An Amplitude and Phase Regulating Magnetic Field Generator for an Eye Movement Monitor

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Abstract—**One common method of eye movement detection uses an ocular search coil within two magnetic fields arranged in spatial and temporal quadrature. An inexpensive circuit is presented that regulates the strength of the two fields and their phase separation. This stabilization minimizes perturbations due to motion of the field's generating coils, motion of metal within or near the fields, and component value drift.**

INTRODUCTION

Quantitative assessment of eye movements has grown in importance in the last several decades until it has become commonplace in both the research laboratory and the clinic. While many diverse eye movement monitors have been developed [8], the technique most favored when high resolution, large bandwidth, and large range are desired remains the magnetic field/search coil technique developed by Robinson [6].

In a basic system, two pairs of coils are arranged orthogonally around the subject. The coils generate two electromagnetic fields in temporal quadrature. The subject wears a contact lens on which are implanted one or two small coils. The voltages induced in these search coils by the electromagnetic fields are proportional to the areas of the coils perpendicular to the fields. These voltages can be decoded by phase-sensitive detectors to determine the orientation of the coils in the fields.

To meet the needs of basic and clinical research many modifications to the original scheme have been introduced. Fuchs and Robinson surgically implanted the search coil under the insertions of the extraocular muscles to facilitate chronic recordings in animals [3]. Collewijn *et al.* developed a soft annulus which does not touch the corneal surface for use in human subjects [2]. Judge *et al.* developed another surgical technique for animal studies which implants a preformed coil behind the conjunctiva but in front of the muscle insertions, minimizing the introduction of strabismus in binocular studies [4]. Sullivan and Kertesz developed a simpler field driver configuration using a quadrature oscillator, and presented an inexpensive search coil decoder based on a phase-locked sampling technique [7]. Collewijn augmented the basic two-coil configuration with additional coils and detected phase relative to a horizontally rotating field, allowing orientation detection anywhere within the coils [1]. McElligott *et al.* introduced a two-frequency field generation technique to improve channel separation and an inexpensive phase-sensitive demodulator based on a synchronous switching technique [5].

THE NEED FOR A NEW FIELD GENERATOR

When we began a research project requiring a moving mirror within the field coils, we felt that none of the existing configurations would stabilize the eye movement signal. We obtained a copy of the circuit used by A. A. Skavenski at Northeastern University because it had an automatic gain controller and was not very sensitive to metal within the field coils. That circuit used a self-oscillatory closed-loop cross coupling of the two LC networks, regulated by an automatic gain controller, and was designed to oscillate at about 5 kHz. Our experimental plan would eventually require single-unit recordings with a bandwidth of 10 kHz, hence we needed to operate the circuit above 20 kHz. Unfortunately, the gain-controlled, close-loop circuit became unstable at frequencies above about 7 kHz because of stray capacitance and inductive coupling between the fields and nearby metal structures. We therefore found it necessary to develop an open-loop gain-controlled driver.

At this point, an additional problem arose, which is common to all of the phase-sensitive magnetic field/search coil systems. In order to obtain the maximal field strength possible with inexpensive audio amplifiers, Robinson designed the coils to operate as series LC circuits driven at resonance. This configuration has a minimum impedance at a resonant frequency $f_r \approx 1/2\pi\sqrt{LC}$. Not only is the impedance a minimum at f_r, but the rate of change of the impedance with changes in frequency or the value of L or C is also a minimum. However, at resonance the phase change introduced by the LC circuit is maximally sensitive to changes in frequency or in the value of L or C. This problem is usually dealt with by obtaining one of the drive signals through inductive coupling with the other coil pair and with inductive feedback from the driven coil [6]. However, since these systems usually have a relatively low gain, the compensation is less than excellent. Moving metal within the field coils, or moving the coils relative to metal structures in the room (as is frequently done when measuring vestibularly induced eye movements) changes the coupling with the LC network, thus changing the resonant frequency. When this happens, the most disturbing effect is the shift in phase, since the eye movement is decoded from the search coil signal with phase-sensitive detectors. To cope with this perturbation, we included a phase separation regulator as well as field strength regulators. This makes the eye monitor insensitive to small changes in L, C, or the driving frequency.

A REGULATED MAGNETIC FIELD GENERATOR

The configuration consists of four parts: the field coils, the power amplifiers, the sense coils, and the field regulator circuit (Fig. 1). The field coils are as described by Robinson [6]. A small (0.5 Ω) resistor is placed in series with each LC circuit to slightly reduce its Q and increase the impedance seen by the power driver. The power driver is a Heathkit AA-1640 200 W/channel stereo amplifier with power meters.

Two sense coils provide the feedback for the field regulator. When no metal moves within the fields, global sense coils wound around the field generating coils can be used. When more precise compensation is needed, we use local sense coils mounted on Plexiglas forms close to the search coil. The sense coils must be grounded at their centers as the sense amplifiers are differential. We used two-turn local sense coils mounted for convenience on a 2 in × 2 in square form.

The field regulator has been fabricated on two standard circuit cards (about 4.5 in × 6 in). Fig. 1 shows a block diagram of the circuit. A Wien-bridge oscillator generates a sine wave, $\sin(\omega t)$. This signal is regulated by an automatic gain controller (AGC) whose output, $A_x \sin(\omega t)$, drives the x-axis (horizontal) power amplifier. The field strength is measured by full-wave rectifying and then low-pass filtering the output of the sense coil amplifier. The difference between this measured field strength and the desired field strength, as indicated by the setting of potentiometer A_x, is integrated to obtain the error signal for the automatic gain controller.

The x-axis reference sine wave is phase shifted by $-225°$ to

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Manuscript received August 20, 1981; revised November 9, 1981. This work was supported by the National Eye Institute and the National Institute of Mental Health.

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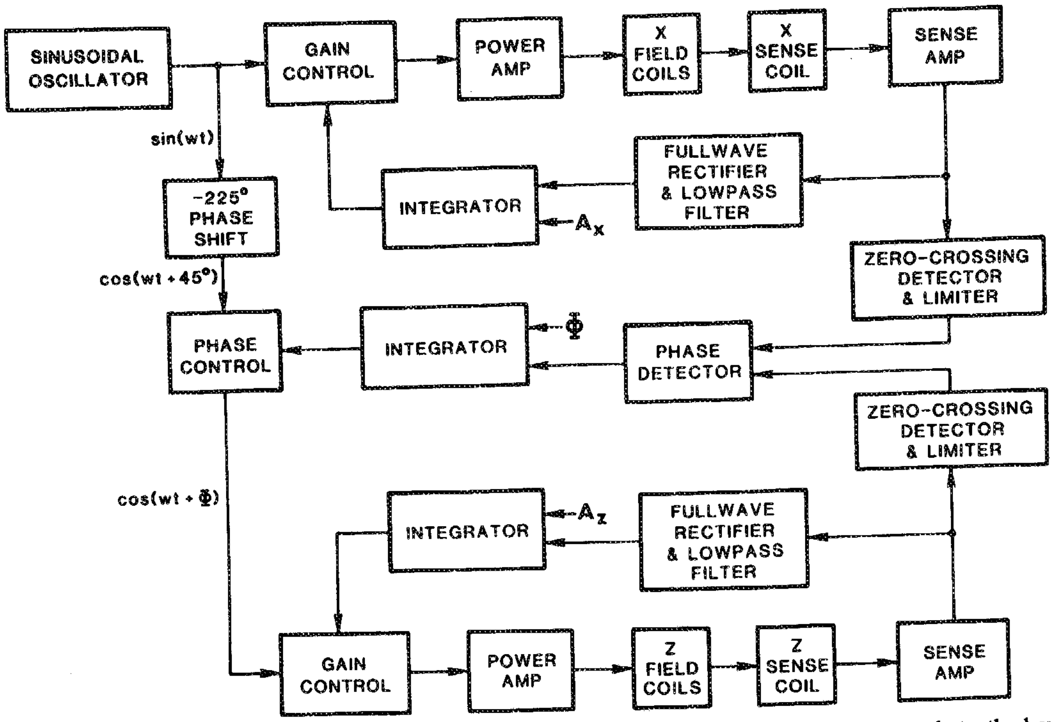

Fig. 1. Block diagram of the stabilized magnetic field generator. The layout of the blocks corresponds to the layout of the components in Fig. 2.

produce a cosine wave 45° out of quadrature, $\cos(\omega t + 45^\circ)$. This signal is shifted by the automatic phase-control loop so that the x field and the z field are in quadrature at the sense coils. The amplitude of this phase-shifted cosine signal is regulated by the z-axis automatic gain controller to have an amplitude of A_z.

The outputs of both field strength sense amplifiers are connected to zero-crossing detectors and limiters. The limiter outputs are relatively insensitive to the strength of the respective magnetic fields, but maintain the correct phase relationships. The phase signals from the limiters are compared by the phase detector. The output of the phase detector is proportional to the phase angle separating the two signals. The difference between the measured phase angle and the desired phase angle (Φ in Fig. 1) is integrated to obtain the error signal used by the phase controller. A voltage regulator provides a stable reference for the integrators.

Fig. 2 shows a schematic diagram of the field regulator circuit. Three amplifiers in the upper left corner of Fig. 2 are connected to form a 21 kHz oscillator and a phase-shift network. The oscillator generates a 16 V (peak-to-peak) sine wave. The phase-shift network is a low-pass filter with a dc gain of 1.41 with a break point at $f_r = 0.16/RC$ where f_r is the resonant frequency of the field coils. The frequency range of the oscillator can be adjusted by changing the input resistor of amplifier $A2$ (currently 11 kΩ in series with a 5 kΩ pot) and/or the 680 pF capacitors. The oscillation frequency is $f = 0.16/C\sqrt{R9.09k}$. The range can be adjusted by changing the ratio of the fixed resistor to the potentiometer.

The static phase shift contributed by the phase-shift network can be altered by changing either the capacitor or the resistor in the feedback path so that $RC \approx 0.16/f_r$. (If the feedback resistor is changed, also change the input resistor to maintain the 1.41:1 ratio.)

When changing the frequency, the sensitivity of the automatic phase controller should also be adjusted by changing the RC network on multiplier $M4$. The values of R and C (now 10 kΩ and 0.005 μF) should be chosen so that $RC \approx 1.2/f_r$.

Since this circuit operates above the high end of the audio-spectrum, some care must be exercised when laying out the circuit. Leads of capacitors and resistors should be kept short. Avoid routing wires from the output of a device past the input side of the same device. All resistors have 1 percent tolerances and all integrated circuits have heat sinks.

CALIBRATION

Once the system is set up, it will instantly lock in when power is applied. Calibration is only necessary when the system is first installed or when its configuration (e.g., sense coil position or cable pathway) is changed.

The most difficult part to adjust is the phase controller. If the phase separation is too large when power is applied, the output of the phase controller will change sign, causing the phase control system to run with positive feedback. The result of this positive feedback will be the maximum phase shift possible. Check that the cosine signal coming from the low-pass filter (output of $A3$) lags about 135° behind the sine wave from the oscillator (output of $A2$).

With the power off:

1) *Stiffness.* Set the stiffness of the automatic gain controllers to about half their full value by setting potentiometers S_x, S_z, and S_Φ to midrange.

2) *Frequency.* Set potentiometer f of the oscillator circuit to midrange.

3) *Amplitude and phase.* Set potentiometers A_x, A_z, and Φ to about $\frac{1}{4}$ of their range.

4) *Power amplifier gain.* Set the gain of the power amplifier to one-half.

Now, turn the power on. The fields should be oscillating (monitor the output of $I1$ and $I2$ to see the fields). The horizontal field (x) should be $A_x \sin(\omega t)$ and the vertical field (z) should be $A_z \cos(\omega t + \Phi)$.

5) *Field strength:* Adjust A_x and A_z to obtain the desired amplitudes of the sine and cosine signals (output of $A9$ and $A10$). (We drive our amplifiers at about 100 W/channel, which gives a field strength measure of about 1 V peak-to-peak.)

6) *Stiffness.* Adjust S_x until the automatic gain control signal (output of $A11$) is about 1 V. Repeat with S_z (output of $A12$) and S_Φ (output of $A13$).

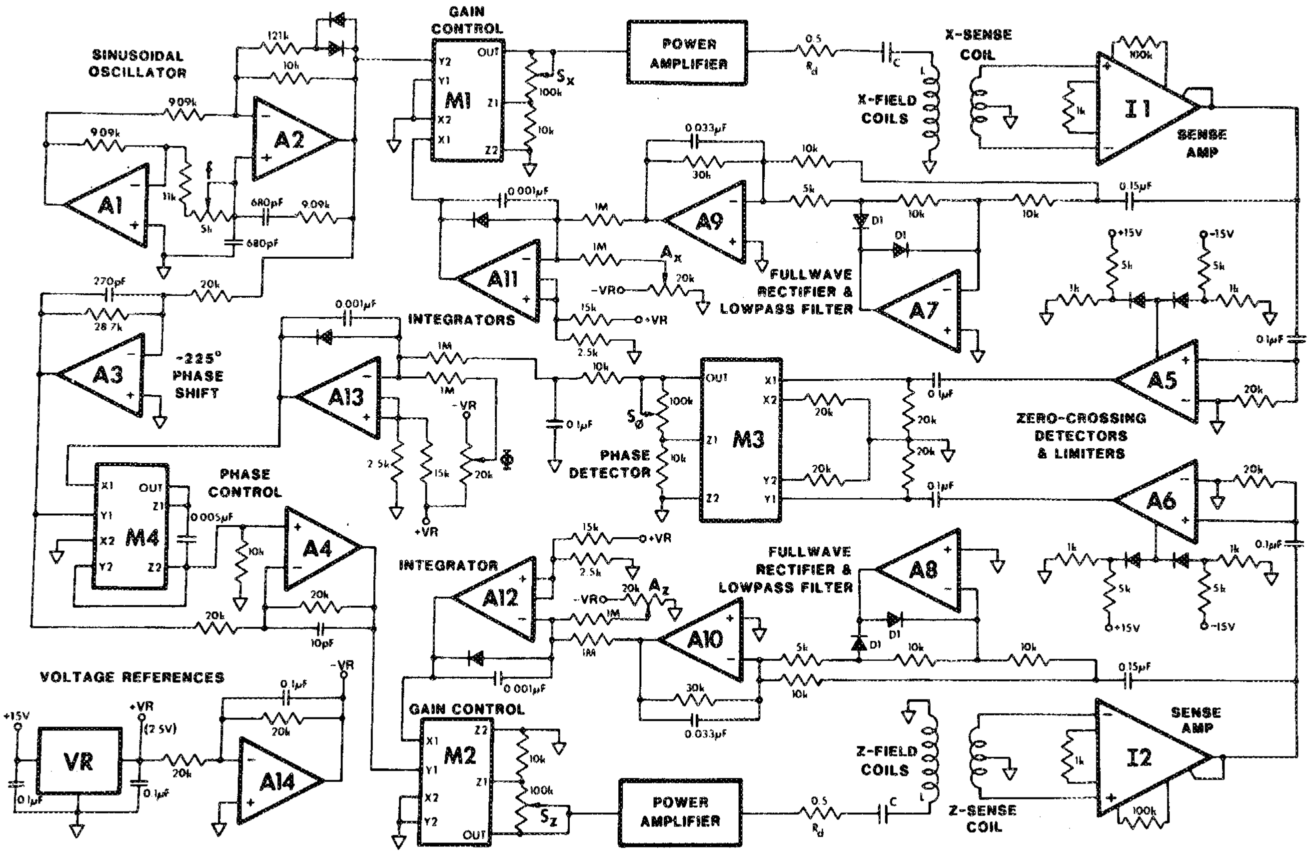

Fig. 2. Schematic diagram of stabilized magnetic field generator. $A1$, 2, 3, 4 are OP15FJ amplifiers. $A5$, 6 are AD507J amplifiers. $A7$, 8 are OP16FJ amplifiers. $A9$, 10, 14 are OP07FJ amplifiers. $A11$, 12, 13 are AD515K amplifiers. $I1$, 2 are AD521K instrumentation amplifiers. $M1$, 2, 3, 4 are AD534KH multipliers. VR is an AD580K voltage regulator. OP integrated circuits are manufactured by Precision Monolithics, Inc., and AD integrated circuits are manufactured by Analog Devices. $D1$ are HSCH 1001 diodes from Hewlett Packard. All other diodes are type IN914. All resistors have 1 percent tolerances. Power supply (connections not shown) provides ±15 V.

7) *Frequency.* Adjust f until the automatic gain control signals (outputs of $A11$ and $A12$) are at a minimum. Since the two field-coil pairs will not be identical, some compromise will be necessary in selecting the optimal frequency. If there is a huge swing in the control voltages for small changes in the frequency, lower the Q of the LC circuit by increasing the series resistance (R_d in Fig. 2).

8) *Phase.* Adjust Φ until the x and z fields are in quadrature. (This can be easily determined by driving the horizontal input of an oscilloscope from $I1$ and the vertical input of the oscilloscope from $I2$. The signals are in quadrature when the elliptical Lissajou figure has orthogonal major and minor axes.) Next, connect in a dummy search coil, which can be rotated independently about the x- and z-field axes. Moving the coil only about the z-axis, adjust the eye monitors until there is a pure horizontal deflection. Then, move the coil only about the x-axis and adjust Φ until a pure vertical deflection is obtained. (This latter technique is used regularly to check orthogonality of the system, since the phase relationships can shift depending on the cables and their surroundings.)

PERFORMANCE

There are currently five of these stabilized magnetic field generators in operation. The typical range of eye movements is ±40° full scale. The signal-to-noise ratio ranges from 300:1 to 500:1, depending on the phase detectors used. A study of the drift characteristics can be performed by monitoring the field strength signals, the control voltages, and the eye position output with a dummy eye coil. During the first 10 min the control voltages change by less than 10 percent and the frequency drifts about 0.02 percent. During the next 24 h the control voltages change by less than 5 percent and the frequency drifts less than 0.01 percent. The controlled variables, field strength and phase, show no measurable change over either the short or the long term. The apparent eye movement drift is always less than the eye monitor's noise level. This indicates that the stabilizing circuit is, indeed, compensating for changes in the system that would otherwise cause eye movement artifacts.

In one system, the field coils are mounted on a metal rotatable chair for human subjects. On this system, the range of eye movement is ±20° and the noise is 0.1°. Rotation of the field coils by a full 360° results in an artifactual eye movement of only ±0.2°.

The response of the system to moving metal in the fields was tested with a servo-controlled motor moving a 30 X 30 cm square of aluminum about 30 cm inside coils which are 70 cm on a side. The aluminum sheet was oscillated sinusoidally with frequencies from 1 to 30 Hz, with an amplitude ranging from 30° to 2°. Although the control voltages changed in correlation with the oscillating metal, there was no detectable change in the field strength or phase.

While the performance of the stabilizing circuit is excellent, it must be remembered that only field strength and phase can be regulated. Eye movement artifacts also arise because the electric component of an electromagnetic field must approach a conductor perpendicularly (otherwise currents flow in the conductor). Since the magnetic field vector is warped near conductors, the presence of conductors within the fields will cause a measurement artifact. The only solution to this problem is to keep conductors away from the search coil and use local sense coils as near the search coil as possible.

ACKNOWLEDGMENT

We would like to thank A. C. Ziminsky, Sr. for help in the fabrication of the circuits, and A. G. Lasker of the Johns Hopkins School of Medicine for suggesting the limiter circuits.

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An Improved Instrument for Pacemaker Analysis Based on the CCD Technique

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Abstract—The instrument described in a previous paper, "A new method for utilizing a standard electrocardiograph for *in vivo* clinical pacemaker analysis" [3] has been improved with the utilization of the charge-coupled device.

This device, used here as an analog shift register of 1024 cells, permits the display of the pacemaker pulse with a standard electrocardiograph in a high-resolution time course; the same time course can be transmitted by telephone for remote analysis.

Furthermore, our technique permits an automatic serializing of the stretched pacemaker pulse and its induced cardiac rhythm on the same trace.

The low-power circuits used by the authors enable operation with a battery supply which implies high noise immunity, safety assurance for the patient, and portability of the instrument for its utilization through the public telephone network.

INTRODUCTION

Pacemaker carrying patients are normally submitted to periodical check [2] in specialized clinics to analyze the status of their prosthesis from two points of view: 1) clinical effectiveness of the pulse and 2) electrical life expectancy; both depend on residual battery charge, circuit efficiency, and catheter and electrode conductivity.

Generally, the electrical analysis is performed by means of ECG and oscilloscope; the oscilloscope displays the pacemaker (*PM*) pulse time course. The instrument presented in this paper is based on the previous instrument [3] with improved implementation through the CCD technique [1].

The previous instrument samples the *PM* pulse time course on 20 analog memory cells (i.e., capacitors) at a sampling rate of 200 μs/sample, then resolves the *PM* signal at a scaled rate (10 Hz) on a standard electrocardiographic recorder.

This apparatus presents two practical problems:

1) The stretched *PM* pulse on the electrocardiographic paper is reproduced with large waveform distortion due to the low number of samples.

2) The amplitude peak evaluation can be obtained, not directly, but by means of an extrapolation of the staircase waveform of the reproduced *PM* pulse.

In the new instrument presented here, the number of the samples has been increased from 20 to 256. This fact prevents the above-mentioned inconveniences and permits a continuous waveform of the stretched *PM* pulse to be displayed on electrocardiographic paper. The new instrument embeds a charge-coupled device (CCD) for sampling the pacemaker pulse and performing the necessary stretching action to display the pacemaker pulse on a standard electrocardiograph. The use of the CCD technique automatically allows the stretched pacemaker artifact and induced cardiac rhythm in real time to be serialized on the same trace.

Furthermore, the new electronics of the instrument permit battery powering and high noise immunity. Safety assurance for patient and portability are, consequently, obtained. A single-channel transmission of the processed ECG signal on the standard public telephone network is provided, using frequency modulation of an acoustic band carrier and acoustic coupling with the telephone headset [4].

METHOD AND MATERIALS

The analog memory of the instrument, based on charge-coupled devices (SAD 1024 by Rethicon), is used as an analog shift register of 2 × 512 cells operated in the differential mode and with a twin clock phase. This way of operation gives 256 useful samples.

The use of charge-coupled devices (CCD) presents various advantages over the capacitor analog memory and digital memory for pacemaker analysis.

1) High ratio "memory size/volume" compared to discrete capacitor memory.

2) Natural real-time processing capability, lower number of chips, and lower power circuits compared to the equivalent method based on A/D conversion, digital storing on RAM, digital recall, and D/A conversion.

The CCD analog shift register is used under control of a timing clock which masters the sampling process of the analog signal operating on a bucket brigade base.

In this application, two sudden clock frequency changes are necessary to obtain a stretching action on *PM* pulse and resolve it at an underscaled rate:

1) A first increase in clock frequency when *PM* pulse is present at the input of CCD (from 1 kHz to 125 kHz);

Manuscript received January 12, 1981; revised October 15, 1981. This work was supported by the Istituto di Fisiologia, Clinica CNR, Pisa, Italy.

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0018-9294/82/0300-0209$00.75