Parametrically-Enhanced Nuclear Magnetic Resonance Spectrometer Prototype

Kenneth Wong

Project Sponsor:
Prof. Carl Michal

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EXECUTIVE SUMMARY

This project evaluates the feasibility of using a strong alternating magnetic field, in addition to the Earth's weaker magnetic field, to improve nuclear magnetic resonance spectroscopy. In this new method of NMR spectroscopy devised by Prof. Michal, an electromagnet, instead of the Earth, is used to generate static magnetic field. A solenoidal coil produces a magnetic field strength of approximately 2.35 mT, over 40 times greater than that of the Earth. The stronger static magnetic field is expected to increase the signal-to-noise ratio of the NMR signal by more than 700 times over traditional Earth's field NMR.

The objective of this project is to produce an engineering prototype demonstrating parametrically enhanced NMR spectroscopy. The prototype consists of a transmitter coil to generate the alternating static magnetic field, a receiver coil to detect the Larmor precession of the test specimen, and an electronic circuit to filter and amplify the NMR signal. By using an alternating static magnetic field, the detrimental spin dephasing caused by field inhomogeneities can be reduced. The prototype necessitates relatively inexpensive components and maintains a portable form factor.

In developing the prototype, the transmitter coil and the receiver coil has been fabricated and characterized. After evaluating the two proposed waveforms for driving the transmitter coil, the sinusoidal waveform is selected and a circuit has been designed and breadboarded. The NMR signal processing circuit successfully rejects 37 dB of the offending noise signal to theoretically allow the Larmor precession to be discerned. Due to unforeseen distortion in the output signal of the power amplifier, the specified static magnetic field strength cannot be achieved. As a result, the parametrically enhanced NMR spectrometer prototype has not been realized within the project timeframe.

Several recommendations are suggested to correct the identified problems and improve the current design. With additional development, this novel NMR spectroscopy method can be developed into inexpensive and portable NMR spectroscopy applications.

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INTRODUCTION

BACKGROUND

Nuclear magnetic resonance (NMR) is a phenomenon discovered relatively recently in 1945, and has revolutionized medical imaging and chemical analysis since. Nuclei with non-zero spin, such as protons, have an intrinsic magnetic moment and spin angular momentum that can be manipulated using an externally applied static magnetic field. Nuclear spins preferentially align with the static magnetic field B_0 to lower their energy state, resulting in a bulk spin magnetization in the field direction. When an appropriate oscillating magnetic pulse is applied, the nuclear spins can be reoriented perpendicular to the direction of B_0. Because of their intrinsic spin angular momentum, nuclear spins precess about B_0 before dephasing and returning to equilibrium parallel to the direction of the static magnetic field. This phenomenon is termed Larmor precession. Using a sensitive magnetic coil perpendicular to B_0, the precessing magnetization from the nuclear spins can be detected. The properties of the signal, such as relaxation time, can be used to characterize the sample under analysis. [1]

The high cost of the equipment to generate the intense static magnetic field, however, has been a major deterrent to the widespread adoption of NMR technology. The homogeneity of B_0 is directly related to the spectral resolution of the NMR signal, which also contributes to the cost. The Bruker BioSpin AVANCE 1000 NMR spectrometer, which incorporates the world's strongest superconducting NMR magnet at 23 T, has a list price of 11.7 million Euros. [2]

The Earth produces a magnetic field that can be utilized as the static magnetic field in NMR measurements, in lieu of an externally generated magnetic field. The strength of the Earth's magnetic field varies approximately from 30 μT near the equator to 60 μT near the geomagnetic poles. [3] The strength of the Earth's magnetic field on the University of British Columbia Vancouver campus (49°15'59", –123°15'13") is approximately 55 μT. [4]

The portable Magritek Terranova-MRI spectrometer uses the Earth's magnetic field to perform spectroscopy and three-dimensional imaging relatively inexpensively. [5]

The spin-½ proton is often the subject of NMR spectroscopy measurement because of its high gyromagnetic ratio and its abundance in molecules in the form of the positive Hydrogen ion. The gyromagnetic ratio γ relates the Larmor precession frequency f_0 to the static magnetic field strength B_0 by

$$f_0 = \frac{\gamma}{2\pi} B_0. \text{ [1]}$$

Thus, deviation in the Larmor precession frequency is directly dependent on the homogeneity of the static magnetic field. On the University of British Columbia Vancouver campus, the Earth's magnetic field results in a proton precession frequency in the audio spectrum:

$$f_0 = (42.6\ \mathrm{MHz\ T^{-1}})(55\ \mathrm{\mu T}) = 2.34\ \mathrm{kHz}. \text{ [6]}$$

The most significant limitation of using the Earth's magnetic field for NMR spectroscopy is the poor signal-to-noise ratio (SNR) of NMR signals at low field strengths. The SNR is predicted to vary dramatically with B_0, per

$$SNR \propto (B_0)^{\frac{7}{4}}. \text{ [7]}$$

Notwithstanding, the excellent homogeneity of the Earth's magnetic field somewhat compensates for its low field strength. The spatial homogeneity of the test specimen's spin magnetization enables a much larger sample to be used without decreasing the spectral resolution due to deviating Larmor precession frequencies. To enhance the magnetization of the nuclear spins and thus the SNR of the NMR signal, the nuclei can be pre-polarized by applying a strong magnetic field before the spins are perturbed from equilibrium. [8]

PROJECT DESCRIPTION

This project evaluates the feasibility of using a strong alternating magnetic field, in addition to the Earth's weaker magnetic field, to improve NMR spectroscopy. The objective is to produce an engineering prototype demonstrating parametrically enhanced NMR using a new method devised by Prof. Michal. The prototype consists of a transmitter coil and a receiver coil, along with the electronic circuits to filter and amplify the NMR signal. Off-the-shelf equipment is used for the transmitter coil signal synthesizer and driver, as well as the pre-polarizing field power supply. Due to time and resource constraints, the prototype only attempts to distinguish between specimens with and without the presence of nuclei of non-zero spin. Two convenient test specimens used are water (the protons contribute spin ½ each) and air (the nitrogen and oxygen molecules contribute spin 0). Future studies may investigate the use of this method for practical NMR spectroscopy or imaging, but these goals are beyond the scope of this project.

DISCUSSION

THEORY

The primary disadvantage of using the Earth's magnetic field for nuclear magnetic resonance spectroscopy is the poor signal-to-noise ratio of NMR signals. By somehow increasing the strength of the static magnetic field B_0, the SNR can be improved significantly. The proposed method literally turns Earth's field NMR spectroscopy on its head.

An electromagnet, instead of the Earth, is used to generate B_0. A solenoidal coil, hereafter called the transmitter coil, is expected to produce a magnetic field strength of approximately 2.35 mT. This field is over 40 times stronger than the Earth's 55-μT magnetic field on the University of British Columbia campus. Thanks of the stronger static magnetic field, the SNR of the NMR signal is expected to increase by

$$\frac{SNR_2}{SNR_1} = \left(\frac{(B_0)_2}{(B_0)_1}\right)^{\frac{7}{4}} = \left(\frac{2.35\ \mathrm{mT}}{55\ \mu\mathrm{T}}\right)^{\frac{7}{4}} = 714 = 57.1\ \mathrm{dB}.$$

If, initially, the spins of the specimen are perpendicular to the static magnetic field generated by the transmitter coil, they would precess about the axis of the transmitter coil. Because the transmitter coil's magnetic field is significantly stronger than the Earth's, the Larmor precession frequency would be proportionally higher, approximately

$$f_0 = \frac{\gamma}{2\pi} B_0 = (42.6\ \mathrm{MHz\ T^{-1}})(2.35\ \mathrm{mT}) = 100\ \mathrm{kHz}$$

where γ is the gyromagnetic ratio of the specimen. The Earth's magnetic field plays a different role in the proposed NMR spectroscopy method. Rather than being used as B_0, the Earth's magnetic field is used to orient the spin magnetization perpendicular to the axis of the transmitter coil.

When the transmitter coil is not conducting current, the spin magnetization of the specimen equilibrates to the direction of the Earth's magnetic field. When the transmitter coil is starts conducting current, the net external magnetic field is along the axis of the coil, due to its much greater field strength. Because of the abrupt change in magnetic field direction, the spins precess about the axis of the transmitter coil, at the Larmor precession frequency. The resulting spin precession of the bulk spin magnetization can be detected in the direction perpendicular to the transmitter coil axis using a second electromagnetic coil, hereafter called the receiver coil.

Because the magnetic field of the transmitter coil is expected to be much less homogeneous than the Earth's magnetic field, the nuclear spins would precess at slightly different frequencies. The destructive interference caused by the different precession frequencies of individual nuclear spins results in the decay of the bulk spin magnetization over time. In traditional NMR spectroscopy, the dephasing of the spins can be corrected by, for instance, using a spin-echo sequence to invert the direction of the spins and allow the slower spins to "catch up" with the faster spins, reconstituting the bulk spin magnetization after one Larmor precession cycle. [1] An analogous method is proposed by Prof. Michal. By reversing the direction of B_0, the nuclear spins of the specimen would precess in the opposite direction, allowing the slower spins to "catch up" to the faster spins. This scheme reduces the negative consequences of inhomogeneities of the transmitter coil's magnetic field. This achievement is possible because the field inhomogeneity of an electromagnet is equal in magnitude but opposite in direction when its current is reversed.

One important distinction to note in the proposed method is that B_0 is no longer time-independent, as its direction reversed periodically. To produce a single Larmor precession frequency of the specimen's nuclear spins, the static magnetic field must be constant for each precession cycle, which implies the transmitter coil should generate a square wave, *i.e.*,

$$B_0(t) = B_0 \operatorname{sgn}\big(\sin\big(2\pi f_{B_0} t\big)\big),$$

where the f_{B_0} is the frequency of the static magnetic field B_0 and not the Larmor precession frequency. To achieve the highest Larmor precession frequency possible at B_0, one Larmor precession is allowed while B_0 is constant. Over one period of the B_0 square wave, the spins precess twice, once in each direction. The NMR signal detected at the receiver coil is a decaying sinusoidal waveform at twice the frequency of the transmitter coil. If the transmitter coil's frequency is 50 kHz, the frequency of the NMR signal would be 100 kHz, in the ultrasonic spectrum.

Driving the transmitter coil with a square wave would produce harmonics that may coincide with the Larmor frequency. Moreover, the solenoidal transmitter and receiver coils may form an RLC circuit with parasitic capacitance to cause ringing. To mitigate these problems, a sinusoidal wave, *i.e.*,

$$B_0(t) = B_0 \sin\left(2\pi f_{B_0} t\right),$$

will also be tested. One disadvantage of a sinusoidally varying B_0 is the fluctuating spin precession speed over each half cycle of B_0. Because the Larmor precession frequency f_0 is directly proportional to B_0, per

$$f_0(t) = \gamma B_0(t) = \gamma B_0 \sin\left(2\pi f_{B_0} t\right),$$

the Larmor precession spectrum broadens, thereby reducing spectral resolution. The NMR signal would no longer be a simple sinusoidal waveform, but a composite function with the form

$$\mathcal{E}_1(t) = |\mathcal{E}_1| \sin(2\pi f_0(t) t) = |\mathcal{E}_1| \sin\left(2\pi \gamma B_0 \sin\left(2\pi f_{B_0} t\right) t\right)$$

The Larmor precession frequency may be extracted from the composite waveform in software using an inverse transform. Both transmitter coil waveforms will be tested empirically to determine the best solution. In either case, the Larmor precession frequency of the nuclear spins is twice the frequency of the alternating static magnetic field.

The major challenge of this project is to detect the low-amplitude NMR signal in the presence of the radiation from the high-current transmitter coil at half the frequency. The signal driving the transmitter coil may be easily coupled to the receiver coil by any misalignment between the perpendicular coils, or from long runs of wire from the coils to the NMR signal detector. The NMR signal processing circuit must be apt at eliminating the

the transmitter coil frequency, which may be orders of magnitude greater in amplitude than the desired NMR signal.

The Earth's magnetic field weakly polarizes the nuclear spins of the specimen. To enhance the magnetization of the nuclear spins and thus the SNR of the NMR signal, the nuclei can be pre-polarized by applying a strong magnetic field using the transmitter coil. [8] Since the axis of the transmitter coil is perpendicular to the Earth's magnetic field, the spin magnetization must be allowed to return to the direction of the Earth's magnetic field after being pre-polarized. This reorientation can be accomplished be ramping down the pre-polarizing magnetic field adiabatically over a time shorter than the specimen's T_1 period. [8]

METHOD

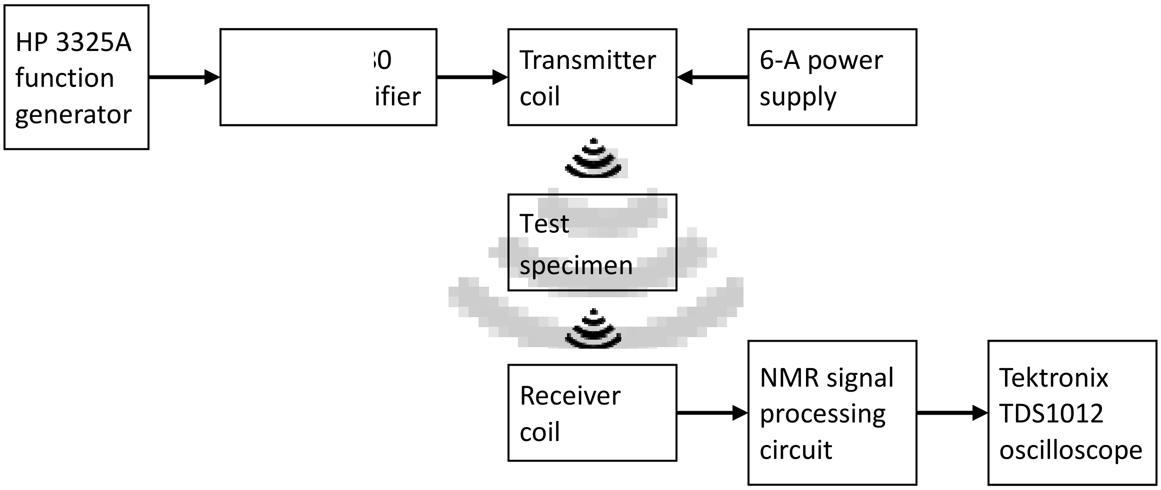

FIGURE 1: BLOCK DIAGRAM OF EXPERIMENTAL SETUP

The experimental setup consists of off-the-shelf and bespoke instruments (Figure 1). A generic 6-A power supply is connected directly to the transmitter coil to pre-polarize the test specimen. After several seconds, the power is manually ramped down to zero to allow the spin magnetization to realign to the Earth's magnetic field. The HP 3325A function generator produces the driving signal for the static magnetic field B_0, which is buffered by the Hafler XL-280 power amplifier. The transmitter coil is oriented perpendicular to the Earth's magnetic field, so the oscillating current perturbs the spin polarization of the test specimen from equilibrium. The resulting Larmor precession of the specimen induces a time-varying voltage in the receiver coil. Because the driving signal of the transmitter coil is also coupled to the receiver coil, the NMR signal processing circuit is needed to remove the offending signal before the NMR signal can be discerned on the Tektronix TDS1012 oscilloscope.

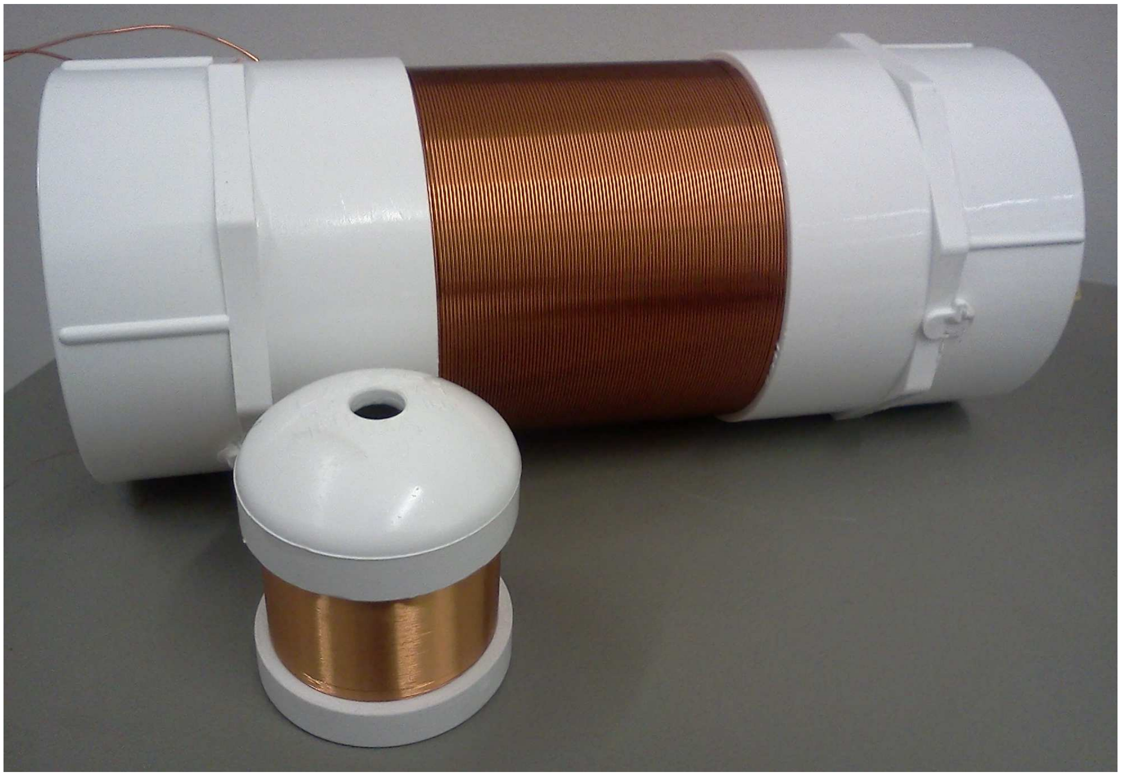

FIGURE 2: PHOTOGRAPH OF TRANSMITTER AND RECEIVER COILS

Two solenoidal coils are fabricated and wound for the transmitter and receiver coils (Figure 2). The coil cores are made by machining and joining off-the-shelf PVC pipes and pipe fittings. Five inches of 4-inch diameter unthreaded pipe forms the core of the transmitter coil. Two NPT-female to socket-weld adapters are solvent welded to the ends of the pipe to act as flanges to fix the windings in place. A threaded plug may be screwed into the adapter to close either or both ends of the coil. For the receiver coil, two inches of 2-inch diameter unthreaded pipe is used. Because the receiver coil fits perpendicularly into the transmitter coil and is constrained by the latter's inner diameter, smaller socket-weld caps in lieu of adapters are used as the winding flanges to maximize the winding area. One of the caps is cut open to permit access to the coil volume.

A Meteor ME 301 coil winder is used to wind round enameled copper wire around the PVC pipes. To tolerate the high current through the transmitter coil windings during the pre-polarization phase, thick 18-AWG wire is used for four layers of windings in series of approximately 100 turns each. The DC resistance through the series coil windings is

$$R = \pi D_o n_0 L \frac{R}{\ell} = \pi(4.5\ \mathrm{in})\left(\frac{4}{0.043\ \mathrm{in}}\right)(5.0\ \mathrm{in})(6.39\ \mathrm{m\Omega\ ft^{-1}}) = 3.50\ \Omega,$$

where D_o is the outer diameter of the solenoid core, n_0 is the turn density, L is the length of the winding area, and R/ℓ is the resistance per unit length of wire. Using a 24-VDC power supply, a current of

$$I_P = \frac{V}{R} = \frac{24\ \mathrm{V}}{3.50\ \Omega} = 6.85\ \mathrm{A}$$

may be applied to the solenoid to pre-polarize the specimen to generate a polarization field strength of

$$B_P = \mu n_0 I_P = (1.26 \times 10^{-6}\ \mathrm{T\ m\ A^{-1}})\left(\frac{4}{0.043\ \mathrm{in}}\right)(6.85\ \mathrm{A}) = 31.5\ \mathrm{mT},$$

where μ is the magnetic permeability. [9] This field strength is more than 500 times greater than that of the Earth's 55-μT magnetic field. To produce the specified static magnetic field strength B_0 of 2.35 mT, the required electric current is

$$I_0 = \frac{B_0}{\mu n_0} = \frac{(2.35\ \mathrm{mT})}{(1.26 \times 10^{-6}\ \mathrm{T\ m\ A^{-1}})\left(\frac{4}{0.043\ \mathrm{in}}\right)} = 0.511\ \mathrm{A}.\ [9]$$

Because the HP 3325A function generator cannot source such a high current, the Hafler XL-280 power amplifier is used to buffer the signal.

The induced voltage in the receiver solenoidal coil due to an oscillating magnetization M of a specimen is

$$\mathcal{E}_1(t) = \frac{B_1}{I_1} V \frac{dM}{dt},$$

where V is the volume of the specimen and B_1/I_1 is the magnetic field strength per unit current through the receiver coil. [10] Assuming a single sinusoidal Larmor precession frequency of ω_0, the magnitude of the NMR signal across the receiver coil is

$$|\mathcal{E}_1| = \frac{B_1}{I_1} V\omega_0 |M| = \mu n_1 V\omega_0 \frac{N\left(\frac{\gamma}{2\pi}\right)^2 h^2 B_P}{4k_B T},$$

where n_1 is the turn density of the receiver coil, h and k_B are the Planck and Boltzmann constants respectively, N, γ, and T are the spin density, gyromagnetic ratio, and temperature of the specimen respectively, and B_P is the polarization field strength applied to the specimen. [10] To maximize the NMR signal, two layers of thin 30-AWG wire is used for the receiver coil windings to increase the turn density. For water, the spin density is the number of protons per unit volume, *i.e.*

$$N = \frac{2\rho N_A}{M} = \frac{2(1000\ \mathrm{kg\ m^{-3}})(6.02 \times 10^{23}\ \mathrm{mol^{-1}})}{(18.0\ \mathrm{g\ mol^{-1}})} = 6.69 \times 10^{28}\ \mathrm{m^{-3}}$$

where ρ is the density, N_A is the Avogadro constant, and M is the molar mass. [11] Assuming a 125-mL test specimen of water at 298 K is pre-polarized to 31.5 mT, the magnitude of the NMR signal is

$$\begin{aligned} |\mathcal{E}_1| &= (1.26 \times 10^{-6}\ \mathrm{T\ m\ A^{-1}})\left(\frac{2}{0.012\ \mathrm{in}}\right)(125\ \mathrm{mL})(100\ \mathrm{kHz}) \\ &\quad \times \frac{(6.69 \times 10^{28}\ \mathrm{m^{-3}})(42.6\ \mathrm{MHz\ T^{-1}})^2(6.63 \times 10^{-34}\ \mathrm{J\ s})^2(31.5\ \mathrm{mT})}{4(1.38 \times 10^{-23}\ \mathrm{J\ K^{-1}})(298\ \mathrm{K})} \\ &= 10.5\ \mu\mathrm{V}. \end{aligned}$$

The realizable voltage that can be detected would be lower than the calculated value above due to the gradual loss of the specimen magnetization after the pre-polarization field is shut off. [9]

When the transmitter coil is driven with a square wave, significant ringing is observed at the receiver coil. Because both solenoids act as large inductors, any parasitic capacitance would produce an RLC circuit that resonates due to the step function of each square wave cycle. [12] The capacitance of the preamplifier circuit, the receiver coil leads, and the winding layers all contribute to parasitic capacitance. The amplitude of the ringing far exceeds that of the NMR signal; damping the ringing to below the threshold of the NMR signal without detrimentally affecting it would be a challenge. To eliminate the ringing associated with the step response, the spectrally efficient sinusoidal wave is tested. With a sinusoidal wave driving the transmitter coil, a faithful representation of the driving signal can be detected by the receiver coil and attenuated using a notch filter.

To measure the microvolt NMR signal at 100 kHz in the presence of the large static magnetic field at 50 kHz, a low-noise amplifier with wide dynamic range is necessary. Logarithmic converters are evaluated for dynamic range compression, but the noise performance of commercially available ICs is inadequate for the application. The 30-$\mathrm{nV}/\sqrt{\mathrm{Hz}}$ input voltage noise of the Burr-Brown LOG series of logarithmic amplifiers would significantly increase the SNR of the desired NMR signal. [13] Moreover, additional circuitry would have to be inserted ahead of the single-ended input of the logarithmic converter to rectify the AC NMR signal, further increasing the noise floor. Low-noise operational amplifiers with wide output voltage swing are considered instead. Operational amplifier ICs such as the Linear Technology LT1028 and Analog Devices ADA4898 feature input voltage noise under 1 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$. [14], [15] Due to ease of availability, however, the Linear Technology LT1037 with input voltage noise of 2.5 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ is used. [16]

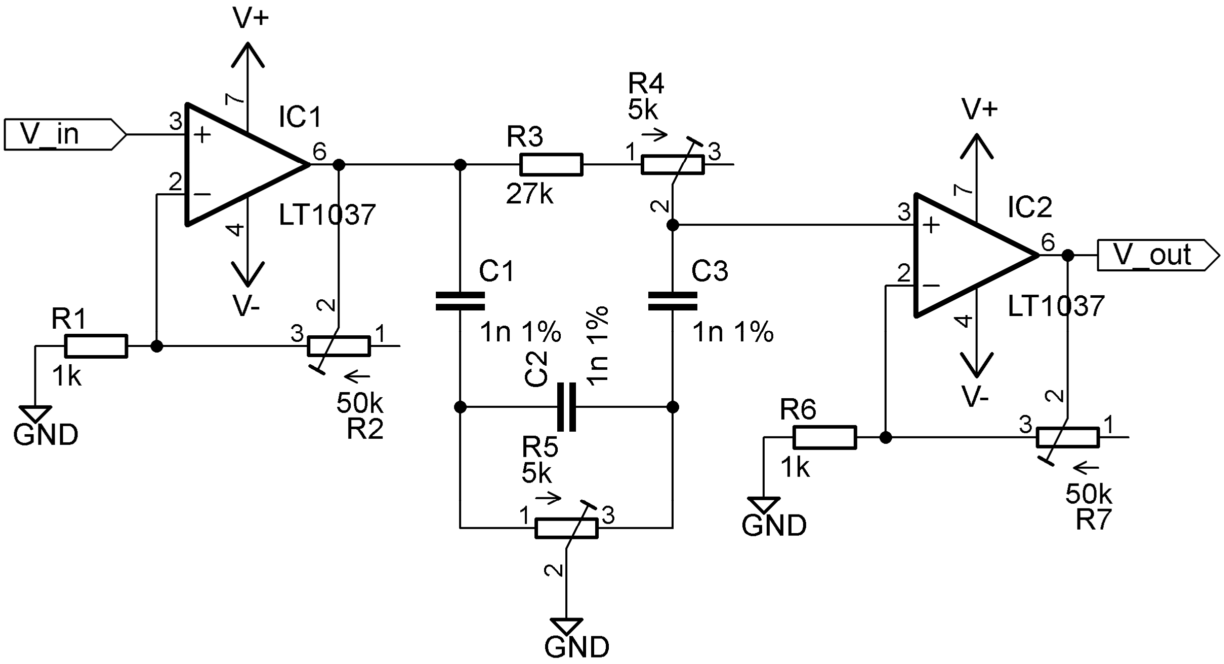

FIGURE 3: SCHEMATIC DIAGRAM OF NMR SIGNAL PROCESSING CIRCUIT

The prototyped NMR signal processing circuit consists of a notch filter with two gain stages (Figure 3). The first stage is a preamplifier to buffer the NMR signal before further filtering. A large gain cannot be used for this stage because the high-amplitude 50-kHz noise signal coupled from the transmitter coil would cause the operational amplifier to clip. A bridged differentiator notch filter follows the preamplifier to attenuate the unwanted 50-kHz signal. A notch filter that removes the narrowband noise signal achieves much greater rejection than a bandpass filter that indiscriminately filters wideband noise. Thus, fewer components are needed to realize the same level of attenuation, resulting in a lower noise floor in the filtered signal. Similar to the twin-T notch filter, the bridged differentiator notch filter splits the input signal into two paths and sums them with a 180° phase shift at the notch frequency to theoretically achieve infinite attenuation. [17] The capacitor values must be well matched obtain a steep null and maximize the quality factor of the filter. The potentiometers *R4* and *R5* are adjusted until the filter frequency is attained and the roll-off slope is maximized, respectively. Once the noise signal is attenuated, the small NMR signal can be amplified without risk of clipping. Additional notch filter stages may be appended to further attenuate the 50-kHz signal.

RESULTS

To characterize the notch-frequency rejection ratio NMR signal processing circuit, sinusoidal waves of equal amplitude at 50 kHz and 100 kHz are fed sequentially into the circuit, which is tuned to reject 50 kHz. The output is measured, and the amplitude of the 50-kHz signal is observed to be approximately 71 times lower than that of the 100-kHz. This value represents a rejection of 37 dB at the notch frequency, reducing the voltage of the noise signal to the same order of magnitude as that of the expected NMR signal. One additional stage of filtering would be enough to attenuate the 50-kHz signal to below the noise threshold. A bandpass filter centered on the Larmor precession frequency may be included as the final stage to reduce wideband noise introduced by the environment and the circuit components.

The frequency responses of the transmitter and receiver coils are characterized by sweeping them with a sinusoidal wave in the frequency bands of interest. Due to parasitic capacitance in series and in parallel with the solenoidal coil, the transmitter coil exhibits a resonance peak near 88 kHz and an anti-resonance null near 35 kHz. The anti-resonance null is predicted to be caused by the four superimposed layers of winding, which act as capacitors. Unfortunately, the null is situated near the driving frequency, thus requiring higher voltage to achieve the same current. The receiver coil exhibits a resonance peak near 80 kHz, below the desired Larmor precession frequency of 100 kHz. Tuning using a capacitor in parallel with the coil can only decrease the resonant frequency further below 100 kHz. The lack of correspondence between the resonant frequencies of the coils and desired frequencies would lead to suboptimal performance of the prototype.

Near the end of the project period, the Hafler XL-280 power amplifier is discovered to distort high-amplitude signals above approximately 20 kHz and generate harmonic frequencies. The second harmonic corresponds to the expected Larmor precession frequency and would obscure the NMR signal. The HP 3325A function generator does not provide sufficient output current to drive the transmitter coil directly and produce the desired static magnetic field strength. Due to time limitations, unfortunately, alternative avenues to drive the transmitter coil or lower the driving frequency have not been explored.

CONCLUSION

This project investigates the feasibility of increasing the signal-to-noise ratio of nuclear magnetic resonance spectroscopy without using massive and costly magnets. The proposed parametrically enhanced NMR spectrometer utilizes the Earth to provide one of the necessary magnetic fields, reducing the cost and size of the instrument. The remaining two electromagnet coils are portable and can be manufactured easily and inexpensively.

In developing the prototype, the transmitter coil and the receiver coil has been fabricated and characterized. After evaluating the two proposed transmitter coil driving signals, the square waveform is deemed unacceptable due to the difficulty in filtering the ringing generated. A filter and amplifier circuit has been designed and breadboarded to extract the NMR signal from the sinusoidal waveform for driving the transmitter coil. The NMR signal processing circuit successfully rejects 37 dB of the offending noise signal, theoretically allowing the Larmor precession to be discerned. Due to the inability to generate a clean high-current sinusoidal waveform at the specified frequency, a positive NMR signal has not been observed within the project timeframe. Nonetheless, progress has been made to enable further development to the design of the prototype. Some recommendations developing the current prototype are described in the next section.

This novel method has the potential to be developed into practical NMR spectroscopy applications, such as the study of sea ice in Antarctica away from a laboratory setting. [18] More research may also be conducted to explore the prospect of exporting this parametrically enhanced NMR spectroscopy method to low-cost magnetic resonance imaging.

RECOMMENDATIONS

A power amplifier that does not distort at the required power and frequency should be procured or constructed to continue exploring this prototype of the parametrically enhanced NMR spectrometer. This crucial link is currently preventing the NMR spectroscopy prototype from being realized.

If new transmitter and receiver coils are to be fabricated, their inductances should be calculated so their frequency response can be optimized. The power required to drive the transmitter coil can be minimized at the desired static magnetic field frequency to allow a lower powered amplifier to be used. The induced voltage in the receiver coil can be maximized at the expected Larmor precession frequency to increase the signal-to-noise ratio of the NMR signal. The coils can be tuned using a parallel capacitor to reduce the frequency of the resonances.

Rather than a solenoidal coil for the transmitter coil, a Helmholtz coil may be employed to enhance the homogeneity of the static magnetic field. [19] The geometry would also allow the receiver coil to be permanently attached to the transmitter coil hardware so the test specimen can be inserted and removed easily. More importantly, the stationary alignment of the receiver coil relative to the transmitter coil would reduce the mutual coupling between the two coils without time-consuming readjustments after each sample is loaded.

Depending on the model used, a soft-start circuit may be connected to the function generator output to ramp up the signal amplitude. During experimentation, the abrupt connection of the HP 3325A function generator to the transmitter coil resulted in transient ringing of the receiver coil. A soft-start circuit that limits the slew rate would reduce the transient ringing and unmask the desired NMR signal.

WORKS CITED

[1] M. H. Levitt, *Spin Dynamics Basics of Nuclear Magnetic Resonance*, 2nd ed. Chichester: John Wiley & Sons, 2008.

[2] T. Thiel. (2009, Jun) 1000 MHz Magnet | Bruker BioSpin. [Online]. http://www.bruker-biospin.com/pr090601.html

[3] J. J. Love, "Magnetic monitoring of Earth and space," *Physics Today*, vol. 61, no. 2, pp. 31–37, Feb 2008.

[4] National Geophysical Data Center. (2010, Sep) NOAA's Geophysical Data Center - Geomagnetic Online Calculator. [Online]. http://www.ngdc.noaa.gov/geomagmodels/IGRFWMM.jsp

[5] Magritek Limited. (2009, Feb) Terranova-MRI. [Online]. http://www.magritek.com/brochures/Terranova-MRI.pdf

[6] Barry N. Taylor and Peter J. Mohr. (2007, March) NIST Reference on Constants, Units, and Uncertainty. [Online]. http://physics.nist.gov/cgi-bin/cuu/Value?gammapbar

[7] D. I. Hoult and R. E. Richards, "The Signal-to-Noise Ratio of the Nuclear Magnetic Resonance Experiment," *Journal of Magnetic Resonance*, vol. 24, no. 1, pp. 71–85, Oct 1976.

[8] S. L. Codd and J. D. Seymour, Eds., *Magnetic Resonance Microscopy: Spatially Resolved NMR Techniques and Applications*. Weinheim: Wiley-VCH, 2009.

[9] Hugh D. Young and Roger A. Freedman, *Sears and Zemansky's University Physics with Modern Physics*, 11th ed. San Francisco: Addison Wesley, 2004.

[10] P. T. Callaghan, C. D. Eccles, and J. D. Seymour, "An earth's field nuclear magnetic resonance apparatus suitable for pulsed gradient spin echo measurements of self-diffusion under Antarctic conditions," *Review of Scientific Instruments*, vol. 68, no. 11, pp. 4263–4270, Nov 1997.

[11] National Institute of Standards and Technology. (2010, Feb) NIST Chemistry WebBook.

[Online]. http://webbook.nist.gov/cgi/inchi/InChI%3D1S/H2O/h1H2

[12] Analog Devices, *Op Amp Applications Handbook*, Walt Jung, Ed. Burlington, MA: Newnes, 2005.

[13] Texas Instruments Incorporated. (2011, Jan) Logarithmic Amplifier - Amplifiers and Linear - TI.com. [Online]. http://focus.ti.com/paramsearch/docs/parametricsearch.tsp?family=analog&familyId=522&uiTemplateId=NODE_STRY_PGE_T

[14] Linear Technology Corporation. (1992) LT1028/LT1128: Ultralow Noise Precision High Speed Op Amp. [Online]. http://cds.linear.com/docs/Datasheet/1028fa.pdf

[15] Analog Devices, Inc. (2010, Feb) ADA4898-1/ADA4898-2: High Voltage, Low Noise, Low Distortion, Unity-Gain Stable, High Speed Op Amp. [Online]. http://www.analog.com/static/imported-files/data_sheets/ADA4898-1_4898-2.pdf

[16] Linear Technology Corporation. (1985) LT1007/LT1037: Low Noise, High Speed Precision Operational Amplifiers. [Online]. http://cds.linear.com/docs/Datasheet/100737fbs.pdf

[17] Paul Horowitz and Winfield Hill, *The Art of Electronics*, 2nd ed. Cambridge: Cambridge University Press, 1989.

[18] C. A. Michal, "A low-cost spectrometer for NMR measurements in the Earth's magnetic field," *Measurement Science and Technology*, vol. 21, no. 10, pp. 1–9, Oct 2010.

[19] Thomas S. Curry, James E. Dowdey, Robert C. Murr, and Edward E. Christensen, *Christensen's Physics of Diagnostic Radiology*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 1990.

[20] Walt Kester. (2009, Feb) High Frequency Log Amps. [Online]. http://www.analog.com/static/imported-files/tutorials/MT-078.pdf