Axially symmetrical coil model
Laboratory exercise instruction

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1. Aim of the exercise

Goal of the exercise is to prepare, make calculations and analyze axially symmetrical coil using CAE (*Computer Aided Engineering*) software. Task is realized in FEMM 4.2 (*Finite Element Method Magnetics*) - http://www.femm.info/wiki/HomePage.

2. Assumption

Analyze is about magnetic field distribution produced by air coil, located in the open space. Analyzed element is on Pic. 1.
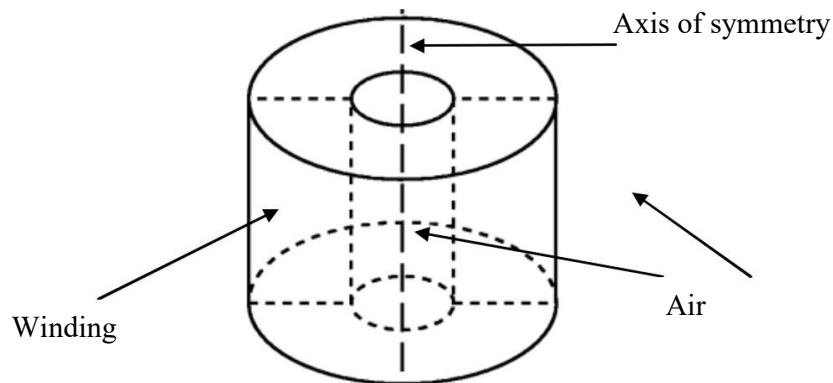
Pic. 1. Air coil

Assumed coil measurements:
- Internal diameter: 20mm
- External diameter: 60mm
- Height: 50mm

Winding: 100 wire 18AWG it is diameter 1 mm (look in attachment).
Value of current: 1.5 A.

3. Construction of the coil model

Coil will be modeled as axially symmetrical. Axis of symmetry is marked on Pic. 1. This will allow the geometry to be drawn for only half of the cross-section.

Issue definition

After starting the FEMM program, select FILE-New or the icon from the menu. In the dialog box, select Magnetics Problem and confirm with OK. A window will appear in which the model in question should be drawn.

The model can be prepared in advance, e.g. with AutoCAD - FEMM allows you to import DXF files.

Because the analysis is carried out for an axial-symmetrical model, select "Problem" from the menu. A dialog box with the settings and parameters is displayed:

- *Problem Type* set as *Axisymetric* – coil geometry will be shown as axially symmetrical. The axis of symmetry is the line with the coordinate r=0.

- *Lenght units set as Milimeters* – the coil dimensions are given in mm, so it is convenient to switch the units to mm (*Lenght units – Milimeters*). The frequency is further defined as follows

- *Frequency* – in exercise assume 0, because the task is solved as a magnetostatic case.

- *Depth* – the depth of the model, i.e. the third, invisible dimension of the drawing, which is not set for the axial-symmetrical model, the default value is 1.

- *Solver Precision* – precision of calculation, default value is 10^{-8}.

- *Min Angle* - the parameter used to construct the finite element grid[1], the default value is 30.

- *AC Solver* – choosing a numerical problem solving method[2], by default *Succ. Approx.* for the iterative method, i.e. the following approximations.

- *Comment* - – a commentary describing the task being performed.

To adopt an axially symmetrical approach, the axis of symmetry of the modelled coil must be the vertical axis of the xy rectangular system..

Definition of the area of analysis

The finite element method used by the program requires the area concerned to be limited. The first task is therefore to limit the analyzed area by drawing its boundaries. The area is also to include the expected magnetic field lines in addition to the coil itself.

The area under consideration should be located in the program window, so the area displayed should be appropriately set in the menu: View/Keyboard. For a considered problem assume:


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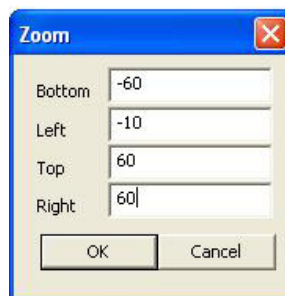
[1] The parameter specifies the minimum angle of triangles forming a finite element grid. The smaller the value, the more accurate the calculation is. In most cases, correct results are obtained for angle 33.8 More complex βroblems may require the parameter to be reduced to less than 20° to ensure that floating point calculations are sufficiently accurate. Values from 1 to 33.8° are accepted.

[2] The method chosen in AC Solver is only relevant for solving problems with AC circuits. In this exercise, the coil is supplied with DC current, so this parameter is irrelevant.

The program window will be resized accordingly. After scaling, one of the values will automatically change depending on the resolution and size of your computer's monitor.

You then define the area that FEMM analyzes. The area is defined by defining its boundary points using the buttons : *Operate on Nodes*:

Operate on Nodes
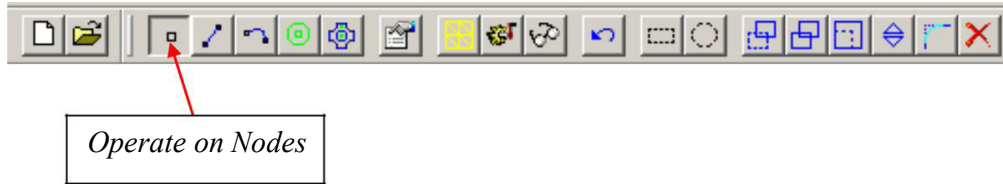
Limit points with coordinates: (0.-50), (0.50), (0.0) shall be placed. You can use the Tab key to enter the coordinates of the points, e.g.:


The axis of symmetry is further defined. Select "Operate on segments", and select previously drawn points with coordinates (0.-50) and (0.50).

Operate on segments

Then select the arc operation: "Operate on arc" and select the points (0.-50) and (0.50). When working on curves, the order in which the points are selected is important.


Operate on arc

A dialog box will then appear allowing you to define the arc parameters. To draw an Arc Angle half-circle, set it to 180. Set the Max Segment parameter to 2.5. The arc is approximated by connecting straight lines. The Max Segment parameter specifies how many degrees the next line is to be drawn. The area of analysis is as follows:
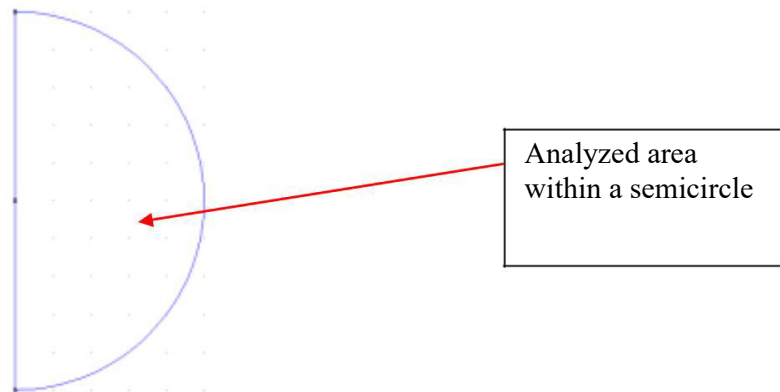
Winding drawing

The program should be switched to node mode. The nodes must be defined in such a way that the distances between them correspond to the cross-sectional dimensions of the coil. Note - only that part of the coil marked on Pic. 2 is drawn.
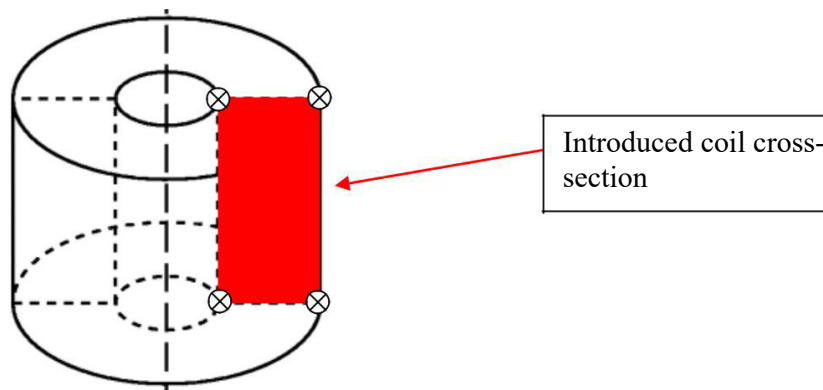
Pic. 2.The coil fragment together with the nodes is introduced in the program.

The coordinates of the knotted points of the coil are as follows: (10, 25), (30, 25), (10, 25) (30, -25) because:

- 50 mm is the height of coil,
- 20 mm is internal diameter,
- 60 mm is external diameter.

The first coordinate is the radius, the second is the height of the coil.

Then switch the program to the straight drawing mode and connect the prepared points to create a rectangle. In this way, a cross-section of the coil winding is obtained..

### *Addition of materials and their allocation to areas*

The next step is to define the material for the areas. In the present case, there are two materials - air and copper. Select the Operate on Labels icon:

Operate on labels

Then indicate two areas - inside the winding cross-section rectangle and outside the coil but inside the semi-circle of the analysis area.

The program uses area names to assign material parameters. In the Properties menu select Materials Library and drag Air and 18AWG from Library Materials to Model Materials - Pic. 3 You can edit the material parameters in Materials Library by double clicking on the material you want to see.
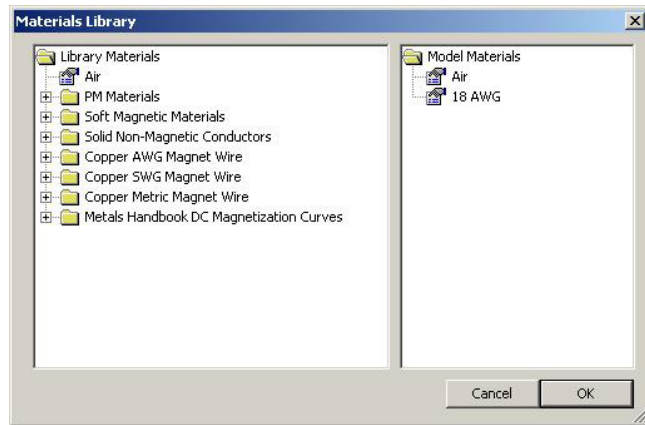
Pic. 3. Materials library window

Select menu: Properties/Circuit. In the dialog box, press the ADD Property button to create the circuit. Enter the name of the winding. Set the Series, which means that all wires in the coil cross-sectional area are connected in series. Enter the assumed value of coil current 1.5 A.

The next step is to assign the drawing areas to the materials and the electrical circuit. Press the right mouse button near the name of the area (color of the area label point changes to red) and then press Space or the icon.

For air, set Block type to Air. Uncheck Let Triangle choose Mesh Size and enter 1 as Mesh size. This parameter defines the largest possible size of the grid element. The grid is made up of equilateral triangles with a side no larger than a defined value. When the Let Triangle choose Mesh Size is selected, the program itself selects the mesh size with as few elements as possible.

In case of winding cross-section - set Block type: 18AWG, In circuit and the number of windings to Number of turns:100.

If the number of windings is positive, the winding direction is counterclockwise and the negative number of windings indicates the winding direction is clockwise[3].

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[3] Clockwise direction when looking at coil from above..

Table 1 shows the keystroke shortcuts available in the FEMM program

Tab. 1. Selected keystroke shortcuts available in the FEMM program

KEY	FUNCTION
Space	Editing the parameters of the selected object
Tab	Displays a dialog where you can define the coordinates of a new point or block.
Escape	Deselects the selected objects
Delete	Deletes the selected objects
Arrows	Move the screen view
Page Up	Enlargement
Page Down	Reduction
Home	Sets the window view so that all entered objects are visible.

4. Calculations

Boundary conditions
From the menu Properties|Boundary select Add Property. Then name the boundary conditions (ABC) and change BC Type to Mixed. The name ABC is an abbreviation of "Asymptotic Boundary Condition" meaning an asymptotic method of solving coastal issues. This condition makes it possible to reproduce the impact of an unlimited external area (even though the analysis itself is carried out in a limited area). For edge condition Mixed4, parameters c0 and c1 must be determined according to:

$$c_0 = \frac{1}{\mu_r \mu_0 R}$$ (1)

$$c_1 = 0$$

where: μ_r – Magnetic transmittance at the edge of the area,

μ_0 – Magnetic permeability of vacuum[5],

R – radius of the semi-circle of the area to be considered (for the case under consideration R = 50 mm, i.e. in the SI unit system R radius=0.05 m).

To assign a boundary condition, switch to drawing arcs, then right-click near the boundary of the area and press Space (or Properties button). Select ABC from the Boundary Cond.

Grid generating
Save the file with the prepared models on your computer and press the grid generator button:
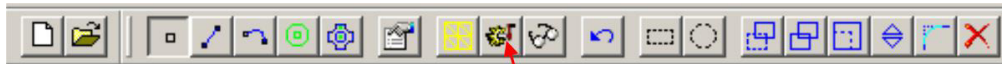

Run mesh generator

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[4] Description in [1] – attachment A.3.2.

[5] $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ H/m

If the grid is too thin / too dense, the parameters of areas, lines and arcs can be edited again.

Calculation start
The calculation can be started by pressing the button:

Run analysis

If the progress of the calculation is not satisfactory, stop it (the calculation for a correctly defined and set problem takes a few seconds). The boundary conditions are likely to have been incorrectly defined.

5. Results analyzes

The results can be analyzed using the button:

View results

Several types of analysis of the results can be carried out:

- Point analysis - button pressed:

  By indicating the appropriate points it is possible to determine the parameters for them, e.g. flux, energy loss, induction. You can enter the coordinates by pressing the Tab key.

- Coil parameters (e.g. inductance, resistance):

- Field distribution along the contour:

Select, for example, points along the axis of symmetry of the coil in the following order: upper, middle, lower to create a line and then press the button:

- Distribution of induction in colour version

6. Exercise plan

1. For the adopted air coil, prepare its model, perform calculations and analyse the results.

2. Place the coil on the iron core. Check how the distribution of the magnetic field and the inductance of the coil change.

   Place an iron ball in the centre line of the coil and determine the force with which the ball is attracted by the coil. Determine the attraction force characteristics as a function of the coil current. Determine the attraction force characteristics as a function of the distance between the ball and the coil.

   Determination of the force with which the ball is attracted requires:

   - check the ball section box by selecting *Operation* → *Area* and Indication of any point inside the ball that will be highlighted in green.,

   - selecting task   *Integrate* →*Force via Weighted Stress Tensor*.

4. Place a permanent magnet in the magnetic field of the coil in the centre line of the symmetry. Check how the distribution of the magnetic field changes. Investigate the distribution of magnetic field for different directions of magnetization.

   Model the actual cylindrical coil in the laboratory and determine the number of coils.

   The coil is wound on a steel core. Pic. 4 shows pictures of the coil and Pic. 5 shows the dimensions of the coil. 0.8 mm copper wire is used for winding the coil. The inductance of the windings was measured in the laboratory at L=9.5 mH.

   Assume current density J=2.5 A/mm2 Assume that the steel core does not protrude beyond the coil contour.

   Determine the winding resistance for the selected number of windings. Calculate the length of wire in meters for winding the coil.
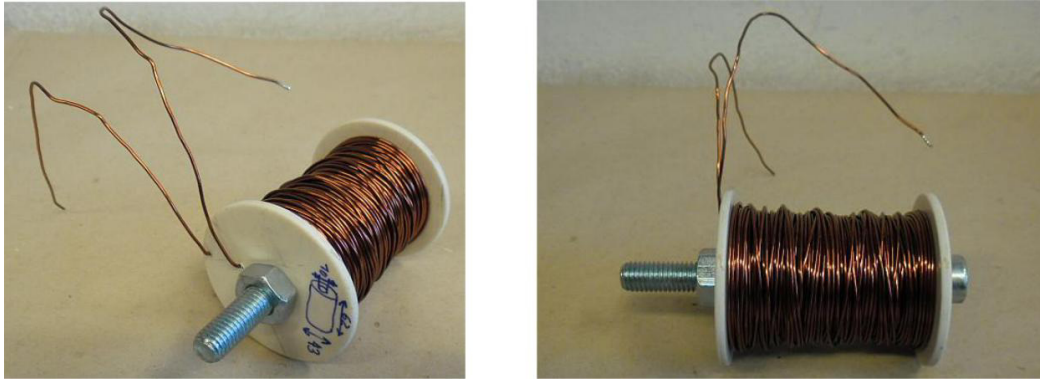
Pic. 4. View of the coil.
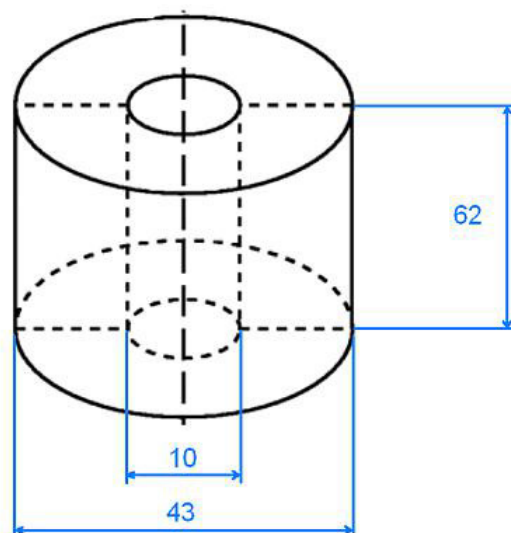
Pic. 5. Dimensions of the coil.

7. Bibliography

1. David Meeker: *FiniteElement Method Magnetics. User's Manual*.

2. David Meeker: *FEMM 4.0 Magnetostatic Tutorial*.

3. Konopiński T., Pac R.: *Transformatory i dławiki elektronicznych urządzeń zasilających*. WNT, Warszawa 1979.

Attachment 1
Determination of wire diameters

Acronym AWG (*American Wire Gauge*) is the designation of an American standard for a series of wire diameters, marked with conventional numbers, used for non-ferrous wires. The conversion of AWG to mm is shown in the table below.

Tabela przeliczeniowa American Wire Gauge (AWG)				Tabela przeliczeniowa American Wire Gauge (AWG)			
Rozmiar AWG	Budowa przewodu	Średnica zewn. [mm]	Przekrój [mm²]	Rozmiar AWG	Budowa przewodu	Średnica zewn. [mm]	Przekrój [mm²]
40	SOLID	0,079	0,005	21	SOLID	0,724	0,412
39	SOLID	0,089	0,006	20	SOLID	0,813	0,514
38	SOLID	0,102	0,008		10/30	0,890	0,504
37	SOLID	0,114	0,010		19/32	0,940	0,612
36	SOLID	0,127	0,013		26/34	0,914	0,520
	7/44	0,153	0,014		41/36	0,914	0,533
35	SOLID	0,142	0,016	19	SOLID	0,912	0,653
34	SOLID	0,160	0,020	18	SOLID	1,020	0,816
	7/42	0,191	0,022		7/26	1,220	0,891
33	SOLID	0,180	0,025		16/30	1,200	0,808
32	SOLID	0,209	0,032		19/30	1,240	0,957
	7/40	0,203	0,034		41/34	1,200	0,819
	19/44	0,229	0,039		65/36	1,200	0,845
31	SOLID	0,226	0,040	17	SOLID	1,150	1,039
30	SOLID	0,255	0,051	16	SOLID	1,290	1,300
	7/38	0,305	0,056		7/24	1,520	1,420
	19/42	0,305	0,060		19/29	1,470	1,216
29	SOLID	0,287	0,064		26/30	1,500	1,310
28	SOLID	0,320	0,080		65/34	1,500	1,300
	7/36	0,381	0,071		105/36	1,500	1,365
	19/40	0,406	0,093	15	SOLID	1,450	1,651
27	SOLID	0,361	0,102	14	SOLID	1,630	2,070
	7/35	0,457	0,111		7/22	1,850	2,260
26	SOLID	0,404	0,127		19/27	1,850	1,930
	7/34	0,483	0,140		41/30	1,850	2,060
	10/36	0,533	0,127		105/34	1,850	2,100
	19/38	0,508	0,153	13	SOLID	1,830	2,630
25	SOLID	0,455	0,163	12	SOLID	2,050	3,290
24	SOLID	0,511	0,203		7/20	2,440	3,610
	7/32	0,610	0,226		19/25	2,360	3,070
	10/34	0,584	0,200		65/30	2,410	3,270
	19/36	0,610	0,239		165/34	2,410	3,300
	41/40	0,584	0,201	11	SOLID	2,300	4,155
23	SOLID	0,574	0,259	10	SOLID	2,600	5,230
22	SOLID	0,643	0,322		37/26	2,920	4,710
	7/30	0,762	0,352		65/28	2,950	5,230
	19/34	0,787	0,380		105/30	2,950	5,355
	26/36	0,762	0,327				

If the construction of the cable is SOLID, it means that it is a wire, and if the Construction of the cable is a number/number designation, it is a multi-core cable - a wire. For example, for 32AWG the value 7/40 means that the cable consists of 7 wires with a diameter of 40AWG, i.e., a wire with a diameter of 1.5AWG and a wire with a diameter of 2.5AWG:

$$7 \times 0.005 \text{ mm}^2 = 0.035 \text{ mm}^2$$

which approximates to a wire cross-sectional area of 32AWG.