Pulse induction metal detector

Experimental system for overcoming magnetic viscosity effects

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Because the author considers buried "treasures" to be the most lasting and potentially most informative repositories of human history, he feels that their detection and excavation should be restricted to approved organisations. This article describes an experimental metal detector, originally developed for detecting gold in Western Australia (so far unsuccessfully), that can be adapted for archaeological or military applications. Particular emphasis is placed on magnetic viscosity and how to eliminate this undesirable effect.

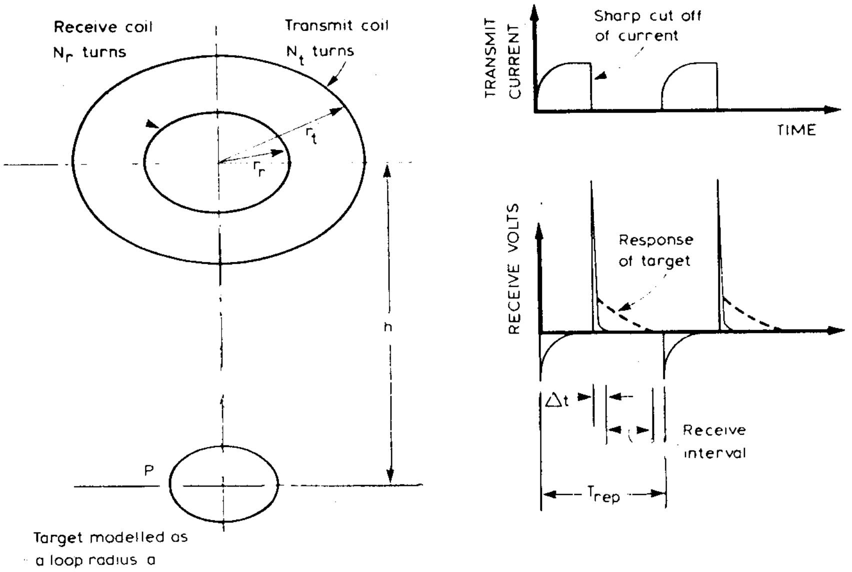


Fig. 1 Elements of a pulse induction system.

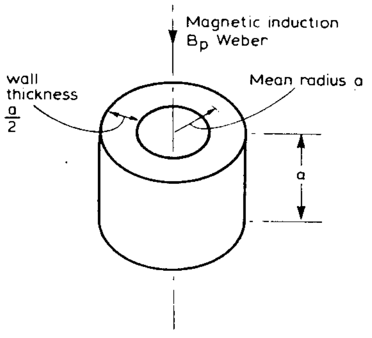


Fig. 2 Standard cylinder target.

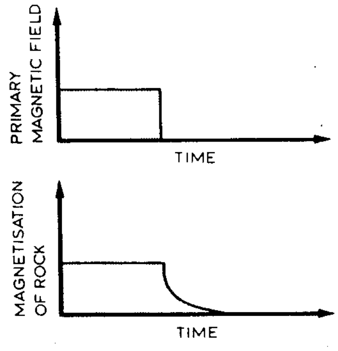


Fig. 3 Response of soil or rock when the primary magnetic field is switched off.

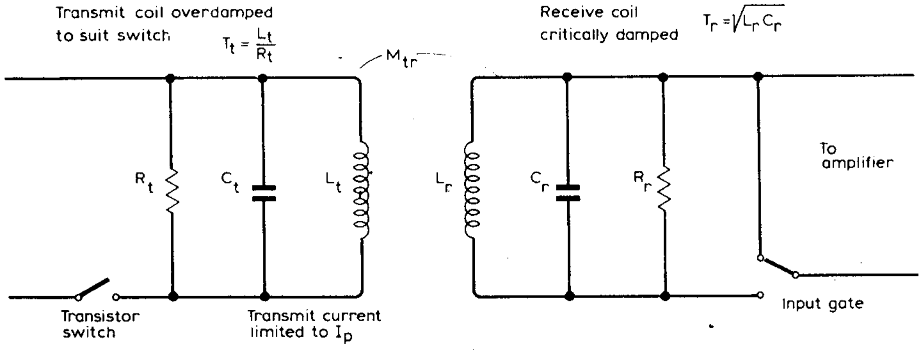


Fig. 4 Equivalent circuit of the transmit and receive coils.

Metal detectors used in searching for buried metallic objects are similar in concept to those used for geophysical exploration. All such instruments depend on the measurement of a magnetic field associated with eddy currents induced in the target by a primary magnetic field. The two main groups of metal detector are the continuous wave type where normally a sinusoidal primary magnetic field produces eddy currents in the target, and the pulse induction system where the primary field is a series of pulses. In a continuous wave detector, coupling between the transmitter and receiver is effected by the geometry of the system which must be rigid for detecting small metallic targets such as archaeological artifacts. Rigid geometry is not so important in a pulse induction system because there is no direct coupling between the transmitter and receiver.

Early metal detectors were mainly continuous wave types because simple circuits could be used. However, pulse induction systems have been described in the geophysical context by Grant and West[1], and in the archaeological context by Colani[2].

In a conventional pulse induction system a primary magnetic field is switched off and induces eddy currents in a conductive target. Voltages induced by the decay of these eddy currents are detected and then displayed. Fig. 1 shows a system comprising circular primary and receive coils which are coaxial with a target illustrated as a conducting loop. Fig. 2 shows the case where a magnetic flux of B_p Weber is normal to a loop of radius a and the self inductance of the loop, R the resistance and i is the current then

$$iR=-\frac{\mathrm{d}}{\mathrm{dt}}[B_p\pi a^2+Li] \qquad (1)$$

If $B_p=B_0$ at $t=0$, $B_p=0$ at $t=\Delta t$ and $i_{\Delta t}$ is the current at $t=\Delta t$,

$$i_{\Delta t}=\frac{\pi a^2}{L}B_0-\frac{R}{L}\int_0^{\Delta t} i\,\mathrm{dt} \qquad (2)$$

If $\Delta t \ll L/R$, equation (2) can be approximated by

$$i_{\Delta t}\approx\frac{\pi a^2 B_0}{L} \qquad (3)$$

If the target is given a standard form of a cylinder with radius a, height a and wall thickness a/2, L can be calculated from an adaptation of Wheeler's formulae

$$L=a\times 2.07\times 10^{-6}\mathrm{H} \qquad (4)$$

Although equation (4) is an approximation it is sufficient for practical purposes because targets are rarely standard shapes. The resistance can be calculated from

$$R=\frac{0.289\times 10^{-6}\times k}{a}\Omega \qquad (5)$$

where it is assumed that the specific resistance of the metal is for gold ($0.023\times 10^{-6}\Omega$m) and k is the specific resistance in relation to gold. When the primary magnetic field is removed the current in the target decays exponentially with a time constant.

$$T=\frac{L}{R}=\frac{7.16a^2}{k}\mathrm{s} \qquad (6)$$

The eddy current induced in the model target is then

$$i=\frac{\pi a^2\mu_0 H_0}{a\times 2.07\times 10^{-6}}e^{-\frac{t\times k}{7.16a^2}}\ \mathrm{A}$$

and setting μ_0 at $4\pi\times 10^{-7}$ H/m

$$i=1.907aH_0e^{-\frac{t\times k}{7.16^2}} \qquad (7)$$

In the pulse induction system of Fig. 1 the primary magnetic field at P is approximately

$$H_0=\frac{\pi r_t{}^2N_tI_p2}{4\pi h^3}=\frac{r_t{}^2N_tI_p}{2h^3}\mathrm{A/m} \qquad (8)$$

The voltage at the receiver coil is determined by the rate of change of flux linkage originating from the target and is given by

$$\frac{r_t{}^2N_tI_p}{2h^3}1.907a\ \left(\frac{-k}{7.16a^2}\right)e^{\frac{-tk}{7.16a^2}}\ \frac{\mu_0a^2}{2h^3}\pi r_r{}^2N_r$$

therefore,

$$V_r=0.262\times 10^{-6}r_t{}^2r_r{}^2N_rN_tI_p\ \frac{ak}{h^6}\ e^{\frac{-tk}{7.16a^2}} \qquad (9)$$

If the received signal is integrated the mean output signal level V_m will be

$$\frac{1}{T_{\mathrm{rep}}}\int_0^\infty V_r\mathrm{dt}=$$

$$1.875\times 10^{-6}\ \frac{r_t{}^2r_r{}^2N_tN_ra^3I_p}{T_{\mathrm{rep}}h^6} \qquad (10)$$

where T_{rep} is the repetion interval defined in Fig. 1 and $T_{\mathrm{rep}}\gg T$.

As an example, consider the case where T_t is 0.6m, T_r is 0.45m, N_t is 54 turns, N_r is 68 turns, a is 0.04m, h is 1m, I_p is 1A and T_{rep} is 0.016s. Equation (10) gives a V_m of 1.1μV and for $k=1$, $T=5.7$ms. This is very approximate because h is not much greater than r_t.

The time constant of a non metallic material in the vicinity of a metal detector can be calculated by appropriate modifications to equation (6) as

$$T=\frac{1.64\times 10^{-6}a^2}{S}\mathrm{s} \qquad (11)$$

where S, is the specific resistance of the material. Substituting $a=1$m and $S=0.2\Omega$m, the approximate specific resistance of sea water, the time constant is 0.8μs.

Most rocks and soils have a specific resistance much higher than this so an effective separation can be made between signals due to metallic targets and conductivity effects in the ground by

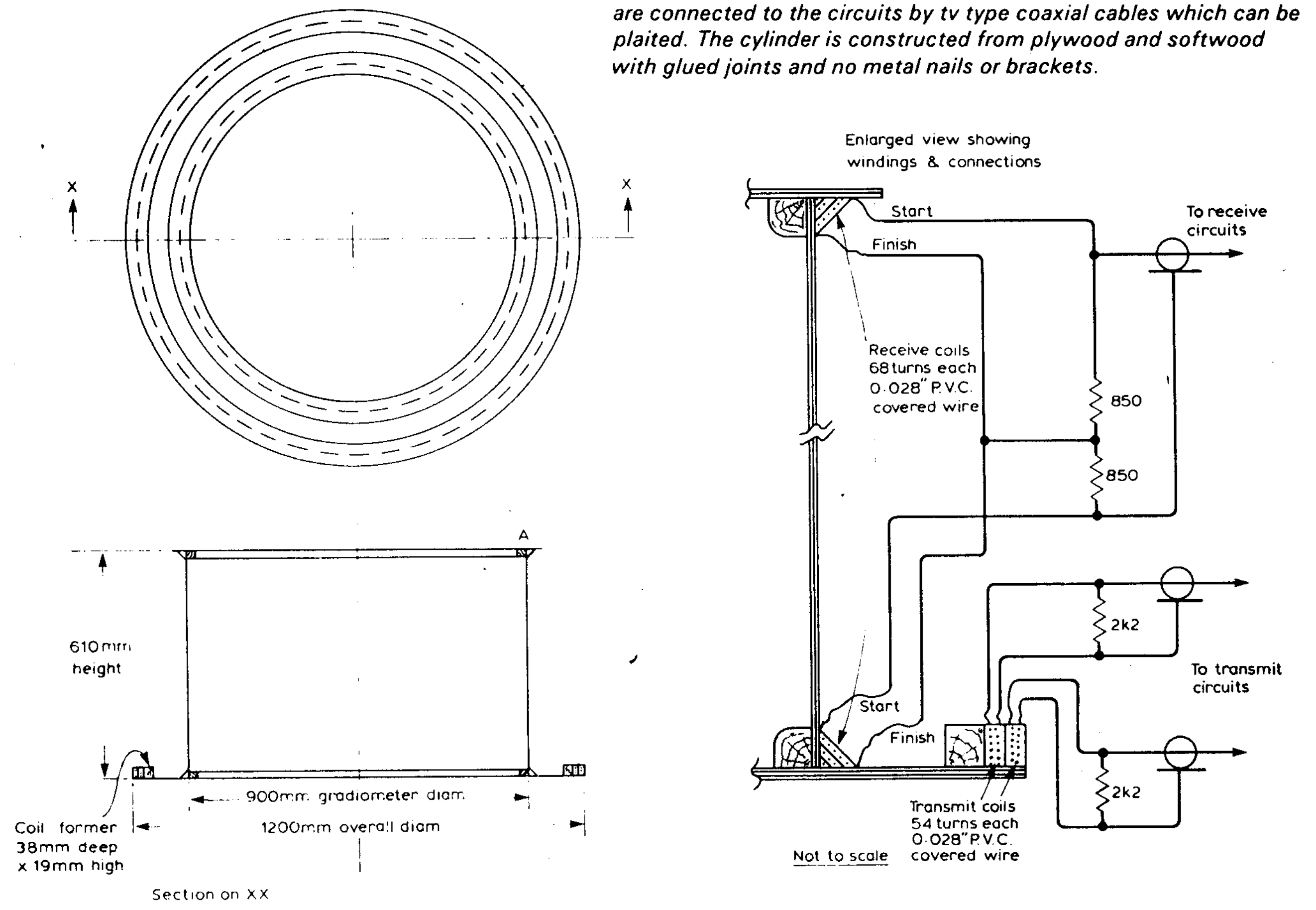


Fig. 5 Metal detector transmit and receive coil assembly. The coils are connected to the circuits by tv type coaxial cables which can be plaited. The cylinder is constructed from plywood and softwood with glued joints and no metal nails or brackets.

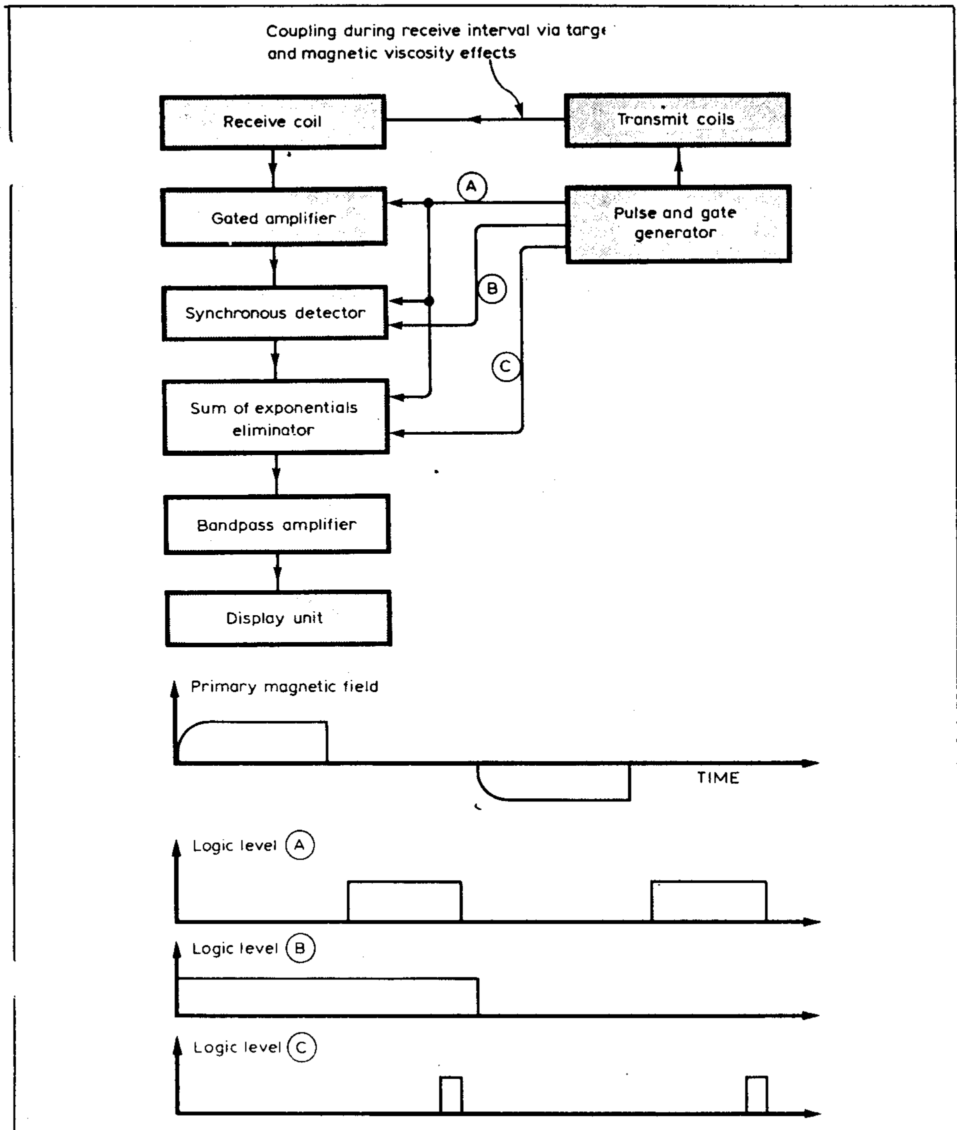


Fig. 6. Circuit block diagram. ▲

introducing a delay Δt between switch off of the transmitter current and observation of the returned signal. In practice delays from 40μs to 300μs are suitable.

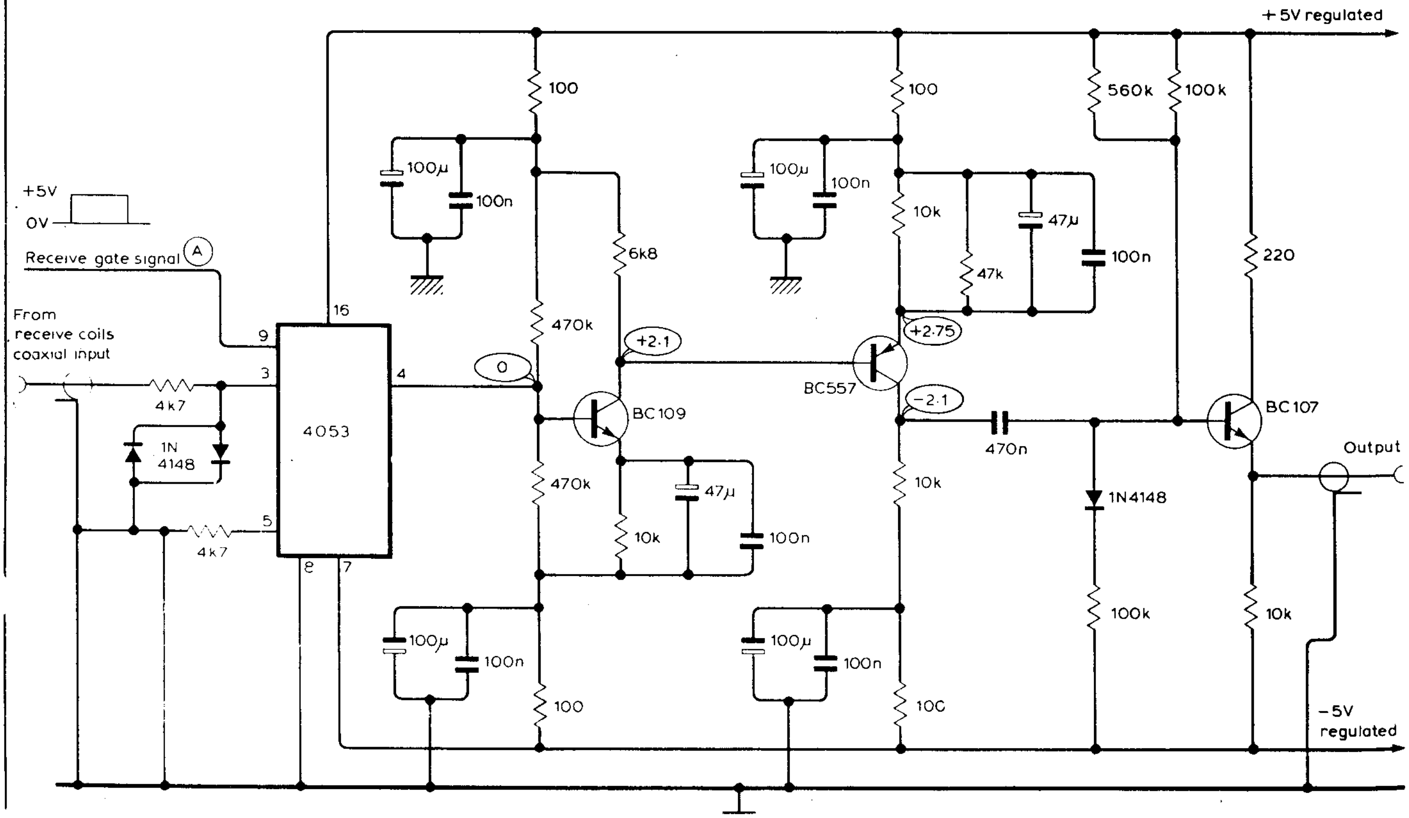
Magnetic viscosity effects

The magnetic properties of soils and rocks are mainly attributable to magnetite and maghaemite. These minerals exhibit a magnetic viscosity effect because their magnetization does not instantaneously follow an applied magnetic field. Magnetic viscosity is qualitatively similar to the effects of a conductor on a metal detector. The direction of temporary magnetization is the same as the primary magnetic field and the magnetic flux in the conductor being detected. Although there is no comprehensive theory of magnetic viscosity, Tropin[3] has critically reviewed Neel's theory which is described by Stacey and Banerjee[4]. Useful data for metal detector design has been provided by Colani and Aitken[5].

When designing a pulse induction metal detector it is necessary to know the response of soil or rock to a decreasing step in magnetic field. A general equation is

$$M \propto K \Delta H g(t) \qquad (12)$$

Fig. 7 Gated amplifier. Note that only one section of the 4053 is used, all unused inputs should be connected to ground. All voltages are d.c., measured with a high impedance meter. All capacitors are ceramic or aluminium electrolytic types.



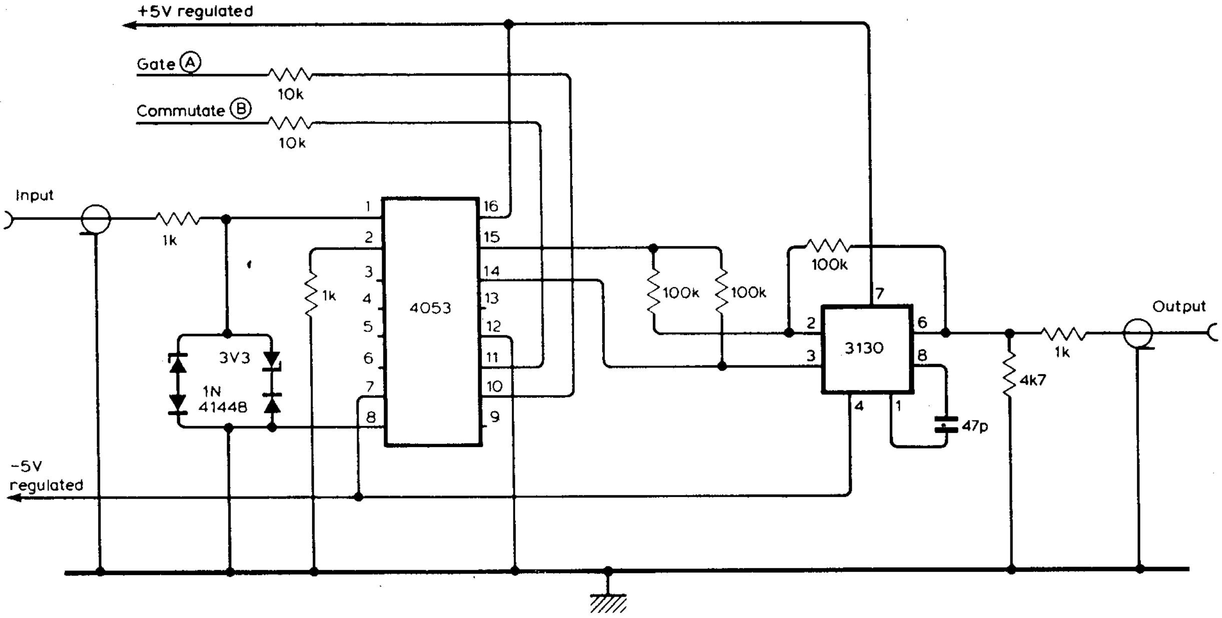


Fig. 8 Synchronous detector. The regulated power supply is shared with the gated amplifier. The 47pF compensation capacitor is soldered directly to the 3130 leads.

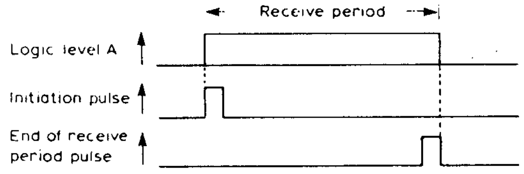
where $\bar{K}$ is the magnetic susceptibility and M is the magnetic moment per unit volume of material resulting from a change ΔH in the magnetic field at time t after this change. Equation (12) is linear in that g(t), which describes the decay of the magnetization, is independent of the primary magnetic field. At $t=0$, g(t) should be finite and as $t \rightarrow \infty$ g(t) should go to zero. Furthermore, g(t) from practical experiences should be a decreasing function of t. Fig. 3 shows the response of a soil or rock to a decreasing step in magnetic field. A review of available literature and some experimental work shows that g(t) can be expressed as a sum of two exponentials. An electronic system was constructed to simulate the sum of exponentials and compare the result with the response of soil or rock. A satisfactory model for the derivative of g(t) is

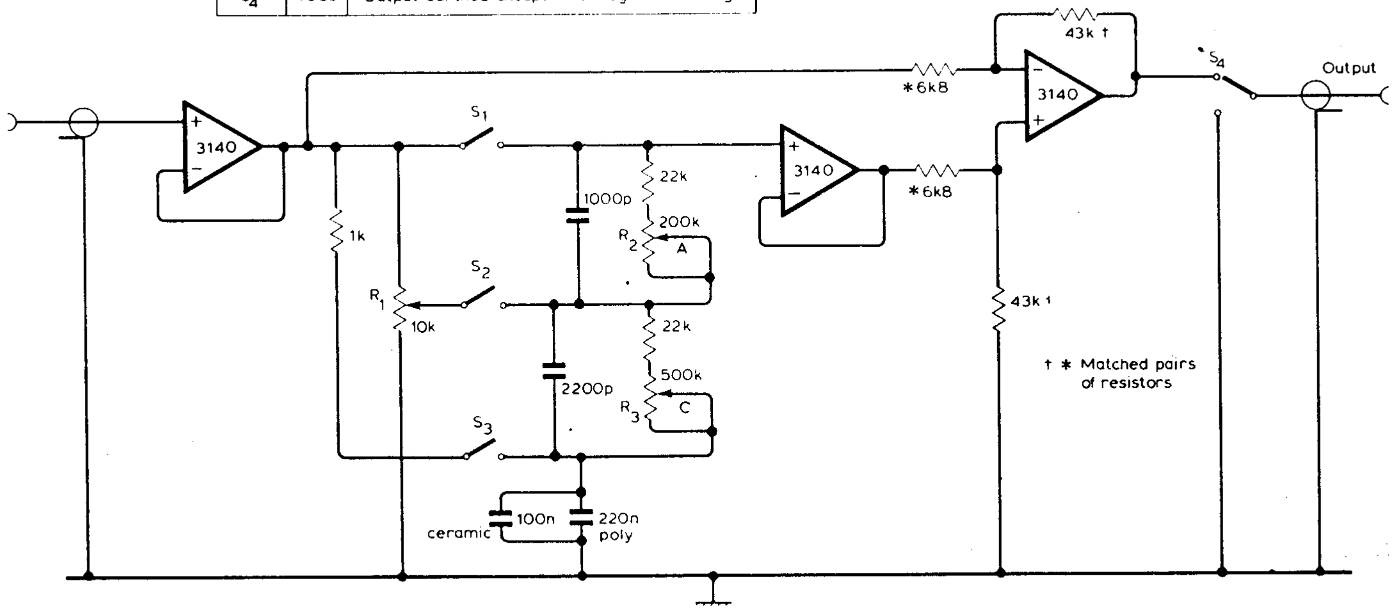
$$g^1(t) = (1-P)e^{-t/T_1} + Pe^{-t/T_2} \quad (13)$$

where T_1 is 75μs, T_2 is 550 to 800μs and P is in the range 0.08 to 0.30. These observations apply to lateritic soils in the goldfield region of Western Australia. The function $g^1(t)$ does not depend on the physical dimensions of the material being magnetized and the form of the decay due to a conductive target is generally a simple exponential decay as in equation (7). I therefore decided to construct a ground effect elimination system for a pulse induction metal detector by determining the difference

Fig. 9 Sum of exponentials eliminator. Resistor R_1 controls the mixture of exponentials, R_2 controls the decay constant T_1, and R_3 controls the decay constant T_2. Production of the initiation pulse from logic level A is shown in Fig. 10.

Switch	Type	Control
S_1	4016	Both closed only when initiation pulse is present
S_2	4016	
S_3	4016	Closed during end of receive period pulse
S_4	4053	Output earthed except when logic level is high





between the response of the ground and the observed response, assumed to be due to magnetic viscosity.

Coil design

Design objectives for the coil system are to maximise the primary magnetic field at the target and the voltage induced in the receiver coil by eddy currents in the target. The noise level due to variations in the earth's magnetic field and movement of the gradiometer over the ground is about 1µV with a coil of 25 turns, an area of 1 m^2 and with a similar coaxial coil 1 m away. This limitation was determined for a receive system with a centre frequency of 200 Hz and a bandwith of 10 Hz. The major noise contribution is from normal variations in the earth's magnetic field and does not account for man-made electrical interference.

The time constant of a critically damped gradiometer constructed with the above limitation is generally under 10µs for a coil diameter above 1 m.

Transmitter coil design is controlled by the decay resistance required to prevent an excessive voltage being applied to the transistor switch, see Fig. 4. Neglecting coil capacitance, the decay of current I through a coil of self inductance L_t and decay resistance R_t is

$$I = I_{to} e^{-t/Tt} \qquad (14)$$

where T_t is the decay constant R_t/L_t and I_{to} is the initial current through the transmit coil. If M_{tr} is the mutual inductance between transmit and receive coils and V_p is the peak voltage permitted at the switch, the voltage decay at the receive coil due to the current decay through the transmit coil is, for $I_r \ll I_t$,

$$V_r = V_p \frac{M_{tr}}{L_t} e^{-t/Tt} \qquad (15)$$

If V_e is the maximum permitted voltage at the receive coil at time Δt

$$\Delta t = T_t \log_e \left(\frac{V_p M_{tr}}{V_e L_t} \right) \qquad (16)$$

With $V_p = 750\text{V}$, $V_r = 1\mu\text{V}$ and $M_{rt}/L_t = 0.1$, equation (16) gives $\Delta t/T_t = 18.1$.

Equation (16) shows that the minimum value of Δt is determined principally by T_t. In practice T_t cannot be much greater than 5% of Δt, depending on the ability of the circuit to reject a background decaying voltage during the receive period.

A circular metal detector array with coaxial receive and transmit coils is shown in Fig. 5. The receive coils are arranged in a gradiometer configuration and the bottom winding is coplanar with the larger transmit coils. Increasing the size of the transmit coils reduces the magnetic viscosity effects due to a relatively intense primary field close to them.

In addition to this array, various circular types have been constructed with diameters from 0.05 to 2 m, and rectangular versions up to 2 m long for searching large areas. For the larger arrays it is desirable to keep coil capacitance as low as possible by careful winding design. As previously noted, rigid system geometry is not essential for a pulse induction system and the simple wooden structure described is sufficient.

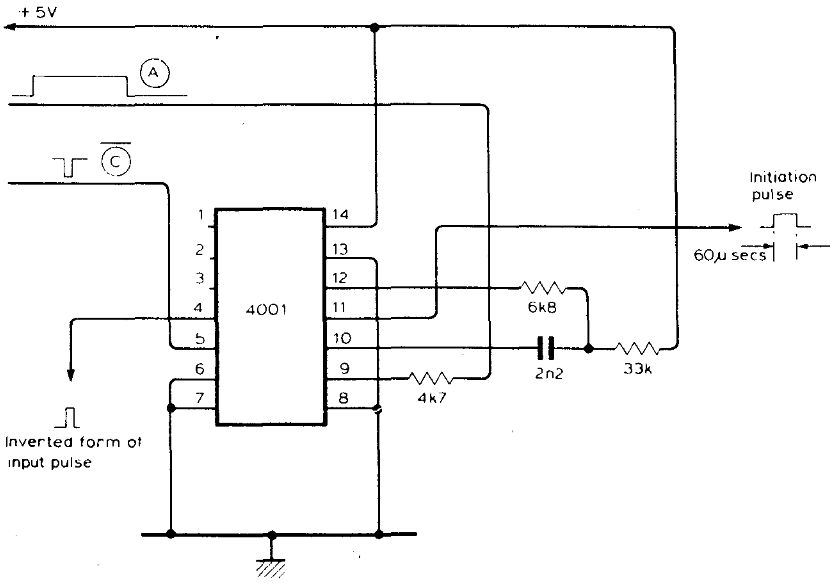
Circuit design

A block diagram of the metal detector circuit is shown in Fig. 6. An alternating primary magnetic field is used to avoid magnetic polarization of the ground and to improve the overall signal-to-noise ratio. The gated wideband amplifier in Fig. 7 consists of a high voltage protection network, a c.m.o.s. analogue switch and a transistor amplifier designed for fast recovery from saturation. The 4053 grounds the amplifier input except during the receive period when the receive coils are connected. The passband of the amplifier is 20 Hz to 100 kHz and the gain is approximately 4000. It is not practical to use a higher gain due to instability and amplifier saturation caused by the decay of current in the transmit coils.

The synchronous detector in Fig. 8 recognises a pulsed alternating signal with a unity-gain sign switched amplifier. The op-amp provides an output of +1 or −1 and the 4053 grounds the input when a useful signal cannot be received. The rise-time of the detector for a square wave is about 25 µs.

A sum of exponentials eliminator is shown in Fig. 9. This circuit takes samples of 60 µs duration at the beginning and end of the receive period and simulates the magnetic viscosity effect of the ground by inserting a function as shown in equation (13). The simulated ground effect is subtracted from the input signal to give an output when the response does not match that caused by the ground. The parameters T_1, T_2 and P can be changed to suit the ground conditions. RC combinations are used for the simulation and a 0.32 µF capacitor stores the background level to which the sum of exponentials decays. With the components shown the range for T_1 is 20 to 240 µs (typically 80 µs), for T_2 50 to 900 µs (typically 800 µs) and P is from 0 to 1.

Fig. 10 Interface, buffer and initiation pulse generator. A 4001 inverts the end of the receive period pulse and derives a 60 µs initiation pulse from the receive period signal.



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