Magnetic Resonance Imaging Methods Used for Weak Magnetic Materials Detection

I. Frollo, P. Andris, J. Přibil, L. Vojtíšek, T. Dermek, L. Valkovič, D. Gogola, O. Štrbák

Institute of Measurement Science, SAS, Bratislava, Slovakia,
frollo@savba.sk

Abstract. *Imaging based on nuclear magnetic resonance (MRI) for mapping and imaging of the weak magnetic field materials placed into the homogenous magnetic field of an NMR imager, is proposed. A sample made of a weak magnetic material was constructed, theoretical computation and testing on an MRI 0.178 T Esaote Opera imager were accomplished. In our experiments a homogeneous phantom (reference medium) - a container filled with doped water - was used. The resultant image represents the magnetic field distribution in the homogeneous phantom. For detection a carefully tailored gradient-echo (GRE) imaging method, susceptible to magnetic field homogeneities, was used. The first results showed the feasibility of the method and some of the possibilities offered in this field of material research.*

Keywords: magnetic resonance imaging, weak magnetic material, gradient echo

1. Introduction

Imaging of proton density based on Nuclear Magnetic Resonance (NMR) methods used for biological and physical structures is a routine investigating procedure. Special case is observed when an object that consists of a weak magnetic material is inserted into a stationary homogeneous magnetic field. This results in a deformation of the basic stationary magnetic field. Using a special homogeneous phantom, filled with a water containing substance, near the sample, it is possible to image the contours of this sample. The acquired image represents a modulation of the basic magnetic field of the imager detectable by gradient echo imaging sequence.

First attempt of a direct measurement of the magnetic field created in living and physical tissue by a simple wire fed by a current was reported in [1]. A method utilizing the divergence in gradient strength that occurs in the vicinity of a thin current-carrying copper wire was introduced in [2]. A simple experiment with thin, pulsed electrical current-carrying wire and imaging of a magnetic field using a plastic sphere filled with agarose gel as phantom, was published in [3]. First attempt of the indirect susceptibility mapping of thin-layer samples using phantoms were described in [4].

In this paper we propose a magnetic resonance imaging method used for weak magnetic materials detection, computation of the magnetic field distribution based on double-layer magnetic theory and a comparison of theoretical results with experimental images.

2. Subject and Methods

We suppose that the magnetic double layer is positioned in the x-y plane of the rectangular coordinate system (**i**x, **j**y, **k**z) and the thickness of the layer is neglected.
According to Fig. 1, we suppose the layer is limited by lengths of 2*a* and *b*, with the left - right symmetry. The layer is moved in +y direction by distance of *g*. The basic magnetic

field B_0 of the NMR imager is parallel with the z-axis. The task is to calculate the $B_Z(x,y,z)$ component of the magnetic field in the point $A[x_0, y_0, z_0]$.

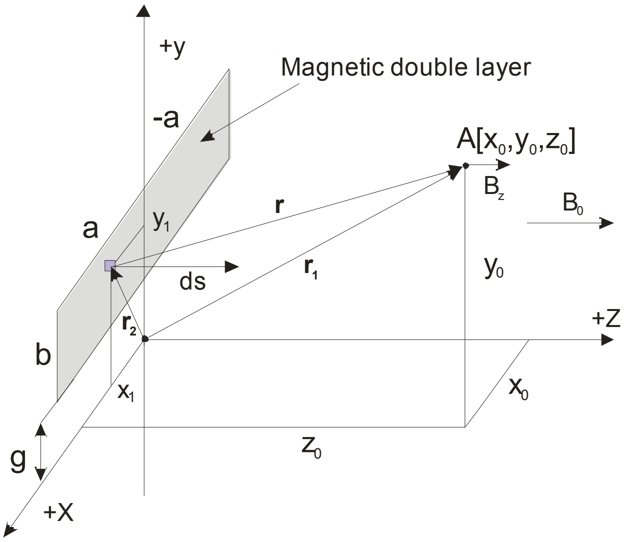

Fig. 1. Basic configuration of the magnetic double layer sample positioned in x-y plane of the rectangular coordinate system. The thickness of the layer is neglected.

In a general definition the magnetic double layer can be considered to have magnetic dipoles continuously distributed on a surface S(a,b). Such a planar magnetic dipoles distribution is called magnetic double layer that is characterised by a surface density of a magnetic dipole moment **M**:

$$\mathbf{m}_s = \int_S \mathbf{M}_S(\mathbf{r})dS \quad \text{and} \quad \mathbf{M}_S = \mathrm{I}\,\mathbf{n} \tag{1}$$

where **r** - is a position vector, I - is a current equivalent to planar density of dipole moment of the magnetic double layer and **n** - is a unite normal vector of a surface S in a particular point.
The formula for magnetic field in the point $A[x_0, y_0, z_0]$ is supposing to use the Biot-Savart law in vector form assuming the equivalency of a current loop and a magnetic double layer (the curve integral is replaced by a surface integral):

$$\mathbf{B} = -\frac{\mu_0 I}{4\pi}\oint \frac{\mathbf{r}\times d\mathbf{s}}{r^3} = \frac{\mu_0 I}{4\pi}\int_S \left(\frac{3\mathbf{r}.\mathbf{r}}{r^5} - \frac{\mathbf{I}}{r^3}\right).d\mathbf{S} \tag{2}$$

From the physical interpretation the calculated magnetic field assuming:

$$\mathbf{r}.\mathbf{r} = r^2 = (x_0 - x)^2 + (y_0 - y)^2 + (z_0 - z)^2$$

we can write the final formula in a double integral form as follows:

$$\mathrm{B}_z(\mathrm{x,y,z}) = \frac{\mu_0 I}{4\pi}\int_{-a}^{a}\left[\int_d^h \frac{3 - I}{r^3}dy\right]dx\,, \tag{3}$$

where limits for integration are: [-a, a] and [d = g, h = g+b], see Fig.1.

After integration of a indefinite double integral (3) we get the final formula for practical calculation as follows:

$$\mathrm{B}_z(\mathrm{x,y,z}) =$$

$$\frac{1}{z_0}\mathrm{ArcTan}\frac{(x - x_0)(b + g - y_0)}{z_0\sqrt{b^2 + 2bg + g^2 + (x - x_0)^2 - 2by_0 - 2gy_0 + y_0^2 + z_0^2}} + \frac{1}{z_0}\mathrm{ArcTan}\frac{(x - x_0)(b - g - y_0)}{z_0\sqrt{b^2 - 2bg + g^2 + (x - x_0)^2 + 2by_0 - 2gy_0 + y_0^2 + z_0^2}}$$

Assuming the following relative values: $\mu_0 I / 4\pi = 1$, $z_0 = 0.5$, a = 7, b = 1, g = 5, the resultant 3D and 2D -plots of magnetic field of relative values for {x0, -10, 10}, {y0, 0, 10} are depicted in Fig. 2.

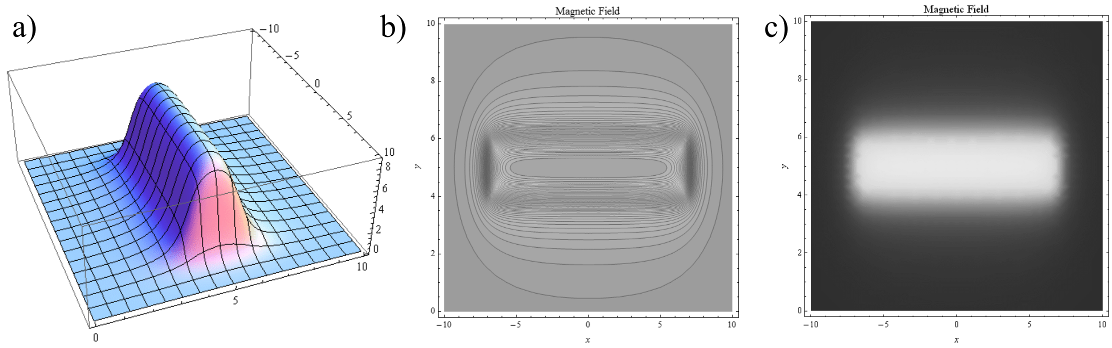

Fig. 2. Calculated magnetic field $B_z(x,y,z)$ of the magnetic double layer sample positioned in x-y plane of the rectangular coordinate system. a) 3D-plot, b) contour plot, c) density plot.

3. Experimental Results

As a physical model, a sample made of 4 low magnetic tapes was used. The sample was placed at the centre of a plastic holder – homogeneous phantom filled with 0,1 wt% solution of $CuSO_4$ in distilled water, see Fig.3.

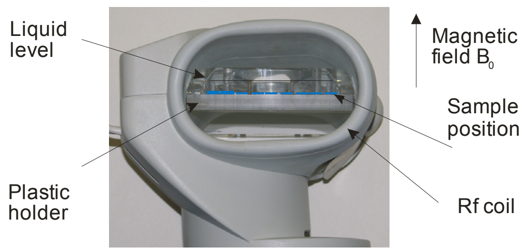

Fig. 3. Horizontal field RF coil, active measuring volume (homogeneous phantom), dimensions 90 x 90 mm.

An NMR imager (ESAOTE Opera), permanent magnet 0,178 T with vertical orientation of the basic magnetic field B_0 was used. The gradient-echo NMR sequence was selected for the measurement. A special feature of this sequence is its sensitivity to basic magnetic field inhomogeneities. The original sample, calculated 3D image of the magnetic field distribution and an NMR image of the double cross sample are seen in Fig.4. and Fig.5.

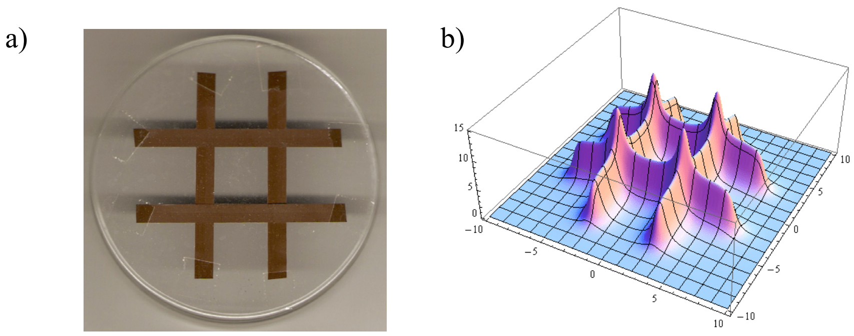

Fig. 4. a) Original sample made of 4 low magnetic tapes, double cross, 6 x 70 mm, distance between tapes 25 mm, audio cassette tape, thickness 11 µm, densely packed pure grained ferric particles.
b) Calculated 3D image of the magnetic field distribution.

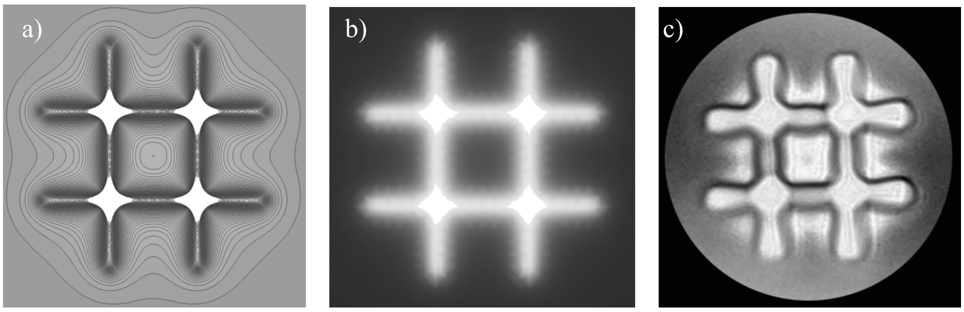

Fig. 5. a) Calculated image of the magnetic field, contour plot, b) density plot, c) NMR image of the double cross sample using GRE imaging sequence.

4. Discussion

A sample made of 4 low magnetic tapes for verification of this methodology was used. Careful adjustment of the GRE imaging sequence parameters to detect weak magnetic materials was necessary. It is evident that imaging of the magnetic field of the weak magnetic samples can be performed by GRE method based on a exteriorization of magnetic field of the sample into a homogeneous planar phantom. Furthermore this magnetic field may cause artefacts if weak magnetic samples are present in the MRI. This effect is strongest if the vector of the static magnetic field $B_0 = B_z$ is perpendicular to the phantom plain. Our experimental results are in good correlation with the simulations. This validates the suitability of the proposed method for detecting weak magnetic materials by MRI.

5. Conclusions

A new method for mapping and imaging of the planar weak magnetic samples placed into the homogenous magnetic field of an NMR imager is proposed. First results showed the feasibility of the method and the importance of detecting the field changes caused by weak magnetic materials, that may cause image artefacts even in the low-field MRI.

Acknowledgements

The financial supports by the Grant Agency of the SAS, project no. VEGA 2/0090/11, The State program ŠPVV no. 2003SP200280203 and project "Creation of the Centre of Excellence for the Research and Development of Construction Composite Materials for Mechanical and Building Engineering and Medical Applications" based on the support of Operational Program Research and Development financially supported by European Regional Development Fund, CEKOMAT, ITMS No. 26240120006 are gratefully acknowledged.

References

[1] Joy M., Scott G., Henkelman M. In vivo imaging of applied electric currents by magnetic resonance imaging, Magnetic Resonance Imaging, Vol.7, 1989, 89-94.

[2] P. T. Callaghan and J. Stepisnik, "Spatially-distributed pulsed gradient spin echo NMR using single-wire proximity," Phys. Rev. Lett., vol. 75, no. 24, pp. 4532–4535, 1995.

[3] Sekino M., Matsumoto T., Yamaguchi K., Iriguchi N., and Ueno S. A method for NMR imaging of a magnetic field generated by electric current, IEEE Trans. on Magnetics, Vol. 40, 2004, 2188-2190.

[4] Frollo I., - Andris P., - Přibil J., - Juráš V. Indirect Susceptibility Mapping of Thin-Layer Samples Using Nuclear Magnetic Resonance Imaging, IEEE Trans. on Magnetics, Vol. 43, no. 8, (2007), 3363-3367.