# 3D Magnetic Field Measurement, Visualisation and Modelling

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***Abstract.*** *Automated apparatus for the measurement of 3D magnetic field was constructed using Hall probes and 2D positioning system. The apparatus was tested by the field of ring permanent magnets. The measured field is visualised by graphs for 1D lines, surfaces for 2D areas and vectors or flux lines for 3D space. The magnetic field was modelled by coupled currents and then by the application of Biot-Savart Law. The agreement with experiment is good either for the simplest assumption of uniform magnetisation. The model can be refined.*

*Keywords: Hall probe, Permanent magnets, Automated measurement, Scientific visualization, Permanent magnet modelling*

## 1. Introduction

The magnetic force in the form of magnetic coupling is used in many technical and scientific applications, especially for contact-less force, momentum, contact-less shaft bearing, levitation, as examples. The survey of magnetic coupling methods and applications can be found in literature [1]. The effective realisation of such apparatus is complicated, money and time consuming. Therefore, ways of optimum theoretical design are welcomed. The first step is the modelling of magnetic field. In the literature either the method of non-existing magnetic charges is used in analogy with electrostatic field [2] or a lot of finite element methods (FEM) are applied. However, other methods exist.

On the other hand magnets are complicated components and their material parameters (magnetization) cannot be known in details. Magnets need to be modelled and the models are subjects of numeric computation. The calculated magnetic field and other properties are approximate ones. The experiment is necessary in order to find the difference between reality and model. It also makes possible the model improvement. Visualization of complete calculated or measured magnetic field is necessary for perfect understanding of the apparatus. It is the reason, why we concentrate to three areas: modelling, visualization and measurement.

## 2. Subject and Methods

According the introduction three areas, magnetic field measurement, visualization and modelling, will be mentioned here. We limit here to permanent magnets, but the approach can be used for electromagnets or any other combinations as well.

As for magnetic field measurement, the 3D Hall probe was found to be the best practical device for magnetic field scanning. In order to make 3D measurement, two perpendicular positioning system of Hall probe is used for its location in a horizontal plane. The vertical probe shift is made manually. The step motors are used for the realization of horizontal motion. The apparatus is controlled by the electronic system that realizes the instructions from computer program that is written in the low level C language for step motor motion and in high level MATLAB for automated measurement. Many parameters can be set in order to make the measurement as quick as possible.

The simplest way of magnetic field visualization is the graph. Graphs are effective quantitative visualization means, but they deal only with a small 1D part of the magnetic field. Therefore, the surface graphs are used for illuminating prezentation of the 2D field in the plane. For 3D field the flux density vectors or lines were found as the best vizualization mean. All the objects are produced by MATLAB after the finishing the measurement or calculation.

As for the permanent magnet model, the magnet is given very simply by its geometrical parameters and magnetization ***M*** that fully describes its magnetic properties. There are two basic ways how to calculate all the magnet effects. They can be derived by superposition either from elementary magnets of magnetic momentum ***M***d*V* in the magnet volume or from the coupled elementary volume $\boldsymbol{i_m}$d*V* and surface $\boldsymbol{j_m}$d*S* currents. Their densities are derived from volume and surface distribution of magnetization by formulas [3]

$$\vec{i}_m(\vec{r}_0) = \mathrm{rot}\,\vec{M}(\vec{r}_0) \qquad \vec{j}_m(\vec{r}_0) = \mathrm{Rot}\,\vec{M}(\vec{r}_0) = \vec{n} \times \left(\vec{M}_2(\vec{r}_0) - \vec{M}_1(\vec{r}_0)\right) = -\vec{n} \times M(\vec{r}_0)\,. \qquad (1)$$

Thanks to its clarity, the method of elementary coupled currents was preferred. The magnetic flux density ***B*** due to coupled currents is then given by Biot-Savart Law

$$\vec{B}(\vec{r}) = 10^{-7} \int_{(S)} \frac{\vec{j}_m \times (\vec{r} - \vec{r}_0)}{\left|\vec{r} - \vec{r}_0\right|^3} \mathrm{d}S + 10^{-7} \int_{(V)} \frac{\vec{i}_m \times (\vec{r} - \vec{r}_0)}{\left|\vec{r} - \vec{r}_0\right|^3} \mathrm{d}V\,, \qquad (2)$$

where $\boldsymbol{i_m}$ and $\boldsymbol{j_m}$ are coupled volume and surface current density, respectively, *S* and *V* are the surface and volume of the magnet, respectively, ***r*** is a position vector of the point, where the flux density ***B***(***r***) is calculated, $\boldsymbol{r_0}$ is the position vector of surface and volume elements d*S* and d*V*, respectively. The formula requires numerical integration and can be used for the calculation not only of magnetic field, but also for magnetic forces.

## 3. Results

The permanent magnet has a shape of a thin ring with inner diameter of 25 mm, outer diameter of 70 mm and height of 4 mm. The magnetization was 1.2 T according to the data sheet of producer. It is the only known material parameter.

We realized fully automated apparatus shown in Fig. 1 together with its block scheme of control. Both the transport devices and 3D Hall probe are the basic parts. The driving step motors, control system and computer make possible the automated measurement. The scanned area is relatively large, about 0.5 times 0.5 meters. Theoretical accuracy is about 0.1 mm; in practice it reduces to a value bellow 1 mm. Due to the small, but non negligible, dimensions of Hall probe, the average flux density is measured rather than its true point value.

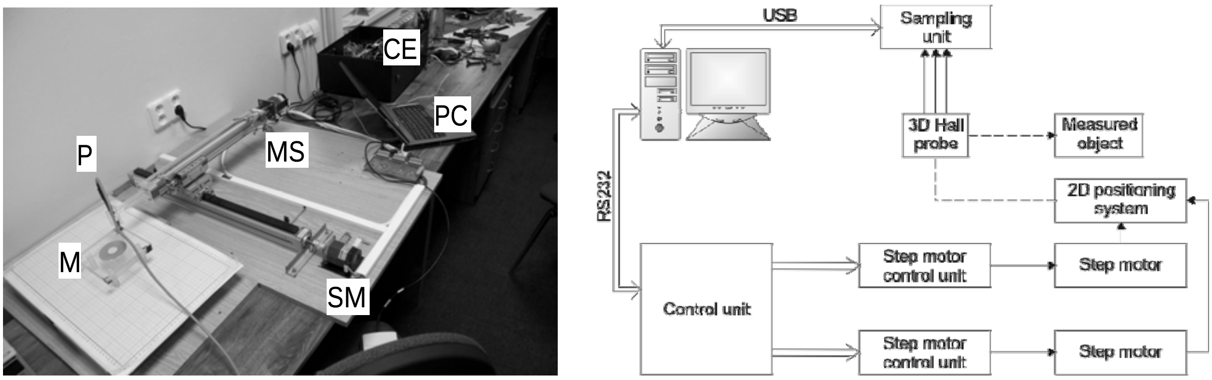


Fig. 1. Apparatus and its block schema: M – magnet, P – probe, MS – mechanical shift, SM – step motor, PC – controlling computer, CE – control electronics.

All the components of the magnetic field were measured by the step of 1 mm in both the *X* and *Y* directions. Typical results in the form of surface graphs are shown in Fig. 2. The *x* component of magnetic flux density, $B_x$, is in left hand side of Fig. 2, while the most important component $B_z$ is in the right hand side of Fig. 2

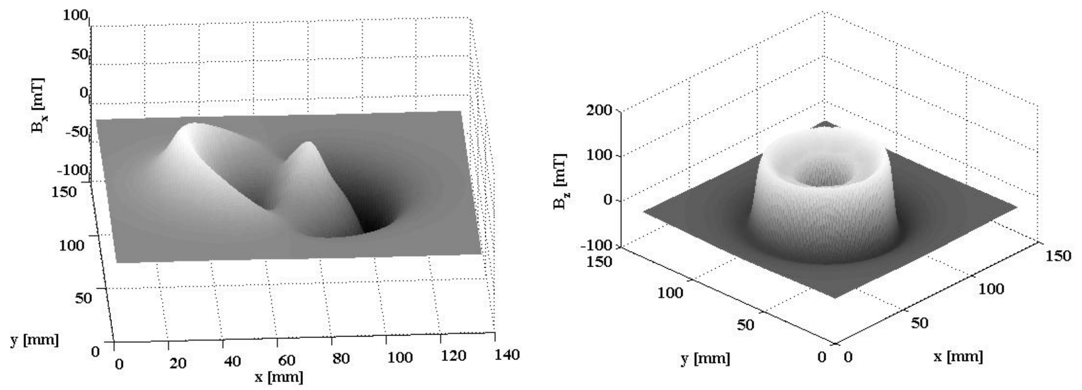


Fig. 2. Surface graphs of magnetic flux density 2 mm from magnet surface. Component $B_x$ is on the left hand side and the $B_z$ one on right hand side.

The same field in the vector form is at Fig. 3. Left hand side shows vector representation of magnetic flux and right hand side displays several important flux lines of magnetic field.

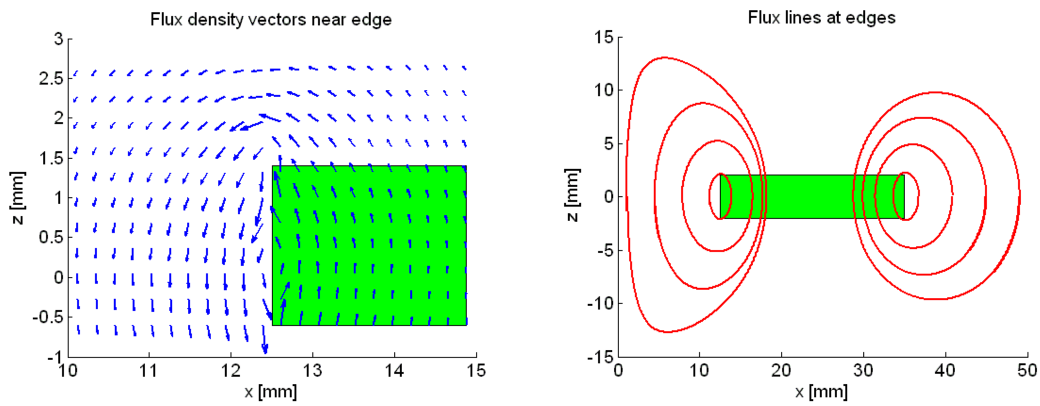


Fig. 3. 2D cut of flux density near permanent magnet edge (left) and flux lines near the face (right)

Comparison of experiment and model for central cut in the form of classical graph is in Fig. 4.

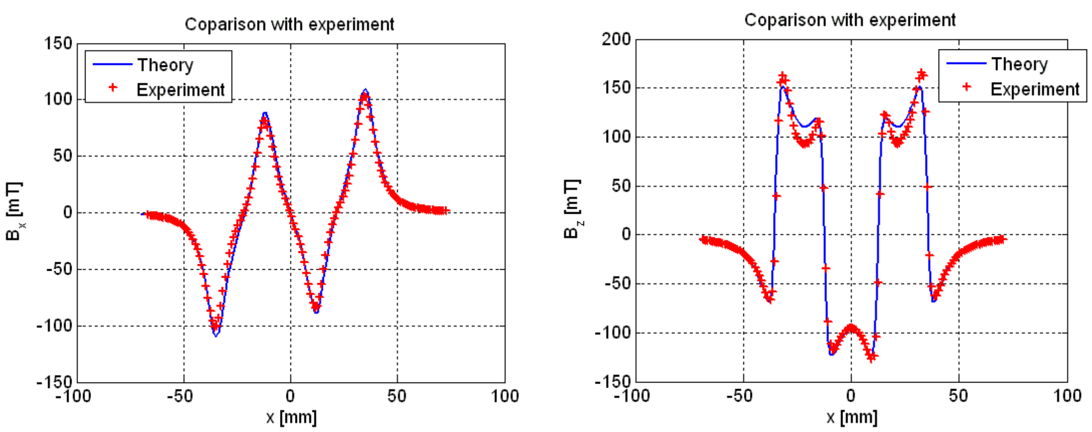


Fig. 4. Comparison with experiment of magnetic flux at permanent magnet surface. X-component of magnetic flux on the left side, z -component on the right side.

## 4. Discussion and Conclusions

Only preliminary results of automated magnetic field measurement were presented. Main problem is the correct position of sample that is necessary for simple comparison of experiment and theory. The use of absolute coordinates with exact and rigid sample positioning should be realized. The speed of measurements is relatively low. Measurement in a plane by 140 x 140 points takes about 300 minutes. Therefore, automation of the shift in the 3rd dimension is not necessary.

Several methods of magnetic field visualization were presented. Although the standard graph contains the smallest part of information with respect to the 3D vector field, the information is ready to direct use, see Fig. 4, for instance. Qualitative information on plane regions is in surface graphs, typical representatives are in Fig. 2. The full description by the use of 3D vectors is not usually transparent. It can be valuable in special cases. However, the use of vectors and flux lines in selected 2D regions is very descriptive, see in Fig. 3.

The main purpose of the work is the comparison of model and experiment. The outlined model needs only geometrical dimension of magnets and one material parameter, magnetization. In the first step we suppose the uniform magnetisation. As it follows from Fig. 4, the agreement with experiment is good with an exception of the field near sample edges. The magnetization is not uniform in rectangular sample cross section and the highest deviations can be expected at sample edges. The agreement can be improved, if we refine the model by the non-uniform magnetization. The only straightforward way how to find the correct distribution of magnetization, is the use the FEM.

We have used the model of coupled currents and integral formulae for the calculations. Usually the FEM is preferred. Our approach has several advantages. The programming is relatively simple, the user has full check at all steps of computation, and there are no problems with boundary conditions especially in infinity. All the quantities can be calculated at any given point and the accuracy can increase to any reasonable value. The only disadvantage is relatively long computation time, but the cluster can be used, if necessary.

The measured and modelled results were used for the numerical calculations of repulsive force between ring magnets used in practice. The results agree well with experiment in several orders of the force [4]. Also the momentum, which is difficult to measure, was found.

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