Stefan Mayer Instruments

MR-3

Triaxial Magnetic Field Compensation System

Compensation coil design and system installation guide

– January 2003 –

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1 Safety precautions

The following safety precautions should be observed before system installation:

The MR-3 system is intended for use by qualified personnel who are familiar with the safety precautions required to avoid possible injury.

Read this guide carefully before constructing compensation coils and installing the system. This guide is intended as an extension of the MR-3 user's manual which is delivered together with the MR-3 instrument. The instrument must not be operated before a careful study of the MR-3 user's manual.

The MR-3 system and compensation coils must not be operated in explosive atmosphere.

It is only permitted to install the compensation system and coils in dry rooms.

Coil construction, system installation and operation is left at user's risk.

Do not connect any load with a resistance below 1 Ω to the MR-3 power output terminals.

Do not exceed the electrical and thermal operating limits, as defined in the specifications section of the MR-3 user's manual. Disregard can cause destruction of the instrument and consequential damages.

Stefan Mayer Instruments shall not be liable for any direct, indirect, special, incidential or consequential damages arising out of the construction, installation, and use of any system components and compensation coils.

The instrument and this manual may be subject to alterations without prior notice. Although this guide has been carefully written, correctness cannot be guaranteed.

2 Introduction

The magnetic field compensation system MR-3 has been designed for automatic triaxial compensation of magnetic field disturbances in the frequency range from 0 to >500 Hz. The system reduces slow disturbances, e. g. caused by trams, elevators or vehicles, as well as magnetic noise produced by power lines (typ. 16.3 Hz, 50 Hz, 60 Hz, and harmonics) by establishing a compensation field with the help of suitable compensation coils.

This manual provides information for the design of suitable compensation coils and system installation. Although the construction of compensation coils is simple and straight-forward, the guidelines described in the following should be observed in order to achieve proper matching between the coils and the MR-3 instrument and successful system operation.

3 Operating principle

The MR-3 instrument measures the magnetic field with a triaxial fluxgate magnetic field sensor. A set of three pairs of Helmholtz-type compensation coils must be constructed around the sensor and aligned with the sensor axes. The coil current is controlled by the MR-3 system in order to compensate for magnetic field changes measured by the sensor.

Ideal compensation coils are the circular Helmholtz coils. They consist of a pair of rings separated by a distance which equals half the ring diameter (Helmholtz condition for maximum field homogenity). Helmholtz coil pairs generate a homogeneous magnetic field in the central region between the coil rings. The direction of the magnetic field is parallel to the centre axis. For triaxial compensation, three orthogonal sets of coil pairs are required (see figure 1).

For many applications, the construction of circular Helmholtz coils is too difficult so that rectangular shaped coils are the preferred design in most cases. Furthermore, the Helmholtz condition (distance equals half diameter) for maximum homogenity can be relaxed in order to avoid complicated "nested" coil designs. The easiest way to make suitable compensation coils is to fix the coil windings at the edges of a cubic or rectangular supporting structure. In many applications, this "supporting structure" are simply the walls of the room where the magnetic field disturbances have to be cancelled. The loss in homogenity for a non-ideal coil design does not cause problems provided that the coil dimensions are large compared with the

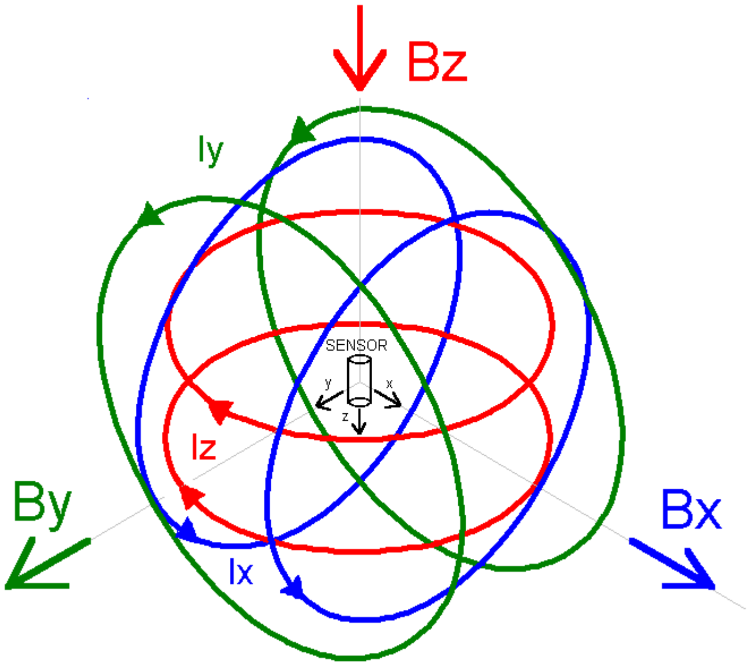

Fig. 1: MR-3 system operating principle, B_x, B_y, and B_z indicate the magnetic field components generated by the coils. I_x, I_y, and I_z are the respective coil currents.

region where maximum compensation is required. The MR-3 system has been optimized for direct connection of low impedance coils. Only a few turns per ring are sufficient, which greatly simplifies the installation procedure. Typical values are 3–6 turns per ring, two corresponding rings connected in series. In many applications, 3- or 5-wire cables known from household electrical installation are used.

4 Magnetic field conditions, sensor location, and system limitations

Before beginning the design and construction of compensation coils it is always recommended to examine the magnetic field conditions in the volume where the magnetic field disturbances have to be cancelled. It is useful to measure the DC and AC components up to 1 kHz in all three directions with a suitable magnetometer. The MR-3 system is intended to cancel magnetic field disturbances of up to a few microtesla amplitude. The exact compensation range depends on the coil layout.

The compensation effect is best in the vicinity of the MR-3 magnetic field sensor. Therefore it is recommended to fix the sensor as close as possible to the place which is most sensitive to magnetic field disturbances (e. g. close to a SEM column). However, there are some limitations which have to be considered:

1.) The sensor cannot handle magnetic field components above 100 μT (roughly twice the earth's magnetic field). That means, the sensor cannot be placed near magnets or objects containing magnetic material (e. g. not to close to the magnetic lenses of a SEM column).

2.) Magnetic material in the vicinity of the sensor can deflect the magnetic field components generated by the compensation coils as well as the magnetic field disturbances to be measured. The consequence will be unsufficient magnetic field compensation. Keep the sensor away from magnetic parts like steel constructions.

3.) The MR-3 magnetic field sensor emits small DC and AC magnetic field components. Although the field generated by the sensor rapidly decreases with distance, the sensor should not be mounted closer than ∼10 cm to sensitive devices.

Since the magnetic field is only measured at a single location in the room, it cannot be expected that compensation is complete at any location in the room. The compensation effect depends on the homogenity of the compensation field as well as on the homogenity of the field disturbances. In general, the compensation effect is poor for strongly inhomogeneous magnetic field (e. g. if the source of magnetic disturbance is within the volume where the field has to be cancelled). The best place for the sensor with respect to field homogenity is the centre of the compensation coil arrangement.

5 Coil design

For successful system operation the compensation coils must fulfil a few requirements which are described in the following sections.

5.1 Coil dimensions

Larger coils yield better field homogenity than smaller ones, but the power required to generate a certain compensation field increases with increasing dimensions. In most applications, the coil rings will be attached to the edges of the room so that the coil dimensions are defined by the dimensions of the room. For good field homogenity the distance between two corresponding coil rings should not be much larger than the side length of the ring. The system has been tested with coil dimensions up to 6 m × 6 m. Much larger coils are not recommended because the output power of the MR-3 system may be too low or the coil inductance becomes too large.

5.2 Number of turns

The number of turns per coil ring defines the magnetic field generated in the centre of the coil arrangement for a given coil current. The magnetic field B in the centre of a rectangular coil pair is given by the following:

$$B = 1.6 \frac{nIab}{\sqrt{a^2 + b^2 + c^2}} \left(\frac{1}{(a^2 + c^2)} + \frac{1}{(b^2 + c^2)} \right). \tag{1}$$

Equation (1) gives the magnetic field measured in microtesla when the dimensions a, b, and c are measured in meters, and the coil current I is measured in ampères. See figure 2 for definitions.

Example: Dimensions $a = b = 6$ m, $c = 3.6$ m, coil current $I = 2.5$ A, and number of turns per coil ring $n = 5$ gives:

$$\begin{aligned} B &= 1.6 \frac{5 \times 2.5 \times 6 \times 6}{\sqrt{6^2 + 6^2 + (3.6)^2}} \left(\frac{1}{(6^2 + (3.6)^2)} + \frac{1}{(6^2 + (3.6)^2)} \right) \mu\text{T} \\ &\simeq 3.2\ \mu\text{T}. \end{aligned} \tag{2}$$

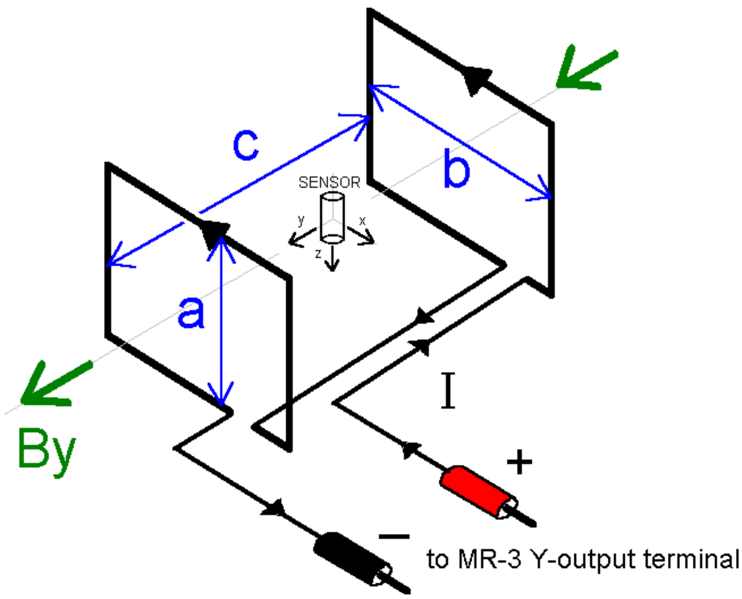

Fig. 2: Rectangular coil pair. Only one turn per ring is shown. In real applications distance c should not be larger than a or b.

The example shows that the maximum MR-3 output current of 2.5 A generates a magnetic field of approximately 3.2 μT in the centre of a 6 m $\times$6 m rectangular coil pair which is separated by 3.6 m. This is sufficient for many applications and a typical example for a good coil design. The loop gain of the MR-3 system can be adjusted to match with different coil field/current ratios. However, it is recommended to select this ratio between 0.5 and 5 μT/A.

5.3 Coil resistance

The recommended resistance of each coil pair connected in series is between 1.5 and 2.0 Ω. A resistance below 1.0 Ω can damage the output amplifiers of the MR-3 instrument and must be avoided. A resistance above 2.0 Ω reduces the maximum output current of the system amplifiers. That does not matter in cases where the maximum output power is not needed. The coil resistance depends on the dimensions a and b (see figure 2, the number of turns per ring n and the wire cross section q. If a and b are measured in meters and q is measured in mm^2 the resistance R measured in Ω of the coil pair made from copper wire is

$$R = 0.07\,\frac{n(a+b)}{q}. \tag{3}$$

Using wires of 2.5 mm^2 cross section the resistance of the example coils from the last section is

$$R = 0.07\,\frac{5 \times (6+6)}{2.5}\ \Omega \ \simeq \ 1.7\ \Omega, \tag{4}$$

which is well within the recommended range. For an exact calculation the resistance of the connection cables should be added, but in most cases their contribution to the coil resistance can be neglected.

6 Coil construction

Since only a few turns per coil ring are required, construction of the compensation coils is easy. It is recommended to use commercially available multi-wire flexible cables. The individual wires are connected in series in order to make a coil ring with the selected number of turns. Two corresponding rings are again connected in series. Connections can be made by screw terminals, cage clamps, crimp connectors or soldering. All connection cables should be kept short and installed pairwise.

In most applications the coils are attached to the walls of the room. The exact shape of the coils is not critical. Use standard plastic cable tubes or housings known from household electrical installation. Although the output voltage of the MR-3 system does not exceed 15 V, it is important to obey the current regulations and safety rules for electrical installations.

In case that the coils cannot be attached to walls it is possible to construct a special supporting structure for the coil rings, for example if the room is too big or if local compensation is required. Such supporting structure can be a cubic frame made from wood or aluminium tubes. A variety of aluminium construction elements is available from different manufacturers and electronics equipment suppliers. Use only non-magnetic material for coil construction. Any supporting structure should be stiff enough to avoid vibration which can influence the compensation effect.

7 Sensor mounting and system connections

The triaxial magnetic field sensor of the MR-3 system must be properly mounted and aligned with the axes of the compensation coil pairs. Use only non-magnetic material and screws for sensor mounting. The sensor must be fixed in space. Even small deviations of its original position can easily cause malfunctioning so that readjustment of the system is required. The sensor cable should be safely fixed.

The coil connection cables are connected to the output terminals at the rear side of the MR-3 instrument with help of the cage clamp connectors delivered with the instrument. Check for correct polarity and correct assignment (see figure 2, see also section "Electrical connections" in the MR-3 user's manual).

Before any disconnection or maintainance of the coils the controller sections and amplifier stages of the MR-3 instrument should be switched off, (rotary switches to position "0" and toggle switches at the rear side to position "OFF", see the user's manual).

8 System adjustment

Once installed the system must be adjusted following the instructions of the MR-3 user's manual. Anyway, an oscilloscope is required for the adjustment procedure.

9 Installation example

The following pictures show an example of an MR-3 installation in a scanning electron microscope (SEM) application. The room dimensions are approximately 3.5 m × 6 m area and 3.2 m height. The SEM is located in the rear part of the room. The coil wires do not surround the whole room but only the rear part. The whole coil arrangement has almost cubic shape. The coil rings are made from 5-wire cables of 1.5 mm^2 wire cross section.

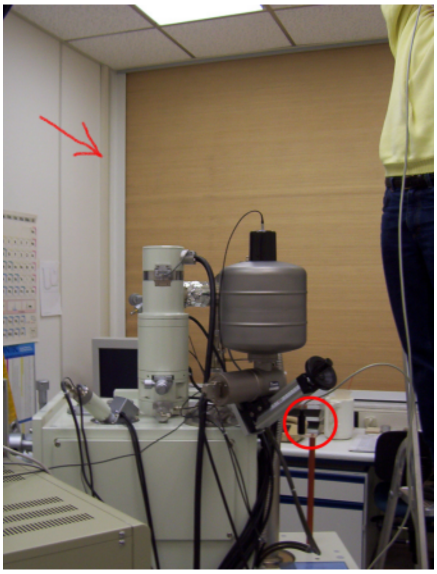

Fig. 3: SEM application. The red circle shows the MR-3 magnetic field sensor mounted on a plastic rod near the SEM column. The arrow indicates a plastic cable housing which contains parts of the compensation coils. The coils are continued in the ceiling.

Fig. 4: The cables of two neighbouring coil rings (part of x- and y-coil) are placed in the same housing. The third cable is the connection cable between the z-coils which are in the ceiling and floor of the room.

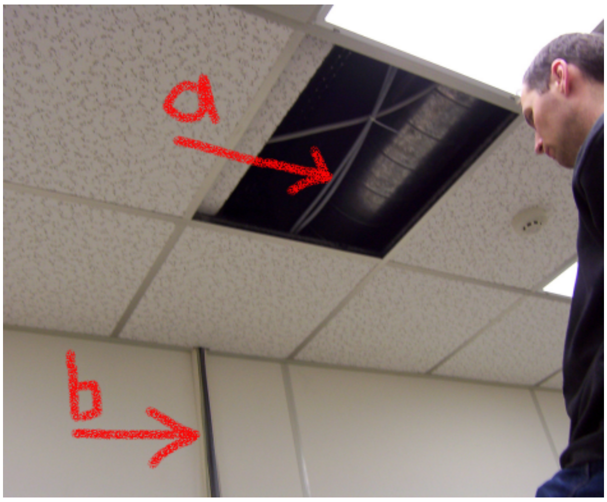

Fig. 5: a) parts of the x- and z-coil fixed together in the ceiling, b) cable housing for x- and y-coil parts as in fig. 4

Fig. 6: Connection of the MR-3 instrument at a corner of the coil arrangement. Coil positions are shown by the dashed lines.

10 Troubleshooting

The following table presents solutions for the most common problems related with the operation of the MR-3 system.

problem	**possible reason**	**solution**
power supply indicator (green LED at the front) does not light	no power connection or blown fuse	check power line chord and fuses at the rear side
field settings cannot be adjusted to analog meter center position	DC magnetic field at the sensor location exceeds adjustment range	choose a better place for the sensor
large AC voltage at one of the measurement output terminals on the front when controller section is switched on	system loop gain too large	immediately switch off the controller rotary switch to position "0", reduce gain by turning the P, I, and D trimmer counter-clockwise, turn on the controller section and check again
same as above, but P, I, and D trimmers already turned to minimum gain	still too much loop gain	reduce number of coil turns
analog meter indicates nonzero uncompensated magnetic field when controller switch is turned from "0" to "L"	wrong coil polarity	reverse polarity of coil for that component, be sure that current flows in same direction in both corresponding coil rings
analog meter immediately shows maximum pos. or neg. coil current when controller switch is turned from "0" to "L"	power amplifier stage is switched off or open coil connection	switch on amplifier stage with toggle switch at the rear side and check coil resistance with an ohmmeter
same as above	wrong coil polarity or interchanged coil pairs	check coil polarity and assignment
analog meters show large average coil current during permanent operation	sensor position or magnetic field conditions have been changed	readjust field settings with the 10-turn pots on the front to zero average coil current