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Senzory a gradiometry pro magnetopneumografii

Sensors and gradiometers for magnetopneumography

Summary

Magnetopneumography is a diagnostic method for examining ferromagnetic dusts in lungs of metal workers like grinders and welders. Traditionally, SQUID sensors are used for this type of biomagnetic measurements. The effort of our research is aimed at developing alternative measuring system using much more affordable and easier to use fluxgate sensors. Suppression of disturbance from distant sources is facilitated by gradiometric measurement of magnetic field. It was demonstrated earlier, that fluxgate sensors are sufficiently sensitive for detection of small amounts of ferromagnetic dusts. This lecture discuses important parameters of the fluxgate sensors used for measurement, and describes other components of the measuring setup. It also takes into account methods for data processing and inversion of the measured field – i.e. estimation of the magnetic sources from measured field values. The total measured field can be used for estimate of the total dust load within lungs (provided the properties of the dusts are known). Moreover, the spatial distribution can be estimated from measured data. The best results were achieved for localized (compact) sources, but partial success was observed also for more general distributions. Forward modeling of magnetic field from known sources helps in evaluation of the methods and in developing inverse solutions.

Souhrn

Magnetopneumografie je neinvazivní diagnostická metoda sloužící k vyšetřování obsahu feromagnetických částic v plicích pracovníků v kovoprůmyslu (brusičů, svářečů). Obvykle se pro tento druh biomagnetických měření používají senzory typu SQUID. Náš výzkum se zaměřuje na vývoj metod použití mnohem dostupnějších a snáze použitelných senzorů typu fluxgate. Potlačení rušení ze vzdálených zdrojů je dosaženo gradiometrickým měřením magnetického pole. Jak bylo ukázáno již dříve, měření fluxgate senzory je dostatečně citlivé k detekci malých množství feromagnetického prachu. Tato přednáška popisuje důležité parametry použitých fluxgate senzorů a popisuje ostatní součásti měřicího systému. Také zmiňuje metody zpracování naměřených dat pro inverzi pole, tj. odhad vlastností zdrojů magnetického pole. Celková velikost změřeného pole může vést k odhadu celkového množství feromagnetického prachu v plicích za předpokladu znalosti vlastností prachu. Navíc z naměřených dat lze odhadnout i prostorové rozložení prachu v plicích. Nejlepších výsledků bylo dosaženo pro kompaktní, dobře lokalizované zdroje, ale částečných úspěchů se podařilo dosáhnout i pro obecná rozložení zdrojů v plicích. Dopředné modelování magnetického pole ze známých zdrojů pomáhá ve vyhodnocení různých metod a ve vývoji řešení zpětného problému (inverze pole).

Klíčová slova
Magnetopneumografie, MPG, magnetometry, gradiometry, fluxgate

Keywords
Magnetopneumography, MPG, magnetometers, gradiometers, fluxgate

Contents

1. Introduction

Magnetopneumography is a noninvasive diagnostic method for detection of ferromagnetic dusts in lungs of metal workers (welders, grinders). It was first devised by Cohen (e.g. [1, 2, 3]) as early as the 1970s. Since then, many authors described the application of MPG for detection of ferromagnetic dust in an effort to provide early diagnosis of dust accumulation, before it leads to pneumoconiosis and other disorders. Localized deposits may be associated with some pathological changes, but generally the dust is dispersed in the volume of lungs. Magnetic measurement is more sensitive (making early detection possible) and definitely less intervening than an X-ray examination, which makes its use for repetitive screening viable.

After magnetization of the subject in strong DC magnetic field, the remanent field of magnetic particles in lungs is scanned in one – or more – measurement planes in front of thorax. The resulting map of magnetic field is further processed with the aim of determining total amount and spatial distribution of dust within lungs. In our research we use discrete model of human lungs composed of 574 cubes, each with volume of 8 cm^3. Most experiments were made with such models composed of plastic cubes with known amount of magnetite dust.

Traditionally, SQUIDs are used in this application for measuring the magnetic field (e.g. [4, 5, 6]). While providing unsurpassed sensitivity, these devices are expensive and difficult to employ. There are efforts to replace SQUIDs with much more affordable fluxgates (e.g. [7, 8, 9, 10]). Our laboratory has been involved in this research for a long time.

The measured magnetic field values from two or more probes are further processed as gradient values. This is in direct correspondence to methods employed in SQUID applications in biomedical measurements. The advantage of using gradients rather than field values is in suppression of signals originating from distant sources (Earth's magnetic field, disturbances from traffic, etc…). The global character of Earth's field can be approximated by a dipole. However, the Earth's field is locally rather homogenous, with gradient of only 25 pT/m or less, and it's time variations are also rather homogenous [11, 12]. If needed, the estimates of geomagnetic field values for specific location can be obtained from geophysical computer models, like the one published by NOAA [13]. The state of Earth's field (calm or disturbed by solar storms interacting with upper atmosphere) can be checked online via Intermagnet network [14]. The data from practical experiments show that for given measurement setup, the dominant source of magnetic disturbance is electrical traction (trams, subway trains) in urban areas. This makes some measurements possible only in late night hours (when trams and subway do not operate).

It must be noted that the gradient as used here is not exactly equivalent to mathematical concept of gradient as a locally defined function. Instead, two absolute field values are subtracted and related to their respective geometrical separation. It is possible to create true gradient probes (as discussed later) but for practical reasons (stability of probes), we chose this approach for most of our experiments.

Mathematically, the gradient is defined as spatial derivative of vector quantity so that the total value in a given point specified by position vector ***r*** can be described by homogenous field component $\boldsymbol{B_0}$ and gradient or ***nabla B***.

$$\boldsymbol{B}(\boldsymbol{r}) = \boldsymbol{B}_0 + \nabla \boldsymbol{B} \cdot \boldsymbol{r} \quad (1)$$

We only approximate this by calculating difference of two field values:

$$\boldsymbol{gradB} = \frac{\boldsymbol{B}(\boldsymbol{r}_2) - \boldsymbol{B}(\boldsymbol{r}_1)}{|\boldsymbol{r}_2 - \boldsymbol{r}_1|} \quad (2)$$

and in fact we further simplify the situation by measuring only the vertical (z) component of magnetic field. This is possible because of the arrangement of examined sources, the magnetometer probes and their directivity.

$$\mathrm{gradB} = \frac{\mathrm{B_z(z_2) - B_z(z_1)}}{|\mathrm{z_2 - z_1}|} \quad (3)$$

The whole system is developed with the aim of final application on living subjects. However, most of our experiments are currently made using phantoms (physically realized models) made of plastic and magnetite dust. Alternatively, some simulations can be made using computer forward model calculating fields from known magnetic sources (using Biot-Savart law and principle of superposition).

2. SQUIDs and other sensors and gradiometers

Besides fluxgates, discussed later, there are some other types of magnetic field sensors that are sometimes combined and arranged into gradiometric setups.

Hall sensors

It is quite common approach in design of industrial sensors to combine two or more Hall devices into a common differential (or gradiometric) system. The most typical application is detection of nearby permanent magnet or ferromagnetic object biased by permanent magnet. The advantage of this approach is increased sensitivity and suppression of static background field sensitivity. However, Hall devices are by far not enough stable and sensitive for biomedical measurements. They can reliably measure artificial fields in the order of 10 mT, not low fields in nT range.

AMR and GMR sensors

Modern magnetoresistors are substantially more sensitive than Hall devices so that they can measure fields with resolution down in 10 nT range. Similar to Hall devices they can be created as differential (gradiometric) systems. Just like Hall devices, their advantage is in their small scale making possible compact designs with small gradiometric baselines. Unfortunately their stability and noise parameters are still not sufficient for the given application.

Proton and Overhauser magnetometers

Proton magnetometers are scalar absolute sensors. They can have sensitivity of 0.01 nT and sampling rate of 1Hz. The main drawbacks are limited range (not working under 20 μT), slow response (1Hz) and certain dead angle. Furthermore it cannot operate in strongly gradient fields. Overhauser magnetometers overcome some of these limitations, with 0.01nT/sqrtHz noise levels, sampling rate of 10 Hz and operating range even below 20 μT and virtually without dead angles. Again, proton and Overhauser magnetometers, in spite of their scalar nature, can be combined into gradiometers. Such devices with typical gradiometric baseline of 1m or more are used in geological prospecting, archeological research and other areas. Otherwise, these devices are used mainly as independent absolute field sensors for calibration of fluxgate magnetometers.

Fluxgates

Fluxgates are discussed in more detail in the next chapter. In this place it suffice to say that they represent the best room-temperature vectorial sensors. They are surpassed only by SQUIDs that are more expensive and difficult to operate. In our laboratory we work with fluxgates of our own construction.

SQUIDs

Superconducting quantum interference devices represent the "golden standard" in biomagnetic measurements. They are the most sensitive instruments with many diverse applications. Noise levels of 1fT/sqrtHz are achieved in practice [15, 16]. SQUIDs were used in the original research by Cohen [1,2,3] and even today they are used for the most demanding measurement like human brain field measurements (100fT range). However, the operation requires cryogenic technology (liquid He or liquid N for "high-T_c" SQUIDs) and usually also magnetically shielded room. Typically, several layers of high-permeability material are used for suppressing of DC field and additional layer(s) of highly conductive material for suppressing of AC fields. This poses serious financial burden. Another possibility is using gradiometric probes as this approach suppresses to great extent disturbance from distant sources. For practical measurement, the SQUID device is usually coupled to external field sensed by pickup coil by superconducting flux transformer. This allows for various magnetometer and gradiometer configurations as shown in the fig. 2.1 below.

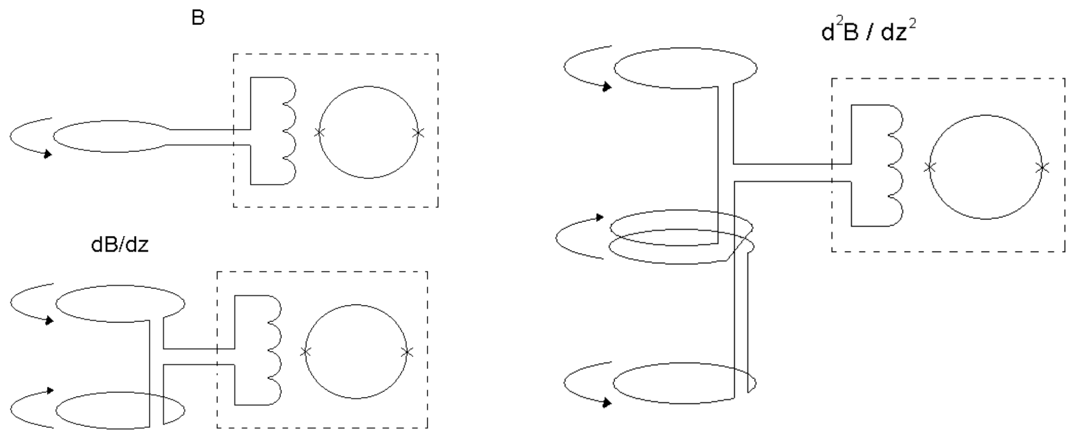

Fig. 2.1 – Superconducting flux transformers used with SQUID. Magnetometer, first-order gradiometer and second-order gradiometer configurations are shown (after [16])

3. Fluxgate sensors and gradiometers

Besides SQUIDs, the fluxgates are practically the only sensors suitable and sensitive enough for biomagnetic applications. The major advantages of fluxgates include operation at room temperature and in normal levels of magnetic field, i.e. outside shielded room, vectorial sensitivity (cosine response to field angle relative to sensor axis) and relatively low cost. Of course, the parameters are much worse than those of SQUIDs – the noise of our fluxgates is about 15pT/sqrtHz at 1 Hz, compared to fT/sqrtHz of low-temperature SQUIDs.

Fluxgates used in our laboratory are usually of the classical Aschenbrenner-Goubau (or ring-core) type, produced in-house. The design and parameters were published earlier – see e.g. [17]. The principal scheme of the ring-core fluxgate is shown in fig. 3.1 (left side) below. It is not the only possible design, however. In the same figure, on the right side is shown a single-core differential (gradiometric) fluxgate.

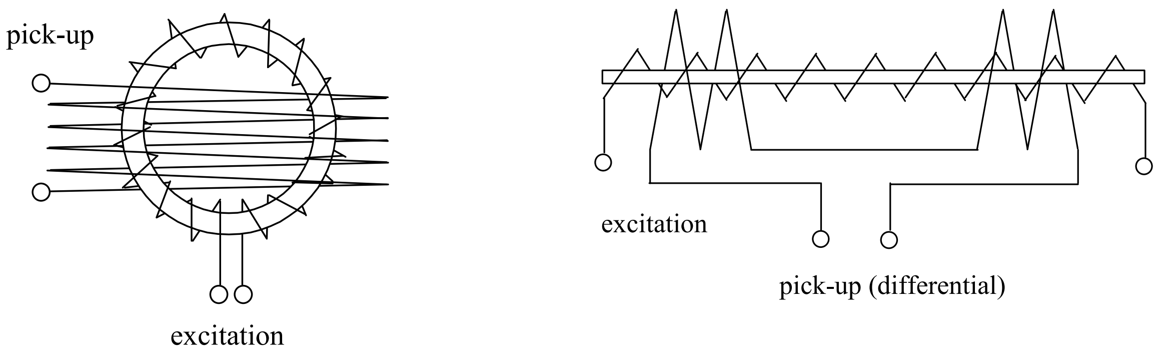

Fig. 3.1 – Ring-core (left) and single wire-core differential fluxgate (right)

Both designs have their respective merits. The ring-core fluxgates typically have better stability and noise parameters but the ring shape causes decreased sensitivity due to demagnetization effects. It may also contribute to unwelcome orthogonal field sensitivity. For noise spectrum of ring-core fluxgate used in our research see fig. 3.2. (Measured in 6-layer mag. shield.)

On the other hand, rod cores have very good sensitivity and immunity to orthogonal field due to small demagnetization. At the same time, noise parameters tend to be worse. In a simple single-core fluxgate, there is also considerable feed-through (signal at first harmonic induced from excitation to pick-up coil by transformer coupling). This is not so much pronounced in the case shown in fig. 3.1 (right side) where the pick-up is differential and thus feed-through and homogenous field response is suppressed. Otherwise, double-rod (Vacquier type) designs are used in order to suppress feed-through. The noise spectrum of single-core differential fluxgate by Tesla Co.

with gradiometric baseline of about 20mm is in fig. 3.3. However, in this case the noise may be predominantly caused by the Tesla electronics.

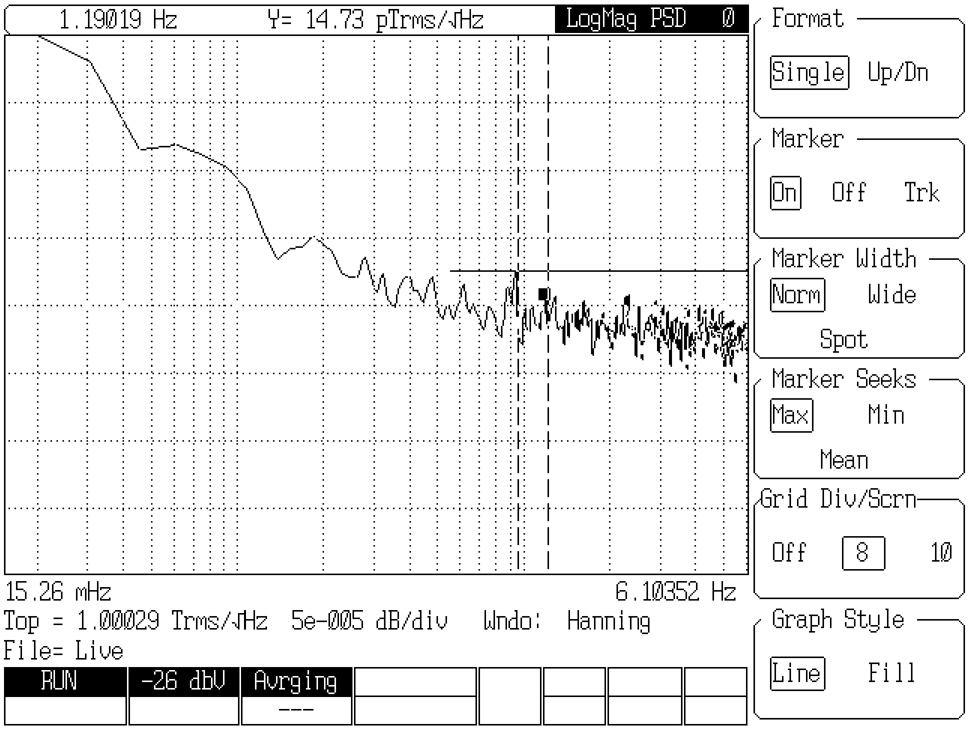

Fig. 3.2 – Noise spectrum (PSD) of ring-core fluxgate sensor in low frequency range. The noise is of 1/f type, about 15pT/sqrtHz at 1Hz

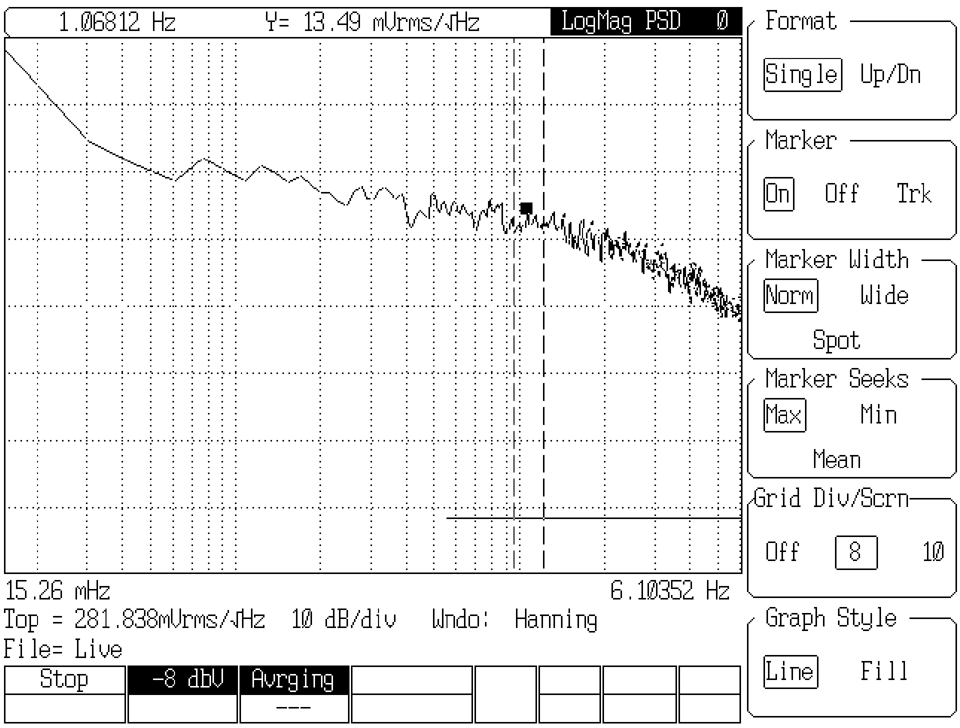

Fig. 3.3 – Noise spectrum (PSD) of single-core differential fluxgate. The gradient sensitivity is about 6.4µT/m/V. The indicated voltage thus corresponds to about 90nT/m/sqrtHz at 1 Hz

Possible compromise design combining advantages of ring-core (low noise) and rod-type (high sensitivity, low demagnetization, suppression of orthogonal field sensitivity) is race-track (oval-core) fluxgate. The fig. 3.4 shows possible combined design with both homogenous-field and gradient field pick-up coils on the same core.

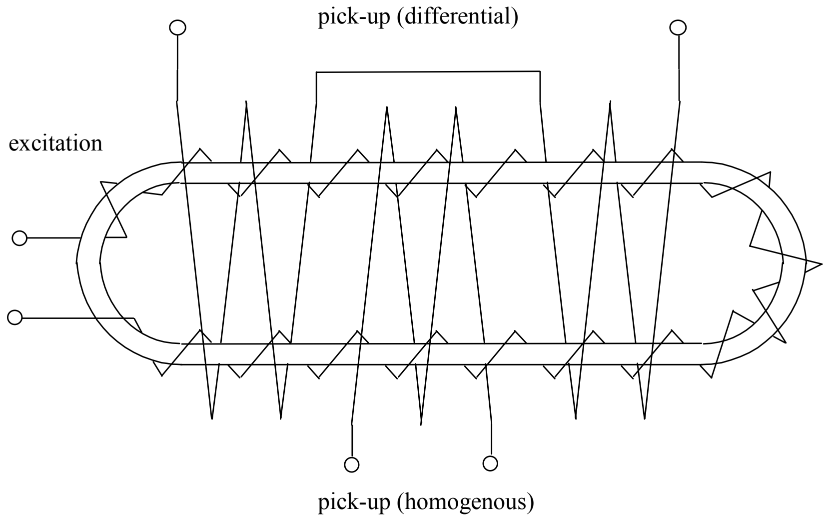

Fig. 3.4 – Race-track core fluxgate with standard (homogenous field) pick-up and (optional) differential pick-up

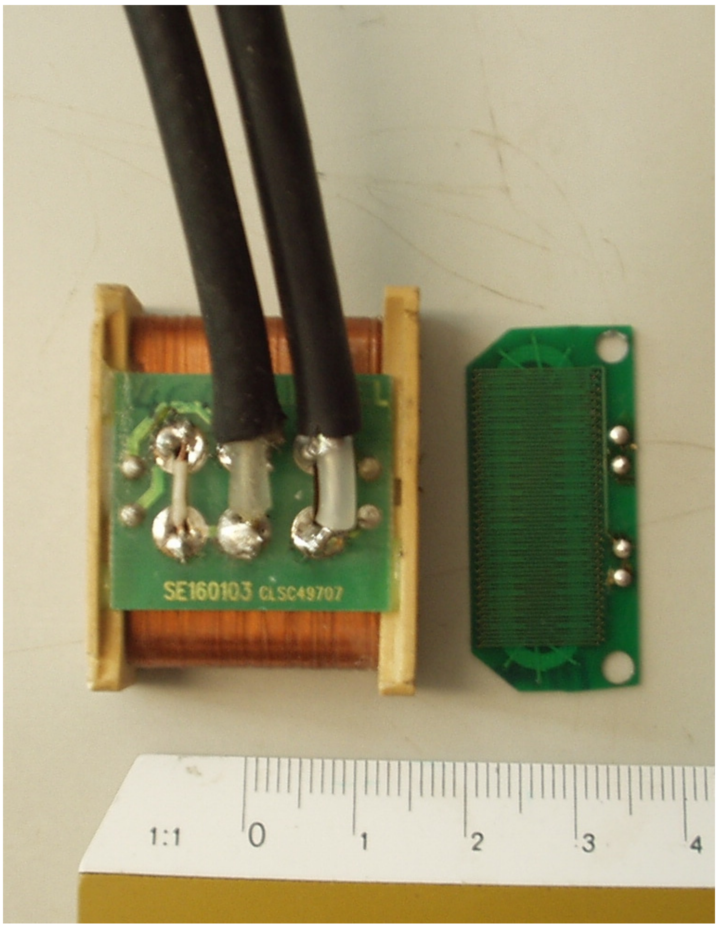

Fig. 3.5 – Ring-core (left) and PCB race-track core (right) fluxgate sensors

It can be made by classical technology or in printed circuit board (PCB) technology as shown in fig. 3.5. This figure shows a comparison between classical technology ring-core and PCB technology racetrack fluxgate sensors [18]. Both were developed and made in-house by our laboratory. Use of race-track fluxgates is an open possibility for future research in the field.

As described above, in our experiments we use combination of two (or more) ring-core fluxgate sensors fixed coaxially in known distance. Signal of each sensor is processed with separate magnetometer channel, and the gradient is calculated by subtracting individual absolute field values. (Only one vector component – the vertical or z – is actually measured.) The signal spectrum of two channels evaluated differentially is shown in fig. 3.6. The two output channels from fluxgate signal processing electronics are connected to FFT spectrum analyzer as A-B signal. The baseline is 10 cm, both sensors are in magnetic shielded chamber. The values are already scaled in pT/m/sqrtHz.

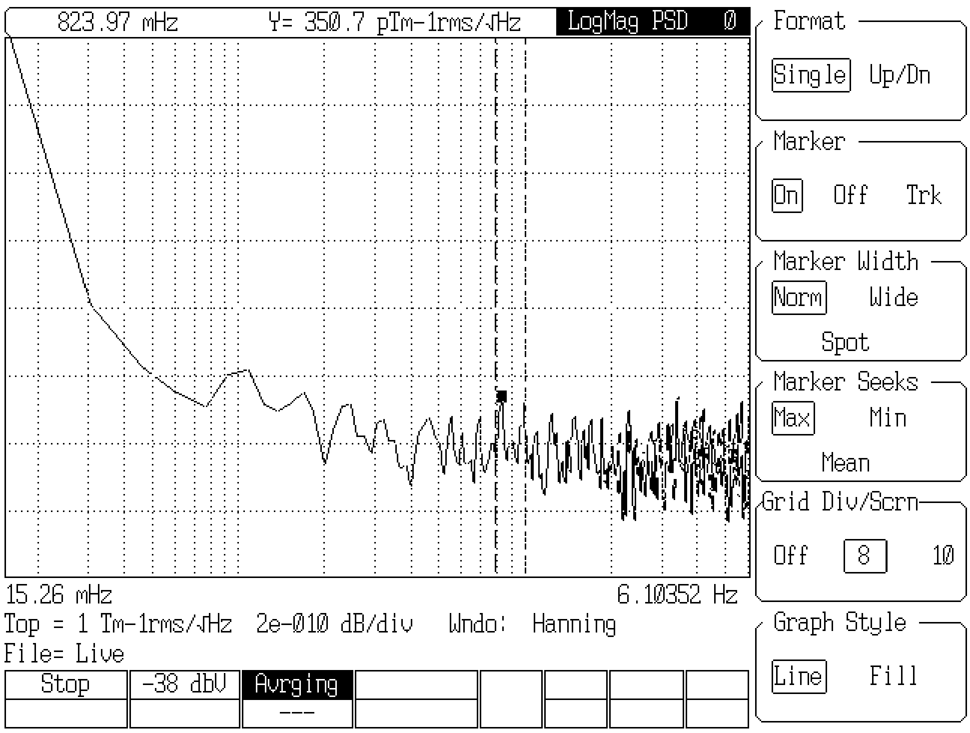

Fig. 3.6 – Noise spectrum (PSD) of gradient signal from two ring-core fluxgates, baseline is 10 cm. The noise is 350 pT/m/sqrtHz at 1Hz.

In this arrangement, the sensitivity to gradient field is about 17 mV/µT/m and homogenous field response is 0.035 T/m/T. This is much better suppression than for combined race-track fluxgate gradiometer in [7].

4. Application for magnetopneumography

As described earlier, we apply multiple fluxgate sensors (magnetometers) for measurement of magnetic field gradient next to examined subject's thorax. The field is created by remanent field of ferromagnetic particles in lungs of metal workers after magnetization in strong DC field. The measurement of gradient suppresses influence of distant sources because these have relatively small gradient. On the other hand, fields from close sources have strong gradient and thus can be discriminated from the homogenous background. This is the consequence of character of the magnetic field of a dipole and similar sources. For a dipole, the intensity of field decreases with third power of distance ($B = f(1/r^3)$) and thus close sources display high gradient.

The nonmagnetic positioning bed for scanning of magnetic field maps just above subject's thorax is shown in the fig. 4.1. The fixture with fluxgate probes (see fig. 4.2) is suspended vertically from solid and vibration-insulated portal above the bed. It is important to move the examined subject and hold the gradiometer in stable position because even small movement of the probes in Earth's field may induce large disturbing signals.

Fig. 4.1 – The nonmagnetic positioning bed for scanning of field maps

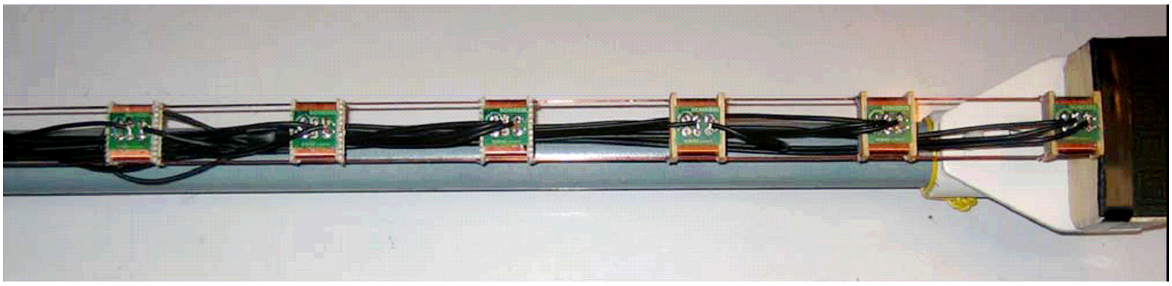

Fig. 4.2 – Fixture with multiple fluxgate sensors forming several first-order gradiometers, each with baseline of 10 cm (from [19])

The measured data are further processed in order to obtain inversion of the field – i.e. an estimate of the field sources (amount of ferromagnetic dust and its distribution within lungs). For the research of methods of interpreting the measured field data, we use computer forward model that can provide field distribution based on known magnetic sources. The fig. 4.3 shows comparison of magnetic (gradient) field calculated by computer forward model and equivalent data from physically realized and measured model.

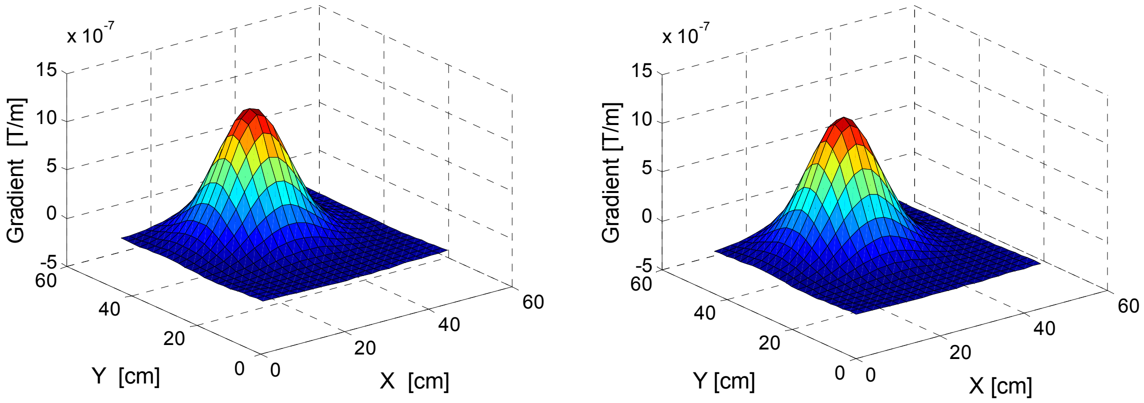

Fig. 4.3 – Comparison of modeled (left) and measured (right) gradient field from a compact source. The closer probe is 18 cm above bed surface, the other is 10 cm further away (from [19])

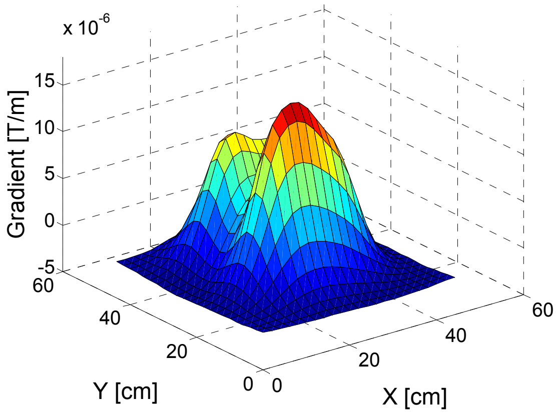

Fig. 4.4 – Modeled field of multiple unit sources randomly distributed in both lung lobes (from [19])

The field shown in fig. 4.3 originates from a compact source. For more general case of distributed sources, the field is more complicated and can no longer be considered a dipole field. In fig. 4.4, there is modeled first gradient for a randomly generated source containing 277 magnetite-contaminated cubes (each having Ampere's magnetic moment of 300 $\times 10^{-6}$ Am^2 measured according to [20]) out of the total 574 cubes composing our phantom of the lungs. The model composed of individual cubes (8 cm^3 volume elements) follows physiological shape of human lungs (compare with [21]).

We have tested several methods for inversion of the measured field (e.g. application of neural networks, search using genetic algorithms, and other approaches) described e.g. in [22, 23, 24, 25]. As can be expected, the results for compact sources were quite good while the accuracy of inversion for general source distribution is far from perfect.

5. Conclusion

We have developed system for magnetopneumography based on fluxgate sensors (magnetometers) arranged in gradiometric setup. We use fluxgate sensors rather than SQUIDs because of their affordability and simplicity of use. Together with powerful electromagnet used for magnetization of subjects (or phantom models) and mechanically stable nonmagnetic positioning bed, we can acquire magnetic field data representing the ferromagnetic dust in subject's lungs.

The used ring-core fluxgates have noise (power spectral density) of about 15pT/sqrtHz at 1Hz. The magnetometer sensitivity is about 10^5 V/T.

In gradiometric system with 10 cm baseline, the gradient noise is about 350 pT/m/sqrtHz. In this arrangement, the sensitivity to gradient field is about 17 mV/µT/m and homogenous field response is only 0.035 T/m/T.

The measured data are processed by computer for estimation of the parameters of sources. For compact sources, we have obtained relatively good results. In case of randomly distributed sources, we have so far achieved only limited success in the inversion process.

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Older:

- NMP2-CT-2003-505265 SENPIMAG “A novel technology for ultra sensitive reliable integrated magnetic sensors” (2003-2005)
- GACR 102/01/1335 “Measurement of Soft Mag. Material Properties” (2001-2003)
- EU Leonardo CZ/PP-134026 "Modular Courses on Modern Sensors" (2000-2003)
- CTU 0211813 "Development of the GMI Permalloy Sensor and its Practical Aplications" (2002)
- CTU 300009503 "Sampling Measurement of Dynamic Hysteresis Loops" (2001)
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