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Fluxgate sensor modeling

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Abstract. The paper presents a finite element analysis to build the fluxgate model using the COMSOL Multiphysics environment. COMSOL Multiphysics is a powerful interactive environment for modeling and solving all kinds of scientific and engineering problems. Recommendations are given to the optimization of the element geometry and settings of materials and the finite element mesh. Specific configure settings are described for the built-in Physics Interfaces and the solver.

1. Introduction

Welding of steel pipes and structures is often accompanied by the magnetic blowout effect induced by residual magnetism. This phenomenon leads to the instability of the welding process, metal scattering, and the formation of such defects in a welded joint as pores, faulty fusion and penetration, slag inclusions, and others. Sometimes, welding is impossible due to the blow-out or electrode sticking [1–5]. The main cause of the pipeline residual magnetism is the use of magnetic-field flow detectors for inspecting mechanical conditions of pipelines.

The additional contributing factors to the pipeline residual magnetism are geomagnetic field, elastic mechanical stresses, processing pipe magnetism, and extremely close transmission cables. As the pipe magnetism does not allow to obtain a good quality welded joint, their demagnetization prior to welding is a necessary technological procedure. Since a complete demagnetization cannot be achieved, welding is allowed therefore to be performed at a weak residual magnetism which does not substantially affect the welding process.

The residual pipe magnetism is measured with magnetometers comprising a magnetic field sensor and an electronics module. A magnetic field sensor is the main element of any magnetometer and intended for the transformation of the magnetic flux density in electric signal, usually, the voltage. In the design of magnetic field sensors, various physical effects such, for example, as Hall effect, Gauss effect, Suhl effect and others are used. Fluxgate sensors and magnetometers are the most preferable devices for measuring residual pipe magnetism. Also fluxgate sensors are widely used in space and geophysical explorations [6–9], navigation, attitude and stabilizing control systems together with gyro and accelerometer [10—12], magnetic resonance imaging, brain imaging etc.

However, a mathematical calculation of the fluxgate, and evaluation of its sensitivity is rather a complicated problem because a fluxgate is a non-linear transducer comprising a ferro-magnetic core [13–14]. It is advisable to involve computer simulation facilities in the fluxgate design. The aim of this paper is to present the finite element analysis to build the fluxgate model using the COMSOL Multiphysics environment.

2. Fluxgate geometry

A differential fluxgate configuration is the most widespread configuration used in the magnetic field measurements. A schematic view of the differential fluxgate is given in Figure 1. This schematic will be used to build the fluxgate model.

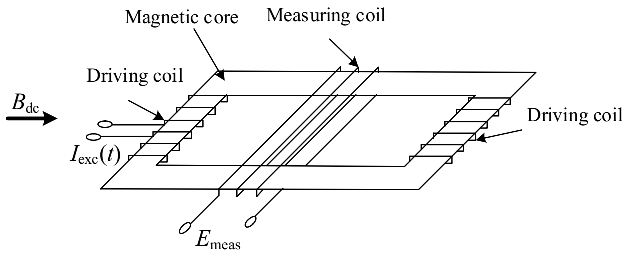

Figure 1. Schematic of differential fluxgate.

The fluxgate modeling in COMSOL Multiphysics begins with the description of its physical shape. In most cases, the main requirement for the fluxgate geometry is to deliver its real dimensions to the computer model as accurately as possible, including necessary assumptions. Thus, sharp edges and corners of diverse model elements must be rounded. This helps to avoid the emergence of extremely tensed areas with a high concentration of magnetic field lines (fringing effect) as illustrated in Figure 2. Owing to this avoidance, a better convergence is achieved when solving the problem of the fluxgate modeling. When modeling non-cylindrical inductance coils, buckling of the conductor must be rounded also. These manipulations are activated with the Fillet operator, which considerably facilitates the formation of turns with the Coil Geometry Analysis setting parameter.

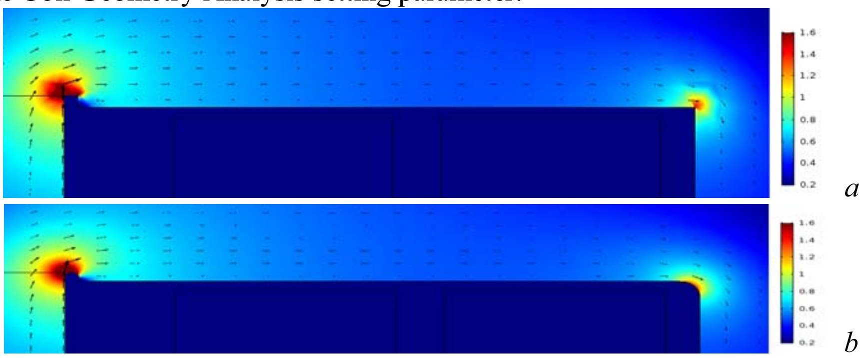

Figure 2. Fillet creation at a corner and magnetic flux density distribution in the fluxgate: *a* – without filleting; *b* – with filleting.

The model of the fluxgate geometry is depicted in Figure 3.

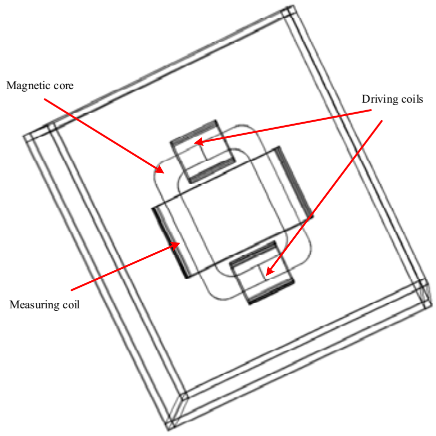

Figure 3. Fluxgate geometry.

3. Built-in materials settings

The material of the core is the essential parameter in the interaction with the magnetic field. Depending on a problem to be solved, the magnetic material can be either soft or hard. The main difference between these materials is the magnetization curve which is the dependence between the magnetic flux density and the field intensity. In COMSOL Multiphysics, HB Curve allows the use of a curve that relates magnetic flux density B and the magnetic field

H. Despite a broad range of built-in materials, COMSOL Multiphysics may not provide the required material, so a user has to modify one of the predefined materials or define a completely new material. The properties of the required material are often known well in advance. Also worth highlighting is the fact that the creation of a new material is accompanied by the indication of a great number of magnetization curve points. The accuracy of solutions will depend on this indication as well as repeatability of ferro-magnetic core properties at a multiple remagnetization. If a user possesses only the approximate data on the material properties, COMSOL Multiphysics offers the Interpolation commands for the diagram description. A linear interpolation allows a user to rather appropriately describe the magnetization curve. As for a cubic interpolation, it provides the magnetization curve with a greater smoothness and, as a consequence, a uniform flux density with the growing field intensity. The curve extrapolation should be linear.

A computation of magnetic fields implies the presence of the airspace. Usually, a coil is in the air. The predefined air material should be additionally modified. The electrical conductivity of the air should be different from zero. This is rather important for the convergence achievement when solving the problem of the fluxgate modeling, since it will not be tackled until the default value of zero for the electrical conductivity of the air is not changed. A real value of the electrical conductivity of the air is about 10–15 S/m. So, it is suffice to set this value between 10^{-4}–10^{-2} S/m. It is worth noting that with increasing value of the electric field, the electrical conductivity will play an ever greater role in the process of modeling.

4. Predefined physics interface variables

Physical processes which relate to measurements of changes in the magnetic field and the direction of the flux density in materials, can be described by the Magnetic Field physics interface. By default, the Physics Interfaces are provided with the discretization of quadratic forms, which require a significant amount of the random access and read-only memories (not less than 16 GB). Therefore, it is advisable to select the discretization of linear forms.

The dependence between the magnetic flux density and the field intensity in the ferro-magnetic core is described by the Ampère's Law feature. For this, we select the HB Curve in Constitutive Relations settings. The magnetic field is created by the coils in which the current flows. The coil properties, the number of turns and the current direction in the coil are described by the Magnetic Fields interface coil features. For solving the non-linear problem, it is important to use the additional calibration of the vector potential of the magnetic field. In the case of the symmetrical finite element model (FEM), its building can be facilitated by its splitting, for example into eight parts. Then, such features as the Perfect Magnetic Conductor and Magnetic Insulation should be additionally applied for the magnetic field. The Magnetic Insulation feature does not allow the magnetic field lines to pass and directs them parallel to the symmetry plane. On the contrary, the Perfect Magnetic Conductor feature allows both the magnetic flux and lines to pass perfectly normal to the symmetry plane.

5. Meshing

Mashing is another important step in the solution of the problem relating to the fluxgate modeling. Due to the fact that the fluxgate is driven by the variable magnetic field, the skin effect is rather essential for the process of modeling. It must be considered in the FE model as early as at 10 kHz frequency. For this, it is necessary to introduce the additional boundary layers in the mesh as depicted in Figure 4. The addition is provided by a click the Boundary Layers node.

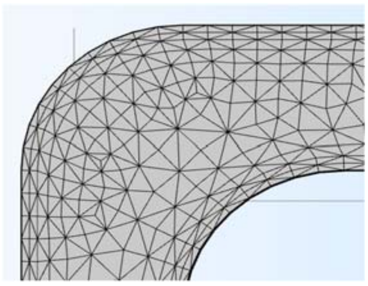

Figure 4. Finite element mesh for ferro-magnetic core. Two boundary layers are added.

For the best symmetry, the FEM should be split into several similar elements. The mesh is then created for one of these element and copied for other ones. This technique allows us to gain the similar size of the finite elements for each side of the symmetry plane. Also, it allows avoiding errors caused by a non-uniform mesh generation inside the element during the automatic meshing. FEM of the fluxgate coils should consider the skin effect and prescribe the mesh accurately enough to generate the coil model without breaks. As a result, the geometry of turns is more precise and the convergence is achieved when solving the problem of the fluxgate modeling. For example, Figure 5 presents the FEM of the fluxgate measuring coil.

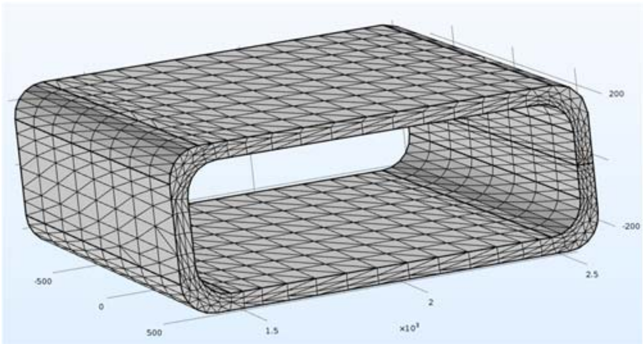

Figure 5. FEM of fluxgate measuring coil.

Figure 6 presents the FEM of the fluxgate with the predefined mesh.

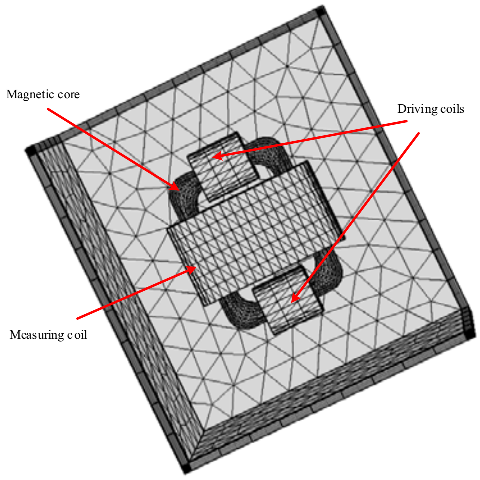

Figure 6. FEM of the fluxgate.

6. Studies and solver settings

COMSOL Multiphysics lets a user to tune solver settings. Our problem is a time-dependent, and its solution includes three steps, namely the Geometry Modeling, and the selection of a Stationary and a Time-Dependent solver. At the first step of the geometry modeling, we analyze both the drive and measuring coils. The second step implies the solution of the stationary problem in the absence of the variable drive field, and the third step includes a modeling of the fluxgate operation at the alternating current of the prescribed amplitude and frequency. In order to improve the convergence of the problem solution, the type of the linear solver should be changed from the iterative to direct. The direct solver is used for modeling the magnetic field. The Jacobian update operator is to be set on Every Iteration. We select the Constant

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(Newton) Iteration for the non-linear method. The maximum number of iterations should not be less than 25. The accuracy class is selected depending on the required accuracy of the study. The Time Stepping option is either selected as BDF Free by default or changed by the Generalized Alpha Strict option, which is more stable.

The direct solver PARDISO is chosen for modeling. The time stepping and the modeling step are selected such that to achieve a satisfactory data display on the studied frequencies, i.e. each signal period should be minimum 100 samples per period.

As a result of calculations, COMSOL Multiphysics builds up the diagram for the flux density distribution. The obtained diagram can be supplemented with arrows which indicate the direction of the magnetic flux density and induced currents. The resulting model of the fluxgate is presented in Figure 7. Figure 8 shows the output signal of the measuring coil obtained during measuring the residual magnetism which equals 10 μT.

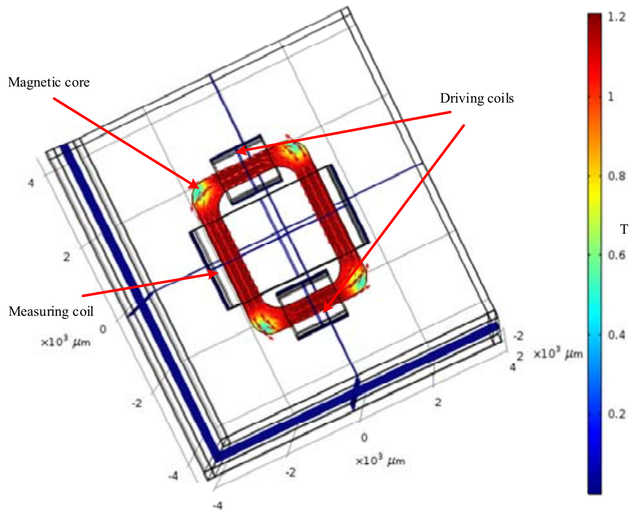

Figure 7. Resulting fluxgate model in COMSOL Multiphysics.

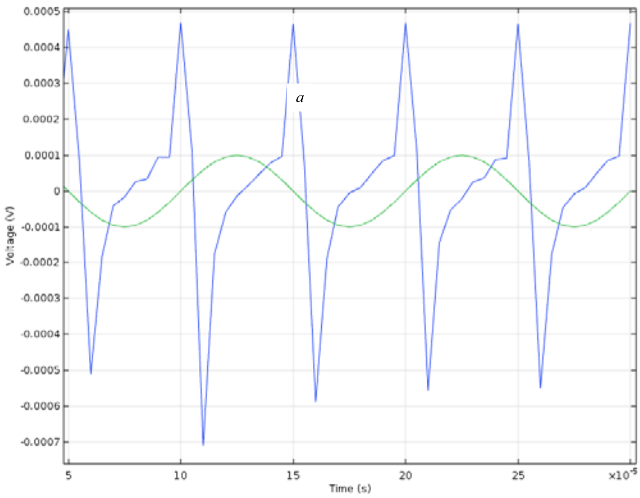

Figure 8. Output signal (a) of the measuring coil obtained during measuring the residual magnetism.

7. Conclusions

A study of non-linear systems, including magnetic systems, is rather complicated from the viewpoint of both modeling settings and the availability of a serious computational power. Nevertheless, the opportunity of modeling magnetic systems in the COMSOL Multiphysics environment allowed us to considerably reduce the labour and time costs and also predict the properties of the object under study. The presented finite element analysis for building the fluxgate model with the COMSOL Multiphysics environment can be recommended for the selection of electrical modes of the fluxgate operation, optimization of the structure and the core material in order to increase the measurement accuracy and upranging.

Acknowledgments

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