Imaging and Mapping of Thin Layer Organic Materials Using Magnetic Resonance Imaging Methods

I. Frollo, T. Dermek, P. Andris

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

Abstract. *Thin organic samples were placed into the homogenous magnetic field of an imager based on nuclear magnetic resonance. Several samples like oil slicks and soft magnetic material (cut from a data disc) were tested. Theoretical computations based on a magnetic double layer were performed. For experimental verification an MRI 0.2 Tesla ESAOTE Opera imager was used. For experiments a homogeneous rectangular parallel piped block (reference medium) - a container filled with doped water - was used. The resultant image corresponds to the magnetic field variations in the vicinity of the samples. For data detection classical gradient-echo imaging methods, susceptible to magnetic field inhomogeneities, were used. Experiments proved that the proposed method is perspective for thin organic and soft magnetic material testing using magnetic resonance imaging methods (MRI).*

Keywords: thin organic samples, weak magnetic material, magnetic resonance imaging, gradient echo

1. Introduction

Imaging methods used for biological and physical structure, based on Nuclear Magnetic Resonance (NMR), have become a regular diagnostic procedure. Specific occurrence is observed when a thin layer organic or inorganic object is inserted into a static homogeneous magnetic field. This results in small variations of the static homogeneous magnetic field near the sample. It is possible to image the magnetic contours caused by the sample using a special rectangular phantom filled with a water-containing substance near the sample. The acquired image represents a variations of the basic homogeneous magnetic field of the imager superimposed with NMR signals directly detected from the sample.

Description of the first attempt of a direct measurement of the magnetic field variations utilizing the divergence in gradient strength that occurs in the vicinity of a thin current-carrying copper wire was introduced in [1]. 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 [2]. Single biogenic soft magnetite nanoparticle physical characteristics in biological objects were introduced in [3]. It was shown that for susceptibility imaging one need to measure local magnetic field variations of the basic magnetic field of the imager representing sample properties [4].

In this paper an imaging method used for thin organic and soft magnetic material detection was proposed. Computation of the magnetic field variations based on double layer magnetic theory and a comparison of theoretical results with experimental images were performed.

2. Subject and Methods

We suppose that the thin layer sample is positioned in the x-y plane of the rectangular coordinate system (x, y, z) and the thickness of the layer is neglected. According to Fig.1a the layer is limited by lengths of 2*a* and 2*b*, 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 $A[x_0, y_0, z_0]$.

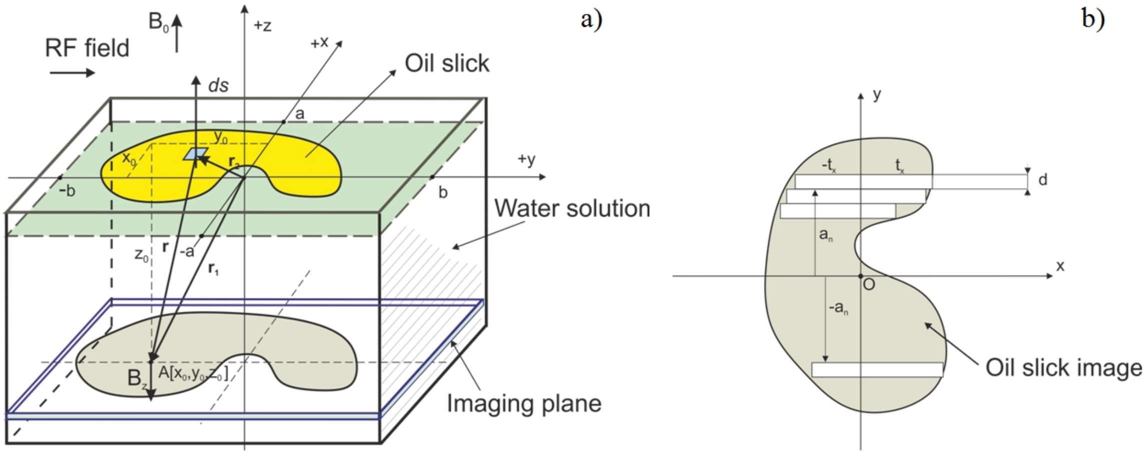

Fig. 1. a) Theoretical configuration of the thin layer sample positioned in x-y plane of the rectangular coordinate system. In calculations the thickness of the layer and imaging planes are neglected.
b) Oil slick thin layer sample positioned in x-y plane of the rectangular coordinate system. Principles of incremental elements integration.

For theoretical calculation of a thin layer sample the magnetic double layer model can be considered to have magnetic dipoles continuously distributed on surface ds. 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:

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

Using general formula for vector potential and magnetic induction $\mathbf{B} = \operatorname{curl}\mathbf{A}$, 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:

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

where $\mathbf{r}$ - is a position vector, I - is a current equivalent to planar density of a dipole moment of the magnetic double layer. Assuming the position vectors according to Fig.1 we can write:

$$\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2 \qquad \text{and} \qquad \mathrm{r} = \sqrt{(\mathrm{x}_0 - \mathrm{x})^2 + (\mathrm{y}_0 - \mathrm{y})^2 + (\mathrm{z}_0 - \mathrm{z})^2} \; . \tag{3}$$

The final formula in a double integral form is in the following shape:

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

where limits for integration are: [-a, a] and [-b, b].

Numerical evaluation of Eq. 4 in analytical form is relatively complicated. After integration one obtaines relatively huge and problematical 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 used a simplified incremental calculation model using rectangular elements, see Fig.1b.

For the final numerical calculation the following simplifying conditions were assumed: thickness of the layer is negligible and for the 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 = 3.2, dimmensions of the magnetic double layer t_x and $-t_x$ were asigned proportional to real slick thin layer dimensions.

The final simplified formula for incremental calculation using rectangular elements is in the form:

$$\mathrm{B_z(x,y,z)} = \sum_{-n}^{+n} \int_{-t_x}^{+t_x} \left[\int_{\pm a_n}^{\pm a_n \pm d} \frac{1}{\left[(x_0 - x_t)^2 + (y_0 - y_n)^2 + (z_0)^2\right]^{\frac{3}{2}}} dy \right] dx \qquad (5)$$

The resultant 3D and 2D plots of relative values of magnetic field for {x0, -40, 40} and {y0, -4, 36} 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.

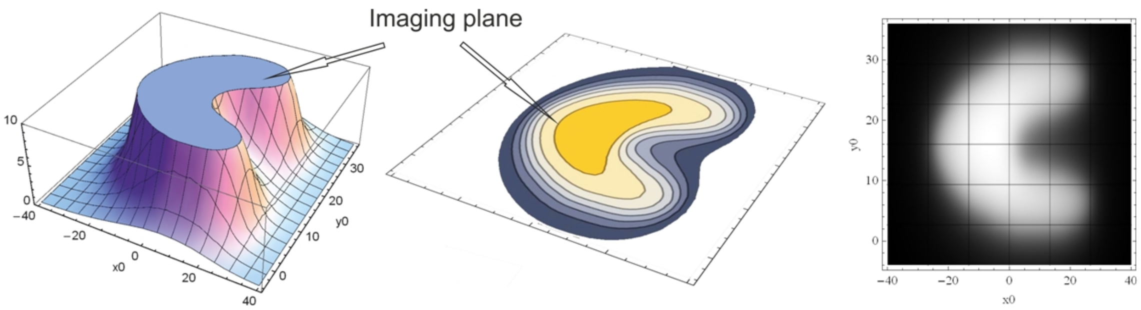

Fig. 2. Calculated magnetic field variations near the organic slick sample positioned in the x-y plane of the rectangular coordinate system, relative values. Left: 3D-plot. Centre: Contour plot. Right: Density plot.

3. Experimental Results

As a physical object, oil slick (dimensions 75 x 60 mm) was used. For comparison, a soft magnetic sample from a data disc, thickness 82 µm and a thin copper wire formed in the shape of an oil slick were used, Fig.3. The samples were placed at the centre of a rectangular plastic holder – homogeneous phantom filled with liquid containing 5 mM $NiCl_2$ + 55 mM NaCl in distilled water.

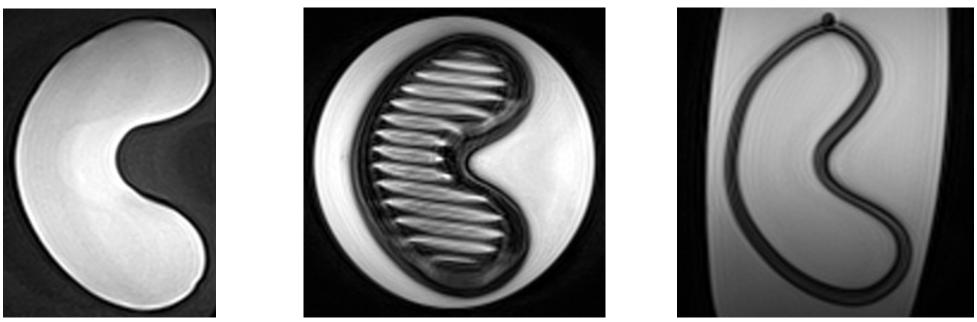

Fig. 3. Left: Image of the oil slick, GRE imaging sequence, TR = 800 ms, TE = 10 ms, slice thickness 2 mm. Center: Image of the soft magnetic sample, GRE, TR = 400 ms, TE = 10 ms, slice thickness 2 mm. Right: Image of the thin coil wire up into the oil slick shape, DC current 20 mA, GRE, TR = 500 ms, TE = 10 ms.

4. Discussion and Conclusion

A modified method for mapping and imaging of the planar organic samples and weak magnetic inorganic samples placed into the homogenous magnetic field of an NMR imager was proposed. First experiments showed the suitability of the method 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 an oil slick shape 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 GRE measuring sequence.

The experiments proved that it is possible to map the magnetic field variations and to image the specific structures of thin samples using a special rectangular holder. The shapes of experimental images, Fig.3, correspond to the real shapes of the samples. Some of the resultant 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 [4].

The experimental results are in good correlation with the mathematical simulations. This validates the possible suitability of the proposed method for detection of selected thin layer organic 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 fibres treated by a solution of nanoparticles in the water used in surgery, and more.

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