Susceptibility of weakly magnetic materials – comparison of NMR and inductive measurement methods

MILOSLAV STEINBAUER*, KAREL BARTUSEK**, DANIEL FOLTYN***
*Department of Theoretical and Experimental Electrical Engineering
** Institute of Scientific Instruments
***Department of Physics
*University of Technology Brno, ** Academy of Sciences of the Czech Republic
*Kolejni 2906/4, 612 00 Brno, ** Kralovopolska 147, 612 00 Brno
*** University of Technology Brno
CZECH REPUBLIC*,**, FRANCE***

Abstract: - This paper shows the way for magnetic susceptibility determination for weakly magnetic materials giving no MR signal by means of induced inhomogeneity. The results obtained by Finite element method (FEM) modeling as well as data measured by MRI are introduced. Data obtained by described method are compared with measurement based on inductive method.

Key-Words: - Nuclear magnetic resonance, magnetic susceptibility, FEM modeling, inductive susceptibility measurement

1 Introduction

Presence of magnetic materials in measured specimen brings about local change of magnetic field homogeneity of MR tomograph, which results in deformation of captured image. Because of high required homogeneity (10^{-6} and better), already materials with very low susceptibility have significant impact.

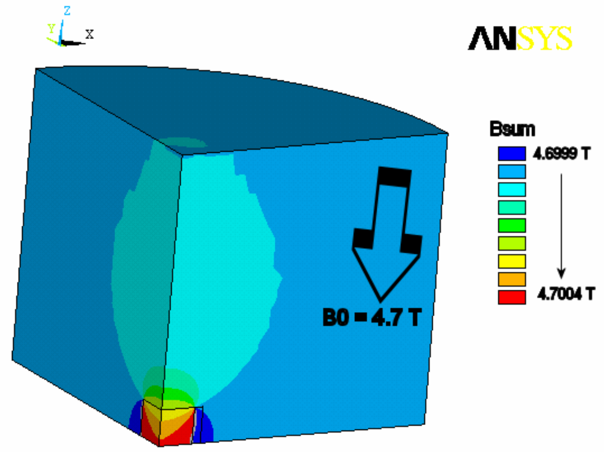

Fig. 1 Impact of paramagnetic specimen on MR field homogeneity

Because of possibility for future elimination of artefact in MR images caused by such materials, knowledge of material susceptibility is important. For example, presence of dental filling, when an MR image of head is made, brings out local loss of picture information.

Measurement of susceptibility can be realized by several methods. Magnetic resonance effect brings one possibility of susceptibility evaluation. Principle of measurement is elementary for materials which gives signal in MR tomography. When suitable imaging method is applied (usually gradient echo – GE), information about local change of magnetic induction of field in sample is phase-coded in obtained image. From known shape of induction, local value of permeability μ or susceptibility χ can be derived using Laplace's equation

$$\Delta \varphi_{\mathrm{m}} = 0 \, . \qquad (1)$$

One of methods for susceptibility measurement of materials, which gives no MR signal, was described in [1]. This method uses comparison with reference materials of known χ (such as water, acetone, …). Because no signal form inside area is acquired and thus change of magnetic induction inside it can't be enumerated, the induction in specimen vicinity is an object of interest.

Below in this paper we will discuss measuring technique, which is suitable for substances with no signal in MR tomography. For illustration see Fig. 1, where is shown slice of MR experiment model with specimen of susceptibility $\chi_{\mathrm{S}} = 1 \cdot 10^{-4}$ in basic field with magnetic induction $B_0 = 4.700\ \mathrm{T}$. Deformation of magnetic induction field in specimen arrive, moreover field in specimen vicinity is affected. This figure has been obtained from Ansys model Fig. 3 below.

2 Principle of the Method

The method is based on presumption of constant magnetic flux in working space of superconducting magnet. Inserting of the specimen of thickness Δx and with magnetic susceptibility χ_s causes local deformation of homogeneous magnetic field (idealized case is in Fig. 2)

$$B_s = B_0 \cdot \left(1 + \chi_s\right). \qquad (2)$$

Assume constant magnetic flux Φ thru normal area of cross-section S of the magnet working space

$$\phi = \iint_S B \cdot dS = const. \qquad (3)$$

Suppose the specimen has enough large length in y-axes direction, so we can neglect boundary effect. For z-x cross-section Fig. 2 in the middle of the specimen we can write

$$\int_{-\varepsilon}^{\varepsilon} \left[B(x) - B_0\right] \cdot dx = 0\,, \qquad (4)$$

what means that sum of hatched areas bounded by curve in Fig. 2 with respect to the base value of induction B_0 is zero, where ε is sufficient distance from specimen with respect to its impact on induction change.

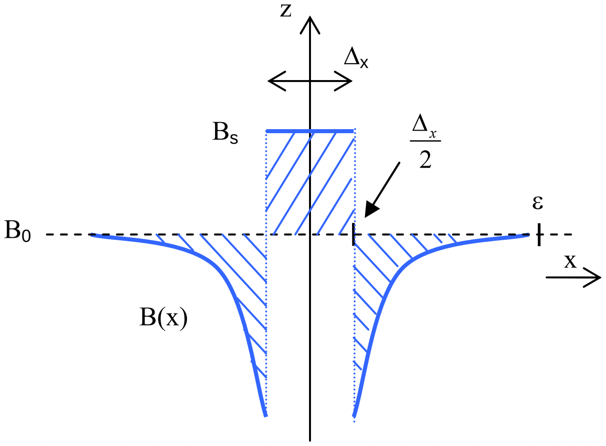

Fig. 2 Theoretical shape of magnetic induction field in paramagnetic specimen and its vicinity

If we can determine the course of $B(x)$ (using suitable MRI technique and reference substance giving MR signal in surroundings of material), we can also enumerate B_s and χ_s values of the investigated specimen material. From principal case in Fig. 2 we can derive:

$$2\int_{\Delta_x/2}^{\varepsilon} \left[B(x) - B_0\right] \cdot dx \cong \Delta_x \left(B_S - B_0\right), \qquad (5)$$

and using (2)

$$\chi_S \cong \frac{2\int_{\Delta_x/2}^{\varepsilon} \left[B(x) - B_0\right] \cdot dx}{\Delta_x \cdot B_0}. \qquad (6)$$

Described method was numerically modelled in Ansys and checked on 200 MHz MR tomograph in Institute of Scientific Instruments, Academy of Sciences.

3 Numerical modeling

Numerical modelling was provided using Ansys 7 software. Using FEM the scalar magnetic potential Φ_m was computed by solving of Laplace's equation (1).

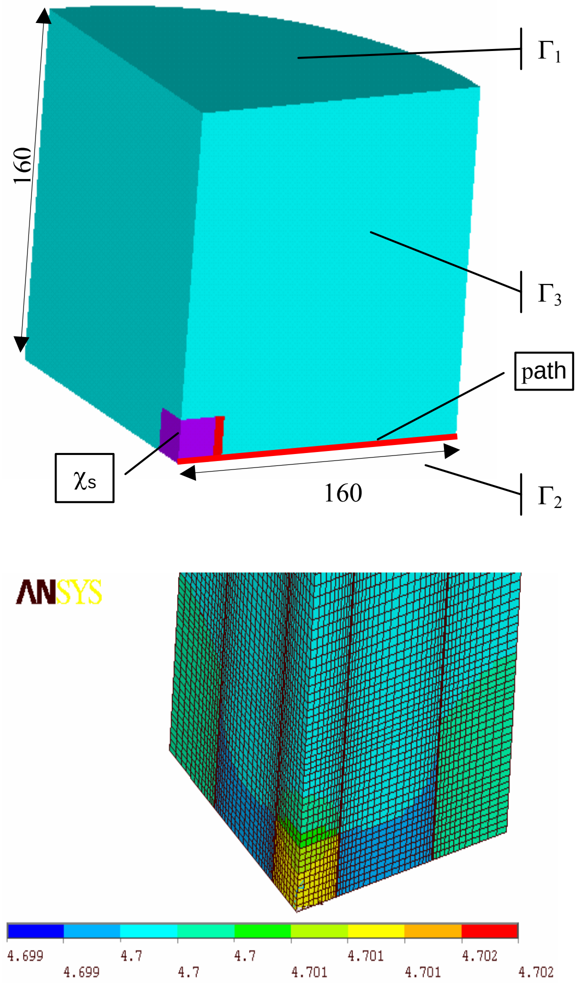

Fig. 3 Ansys models: desription (upper), dimensions are in mm, another meshed model (bottom)

One of used model is in Fig. 3. Here weakly paramagnetic specimen is surrounded by diamagnetic reference substance. The model was meshed with Solid96 element type. Boundary conditions were set up to achieve induction $B_0 = 4{,}700$ T in z-axes direction:

- $\Phi_m = const.$ on the surfaces Γ_1, Γ_2,
- $\frac{\partial \Phi_m}{\partial n} = 0$ on the shell surface Γ_3.

The module of magnetic induction B along the “path” marked in Fig. 3 top, obtained by solving of mentioned model, is depicted in Fig. 4.

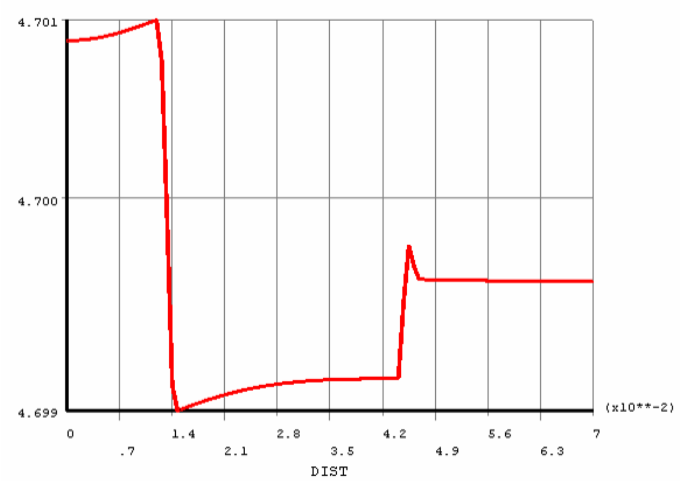

Fig. 4 Course of magnetic induction in section of models in Fig. 3

In real experiment the reference material and the specimen are separated with thin layer, e.g. cuvette wall. In model we considered 1 mm thick cuvette made from PE. Because polyethylene is paramagnetic, little peak occurs in graph Fig. 4.

4 Experimental measurement

Presented method was experimentally verified with number of specimens on 200 MHz MR tomograph in ISI AS Brno. Reference substance was water ($\chi_{H2O} = -9.04\cdot10^{-6}$) filled into cuvette. The method of Gradient echo [3] was used to acquire MR image with contrast corresponding to the magnetic induction changes in measured volume of specimen vicinity.

One of GE method property is its sensitivity on basic field inhomogeneity and inhomogeneity induced by magnetic material in the specimen. GE MR image is phase-modulated by magnetic induction change [2], [3] and on condition of proper experiment arrangement we can obtain image of magnetic field distribution in specimen vicinity and finally enumerate specimen susceptibility (6).

Using described GE method we obtained MR image with phase-contrast – Fig. 5 top, which was further processed in Matlab. After de-noising by the limitation of signal the spatial deformation evoked by magnetic field inhomogeneity in specimen vicinity was eliminated. Acquired phase images were consequently subtracted to eliminate inhomogeneity of the basic field and unwrapped (this means discontinuities in phase change between $-\pi$ and π were removed) – result is on Fig. 5 bottom. By properly selected slice of this image we get the curve of phase change $\Theta(x)$ of the water MR signal in the specimen vicinity, see Fig. 6.

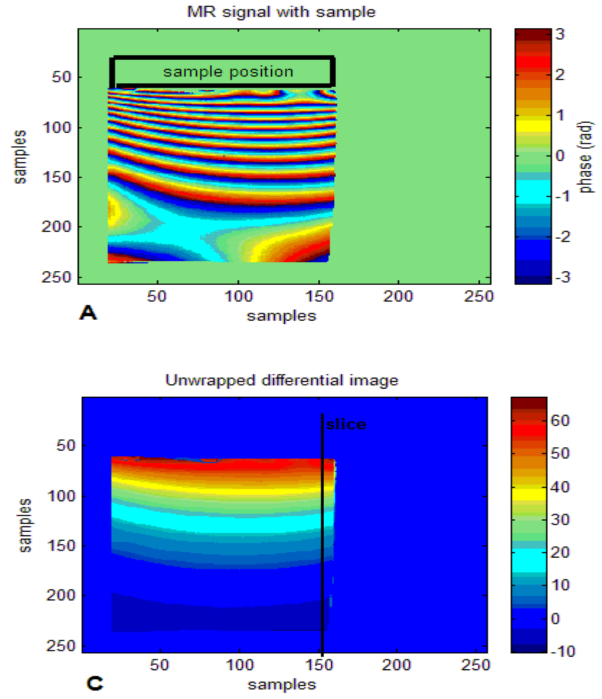

Fig. 5 Images obtained from experimental verification of the method, processed in Matlab

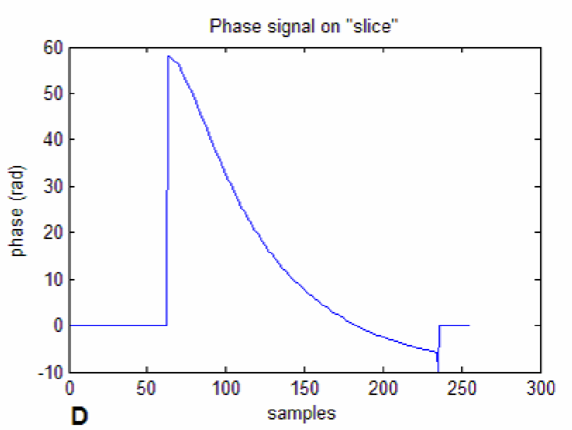

Fig. 6 Unwrapped curve of signal phase change in specimen vicinity

For the used MR technique the phase change $\Theta(x)$ response to the magnetic induction change

$$B(x) = \frac{\Theta(x)}{\gamma \cdot T_E} + B_0 , \qquad (7)$$

where γ is gyromagnetic ratio of water and $T_E = 5.56$ ms was used echo-time. In this way we can identify the course of magnetic induction change in water nearby the specimen. From known thickness Δ_x of the specimen with use of (6) the susceptibility of specimens can be calculated.

5 Inductive method

Ten ceramic specimens, mostly of building materials for sanitary ceramic, were measured by means of described NMR method. The same collection of specimens was measured by inductive method for comparison.

Principle of inductive method is in change of inductive coefficient of coil, caused by influence of specimen. We have used bridge Kappabridge KLY-2 with working intensity 300 A/m and accuracy 0.2 %.

Specimen	Inductive	NMR
1	5,68E-04	1,03E-04
2	7,29E-04	3,13E-05
3	2,41E-05	
4	6,02E-05	9,65E-05
5	8,37E-03	
6	6,08E-05	7,95E-05
7	1,23E-04	1,65E-04
8	6,61E-05	9,90E-05
9	3,47E-04	4,97E-05
10	6,19E-05	9,00E-05

Tab. 1 Comparison of specimen susceptibility measured by inductive and NMR methods

Significant difference of values in Tab. 1 can has some reasons. First, specimens were measured primarily in NMR and strong magnetic field 4.7 T of superconductive magnet may induce magnetic remanence of them. Second, nonlinearity of specimen magnetic properties can result in this disproportion, whenever the methods use very different value of induction B.

Now, we are working on some experiments to validate this theory.

6 Conclusion

The method designed for magnetic susceptibility measurement based on MR tomography techniques enables to determine the magnetic susceptibility of such materials, which give no MR signal. Principle of the method was designed using Ansys modelling and experimentally verified in laboratory. After an optimization this method can be used for investigation of the materials used in MR tomography as well as of biological tissues affecting quality of MR images.

7 Acknowledgement

This work has been partially funded by a grant GAČR 103/03/7048 and grant GAAV IAA2065201.

References:

[1] ZEMAN, V. Měření magnetické susceptibility pomocí NMR. Tesla Brno, interní zpráva, 1981

[2] BLUMLICH, B. NMR Imaging of Materials. Clarenton Press, Oxford, 2000, ISBN 0 19 850683 X

[3] ERNST, R. R. – BODENHAUSEN, G. – WOKAUN, A. Principles of NMR in One and Two Dimensions. Oxford Science Publ. 1987, ISBN 0-198-55647-0

[4] LEVITT, M. H. Spin Dynamics: Basics of Nuclear Magnetic Resonance. John Wiley & Sons, 2001, ISBN: 0-471-48921-2

[5] HROUDA, F. A determination of the symmetry of the ferromagnetic mineral fabric in rocks on the basis of the magnetic susceptibility anisotropy measurements. Gerl. Beitr. Geophys., 82,1973, pp.390-396

[6] HROUDA, F. Magnetocrystalline anisotropy of rocks and massive ores: a mathematical model study and its fabric implications. J. Struct. Geol., 2, 1980, pp.459-462

[7] Stepnišik, J.: Measurement of susceptibility magnetic field gradient in a porous media by modulated gradient spin echo, EENC 2000