T 170 ELEKTRONIKA

Modeling of Magnetic Field created by Coil in 3-D space

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Introduction

The classical fields of physics are governed by partial differential equations. Some exact solutions are available, but not commonly in cases of practical interest. Even when solutions exist, they tend to be complicated and must be evaluated numerically for graphical presentation in digestible form. Finite element analysis (FEA) is a numerical approach in which the field domain under study is divided into a multitude of regions, each giving rise to one or more equations. The main task is to solve all these hundreds of simultaneous equations, which was impracticable before the days of computers.

Some twenty years ago, the choice was between writing one's own programs or abstaining completely from FEA. Today, expert software saves from worrying about programming strategy, formatting, indices and graphics. The tools of FEA are now on anyone's desk, since the average personal computer is adequate for solving a large number of such problems. *ANSYS Emag* (ANSYS Inc.) is one of most popular programs for electromagnetic field modeling. *ANSYS Emag* contains a comprehensive tool set for static, harmonic low-frequency electromagnetic studies, permitting the simulation electrostatic, magnetostatic, electromagnetic, electric circuit and current. The program also can simulate charged-particle tracing in both electrostatic and magnetostatic fields.

The ANSYS program uses Maxwell's equations as the basis for magnetic field analysis [1-3]. The primary unknowns (degrees of freedom) that the finite element solution calculates are either magnetic potentials or flux. Other magnetic field quantities are derived from these degrees of freedom. Depending on the element type and chosen element option, the degrees of freedom (DOFs) may be scalar magnetic potentials, vector magnetic potentials, or edge flux.

The magnetic scalar potential (MSP) formulation is recommended for most 3-D static analysis applications. The scalar approach allows to model current sources as primitives rather than elements; therefore, the current sources do not need to be part of the finite element mesh. The scalar method offers the following: brick, wedge, pyramid, and tetrahedral element geometries; current sources defined by primitives (coils, bars, and arcs); permanent magnets; linear and nonlinear permeability; node coupling and constraint equations. In addition,

modeling of current sources is simpler with the scalar formulation. This is so because you can simply specify current source primitives in the proper locations to account for their magnetic field contribution.

The magnetic vector potential (MVP) formulation is nodal-based method for 3-D static, harmonic, and transient analyses. The MVP formulation has three DOFs per node: AX, AY, AZ, the magnetic vector DOFs in the X, Y, Z directions. Voltage-fed or circuit coupled analysis may add up to three additional DOFs to the magnetic vector DOFs: current, electromotive force drop, and electric potential. The MVP formulation has to be used for a 2-D static magnetic analysis; doing so results in a single magnetic vector potential DOFs, AZ. With the MVP formulation, current sources are modeled as an integral part of the finite element model. However, the MVP formulation runs more slowly than the scalar formulation because of the added DOFs. The MVP formulation can be also used for 3-D static, harmonic or transient magnetic analysis. In this case attention has to be paid when including permeable materials in the model due to a loss of accuracy using the 3-D MVP formulation.

The edge method associates DOFs with element edges rather than element nodes. The method offers 3-D static and dynamic solution capability for low frequency electromagnetics. Edge-based analysis performs more accurately than the nodal-based MVP method in cases where both methods share the same functionality, particularly when models contain iron regions. Edge-based analysis also is more efficient than the MVP method in terms of the active DOFs. The edge formulation is the recommended method for most 3-D harmonic and transient electromagnetic analyses. Edge-based analysis is not available for 2-D models.

General modeling algorithm

Generalized modeling algorithm of magnetic field created by coils with cores and without them is shown in Fig. 1. At first coil and (or) core construction model library is created. This library is created in order to increase modeling performance, e.g. it is possible to use coil of the same construction with different cores. Construction of coil is created using finite element *SOURC36* [4]. Overall construction model is assembled automatically using specific command file (**.lgw*) (Fig. 1). Using this file

creation of model is accelerated, because it is sufficient to point, what coil and what core will be used in model creation, and how to place them in space. Created overall construction model is saved to ANSYS „*All 1 file COMB*" file (Fig. 1). Individual modeling stages are separated using this file type. It is particularly important when performing modeling using command files.
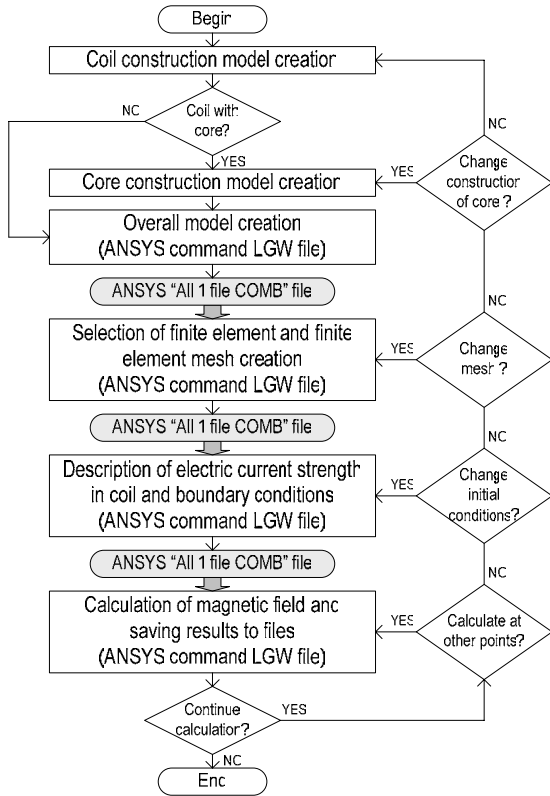

Fig. 1. General coil modeling algorithm

In the next stage finite element mesh is created. In order to create mesh (mesh is not created in coil) finite element *SOLID96* [4] is used, which is designed for magnetic field modeling. Using created command files (Fig. 1) it is possible to change mesh spacing in different zones of model. Created mesh is saved to „*All 1 file COMB*" file. Further electric current strength or electric current density in coil is selected. Also boundary conditions are selected. This information is also saved to „*All 1 file COMB*" file. After performing magnetic field modeling, results are displayed in graphic form and saved to text files.

Coil model creation

As it was mentioned above, coil construction model is created using finite element *SOURC36* [4]. In a 3-D scalar potential analysis, current sources are not modeled as an integral part of the geometry. Instead, "dummy" finite element, *SOURC36*, is used to represent the shape and location of current sources. It is possible to define coils, bars, or arcs at any location in the model. The amount of current and other current-source data are specified as element real constants. The entire current

source has to be modeled even if the rest of the model uses half-symmetry or quarter-symmetry. Coil and arc elements cannot have a zero inside radius. Because *SOURC36* elements are not true finite elements, you can use only direct generation (not solid modeling) to define them.
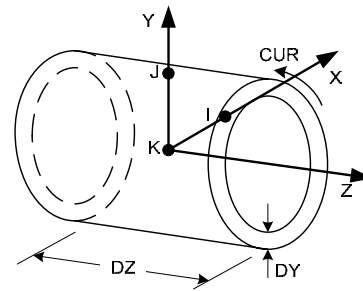

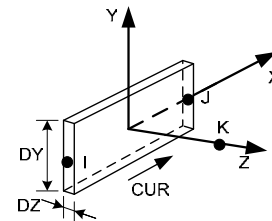**Fig. 2.** Current source element *SOURC36* (type 1 or 4 – coil)

Fig. 3. Current source element *SOURC36* (type 2 – bar)
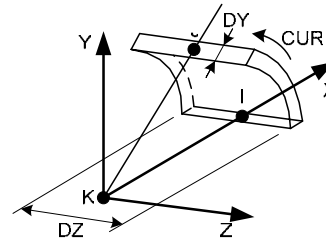

Fig. 4. Current source element *SOURC36* (type 3 or 5 – bar)

SOURC36 is a primitive (consisting of predefined geometries) used to supply current source data to magnetic field problems (Fig. 2-4). The element represents a distribution of current in a model employing a scalar potential formulation. The currents are used to calculate a source magnetic field intensity using a numerical integration technique involving the Biot-Savart law. The magnetic field intensity term is used in the formulation as a magnetic load on the model.

RACE invokes an macro [5] which defines a "racetrack" current source (Fig. 5) in the working plane coordinate system:

RACE, *XC*, *YC*, *RAD*, *TCUR*, *DY*, *DZ*, , , *Cname*

where: *XC* – location of the mid-thickness of the vertical leg along the working plane *x*-axis; *YC* – location of the mid-thickness of the horizontal leg along the working plane *y*-axis; *RAD* – radius of curvature of the mid-thickness of the curves in the racetrack source; *TCUR* – total current, ampere turns, flowing in the source; *DY* – in-plane thickness of the racetrack source; *DZ* – out-of-plane thickness (depth) of the racetrack source; *Cname* – a name assigned as a component name to the group of *SOURC36* elements created by the command macro.
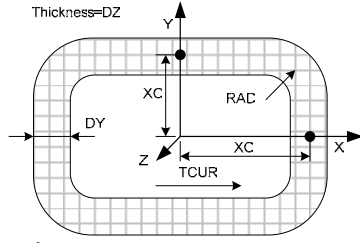
Fig. 5. Racetrack current source

The macro is valid for use in 3-D magnetic field analysis using a scalar potential formulation. Current flows in a counter-clockwise direction with respect to the working plane.

Finite element mesh creation

Mesh is created in all regions of model except coil using finite element *SOLID96*. 3-D magnetic scalar solid finite element *SOLID96* has the capability of modeling 3-D magnetic fields. Scalar potential formulation is available for modeling magnetic fields in a static analysis. The geometry, node locations, and the coordinate system for this element are shown in Fig. 6. The element is defined by eight nodes and the material properties. A tetrahedral-shaped element may be formed by defining the same node numbers for nodes *M, N, O, P* and nodes *K, L*. A wedge-shaped element and a pyramid-shaped element may also be formed as shown in Fig. 6. Shape function for *SOLID96* is:

$$\varphi = \frac{1}{8}\big(\varphi_I(1-s)(1-t)(1-r)+\varphi_J(1+s)(1-t)(1-r)+$$
$$+\varphi_K(1+s)(1+t)(1-r)+\varphi_L(1-s)(1+t)(1-r)+$$
$$+\varphi_M(1-s)(1-t)(1+r)+\varphi_N(1+s)(1-t)(1+r)+$$
$$+\varphi_O(1+s)(1+t)(1+r)+\varphi_P(1-s)(1+t)(1+r)\big). \quad (1)$$

The standard 3-D integration formulas which are used in the element library are of the form:

$$\int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} f(x,y,z)dxdydz =$$
$$= \sum_{k=1}^{n}\sum_{j=1}^{m}\sum_{i=1}^{l} H_k H_j H_i f(x_i, y_j, z_k); \quad (2)$$

where: $f(x,y,z)$ – function to be integrated; H_k, H_j, H_i – weighting factor; x_i, y_j, z_k – locations to evaluate function (these locations are usually the s, t, r coordinates); n, m, l – numbers of integration points (Fig. 7).

The finite element matrix equations can be derived by variational principles. These equations exist for linear and nonlinear material behavior as well as static and transient response. Based on the presence of linear or nonlinear materials, the program chooses the appropriate Newton-Raphson method. The scalar potential formulations are restricted to static field analysis with partial orthotropic nonlinear permeability. The DOFs, element matrices, and load vectors are presented here in the following form:

$$\big[K^m\big]=\big[K^L\big]\big[K^N\big]; \quad (3)$$

$$\big[K^L\big]=\int_{vol}\left(\nabla\vec{N}^T\right)^T\left[\mu\right]\left(\nabla\vec{N}^T\right)d(vol); \quad (4)$$

$$\big[K^N\big]=\int_{vol}\frac{\partial\mu_h}{\partial|H|}\left(\vec{H}^T\nabla\vec{N}^T\right)^T\left(\vec{H}^T\nabla\vec{N}^T\right)\frac{d(vol)}{|H|}; \quad (5)$$

$$\big[J_i\big]=\int_{vol}\left(\nabla\vec{N}^T\right)^T\left[\mu\right]\big(|H_g|+|H_c|\big)d(vol); \quad (6)$$

where: $\vec{N}$ – element shape functions ($\varphi=\vec{N}^T\vec{\varphi_e}$), $\vec{\varphi_e}$ – magnetic scalar potentials at nodes of element; ∇T – gradient operator, vol – volume of the element, $\vec{H_g}$ – preliminary or "guess" magnetic field, $\vec{H_c}$ – coercive force vector, $[\mu]$ – permeability matrix, $d\mu_h/d|H|$ – derivative of permeability with respect to magnitude of magnetic field intensity.
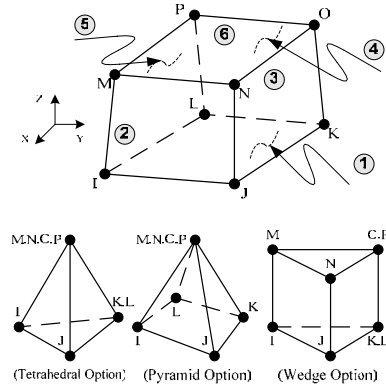

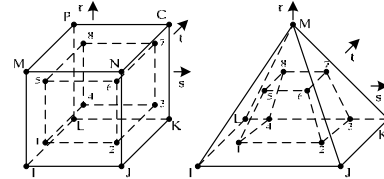**Fig. 6.** 3-D magnetic scalar solid finite element *SOLID96*

Fig. 7. Integration point locations for bricks and pyramids

Magnetic field modeling

The basic electromagnetic field results include magnetic field intensity, magnetic flux density, magnetic forces and current densities. The first derived result is the magnetic field intensity which is divided into two parts a generalized field $\vec{H_g}$ and the gradient of the generalized potential – $\nabla\varphi_g$. This gradient (referred to here as $\vec{H_\varphi}$) is evaluated at the integration points (Fig. 7) using the element shape function as:

$$\vec{H_\varphi}=-\nabla\vec{N}^T\vec{\varphi_g}; \quad (7)$$

where: ∇T – gradient operator; $\vec{N}$ – element shape functions; $\vec{\varphi_g}$ – nodal generalized potential vector.

The magnetic field intensity is then:

$$\vec{H}=\vec{H_g}+\vec{H_\varphi}. \quad (8)$$

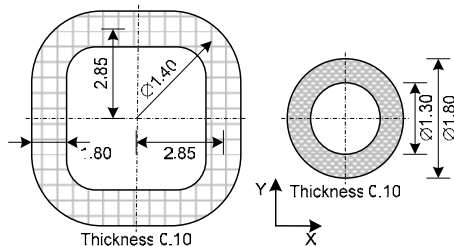Nodal values of field intensity and flux density are computed from the integration points values.

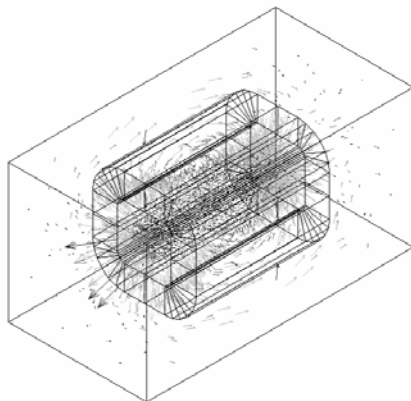**Fig. 8.** Parameters of coil and core

Fig. 9. Distribution of magnetic field

Further modeling example of magnetic field created by coil with core is presented. Construction model is formed using created algorithm and pre-made command files. Parameters of construction model are shown in Fig. 8. Number of coil turns n=500, current per turn i=6. Values and distribution of calculated magnetic field strength are shown in Fig. 9.

Conclusions

MSP formulation is most suitable to model magnetic field created by coils with or without cores in 3-D space. The scalar approach allows you to model current sources as primitives rather than elements; therefore, the current sources do not need to be part of the finite element mesh; this factor accelerates modeling process.

Created modeling algorithm allows to model different construction coils with or without cores. Library of various construction coils and cores was created.

Individual modeling stages (construction model creation, finite element mesh creation, etc.) are separated in this algorithm using „*All 1 file COMB*" files. Thus it is possible to repeat magnetic field calculation, beginning with any stage, for example, it is possible to select different values of electric current strength and calculate magnetic field strength for several times using „*All 1 file COMB*" created after mesh formation.

Created command files (for overall model creation, finite element mesh creation, selection of boundary conditions, magnetic field calculation) enables automation of modeling process.

References

1. **Tarvydas P.** Ritės sukuriamo magnetinio lauko modeliavimas baigtinių elementų metodu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2001. – Nr. 1(30). – P.33-36.
2. **Theory** Reference: http://www.ansys.com/
3. **Electromagnetic** Field Analysis Guide: http://www.ansys.com/
4. **ANSYS** Element Reference: http://www.ansys.com/
5. **ANSYS** Commands Reference: http://www.ansys.com/

P. Tarvydas, E. Pačėsaitė, A. Noreika. Ritės sukuriamo magnetinio lauko modeliavimas erdvėje // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2004. – Nr.7(56). – P.29-32.

Nagrinėjamas ričių su šerdimis ir be jų erdvėje sukuriamų magnetinių laukų modeliavimas baigtinių elementų metodu. Pateikiamas sudarytas apibendrintas modeliavimo algoritmas ir pasiūlyta magnetinių laukų modeliavimo erdvėje metodika. Nagrinėjami ričių ir šerdžių konstrukcijų bei jų bibliotekų sudarymo klausimai. Analizuojamas įvairių tipų baigtinių elementų taikymas ričių konstrukcijų modeliams sudaryti ir šerdims bei kitoms modelio sritims aprašyti. Aptariami baigtinių elementų tinklelio sudarymo klausimai. Pateikiamas ritės su šerdimi sukuriamo magnetinio lauko modeliavimo pavyzdys. Il.9, bibl.5 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

P. Tarvydas, E. Pačėsaitė, A. Noreika. Coil Magnetic Field Modeling in 3-D Space // Electronics and Electrical Engineering.-Kaunas: Technologija, 2004. – No.7(56). – P.29-32.

Problem of modeling of magnetic field created by coils with or without cores in 3-D space using finite element method is investigated. Created overall modeling algorithm is presented and magnetic field modeling method in 3-D space was proposed. Problems of coil and core construction library creation are investigated. Questions concerning application of different type finite elements in creation of coil construction models and description of core and other regions of model are analyzed. Finite element mesh creation is discussed. Example of modeling of magnetic field created by coil with core is presented. Ill.9, bibl.5 (in English; summaries in Lithuanian, English and Russian).

П. Тарвидас, Э. Пачесайте, А. Норейка. Моделирование магнитного поля, создаваемого катушками в пространстве // Электроника и электротехника. – Каунас: Технология, 2004. – № 7(56). - C.29-32.

Изучаются вопросы моделирования магнитных полей, создаваемых в пространстве катушками с сердечниками и без них, методом конечных элементов. Предоставлен составленный обобщенный алгоритм моделирования и предлагается методика моделирования магнитных полей в пространстве. Изучаются конструкции катушек и сердечников, а также вопросы создания их библиотек. Анализируются вопросы по применению разных видов конечных элементов для создания моделей конструкций катушек и по описанию сердечников и других областей модели. Обсуждаются вопросы составления сети конечных элементов. Предоставлен пример моделирования магнитного поля, создаваемого катушкой с сердечником. Ил.9, библ.5 (на английском языке; рефераты на литовском, английском и русском яз.).