Simulation of Flaw Signals in a Magnetic Flux Leakage Inspection Procedure

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Abstract: In the inspection of steel products with respect to flaws a magnetic flux leakage (MFL) test procedure can be applied. In this procedure a "horseshoe" shaped yoke is used, whose legs are wrapped with coils through which an alternate current with a high frequency (3 kHz) is flowing. Hereby, a thin magnetic field (~0.46 mm, skin effect) is induced near the surface of the test object which leaks from the material if a discontinuity (e.g. a flaw) is present. This leakage is measured by a hall probe. The aim of the simulation is to find out how different flaw geometries and orientations influence the measured signal. We confine our work basically to block-shaped flaws (notches). In a first step, we simulated a 2D-cross-section and varied width, depth and orientation of the notch. In a second step, 3D-simulations were performed. Here the necessity to adequately resolve the very thin magnetic field led to an excessive amount of nodes. The computation on a fully meshed geometry was only possible with a swept mesh and the use of symmetries. With the so called impedance boundary conditions we could avoid meshing the steel domain which saved a lot of nodes. Hereby, the complete 3D-model could be simulated and arbitrary notches could be modelled. Different geometries and orientations of the flaws were automatically generated using Matlab scripts. As a result, the influence of different notch geometries or orientations and a comparison to real measured data is shown.

Keywords: Magnetic Flux Leakage, steel inspection, skin-effect

1. Introduction

In the processing of steel products, several types of flaws can occur, for example, cracks, holes, notches etc. To find flaws near the surface, a magnetic flux leakage (MFL) inspection system can be applied. In this procedure a "horseshoe" shaped yoke is used (see Figure 1), whose legs are wrapped with coils with an applied alternate current (3 kHz).
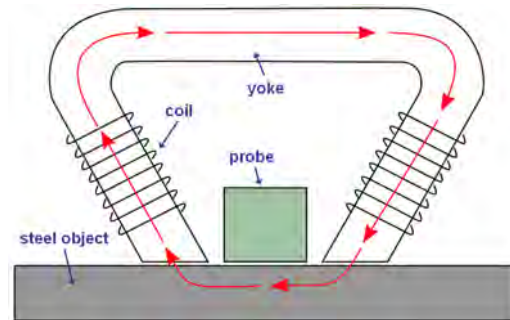
Figure 1. Sketch of the MFL inspection.

Thus, a thin magnetic field (~0.46 mm, skin effect) is induced near the surface of the pipe which leaks from the material if a flaw near the surface is present (see Figure 2). This leakage between the two coils can be measured (usually the x-component of the magnetic flux density, B_x), e.g. by a hall probe.

During the inspection, the yoke moves across the steel object to scan its whole surface.
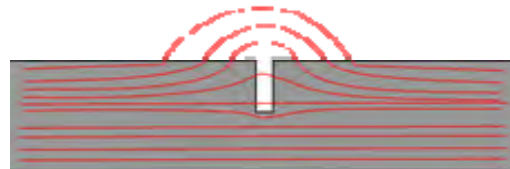
Figure 2. Magnetic field, leaking from the material at a notch.

The aim of our simulation is to find out how different flaw geometries and orientations influence the measured signal. Finally, we want to infer the flaw geometry from the signals. However, the focus of this work is the technical realization of the simulation - especially the handling of the very thin magnetic layer in 3D.

We limit our work mainly to block-shaped flaws (notches) which we varied in width, depth and orientation. In 3D we also performed some simulations with round structures (drill holes).

The paper is organized as follows: After briefly describing the use of COMSOL Multiphysics we consider first simulations on a 2D cross-section. Section 4 deals with the 3D simulation and the problem of saving degrees of freedom (DOFs). Finally a comparison between 2D and 3D simulation is given, followed by a validation with real measurements.

2. Use of COMSOL Multiphysics

For our simulations we used COMSOL Multiphysics 3.5a with MATLAB R2007b. The situation is modeled using the "Electric and Induction currents" application mode contained in the AC/DC module. We used a time harmonic analysis and solved for both the electric and magnetic potential. As the yoke moves rather slow over the steel object's surface, the influence of this movement to the induced magnetic field is negligible. Hence, we set v=0 in the model.

3. 2D simulation

We start with the simpler and less memory and time consuming simulations in 2D. These simulations were performed on a cross section of the inspection system, such that the current through the coils is perpendicular to the geometry plane.

3.1 Geometry

With the 2D simulation taking place in the x-z-plane, we use the following axis convention:

- x-axis: the horizontal direction (this is the direction in which the yoke moves)
- y-axis: the height direction
- z-axis: perpendicular to 2D simulation

The 2D cross section shape (x-y-plane) of the yoke has been approximated by Beziér-curves. Concerning the coils, we waive to model single excitation windings. Instead, we define an external current on the cross section area.

The steel object is a rectangular of 10 mm height and 115 mm width. The whole inspection scene is enclosed in a rectangular air region.
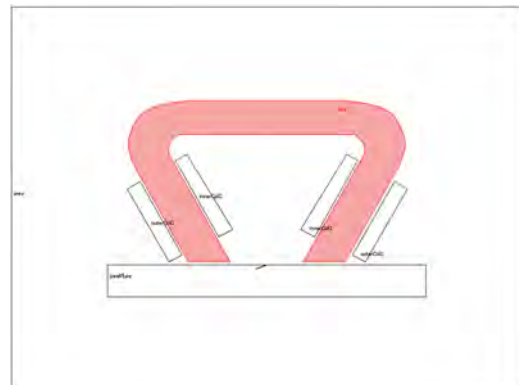

Figure 3. 2D geometry of the cross sectional model.

3.2 Mesh

The high frequency of the induction current leads to a very thin magnetic field (skin effect), in our case the skin depth is about 0.46 mm. We have to take care that this skin depth is resolved with at least 3-4 elements (see Figure 4 and Figure 5).
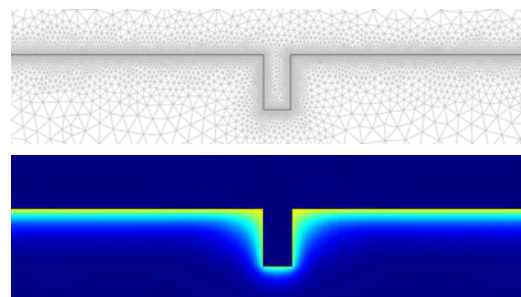

Figure 4. The mesh adequately resolves the thin magnetic layer at the top surface of the steel object.
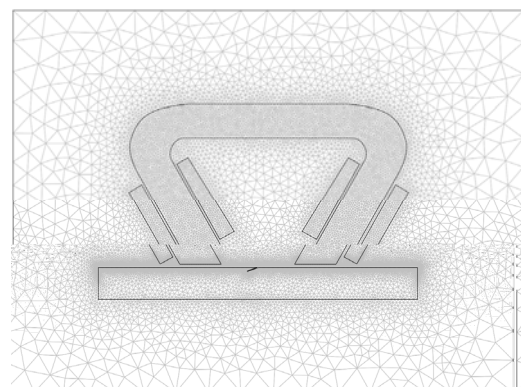

Figure 5. The complete mesh consists of about 190.000 elements.

3.3 Different notch shapes (2D)

During the inspection the yoke moves in horizontal direction over the surface. This movement is simulated by varying the x-position of the notch. A MATLAB script was written that creates a notch of given width, height and angle at a specified horizontal position (see Figure 6). With this script the movement of the notch could be achieved automatically.

This simulation was performed for different notch width, depth and angles to analyze the influence of these geometric parameters on the magnetic flux density.

Figure 6. Different notch geometries (wide, deep, oblique).

An example result of the signal of the notches with different width is shown in Figure 7. On the x-axis the x-position of the probe (simulated by x-position of the notch) is depicted, the y-axis gives the x-component of the magnetic flux density Bx. Each curve represents the signal of one notch traverse, the single curves correspond to one notch width. One can observe that the maximum of the signal curve is split for increasing width.
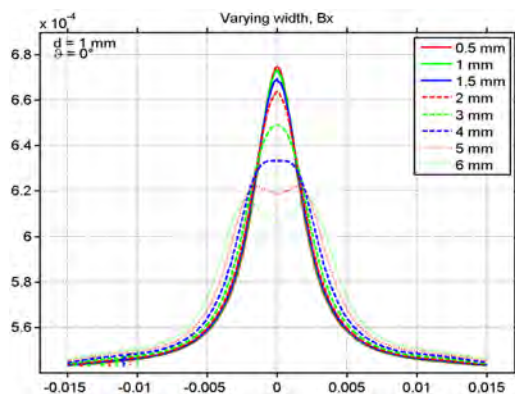
Figure 7. Resulting x-component of the magnetic flux density (in Tesla) for notches of different depth. The x-axis shows the position of the probe (in m).

Solving a 2D system is very fast, but has two major drawbacks:

1) We do not consider any magnetic field in z-direction, possibly flowing around the notch.

2) We can only model obliqueness in the x-y-plane, but not with components in z-direction.

Hence, simulations in 3D are necessary.

4. 3D simulation

4.1 Geometry and initial values

The 3D geometry is defined in two steps: First, we extrude the 2D geometry in z-direction, afterwards we have to close the coils by some round completions regarding the correct coil obliqueness. Finally we have to extend the definition of the external current, which is a little more complicated in 3D than in 2D (see Figure 8).
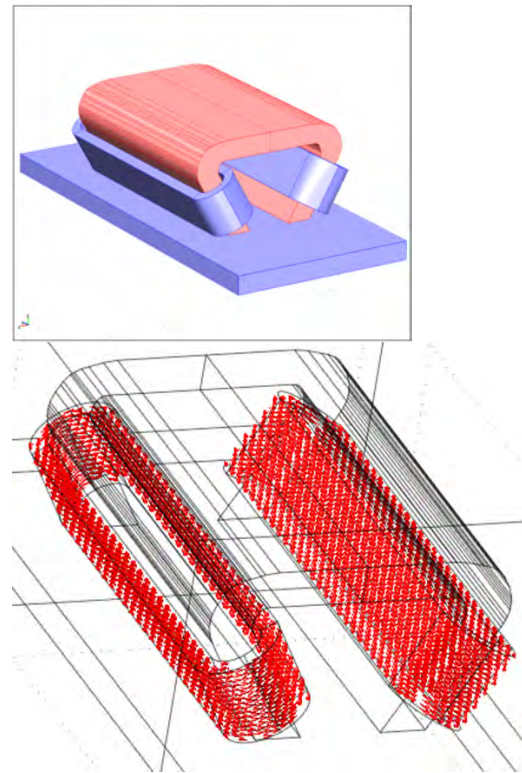

Figure 8. Top: complete geometry in 3D. Bottom: external currents defined on the coil subdomains.

Due to the skin effect we have to choose a very dense mesh near the boundary. While this was a straightforward process in 2D, meshing the whole 3D model with the same accuracy would result in about 20 millions of DOFs, which is not

capable for our system. Consequently, we have to reduce the number of DOFs.

4.2 Using symmetries

The yoke, coils, and plate are symmetric with respect to the x-y-plane and to the y-z-plane. If we confine our simulation to notches which are symmetric in the z-direction, we can omit one halve of the scene. This results in about 10 million DOFs which is still too much. Confining to notches which are also symmetric in the x-direction leads to a quarter model (see Figure 9).
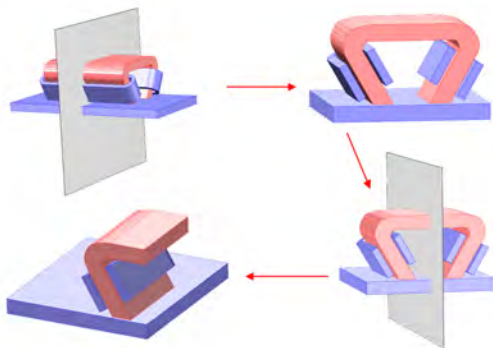

Figure 9. Top left: the complete geometry is divided by a symmetry plane into two halves. One resulting halve (top right) is again divided (bottom right) and results in a quarter scene (bottom left).

4.3 Using a swept mesh

To save further nodes and to allow for the special structure of the magnetic field we want to define a mesh that is very dense near the boundary and coarser far away from the boundary. For this purpose we use a swept mesh.

One problem with this approach is the notch which we want to be round in the front corner with a rounded ground. Here, the swept mesh can not be applied. Hence, we leave out a rectangular part in the corner, apply the swept mesh to the remaining steel plate and afterwards use a standard tetrahedral mesh for the rectangular part in the corner (see Figure 10).
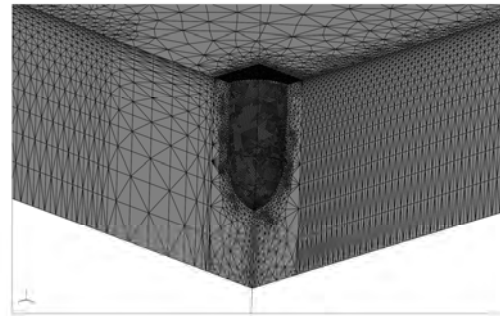
Figure 10. A swept mesh is used to account for the skin effect. Only the symmetric notch in the corner is triangulated with usual tetrahedra.

By this we end up with a system of equations with 4.7 mio DOFs which we could solve. In Figure 11 the norm (top) and the x-component of the magnetic flux density in a zoom (bottom) are shown. Unfortunately, it is possible to clearly recognize the transition between the swept mesh and the usual tetrahedral mesh at the top surface. For some reasons slight discontinuities developed at this transition.
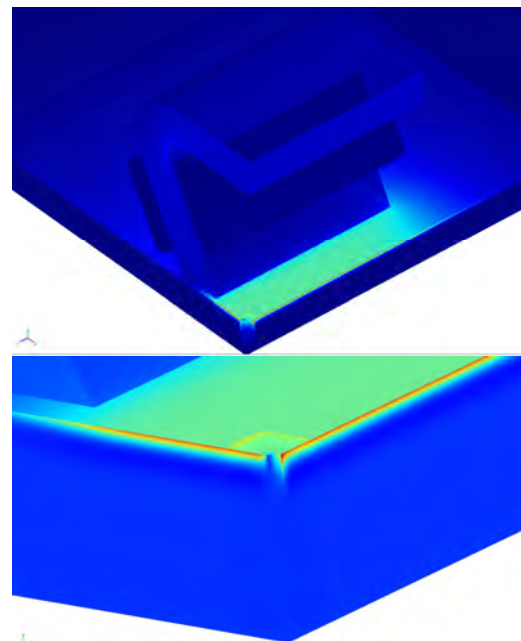

Figure 11. Solution plotted on the surface of the fully meshed quarter scene (top: |B|, whole scene, bottom: |Bx|, zoom in).

4.4 Impedance boundary conditions

Using symmetries and the swept mesh as described above, we were finally able to compute a solution for a fully meshed 3D situation. But we could only handle symmetric notches, which is too restrictive for our studies. Another way of treating the skin effect is the so called "impedance boundary condition" (cf. [1]). Here, the phenomena in the thin boundary layer are "projected" to the surface – an approximation which is very good if the thickness of the steel is more than 4 times higher than the skin depth. In our case the factor is approximately 21, thus, the approximation is applicable.

Using this boundary condition we can skip meshing the interior of the steel object and mesh only its surface. This saves a lot of nodes in the simulation (we end up with 1.7 million DOFs for the whole scene). In this way we can use the whole 3D geometry and define arbitrary notches without taking care of any symmetry issues. In Figure 12 |B| is plotted on the domain surfaces in different zooms for different color ranges.
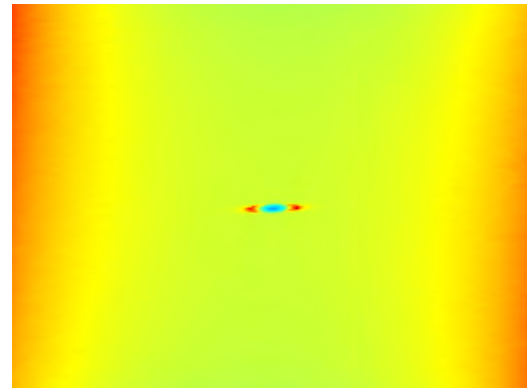
Figure 12. Solutions (|B|) of the complete 3D model with impedance boundary conditions. Top: the whole model, middle: only top surface of the steel plate (color range rescaled), bottom: zoom in to the solution in the vicinity of the notch (again rescaled color range).

Figure 13 shows resulting curves for notches with different obliqueness angle in the x-z-plane.
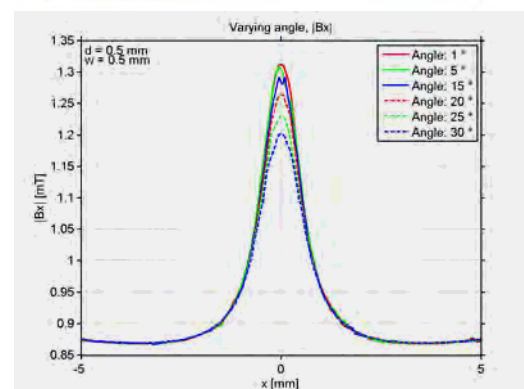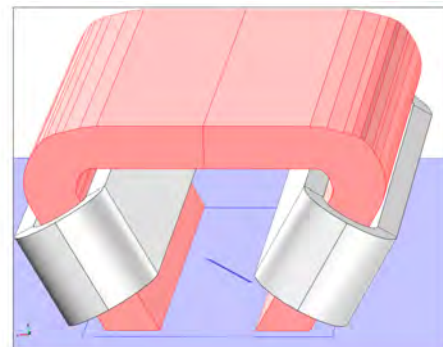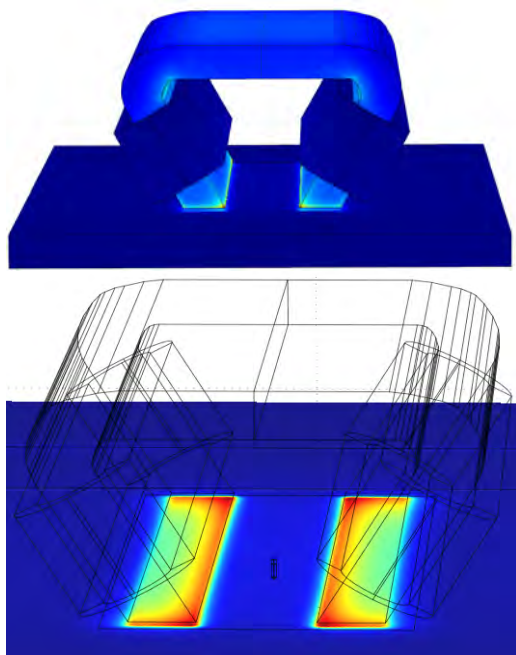
Figure 13. Top: Geometry with a notch of 30° obliqueness in the x-z-plane. Bottom: curves that represent Bx along a line parallel to the x-axis for different obliqueness angles in the x-z-plane.

4.5 Plausibility check: Comparison of the 2D model with an elongated 3D notch

In theory, the simulation of a notch in 2D corresponds to a 3D simulation with an infinite long notch. Hence, to verify our 2D simulation, we generated a rather long (40 mm in z-direction) notch in 3D and compared the magnetic flux density with the flux-density of a corresponding 2D simulation (both with a small lift-off). As one can see in Figure 14 the two signals are qualitatively very similar, but the absolute values differ by a factor of about 67. We don't have an explanation for this difference, so far.
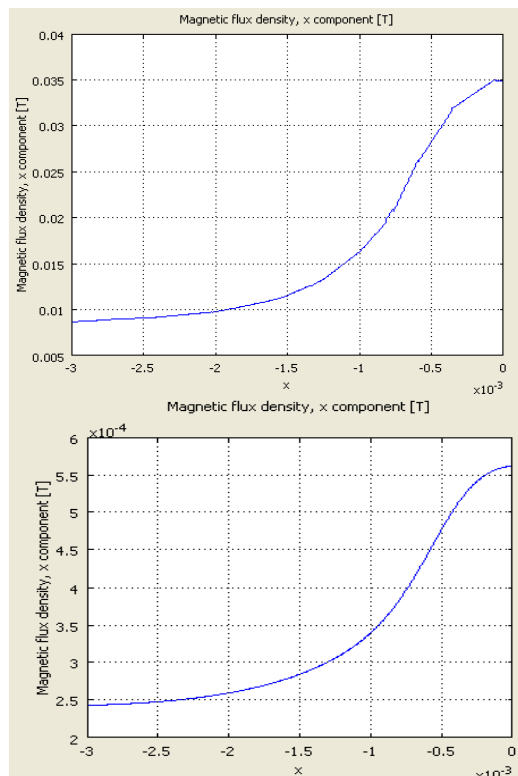

Figure 14. Comparison of a very long notch (3D, top) with the corresponding 2D simulation (bottom).

4.6 Validation with measured data

To validate the simulation at all, we compared the amplitude (in dB) of our simulation results with data measured on a test object with several notches of varying depth. As one can see in Figure 15, the curves are qualitatively quite similar.
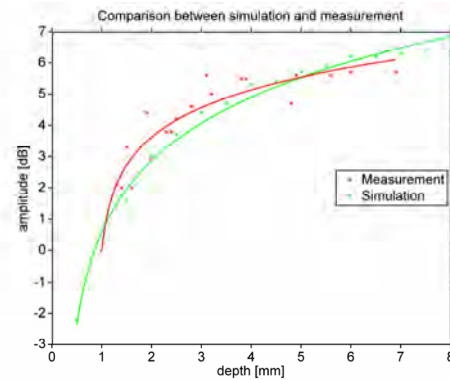

Figure 15. Comparison of simulation results with measured data. The two curves coincide quite well.

5. Conclusion

In our work we simulated the MFL inspection system and analyzed the signal of different notch geometries. However, the focus of this paper is the technical realization of the model as the magnetic field is concentrated in a thin layer near the surface due to the skin effect.

In first 2D simulations it was uncomplicated to resolve this layer adequately, however, in 3D the necessary number of DOFs let us reach our limits of memory.

By using symmetries and the swept mesh it was possible to compute the process on a quarter scene, but this restricted us to symmetric notches. With impedance boundary conditions it was possible to skip the meshing of the inner steel object and to mesh its surface only. By this we could take into account the complete 3D scene and incorporate arbitrary shaped notches.

A plausibility check of the 2D simulation and a comparison of simulation results with real measurements round out the picture.

6. References

1. Jianming Jin, *The Finite Element Method in Electromagnetics*, 753 pages, John Wiley & Sons, Inc., New York (2002)
2. T. Schmitte, A. Koka, *Using Drilled Holes as Reference in Magnetic Flux Leakage*

Measurements: An Investigation Based on Finite Element Modelling, www.ndt.net, 2008

3. A. Groos, S. Nitsche, T. Schmitte, *Modelling of Magnetic Flux Leakage Measurements of Steel Pipes*, www.ndt.net, 2006

4. T. Schmitte et. al., *Wavelet-Filterung zur Verbesserung der Empfindlichkeit der Streufluss-Prüfung*, www.ndt.net, 2009

5. T. Orth et. al., *Wavelet signal processing of magnetic flux leakage signals*, www.ndt.net, 2009