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Utilization of open-source FEM software in modeling of magnetic field distribution around unusually shaped conductor

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Abstract— The modeling of the magnetic field distribution is required in many engineering research applications. It is crucial in simulation of transformers properties, as well as in achieving electromagnetic compatibility. Analytical solutions are suitable only in special or idealized cases. Another, more general approach is based on finite element method. Basing on FEM, approximate solutions of most cases could be calculated in acceptable time. On the other hand, many FEM softwares have significant limits on the geometry of input model of simulated elements. The following paper presents partial solution of this problem, as well as exemplary results of simulations.

Index Terms—ElmerFEM, Finite Element Method, Magnetic Field Distribution, Magnetic Field Modeling, Maxwell Equations, Netgen, Whitney Elements

1 Introduction

THE modeling of magnetic field with utilization of finite element method is common alternative for analytical solutions. It provides approximately accurate results and is suitable not only for idealized or special cases. In general it is based on discretization of partial differential equations which define physical phenomena (ie. Maxwell equations in electromagnetism or Navier – Stokes equations in fluid mechanics). Modeled continuous object is divided into smaller parts, with constant values of viariables in volumes.
Many softwares for finite element method calculations provide results only for very simple geometry. Those problems does not occure in the newly developed open source FEM software – ElmerFEM. Paper presents a method of calculating electromagnetic fields around unusually shaped element.

2 Modeling Methodology

Utilized method of modelling of magnetic field distribution around curved conductor utilizes Netgen 5.3 and ElmerFEM software. Both programs are open-source, free and with wide compatibility with popular OS (MS Windows, most Linux distibutions). Also ElmerFEM is customizable and leaves end-user opportunity for writing own solvers for specialized FEM calculations.

2.1 Mesh generation

Geometrical model of curved wire was created with utilization of unstandrard primitives available in Netgen software [3]. In order to calculate a distribution of magnetic flux around the conductor, model was placed inside a sphere. Also external surface of the sphere was used in order to apply proper boundary condition [2] for finite elment method calculations.

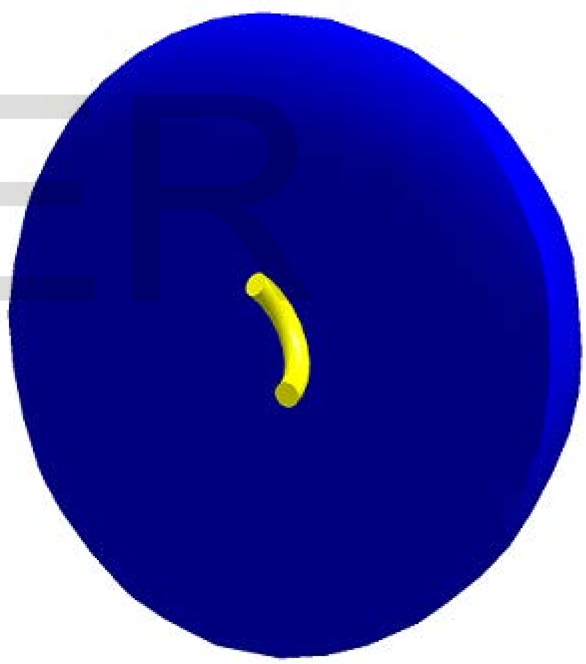

Fig. 1 Model of simulated conductor (yellow) placed inside sphere (blue).

Created model was meshed with utilization of Delaunay algorithm [6] by Netgen] software. Created mesh contained 653426 first order finite elements creating wire and 1181483 first order elements creating sphere around the wire. View of declared boundaries of model is presented on figure 1 and figure 2 present meshed model. Significantly higher density of nodes in wire is clearly visible. Due to small size of single finite element highly homogenous mesh is obtained all along the model.

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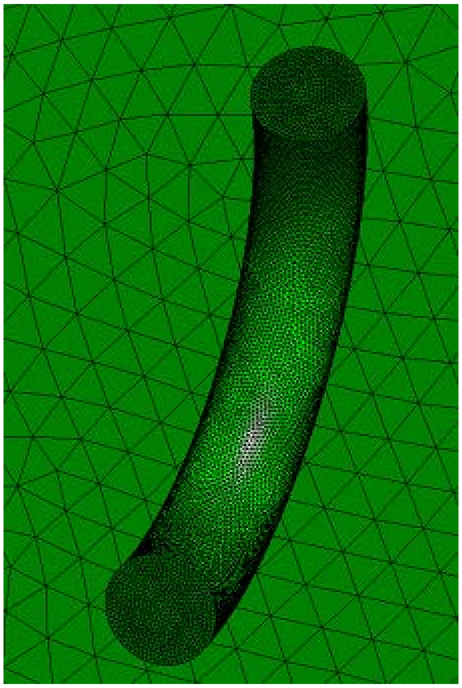

Fig.2 The view of meshed model of curved conductor.

2.2 Finite element method calculations

Simulation is conducted with utilization of Elmer FEM software. Described simulation due to software limits requires two separate solvers. Firstly static current solver is utilized to calculate current flow in the modeled conductor caused by pre determined potentian difference on the edges.

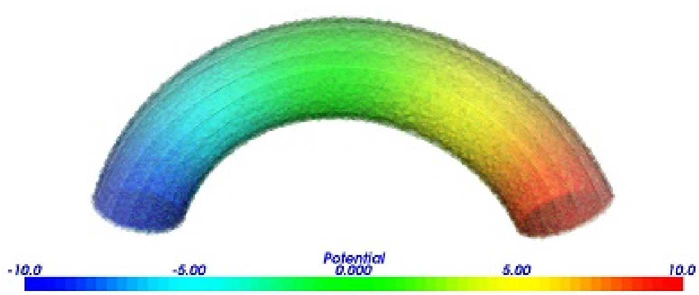

Fig.3 Distribution of electric potential along the conductor

Utilized finite element method solver is suitable for calculating electrostatic potential in conducting medium. As a result information about volume currents is obtained as well as power loss caused by Joule heating. Solver utilizes approximation of Maxwell's equations for electrostatic (1) (2) and (3).

$$\nabla \cdot \vec{D} = \rho \quad (1)$$

$$\nabla \times \vec{E} \simeq 0 \quad (2)$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad (3)$$

Based on that electric field can ben defined as an scalar of electric potential (4) and basing on (1) and (3) one can obtain continuity equation for electric charges (5)

$$\vec{E} = -\nabla \phi. \quad (4)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \vec{J} = 0. \quad (5)$$

In order to calculate current in conductor Ohm's law is applied (6). Applying (4) and (6) to (5) results with final Poisson equation utilized for calculating the electric potenctial (7).

$$\vec{J} = \sigma \vec{E} \quad (6)$$

$$\nabla \cdot \sigma \nabla \phi = \frac{\partial \rho}{\partial t} \quad (7)$$

As a result both volume currents in nodes can be calculated (8) as well as density of Joule heting in node (9). In order to calculate total loss in conductor one should integrate (9) over interested volume.

$$\vec{J} = -\sigma \nabla \phi. \quad (8)$$

$$\nabla \cdot \sigma \nabla \phi = \frac{\partial \rho}{\partial t} \quad (9)$$

Figure 3 presents the distribution of electric potential calculated with (7) and figure 4 presents vectors of current flow in modeled inductor. In simulation constant conductivity was applied to material but in Elmer FEM one can create function describing required changes in all parameters [1],[2],[4] as a MATC function. Figure 5 presents density of volume current along the cross section of modeled element. One can see, that because of element shape density of volume current is not homogenous. This caused by lowest resistance of current path and also confirms proper implementation of finite element method solver.

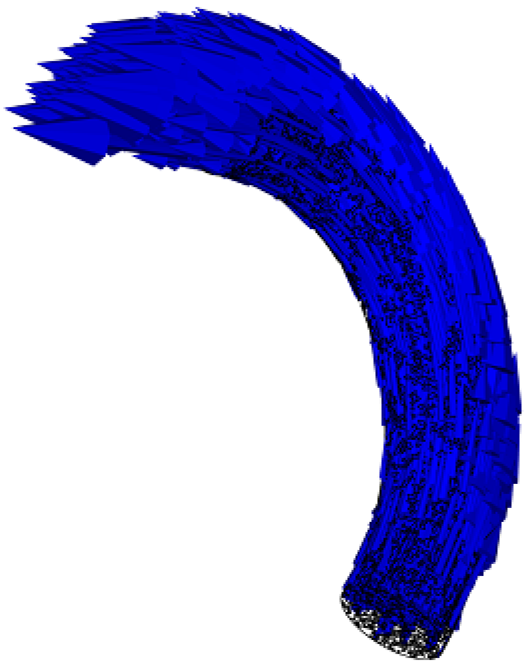

Fig.4 Vectors of current in conductor

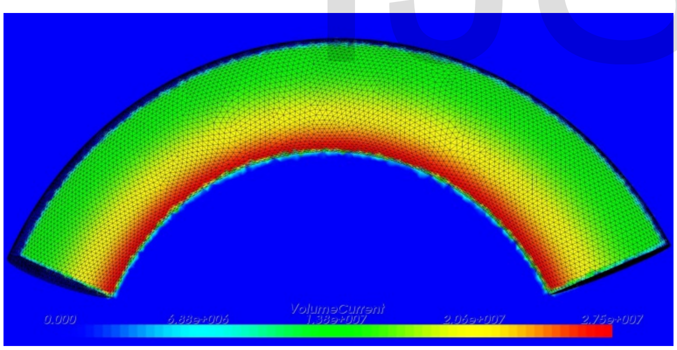

Fig. 5 View of volume current density along the cross section of modeled wire

After proper execution of static current solver, current density values, caused by potential difference on the conductor edges, the distribution, are prescribed as a body force for magnetic solver. This solver utilizes Maxwell equations and calculates vector of magnetic potential by discretization of low order Whitney edge elements [4],[5] Scalar values of potential are calculated by Lagrange interpolation. Due to utilization of edge Whitney edge elements solver is suitable only for three dimensionals problems.
Solver is based on magnetostatic Maxwell equations which describe the dependencies between magnetic and electric field and also the properties of the magnetic field (10). Other equations utilized in solver are Gauss's law (11) and Faraday's law (12).

$$-\sigma\vec{E} + \nabla \times \left(\frac{1}{\mu}\vec{B}\right) = \vec{g}, \tag{10}$$

$$\nabla \cdot \vec{B} = 0, \quad \text{with } \vec{B} = \nabla \times \vec{A}, \tag{11}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{12}$$

As mentioned before current density obtained from static current solver was prescribed. Based on (10), (11) and (12) distribution of magnetic flux around the conductor was calculated. Figure 6 presents the view on the top of the simulated conductor. Distribution of vectors of magnetic flux confirms proper implementation of Faraday's law with clearly visible results of right –hand rule. Solver

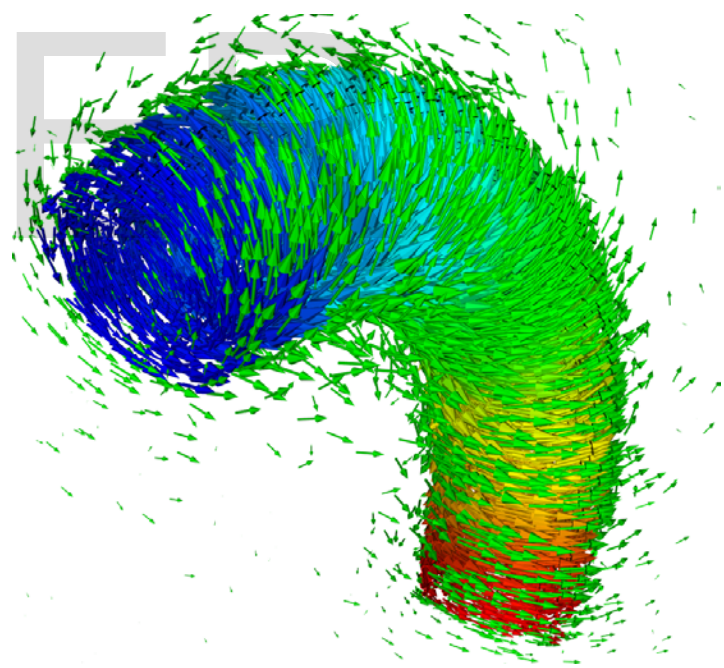

Fig.6 Wiew on the vectors of magnetic flux density around wire (green) in potential function (from blue to red)

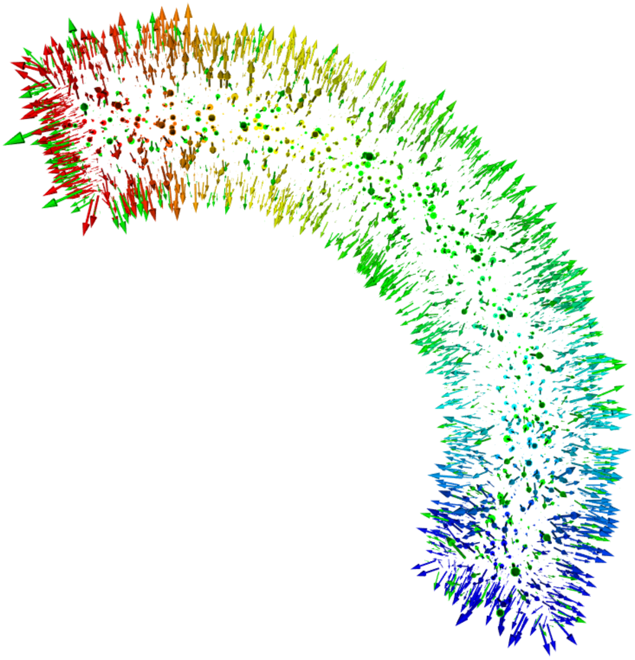

Fig.7 Wiew on the vectors of electric field around the modeled wire

3 Coclusion

In paper method of simulating magnetic flux around unusualy shaped conductor was presented.Desribed solution is based on two step calulations utilizgm finite element method. Firstly static current solver computes current density in conductor. Proper computation is confirmed by expected potential variation across the model, proper direction of current vectors and distribution of volume current density in curved conductor. Afterwards computed current is prescribed as a body force for magnetic solver. This solver utilizes Whitney edge elements in order to calculate the distribution of magnetic flux and electric field around the conductor. Proper and reliable calculations are confirmed by direction of vectors of those fields.

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