Identification of Objects by Magnetometry

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BIOGRAPHICAL NOTES

prof. Ing. Milan Oravec, PhD. (1960) is employed at the Department of Safety and Quality of Production, Faculty of Mechanical Engineering, Technical University of Košice. He has been working in the field of Risk Assessment since the establishment of the field at the Technical University of Košice (1990). In 1992, he successfully defended his PhD thesis in the area of oscillation (Mutual Interaction of the Load Spectra of an Overhead Crane). In 1995, he was awarded the associate professor title in the field of Production Quality and Safety of Technical Systems (Identification and Control of Technical Risks). In 2009, he was awarded the full professorship at the Technical University of Ostrava in the field of Safety and Fire Protection (Risk Assessment of Selected Technological Units).

Ing. Juraj Glatz, PhD. (1977) graduated from the Faculty of Mining, Ecology, Process Control and Geotechnology, Technical University of Košice (2004), in the field of Fire Emergency and Safety Technology. He is currently employed as a research worker at the Department of Safety and Quality of Production, Faculty of Mechanical Engineering, Technical University of Košice. His research focuses on major industrial accidents, safety of pipeline constructions and risk assessment. His doctoral thesis was devoted to Accident Planning in Road Tunnels. He has published his research findings at several domestic and international events. He has authored or co-authored research papers on the application of risk theory in the road tunnels and in the field of the prevention of major industrial accidents.

Ing. Slavomíra Vargová (1986) is a graduate of the Department of Safety and Quality of Production, Faculty of Mechanical Engineering, Technical University of Košice, in the field of Safety of Technical Systems. In 2010, she defended her Master thesis on Risk Forecasting in the Critical Infrastructure Sector – Water Resources Management. In the same year, she enrolled in a PhD program, where she currently focuses on the interrelations between technological safety and civil security. She has completed two mobility programs at the partner University of Wuppertal, Germany, which have resulted in continuous collaborative research into interactions between safety and security.

KEY WORDS

Electromagnetic field, magnetic field, identification of objects, magnetometry.

ABSTRACT

Changes in the presence, location and shape of even small magnetized and paramagnetic objects can be monitored both in the Earth's magnetic field as well as in the local magnetic field. The basic condition that has to be met when employing magnetometry for such tasks is the magnetic contrast of single objects against their surroundings. The paper shows the possibility of identifying cyclic and acyclic movements in the area of approximately 6 x 6 x 4 m (standard office space). Triaxial magnetometer with a sensitivity of 2 nT and range 0-250 Hz was used for measurements. The evaluation was

carried out in time and frequency area.

The objective of the experiment was to monitor interactions between sources of magnetic field in the defined area. The relation between the distance and the induction of selected objects was monitored. The monitored area was not magnetically shielded and therefore the potential influence of other sources outside the monitored space was also observed.

1. Introduction

Electromagnetism is a phenomenon present throughout the universe. On the macro-object level, the principle is utilized in everyday objects (speakers, display screens, electromagnets, induction heating, etc.). On the micro-object level, electromagnetism can be utilized in a wide range of areas, such as electrical engineering and diagnostics of technical system parameters. Most animals (80%) use magnetism for orientation during migration [1]. The fact that the intensity of geomagnetic field (GMF) varies over time was discovered centuries ago. Daily variations cause changes in the intensity up to tens nT, magnetic storms up to hundreds nT. They result from processes occurring in the cosmic space. Another phenomena influencing local magnetic field are changes in the mass flow in the outer core of the Earth [2].

This paper points at the possibilities of utilization of magnetic field of objects for their identification and localization, if they are within the GMF. The fundamental condition allowing the application of magnetometry in such tasks is the magnetic contrast of these objects against their environment.

Another possibility lies in the local identification of objects in selected areas of local magnetic field.

2. Applied Principle

Theoretical and practical knowledge about electromagnetic phenomena applicable for technology were summarised by J.C. Maxwell [3]. Maxwell's differential equations (1) to (4) express the relations between electric and magnetic phenomena. Electric and magnetic fields are specific cases of the electromagnetic field. Some of their properties are identical; others are unique (specific).

$$div\vec{D} = \rho \qquad (1)$$

$$rot\vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad (2)$$

$$div\vec{B} = 0 \qquad (3)$$

$$rot\vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t} \qquad (4)$$

where:

$\vec{E}(\vec{r},t)$ is the electric field intensity [V.m^{-1}]

$\vec{H}(\vec{r},t)$ is the magnetic field intensity [A.m^{-1}]

$\vec{D}(\vec{r},t)$ is the electric induction [C.m^{-2}]

$\vec{B}(\vec{r},t)$ is the magnetic induction [T]

$\vec{j}(\vec{r},t)$ is the current density [A.m^{-2}]

$\rho(\vec{r},t)$ is the total charge density [C.m^{-3}]

$\vec{r}$ is the location vector

t is the time

Permittivity, permeability, and conductivity describe electric and magnetic properties of the environment. Permittivity of the environment ε can be calculated as:

$$\varepsilon = \varepsilon_0 . \varepsilon_r \qquad (5)$$

where: $\varepsilon_0 = 8.85.10^{-12}$ [Fm^{-1}] is the vacuum permittivity and ε_r is the relative permittivity. Similarly, the permeability of the environment can be calculated as:

$$\mu = \mu_0 . \mu_r \qquad (6)$$

where: $\mu_0 = \pi.10^{-7}$ [Hm^{-1}] is the vacuum permeability and μ_r is the relative permeability.

In general, permittivity, permeability and conductivity of the environment are tensors, as they are functions of spatial coordinates. From this point of view, an environment can be classified as homogenous, non-homogeneous, isotropic or anisotropic.

Considering the utilization of these phenomena, Curie-Weiss law [4] has to be mentioned, which says that magnetic susceptibility χ of paramagnetic material depends on its temperature according to equation:

$$\chi = C / (T - T_c) \qquad (7)$$

where: T_c is the critical temperature, at which a material's ferromagnetism changes to paramagnetism and C is the Curie constant. The Curie temperature for iron is 770°C, nickel 358°C, some alloys 60°C to 37°C [5]. Above the Curie temperature, the magnetic dipole moments are randomly, chaotically aligned without a preferred direction. When a ferromagnetic cools below the Curie temperature, its moments spontaneously align in one direction. It is a spontaneous distortion of symmetry, because the non-magnetic phase has a higher symmetry (all directions are equivalent and the field is isotropic), than magnetic (with a preferred direction of spontaneous magnetization).

According to the value of magnetic susceptibility, materials can be divided to:

1. diamagnetic $(\chi < 0)$
2. paramagnetic $(0 < \chi < 1)$
3. ferromagnetic $(\chi > 1)$

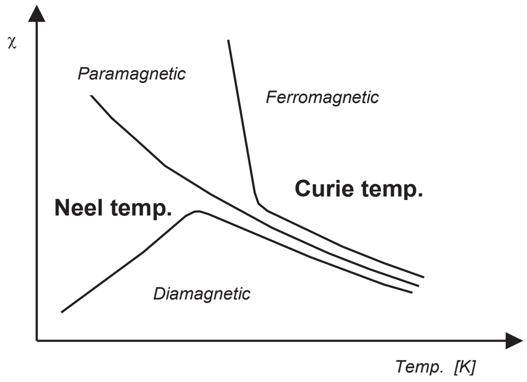


Fig. 1: *Relation between temperatures and material properties*

According to current knowledge about electron structure of atoms and structure of materials, all materials are magnetic [6]. Electrons, protons and neutrons as subatomic particles also have their own magnetic moments – spins. Electrons – negatively charged particles move, thus creating a magnetic moment.

Mathematical apparatus describing the magnetic field of several sources and their interaction is very complex. Current methods of solving non-linear differential equations have mathematical as well as numerical limitations. They require simplifications of the actual state and physical models. Interdisciplinary approaches [7], [8] utilize tools that make the calculation faster and easier. That applies especially to the fields of deterministic chaos and phase jumps in the process of description of causal dependence of the observed phenomena [8], [9].

The abovementioned facts can be used in the identification of objects' movement and properties in a real environment; mostly for activities that cannot be sufficiently monitored by video equipment.

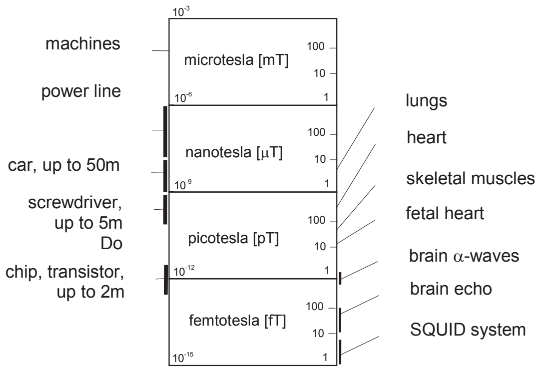


Fig. 2: *Magnetic induction values of selected objects*

3. Process of Object Identification

The area of object safety can utilize the principle of magnetic induction change, which represents a particular change caused by an object in its real environment. In the real environment E_3 and a particular time t, there exists a state defined by the set of values $\Omega \in E_3(t, B_x, B_y, B_z)$, which varies and creates a mediated image $\Psi \in (t, u, v, z)$. The relation between the state and the image is called transformation.

$$\Omega \in E_3(t, B_x, B_y, B_z) \rightarrow \Psi \in (t, u, v, z) \quad (8)$$

where:

t - is the time; Bx,By,Bz - is the magnetic induction in directions x,y,z; u,v,z - are the parameters of the image.

The aim of the transformation is to create a tool able to analyze particular changes that are observed with regard to equations (1) to (4). Since the observed activities occurred below the Curie temperature, equation (7) does not have to be taken into consideration.

When determining the environment parameters with regard to the nature of the observed activities (in the first phase, cyclic movements were chosen in order to monitor the frequency and amplitude of respective oscillations), Fast Fourier transform (FFT) was used. The real process is transformed into frequency area according to equation (8), where the observed cyclic changes relating to particular sources are analysed. The movement in the observed space included acyclic activities, which were observed during a particular time span.

Post-processing enables monitoring also other parameters of the process. This type of activity is applied in modelling particular states, providing that the sources' impact on the environment is known. Besides the frequency analysis, changes in the magnetic induction described by the resulting vector of magnetic induction also allow observation of any position changes of an object in its environment.

The practical utilization requires the following procedure:

1. It is necessary to know the initial state in a particular time and space. This state is expressed by a particular value, which is a function of the particular time t_1, position expressed by GPS technology, magnetic background (noise):

$$\Omega_1 \in E_3(t_1, B_{x1}, B_{y1}, B_{z1}) \qquad (9)$$

2. In a particular time t_n, the following values are observed:

$$\Omega_n \in E_3(t_n, B_{xn}, B_{yn}, B_{zn}) \qquad (10)$$

3. The final change that is considered in the evaluation process results from the change between states Ω_1 and Ω_n. This change is observed indirectly, using equations (8), (9), (10) and (2), (3).

1. Description of the Equipment

The apparatus series VEMA-041 is designated for vector measurements and oscilloscopic representations of the development of magnetic induction of stationary and low-frequency field [11,12], for conducting and recording sets of time and spatial measurements, as well as analysis in the time, frequency and spatial area. The equipment is able to simultaneously measure three components of the magnetic induction vector, as defined by the user. The probes have a core made of amorphous, magnetically soft metal alloy, and use alternate magnetization up to saturation (Fig. 3), which allows achieving the resolution in nanoteslas. The magnetometer uses constant sampling frequency 1 kHz, up to 250 Hz at the sensitivity ≥ 2 nT. It is possible to export the measured data for post-processing and analyses in standard files, the only limiting factor is the capacity of the medium used for data recording.

;The evaluation and processing is possible by means of interconnection with standard statistical software. The evaluation (both real time and post-processing) uses OtVema (open source) software. It enables processing the data collected by magnetometer. The primary function of the software is the visualization of the processed data for the user and their recording in accordance with a selected time schedule. Batches of magnetometer data are processed in real time and displayed in an oscilloscopic mode on the screen. Additional features of the program include FFT representation, correlation function and representation of the resultant magnetic induction vector in space. Figure 4 shows the magnetometer and the processing software.

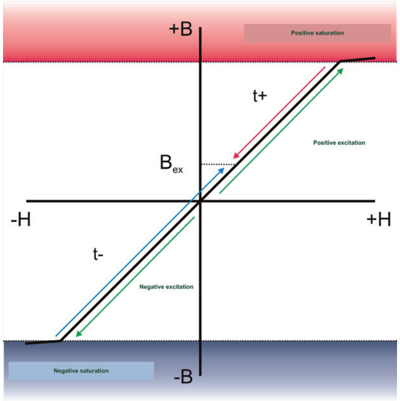


Fig. 3: *The function principle of a magnetometer probe.*

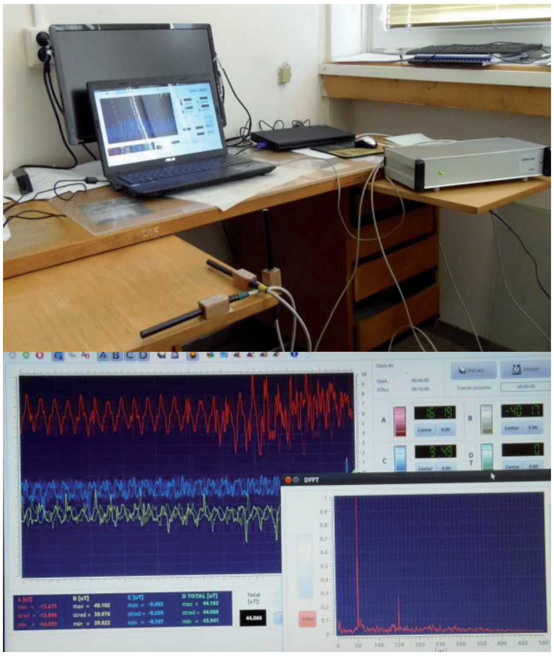


Fig. 4: *Measuring unit and the processing software.*

2. 2. Measuring selected parameters of an object's magnetic field

Measurements were conducted in a standard office space (Fig.5) with GPS coordinates φ 48°43", λ 21°14", elevation 230 m above sea level, and office dimensions 6 x 5.8 x 3.4 m. This location specification is related to the GMF value at a particular place (measurements track changes in the local field). The office space contained common office equipment, power supply, audiovisual technology (which was switched on during measurements). The location of the coordinate system origin is shown in Figure 5.

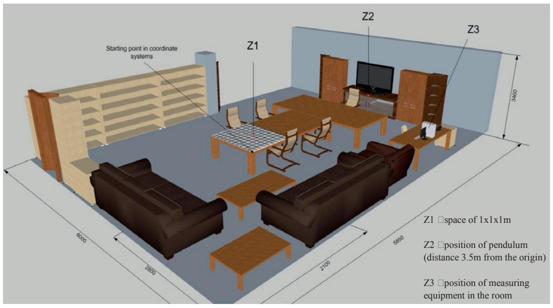


Fig. 5: *Layout of the monitored space and equipment.*

4.1 Measurement and verification of assumptions

Measurement 1

Measurement objectives included

1. Monitoring mutual interactions between sources of magnetic field in a defined space of 1 x 1 x 1 m, and subsequently in the entire office space. Dependence between distance and induction of selected objects was monitored with regard to the defined space.
2. Secondary task was monitoring standard power supplies with frequency of 50Hz and their first to fifth harmonic and subharmonic frequencies.
3. Confirming or refuting the assumption about potential interaction with other sources located outside the monitored space and their influence on the monitored area (which was not magnetically shielded).

Measurement procedure

A simple model shown in Fig. 6 a,b was used to verify the assumptions. The measurement proceeded as follows:

1. Probes functionality test and measuring device calibration were carried out,
2. GMF parameters were obtained,
3. The position of the frame of reference in the monitored space was defined (Fig. 5), and probes were situated at its origin,
4. Calibration to a standard source of magnetic induction was performed. Sources functioning at 50 Hz frequency were verified in the entire space of 6 x 5.8 x 3.4 m,
5. Magnetic induction changes in particular directions of time and frequency area (frequency spectra) were observed on display units, (see images in Table 2: LCD screen, computer monitor), and courses of magnetic induction over time in x, y, z directions, frequency spectra and the resulting induction vector for selected object movements in space in relation to time were recorded on a disc,
5.1 a reduced space grid was delimited to 1 x 1 x 1 m, (see Fig. 5), and the measured data were evaluated,
5.2 a wider space grid was defined as the entire office space of 6 x 5.8 x 3.4 m,
6. Measurements performed in the monitored space using various objects were evaluated. Oscillating objects (cyclic movement, see Fig. 6a) included nuts M4 and M8 and a neodymium ball K-05-C, whose parameters are shown in Table 1 [13]. The magnetic properties of nuts compared to neodymium ball are negligible. A nut served for the fixation of the magnetic ball. Induction values of the nuts and nut-ball set in motion were compared. Acyclic movement was performed by rolling the neodymium ball on the raster of the monitored space (see Fig. 6b). Various magnetic and paramagnetic objects were used; they were rolled and moved along various planes of the monitored space.

Table 1: *Parameters of neodymium ball K-05-C [13].*

Article	K-05-C
Shape	Sphere
Diameter	5 mm
Tolerance in size	+/- 0,1 mm
Material	NdFeB (Neodymium Iron Boron)
Type of coating	Chrome-plated nickel (Ni-Cu-Ni-Cr)
Strength	400 g
Weight	0.4974 g
Maximum working temperature	80 °C
Residual magnetism Br	(12900-13200 G) 1.29-1.32 T
Coercive field strength bHc	(10.8-12.0 kOe) 860-955 kA.m^{-1}
Coercive field strength iHc	(Hci ≥12 kOe)≥955 kA.m-1
Energy product	(B x H)max 40-42 MGOe 318-334 kJ.m-3

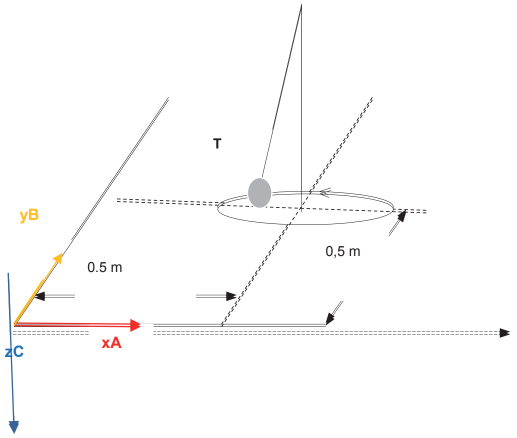


Fig. 6a: *Monitored cyclic rotation.*

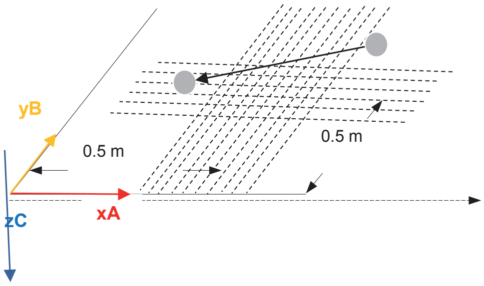
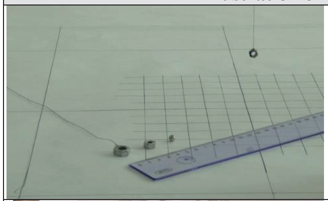
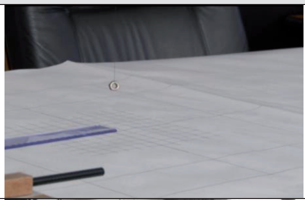
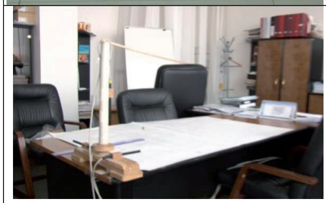
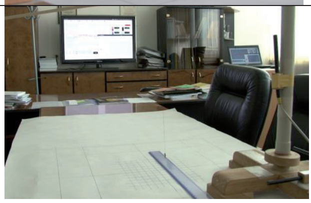
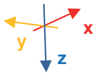
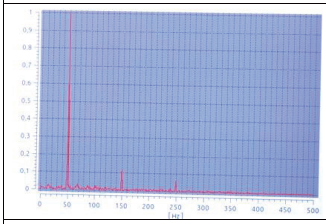
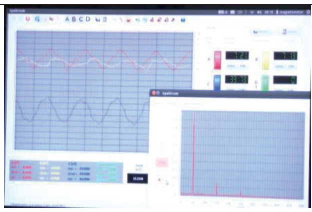
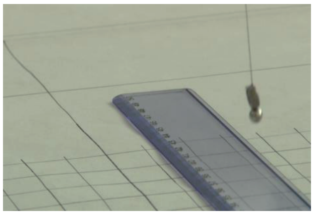
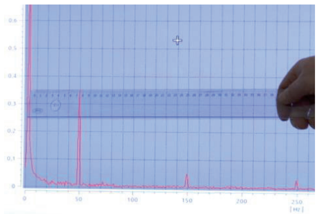
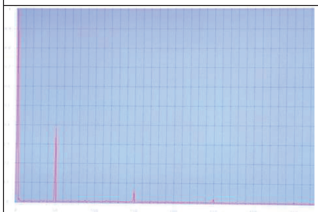
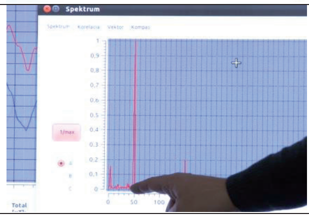


Fig. 6b: *Monitored movement along a curve.*

Task I, II, III

Table 2 contains selected monitored activities and the reasons for observation.

Table 2: *Selected measurements related to tasks I, II, III in space according to Figure 5.*

Illustration of measurement	Measurement description
 	Testing objects in the monitored space. Comparison of magnetic induction in oscillation of particular objects. The values of oscillating nuts were insignificant in comparison to the neodymium ball.
 	Room layout and positions of sensors. Definition of reduced and wider areas. Position of sensors axes. The colour of the axis corresponds to the spectrum colour and time record as shown below. 
 	Displays of time and frequency records. Background frequency, 50 Hz and its harmonics (1st to 3rd). Spectral line 50 Hz corresponds to the sources of power supply in the monitored space.
 	Oscillation of nut M8 with a neodymium ball. Background frequency of 50 Hz has a lower amplitude than the oscillating movement frequency of nut and ball. The movement of the nut was cyclical (Fig.6a), in a plane parallel to $\|x,y\|$ plane in 5 cm distance above the $\|x,z\|$ plane.
 	Observation of approaching and retreating the nut-ball set and measuring induction at the retreatment. The object was rotating cyclically at the frequency of 1 Hz, which is obvious in the frequency spectrum. 50 Hz frequency was also observed.

Summary

1. The sources operating at 50 Hz frequency produce first to third harmonics. It is necessary to filter off these frequencies as well as their subharmonics, during the measuring process;

2. Common metal objects that have been magnetized can be identified up to 2 m even without filtering off 50 Hz frequencies and their harmonics;

3. Standard autocorrelation function included in the software package can be used for quick recognition of background and noise and real-time evaluation is therefore possible;

4. It is appropriate to evaluate cyclic movements by FFT. Real objects generally move in space along curves. After spectra and states defined in equations (8) and (9) have been evaluated, these movements can be identified, as they are above the noise level;

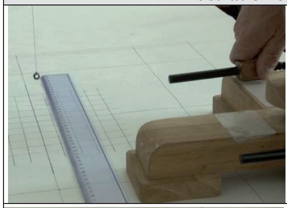
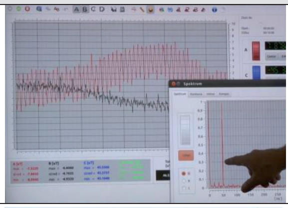
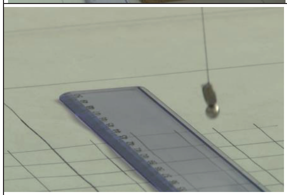
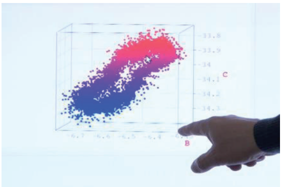
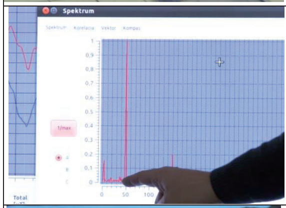
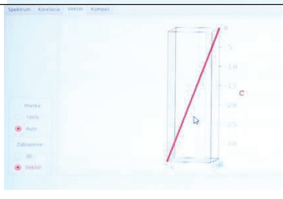
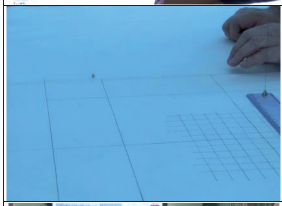
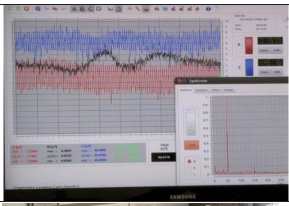
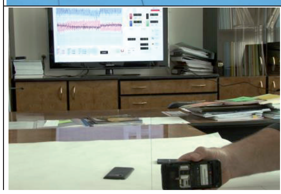
5. The issue of noise should be perceived in the context of technological limitations of the measurement procedure and the possibility of complementary measurement of other parameters should be considered.

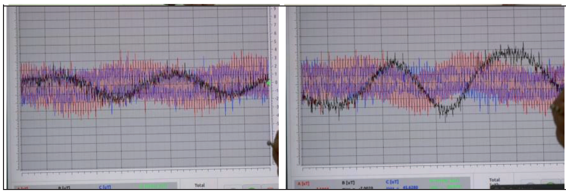
Measurement 2

Measurement objective was:

IV – to verify the assumption that it is possible to identify the position of objects in a particular space by monitoring the changes in the magnetic induction in directions x, y, z. Ferromagnetic material (neodymium ball; its parameters are shown in Tab.1) and metal objects were used for the experiment. The measurement was conducted at selected points Z1, Z2, Z3 of the monitored space shown in Figure 5. The procedure was identical to the first measurement. Table 3 shows selected monitored activities and the reasons for the observation.

Table 3: *Selected measurements related to task IV in space according to Figure 5.*

Illustration of measurement		Measurement procedure
		Preparation of probes and gradient measurement in the direction of *x*-axis. The probes were situated in 30 cm and subsequently in 1 m distance. Time and frequency record was monitored at the cyclical oscillation of neodymium ball (see Tab. 1 for parameters) and nut M4.
		The oscillation of neodymium ball and nut M4. The trajectory of points in space was monitored in relation to the frame of reference and GMF. The colouring represents the induction changes on *x*, *y* and *z* axes during the rotating movement.
		Observing the functional dependency of the distance of the oscillating object from the reference coordinate system. Observation of 50 Hz frequency and the oscillating object s frequency. Observation of the trajectory of the resulting rotating magnetic induction vector.
		Movement along the curve of the neodymium ball and the corresponding time record important for post-processing. Movement of various objects up to ±3m from the reference frame.
		Monitoring the changes caused by the position of a mobile telephone and the corresponding magnetic induciton in a time record, in the distance of 1 m from the probes. Position changes of the complete telephone and its parts were monitored.



Oscillation of two to five neodymium balls in the distance of 3 m from the origin of the coordinate system.
Point Z3 is shown in Figure 5. Cyclic rotation and movement along a curve were monitored.

Summary

1. magnetic induction spectra can be used to identify cyclically moving (oscillating) objects,

2. moving objects that do not perform repeated cycles can be identified using a time record which has to be evaluated by tools other than frequency and phase spectrum,

3. real-time movement can be identified by the resulting magnetic induction vector. It is appropriate to use a combination of mathematical apparatus (morphological description of the spatial relations) [14] and actual results of real-time processing,

4. functional dependency for possible identification of passive and active sources was verified (observation of various power outputs, frequencies and distances from the frame of reference) in various points of the monitored space (up to the borders of 6 x 5.8 x 3.4 m),

5. also passive objects (mobile phone whose battery had been removed) can be identified when changing position, since the construction of the panel, speakers and metal parts of the mobile telephone induce values identifiable up to the distance of 1.5 m,

6. movements along the curve and the corresponding changes have to be evaluated from the time spectra, where changes in the magnetic induction are obvious even in the real-time observation process.

5. Conclusion

Magnetic field is a dynamic field containing local nonlinearities and extremes; nevertheless, it is possible to determine dependencies even in such fields. Sensing magnetic field is a method allowing indirect and contactless measurement of direction, orientation, presence, rotation, angle and electric current, based on the evaluation of changes that the observed object causes by its activity in the magnetic field. Magnetic measurements therefore have a wide spectrum of applications [15].

The evaluation of individual experiments pointed out the possibility of utilizing the method to monitor positions, changes and shapes of objects with values ranging from 10^{-6} - 10^{-9} T.

The following possibilities result from the conducted measurements:

1. Changes in the presence, position or shape of even small paramagnetic objects can be monitored within the distance of ±1 m from the origin of the frame of reference. Current technologies applied in the manufacturing of neodymium allow the production of various shapes and sizes of objects of negligible weight (0.5 g), which can be locally identified,

2. Cyclic and acyclic movements of everyday objects can be monitored within ±3 m from the origin of the reference frame. Change in the position of an object is a sufficient indicator. Even a slight movement of a common object such as mobile telephone without a battery causes magnetic induction identifiable on the level of 10^{-8}T up to the distance of 1.5 m,

3. Majority of electrical appliances operate at the frequency of 50 Hz, demonstrated by the 1st to 3rd harmonic frequency. These frequencies are cyclical and clearly identifiable in the frequency spectrum,

4. Identification of objects by means of magnetic fields can be used in combination with other physics principles, in order to increase the reliability and reduce costs (redundancy and diversification principles),

5. In the area of post-processing, it is advisable to focus future attention on analytical methods based on equation (8),

6. Based on the initial measurements, the reference frame can be positioned in a manner that allows for measuring the induction gradient in a specific direction. This location enables us to measure specific acyclic movements, such as movement of successive objects along the same trajectory, since the resulting induction vector is a movement superposition of these two objects. Gradient measurement allows detecting such movements,

7. In case of monitoring large areas, it is appropriate to constitute a specific combination of sensors and probes in the particular space in question, up to the cell size of 6 x 6 x 6 m,

8. It is also possible to create active sources in the low frequency area (e.g. up to 25 Hz), which will be identifiable on the basis of the specific frequency, its corresponding harmonic and the noise.

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