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# Magnetic disturbances caused by magnetic contamination of plastics

***Abstract**. In the study of low magnetic fields precision magnetometers working in a differential system are used. Two optically pumped magnetometers working in a differential system allow for precise measuring of disturbances in the magnetic field. In order to attain high accuracy of magnetic field measurement, it is necessary to use appropriate materials for the construction of a magnetometric system, particularly of those located closely to the magnetometric sensor. These materials can disturb the magnetic field.*

***Streszczenie.** W pomiarach słabych pól magnetycznych stosowane są precyzyjne magnetometry pracujące w układzie różnicowym. Dwa magnetometry pompowane optycznie pracujące w układzie różnicowym pozwalają na dokładne pomiary zakłóceń pola magnetycznego Ziemi. W celu osiągnięcia dużej dokładności pomiaru pola magnetycznego konieczne jest stosowanie odpowiednich materiałów do budowy systemu magnetometrycznego, szczególnie tych znajdujących się blisko czujnika magnetycznego. Materiały te mogą zaburzać pole magnetyczne.* ***(Zaburzenia pola magnetycznego wywołane przez zanieczyszczenia magnetyczne tworzyw sztucznych)***

**Keywords**: magnetometer, magnetic field, plastics
**Słowa kluczowe**: magnetometr, pole magnetyczne, tworzywa sztuczne

## Introduction

Every ferromagnetic object built of ferromagnetic materials, which is located in the Earth's magnetic field, disturbs the uniformity of this field. This disturbance depends on the shape, dimensions and ferromagnetic properties of the object and its orientation in relation to the Earth's magnetic induction vector. If the shape of the disturbance in the magnetic field is known, it is possible to detect, localize and identify the object [1], [2]. Due to very low values of disturbance scalar magnetometers and SQUID of very high sensitivity are used [3]. Modern optically pumped magnetometers, further referred to as scalar magnetometers, allow to measure the magnetic induction module with the sensitivity of 4 $pT/Hz^{0,5}$. The actual sensitivity of the magnetometers operating in a differential system amounts to approximately several dozen $pT/Hz^{0,5}$ [4]-[5]. In order to take measurements of so low magnetic fields it is crucial to choose appropriate materials for the construction of the magnetometric system, particularly an appropriate measuring stand on which the magnetometers are installed. The stand should be made of amagnetic materials so as not to disturb the magnetic field distribution. During the actual manufacturing process and mechanical treatment of particular materials or parts made of these materials, they become contaminated with small particles or metal filings with ferromagnetic properties. This paper presents the results of the study of the disturbance in the Earth's magnetic field caused by a thin magnetic layer on the surface of an amagnetic cylinder and a single ferromagnetic filing. The results of the experimental study of disturbance in the amagnetic field caused by parts made of plastic are also presented in this paper.

## Analysis of magnetic field disturbance

The effects of the contamination of the surface layer of the cylinder made of plastic and contaminated with a ferromagnetic layer on the disturbance in the magnetic field distribution was tested for a 2D model. For the sake of simplification it was assumed that the contamination with ferromagnetics of relative magnetic permeability $\mu_r$ was uniform in the thin layer on the cylinder surface (Fig. 1). The cylinder was placed in a uniform, stationary magnetic field intensity $\boldsymbol{H}_o$, perpendicular to the cylinder axis. In the coordinates system of the cylinder, magnetic field depends only on the coordinates $r$ and $\theta$ (Fig. 1).

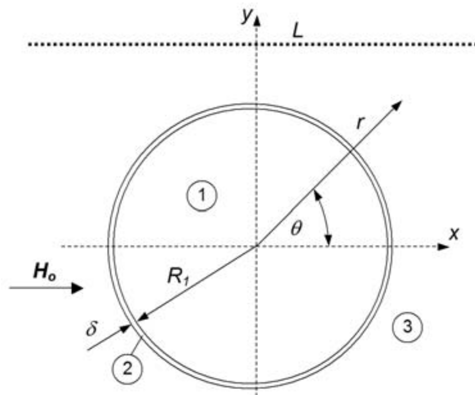


Fig. 1. Amagnetic cylinder with a thin ferromagnetic layer: 1 – inside subarea of the amagnetic cylinder, 2 – a layer with ferromagnetic properties, 3 – outside subarea

In particular subareas of the cylinder the magnetic scalar potential $V_m$ satisfy Laplace's equation, which in the coordinates is described by the equation:

(1) $$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V_m}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 V_m}{\partial \theta^2}=0$$

General results of the equation (1) in three subareas (Fig. 1) are described as follows:

(2) $$V_{m1}=\mathrm{A}_1 r\cos\theta \quad 0\le r\le R_1$$

(3) $$V_{m2}=(\mathrm{A}_2 r+\frac{\mathrm{A}_3}{r})\cos\theta \quad R_1<r\le R_2$$

(4) $$V_{m3}=(-H_o r+\frac{A_4}{r})\cos\theta \quad r>R_2$$

Components of magnetic field intensity in each of the subareas are expressed by the dependence:

(5) $$H_r=-\frac{\partial V_m}{\partial r}$$

(6) $$H_\theta=-\frac{1}{r}\frac{\partial V_m}{\partial \theta}$$

In accordance with magnetic field boundary conditions the tangential component of the magnetic field intensity and the normal component of magnetic flux density are continuous at the boundary surfaces for $r = R_1$ and $r = R_2$ ($R_2 = R_1+\delta$). After the boundary conditions had been taken into account and the system of equations had been solved, the following dependences were obtained:

(7) $$H_r = H_o \cos\theta (1 + \frac{A}{r^2})$$

(8) $$H_\theta = H_o \sin\theta (\frac{A}{r^2} - 1)$$

(9) $$A = R_2^2 \frac{(R_2^2 - R_1^2)(\mu_r^2 - 1)}{R_2^2(\mu_r + 1)^2 + R_1^2(\mu_r - 1)^2}$$

The distribution of lines of force outside of the cylinder was showed in fig.2.

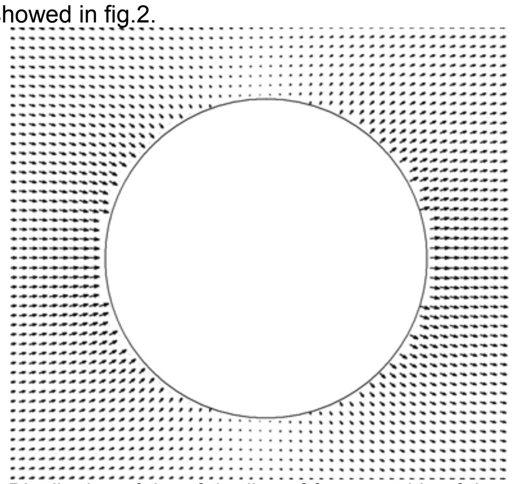

Fig. 2. Distribution of the of the line of force outside of the cylinder ($\mu_r$ = 100, $R_1$ = 5 mm, $\delta$ = 100 mm)

Basing on the dependence (7)-(9) an analysis of the effect of a ferromagnetic layer on the disturbance in the magnetic field was made. It was assumed that the relative, equivalent magnetic permeability of the layer contaminated with particles with ferromagnetic properties was dependant on the magnetic permeability of the particle material and their number in a unit of volume (density). Therefore, a relative density of the magnetic layer on the surface of the cylinder with the radius $R_1$ per a unit of length was assumed:

(10) $$g = \frac{R_2^2 - R_1^2}{R_2^2} 100\%$$

It was assumed in the analysis of the disturbance in the magnetic flux density that the maximum disturbance $\Delta B(x, y{=}10R_1)$ amounted to 60 pT along the line $L$ (Fig. 3) (the radius of the cylinder $R_1$ = 5 mm). This simple example shows that an extremely thin magnetic layer disturbs the magnetic field on assumed level.

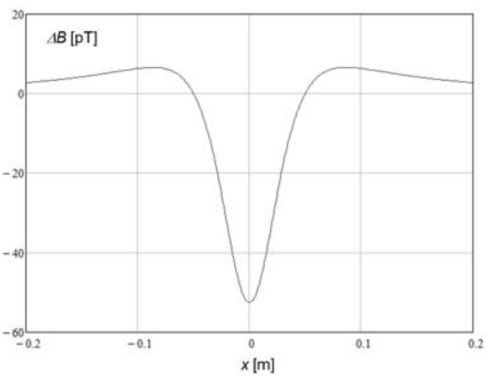


Fig. 3. Disturbance in the distribution of the magnetic flux density caused by a ferromagnetic layer with the thickness $R_2$ - $R_1$ =10 nm on the amagnetic cylinder with the radius $R_1$ (for $H_o$ = 39.788 A/m, $\mu_r$ = 100)

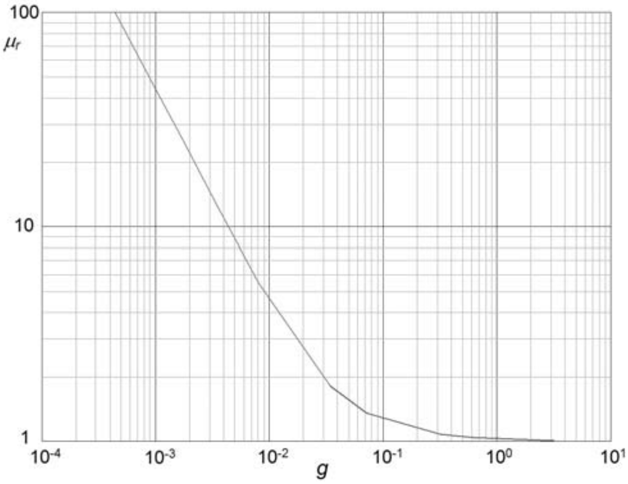


Fig. 4. Calculated dependence between equivalent, relative permeability of the magnetically contaminated layer of an amagnetic cylinder and relative density of magnetic contamination (for the initial value $\mu_r$ = 100 and $g = 5\ 10^{-4}$).

For the relative permeability of the ferromagnetic particles $\mu_r$ = 100, the disturbance in the magnetic flux density amounts to 60 pT (for the parameter $g = 5{\cdot}10^{-4}\%$) which corresponds to the thickness of the ferromagnetic layer equal 10 nm (Fig. 4).

The thicker the magnetic layer, the smaller its relative, equivalent value of magnetic permeability that causes the same disturbance in the magnetic field. For the parameter $g > 1\%$ the magnetic properties of the layer of the material on the cylinder surface are equivalent to the parameters of paramagnetics. The performed analysis shows that the contamination of plastics with negligible amounts of ferromagnetic material results in the disturbance in the magnetic flux density. It is a significant phenomenon in the case of taking measurements of very low magnetic fields. An analysis of the disturbance of the Earth's magnetic field was also performed for a single ferromagnetic filing ($\mu_r$ = 100) with the length of 1.75 mm and the diameter of 0.175 mm. A model of a magnetic dipole [2] of the filing was used for the purpose of the analysis, which showed that disturbance amounted to about 60 pT (Fig. 5) at the distance of 5 cm (a length about 28 times larger than the length of the filing). The performed analysis of the disturbance in the magnetic field shows that in the case of taking measurements of low magnetic fields it is crucial to choose appropriate materials for the construction of the device on which the magnetic sensor is to be installed.

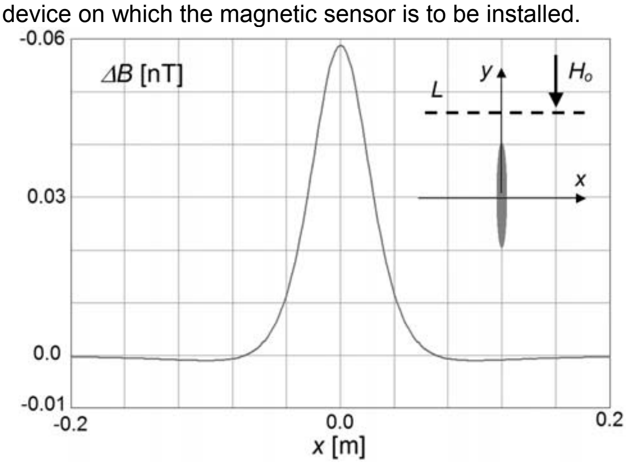


Fig. 5. Disturbance in the magnetic flux density caused by a ferromagnetic filing ($\mu_r$ = 100) with the length of 1.75 mm and the diameter of 0.175 mm.

**Experimental study**

The device in which the sensor of the magnetometer shall be installed should be built from the materials that are possibly least contaminated with ferromagnetics. The effect of the relative content of ferromagnetic dust (8) added to the mixture of water and dust in a test tube (Fig. 7) on the disturbance in the magnetic flux density was shown in Fig. 6 (for the distance between the test tube and the sensor of 5 cm). The ferromagnetic dust was degaussed before the measurements [6]. The percent volume $V_{\%}$ of the ferromagnetic dust was described by the following dependence:

$$V_{\%} = \frac{V_{FE}}{V} 100\% \tag{11}$$

where: $V_{FE}$ - volume of ferromagnetic dust, $V$ – volume of the test tube (5 cm$^3$).

The tests were performed with the use of two stationary magnetometers G823A operating in a differential system. Therefore, it was possible to take measurements of disturbances in the magnetic flux density with the precision of the pT order of magnitude. After the test tube with the ferromagnetic dust was shaken, the level of disturbance in the magnetic flux density was measured at the distance of about 5 cm from the axis of the sensor of one of the two magnetometers (the sensor diameter - 6.3 cm). It could be observed that even a small, several percent volume of the dust in the test mixture resulted in the disturbances of the order of magnitude of several nT. The results of the conducted research showed that particularly the elements made of textolite had a considerable effect on the disturbances in the Earth's magnetic field. Each element that undergoes mechanical treatment becomes contaminated with ferromagnetic materials. In the case of textolite, apart from contaminations on the surface, there were also magnetic intrusions in the material. The tested element made of textolite (Fig. 9) caused a disturbance of the Earth's magnetic flux density as large as 6 nT (Fig. 10). Tests were carried out with regard to the construction elements of the workstation (fig.8) for testing metrological parameters of magnetometers.

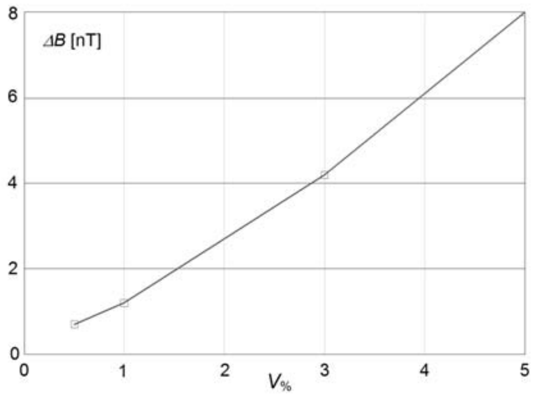


Fig. 6. Effect of the percent volume of the ferromagnetic dust on the disturbance in the magnetic flux density.


Fig. 7. Test tube with ferromagnetic dust in water (before shaking)

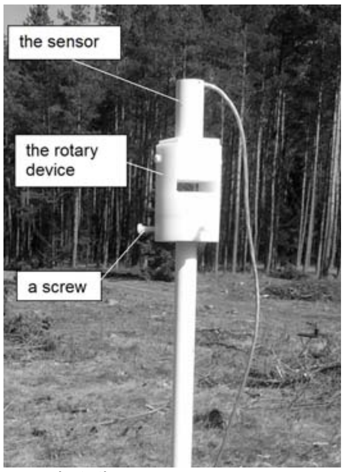


Fig. 8. Measuring workstation.

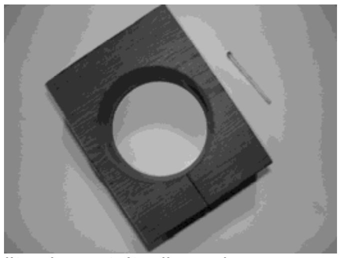

Fig. 9. The textolite element. Its dimensions are compared with the dimensions of a match.

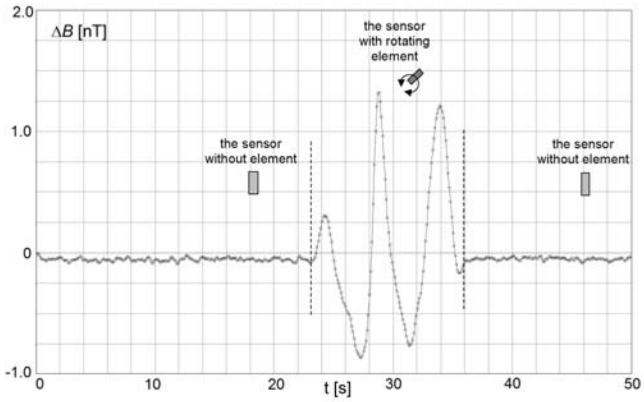


Fig. 10. Disturbances in the magnetic flux density caused by a textolite element after chemical cleaning (from the distance of 5 cm from the magnetometer sensor)

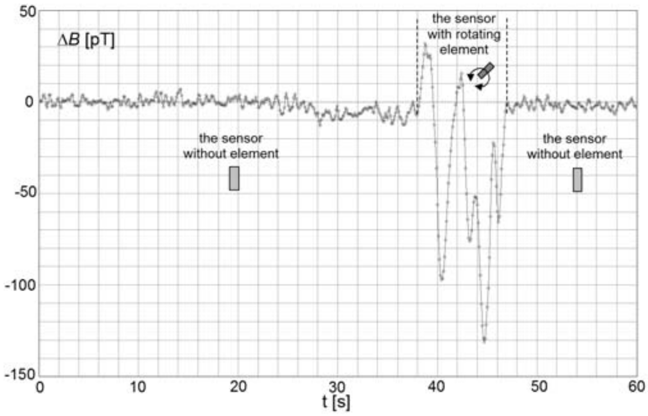


Fig.11. Disturbances in the magnetic flux density caused by a polyamide screw before magnetic cleaning (from the distance of 5 cm from the magnetometer sensor)

After the element had undergone the process of chemical cleaning, the values of disturbance dropped down almost threefold to the level of about 2.2 nT. The study shows that the tested textolite cannot be used for the construction of the measuring devices used for taking measurements of low magnetic fields. Figure 11 shows changes in the magnetic flux density caused by a polyamide screw (length 5 cm, diameter 8 mm). In this case the disturbances are much smaller and amount to approximately 160 pT. After the element had undergone the process of chemical cleaning, the values of disturbance dropped down below the noise level. It shows that the screws made of polyamide could be magnetically contaminated on the surface.

**Materials cleaning technology**

The disturbances in the magnetic flux density can be caused by iron compounds such as FeO and $Fe_2O_3$ that gather with other contaminants on the surface of the measuring system elements, which are made of plastics. The contamination formed during mechanical treatment of the materials used, which are made of plastics, that is performed with the use of steel tools could be another cause of disturbances. In the course of treatment the tools undergo wear and tear and contaminate the surface of the element undergoing treatment. These contaminations are not visible to the naked eye. Steel contaminants undergo corrosion to form oxides also on the surface of the element. What is crucial is that the iron oxides can come together to form tiny particles of the $Fe_3O_4$ oxide, which is a component of magnetite – a material with good magnetic properties. Hydrophobic properties of plastics are a favouring factor for gathering of the iron compounds on the surface of those materials. The tiny particles of lubricants that appear on the surface of plastics are an additional favouring factor for gathering of the oxides and making their removal more difficult. It was assumed that the contaminants could have a highly diversified composition and properties, therefore, a two-phase chemical process with the use of two mixtures applied at different phases of cleaning was used to remove them:

- the first phase of decontamination consisted of a bath in a mixture of orthophosphoric acid, a superficially active compound and a coordination compound coordinating the iron compounds in acidic environment,
- the second phase of decontamination consisted of removing contaminants in highly basic environment in the presence of a superficially active compound and a coordination compound suitable for basic conditions. In order to increase the efficacy of decontamination the process was carried out at a higher temperature and in an ultrasonic bath with appropriately set parameters.

Efficacy of the elements decontamination process was verified by taking measurements of the disturbances in the magnetic flux density before and after the process.

**Conclusions**

It can be concluded from the results of the study presented in this paper that the selection of elements made of plastics for the construction of magnetometric measuring system for taking measurements of very low magnetic fields is a very important issue. During mechanical treatment of the material microscopic size ferromagnetic particles get forced into its surface from e.g. the turning tool. These particles or superficial contamination with steel dust that is present in the machine tool can be effectively removed by chemical cleaning. The experimental study performed proved high efficacy of this method. It was concluded on the basis of experimental studies that the materials suitable for the construction of a workstation for testing scalar magnetometers included: polyamide, polyethylene and polyoxymethylene (Delrin).

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