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Soft Magnetic Material Testing Using Magnetic Resonance Imaging

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Abstract. Soft magnetic field samples were placed into the homogenous magnetic field of an imager based on nuclear magnetic resonance. Several samples made of a soft magnetic material (cut from a data disc) were tested. Theoretical computations on a magnetic double layer were performed. For experimental verification an MRI 0.178 Testa ESAOTE Opera imager was used. For our experiments a homogeneous circular holder (reference medium) - a container filled with doped water - was designed. The resultant image corresponds to the magnetic field variations in the vicinity of the samples. For data detection classical gradient-echo and spin-echo imaging methods, susceptible to magnetic field inhomogeneities, were used. Experiments proved that the proposed method is perspective for soft magnetic material testing using magnetic resonance imaging methods (MRI).

Introduction

Methods used for biological and physical structure imaging, based on Nuclear Magnetic Resonance (NMR), have become a regular diagnostic procedure. Specific occurrence is observed when an object, consisting of a soft magnetic material, is inserted into a static homogeneous magnetic field. This results in small variations of the static homogeneous magnetic field near the sample. Using a special phantom filled with a water-containing substance near the sample, it is possible to image the magnetic contours caused by the sample. The acquired image represents a modulation of the basic homogeneous magnetic field of the imager detectable by gradient-echo (GRE) or spin-echo (SE) imaging sequences.

Description of the first attempt of a direct measurement of the magnetic field variations created in living and physical tissues by a simple wire fed by a current was published 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]. Comparison of traditional segmentation methods with 2D active contour methods was discussed in [4]. Single biogenic soft magnetite nanoparticle physical characteristics in biological objects were introduced in [5].

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

Subject and Methods

We assume an ideally homogeneous magnetic field of an MRI. When a very thin soft magnetic object is placed into the homogeneous magnetic field, the field near the sample is changing. For the theoretical analysis and optimal physical interpretation, a magnetic double layer model is used [6].

Let us suppose that the magnetic double layer is positioned in the x-y plane of the rectangular coordinate system (x, y, z), Fig. 1.

We suppose the layer is limited by lengths of $2a$ and $2b$, with the left - right symmetry. 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 $A[x_0, y_0, z_0]$. For the calulation the layer thickness t will be neglected.

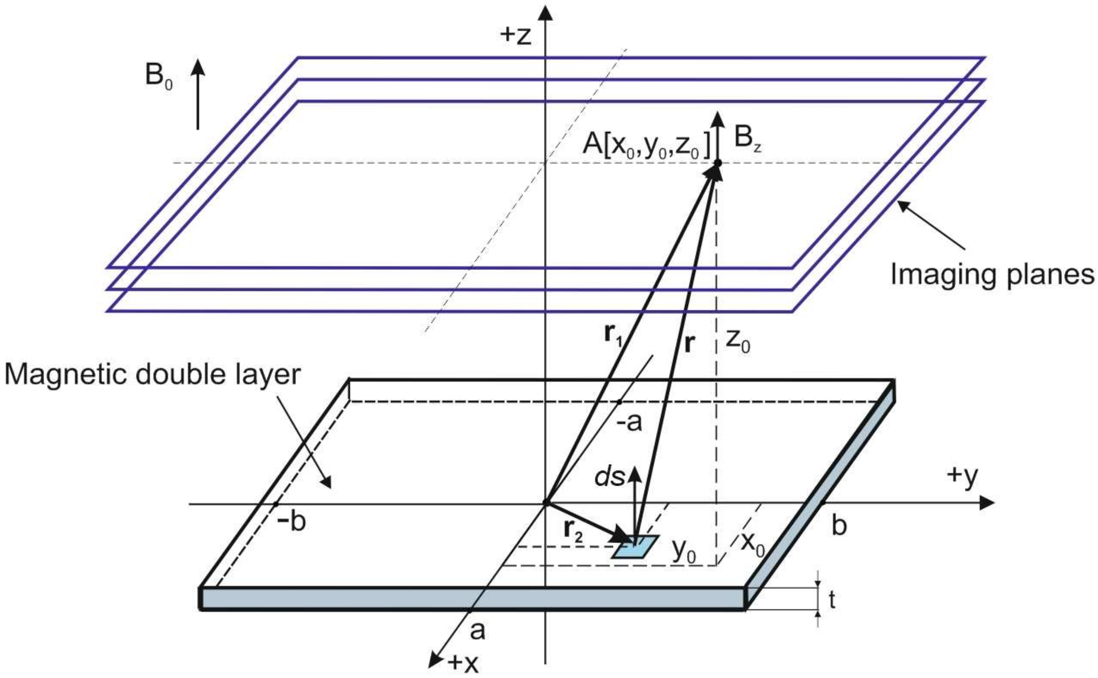

Fig. 1. Basic configuration of the magnetic double layer sample positioned in the x-y plane of the rectangular coordinate system.

Theoretically, it is possible to consider the magnetic double layer as magnetic dipoles continuously distributed on the surface S. Then, the overall magnetic moment **M** relating to the surface S could be expressed by a surface integral:

$$\boldsymbol{m}_{\mathrm{s}} = \int_{\mathrm{S}} \boldsymbol{M}_{\mathrm{S}}(\boldsymbol{r})\,\mathrm{dS} \quad \text{and} \quad \boldsymbol{M}_S = I\,\boldsymbol{n}\ , \tag{1}$$

where: $\boldsymbol{m}_{\mathrm{s}}$ - is magnetic dipole moment in a particular point, $\boldsymbol{r}$ - is a position vector, I - is a current equivalent to planar density of dipole moment of the magnetic double layer, and **n** - is a unit normal vector of surface S in a particular point.

Magnetic double layer is considered having a homogeneous density of the dipole moment that is oriented in every point in the direction of surface normal vector perpendicular to the layer surface. Bearing in mind the superposition principle, it is possible to express the vector potential of the double layer in the shape of surface integral:

$$\mathbf{A}(\boldsymbol{r}) = \frac{\mu_0}{4\pi} M_S \int_{\mathrm{S}} \frac{\mathrm{d}\boldsymbol{S}\times\boldsymbol{r}}{r^3} = -\frac{\mu_0}{4\pi} M_S \int_{\mathrm{S}} \mathrm{grad}\frac{1}{r}\times \mathrm{d}\boldsymbol{S}\ . \tag{2}$$

Using general formula for vector potential and magnetic induction $\mathbf{B} = \mathrm{curl}\,\mathbf{A}$, we get the final formula for magnetic induction of the magnetic double layer, which is also applicable for the closed current loop calculation as follows:

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

Assuming the position vectors according to Fig. 1:

$$\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2 \quad \text{and} \quad \mathrm{r} = \sqrt{(\mathrm{x}_0-\mathrm{x})^2 + (\mathrm{y}_0-\mathrm{y})^2 + (\mathrm{z}_0-\mathrm{z})^2}\ , \tag{4}$$

we can write the final formula for magnetic field induction generated by magnetic double layer in the space outside of the layer as follows:

$$\mathrm{B_z(x,y,z)} = \frac{\mu_0 I}{4\pi}\int_0^t\left[\int_{-a}^{a}\left[\int_{-b}^{b}\frac{3-I}{\left[(x_0-x)^2+(y_0-y)^2+(z_0-z)^2\right]^{\frac{3}{2}}}dy\right]dx\right]dz\,, \qquad (5)$$

where: t- thickness of the layer, [-a, a] and [-b, b] - horizontal dimension of the layer, integration limits. It is evident that vector potential of the magnetic double layer is equivalent to an expression for vector potential of the magnetic field of a very thin closed current loop on the condition that its current is equal to the surface density of a dipole moment of the double layer: $\boldsymbol{M}_S = I\,\boldsymbol{n}$.

Numerical evaluation of Eq. 5 is relatively problematic. After integration, we obtained relatively huge and complicated expressions. To calculate the general resultant expressions in analytical and numerical form, and to obtain the final graphical interpretation of the $B_z(x,y,z)$ component, we tried to exercise several methods: a) direct integration using surface integral in rectangular coordinate system, b) polar coordinate system, c) incremental calculation using rectangular elements.

For the final numerical calculation the following simplifying conditions were assumed: t- thickness of the layer is negligible, $t = 0$. For graphical interpretation of a rectangular magnetic double layer sample we assume the following relative values: $\mu_0 I / 4\pi = 1$, position of the imaging plane $z_0 = 0.5$, dimmensions of the magnetic double layer a = 3, b = 2. The resultant 3D and 2D plots of relative values of magnetic field for {x0, -5, 5}, {y0, -5, 5} are depicted in Fig. 2. The experimental results confirmed that the density plot representation corresponds best with the obtained MR image, see Fig. 2 right.

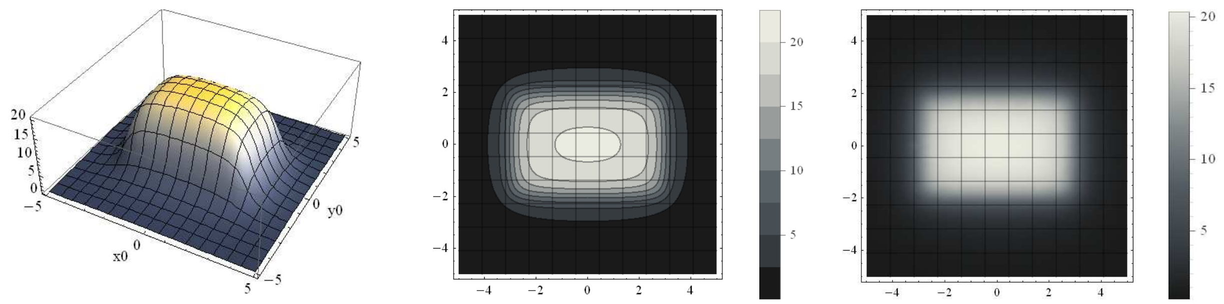

Fig. 2. Calculated magnetic field of the rectangular magnetic double layer sample positioned in the x-y plane of the rectangular coordinate system, relative values. From left to right: 3D-plot, contour plot, density plot.

Experimental Results

As a physical object, the soft magnetic sample made as a frame from a data disc, thickness 82 μm, was used. The sample was placed at the centre of a plastic holder – homogeneous phantom filled with liquid containing 5 mM $NiCl_2$ + 55 mM NaCl in distilled water. For the purpose of our experiments an MR imager (Esaote, Genoa, Italy), open-air permanent magnet 0.178 T with vertical orientation of the static magnetic field B_0, and horizontal radiofrequency coils with external tuning was used.

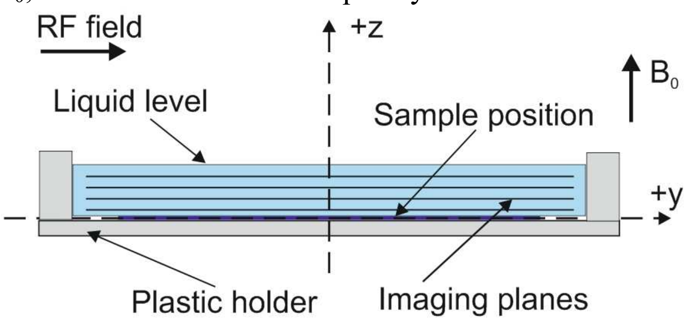

Fig. 3. For sample positioning, a plastic holder was constructed. Static magnetic field of the imager $\mathbf{B}_0$ is perpendicular and RF field is parallel with the plane of the holder.

A circular plastic holder used for sample positioning is depicted in Fig. 3. A very thin isolating membrane was placed at its bottom, separating the sample from the liquid. The height of liquid could be up to 15 mm. This liquid solution was used to shorten the measuring time of the imaging sequence GRE or SE and to speed up the data collection [7,8].

A special solenoidal RF transducing coil was constructed. The plastic holder together with the sample was placed into the centre of the permanent magnet of the imager, perpendicular to the orientation of the static magnetic field (B_0).

The next series of pictures shows theoretical and experimental results with imaging of magnetic field variations near the very thin soft magnetic materials detected by the magnetic resonance imaging method using carefully tailored GRE and SE measuring sequences.

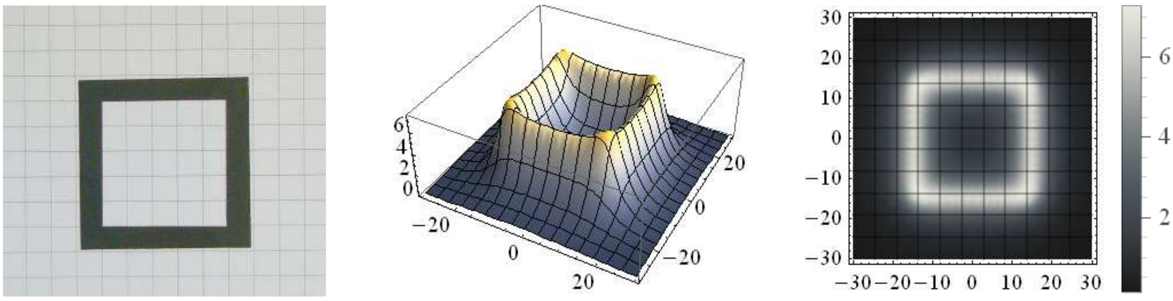

Fig. 4. Left: Original sample made as a frame (32 x 32 mm, width 4 mm) cut from a data disc, thickness 82 μm. Center: Calculated 3D image of the magnetic field distribution, 2 mm above the frame. Right: Calculated image of the magnetic field of the frame, density plot.

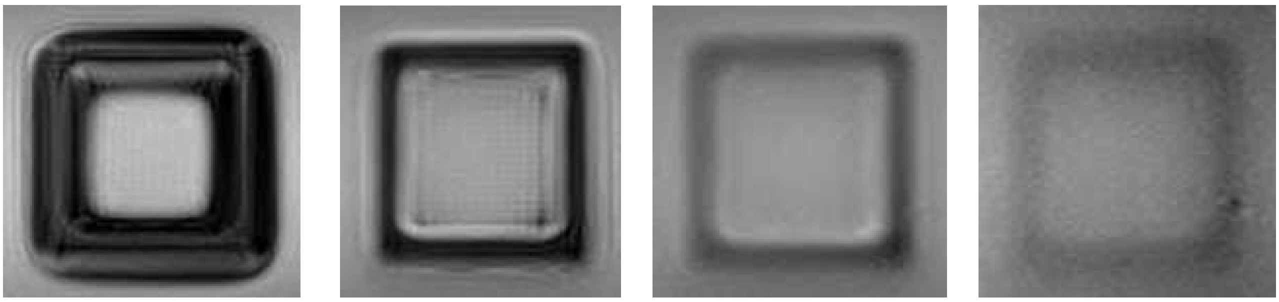

Fig. 5. Series of NMR images of the frame sample using GRE imaging sequence, TR = 440 ms, TE = 10 ms. Imaging distance from the plane of sample, from left to right: 4, 6, 8, and 10 mm. Thickness of the imaged layer: 2 mm.

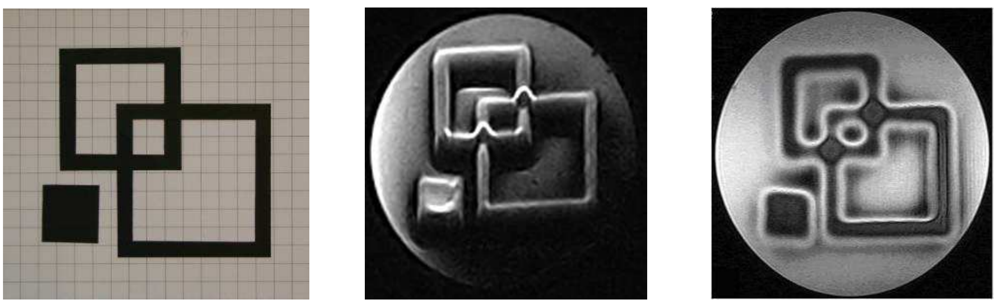

Fig. 6. Left: Photo of the 3 frame objects (cut from a data disc). Center: MR image using SE imaging sequence, imaging layer distance from the plane of the sample: 4 mm. Right: MR image using GRE sequence, imaging layer distance from the plane of sample: 6 mm. Thickness of the imaged layer: 2 mm.

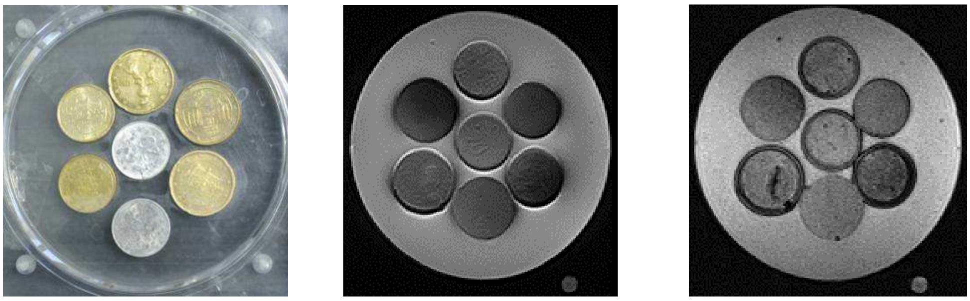

Fig. 7. Examples of imaging of commercial coins. Left: Photo of 7 coins. Center: MR image using SE sequence. Right: MR image using GRE sequence. Material inhomogeneities are clearly visible when GRE sequence was used. Imaging parameters are similar to Fig. 5.

Summary

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 field change detection caused by weak magnetic materials that may cause image artifacts even in the low-field MRI.

The goal of this study was to propose an MRI method used for soft magnetic material detection. Computation of the magnetic field variations based on double layer magnetic theory showed acceptable correspondence of theoretical results with experimental images.

Mathematical analysis of a rectangular object, representing a shaped magnetic double layer, showed theoretical possibilities to calculate magnetic field around any type of sample. Calculated 3D images showed expected shapes of the magnetic field in the vicinity of the double layer samples. Density plot images showed magnetic field variations caused by samples placed into the homogeneous magnetic field of the NMR tomograph, very similar to the images gained by magnetic resonance imaging using a carefully designed GRE measuring sequence.

Our experiments proved that it is possible to map the magnetic field variations and to image the specific structures of thin soft magnetic samples using a special plastic holder. The shapes of experimental MR images, Fig. 5, 6 and 7, correspond to the real shapes of the samples.

The resultant MR images are encircled by narrow stripes that optically extend the width of the sample. This phenomenon is typical for susceptibility imaging, when one needs to measure local magnetic field variations representing sample properties [9,10].

It is evident that imaging of the magnetic field variations of the soft magnetic samples can be performed by the GRE method based on the transfer of magnetic properties of the sample into the homogeneous planar phantom. This effect is strongest if the vector of the static magnetic field $B_0 = B_z$ is perpendicular to the sample plain.

Our experimental results are in good correlation with the mathematical simulations. This validates the possible suitability of the proposed method for detection of weak magnetic materials using the MRI methods. Presented images of thin objects indicate perspective possibilities of this methodology even in the low-field MRI.

The proposed method could be used in a variety of imaging experiments, e.g., on very silky samples, textile material treated by magnetic nanoparticles, biological samples, documents equipped with hidden magnetic domain, magnetic tapes, credit cards and travel tickets with magnetic strips, banknotes, polymer fibers treated by water solution nanoparticles used in surgery, and more.

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