ANSYS ANALYSIS OF WEAKLY MAGNETIC MATERIALS IN MR TOMOGRAPHY

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Summary The paper deals with the impact of weakly magnetic materials on magnetic field in MR tomography. The results obtained by finite element method modelling as well as data measured by MR tomography are introduced. Method of magnetic susceptibility determination using MRI is discussed.

1. INTRODUCTION

Basic field homogeneity is one of the principal requirements in MR tomography. Presence of magnetic materials in measured specimen brings about local perturbation of this field, 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.

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

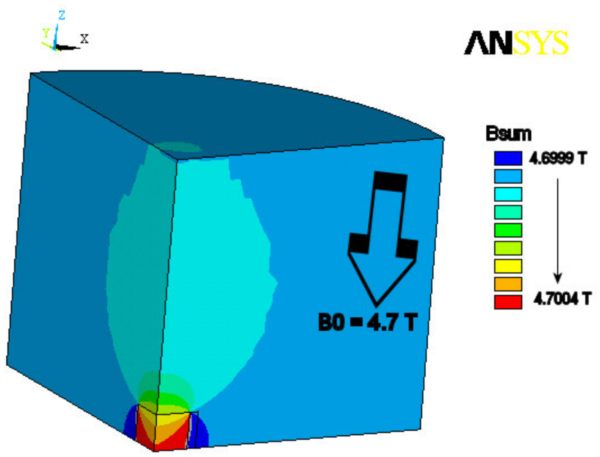


Fig. 1 Impact of paramagnetic specimen on MR field homogeneity

Measurement of susceptibility can be realized by several methods. One method based on low-frequency inductive bridge with field intensity about 300 A/m was developed by AGICO Company [5], [6]. Achieved sensitivity of this method allows measurement of material with susceptibility of order 10^{-5}, moreover magnetic anisotropy can be observed.

Magnetic resonance effect brings another 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 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)

$$B_{\mathrm{s}} = B_0 \cdot \left(1 + \chi_{\mathrm{s}}\right). \qquad (2)$$

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.

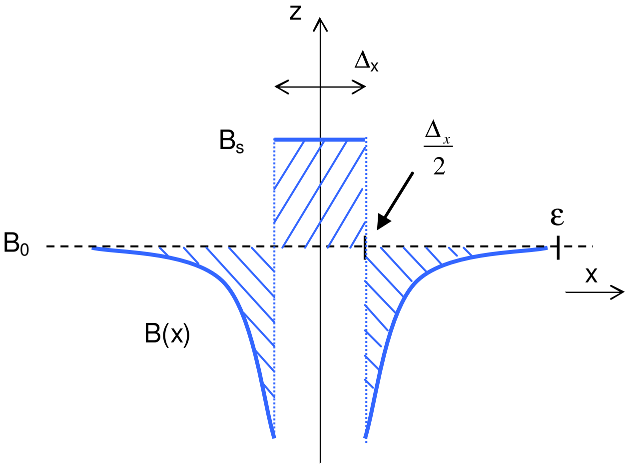


Fig. 2 Change of magnetic induction field in paramagnetic specimen and its vicinity – idealized case

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:

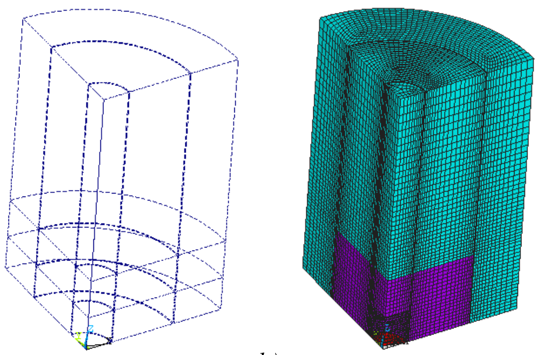
$$2\int_{\Delta_x/2}^{\varepsilon}\left[B(x)-B_0\right]\cdot dx \cong \Delta_x\left(B_S-B_0\right), \qquad (5)$$

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



a) b)

Fig. 3 Geometrical and meshed model (cylindrical arrangement)

One of used Ansys 3D models is on Fig. 3 (a - geometrical model, b - meshed model). Volumes with different magnetic properties have different colour.

Numerical modelling was provided using Ansys 6.1 software. Using FEM the scalar magnetic potential Φ_m was computed by solving of Laplace's equation (1).

One of used model is in Fir. 4. 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,
- $\dfrac{\partial \Phi_m}{\partial n} = 0$ on the shell surface Γ_3.

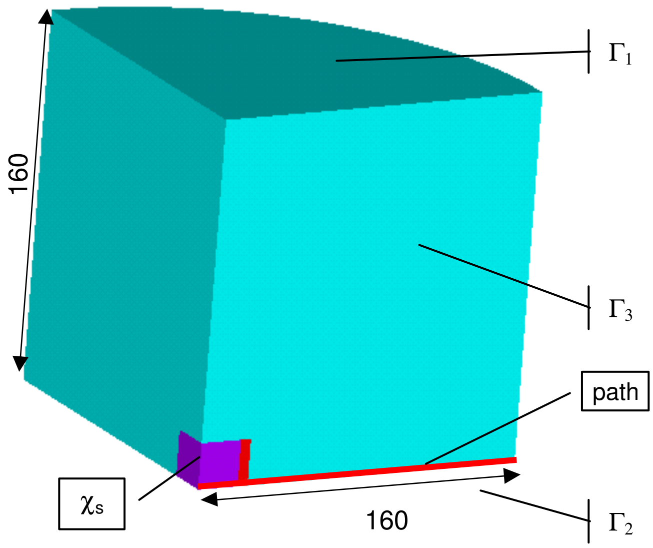


Fig. 4 Simple Ansys model, dimensions are in mm

The module of magnetic induction B along the "path" marked in Fig. 4, obtained by solving of mentioned model, is depicted in Fig. 5.

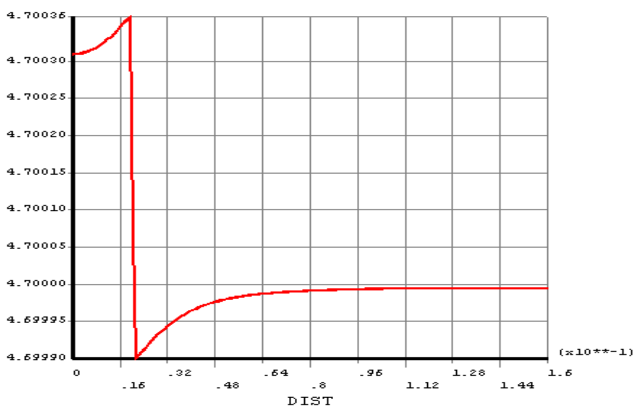


Fig. 5 Course of magnetic induction in section of model in fig. 4

Another model, used for verification of susceptibility measurement is in Fig. 6. Here weakly paramagnetic specimen is surrounded by diamagnetic reference substance. Obtained course of B in section is in Fig. 7.

In real experiment the reference material and the specimen are separated with thin layer, e.g. cuvette wall. In model (Fig. 6) we considered 1 mm thick cuvette made from PE. Because polyethylene is paramagnetic, little peak occurs in graph Fig. 7.

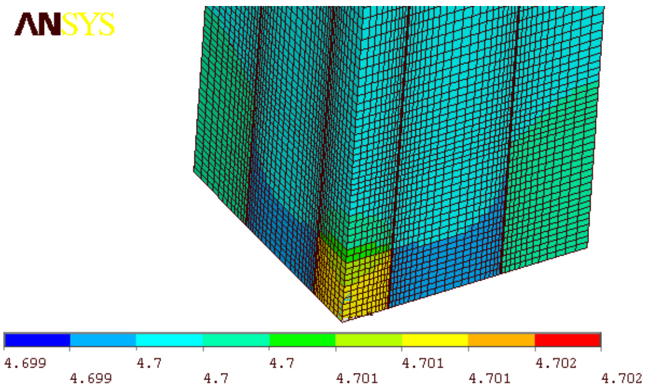


Fig. 6 Magnetic induction field projected on meshed model

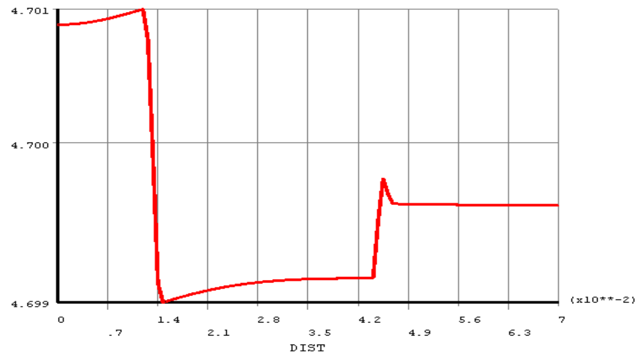


Fig. 7 Course of magnetic induction in section of model in Fig. 6. Peak is caused due to PE cuvette

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 ($\chi_{H2O} = -9.04 \cdot 10^{-6}$) 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. Used measuring sequence of GE is on Fig. 8.

Excitation of hydrogen nucleus provides HF pulse 90°, which drops vector of magnetization spin M_0 from direction z (parallel to B_0) to transversal plane x-y. Energy of this pulse causes phase-matching of nucleus spins. During excitation, slice gradient G_S allocates measured specimen layer. Only this layer is excited and only from this layer the MR image is consequently acquired.

Read-out gradient G_R causes coding of x-position into frequency and at the same time phase gradient G_P causes coding of y-position into phase of result MR signal.

Spin-spin incidence and gradient fields induce lapse of phase-matching of magnetization vectors, so re-matching of spins by read-out gradient inversion is used. Signal acquisition is performed in echo time TE after excitation.

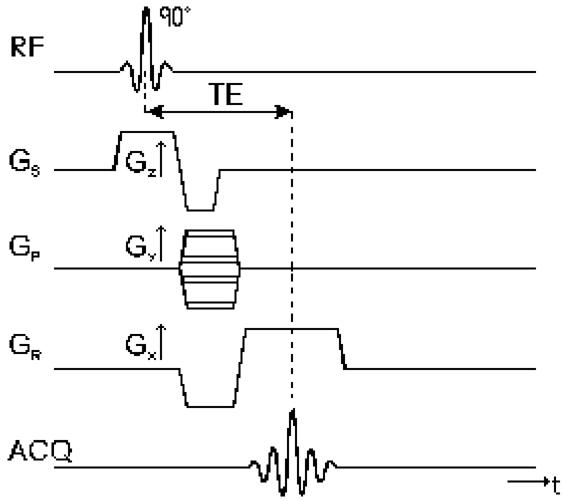


Fig. 8 Principle of gradient echo measuring sequence

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).

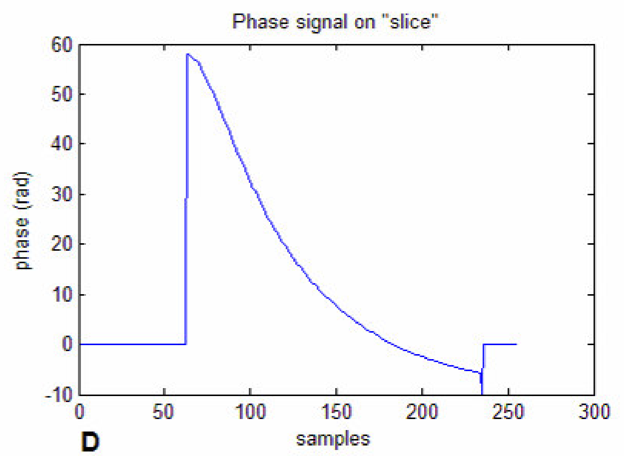


Fig. 9 Unwrapped curve of signal phase change in specimen vicinity

Using described GE method we obtained MR image with phase-contrast – Fig. 10 upper, 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. 10 lower. 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. 9.

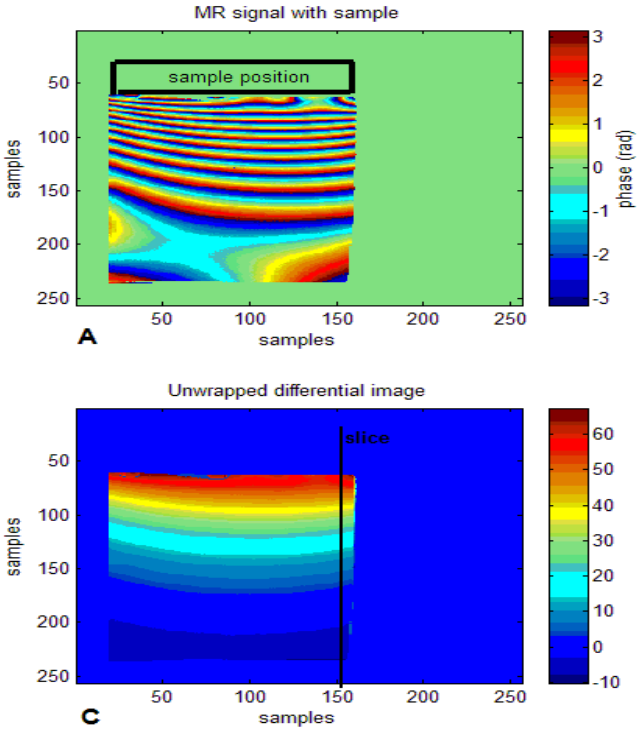


Fig. 10 Images obtained from experimental verification of the method, processed in Matlab

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 finally calculated.

5. CONCLUSION

The method designed for magnetic susceptibility measurement based on MR tomography techniques is simple and 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.

ACKNOWLEDGEMENT

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