JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 5 No 4, 04006(4pp) (2013)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 5 № 4, 04006(4cc) (2013)

Practical Simulation of Magnetic Field of Permanent Magnets System to Explore Size of Magnetic Nanoparticles

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(Received 05 August 2013; revised manuscript received 05 November 2013; published online 10 December 2013)

We present the approach for computer simulation of magnetic field in a gap between two cylindrical permanent magnets connected by a yoke using FLEXPDE software. Proposed approach shows that this implementation allows using program code written "almost natural mathematical language" for successful simulation in practical goals of physical experiments. Particularly, the provided program code and idea of introduction of an effective backsides curvature of magnets have been used in the series of acoustomagnetic studies, i.e. this publication serves also as an example of "reproducible calculations" ideology providing all actual computational details and code.

Keywords: FlexPDE, Finite elements method, Computer support of experiments.

PACS numbers: 07.05.Tp, 75.75.Jn

1. INTRODUCTION

Modeling and simulation of a stationary magnetic field for various configurations of permanent magnets [1] is a one of classical magnetostatic problem keeping at the same time actuality up to present. First of all it is connected with the development electric motors and generators, where permanent magnets are a sufficient part, see for example a review corresponding modeling approaches in the book [2] and review [3].

Another hot topic of a permanent magnet configuration development and a simulation of their fields is low-field Nuclear Magnetic Resonance (NMR) setups [4, 5]. The construction principally close to this, which is also widely used for study of ferrofluids on a base of acoustomagnetic effect, see for review e.g. [6, 7, 8] and references therein. The difference consists of the usage oscillating sound field instead of electromagnetic one. Variations in concentrations and orientations of magnetic particles placed in a strong permanent magnetic field, which are induced by a sound wave, produce inductive signal detected by an inductor coil. This allow to explore microscopic size distributions of magnetic nanoparticles, details of sound wave propagation in confined liquids, etc.

However, the details of interactions leading to the generations of this inductive signal, sufficiently depends on mutual orientation of oscillating sound wave vectors and applied permanent magnetic field. Thus, its topology is an important characteristic in acoustomagnetic experiments. At the same time, it should be pointed out that requirements to the accuracy of magnetic field calculations are not so restrictive in the macroscopic magnetoacoustic experiments comparing with, say, high-effective electrogenerators and NMR setups due to averaged character of acoustomagnetic inductive signal. Thus, one need a relatively simple and straightforward tools, which allow to simulate the magnetic field of used system permenant magnets in the region overlapping direct measurements area, and to concentrate on issues more related to the acoustomagnetic details of an experiment.

For this reason, "on shelf" software seems to be more appropriate for usage by physicists in such a situation. Thus, the main goal of this work is to present method of simulation and corresponding program code for FLEXPDE software [9], which allows to evaluate appropriate computer simulations, and which was actually used for successful acoustomagnetic experiments [10].

2. MATHEMATICAL MODEL AND PROGRAM CODE

The view of magnetic system, which needs to be modeled is presented in the Fig. 1. Two coaxial cylindric magnets are fixed in a yoke forming magnetic circuit with a relatively wide gap. It should be pointed out that the construction can not be disassembled; thus the exact length of invisible parts of magnets inside fixing metal rings is unknown. The usage of light steel needles free arranged by magnetic force lines indicated also the following facts important for simulation: the metal yoke is sufficiently far for ideal, namely, the direction of needles shows that they are strictly directed to the permanent magnets even near the surface of curved and vertical parts of the yoke; needles are not parallel to horizontal parts of permanent magnets even near their surface; moreover, needles are directed practically normally to the cylindrical part around the rears of fixing rings near their connection with the curved yoke and fast take an inverse slope (i.e. directed to the backside of permanent magnet).

Thus, all these observations indicate that considered magnetic circuit is far from ideal one, which would closing magnetic lines inside of it. Combining with impossibility of disassembling the system and measurements of its inner magnetic properties, this situation requires to use effective boundary conditions, which would lead to reproduction of real structure and intensity of the magnetic field.

To control the value of magnetic induction, there were evaluated its measurements in the gap between magnets using Hall magnetometer with a relative error 1.5 % within the possible interval 1-300 mT. Referent

The article was reported at the International Conference «Physics and Technology of Nanomaterials and Structures», Kursk, 21-22 November, 2013 points were taken along the symmetry axis between magnets from central point upward with the step 5 mm. The set of numerical data is provided in the Appendix.

In this case, the most direct method for the calculation of magnetic field outside the magnets and yoke connecting them is the usage of a scalar magnetic potential ψ satisfying Laplace equation $\nabla^2\psi = 0$ in this free space.

However, the most important part of the problem statement is a formulation of proper boundary conditions. First of all, let us note that the yoke in our case only perturbs magnetic field of two permanent magnets. At second, the principal region of interest in physical experiments connected with a usage of this setup, is sufficiently wide gap between magnets. Particularly, in the works [7, 10], the pipe filled by ferrofluid had diameter 16 mm and was placed along the symmetry axis between magnets. At the same time, the column of ferrofluid had height up to 250 mm that is larger than the diameter of magnets. Thus, the magnetic field distribution in the normal direction to the common axes of magnets is an important parameter.

Thus, we use for simulation cylindrical co-ordinate system with axis coinciding with the common axis of both magnets. Correspondingly, the boundary condition along this axis is $\partial_r\psi = 0$, i.e. command natural (psi) = 0 in FlexPDE). The area of calculation is chosen in such a way that one can take the magnetic potential is taken as zero on its boundary and its derivatives (i.e. components of magnetic field) are practically equal to zero there. Corresponding properties for the values $R_d = 300$ mm and Delta = 200 mm for radial and longitudinal distances are confirmed by the direct magnetometer measurements. Whence, the boundary conditions on the outer boundary of the embedding space are $\psi = 0$ (the command value(psi) = 0 in FlexPDE).

The most important are boundary conditions on the surface of magnet. Ideal solitary cylindric permanent magnet has constant magnetization along its axis,

Fig. 1 – The magnet system: radius of cylindrical magnets 55 mm, height of cylinder 40 mm, where length of visible magnetic part 9 mm. The width of gap: 91 mm. Light steel needles free hanged by length fibers are arranged along magnetic induction lines visualizing them

surface of magnet. Ideal solitary cylindric permanent magnet has constant magnetization along its axis, i.e. magnetic are lines normal to its bases and parallel to its generator. In our case, the boundary conditions on the parallel surfaces divided by the gap are certainly $\psi = \text{const}$ as well, due to axial symmetry of the system.

On the other hand, the magnets in the considered system are connected by the yoke, i.e. it is magnetic circuit. Fig. 1 demonstrates that the lines of magnetic field are practically normal to the sides of magnets and are directed to them in the backside region. Therefore, to simplify the simulation we take $\psi = \text{const}$ over all boundary of magnetic region, representing additionally the backsides as curved surfaces. This gives the second set of adjustment parameters. Since the active magnetic regions of the system are smaller than the full yoke construction (see Fig. 1) and we are primarily interested in the simulation of magnetic field inside the gap between permanent magnets, we can neglect by the decreasing of magnetic potential (by absolute value) downto the base of yoke. However, the overall presence of the circuit is taken into account introducing reverse sign of the potential for the second magnet.

The resulting program code, which uses features described above, is presented below.

```
COORDINATES
xcylinder("z","r")
SELECT
nominmax
textsize = 25
contours = 40
vectorgrid = 25
VARIABLES
psi !Scalar magnetic potential
DEFINITIONS
{Loading of experimental data}
expdata = splinetable('magnetdataZ0.txt')
{magnets}
Rm = 55 !Radius of the disc
Hm = 40 !Thickness of the disc
Rd = 20 !Length of the curved part
Pm = 6.05e3 !Magnetic potential of the magnet surface {Gap between magnets}
Gap = 91
{Embedding Space}
{Distance from the magnet to outer boundary along axis}
Delta = 200
Length = 2·(Hm + Rd + Delta) + Gap {Length of the embedding space}
Rad = 300 {Radius of the embedding space}
{Definition of a magnetic induction}
B = – grad(psi)
INITIAL VALUES
psi = 0
EQUATIONS
del2(psi) = 0
BOUNDARIES
Region 'Empty Space' {The space around magnet}
!Axis of symmetry
start(0,0) natural(psi) = 0 line to (Delta,0)
!1st magnet's backside
value(psi) = Pm
```

```
spline to (0.05·Rd + Delta,Rm·0.2) to
(0.1·Rd + Delta,Rm·0.25)
to (Delta + Rd,Rm)
!1st magnet's top
line to (Delta + Rd + Hm,Rm)
!1st magnet's plane face
line to (Delta + Rd + Hm,0)
!Axis of symmetry
natural(psi) = 0 line to (Delta + Rd + Hm + Gap,0)
!2nd magnet's plane face
value(psi) = – Pm line to
(Delta + Rd + Hm + Gap,Rm)
!2nd magnet's top
line to (Length – Delta – Rd,Rm)
!2nd magnet's backside
spline to (Length – (0.1·Rd + Delta),Rm·0.25)
to (Length – Delta – 0.05·Rd,Rm·0.2)
to (Length – Delta,0)
!Axis of symmetry
natural(psi) = 0 line to (Length,0)
!Outer boundary
value(psi) = 0
line to (Length,Rad) to (0,Rad) to close
PLOTS
vector(B) zoom(0.75·Delta,0,Length 1.5·Delta,
1.5·Rm)
as 'Induction of the magnetic field'
elevation(fit(xcomp(B)),expdata)
from(Length / 2,0)to(Length / 2,100) as 'Bz '
contour(xcomp(B)) zoom(0.5·Delta,0,Length-
Delta,2·Rm)
as 'Bz'
contour(ycomp(B)) zoom(0.5·Delta,0,Length –
 Delta,2·Rm) as 'Br'
END
```

Results of its implementation are shown in Figs. 2-3. The obtained configuration has allowed to use two properties of the magnetic field configuration: i) its horizontal direction along the vertical line of symmetry, where the tube filled by ferroliquid was placed and satisfactory uniformity within each tube's cross-section (the described numerical simulation namely allows to explore required field configuration) and ii) non-uniformity of the field strength along the tube (as well controlling field's configuration within regions corresponding filled parts of the tube). Whence, this all results in a detailed study of the influence of crossed acoustic and magnetic field on acoustomagnetic phenomena, see the details in [10].

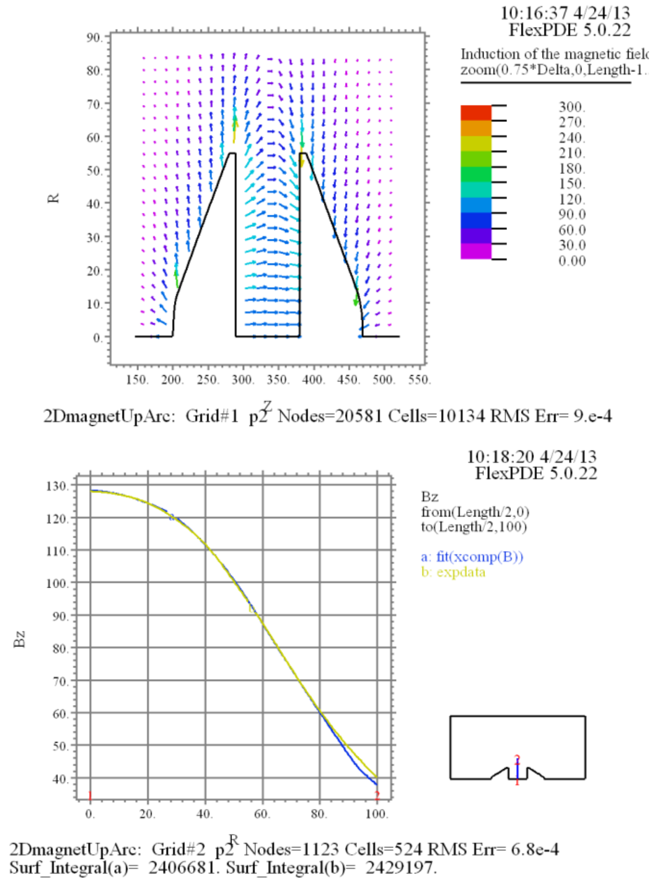

Fig. 2 – Plots of the calculated magnetic field (in mT). Left panel: vector plot of magnetic induction, where lengths of vectors are proportional to the it's absolute value. Right panel: comparison of calculated magnetic field induction (dark (blue in color online) curve) and experimental referent one (light-gray (yellow in color online) curve) along the line normal to the symmetry axis and crossing it in the middle point between magnets

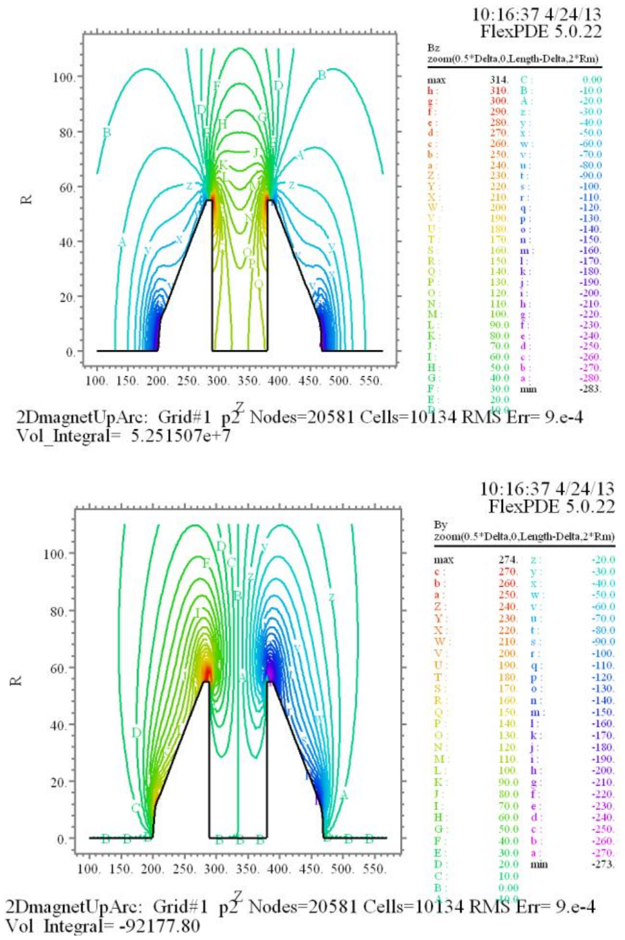

Fig. 3 – Plot of magnetic induction lines for the axial (left) and radial (right) components of magnetic field (in mT)

3. SUMMARY

In this work we have presented explicitly the program code for FLEXPDE software and discussed its development for the computer simulation of a magnetic field in the gap between two coaxial permanent magnets fixed by a yoke. It has been shown that yoke's influence can be successfully reproduced by introduction of effective curved backsides of magnets. Thus, one need only two parameters: this quantity and a value of scalar magnetic potential on magnets surface. To adjust these parameters, a user need simply collate experimental data along of one characteristic line (that could be easily obtained) and results of simulations. Here the value of magnetic induction on the middle point of axes primarily determines value of surface scalar potential and a shape of curve is influenced by the parameter of the effective backside.

As well, we consider this work in accordance with "reproducible computations" ideology [11], i.e. providing to readers all possible data, computational approaches and code, which was used for obtaining scientific results. Particularly, the provided code has been implemented for the analysis of experimental investigations and their physical interpretations in [10].

ACKNOWLEDGEMENT

AMS is grateful for funding of this work via the Grant of the President of the Russian Federation for support of young researchers № 14.124.13.5498-МК "The Details of Mechanisms of magnetization disturbance of magnetic fluid in a sound wave".

APPENDIX A

The experimental data on induction of magnetic field (in mT) in referent points (in mm along radial direction), containing in the text file magnetdataZ0.txt:

```
r 14
0
5 10 20 30 40 50 60 70 80 90 100 110 115
data
128
127.7 127 124.4 119.3 111.75 100.35 87.5
73.55 60.6 49.35 40.1 32.5 29.75
```

The structure of the data representation: name of the co-ordinate (z), number of referent points (14), the string of values of z-co-ordinate in these points; identifier (data), the string of values of magnetic induction in above- mentioned referent points.

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