The Experiment 3 of Engineering Electromagnetics: The Analysis of the Magnetic Field Distribution Generated by Two Parallel Current Loops

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***Abstract*—This experiment uses Matlab to plot and analyze the magnetic field distribution generated by two parallel current loops. When the distance between two parallel current rings is equal to their radius, the system formed by these two current rings is usually called Helmholtz coil. This experiment studies the distribution of the magnetic field of Helmholtz coil. Matlab is used to draw the vector distribution of the magnetic field intensity (represented by the arrow family) and the distribution of the magnetic field intensity value. There are two situations in this experiment. In the first case, the currents in the two current rings are in the same direction. Drawing the magnetic field distribution in this case, it can be found that the magnetic field distribution in the space between the two current rings is very uniform. In the second case, the currents in the two current loops are in opposite directions, and the magnetic field distribution in the same area is studied and analyzed graphically.**

***Index Terms*—Magnetic field distribution, Helmholtz coil, Matlab.**

I. Introduction

THIS is a experiment to analyze the magnetic field distribution generated by two parallel current loops. When the distance between two parallel current loops is equal to their radius, the system formed by these two current rings is usually called Helmholtz coil. A characteristic of Helmholtz coils is that the magnetic field in the space between the two current loops is very evenly distributed. Therefore, this experiment takes Helmholtz coil as the research object to study the magnetic field distribution generated by the system. In order to more intuitively observe the magnetic field effect and characteristics generated by the system, the experiment uses Matlab to plot the magnetic field distribution of the system, including the magnetic field intensity vector distribution diagram (represented by arrow cluster), magnetic field intensity value distribution diagram and the magnetic field line diagram. And we can also study the what the distribution look like if the current direction is opposite.

II. Theoretical analysis

On the basis of experiments, Biot and Savar derived the expression of magnetic field intensity generated by current element, which is called Biot - Savar law, which is as follows:

$$d\boldsymbol{H} = \frac{Id\boldsymbol{L} \times \boldsymbol{a_R}}{4\pi R^2} = \frac{Id\boldsymbol{L} \times \boldsymbol{R}}{4\pi R^3} \tag{1}$$

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Where H is the magnetic field intensity vector, IdL is the current element vector, R is the vector from the current element IdL to the field point P, and its magnitude is R.

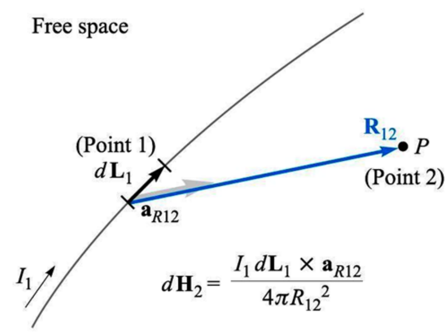

Fig. 1: The strength of the magnetic field generated by the current element

Similar to electric field, magnetic field also follows the superposition principle, so we can also divide the current carrying conductor into many current elements, and the magnetic field generated by the whole current carrying conductor is the superposition of the magnetic field generated by these current elements. Based on this idea, we can solve the distribution of the magnetic field established by the current loop at any field point with the help of Matlab programming.

III. Case1: Magnetic Field Distribution Generated by Two Parallel Current Loops with Same Current Direction

A. Declaration

In this case, these two parallel current loops have the same current direction. Their radius a is 2 m, and their current load size I is 500 A. The two current rings are placed parallel to the xy plane, with their centers at $O1(0, 0, -1)$ and $O2(0, 0, 1)$ respectively. The placement diagram of the two current rings is roughly as follows

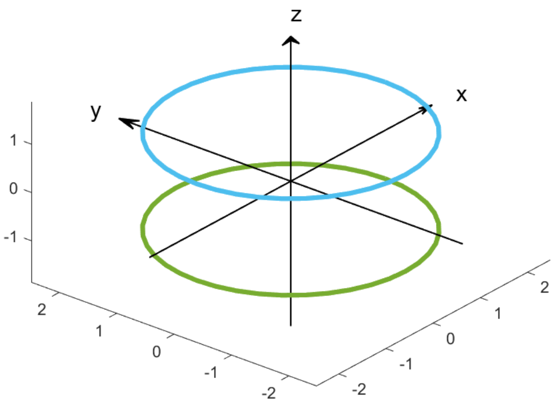

Fig. 2: The placement diagram of the two current rings

Before the experimental code is written, it is necessary to explain and set the parameters of the current loop and field field. Some parameters of the field field need to be adjusted and changed constantly to make the image the clearest and most reflective of the experimental effect. The following parameters are the appropriate ones after debugging, and this section of code is presented next.

```
clear all;
figure;
a=2;
% diameter value of the current ring
I=500;
% the current value of the current ring
C=I/(4*pi);
% Merging constant
N=100;
% Set the number of current loop segments
ym=3;
% Sets the range in the y direction of the field
zm=3;
% Sets the range in the z direction of the field
y=linspace(-ym,ym,60);
% Divide the Y-axis into 60 equal parts
z=linspace(-zm,zm,60);
% Divide the z-axis into 60 equal parts
theta0=linspace(0,2*pi,N+1);
% The circumference of the ring is segmented
theta1=theta0(1:N);
x1=a*cos(theta1); y1=a*sin(theta1);
% Starting coordinates x1,y1 for each vector in
    the loop
theta2=theta0(2:N+1);
x2=a*cos(theta2); y2=a*sin(theta2);
% End point coordinates y2,z2 for each vector in
    the loop
zc1=-1; xc1=(x2+x1)./2; yc1=(y2+y1)./2;
zc2=1; xc2=(x2+x1)./2; yc2=(y2+y1)./2;
% Calculate the three coordinate components of
    the center points of each segment of the
    ring vector
dlz=0;dlx=x2-x1;dly=y2-y1;
% Calculate the three length components of each
    segment of the ring vector dl
```

B. Vector Distribution of Magnetic Field Intensity

1) Matlab Codes:

Based on the theoretical formula of magnetic field strength of the current segments derived above and the superposition theorem, the contribution of current segments on the current ring to the magnetic field was superimposed to calculate the magnetic field intensity generated by each current ring in the field domain. Then, the effect generated by the two current rings was superimposed to obtain the distribution of magnetic field intensity in the field domain, and the corresponding graph was drawn. For the sake of simplicity, only the magnetic field distribution in the yz plane is analyzed in this experiment, especially in the regions y=[-2,2], z=[-1,1]. In order to observe the features of the system and y = [2, 2], z = [1, 1] area of the magnetic field distribution, we will coordinate axis region is set to y = [2.5, 2.5], z = [1.5, 1.5]. The code for this section is as follows:

```
NGx=60; NGy=60;
% Number of grid lines
Hy=zeros(60);Hz=zeros(60);H=zeros(60);
% Let's set up the matrix of H
for i=1:NGy
% The H (x,y) value at each dot is computed
    iteratively
    for j=1:NGx
    rx1=0-xc1; ry1=y(j)-yc1; rz1=z(i)-zc1;
    rx2=0-xc2; ry2=y(j)-yc2; rz2=z(i)-zc2;
% Calculate the three length components of the
    diameter vector r on the surface of z=0
    r3_1=sqrt(rx1.^2+ry1.^2+rz1.^2).^3;
    r3_2=sqrt(rx2.^2+ry2.^2+rz2.^2).^3;
% Calculate the third power of r
    dlXr_y1=dlz.*rx1-dlx.*rz1;
    dlXr_z1=dlx.*ry1-dly.*rx1;
    dlXr_y2=dlz.*rx2-dlx.*rz2;
    dlXr_z2=dlx.*ry2-dly.*rx2;
% Calculate the Y and Z components of ×dlr, and
    the X component is 0
    Hy(i,j)=sum(C.*dlXr_y1./r3_1)+sum(C.*dlXr_y2
        ./r3_2);
    Hz(i,j)=sum(C.*dlXr_z1./r3_1)+sum(C.*dlXr_z2
        ./r3_2);
% Sum up the components of magnetic field
    strength generated by the various sections
    of the ring
    H=(Hy.^2+Hz.^2).^0.5;
% Calculate the magnitude of H
    end
end
quiver(y,z,Hy,Hz);
% Draw a magnetic field strength vector
axis([-2.5,2.5,-1.5,1.5]);
hold on;
plot(2,1,'ro',-2,1,'bo',2,-1,'ro',-2,-1,'bo'),
% Plot the standard coil profile
title(["Vector distribution of magnetic field
    intensity ";"(represented by arrow family)
    ";" 12113010"],"fontsize",13);
xlabel('y(m)'),ylabel('z(m)'),
% Modify the figure and label the axes
hold off;
hold on;
line([2,-2],[1,1]);
line([2 2],[-1 1]);
line([-2 2],[-1 -1]);
line([-2 -2],[1 -1]);
% Draw the boundary of the region y=[-2,2], z
    =[-1,1]
hold off;
```

2) Result and Analysis:

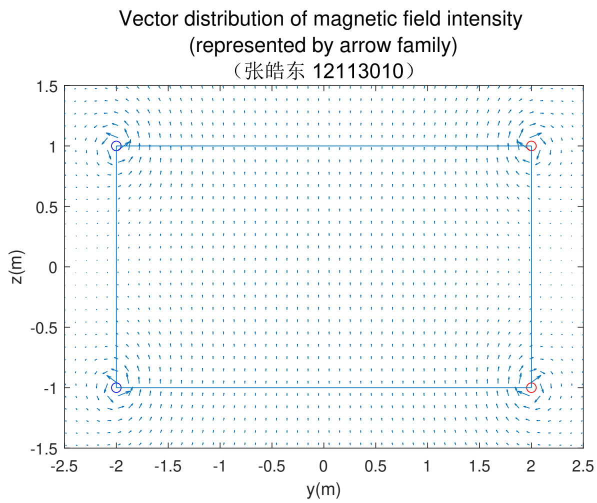

Fig. 3: Vector distribution of magnetic field intensity (represented by arrow family)

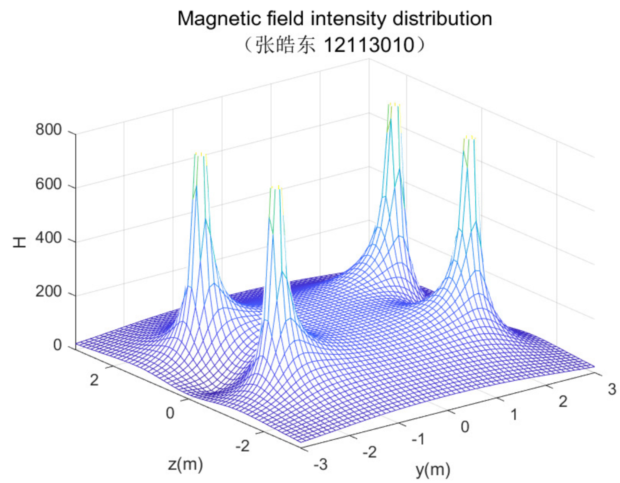

Fig. 4: Magnetic field intensity distribution

The result obtained is shown in Figure 3. We used small circles at the cross section of the current loop to show it in the figure. Meanwhile, in order to more clearly show the area to be observed, we selected the regions y=[-2,2] and z=[-1,1] with straight lines.

As can be seen from Figure 3, The magnetic field near the current loop will be significantly stronger than that around it, and its strength will decay rapidly with distance. And the direction and magnitude of magnetic fields in the rectangular region selected by the frame are almost the same, so it can be concluded that the magnetic field distribution in the space between the two current rings is relatively uniform, which is also in accordance with the characteristics of Helmholtz coil.

C. *Magnetic field intensity distribution*

1) Matlab Codes:

After calculating the magnetic field intensity H in the field, the distribution of the magnetic field intensity value can be drawn. The code is as follows:

```
figure;
mesh(y,z,H);
%Plot the magnetic field strength
axis([-3,3,-3,3,0,800])
xlabel('y(m)'),ylabel('z(m)'),zlabel('H');
title(["Magnetic field intensity distribution";"
    12113010"],"fontsize",13);
```

2) Result and Analysis:

The distribution of magnetic field intensity generated by the two current ring systems can be more clearly seen from Figure 4. It can be seen that the magnetic field intensity near the current ring is significantly greater than the surrounding magnetic field, and the magnetic field intensity decreases rapidly as the distance increases.

D. *Magnetic field lines distribution*

1) Matlab Codes:

Next, in order to observe and analyze the distribution and magnitude of the magnetic field more clearly, we can draw the magnetic field lines. Through the distribution of the magnetic field lines, we can more clearly analyze the size change, distribution, uniformity and other characteristics of the magnetic field. In the code, We take two straight lines passing through two current loops respectively, and take points on the lines as starting points for drawing magnetic force lines. In order to show whether the magnetic field in the middle is uniform or not, we set the interval of taking points in the middle part to be equal interval. In order to make the magnetic field lines near the loops in the diagram not difficult to be dense, we can enlarge the spacing of the points at this point. And that can shows a more intuitive picture. Then, the streamline() function is used to connect all points in the field with the starting points of the previous construction through the obtained Hy and Hz vector directions. Then the magnetic force line distribution of this system can be obtained by the following code:

```
figure;
ys2 = [-3:0.5:-2.5,-2:0.2:2,2.5:0.5:3];
%Set the starting y coordinate of the power line
zs2 = ones(1,25);
%Set the starting z coordinate of the power line
streamline(y,z,Hy,Hz,ys2,zs2);
%Draw lines of magnetic force outward from the
    starting circle
streamline(y,z,-Hy,-Hz,ys2,zs2);
%Draw lines of magnetic force inward from the
    starting circle
streamline(y,z,Hy,Hz,ys2,-zs2);
%Draw lines of magnetic force outward from the
    starting circle
streamline(y,z,-Hy,-Hz,ys2,-zs2);
%Draw lines of magnetic force inward from the
    starting circle
xlabel('y(m)'),ylabel('z(m)');
title(["Magnetic field lines distribution";"
    12113010"],"fontsize",13);
```

2) Result and Analysis:

In Figure 5, we have drawn the distribution of magnetic field lines in the field, through which we can clearly and intuitively see the distribution of magnetic field. It can be obviously found that in the area close to the current ring, the magnetic field lines will be much denser than the middle part, which indicates that the magnetic field near the current ring will increase significantly. When we look at the middle part, we can find that the power line here is similar to a straight line, and the distribution is relatively uniform, indicating that the magnetic field here is approximately uniform, which is also in line with the characteristics of Helmholtz coil, which gives us more intuitive evidence.

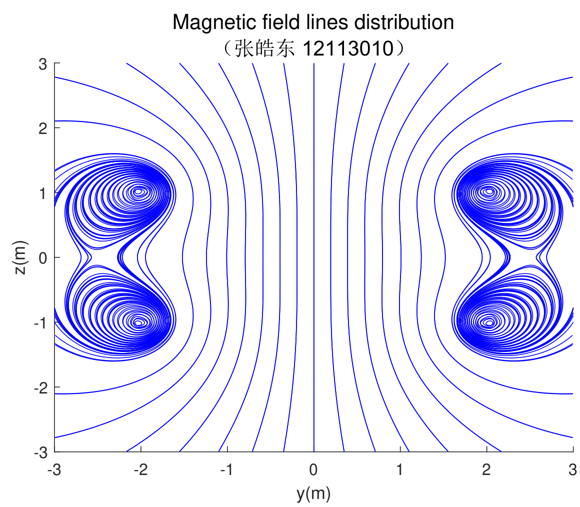

Fig. 5: Magnetic field lines distribution

IV. Case2: Magnetic Field Distribution Generated by Two Parallel Current Loops with Opposite Current Direction

A. Declaration

In this case, the current direction of the two current loops are set to be opposite. The only place need to modify is the parameter I and C. The codes to declare the parameters of the current loop and field field are as follows:

```
clear all
figure;
a=2;
% diameter value of the current ring
I1=500; I2=-500;
% the current value of the current ring
C1=I1/(4*pi); C2=I2/(4*pi);
% Merging constant
N=100;
% Set the number of current loop segments
ym=3;
% Sets the range in the y direction of the field
zm=3;
% Sets the range in the z direction of the field
y=linspace(-ym,ym,60);
% Divide the Y-axis into 60 equal parts
z=linspace(-zm,zm,60);
% Divide the z-axis into 60 equal parts
theta0=linspace(0,2*pi,N+1);
% The circumference of the ring is segmented
theta1=theta0(1:N);
x1=a*cos(theta1); y1=a*sin(theta1);
% Starting coordinates x1,y1 for each vector in
    the loop
theta2=theta0(2:N+1);
x2=a*cos(theta2); y2=a*sin(theta2);
% End point coordinates y2,z2 for each vector in
    the loop
zc1=-1; xc1=(x2+x1)./2; yc1=(y2+y1)./2;
zc2=1; xc2=(x2+x1)./2; yc2=(y2+y1)./2;
% Calculate the three coordinate components of
    the center points of each segment of the
    ring vector
dlz=0;dlx=x2-x1;dly=y2-y1;
% Calculate the three length components of each
    segment of the ring vector dl
```

B. Vector Distribution of Magnetic Field Intensity

1) Matlab Codes:

Similarly, the contribution of current segments on the current ring to the magnetic field was superimposed to calculate the magnetic field intensity generated by each current ring in the field domain. Then, the effect generated by the two current rings was superimposed to obtain the distribution of magnetic field intensity in the field domain, and the corresponding graph was drawn. For the sake of simplicity, only the magnetic field distribution in the yz plane is analyzed in this experiment, especially in the regions y=[-2,2], z=[-1,1]. In order to observe the features of the system and y = [2, 2], z = [1, 1] area of the magnetic field distribution, we will coordinate axis region is set to y = [2.5, 2.5], z = [1.5, 1.5]. The code for this section is as follows:

```
NGx=60; NGy=60;
Hy=zeros(60);Hz=zeros(60);H=zeros(60);
for i=1:NGy
    for j=1:NGx
    rx1=0-xc1; ry1=y(j)-yc1; rz1=z(i)-zc1;
    rx2=0-xc2; ry2=y(j)-yc2; rz2=z(i)-zc2;
    r3_1=sqrt(rx1.^2+ry1.^2+rz1.^2).^3;
    r3_2=sqrt(rx2.^2+ry2.^2+rz2.^2).^3;
% Calculate the third power of r
    dlXr_y1=dlz.*rx1-dlx.*rz1;
    dlXr_z1=dlx.*ry1-dly.*rx1;
    dlXr_y2=dlz.*rx2-dlx.*rz2;
    dlXr_z2=dlx.*ry2-dly.*rx2;
% Calculate the Y and Z components of ×dlr, and
    the X component is 0
    Hy(i,j)=sum(C1.*dlXr_y1./r3_1)+sum(C2.*
        dlXr_y2./r3_2);
    Hz(i,j)=sum(C1.*dlXr_z1./r3_1)+sum(C2.*
        dlXr_z2./r3_2);
    H=(Hy.^2+Hz.^2).^0.5;
% Calculate the magnitude of H
    end
end
quiver(y,z,Hy,Hz);
% Draw a magnetic field strength vector
axis([-2.5,2.5,-1.5,1.5]);
hold on;
plot(2,1,'ro',-2,1,'bo',2,-1,'ro',-2,-1,'bo'),
% Plot the standard coil profile
title(["Vector distribution of magnetic field
    intensity ";"(represented by arrow family)
    ";" 12113010"],"fontsize",13);
xlabel('y(m)'),ylabel('z(m)'),
% Modify the figure and label the axes
hold off;
hold on;
line([2,-2],[1,1]);
```

```
line([2 2],[-1 1]);
line([-2 2],[-1 -1]);
line([-2 -2],[1 -1]);
% Draw the boundary of the region y=[-2,2], z
    =[-1,1]
hold off;
```

2) Result and Analysis:

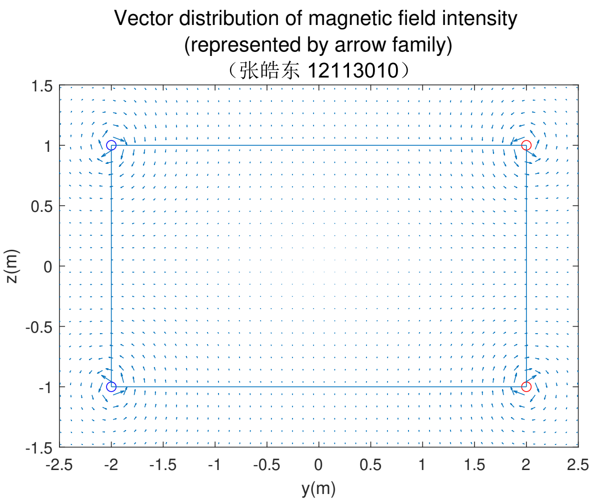

Fig. 6: Vector distribution of magnetic field intensity (represented by arrow family)

As can be seen from Figure 6, the vector distribution of the magnetic field in this case is different from that in case 1. The magnetic field in the area surrounded by the current ring is no longer uniform and in the central position, where the magnetic field is almost zero.

C. Magnetic field intensity distribution

1) Matlab Codes: After calculating the magnetic field intensity H in the field, the distribution of the magnetic field intensity value can be drawn. The code is as follows:

```
figure;
mesh(y,z,H);
%Plot the magnetic field strength
axis([-3,3,-3,3,0,800])
xlabel('y(m)'),ylabel('z(m)'),zlabel('H');
title(["Magnetic field intensity distribution";"
    12113010"],"fontsize",13);
```

2) Result and Analysis: The distribution of magnetic field intensity generated by the two current ring systems can be more clearly seen from Figure 6. It can be seen that the magnetic field intensity near the current ring is significantly greater than the surrounding magnetic field, and the magnetic field intensity decreases rapidly as the distance increases.

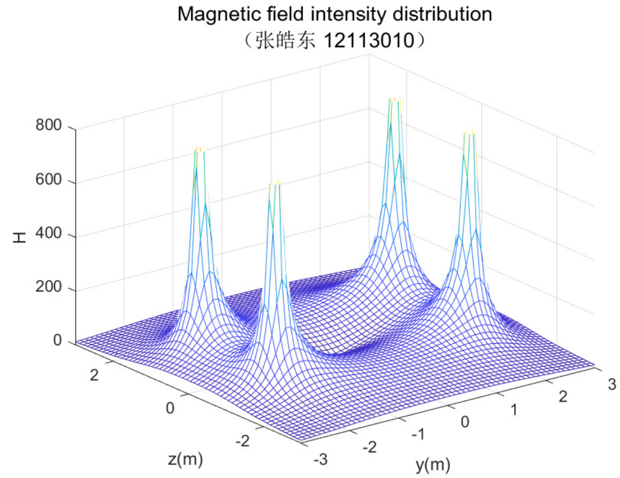

Fig. 7: Magnetic field intensity distribution

D. Magnetic field lines distribution

1) Matlab Codes: Next, in order to observe and analyze the distribution and magnitude of the magnetic field more clearly, we can draw the magnetic field lines. Through the distribution of the magnetic field lines, we can more clearly analyze the size change, distribution, uniformity and other characteristics of the magnetic field. In the code, We take two straight lines passing through two current loops respectively, and take points on the lines as starting points for drawing magnetic force lines. In order to show whether the magnetic field in the middle is uniform or not, we set the interval of taking points in the middle part to be equal interval. In order to make the magnetic field lines near the loops in the diagram not difficult to be dense, we can enlarge the spacing of the points at this point. Then, the streamline() function is used to connect all points in the field with the starting points of the previous construction through the obtained Hy and Hz vector directions, and the magnetic force line distribution of this system can be obtained by the following code:

```
figure;
ys2 = [-3:0.5:-2.5,-2:0.2:2,2.5:0.5:3];
%Set the starting y coordinate of the power line
zs2 = ones(1,25);
%Set the starting z coordinate of the power line
streamline(y,z,Hy,Hz,ys2,zs2);
%Draw lines of magnetic force outward from the
    starting circle
streamline(y,z,-Hy,-Hz,ys2,zs2);
%Draw lines of magnetic force inward from the
    starting circle
streamline(y,z,Hy,Hz,ys2,-zs2);
%Draw lines of magnetic force outward from the
    starting circle
streamline(y,z,-Hy,-Hz,ys2,-zs2);
%Draw lines of magnetic force inward from the
    starting circle
xlabel('y(m)'),ylabel('z(m)');
title(["Magnetic field lines distribution";"
    12113010"],"fontsize",13);
```

2) Result and Analysis: The distribution of magnetic field lines obtained in this case is quite different from that in case 1, because the current direction is opposite, there are not many connections between the two current rings. It can also be seen that the magnetic field lines in the area near the current ring are significantly dense, which means that the magnetic field intensity here increases significantly. In the middle area, it is no longer uniform magnetic field, but very small magnetic field intensity herealmost to zero.

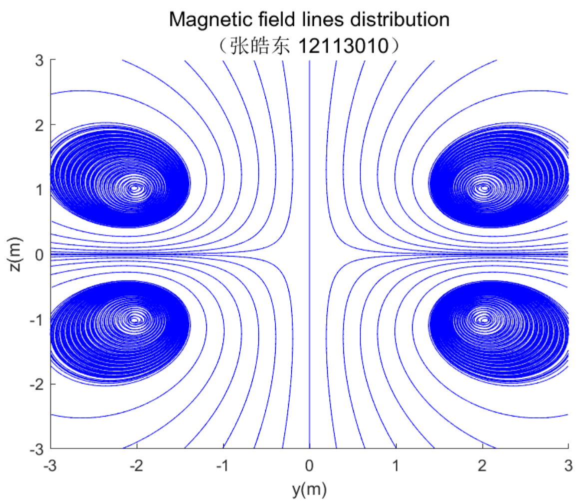

Fig. 8: Magnetic field lines distribution

V. Conclusion and Experience

Therefore, when two parallel current rings are separated by a distance equal to their radii, and the currents in both current rings are in the same direction, the magnetic field in the space between the two current rings will be very evenly distributed. But when the current is in the opposite direction, it will show a completely different phenomenon, and the magnetic field in the middle will no longer be uniform, or even close to zero.

Through this experiment, we have an intuitive understanding and recognition of the magnetic field distribution generated by the system composed of two parallel current rings, and we have learned an important knowledge point is that when the distance between two parallel current rings is equal to their radius, the system formed by the two current rings is usually called Helmholtz coil. A characteristic of Helmholtz coils is that the magnetic field in the space between the two current loops is very evenly distributed. And through the experiment we have an intuitive and profound understanding of this conclusion. When the current is in the opposite direction, this characteristic no longer appears. Through this experiment, we also learned how to use Matlab to calculate and draw the vector distribution of magnetic field, scalar distribution and magnetic field line distribution. In the programming process, we deepened the understanding of theoretical knowledge, but also know a lot of programming details, such as the adjustment of parameters to make the image can better reflect the results we want.

Acknowledgment

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