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High-Resolution Magnetic Field Mapping System With an NMR Probe

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Abstract

This paper presents a high-resolution magnetic field mapping system in development that is capable of collecting spatial magnetic field data for NMR magnets. An NMR probe was designed and built with a resonant frequency of 5.73 MHz. The measured Q-factor of the NMR probe is ~ 191 with a half-power bandwidth in the range of 5.72–5.75 MHz. An RF continuous-wave technique with magnetic field modulation was utilized to detect the power dispersion of water molecules. The zero-crossing frequency of the NMR dispersion signal corresponds to the magnetic

field at the center of the water sample. An embedded system was developed to sweep the frequency and record the reflected RF power simultaneously. A numerically controlled digital oscillator is able to provide a precise frequency step as small as 0.02 Hz, which is equivalent to 4.7 e-7 mT for hydrogen atoms. An RF preamplifier was built to supply up to 4 W of RF power to a bidirectional coupler. The coupler supplies RF power to the NMR probe and channels reflect the RF power back to the detection circuit, which detects the reflected RF power from the NMR probe during the frequency sweep. The homogeneity of an NMR magnet can be determined by magnetic field data.

Keywords

Magnetic field mapping; NMR; RF engineering; sensors

I. INTRODUCTION

A high resolution magnetic field mapping system is essential for determining the homogeneity of a high-field NMR magnet. A modern NMR instrument requires extremely high homogeneity field through the sample volume. For instance, an 800-MHz, 63-mm bore NMR Magnet at the National High Field Magnet Laboratory (NHMFL) has a field homogeneity of 1 part per billion (ppb) in 10-mm DSV. Thus, to determine its homogeneity, a magnetic field sensor must have a resolution of 18 μ T.

A Hall probe can measure magnetic field up to 35 tesla, with a field resolution down to 1.0 mT [1]–[3], still insufficient to determine the homogeneity of the 800-MHz NMR magnet. Another type of magnetic field sensor, a fluxgate sensor, has a resolution in the μ T range [4]–[6]. The drawback is that the high permeability iron cores are easily saturated at fields of a few milliteslas. Additionally, the Earth magnetic field and other extraneous fields may reduce the field measurement accuracies. Other researchers have mapped NMR magnets charged at a low field [7].

By using the latest digital electronics and RF technologies, we are developing an all-digitally controlled magnetic field mapping system as shown in Fig. 1. To meet the field measurement resolution and withstand a high magnetic field strength, we have designed and built NMR probes to detect the NMR power dispersion line shape, or the derivative of the NMR absorption line shape, with classic continue wave (CW) techniques [8]. By detecting the peak frequency of the NMR power absorption, we have been able to determine the magnetic field strength with high resolution.

The NMR probe is attached to a rigid rod, which is driven by a stepper motor with a Texas Instruments DRV8825 micro stepping motor driver. A single field programmable logic array (FPGA) chip in the DSP unit provides control tasks that include:

- Frequency control for the RF circuit board to provide RF power to the NMR probe with accurate frequency sweep.
- Recording detected NMR signals along with position of the probe to a computer through a USB cable.

- Precise motion control for the positioning board, such that the tip of the NMR probe follows a predetermined cylindrical path.

II. NMR PROBE DESIGN AND TESTING

The NMR probe is an RLC resonant circuit, where the resonant frequency f_r of the probe is determined by the following equation:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

where L is the probe coil inductance, which is a constant when the coil parameters are fixed with 6-turns, and 5 mm in diameter. C is the total circuit capacitance. As shown in Fig. 2(a), the coil inductance is L_1 . The coil resistance R_1 is the copper wire resistance plus equivalent resistances of the NMR power absorption. The total capacitance includes C_1 , C_2 , C_3 , and C_4 . The resonant frequency of the probe circuit in Fig 2(a) is around 38 MHz. By adjusting the amount of capacitance in the circuit, we can tune the resonant frequency to the proper value for the corresponding magnetic field. The NMR probe, designed and built in-house, shown in Fig. 2(b), is made from a 6-turn bare copper coil with non-magnetic capacitors, and a NMR sample container with 0.45 cm³ volume for liquid samples. It is very important to have 50-Ω impedance matching throughout the probe circuit to deliver the maximum RF power to the coil. A 50-Ω RF SMA connector, soldered to the background plane with four grounding points, reduces the resistive losses and background noises. The surface-mount nonmagnetic capacitors have very low equivalent series resistance (ESR) and small parasitic inductances.

An NMR probe stores magnetic energy in the coil. When the NMR phenomena occur, the amount of RF energy absorbed by the sample nucleus equals the energy gap between the low and high-energy quantum states. In our approach, the probe detects the NMR dispersion of the hydrogen atom (¹H). By observing the zero-crossing frequency of the NMR dispersion line shape, we can determine the magnetic field strength based on the Larmor frequency with the following equation [9]:

$$B = \frac{2\pi f_{1H}}{\gamma_N} \quad (2)$$

where the gyromagnetic ratio of the hydrogen atom is $\gamma_N = 2.675 \times 10^8 \text{ T}^{-1}\text{s}^{-1}$, and f_{1H} is the detected Larmor frequency. For a magnetic field of 1 T at the NMR probe, the corresponding Larmor frequency is approximately 42.58 MHz. Magnetic-field mapping with an NMR probe detects a Larmor frequency with high resolution at different locations in the warm bore of a superconducting NMR magnet. The sensitivity of an NMR probe can be determined by the quality, or Q factor, which is an indicator of the stored magnetic energy vs. resistive losses. The higher the Q factor, the higher the sensitivity of the NMR probe.

By utilizing a network analyzer, we measured the probe's scattering parameters, capturing an S11 plot shown in Fig. 3. A sharp dip in the S11 curve indicates that near 5.753 MHz, there is very little reflected power, thus the signal from the reflect port of the RF coupler is at the minimum level. The Q factor can be calculated as equation (3).

$$Q = \frac{f_{\text{center}}}{f_{\text{Hi}} - f_{\text{Lo}}} \quad (3)$$

where f_{center} is the center resonant frequency, and the f_{Hi} and f_{Lo} are the high- and low-half power frequencies. The measured Q factor is 191, which is comparable to commercial available room-temperature NMR probes. If the operating RF frequency were to be set at 5.753 MHz, the corresponding magnetic field is 0.1351 T.

III. DESIGN AND TEST OF THE RF CIRCUITS

By using a high performance FPGA chip, we set up the frequency sweep of the NMR probe with a numerically controlled oscillator (NCO). Unlike the analog voltage controlled oscillator (VCO), the NCO is embedded in the FPGA, and the noise background is significantly lower. The NCO, controlled by a 32-bit register, has a built-in dithering mode to minimize digital quantization errors. With a 100-MHz system clock, the precision of the NCO, expressed by Δf (smallest frequency step), may be given by:

$$\Delta f = \frac{f_{\text{clk}}}{2^{32}} = 0.023\text{Hz} \quad (4)$$

where f_{clk} is the system clock. Note that Δf can be more precise if a faster system clock is used, because $\Delta f \propto 1/f_{\text{clk}}$. If a pure water sample is used, the corresponding magnetic field step is approximately:

$$\Delta B \approx \frac{0.023}{42.58 \times 10^6} \times 1.0 \times 10^3 \text{mT} \approx 4.7 \times 10^{-7} \text{mT} \quad (5)$$

For a 38.12-MHz NMR magnet, the resolution level is ~0.6 ppb; therefore, by magnetic field mapping our NMR probe should be capable of determining the field homogeneity of an NMR magnet operating over a wide frequency range.

The major components of the RF generator and detection circuits are shown in Fig. 4. The DSP unit provides main control for the rest of the components with a single FPGA chip. A microprocessor, NCO, and other control circuits were designed and embedded in the FPGA. The DSP unit outputs a digital signal with precisely controlled output frequency. The digital signal voltage is 3.3 V. Because the current driving capability of the DSP unit is very low, a 15-V DC power source was used to deliver up to 4.5-W (36.5 dBm) RF power to the probe

terminals. Four MOSFET transistors in the RF circuit board were connected in parallel to carry the required high-frequency probe current.

A three-way RF coupling device detects the reflected power signal and also channels the input RF signals to the NMR probe. The coupler has maximum 0.13 dB insertion loss between 1 MHz and 60 MHz. The NMR probe circuit was tuned to perfect impedance matching and the reflected RF signal is at the minimum. When the NMR probe is at the Larmor frequency, the hydrogen nucleus absorbs energy to go to the higher energy state, which results in a large reflective signal through the RF coupler. A phase sensitive detector circuit in the DSP unit filters and amplifies the signal from an RF power detection chip and record the data in a computer connected to the DSP unit through a USB cable. The power detection chip was calibrated with an RF signal generator. All components on RF circuit board were tested.

IV. TEST SETUP FOR NMR SIGNAL DETECTIONS

A 1-T high-temperature superconducting (HTS) magnet was energized to test the RF circuit and our NMR probe. The HTS magnet is submerged in a liquid nitrogen bath. The NMR probe coil was positioned at the magnet center with a thermal isolation tube to keep the NMR probe coil at close to room temperature. The NMR probe was fixed to have the external magnetic field perpendicular to the probe coil similar to a typical NMR sample orientation. The DSP unit frequency signals (square waveforms), and the coil voltage signals (sinusoidal waveforms) are shown in Fig. 5, where the measured frequency is close to the NMR probe resonant frequency. The measured peak-peak voltage across the coil terminal is ~30 V. However, NMR signals were not detected without magnetic field modulation and a phase sensitive detector, because NMR signal strength was weaker than that of the background noise. Further, the water sample was frozen quickly by the liquid nitrogen vapor.

To increase the signal to noise ratio, a magnetic field modulation coil with 24 turns, 12 mm long, and 16 mm in diameter was built and placed around the probe coil. The RF circuit board provides a 5.0 V (peak to peak), 100 Hz voltage source to the field modulation coil, which generates a small AC magnetic field. A large permanent magnet was utilized to provide magnetic field strength up to 2200 Gauss near the surface [10]. As illustrated in Fig. 6, the NMR probe was scanned up and down near the magnet surface. The RF circuit board output frequency was set at 5.753 MHz and a large NMR signal was captured by an oscilloscope.

As shown in Fig. 7 the peak to peak voltage of the reflected RF power signal after a phase sensitive detector is about 28 V with a frequency of 100 Hz. The RMS value of the RF power signal vs. estimated magnetic field strength is plotted in Fig. 8. The zero-crossing of the NMR power dispersion signal is equivalent to the NMR power absorption peak signal. The NMR resonant point is around 1351 Gauss, which is corresponding to the Larmor frequency of 5.75 MHz for water sample.

V. CONCLUSION AND FUTURE PLANS

A High Q-factor NMR probe and an RF detection circuit were designed and built to investigate a high-precision magnetic field mapping technique. Resonant voltages were measured at the NMR probe coil terminals, no observable reflected RF signals were detected without magnetic field modulations because the NMR absorption signals were buried in the background noises.

After implementing magnetic field modulation and phase sensitive detection, a large NMR signal was detected with a permanent magnet. The next step is to implement the frequency scans with the NMR probe fixed in the space. Other digital signal processing techniques will be investigated to map an HTS magnet. Other NMR samples will also be tested in the future. A motion control system will also be completed to adjust the position of the NMR probe tip automatically with more precise steps. We plan to develop this technique to determine the spatial field homogeneity of a 1.3-GHz NMR magnet currently under development at the MIT Francis Bitter Magnet Laboratory, Plasma Science and Fusion Center [11].

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Fig. 1.
High-resolution magnetic mapping system diagram.

(a)

(b)

Fig. 2.

(a) NMR probe circuit model. (b) Photo of an NMR probe with a 6-turn coil and capacitors.

Fig. 3.

S11 scattering parameter measurements with a network analyzer.

Fig. 4.
Photo of NMR probe test apparatus, including a DSP unit, coupler, dc power sources, and an RF circuit board.

Fig. 5.
Screenshots of the driving digital signal (square waveform) and NMR probe coil voltage (sinusoidal waveform).

Fig. 6.
The NMR probe travels from 20 mm away from the magnet surface for about 40-mm distance.

Fig. 7.

Oscilloscope captures of the reflected power signal after the phase sensitive detector; the signal frequency is at 100 Hz.

Fig. 8.

The reflected power signal RMS value plot clearly shows an NMR dispersion signal.