

Dynamic shielding of the magnetic fields

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Abstract—The paper presents a comparative study of the methods used to control and compensate the direct and alternative magnetic fields. Two frequently used methods in the electromagnetic compatibility of the complex biomagnetism installations were analyzed. The two methods refer to the use of inductive magnetic field sensors (only for alternative fields) and of fluxgate magnetometers as active transducers which measures both the direct and alternative components of the magnetic field.

The applications of the dynamic control of the magnetic field are: control of the magnetic field of the military ships, control of parasite magnetic field produced by power transformers and the electrical networks, protection of the mass spectrometers, electronic microscopes, SQUID and optical pumping magnetometers for applications in biomagnetism.

Index Terms—active shielding, biomagnetics, dynamic shielding, magnetic field, magnetic shielding

I. INTRODUCTION

The magnetic field compensation and control are of interest for extremely diverse fields. The classical method for diminishing the environmental magnetic field intensity consists in the utilization of shields made of ferromagnetic materials [1], [2]. For alternative magnetic fields, depending on frequency, one can also use shields made of high conductivity non-ferromagnetic materials [3]. This manner to diminish the field represents a *passive shielding*, since one does not intervene with other magnetic fields from outside. The present necessities determined by performances, cost price and the appearance of new research equipment imposed the development of new combined shielding techniques which make use of both magnetic shielding and electronic systems for cancelling the environmental magnetic fields. The active systems can also be self-contained, able to work without shields [4].

The first wide scope applications of the magnetic field control appeared as the result of the necessity to protect the ships against marine mines endowed with magnetic sensors [5]. The motion and change of position of bulk ferromagnetic bodies (corresponding to military ships) determine major disturbances of the geomagnetic fields. The ships possess, by construction, their magnetic moment due to both the position they had during the construction and the welding operations applied to different elements. Thus, since the ship is permanently under the influence of the geomagnetic field, it is differently magnetized along the three directions (longitudinal, transversal and vertical).

The ship magnetization which appears during the construction period is named permanent magnetization. The ship permanent magnetism is stable and has a value specific to each ship. The permanent magnetic field can change when: the ship is displaced in zones where the geomagnetic

field is different, the ship body is subjected to the action of high intensity vibrations produced by equipment, artillery fire or explosions. Beside the permanent magnetization, the ship is also characterized by the inductive magnetization produced as the result of the ship motion inside the geomagnetic field. The direction and size of this magnetization depend on the ship geometry, the ratio between its main dimensions (length, width, draught), on the geographic latitude, the ship course and the magnetic properties of the construction materials. The values of the components of the ship permanent and inductive magnetization, as well as their distribution along the main axes, define the ship magnetic signature.

The characterization from a magnetic standpoint is carried out in especially arranged polygons, by measuring the field components in terms of the ship coordinates system and the four main ship courses (E, W, N, S). The ship magnetic field is exploited by the specialists in marine weapons in order to detect and destroy it. That is why it is necessary to diminish the ship magnetic field under certain imposed limits. This is carried out by magnetic processing of the ship, which consists in ship demagnetization by which the permanent components of the magnetic signature are diminished, and by field compensation using artificial fields by whose means the inductive components are diminished [6].

This compensation is carried out by means of high size coils installed on the ship, according to the coordinate system. Currents with intensity changing in proportion with measured magnetic field are injected through the coils by means of a triaxial magnetometer mounted on the mast. This type of compensation can be called *dynamic compensation*, since the field control is carried out in time, the magnetic field produced by the coils being proportional with the intensity of the measured field. This system does not operate as a negative feedback assembly, since the magnetometer measures the field outside the ship and not under the ship deck, in the zones where the three directional compensation coils are acting.

Several terms are used in literature, like: active compensation [7], [8], [9], active shielding [10], [11], [12], dynamic shielding [13], magnetic field cancellation [14], magnetic field stabilization [15] or hybrid technique [16]. All these terms define compensation systems which operate in negative feedback regime. The feedback loop closes through a field sensor, a magnetometer, power amplifiers and compensation coils. The sensor is located in the area which must have a minimum magnetic field, inside the compensation coils. These systems are especially used to obtain minimum magnetic fields within different volumes in which research, investigation and magnetic diagnosis equipment are due to operate. The most important

applications are in studies on biomagnetism [17], [18], [19], satellites [20], equipment generally using electron guns, or ion sources and mass spectrometry [21], photomultipliers and nuclear physics [22], [23], masers and atomic clocks [24], electron microscopy and transmission electron microscopy [25], SEM (scanning electron microscopy) [26], SQUID [27], MRI [28], [29], electron beam instruments [30].

There are also some domestic applications through which the intensity of the magnetic field produced by electrical network within the dwelling spaces is diminished [31]. Researches are also carried out to use it in offices and laboratories. The frequency range within which these are operating depends on both the principle used for magnetic field measurement, and the applications. The utilized sensors are of inductive type when one aims to diminish alternative fields with frequencies exceeding 5-10 Hz. For the range of continuous or slowly variable fields, saturable fluxgate [32], [33] or GMI [34] magnetic transducers are used. The most used coil systems are of rectangular classical Helmholtz type, due to the small volume they occupy and the bigger volume where a uniform magnetic field is provided. Their main advantages are: easy to manufacture, low volume, and allow for a speedy assemblage and disassemblage.

II. THEORETICAL BACKGROUND

In the theoretical study two main types of dynamic compensation systems are approached, that work in negative feedback regime: systems with inductive transducer and systems with saturable fluxgates. The transfer characteristic of the both types of magnetometers is cosinusoidal, carrying out a vectorial field measurement.

In order to analyze a magnetometric system applied for the environmental field compensation by using the field negative feedback, the diagram presented in Fig. 1 is considered.

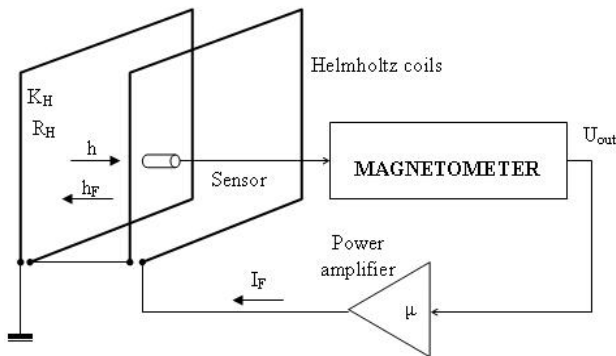


Figure 1. Negative feedback system

The active compensation system consists of a magnetometer with the sensitivity $S(V/T)$. The magnetometer sensor can be either passive (search coil) or active (fluxgate, Hall, GMI). The voltage delivered at the magnetometer output controls, through a power amplifier (voltage amplifier or voltage controlled current source) the negative feedback current I_F in a magnetic field generator (solenoid or Helmholtz system). This generates a field with the intensity h_F whose sense is defined by sense of the environmental field h ; this happens under the condition that the magnetometer sensor is situated inside the volume where

the negative feedback coil system produces the field h_F . The Helmholtz coil system is characterized by the current constant K_H (T/A) and the winding resistance R_H . Under these circumstances, the magnetometer output voltage is determined by the error field $h-h_F$ according to the relation:

$$U_{out} = S(h - h_F). \quad (1)$$

The intensity of the negative feedback current is determined by the relation:

$$I_F = \frac{\mu U_{out}}{R_H} \quad (2)$$

where μ is the amplification factor of the power amplifier.

From the relations (1) and (2), it follows that:

$$h_F = K_H I_F = \frac{K_H}{R_H} \mu S (h - h_F). \quad (3)$$

The intensity of the feedback field is given by the relation:

$$h_F = \frac{\frac{K_H}{R_H} \mu S}{1 + \frac{K_H}{R_H} \mu S} h \quad (4)$$

The residual field Δh represents the error signal applied to the magnetic field transducer. The ratio between the error signal and the field intensity h which need to be compensated is obtained from the relation:

$$\frac{\Delta h}{h} = \frac{h - h_F}{h} = \frac{1}{1 + \frac{K_H}{R_H} \mu S} \approx \frac{R_H}{K_H} \frac{1}{\mu S}. \quad (5)$$

The relation (5) shows that, for an efficient compensation, the following condition must be satisfied:

$$(K_H / R_H) \mu S \gg 1. \quad (6)$$

Since K_H and R_H are parameters which determine the current through the coils and the voltage applied to them, it is preferable to use power amplifiers with $\mu \gg 1$. Under these conditions, it follows that the factor $K_H/R_H S$ can equal the unit. The relations (5) and (6) are valid for any kind of magnetometer, with active or passive transducer, that operates in a negative feedback loop of magnetic field.

A. Systems with inductive magnetic field transducers

The magnetometers with magnetic field inductive transducers make use of coreless coil sensors.

TABLE I.
PRINCIPAL TYPES OF SEARCH COIL MAGNETOMETERS [35]

a		Coil with voltage amplifier $U_{out} = \left(1 + \frac{R_2}{R_1}\right) \frac{R_s}{R_s + R} n S \omega \mu H$
b		Coils with frequency compensation by negative feedback $U_{out} = \frac{R_s}{R_s + R} \frac{n S \mu}{C_0 L_0} H$
c		Coil with current amplifier $U_{out} = \frac{\mu n S R}{L} H$

Their sensitivity is mainly determined by the coil cross section and the number of turns. The sensitivity and the signal/noise ratio depend on the quantity of material (copper) the coil is made of, and the conductor diameter [36], [37].

There are three main configurations for the utilization of the inductive sensors with operational amplification devices presented in Table I. In the simplest configuration, consisting of a coil coupled with an operational amplifier, the output signal is proportional with the magnetic field intensity and frequency. This is true for the frequency range at which sensor coil resonant phenomena are not present. The disadvantage of the configuration consists in the proportionality between the output signal amplitude and the field frequency. This can be eliminated by introducing an additional stage with its transfer characteristic changing in proportion with $1/\omega$ (Fig. 2).

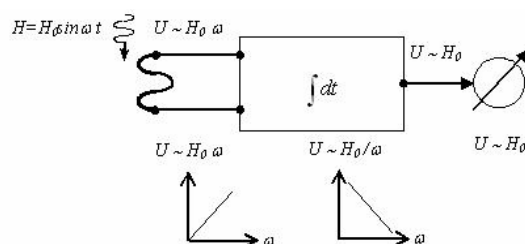


Figure 2. Compensation of the transfer characteristic of the inductive transducer using an integrator.

The transducer frequency compensation can be made by using the configuration from Table I.b. The output signal is only changing in proportion with the intensity of the applied field.

Still another configuration (Table I.c) concerns the sensor connection to a current amplifier. This structure is preferred in most of the applications, since it is simpler than that from Table I.b, and the output signal changes in proportion only with the field intensity.

Starting from these three basic structures, a magnetometer for alternative fields also includes a detection system and elements for measured field intensity display. The main shortcoming consists in the fact that this magnetometer is not able to measure slowly changing signals.

B. Systems with fluxgate active transducer

The most used magnetometers for magnetic field compensation are those with saturable fluxgate, due to the following advantages: they can measure the continuous, slowly variable or alternative components of the magnetic field within the frequency range that can reach some hundreds of Hz; the magnetometer output signal has a minimum phase difference with respect to the applied field. The relations (5) and (6) are also valid for the magnetometers with saturable fluxgate, to control both the continuous and alternative magnetic fields.

III. APPLICATIONS AND EXPERIMENTAL RESULTS

The applications of the dynamic compensation systems concern:

- Compensation of the ship magnetic field
- Control of the director magnetic field in ion trap of the maser for atomic clock
- Magnetic field control at the MAT 252 Finnigan mass spectrometer
- Magnetic field control of the installation for biomagnetometry research.

A. Compensation of ship magnetic field

The naval applications concern the compensation of the ship magnetic field. With this purpose in view, a triaxial magnetometer is used, fixed on the ship mast at a height of about 10- 15 m from the deck. The magnetic axes of the magnetometer coincide with the ship geometric axes: longitudinal, transversal and vertical. The components of the permanent magnetization are diminished as the result of magnetic processing of the ship by using polygons for magnetic processing. In order to compensate the inductive magnetic components, magnetic fields are used generated by groups of coils disposed in three compensation windings named as follows: PL- parallel latitude; OD- horizontal course; SD- solenoidal course and VD- vertical course. Since, as the result of the magnetic treatment, residual vertical components still remain; their intensity can be reduced by using coils named main adjusting windings. The currents through the three winding groups can be adjusted by means of high power current sources which deliver through windings currents whose intensity and polarity is determined by the signal arrived from the triaxial magnetometer, depending on the ship orientation in relation with the magnetic meridian and corresponding to certain latitude.

The main parallel latitude winding PL Fig. 3, is usually located under the main deck in horizontal plane and is meant to compensate the vertical inductive magnetization, Z_{IZ} .

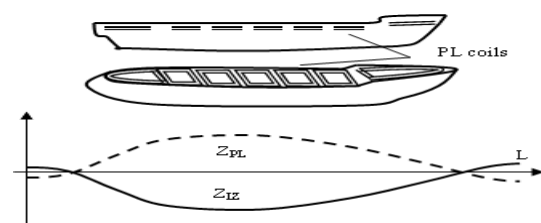


Figure 3. The parallel latitude (PL) compensation coil

The winding consists of more sections, in order to facilitate the current adjustment on sections along the ship main axis, beneath the keel, depending on the distribution of the ferromagnetic masses. The current intensity depends on the ship latitude.

The main course winding OD is located, in principle, on the same paths with the winding PL; it consists of more sections concentrated toward the ship aft and bow, Fig. 4. Its role is to provide the compensation of the vertical component of the inductive longitudinal magnetization, Z_{IX} . The intensity of the current from this winding is adjusted depending on the magnetic latitude of the place where the ship sails and on the ship magnetic course. The ship inductive longitudinal magnetization is produced by the projection of the geomagnetic field on the ship longitudinal

axis, $X_T = H_T \cos D_m$, where X_T is the ship longitudinal component, H_T the horizontal component of the geomagnetic field, D_m – the magnetic course (the angle between the ship longitudinal axis and the magnetic meridian of the place). In certain specific situations, it is preferred to compensate this magnetization by replacing the OD winding with a solenoidal course winding SD.

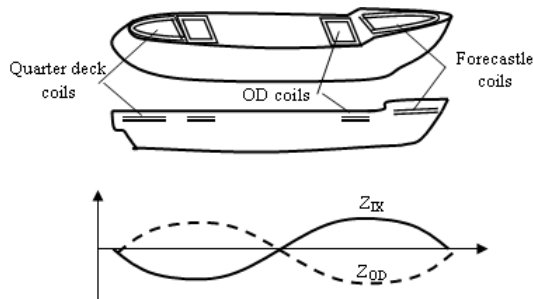


Figure 4. The main course (OD) coils

The solenoidal course winding SD, Fig. 5, is more efficient than the OD winding in terms of the compensation of the Z_{IX} component, but this is difficult to carry out in practice, given the construction of the ship body, the OD windings being preferred. The currents through this winding are adjusted similarly to the OD winding.

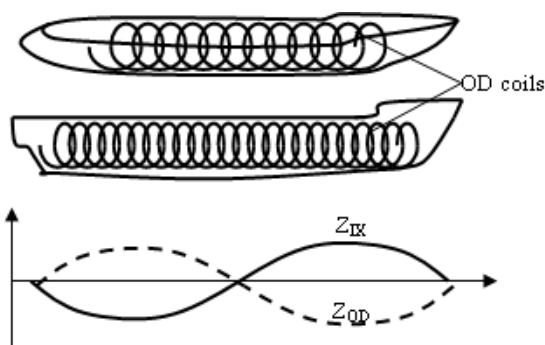


Figure 5. The solenoidal course winding (SD)

The vertical course winding VD, Fig. 6, is used to compensate the ship transversal inductive magnetization whose vertical inductive component is Z_{IV} . The ship transversal inductive magnetization is produced by the Y_T component (transversal ship component) of the geomagnetic field $Y_T = H_T \sin D_m$. The current through the VD winding is adjusted depending on the magnetic latitude and the magnetic course. For an efficient adjustment, this winding is executed on sections.

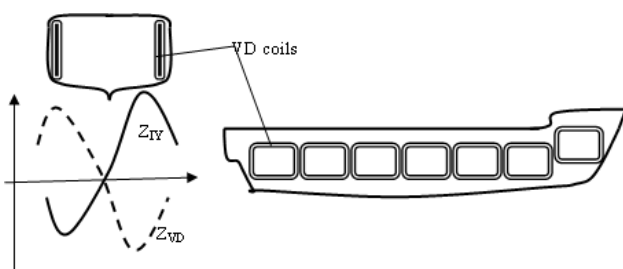


Figure 6. The vertical course winding (VD)

The block diagram of the installation for automated adjustment of the currents through the windings PL, OD and VD, for ship magnetic field compensation is presented in Fig. 7. Every magnetometric channel is located such that to provide mainly the decomposition of the geomagnetic field along the ship axes and the efficient modification of the currents through the windings, depending on the ship course and swing. The signal delivered by the magnetometer controls, by means of power electronic amplifiers or of amplidyne, currents proportional with the projection of the measured magnetic field. As a rule, these currents are superposed on the permanent component established during the magnetic processing of the ship. The system is endowed with circuits for magnetometer compensation and calibration, to periodically test the accurate operation.

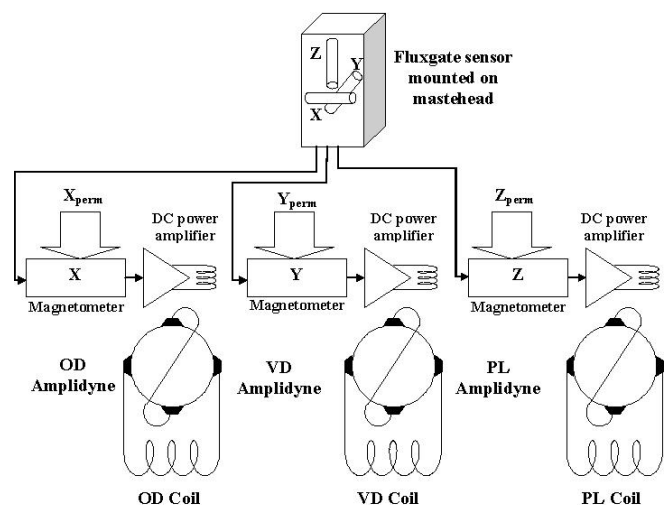


Figure 7. Triaxial installation for compensation of ships magnetic fields

When amplidyne are used, a negative feedback loop is introduced to make the amplidyne response linear, such that the value of the current through the windings follows as faithfully as possible the variations of the field measured by the magnetometer.

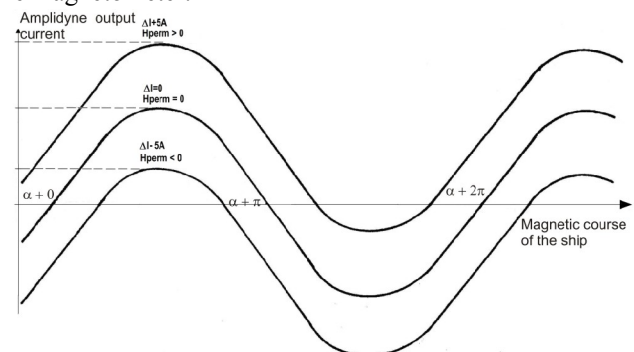


Figure 8. Dependence of the amplidyne intensity current versus magnetic course of the ship

Each channel for field measurement and current adjustment automatically maintains through the windings currents, changing in proportion with the intensity of the geomagnetic field decomposed after the ship axes. In Fig. 8, the dependence of the amplidyne intensity current versus magnetic course of the ship is presented.

The performance of such a system concern:

- Measuring channels: 3 orthogonal magnetometric channels
- Measuring range: $\pm 60,000$ nT
- Power delivered to the windings of a compensation channel: (1-7) kVA
- Current constant: $\pm (10^{-5}-10^{-6})$ T/A
- Non-linearity of the delivered current: 1%
- Protection factor: IP 65.

B. Control of the director magnetic field in the maser ion trap for atomic clocks

The systems of atomic clocks that use hydrogen masers are introduced in multi-layered magnetic shields. Their performance can be influenced by the diurnal variation of the geomagnetic field during the periods of maximum sun activity, as well as the presence of field disturbing sources with frequency of 50 Hz. In case of a reduced efficiency of the magnetic shields, the effect of these disturbances can be diminished through the control of the axial magnetic field inside a cylindrical magnetic shield. For this, a solenoidal winding is executed on the first layer inside the shield, through which an electric current is injected, its intensity being controlled by a fluxgate magnetometer whose transducer is introduced in the shield centre, Fig. 9.

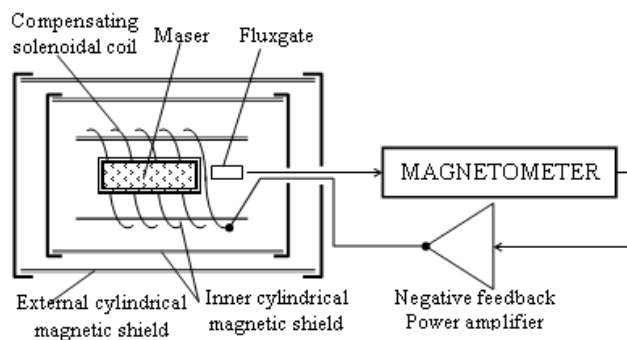


Figure 9. Compensation field in maser

This system was applied at the masers accomplished at IFTAR Magurele, Romania. The characteristics of the magnetometer assembly are:

- Measuring range: $\pm 50,000$ nT
- Current supplied through the compensation winding: ± 100 mA
- Factor of dynamic compensation: 10^{-2} .

C. Control of the magnetic field at Finnigan mass spectrometer

The installation for magnetic field control at the mass spectrometer type MAT 252 Finnigan uses also the negative feedback, but the transducer is of inductive type, consisting of an air coil. The conditions for spectrometer installation and setting working imposed a maximum admissible residual field of 1,000 nT, at the frequency of 50 Hz. The place chosen for spectrometer location was at the floor right below the power station of the Institute of Geology and Geophysics Bucharest. To secure this condition, the room where the spectrometer was to be installed had to be shielded. Given the high price of the shield, a simpler and more efficient solution was adopted, with a better performance/price ratio. The solution consisted in the

utilization of a Helmholtz coils system meant to control the disturbing magnetic field intensity. The current intensity through the coils is determined by the level of the disturbing field intensity measured by means of a magnetometer with inductive transducer with coreless coil. Through a power amplifier, the signal coming from the magnetometer delivers currents with such a phase that, by means of the produced field, a negative feedback loop can be closed through the assembly transducer \rightarrow magnetometer \rightarrow power amplifier and Helmholtz coils (Fig. 10).

Even if the sector electromagnet is supplied by a highly accurate current source, a vertical field component can disturb the induction value both at the input and the output of the electromagnet. The ion collectors located in the focal plane of the collector with stigmatic geometry are separated by construction and electrically shielded; at the same time, they are kept out from the emission of the secondary electrons which are trapped.

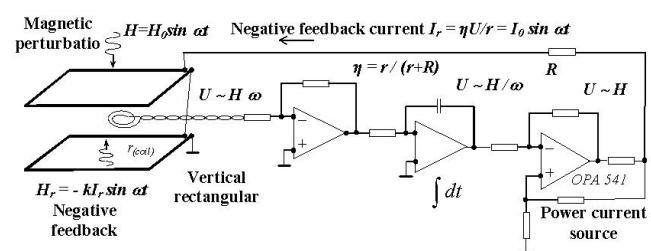


Figure 10. The diagram of the 50 Hz magnetic field compensation system

The action of an alternative vertical component produces the modulation of the ion flux due to their deviation from the trajectory established by sector electromagnet. The position of the mass spectrometer is such that the collector is in the centre of the Helmholtz coil system. The magnetometer field transducer is located in close vicinity of the collector, since in the area close to it the negative feedback effect is maximum (Fig. 11).

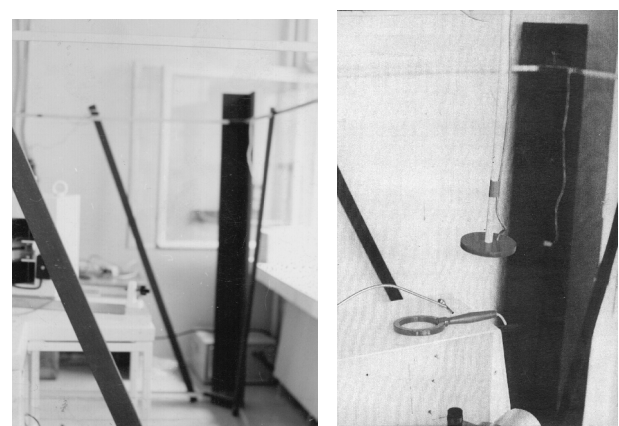


Figure 11. MAT 252 mass spectrometer with 50Hz magnetic field cancelling system

In order to check the field in the laboratory, the system is endowed with a secondary magnetometer having the same characteristics as the one from the negative feedback loop.

The characteristics of the system are:

- Helmholtz coil dimensions: (3.16 x 3.16) m
- Controlled field: vertical component

- Maximum compensation range: 8,000 nT
- Frequency: (20 – 400) Hz at 3 dB
- Attenuation: 40 dB.

D. Magnetic field control in the installation for biomagnetometric research from the Faculty of Medical Bioengineering, UMF Iasi

The biomagnetism studies are carried out by means of SQUID type magnetometers. The utilization of a SQUID magnetometer to measure the biological fields needs a thorough location study, in order to find the location with the lowest level of the artificial magnetic disturbances. At the same time, the presence of the geomagnetic field embarrasses its operation if one does not secure solutions to compensate it. The location can not always be the most adequate and for this reason technical solutions were chosen with an advantageous performance/cost ratio. Since the building was not destined by construction to provide conditions specific to a laboratory of biomagnetism, certain compromises were made in terms of location. For this reason, the laboratory of biomagnetism is located at a distance of 25 m from the transformers of the building power station having a power of (2x600) kVA. The disturbance sources from this location are as follows: electric power supply stations with a frequency of 50 Hz, operation of some medical equipment, vehicle motion inside the building perimeter, the geomagnetic field with its continuous and slowly variable components, and the electromagnetic field existing due to the GSM relays, data transmission, wireless and Bluetooth networks from the building. The solution chosen to secure the operation of a SQUID biomagnetometer concerns: shielding against the external electromagnetic environment, compensation of the continuous components of the geomagnetic field, and the dynamic control of the environmental magnetic field within the low frequency range, 50 Hz included.



Figure 12. Shielded room

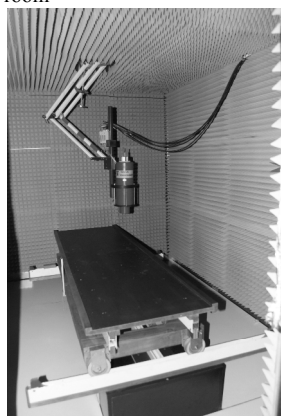


Figure 13. Shielded room - inside

The shielded room (Fig. 12) with the dimensions of (2x3x4) m is executed from 12 mm thick aluminium panels. The room interior has an anechooidal structure, realized with pyramidal panels made of material absorbent for electromagnetic fields (Fig. 13).

The shielding factor of the utilized aluminium plate is presented in Fig. 14 for the frequency range (0- 200) Hz.

In order to compensate the magnetic field, a mixed solution was chosen, consisting of manual compensation of the magnetic field, combined with the automated compensation which works in the negative feedback loop.

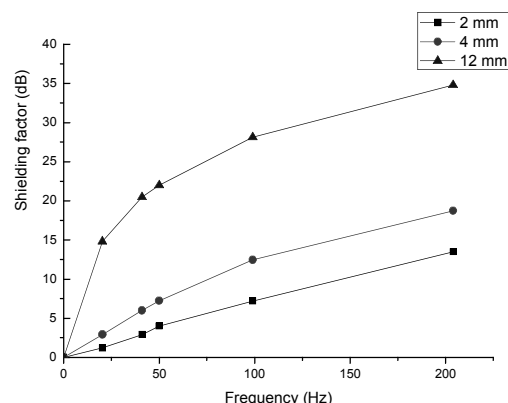


Figure 14. Shielding factor of the aluminium sheets

The application of the a.c. field negative feedback when the volume within which the compensation is carried out contains non-ferromagnetic metallic masses presents the following peculiarity: the Foucault currents induced in the aluminium walls of the shielded room produce, in turn, magnetic fields whose phase changes with the frequency, Fig. 15.

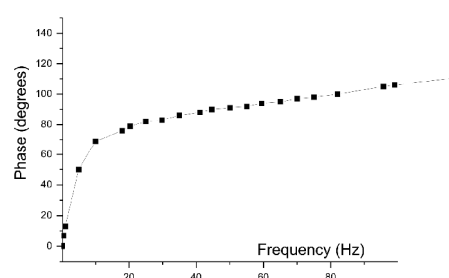


Figure 15. Phase variation of the shielded magnetic field in centre of the room

This is a shortcoming since it narrows the frequency spectrum of the compensation assembly through negative feedback. In order to improve this shortcoming, a phase correction circuit must be introduced in the negative feedback loop. The lack of the phase correction may determine the oscillations appearance due to the positive feedback at certain frequencies.

The constant component can be annulled by using a triaxial Helmholtz system in line with the cartesian coordinate system Fig. 16.

The chosen system has its Ox axis parallel to the

magnetic meridian, Oy perpendicular to it, and Oz as the place vertical. In the laboratories, the values of the three components are: $H_x=19,000$ nT; $H_z=37,000$ nT and $H_y=0$.

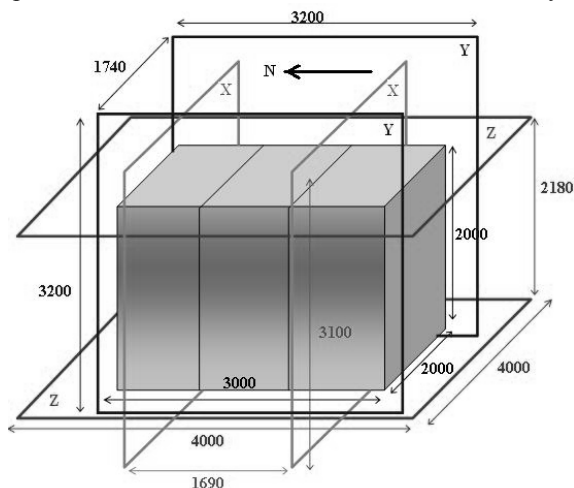


Figure 16. Triaxial Helmholtz system

The Fig. 17 presents the block diagram of the system for manual compensation of the magnetic field vector from the laboratory. This vector can be decomposed in two components: a constant and a variable one.

The manual compensation circuit consists of the voltage controlled current source, which has three winding of the Helmholtz system as its load.

The current source control can be carried out analogically or by a digital keyboard. In principle, the manual control can be carried out up to a level of ± 1 nT, on which the variable components of the magnetic field vector are overlapped. Practically, this compensation can be considered up to a level of ± 10 nT, which represents a compensation factor $\Delta h/h$ of about 2.4×10^{-3} (72 dB) for the total field (42,000 nT).

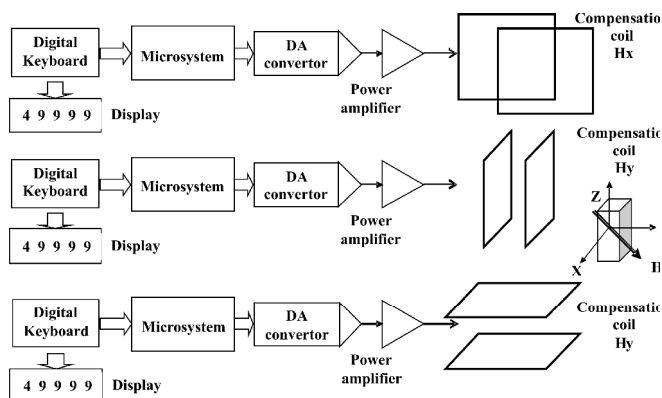


Figure 17. Manual magnetic field compensation diagram

The compensation in negative feedback regime controls the variable components of the geomagnetic field. These components are both due to the natural variations of the geomagnetic field, and the human activity. Their intensity only seldom exceeds 10,000 nT, and the current values do not exceed 5,000 nT. The realized system consists of a triaxial magnetometer, each channel operating according to the diagram from Fig. 18. The utilization of this system permits both to reduce the continuous residual components and the variable components of the magnetic field; it also

reduces the possible fluctuations or drifts that can occur in the manual compensation system.

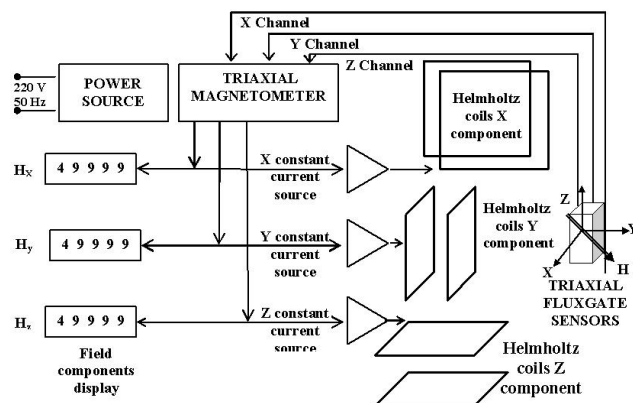


Figure 18. Dynamic magnetic field compensation

The Fig. 19 presents the magnetic field inside the Helmholtz system for the H_x component parallel to the magnetic meridian, with the feedback loop open and closed. The field attenuation is of about 1.3×10^{-2} .

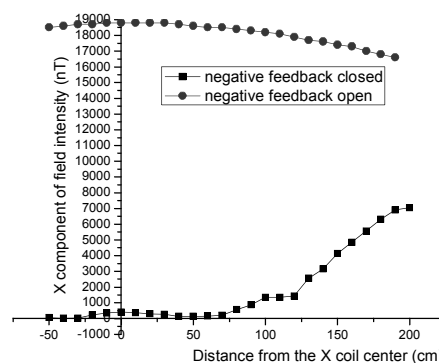


Figure 19. Magnetic field intensity (Ox component) with the feedback loop closed and open.

IV. CONCLUSIONS

The magnetic field dynamic compensation shows certain advantages as compared to the classical magnetic shields, due to a much higher performance/cost ratio.

The utilization of the Helmholtz coils permits easy access to the protected installations.

The application field is wide, from the military ships to the electron microscopy systems and the SQUID biomagnetometers.

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