charge electric field

```
>>view([0 0 10]) %projection of lines on the plane X-Y
```

The result of this projection is shown in Figure 2.

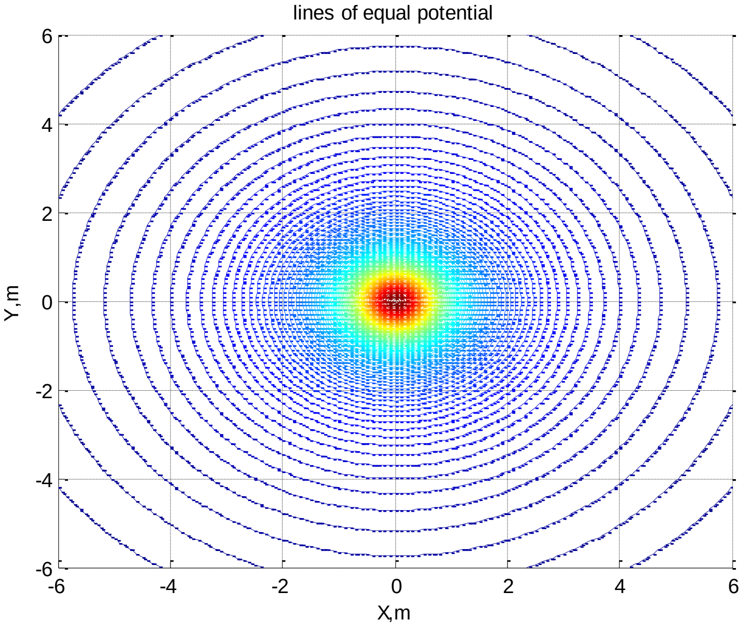

Figure 2

Equipotential lines of a point charge electric field in the projection on the plane X-Y

Equipotential lines of a point charge electric field make concentric circles with density decreasing as the distance from the charge increases.

```
>> E=(q./(4*pi*e0*r.^2)); % calculation of electric field
>> plot(r,E,'k-') %visualization
>> grid on %drawing of  the coordinate grid
>> xlabel('r, sm') %input the name of the axis
>> ylabel('E, V/sm') %input the name of the axis
>> title('E=F(r)') %input the name of the graph
```

The result of the calculation is shown in Figure 3.

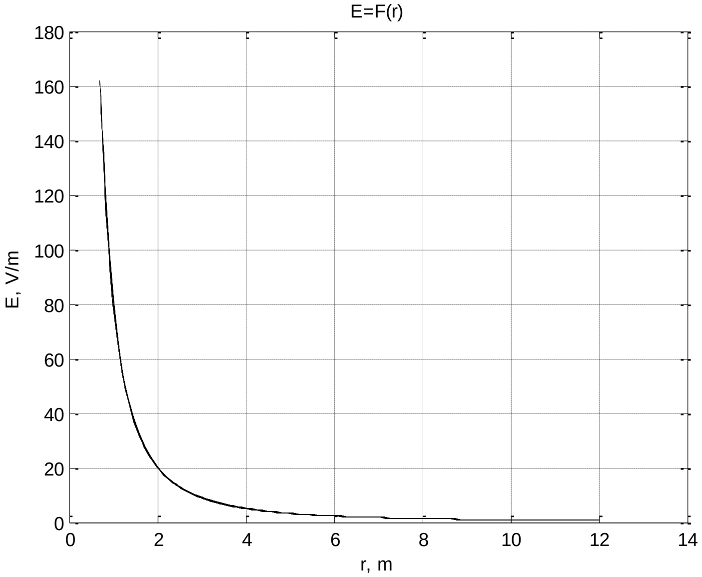

Figure 3
The electric field of a point charge versus distance

```
>> fi=(q./(4*pi*e0*r)); % calculation of a potential
>> plot(r,Z,'k-') % visualization (plotting the graph)
>> xlabel('X,m') % input the name of the axis
>>ylabel('Y,m') % input the name of the axis
>> grid on%drawing of the coordinate grid
```

The result of the calculation is shown in Figure 4.

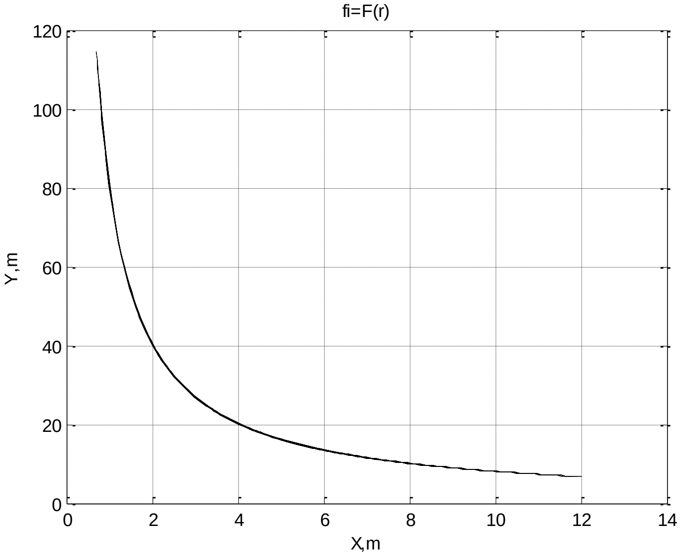

Figure 4
The potential of a point charge electric field versus distance

Comparison of the curves of the electric field (Fig. 3) and potential (Fig. 4) versus distance shows that with increasing of the distance from the point charge its electric field decreases quicker than its potential. At the end of the laboratory work students do this experiment independently for the charge with different quantity and sign.

2.2. Laboratory Work № 2. “Calculation and Visualization of an Electric Field of a System of Two Oppositely Charged Threads” in the MATLAB Program Language

The aim of the work: to work out the program of calculation and visualization of an electric field of a system of two oppositely charged threads.

There are two parallel and infinitely long threads which are evenly and oppositely charged with a linear charge density $+\tau$ and $-\tau$ to be in air (ε=1) (Figure 5). We will draw the diagram of these threads in the cross section plane (the threads are represented by two dots at the distance $2a$ from each other).

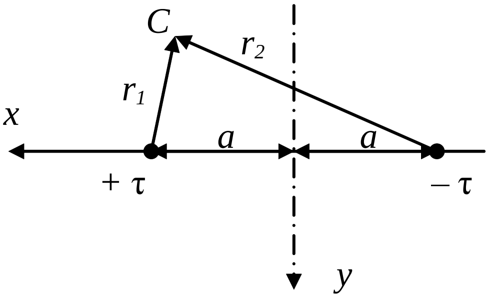

Figure 5
The diagram of the charged threads in the cross section plane

The potential of the system at the point C is equal to the sum of potentials of each charged thread's electric field:

$$\varphi(C)=\varphi_{+}+\varphi_{-}=+\frac{\tau}{2\pi\varepsilon_0\varepsilon}\ln(r_1)-\frac{\tau}{2\pi\varepsilon_0\varepsilon}\ln(r_2)+A=\frac{\tau}{2\pi\varepsilon_0\varepsilon}\ln\left(\frac{r_1}{r_2}\right)+A$$

where τ is the linear charge density of the thread, ε_0 is the electric constant, ε is the dielectric permeability of a medium, r is the module of the radius vector of a point where the potential of an electric field is calculated.

If to accept that $\varphi(x=0) = 0$, i.e. on an axis of symmetry the potential is zero, then $A=0$. Now we will define the equation of equipotential surfaces. On these surfaces $r_2/r_1=k$ = const. Here k is the parameter of equipotential lines family in the plane of the figure.

We will express r_2 and r_1 in the Cartesian coordinates and derive the equipotential equation in a canonical form relative to coordinates x and y.

$$r_2= ((x+ a)^2 + y^2)^{0,5};\ r_1= ((x-a)^2 + y^2)^{0,5}$$

$$(x+a)^2 + y^2 = k^2 (x-a)^2 + k^2y^2$$

$$(x+a)^2 - k^2 (x - a)^2 + y^2(1 - k^2)= 0$$

$$x^2(1 - k^2) + 2ax(1 + k^2) + a^2(1 - k^2) + y^2(1 - k^2) = 0$$

$$x^2 + 2ax(1 + k^2)/(1 - k^2) + y^2 + a^2 = 0$$

$$(x+a(1 + k^2)/(1 - k^2))^2 + y^2 = (a(1 + k^2)/(1 - k^2))^2 - a^2 = (2ak/(1 - k^2))^2$$

Here we get the equation of a circle in a canonical form:

$$(x-s)^2 + y^2 = R^2(1)$$

where $s=a(k^2+1)/(k^2 - 1)$ is the coordinate of a circle center. $R=a|2k/(1 - k^2)|$ is the circle radius.

We have received expressions for the coordinate of the center and for the radius of the equipotential line with given parameter *k*, where $k = \exp\left(2\pi\varepsilon_0\varepsilon\phi / \tau\right)$.

According to the equation (1) the lines of equal potential make circles, and the surfaces of equal potential make circular cylinders with geometrical axes displaced relative electric axes. One of these surfaces degenerates to the plane with zero potential (at *k* = 1: $S \rightarrow \pm\infty$; $r \rightarrow \infty$).

The lines of the electric field make the circle arches emerging from the axis with a positive charge and ending on the axis with a negative charge.

If to cut the family of equipotential surfaces with parallel planes which are perpendicular to the charged axes, then in each plane there will be the same picture of lines. The fields having such property are called plane-parallel (or they are called two-dimensional fields).

Defining the picture of the field and use of the uniqueness theorem consequence creates many new tasks to be solved. The number of tasks is determined by the number of pairs of equipotential surfaces, which can be considered as surfaces of conductors.

Let us consider the most important special cases of such tasks.

Calculation and visualization program

```
>>t=2*10.^-9'; % input the linearcharge density of the thread
>>x=-6:0.1:6; % input the vector of an x coordinate
>>y=-6:0.1:6; % input  the vector of an y coordinate
>> [xx,yy]=meshgrid(x,y); %drawing the grid with coordinates x and y at its knots
%(arrays X and Y).
>>a=0.5; % input of a parameter
>>r2 = ((xx + a).^ 2 + yy.^ 2).^0.5; %calculation of the distance from the positively charged  %thread
>>r1 = ((xx - a).^ 2 + yy.^ 2).^0.5; %calculation of the distance from the negatively charged  %thread
>>e0=8.85*10.^-12; %  input  an electric constant
>>zx=(t./(2*pi*e0))*log(r1./r2); %calculation of a system’s potential
>>contour3(xx,yy,zx,100); %drawing the lines of  levels
>>xlabel(‘X,m’)
ylabel(‘Y,m’)
```

```
zlabel(‘fi, V’)
title(title('lines of equal potential′) %input the name of the graph
```

The result of calculations are shown in Figure 6.

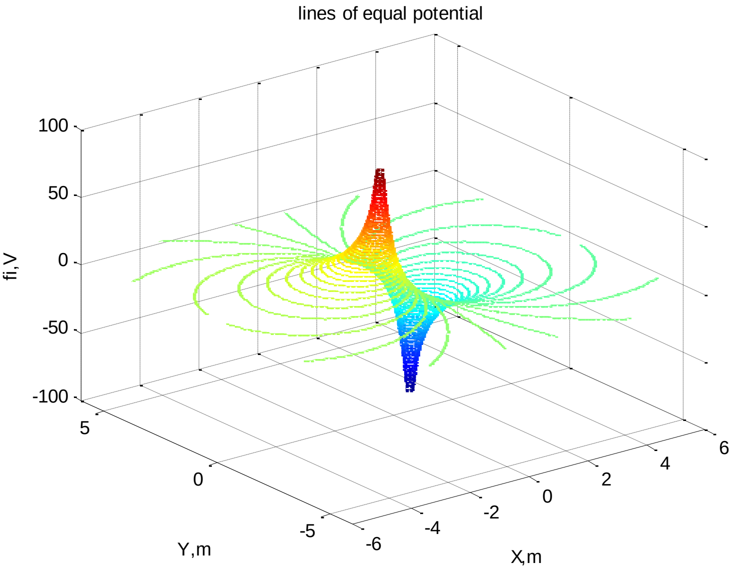

Figure 6

The result of visualization of the field of two oppositely charged threads in three-dimensional space

```
>>view([0 0 10]) %  projection of the field on the X-Y plane
```

The result of the projection is presented in Figure 7.

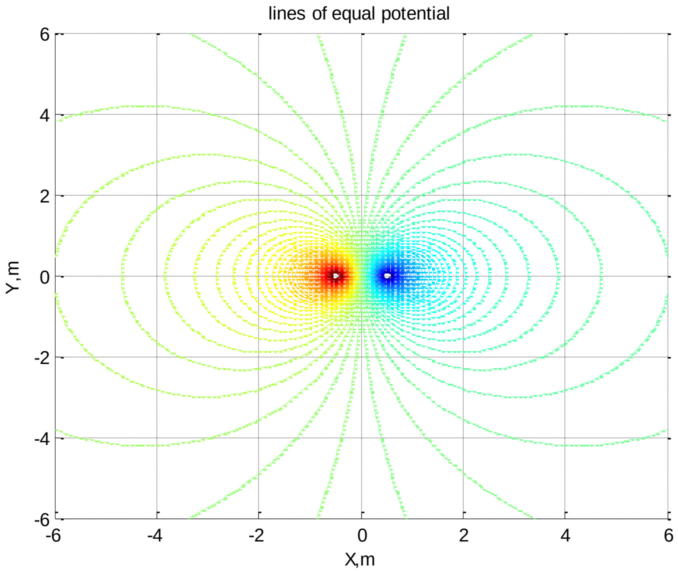

Figure 7

The result of visualization of the field of two oppositely charged threads in the projection on the *X*-*Y* plane

At the end of the laboratory work students do experiment independently by changing the density of charges and the distance between threads.

2.3 Laboratory Work №3. ”Calculation and Visualization of a Magnetic Field of an Infinitely Long and Thin cuRrent-Carrying Conductor” in the MATLAB Program Language

The aim of the work: To work out the program of calculation and visualization of a magnetic field of an infinitely long and thin current-carrying conductor.

Let an electric current of $I = 2$ A to flow through an infinitely long and thin conductor. It is necessary to calculate the magnetic induction around the conductor as a function of the distance *b* from the center of its axis.

Induction of a magnetic field of an infinitely long current-carrying conductor as a function of the distance *b* from the center of its axis is calculated by the formula:

$$B = \frac{2\mu_0 I}{4\pi b}$$

where μ_0 is the magnetic constant, I is the electric current, b is the distance between the center of the conductor axis and the point where the magnetic induction is calculated.

Calculation and visualization program

```
>> x=-6:0.1:6;% input  the vector of an x coordinate
>>y=-6:0.1:6; % input  the vector of an y coordinate
>> I=2; % input  the current magnitude
>> m0=4*pi*10e-7; % input  the magnetic constant
>> r=sqrt(x.^2+y.^2);%calculation  r
>> b=0:0.1:1; % input  the distance vector
>> B=2*m0*I./(4*pi*b); %calculation of the magnetic induction magnitude
>> plot(b,B,'k-') %visualization (plotting the picture of a magnetic field)
>> grid on%drawing the coordinate grid
>> xlabel('b, m') %input the name of the axis
>> ylabel('B, Tl') %input the name of the axis
>> title('B=F(b)') %input the name of the graph
```

The result of the calculation is given in Figure 8.

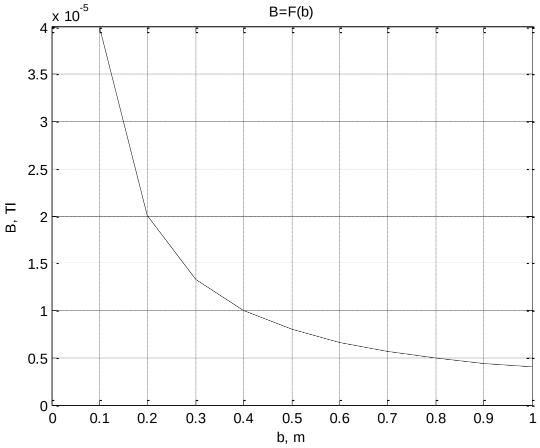

Figure 8

Magnetic induction of an infinitely long current-carrying conductor as a function of the distance *b* from the center of its axis

Figure 8 shows that the magnetic induction of the thin and infinitely long current-carrying conductor decreases as $1/b$ with increase of the distance b from the conductor axis.

The program of visualization of magnetic field lines in colored three-dimensional space:

```
>> [X,Y]=meshgrid(x,y)% drawing the grid with coordinates x and y at its knots
%(arrays X and Y).
>> r2 = ((X + 0.2).^ 2 + Y.^ 2).^0.5; %calculation of the distance
>> r1 = ((X - 0.2).^ 2 + Y.^ 2).^0.5; %calculation of the distance
>>  r=sqrt(r1.^2+r2.^2); %calculation of the distance
>>  Z=2*m0*I./(4*pi*r); %calculation of the magnetic induction
>> contour3(X,Y,Z,100); %drawing the lines of levels
>> xlabel('x,m') %input the name of an x axis
>> ylabel('y, m') %input the name of an y axis
>> zlabel('B, Tl') %input the name of an z axis
>> grid on%input the coordinate grid
```

The result of visualization is shown in Figure 9.

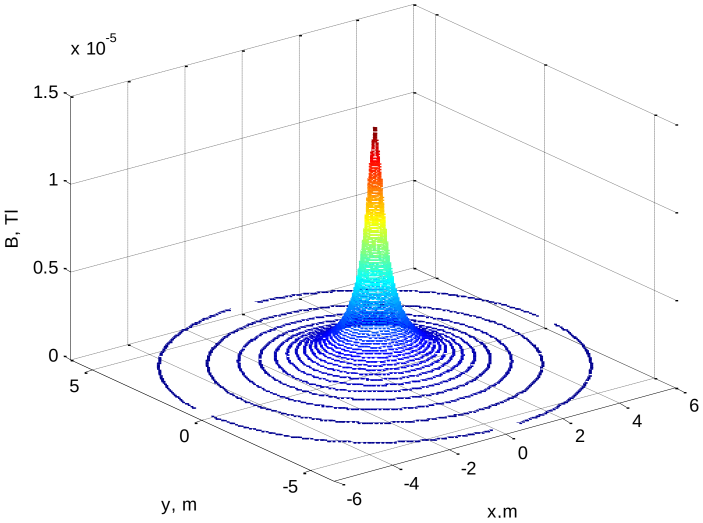

Figure 9

The lines of the magnetic induction of a thin and long current-carrying conductor

```
>> view([0 0 100]) %projection on X-Y plane of support
>> gtext('B') %input the text in the figure
```

The result of the projection is presented in Figure 10.

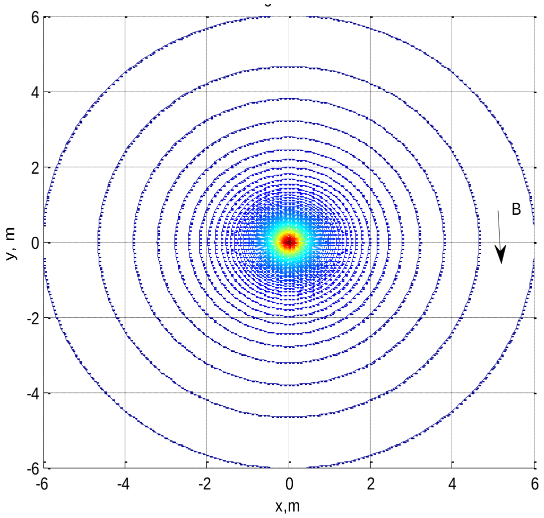

Figure 10
The projection of lines of the magnetic induction of a thin and long current-carrying conductor on *X*-*Y* plane

Figure 10 shows that the magnitude of the magnetic induction of a long straight current-carrying conductor decreases with increase of the distance *b*, namely from $4\cdot10^{-5}$ T at *b*=0.1m to $0.5\cdot10^{-5}$ T at *b*=0.8m. Figures 9, 10 show that lines of magnetic induction are concentric circles around the center of the conductor. The density of lines decreases with removal from the conductor that verifies the idea that induction magnitude decreases with increase of the distance from the conductor axis.

At the end of laboratory work students do experiments independently by changing the magnitude and direction of the current through the conductor.

2.4 Laboratory Work № 4. "Calculation and Visualization of a Magnetic Field of a Long Cylindrical Current-Carrying Conductor" in the MATLAB Program Language

The aim of the work: To work out the program of calculation and visualization of a magnetic field inside and outside of a long cylindrical current-carrying conductor.

Let the electric current of *I* = 7.0 A evenly distributed with density $j = \dfrac{4I}{\pi d^2} A/m^2$ to flow through the cylindrical conductor with diameter of *d* = 6.0 mm.

Hence, we find out the magnetic field strength inside the cylindrical conductor using the formula $H_i = \frac{jr}{2}$, where *r* is the distance between the cylinder centre and its surface; outside the conductor - $H_o = \frac{jd^2}{8r}$, where $j = \frac{4I}{\pi d^2}$ is the current density or $H_o = \frac{I}{2\pi r_o}$, where r_o is the distance from outside surface of the cylinder to the point where the magnetic field strength is calculated.

a) Program of calculation and visualization of a magnetic field strength inside the conductor:

```
>> d=6e-3; I=7; % input parameters
>> j=4*I./(pi*d.^2) % calculation of a current density
j =  2.4757e+005 % result
>> r=d./ 2 % calculation of a conductor radius
r =   0.0030 % result
>> x=-r:0.01*r:r; % input the vector of x coordinate
>>y=-r:0.01*r:r; % input the vector of y coordinate
>> [X,Y]=meshgrid(x,y) % drawing the grid with coordinates x and y at its knots
% (arrays X и Y).
>> r1 = ((X - 0.2).^ 2 + Y.^ 2).^0.5; % calculation of the distance
>>r2 = ((X + 0.2).^ 2 + Y.^ 2).^0.5; % calculation of the distance
>>r=sqrt(r1.^2+r2.^2); % calculation of the distance
>> H=j*r./2; % calculationof a magnetic field strength magnitude inside the conductor
>>Z=H; % redenotation
>>plot(r,H,'k-') % visualization
>> xlabel('r,m') % input the name of x axis
>> ylabel('r,m') % input the name of y axis
>> title('H=F(r') % input the name of the graph
>> grid on% input the coordinate grid
```

The result of calculation is shown in Figure 11.

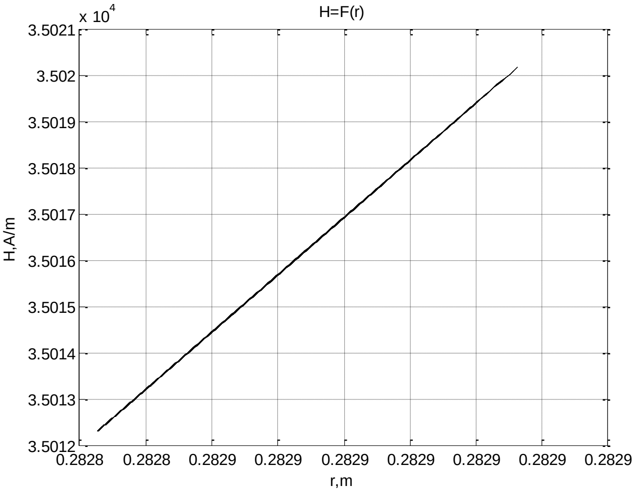

Figure 11

The magnetic field strength versus distance *r* between the points inside the cylinder and its surface.

```
>> contour3(X,Y,Z,100); % drawing the lines of levels
>>  xlabel('x,m') % input the name of x axis
>> ylabel('y, m') % input the name of y axis
>> zlabel('H, A/m') % input the name of z axis
```

The result of visualization is shown in Figure 12.

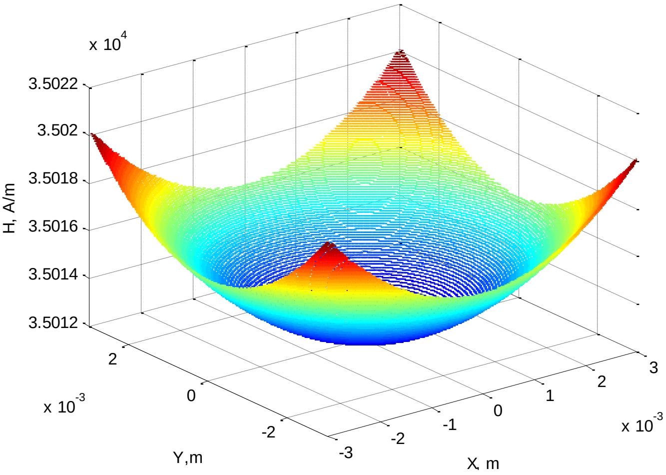

Figure 12

The lines of the magnetic field strength inside the cylindrical current-carrying conductor

view([0 0 100]) % projection on *X*-*Y* plane of support.

The result of projection is given in Figure 13.

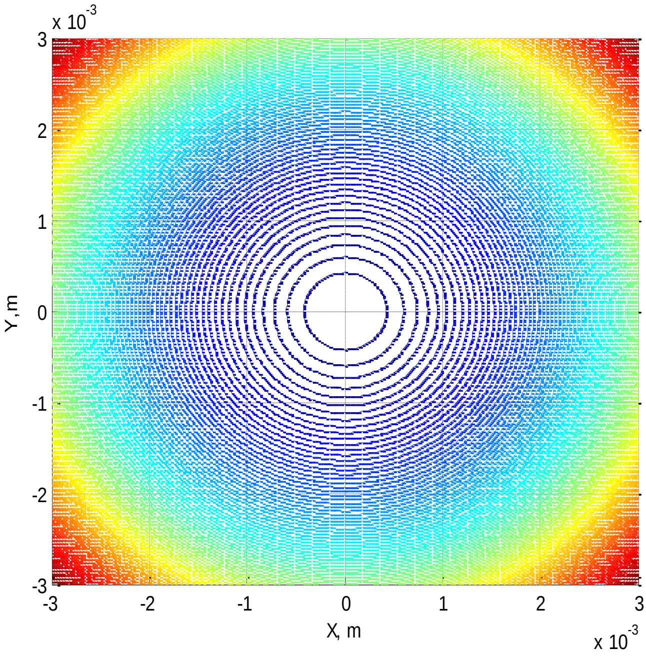

Figure 13
The projection of lines of the magnetic field strength inside the cylindrical current-carrying conductor on the X-Y plane

Figure 13 shows that the density of lines of magnetic field strength increases with the approach to the surface of the conductor that demonstrates that the magnitude of the magnetic field strength increases proportionally to distance *r* from the center of the conductor to its surface.

b) Program of calculation and visualization of a magnetic field strength outside the conductor:

```
>> rc= r:0.1*r:10*r; % input vector of distance

>> Hc=j*d.^2./(8*rc); % calculation of the field strength magnitude in dependence on the distance

>>plot(rc,Hc,'k-'); % visualization

>>grid on % drawing the coordinate grid

>>xlabel('r,m') % input the name of x axis

>>ylabel('H,A/m') % input the name of y axis

>>title('H=F(rc)') % input the name of the graph
```

The result of this program is shown in Figure 14.

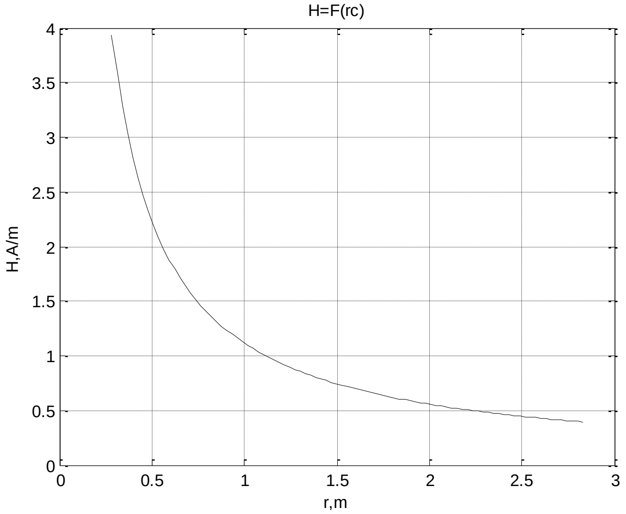

Figure 14

The magnetic field strength versus distance outside the cylindrical conductor

The magnetic field strength outside the cylindrical conductor decreases in proportion to the distance of a considered point from the conductor surface, as in the case of a long current-carrying conductor. The picture of the lines of magnetic field strength outside the cylindrical conductor is similar to the picture of the lines of magnetic field strength of the infinitely long current-carrying conductor. Students conduct this part of work by themselves.

Conclusions

The survey presents calculations and visualization of an electric field of a point charge (equipotential lines) and systems of oppositely charged threads, of magnetic field lines of a thin long and straight current-carrying conductor, and magnetic field lines inside of a cylindrical conductor with evenly distributed current made using the MATLAB language. Calculations of an electric field and potential of a point charge as a function of a distance are provided as well as a potential of a system of oppositely charged threads, magnetic induction of a thin, long current-carrying conductor as a function of a distance and magnetic induction inside the cylindrical conductor are performed. The graphs of these dependencies are drawn. So, the article is a fundamental research and gives a methodology of organization and performance of the laboratory work “Visualization of electrostatic and magnetic fields in the MATLAB language”.

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