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MODELLING THE MAGNETIC FIELD DISTRIBUTION IN THE MAGNETIC SUSCEPTIBILITY BALANCE DESIGN

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The following paper describes the modelling of the magnetic field distribution during the design phase of a new magnetic susceptibility balance. Various permanent magnets arrangements were tested, to find one with the closest to linear magnetic field gradient area. The modelling was performed with the Whitney elements method and magnetostatic Maxwell equations using the free open-source Elmer FEM software. The software shows significant flexibility and allows for user-defined solvers, methods and equations. The meshes were made with the open-source Netgen 5.3. The spatial distribution of the calculated magnetic field is presented in both cases: with and without the sample.

Keywords: magnetic field modelling, magnetic susceptibility balance, finite element method.

1 INTRODUCTION

The devices such as the Faraday balance, Gouy balance and Evans balance are designed for the magnetic susceptibility measurements of various dia- and paramagnetic materials [1]. They rely on the specially designed electromagnet poles, or permanent magnet arrangement to create and measure the force or torque between the magnetic field source and the investigated sample [2]. In the design process of these devices, the magnetic field spatial distribution is of highest importance, and imposes the working principle of the given balance type. In the case of permanent magnet balances, the area with linear gradient of the magnetic field is desirable, as it greatly simplifies the calculation of the susceptibility on the base of measured force.

During the thermogravimetric analysis of superparamagnetic samples [3], an idea to measure the change in their magnetic susceptibility, depending on temperature, has emerged. There is, however, no possibility of designating this value on previously proposed test stand. A precise value of magnetic induction on accurate positioned sample was necessary, along with the description of its geometry. All of them are possible to calculate and determine with computer simulations. Our calculations utilized the finite element method handled by Elmer software, which allowed to visualize the distribution of the magnetic field in space depending on sample's current position [4].

2 MAGNETIC SCALES

For measuring the magnetic susceptibility in test stand, it would be best to apply static magnetic weight [5]. Static methods are based on the measurement of the force acting on the sample. If this field is inhomogeneous then the magnetic force is described by the following formula

$$F = \mu V * \frac{dH}{dz} \tag{1}$$

where V is volume of the sample, dH/dz is field gradient, μ is the relative magnetic permeability of the sample.

Now for the measurement of magnetic susceptibility, several kinds of balances are used; those most commonly used are described below.

In Gouy balance the sample is placed between the flat magnetic poles' surfaces. The force acting on the sample is balanced by the weight on the opposite beam. It is essential to maintain constant cross section of the sample, which is often achieved by pouring powdered sample into a suitable container. This allows to specify the volume of the sample and thus, simplify the formula [5] for magnetic force.

The other condition of a correct setup is that there is a significant difference between magnetic field values on both ends of the sample. It would be best if the end of the sample farther from the center was surrounded by a smaller field than the other. Whole sample should also be in the field with linear characteristics which strongly simplifies the formula describing the force acting on the sample (as in Gouy balance, shown in Fig.1) [5]

$$F = \frac{1}{2}\chi S(H^2 - H_0^2) \tag{2}$$

where H and H_0 is respectively the strength of magnetic field on the bottom and the top end of sample, S is the cross sectional area of the sample, χ is the sample's magnetic susceptibility.

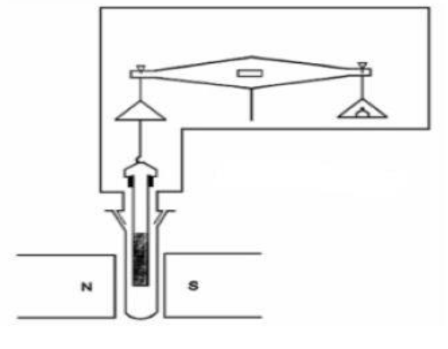

Fig. 1. Gouy balance [5]

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Faraday scale allows for measurements of small samples only. It is required by the condition that the entire sample has to be in the magnetic field. A large value of *H*.d*H*/dz product is also important and is achieved by using wedge-shaped magnets. In addition to the measurement of the magnetic susceptibility of the materials, a Faraday balance allows to analyze the saturation magnetization, Curie temperature and qualitative analysis of ferromagnetic phases.

Sucksmith balance is a mechano-optical device. The force that acts on the sample deforms phosphor bronze ring on which two mirrors are placed. This causes a shift of the light dot in proportion to force value. Possible temperature range is 4-1300 K, and the measured force should be contained between 10^{-5}-10^{-1} N.

The main difference between Evans balance [6] and the previous devices is that it measures the force exerted on magnets rather than on the sample itself. The sample is typically placed in a test-tube between one pair of magnets on the beam. The second pair is fitted on the other side of it. The sample interacts with magnets, causing the beam to rotate horizontally by a small angle. This movement causes a change in magnetic field of a coil placed between the second pair of magnets. The rotation is detected by the optical transducer located below the beam. It sends a control signal in order to adjust coil's electric current and consequently – balance the beam. The force between the sample and the magnets is proportional to the mentioned electric current. One of the advantages of this device is a relatively low cost, since it does not need precise weighing unit. Another is the speed of action, as in case of Faraday and Gouy balance the measurement is very time consuming and requires immense precision. The sample must be precisely positioned in order to receive correct values of constants. Evans balance offers a complete measurement in a matter of seconds at the cost of slightly lower accuracy and sensitivity. This device allows for measurement of the susceptibility of solids, liquids and gases from a wide range of dia- and paramagnetic materials.

For further analysis of superparamagnetic materials, a new type of balance will be introduced. It bases greatly on Gouy idea, since it is the simplest one design- and concept-wise. In this case, we will be interested in the linear distribution of the magnetic field in a fairly wide range, so to be able to fit the sample in it.

3 DISTRIBUTION OF MAGNETIC FIELD

In order to conduct necessary simulations, an appropriate digital model was required. The meshes were created in the open-source environment: Netgen 5.3. The modelling itself was performed using Whitney elements method and magnetostatic Maxwell equations implemented in open-source Elmer FEM software. Further simulations and visualizations of magnetic fields were grounded on finite element method. A series of simulation previews has been conducted including numerous configurations of magnet shapes (disc, ring), numbers (single, double) and samples (plate, cylindrical or without a sample). The absolute and component values of magnetic fields were mapped and presented as a color maps. The analyzed field was generated by the ferrite F30 magnets. Field distributions were examined in the case of a single magnet and a pair of magnets with poles oriented both correspondingly and not.

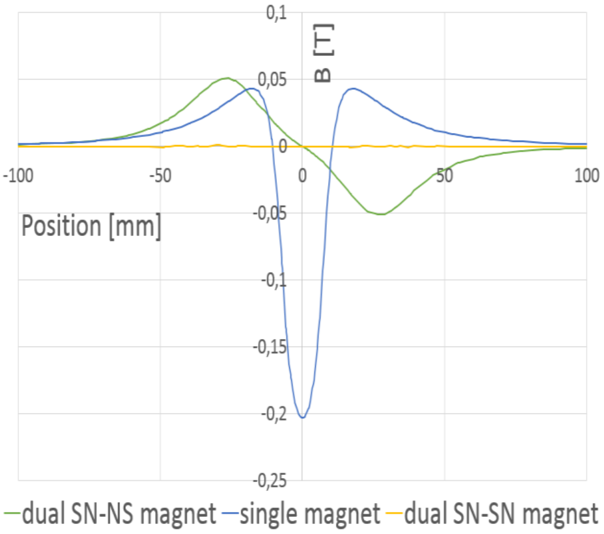

Fig. 2. Field distributions of magnets setups.

As shown on the chart (Fig.2), in the case of a pair of magnets arranged non-correspondingly (SN-SN), marked with a yellow line, magnetic flux density in the vertical direction will be eliminated and thus, will not be suitable for this specific magnetic scale.

Single magnet, marked with a blue line, has two sections with nearly linear characteristics. The first is located at a distance of about 60 to 20 mm from the center of the magnet; the second - from 15 to 5 mm. Second section is not relevant, due to relatively short range divided to two areas of different signs around zero. Although the first section has worse linearity, it covers far wider area and the field does not change its sign.

In case of a pair of magnets arranged noncorrespondingly (SN-NS), marked with green line, we can also designate two sections with linear characteristics. The first one lies between 60 mm and 30 mm and the other from 20 mm to the center of the system. The problem with the second section lies in the fact that the field decreases while approaching the center of the layout. Gouy scale provides that the field is increasing in the direction of the center of the system, so that the farther end of the sample is located in lower field. Since the force exerted on the sample is proportional to the difference of magnetic flux densities on sample's ends and the length of the sample is fixed, the greater the overall flux density the better. Thus the setting with two magnets seems to be more beneficial than the one with a single magnet. The distance of 30 mm is sufficient for placing a sample.

The tests were carried out using the ring magnets. It was examined whether the field of cylindrical magnets differs from the one coming from ring magnets. The comparison of both fields is presented in Fig. 3.

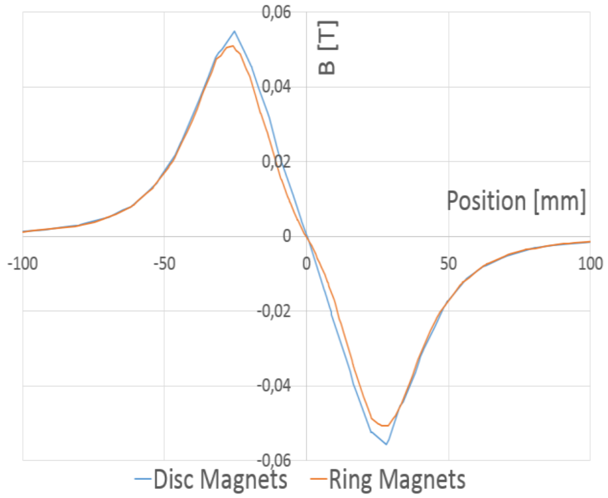

Fig. 3. Field distributions of ring and disc magnets

The comparison of the results received for disc and ring magnets has shown that geometrical difference does not influence neither the quality of measurement nor output values. The experiment showed that the difference between magnetic field distributions is insignificant for both types of magnets. The main difference reveals itself around the maximum and minimum, where it reaches 4 mT.

In Fig.4 there are six cross-sections in the XY plane presented, showing the distribution of the magnetic field at the distance of: 0, 12, 24, 36, 48 and 60 mm from the center of the layout. Unlike graphs, these show the spatial distribution of the fields in which the sample will be placed.

4 MAGNETIC SAMPLE

In this case, the superparamagnetic sample will be used. This is an innovative material that combines the characteristics of a para- and ferromagnetic materials. Same as the paramagnetic material, superparamagnet does not have an internal magnetic field without the external magnetic field. Superparamagnetic material consists of small (up to 10nm) single domain particles and their magnetic susceptibility is much greater than in paramagnets. These features make it to similar to ferromagnets. After specifying a range in which the sample will be located, it had to be put there virtually. An analysis of the field distribution after its introduction has been performed. For sake of comparison, the simulation has been carried out for 3 different sample positions. The sample has the shape of a cylinder, and the value of its magnetic susceptibility is 20.

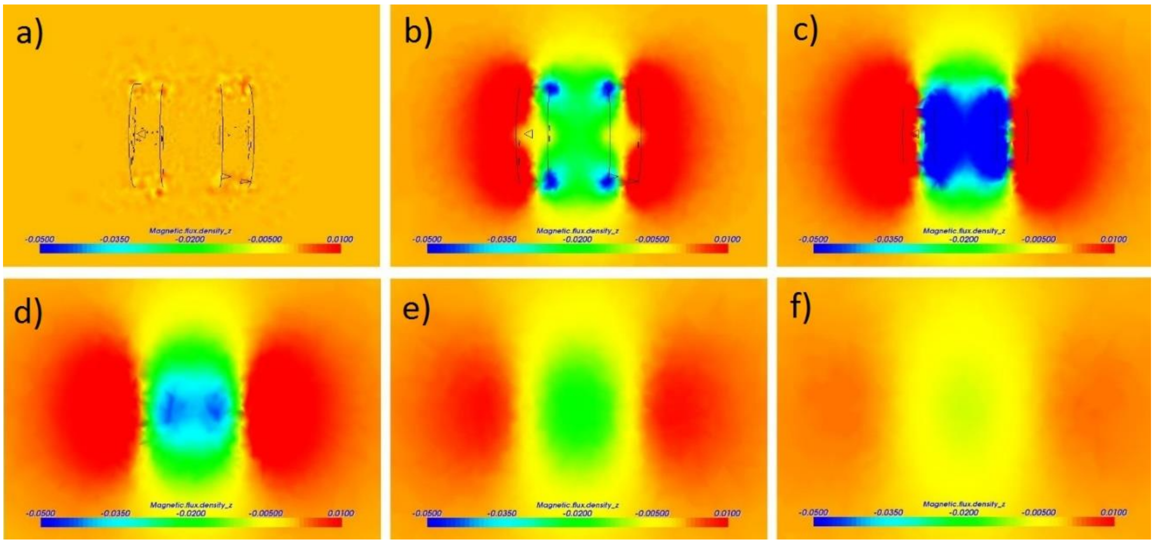

Fig. 4. Distribution of the magnetic field at the distance of: 0, 12, 24, 36, 48 and 60 mm from the center of the system. Values range from -0,05 T to 0,01 T

From Fig. 5 we can see that, depending on the placement of the sample, the distribution of magnetic field varies significantly. The greater the value of the field in which the sample is, the larger the sample's inner field. The chart on Fig.6 shows the differences in both the shape and the value of magnetic field in the sample depending on whether the field increases, decreases or reaches its maximum along the sample. The shape of the sample is also important. Two sample shapes were analyzed: cylindrical and flat, which can be seen on the following figure.

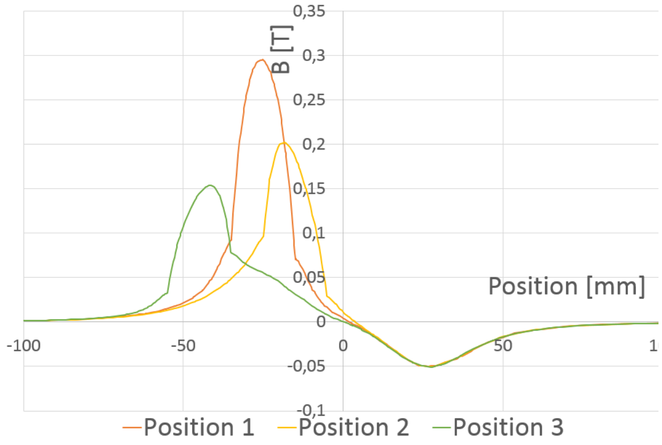

Fig. 5. Field distribution depending on sample position

A flat sample, represented by the orange line, has a jagged course feature on the contrary to the smooth one of the cylindrical sample (yellow line). The value of the magnetic field of the sample is growing rapidly and are characterized by strong variations, other that the cylindrical one, in which the variations are minimal. In both cases, there are visible variations of the magnetic field in the vicinity of the sample edge, outside its volume, but they are similar for both shapes. It is caused both by the demagnetization fields, and numerical noise in calculations.

5 SUMMARY

Superparamagnets are a relatively new type of materials. The means and methods to measure their properties, especially the magnetic ones, are still under development. In this paper we intended to contribute to this process. After reviewing contemporary solutions of the measurement of magnetic susceptibility of paramagnets it was decided that the static magnetic balance is the most appropriate type. The presented test stand idea is based on Gouy balance principle.

Results given by the magnetic field distribution simulations were further compared to ones received on a teslameter test stand constructed in the Institute of Metrology and Biomedical Engineering. Both simulation method and its final output were highly corresponding with test results, which proves that this modelling methodology can be successfully used for further simulations in the design phase of permanent magnet devices. All of the software used is open-source, and provides cost-free solution for academic and industrial designers.

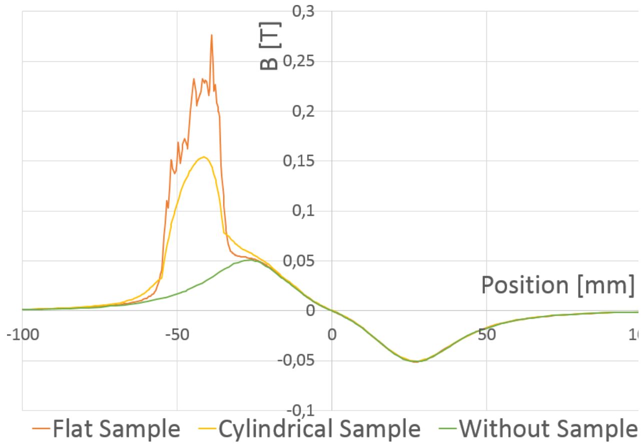

Fig. 6. Field distributions depending on sample shape

Furthermore, the shape of the sample is a critical factor determining the distribution of the magnetic field inside the sample itself, mainly because of demagnetizing fields. A cylindrical shaped sample is far more suitable for measurements than a flat ribbon one.

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