Time Stability of Static Magnetic Field for Resistive Magnet Systems in NMR Tomography

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Abstract: *NMR tomography based on the resistive magnets is advantageous, because of inexpensive operation. Disadvantage is relatively complicated stabilization of the current, which supplies resistive magnet [1,2,3]. Current stabilization has to be used to overcome mistakes in main current caused by the drifts in the power supply, temperature changes of magnet coils, magnet construction, control electronics and shunt-resistor. Current stabilizer compensating problems listed above has been made. Such type of stabilizer has to be used for current stabilization and corresponding magnetic field* B_0 *stabilization of NMR scanners with resistive magnets.*

1. Introduction

Demand on the time stability of B_0 magnetic field in NMR tomography is very high. In order to reduce image artifacts on the experimental 0.1T NMR tomograph, one has to achieve time stability better than 5ppm within one measurement. Although typical time of one measurement in clinical practice is about 30 minutes, but in case of experimental NMR laboratory, time of one measurement can be several hours. Drifts in power supply and changes of magnet temperature and electronics temperature within these several hours can be significant. Therefore the best solution is sophisticated current stabilizer, equipped with the thermostatic control electronics and thermostatic selected parts as well. We wish to discuss various problems of B_0 magnetic field stability for resistive magnet based NMR scanners.

2. Theoretical Analysis and Design

Theoretically there are following problems, which have potential influence on time stability of the B_0 static magnetic field:

- temperature stability of magnet coils and supporting magnet construction
- current feedback temperature properties

2.1. Temperature stability of magnet coils and supporting magnet construction
Generally, power consumption of resistive magnet is very high (in our case 25kW) with corresponding demands on cooling efficiency. Inevitably, temperature of magnet rises until steady-state is reached. Due to rise of coil temperature, coil material dilates. Magnet dimensions are linearly proportional to the temperature, therefore magnetic field is inversely influenced by this effect.

$$l(T) = l(T_0)\cdot\left(1+\lambda(T-T_0)\right)$$

where λ is length dilatation coefficient
T_0 = reference temperature, [°C]
T = operating temperature, [°C]

In our case, coil is made of copper with $\lambda = 16.10^{-6}$ °C^{-1} and temperature change is up to 15°C. Relative dilatation is 240 ppm.
Moreover, we have observed step changes in magnetic field intensity, which are probably caused by the tension in magnet construction.

2.2 Current feedback performance
Critical parameters of current feedback control circuit (Fig.1) are as follows:

- shunt resistor thermal coefficient
- reference voltage temperature drift
- summing resistors thermal coefficients
- differential amplifier input offset voltage drift and open loop gain
- instrumentation amplifier gain temperature dependence and input offset voltage drift

Supposing severe demands on the stability of current feedback control circuitry, we used the thermostatic housing with the temperature stability better than ±0.5°C

2.2.1 Shunt resistor
Thermal coefficient of shunt resistor (TCR) 'R' is one of the most critical parameters of the stabilizer. In our case manganin material with the thermal coefficient of –20 ppm/°C (measured value) at working temperature (50°C) has been used. To stabilize its value within 1 ppm, temperature stability within ±0.05°C would be required. We use manganin plate in oil bath inside of separate thermostatic massive aluminium box.

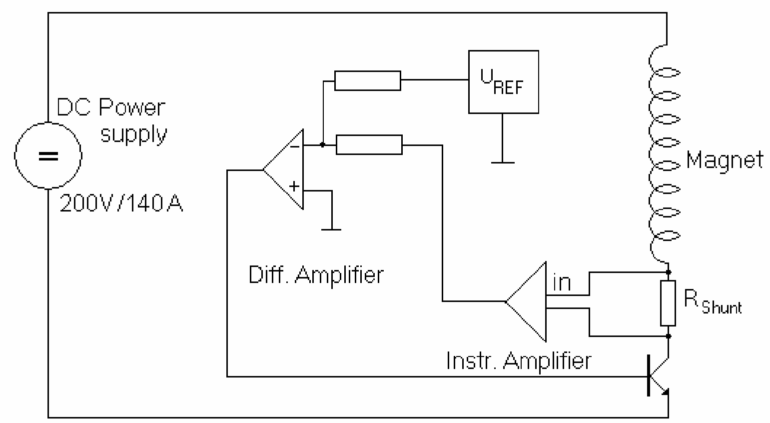

Fig.1. Schematic diagram of current stabilizer

2.2.2. Reference voltage temperature drift
There is a linear relation between reference voltage (Fig.1) and output current. It is therefore of vital importance to have sufficient stability of reference voltage source (less than 1 ppm).

2.2.3. Summing resistors thermal coefficients
Both of the summing resistors must have difference of their TCRs less then ±1 ppm /K

2.2.4. Differential amplifier input offset voltage drift and open loop gain
It can be shown, that for defined temperature stability of thermostat, input offset voltage drift should be lower than 5µV/K. Due to heating of magnet coil, its resistance changes as follows:

$$R_{t0} = R_{t20} \cdot (1 + \alpha(T_0 - 20))$$

R_{t0} = Resistance at operating temperature (°C), [Ω]
R_{t20} = Resistance at 20°C, [Ω]
T_0 = Operating temperature, [°C]
α = 0.00381 [1/°C], thermal coefficient of resistance for hard-drawn copper, based on ASTM Standard Specifications [4]

For temperature change of magnet by 15°C, it corresponds to relative change of resistance by 6%. To reduce influence of this change to less than 1 ppm, the loop gain has to be at least $6*10^4$. Taking into account drifts in power distribution system (inrush currents of elevators, milling machines, air-conditioners etc.), open loop gain of differential amplifier should be even much higher. This puts also requirements for the reaction time of the regulation circuitry.

2.2.5. Instrumentation amplifier gain temperature dependence and input offset voltage drift
It can be shown, that for defined temperature stability of thermostat, input offset voltage drift should be lower than 0.28 μV/K. Similarly it can be shown, that gain temperature dependence of instrumentation amplifier should be better than ±1 ppm /K.

3. Results and Discussion

Current stabilizer based on the schematic diagram (Fig.1) has been built. Total current of 140 Amperes DC at 200 V was stabilized. Data presented in the figure 2 show process of the stabilization 0.1T B_0 as function of time. There is transition period, when overcompensation of the shunt resistor temperature caused several oscillations of the B_0 value around stationary value. This period takes approximately 1 hour. Oscillations were caused by the slow stabilization of shunt temperature. Only after this time, stabilization was good enough and required deviation of magnetic field was obtained. Data presented were acquired using Bruker NMR gaussmeter ER 035M. Data were transferred from Bruker gaussmeter to the PC using serial port communication. The data were acquired every 10 seconds and processed in PC.

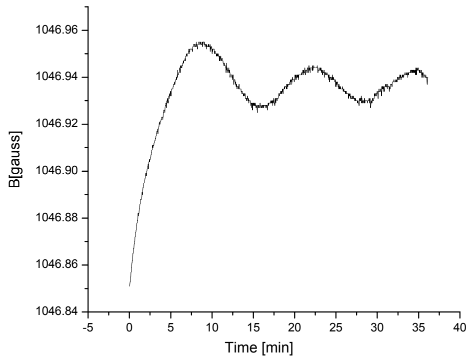

Fig. 2 Transition period of the static magnetic field B_0 as function of time

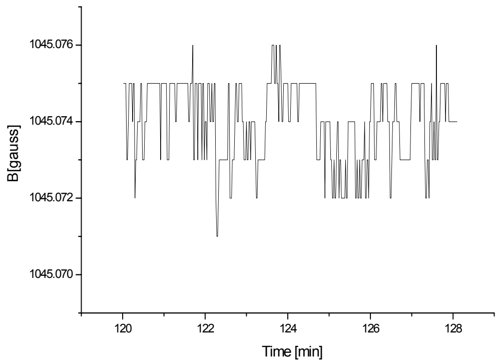

Fig. 3 Stabilized period of the static magnetic field B_0 as a function of time

Data presented on figure 3 show detail of B_0 deviation after transition period, when current stabilizer should not allow deviation higher then 5 ppm, which is required for NMR imaging. Smallest step of 1/1000 Gauss corresponds to the B_0 deviation of 1 ppm. Precision of measurement was limited to 1ppm by the Bruker gaussmeter itself. Maximum deviation presented from figure 3 was ±3 ppm in 8 minutes. In fact, deviation of ±3 ppm is maximum even in several hour measurements as long as temperature of magnet itself is stable. Therefore we can make conclusion, that stabilizer fulfilled requirements and improves time stability of B_0 static magnetic field to the level necessary for NMR imaging. Further improvements can be done in transition period, which could be shorter. Experience showed that the transient period is given by the time necessary to reach equilibrium temperature condition in both the magnet and the shunt resistor. First can be achieved by better control of magnet cooling while the second will require change of placement of heating elements in shunt thermostat. Another vital improvement is reduction of shunt's TCR by compensation of manganin negative TCR with thin layer of metal having opposite TCR (e.g. gold). Proper amount of plating material would ensure TCR close to 0 at working temperature and moreover the gold plating will guarantee long term stability of shunt resistor value. Such a multi-layer shunt decreases requirements on the precision of thermal stability of shunt itself.

4. Conclusion

The experiments on the current stabilizer of 0.1T NMR tomograph confirmed, that implemented modifications improved stability of basic magnetic field and compensated short-term drift of the magnetic field. Further combination of current stabilizer with NMR stabilizer can improve long-term stability of B_0. Experiments also confirmed that temperature of shunt resistor, temperature of control unit, temperature of magnet coils and magnet construction is critical and has to be stabilized in order to maintain required 5ppm time stability. Further dynamic analysis can be performed in the future, in order to improve reaction time to the spikes in the power supply.

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