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NMR stabilization of a Hall-controlled electromagnet

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ABSTRACT. A circuit is presented for stabilizing the field of an electromagnet regulated by a Hall-effect probe, against variations, amounting to a few ppm, which result from thermal changes in this probe and in the rest of the control circuit. The circuit mixes a phase-detected dc signal from a nuclear magnetic resonance (NMR) magnetometer with one derived from the Hall probe field-regulating circuit through a suitable attenuator. The two signals are mixed in the appropriate sense to correct the signal variations resulting from changes in the Hall voltage. The resulting signal is fed into the basic control circuit of the electromagnet power supply. The field stability thus obtained depends primarily on the stability of the operating frequency of the NMR magnetometer which in our apparatus is better than 1 ppm. It is also possible with this instrument to perform precise frequency controlled sweeps of the magnetic field for studies of spectral lines in magnetic resonance spectroscopy.

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1. INTRODUCTION

Precise control and measurement of magnetic fields between 0.3 and 1.5 T is necessary for all kinds of magnetic resonance experiments, electron paramagnetic resonance (EPR), nuclear magnetic resonance (NMR) or laser magnetic resonance (LMR). Due to its inherent simplicity and broad range of response to magnetic fields, the Hall effect is widely used for these operations. In modern electromagnets a Hall-effect probe excited by a constant ac current is employed to sense the magnetic field [1]. The resulting Hall voltage is compared in a summation circuit to a separate field setting voltage. The resulting error signal is amplified, integrated in a phase sensitive detector and used as a control signal in the electromagnet power supply. If the gain of the error amplifier is made very high, only a very small error signal is required to drive the magnet power supply and the magnetic field will be held very closely to the level required to generate a Hall voltage which equals the

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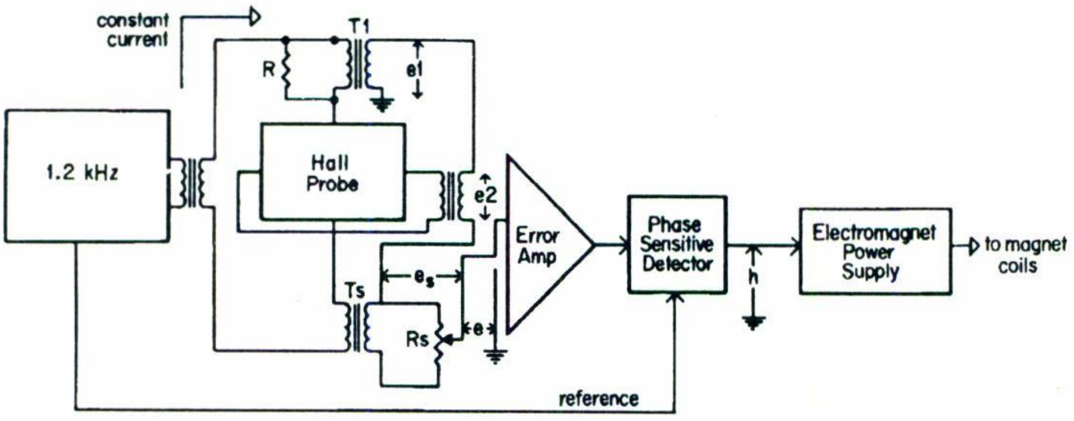

FIGURE 1. Basic circuit of control of the magnetic field of an electromagnet by means of a Hall effect probe.

field setting voltage. The field control accuracy attainable by this method would then be quite high were it not for the variations of the Hall voltage resulting from the $1/T$ temperature dependence of the charge-carriers mobility, as deduced from the Einstein relation [2]. The Hall probe temperature is then kept as constant as possible with a suitable temperature control device. The stability of the magnetic field control is then, in fact, turned over to this device, with all the advantages and shortcomings of temperature regulation. All in all, a field stability of a few ppm can be expected in commercial electromagnets with regulation based on Hall-effect probes.

In experiments requiring the measurement of Zeeman components with high accuracy, or the accurate recording of magnetic resonance lines, this field stability may be insufficient. A temperature independent field regulation is then necessary. We have designed and built an instrument, based on a nuclear magnetic resonance magnetometer and hence dependent only on the stability of its operating frequency, which coupled to the Hall-effect field regulating circuit of a Varian E-9 electromagnet brings a ten-fold improvement to its field regulation and stability making it better than 1 ppm.

2. CIRCUIT DESCRIPTION

The basic circuit of magnetic field control by a Hall-effect probe is shown in Fig. 1. An amplifier supplies a constant ac current through a field set reference resistor R and the Hall probe. A reference voltage is set across R and developed as a field-set voltage e_1 in the secondary of transformer T_1. A field-scan voltage e_s, developed across a different transformer T_s and a variable resistor R_s, may be added to e_1. The resulting voltage is algebraically added to the transformed Hall voltage e_2 and the resulting difference signal e is fed to the error amplifier and its output is phase-detected and rectified at the phase sensitive detector. The rectified signal h is fed as a control signal to the electgromagnet power supply in a negative feedback configuration. Due to the high gain of the error amplifier, only a very small signal is needed to drive the electromagnet power supply. The thermal variations of the Hall voltage will then be reproduced as proportional changes in the magnetic field.

A thermal variation in the rectified error signal h can be offset by adding to it, at the power supply input amplifier, an opposing temperature-independent signal proportional to the change in the magnetic field induced by this variation. One such signal can be derived from a first-derivative nuclear magnetic resonance spectral line from a NMR magnetometer locked to the frequency of a precision oscillator (Fig. 2). If a small temperature change occurs in the Hall probe, it will induce a proportional change in the Hall voltage and in the magnetic field. This, in turn, will offset the NMR magnetometer phase detector from its near-zero value producing a dc voltage proportional to the thermal change in the magnetic field. By feeding this voltage into the power supply input amplifier in opposition to the original change in the magnetic field, this is corrected back towards the value where the magnetometer output nears zero; *i.e.*, to the value determined by the rf oscillator. The magnetic field will then be as stable as the frequency from the rf oscillator. With crystal controlled oscillators the stability can be expected to be as high as 0.1 ppm although still dependent in temperature in this limit through the crystal thermal properties. If, however, the radio frequency is derived from a Cs standard the stability will be higher and truly independent of temperature.

The NMR magnetometer is an improved version of one previously designed and built at our laboratory [3] to which an appropriate phase detector, also of local design, has been added (Fig. 3). A proton-rich liquid sample located inside the coil of a tank circuit is the magnetic field probe. Electromagnetic power from a precision radio frequency oscillator, at the resonance frequency f of the tank circuit, is very loosely coupled to this basic circuit through a very small capacitor. The magnetic field is sensed by the power absorption which takes place when the proton Zeeman levels are exactly a the energy separation $\Delta E = hf$ required by Planck's law. This absorption is reflected as a change in the rf voltage developed across the tank circuit. By modulating the magnetic field at a low frequency around the resonance field, 35 Hz in our apparatus, the radio frequency signal trasmitted by the tank circuit is amplitude modulated at the same frequency. This signal is amplified and detected in amplitude and phase by the circuit following the tank circuit [4].

The amplitude-modulated signal is amplified by a cascode rf amplifier followed by a transistor which provides further amplification and a feedback voltage to the first stage of the cascode for stabilizing both its gain and its operating point. The load of the second stage in the cascode is made dynamically high, and its overall gain

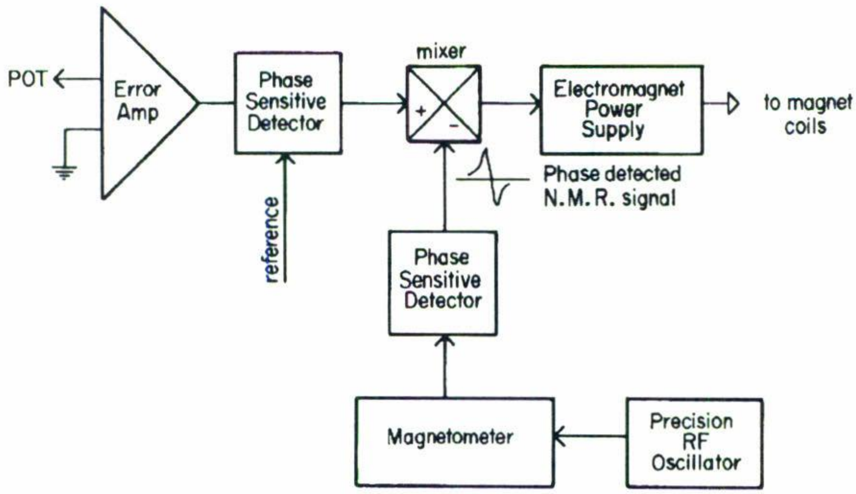

FIGURE 2. Basic circuit for stabilization of a Hall-effect controlled electromagnet by means of a NMR signal.

improved, by means of a bootstrap connection to the emitter of the next transistor. This results in a closed loop gain of about 26 dB.

Detection of the am signal is accomplished in a diode detector in which the diodes operating point is optimized by polarizing with an active circuit which also compensates variations of voltage drop with temperature. A π filter after the diodes attenuates the residual rf to more than 80 dB.

The 35 Hz demodulated audio signal from the detector is amplified by a tuned active filter of the Wien bridge type with a Q of 10. The resulting signal is further amplified by 5 and may be observed in an oscilloscope for purposes of tuning the resonant circuitry or to rapidly check for the NMR signal from the magnetometer.

The dc control signal is obtained by phase detecting the 35 Hz signal from the audio stage in synchronism with the 35 Hz field modulation. The need for a phase adjustment, typical of this kind of detectors, is eliminated by deriving the reference signal from a resistor connected in series with the field modulation coils. The reference signal is amplified, squared and split into two square waves shifted 180° with respect to each other which are, in turn, applied to the control inputs of two linear CMOS gates. A direct and an inverted NMR signal are fed to the active inputs of these gates which work, then, as a full wave synchronous detector in which the dc shift of the amplifiers is almost completely cancelled out. After going through two more stages of low pass filtering and dc amplification the signal may be plotted, further amplified or fed to a mixer where it is algebraically added to a signal coming from the Hall probe. The mixer output is fed to the normal control circuit of the magnet power supply.

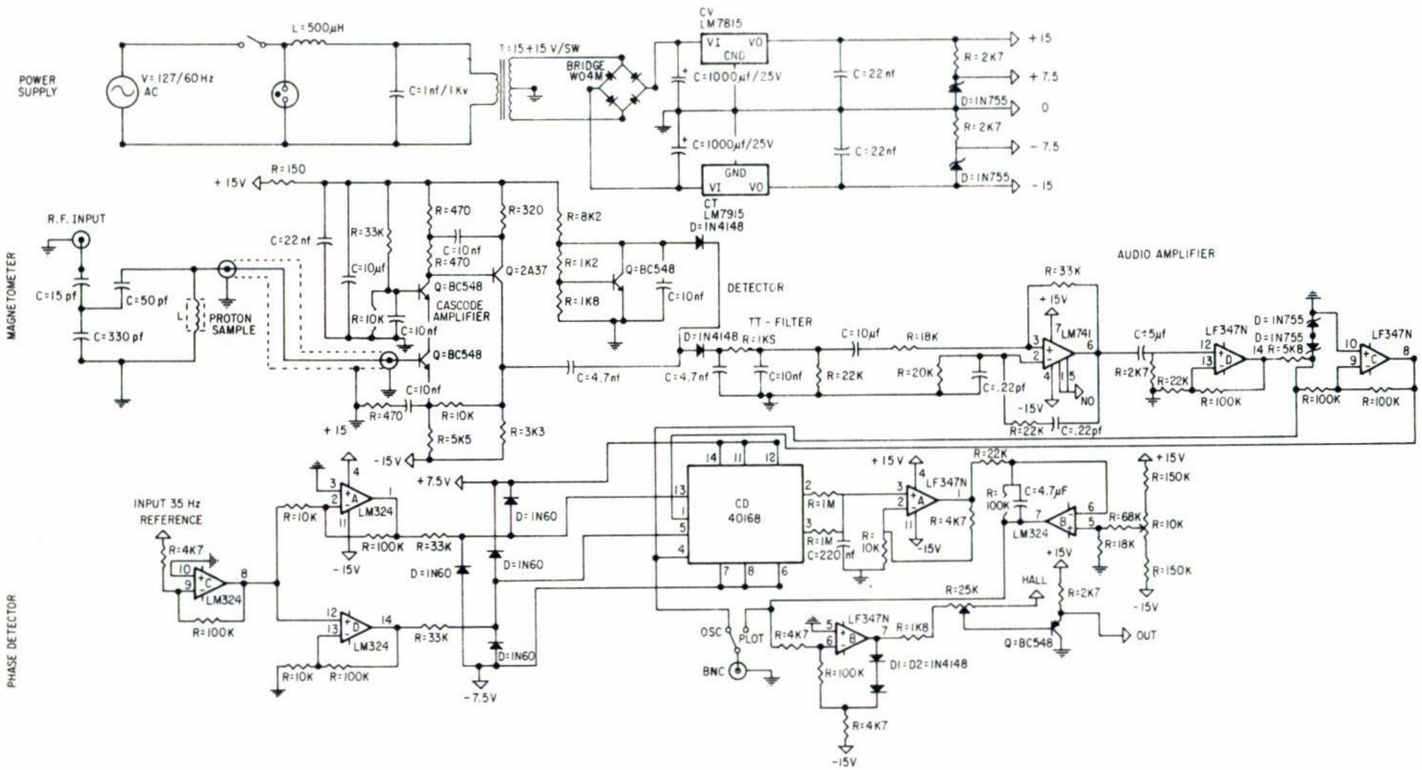

FIGURE 3. Schematics of the NMR control circuit for stabilizing an electromagnet controlled by a Hall-effect probe.

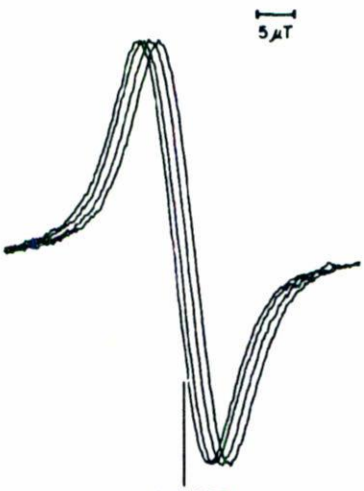

FIGURE 4. Four succesive recordings of the $M = 1 \Rightarrow 0$, $^3P_2$ electron paramagnetic resonance line of atomic oxygen in gas phase, with only Hall-effect regulation of the electromagnet. Recording time for each pass is 4 min. Radio frequency was 9.201204 (1) GHz for the first three, and 9.201210 (1) GHz for the last one, of the recorded lines. Thermal drift of the line in the graph amounts to ≅ 1.3 ppm.

3. RESULTS

This circuit was tested by recording several times in succesion a narrow first-derivative electron paramagnetic resonance (EPR) spectral line in synchronism with a linear sweep of the scan voltage e_s, generated by driving the wiper of the potentiometer with the horizontal drive mechanism of an X–Y recorder (Fig. 1). The $M = 1 \Rightarrow 0$ microwave Zeeman transition from $O(^3P_2)$ in gas phase was used to perform this test [5]. This line appears at a field of 0.43808 T for a microwave frequency of about 9.2012 GHz which was held constant to less than 1 ppm for the duration of the measurement. At the conditions of our experiment the peak-to-peak linewidth was about 18 ppm. For a 0.0002 T field scan, a field shift of 1 ppm would be discernible as a 0.9 mm change in the position of the line.

Figure 4 shows four succesive recordings of the $O(^3P_2)$ line after a two-hour warm up period of the electromagnet, without the NMR control system. The radio frequency was measured continuosly with a high-stability HP 5340A frequency counter. Recording time for each pass was 4 min. The lines are seen to recede about 1.3 ppm after each pass, indicating a thermal variation of 1.3 ppm also in the control signal to the electromagnet power supply.

Figure 5 shows the result of a series of three recordings of the $O(^3P_2)$ line with the NMR control circuit connected to the system. The recorded lines are seen to be precisely coincident with each other to the accuracy of the position measurement;

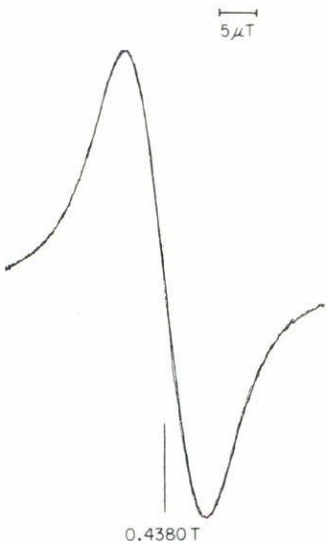

FIGURE 5. Three succesive recordings of the $M = 1 \Rightarrow 0$, $^3P_2$ electron paramagnetic resonance line of atomic oxygen in gas phase, with NMR stabilization of the Hall-effect controlled electromagnet. Recording time in each pass is 4 min. Drift of lines is less than 0.1 ppm. Radio frequency was 9.201225 (1) GHz throughout.

i.e., to about 0.1 ppm, which was also the frequency drift of our rf oscillator, a Hewlett-Packard 8640A, during the recording time.

An immediate application for this instrument will be the measurement of magnetic moments of light atoms to an accuracy that will permit an order of magnitude improvement in the evaluation of the effect of correlation in atomic magnetism [6]. But it will also find application in the accurate recording of laser magnetic resonance lines of magnetically "strong" atoms and molecules [7].

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RESUMEN. Se presenta un circuito para estabilizar el campo de un electroimán regulado por medio de una sonda de efecto Hall, contra variaciones resultantes de cambios térmicos en esta sonda y en el resto del circuito de control. El circuito mezcla la señal de corriente directa proveniente del detector de fase de un magnetómetro de resonancia nuclear magnética (NMR), con la señal de regulación del campo, proveniente de la sonda Hall, convenientemente atenuada y en el sentido apropiado para que se cancelen las variaciones debidas a cambios térmicos en esta última sonda. La señal resultante se alimenta al circuito básico de control de la fuente de poder del electroimán. La estabilidad de campo que así se consigue depende primordialmente de la estabilidad de la frecuencia de operación del magnetómetro, que en nuestro instrumento es superior a 1 ppm. También es posible con este instrumento hacer barridos precisos del campo magnético controlados por la frecuencia de un oscilador, para hacer estudios de precisión sobre líneas espectrales en espectroscopía de resonancia magnética.