Fluxgate gradiometer for high-resolution magnetometry

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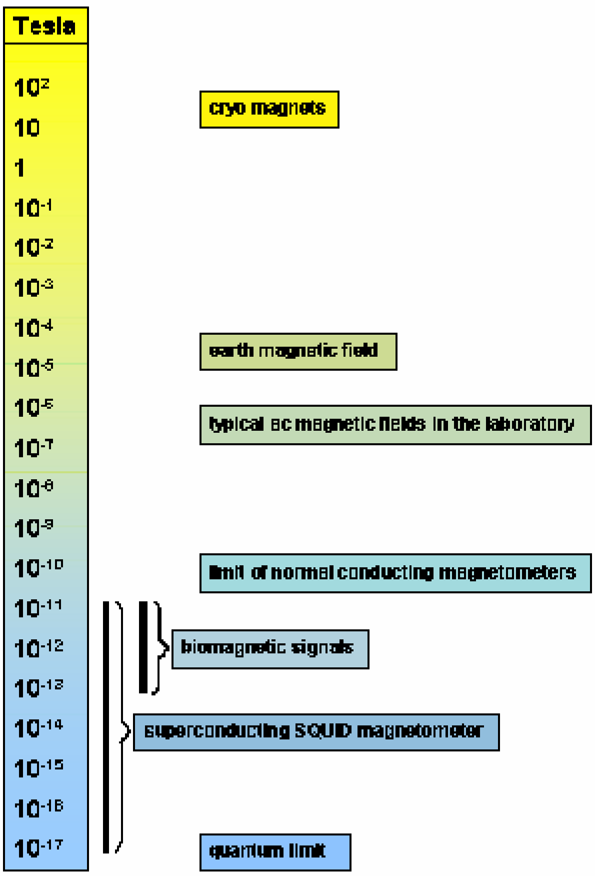
Abstract

Most sensitive fluxgate magnetometers are combined to give a highly balanced gradiometer. This system practically excludes natural and man-made magnetic noise. So it is possible to exploite the extremely low intrinsic noise of the magnetic sensors when measuring in unshielded environment. Then the magnetic noise density is smaller then 5 pT/sqr(Hz) at frequencies greater then 10 Hz. Furthermore it is possible to detect extremely small magnetized iron particles in considerable distances: 60 µg at 10 mm and a few mg at 100 mm.

1. Introduction

The magnetic field strength or the magnetic flux density which is accessible to human beings may vary over several orders of magnitude, see figure 1. Due to their intrinsic noise normal conducting magnetometers can be used to measure magnetic fields down to about a few pT. Smaller magnetic fields can only be detected by superconducting SQUID (superconducting quantum interference device) magnetometers.



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The measurement of small magnetic fields is important in medical applications, non-destructive testing, physics with special emphasis in geophysics and further fields of science and technology.

Examples of normal conducting magnetometers are induction coils, Hall-effect devices, magnetoresistance and giant magnetoresistance devices, fluxgate magnetometers and Cesium magnetometers. The SQUIDs need cryogenic cooling for their operation, that means down to about 4 K in the case of Low-T SQUIDs and to about 77 K in the case of High-Tc SQUIDs.

When measuring small magnetic fields, in addition to the intrinsic noise of the magnetic sensor the most important point is the external noise which has to be excluded. This external noise can be the natural variations of the earth magnetic field. It can also be man-made noise for example originating from ac currents in powerlines.

One method to exclude the external noise or background field is the use of a magnetically shielded room. As an example in [1] a system is described consisting of a fluxgate magnetometer within a shielded room. A second method to exclude the background field is the use of two magnetic sensors. If properly placed and if the background field is homogeneous then the difference of both signals makes the background field zero and leaves the magnetic field which stems from a source in the vicinity of the sensors. Mathematically speeking such a system measures the gradient of the magnetic field. Using more than two sensors is advantageous and gives a gradiometer of higher order. As an example reference [2] shows a High-Tc SQUID gradiometer system of second order.

SQUIDs are rather complicated to handle because of their need for cryogenic cooling. For practical applications therefore fluxgate magnetometers with lowest intrinsic noise seem to be advantageous. Furthermore magnetically shielded rooms are expensive and limit the size of objects under test. Therefore the gradiometer method for the exclusion of background fields often is advantageous. Based on these reasons in the following a fluxgate gradiometer of second order is described.

2. Measurement setup

The key components of the measurement setup are fluxgate magnetometers. Their shape is that of a rod with circular cross section. These fluxgates measure that component of the magnetic field which is parallel to their axis.

Figure 2 shows a sketch of the measurement setup. On the turntable normally the device under test is placed. The turntable is made from material which is free of magnetic parts. A crane, also free of magnetic material, holds the fluxgate gradiometer.

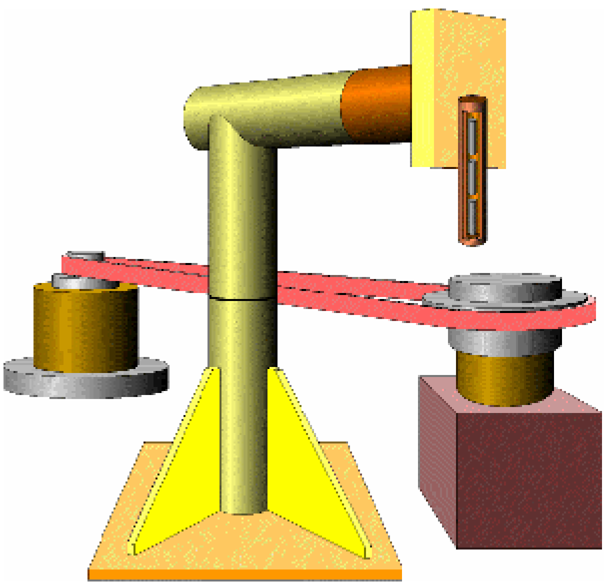

Figure 2 : Sketch of the Measurement Setup

Figure 3 shows the principal view of the fluxgate gradiometer. It consists of three fluxgate sensors which are mounted on one axis. Not shown in figure 3 are means for mechanically balancing of each of the sensors.

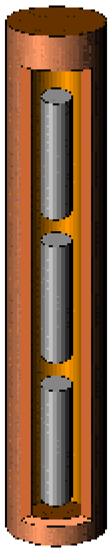

Figure 3 : Principal View of Fluxgate Gradiometer

Figure 4 shows the block diagram of the measurement system. The fluxgate sensors are of the type Bartington MAG-03IEL 100 followed by the power supply unit MAG-03PSU. The analog signal processor performes the mathematical operations to obtain the second order gradient signal. This can be given either to a spectrum analyser or to an amplifier and a lowpass filter followed by an oscilloscope. The cutoff frequency of the lowpass filter is 8 Hz.

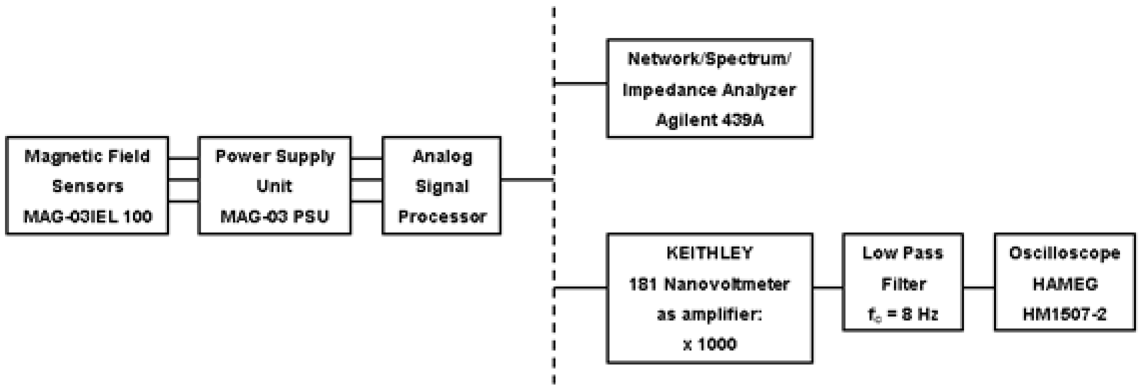

Figure 4 : Block Diagram of Measurement System

This gradiometer only works sufficiently if it is balanced to a high degree. This balancing has to be done in order to reduce the background signal as far as possible. The balancing includes a mechanical balancing using tuning screws in the fluxgate gradiometer. It also includes an electronic balancing of the various signal branches in the signal processor. The measurement results, which are described in the following paragraph, were obtained after balancing such that the background field which stems from a nearby electrical train was minimized. The train distance is about 200 m. Its electrical current and therefore also its magnetical field has a frequency of 16 2/3 Hz.

3. First measurement results

Figure 5 shows the noise spectrum as obtained without any device under test. The figure shows a screen plot of the spectrum analyser with a vertical axis of magnetic flux density in addition. The horizontal frequency axis extends from 0 Hz to 100 Hz. Values below 10 Hz however are to be disregarded. Figure 5 shows the averaged results of 16 measurements. There is a small peak at 16 2/3 Hz. This is the residual signal from the nearby electrical train. The signal is largely suppressed by the gradiometer arrangement.

Also suppressed is the 50 Hz line. This stems from the ordinary powerline supply in the neighbourhood. Also its harmonic at 100 Hz can be seen.

Figure 5 : Residual Noise Spectrum of Magnetic Flux Density BN . Frequency Span: 0...100 Hz

Apart from the discussed peaks the spectrum is rather smooth. In a bandwidth of 1 Hz it starts at BN ca. 5 pT at 10 Hz going up to BN ca. 2.5 pT at 100 Hz signal frequency. According to the data sheets the intrinsic noise of a single sensor is typically BN ca. 2.5 pT/vHz at a signal frequency of 10 Hz. Figure 5 shows that the background field is reduced to only about two times this value. That means that the gradiometer is close to the noise limits which are given by the intrinsic noise of the single sensors. Furthermore the residual noise of this fluxgate system is near to the residual noise of a comparable High-Tc-SQUID system.

In the following an elementary example is described which gives an idea of the possibilities of the measurement system. A particle of pure iron and a mass of about 160 µg was magnitized to saturation by a strong permanent magnet. Then it was placed on the nonmagnetic turntable as shown in figure 2. The turntable was turned around and the output signal of the measurement system was given to an oscilloscope according to the lower path of the block diagram in figure 4. The result is shown in figure 6 which is a combination of 3 single results for different distances between the particle and the bottom of the lowest sensor. These distances are 6 mm, 11 mm and 14 mm for the 3 signals in figure 6, respectivly. For the smallest signal the signal to noise ratio is about 13 dB. Converting this result to a slightly different situation leads to the following statement: In a distance of 10 mm below the bottom of the lowest sensor an iron particle of 60 µg can well be recognized. It should give a signal to noise ratio of 6 dB. In distances of about 100 mm iron particles of a few milligramm can be recognized.

Figure 6 : Signals of iron particles of mass 160 µg. Combination of 3 oscilloscope traces for various distances d between iron partical and bottom of the lowest magnetic sensor. For the signals from left to right holds d=14 mm, 11 mm and 6 mm. Vertical axis: 10 mV/division corresponding to 100 pT/division

4. Conclusions

Based on most sensitive fluxgates sensors a fluxgate gradiometer has been developed.The residual noise in unshielded environment is smaller than 5 pT/sqr(Hz) for frequencies greater than 10 Hz. The present system performance is such that iron particles down to 60 µg can well be detected at distances of 10 mm. So can iron particles down to a few milligramm at a distance of about 100 mm. There are good chances to increase the system performance in the future.

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