Principles of Metal Detection

ETI looks at the history, techniques and uses of all kinds of metal detecting, from treasure-hunting to bomb disposal.

by Richard Turner

METAL DETECTION is a subject seldom mentioned in electronics journals, but recently it has attracted much attention in the daily press. Detectorists have been featured on many a front page with their finds of explosives or buried treasure, and perhaps even more while assisting the police in searches for weapons in some very controversial murder cases. However, metal detection has been around for about ten decades now and has been used for a very wide range of applications, and thus should be of interest to electronics enthusiasts.

Histories

While for hundreds of years treasure seekers and prospectors have used devices such as divining rods, magnetic needles and a variety of "doodlebugs" to aid their searches, it was not until 1879 that the first practical, scientifically proven instrument was built. The credit for this dicovery goes to Professor D.E. Hughes, who demonstrated his 'Induction Balance' to the Royal Society in that year.

The Induction Balance attracted a great deal of interest among the scientists of the day, including the Chief Chemist of the Royal Mint who acquired one of the first units for the assaying of coins. Alexander Graham Bell applied the Induction Balance to the location of an assissin's bullet in the body of American President James Garfield.

This 'electric' metal detection had a good scientific start and it is worth examining in closer detail some of the many uses of the technology.

In Hughes' Induction Balance, a Leyden Jar supplied current to a microphone which was placed in contact with a ticking clock. Alternating current was achieved by a manually activated resonating spring contact assembly feeding two induction coils wound in opposition to each other. The pick up consisted of another pair of identical coils wired as a circuit with a further three coils and a telephone. This arrangement was adjusted for complete silence in the telephone. To 'detect' or 'analyse' metal, the sample was placed on the primary coils, thus disturbing the mutual induction so that sound was heard in the telephone. Then the indicating coil in the secondary circuit was moved along a scale marked in degrees until silence was obtained again. Different samples could be identified against a previously prepared chart. This instrument was sensitive to such a degree that coins of the same denomination, but with varying amounts of wear, could be distinguished from each other.

Another detection principle developed in Victorian days worked on 'Secondary Induction'. This involved a complex set-up but gave a considerable detection range. And indeed, when demonstrated at a Welsh metal mine at the turn of the century, it was found that metal ores could be detected up to three hundred yards away.

Briefly, the set-up was as follows: a battery supplied the primary current to a motorized contact breaker which 'chopped' it into a high frequency and fed the primary winding of a transformer, where the voltage was stepped up. The secondary output was fed to a pair of probes placed in the earth. A similar pair of probes placed some distance away fed another transformer to which there was connected a galvanometer. If there was no metal in between probles, the input signal would 'scatter' in all directions and the galvanometer would remain at zero. The presence of ores or large metal objects would attract the voltage fed into the ground, producing an indication on the meter.

Electronic Principles

With the advent of electronics, the transmit-receive technique was quite accidentally developed. During World War One, the military developed sound ranging and direction finding equipment. It was soon found that large masses of metal such as bridges, railways and ships at sea interfered with the equipment and much re-design was necessary for proper operation. However, the 'interference' turned out to be a benefit as this led to the development of metal detectors for sensing enemy submarines and tanks at a considerable distance.

In the post World War One years, the transmit-receive technique was used for electrical prospecting and forms the basis of most metal detectors today. The heterodyne principle found much favour in the late 1930s and was used extensively until about five years ago. A more recent innovation in metal detection technology operates on the DECCO principle which was developed at Oxford Archaeological Research Laboratory in 1966. *Decay of Eddy Currents in Conducting Objects* is now better known as pulse induction. Few people are aware of what an important function metal detectors perform for their wellbeing and comfort. Most and possibly all food and pharmaceutical products are passed through metal detectors to ensure there are no nuts, bolts, swarf, pins or other alien items in them. Medicines like pills and powders receive the same treatment. Shoes are tested for unwanted insole tacks and even such products as textiles, carpets and linoleum are passed through a metal detector before dispatch to the customer.

In quarrying and mining industries the burden is checked for tramp metal such as drill rods, dipper teeth, and pick and shovel ends to prevent damage to cutters and diamond tipped grinders. Most of the world's airports are equipped with 'walk through' metal detectors to combat the carrying of illegal weapons. Accurate location of pipes has to be known when mechanized road or trench digging takes place. Lumber jacks and tree surgeons screen trees to detect bracing tie bars, bolts or nails which may be covered by growth and thus prevent a danger to power operated saws. Reclaiming timber is very much a practice with DIY enthusiasts, but why risk damage to your electric plane or sander by nails etc, when a quick scan will save the expense of new plane blades or sanding strips?

Medical Applications

As already mentioned, Bell used the Induction Balance to detect a bullet in a human body, and ever since that time medical metal detection has flourished. In 1885 the Royal Army Medical Corps developed quite a different metal detector for locating bullets and shrapnel in wounded soldiers. During World War Two electronic metal detectors were developed in Britain (Barnato Joel Laboratories), Germany (Siemens Electric) and the USA (Waugh Laboratories). The European detectors used the heterodyne principle at VHF, while the American unit was an electronic version of Induction Balance.

Currently the world's most advanced medical and veterinary detectors are of British manufacture, the Rope-Hall locator for Opthalmic and Medical applications (Keeler Instruments) and Tektamet Pl for veterinary use (Goring Kerr PLC). These high technology and patent protected detectors not only distinguish ferrous from non-ferrous metals but also indicate which metal is predominant. Thus the surgeon or vet has an instant indication as to what technique to use for extraction. If the metal is non-ferrous, a conventional cut and sew method would be employed, but a metal which has ferrous content can be removed by an electromagnetic extraction technique, eliminating surgery.

Treasure Seeking

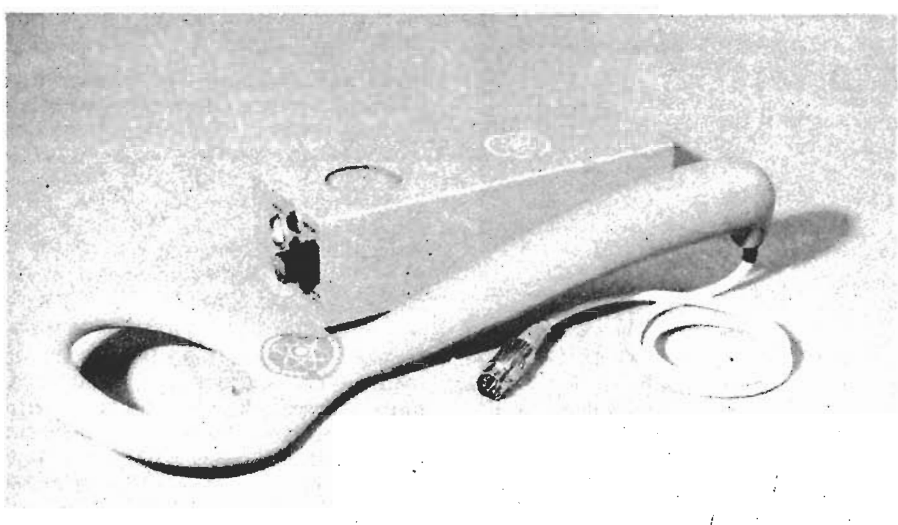
With the Royal Mint using the Induction Balance for the assaying of coins, it became apparent that this instrument could be adapted for the location of precious metals. Soon 'Buried Treasure Finders' were very much the fad of Victorian society, and were seen wandering about the countryside with very strange looking devices. However treasure hunting did not reach its peak until the early Twenties, when an Englishman by the name of Williams emigrated to Panama where he got a concession from the government to seek out the treasure concealed before the sacking of Panama City by the notorious pirate Captain Morgan.

Devising a transmit-receive metal detector capable of locating metals up to forty feet beneath the ground, he soon located cellars and secret tunnels packed with precious metals. Williams became very rich and his fame spread far and wide. Being a generous man he gave the plans for his metal detector to anybody who asked for it, and some of those ungrateful individuals even filed patents for it as their own invention. Thus with metal detectors being produced on a large scale, the rich with time on their hands once again took up the seeking of buried treasures. Most of them headed for the Cocos Islands where legend said that much treasure had been concealed by pirates. Franklin D. Roosevelt, a prominent lawyer, was one of the first to land, and even after he had become President of the USA he returned for another try. Malcolm Campbell, Admiral Nicholson and Commander Worlsey also led expeditions to the Cocos Islands.

Detectorists Today

However, pirate and legendary treasures are very much of a myth and today's detectorists take a much more practical view, seeking lost coins, jewellery and the like which has accumulated in the ground over the last two thousand years. Many previously unknown coins and artifacts have enriched our museums after being found in that way. Occasionally large hordes of coins are found.

Even wrecked ships can spread danger on the coasts, and an example of



The portable, belt-carried MD 199 can be used with a variety of probes. The one shown is a hand probe.

this was the wreck of *Aeolian Sky* which discharged its cargo of deadly cyanide canisters. In a situation like this a prompt search and recovery operation is required with metal detectors, as shifting sands and seaweed were quickly concealing the canisters. In this particular instance, the Detector Information Group (DIG) organized a search to assist Coastguards and Police, whose resources were stretched to the limit. This operation proved such a success that an annual beach clearance now takes place in May along the South Coast of England.

In the second half of this article, we shall take a closer look at the technical aspects of various detection techniques and brief specifications of commercial equipment. The block diagrams are in simplified form and show only the basic requirements for such detectors.

Heterodyne (BFO) Principle

Of all the possible ways of detecting metal, the heterodyne principle is perhaps the best known. After all, most radios use BFO (Beat Frequency Oscillator), so the system is easily understood even by a layman. The technique is simple, economical and produces very satisfactory results. The detector can be constructed from readily available radio parts; if a search coil of small but intense field is required (for instance, for medical applications) a ready made ferrite rod aerial can be used!

For larger areas and deeper penetration, the search coil is usually wound in multilayers on a circular former although printed circuit coils are also known. On a detector with wide range tuning, it is possible to detect metal against a metallic background, for instance, copper pipe embedded in reinforced concrete.

Off Resonance Discrimination (ORD)

In this technique, the search coil is driven by a frequency which typically differs by about 3 dB from the natural resonant frequency of the tuned circuit. This arrangement automatically gives a very selective detection. If for instance a discriminating detector is required for non-ferrous metals, the signal generator is driven at a higher frequency, but for ferrous metals at a frequency which is below the natural resonant frequency of the search coil. Thus in "treasure hunting" applications, excellent rejection of unwanted objects (nails, bottlecaps etc.) is achieved while retaining good sensitivty to desirable finds of coins, jewellery and the like. The main drawback of the system is thermal instability, for instance, if the detector is kept in the trunk of a car during hot weather, the search coil alters its natural resonance, and the separation between the drive and natural frequency of the tuned circuit drifts so far apart that detection becomes difficult, if not impossible.

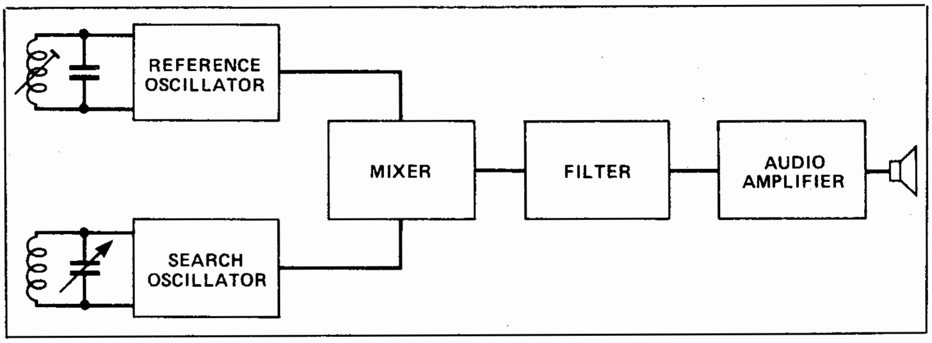


Fig. 1. A block diagram for a Heterodyne Principle (BFO) detector, the simplest type for a home constructor to design.

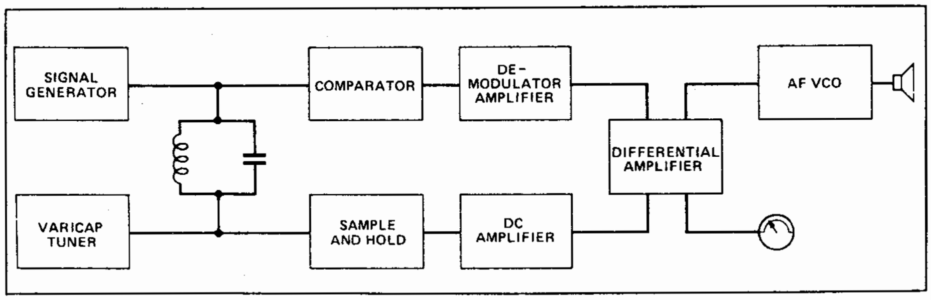


Fig. 2. The Off Resonance Descrimination System. Very selective, this method is favoured by "treasure hunters".

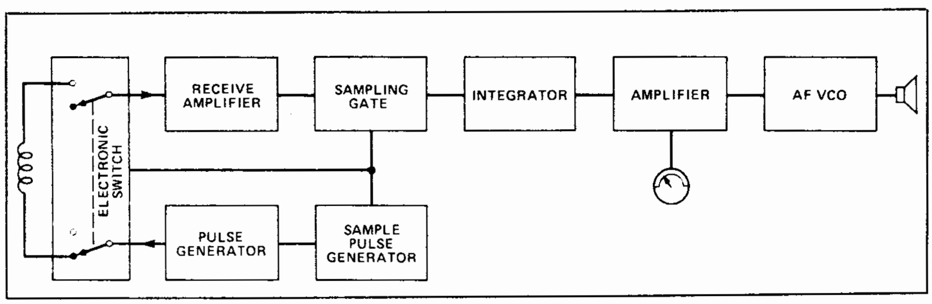


Fig. 3. The block diagram of a pulse induction system. This method uses the ability of metal objects to absorb and reflect electromagnetic radiation as eddy currents which can be detected.

Pulse Induction System (P.I.)

This system differs from all the other methods as no oscillators or tuned circuits are required. Detection is achieved by the phenomenon of decaying currents in metal objects (DECCO). Thus a high amplitude short duration pulse is injected into the search coil, which emits electromagnetic radiation within its range. Soft objects such as soil or even aluminum foil allow the energy to penetrate and disperse while solid metals, especially magnetic metals, absorb and reflect this energy in the form of eddy currents which readily produce EMF in the search coil, generating a signal in the receive amplifier.

The main drawback of this principle is that Earth's magnetic field renders the detector oversensitive to ferro-magnetic metals. Although discriminating-type pulse detectors are now available, these do not provide such a good selection of desirable objects as continuous wave discriminators.

Induction Balance Method (IB)

This old and complicated, but most sensitive, detection principle requires several (or multitapped) search coils, and so is not exploited very much these days. However its sensitivity to precious metals is unsurpassed. As explained earlier in this feature, with a suitable arrangement even worn coins can be distinguished from new ones. This is achieved by phase-anti-phase magnetic fields which can be generated by

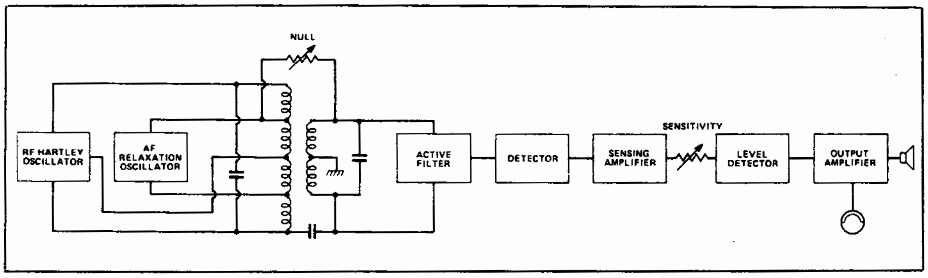


Fig. 4. Induction Balance, the oldest and most sensitive method of detection, is now not much used because of its complexity.

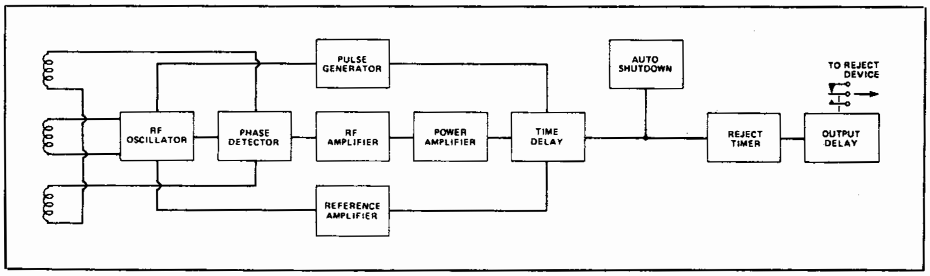


Fig. 5. The Balanced Coil method, a simplified version of Induction Balance, favoured for "production line" detectors because it is very sensitive at speed.

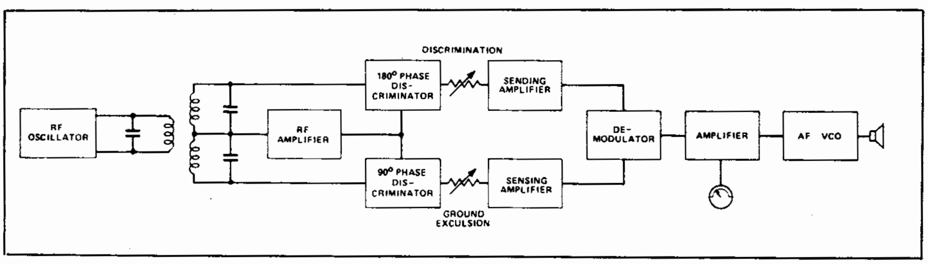


Fig. 6. A block diagram for the Transmit-Receive Radio Technique, popular for its simplicity and ability to discriminate between worthless and valuable metals.

complex coil arrangements, but energized by simple electronic circuitry with a very modest current consumption.

Balanced Coil Application (BC)

This is a simplified adaptation of the Induction Balance very much favoured by manufacturers of industrial detectors. And indeed the block diagram shows in simplified form an arrangement for a "feedthrough" conveyer type instrument. The search coils are usually of rectangular form wound in single layers, offering very high sensitivity. Typically a one millimetre metal sphere can be detected at a velocity of 40ft per minute through a 12 x 4in aperture.

The oscillator also initiates the pulse generator which is connected in a feedback circuit, thus offering a self checking function and automatically stopping the detector should a fault occur. If unwanted metal is detected, the reject timer allows the product to leave the search head and reach the rejection point where it is removed automatically from the conveyor belt.

Transmit-Receive Radio Technique (T-R)

This technique operates on true radio principles, and it can be seen why metal detectors come under the scope of Wireless Telegraphy Act. In early equipment (as already explained) the transmitter was quite a separate item from the receiver which could be placed a considerable distance away, offering very deep penetration. However in recent times the trend has been to combine both units into one case for compactness and portability. A simple sine wave oscillator drives a tuned circuit of a suitable frequency. A tuned search coil (or coils) feeds an RF amplifier to boost the incoming signal for the purpose of phase discrimination, eliminating unwanted signals from the ground (minerals etc.) and offering discrimination between unwanted objects and precious metals. Straightforward output ciruitry is employed. The simplicity of this technique makes it a very attractive proposition to manufacturers of 'hobby' type detectors which usually operate in the VLF spectrum.

Equipment Survey

To conclude this article, a survey is included of some commercially manufactured equipment manufactured in the UK. Each company has been limited to a maximum of five entries.

Some explanatory notes are worthy of inclusion as some readers may wonder, for instance, what is the difference between a hand and portable detector? A hand detector is a completely self contained one-piece unit whose total length does not usually exceed eighteen inches. However, headphones or earpieces may be supplied as optional extras. Portable units will have a separate search coil (or coils) or probes and electronics case, and can be in a shoulder-slung case or a hip mount design. Usually a range of optional extras are available, as in the case of medical detectors where even a reset foot switch is provided. A bench unit would be usually powered by mains and have a range of search probes for various applications.

Walk Through, as its name suggests, is a weapons type detector and at least one company manufactures such a unit in a 'portable' version which can be folded up and transported in the trunk of a car! Hobby detectors are usually of one-piece construction with the search coil for ground searching mounted on an adjustable shaft which may be mounted on an electronics case. Some models are available in hip mount versions. This description also applies to underwater detectors. Conveyer type detectors are limited to industrial applications, and such detectors are available with search coils from about 1 inch diameter (for pharmaceutical applications) to 50 feet for textile industries.

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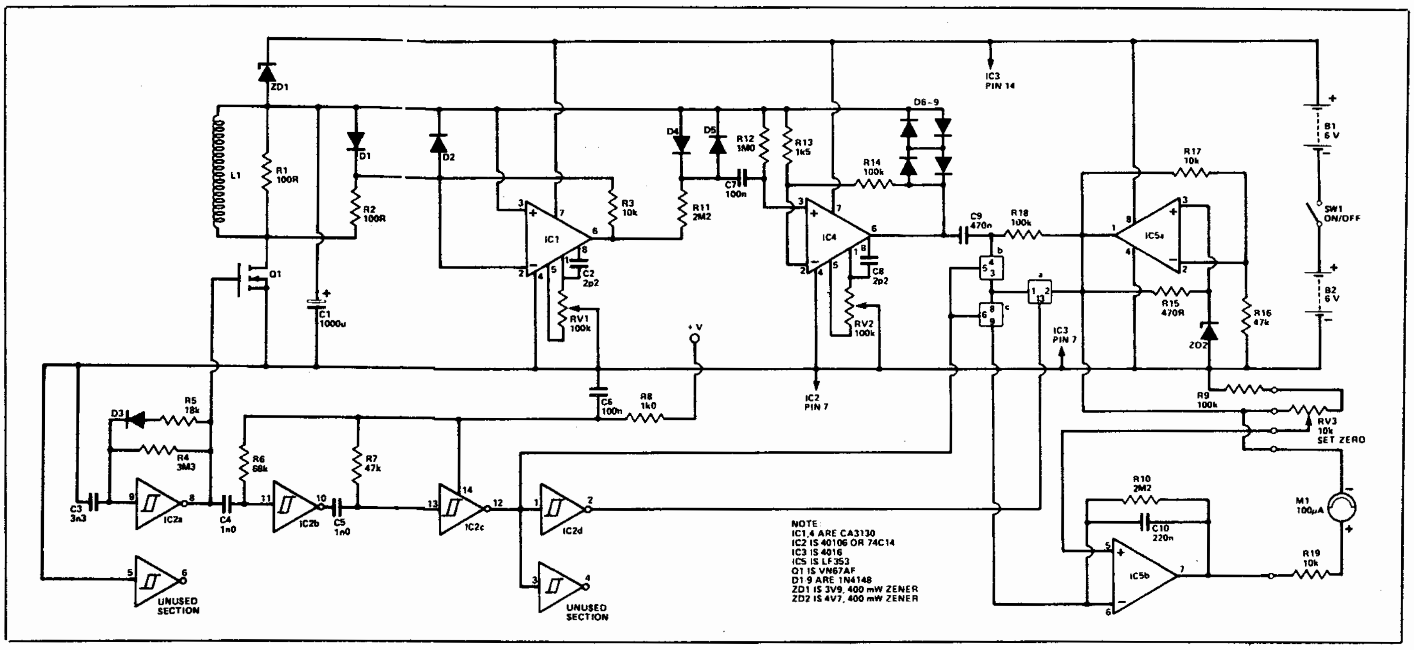
A Pulse Induction Metal Detector



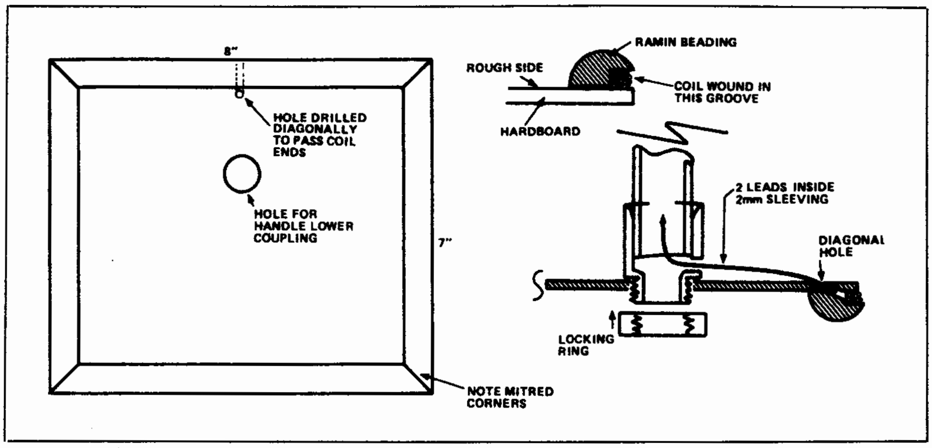
The schematic of a pulse induction type of metal detector.

HOW IT WORKS

Oscillator IC2a generates a positive pulse which turns on Q1, with the result that a current builds up in search coil L1. At the end of this pulse, Q1 is turned off and the voltage waveform shown below appears across the coil, and falls to zero in time X. If metal is near the coil, the voltage falls more slowly to zero (i.e., time Y). Operational amplifiers IC1 and IC4 amplify the coil voltage 10,000 times. Monostable multivibrators IC2b and c generate a second pulse, accurately timed after the first pulse, which is used to turn on an electronic switch (formed by IC3a,b and c) just as the coil voltage is reaching zero.

As metal approaches the coil, the voltage across it decays more slowly. Therefore, the pulses passed by the electronic switch get bigger.

Integrator IC5b amplifies and smooths the pulses from the electronic switch and drives meter ME1. The output voltage from the integrator thus increases as the coil approaches metal, and this is registered on the meter.

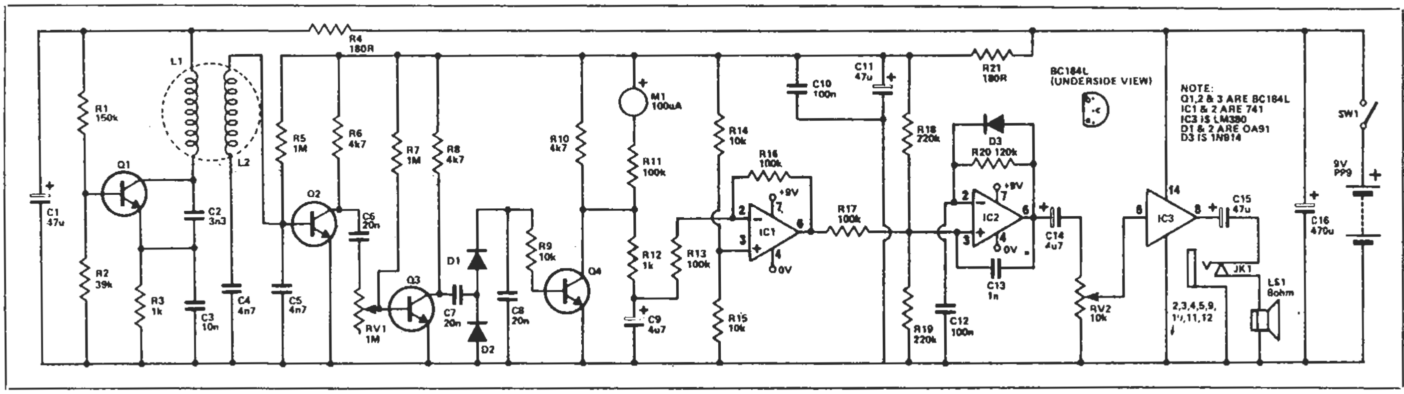


The underside of the search coil head and sections of the head showing coil wire leadout and routed up into the handle.

Winding The Coils

The housing is plywood or hardboard. 178 mm x 203 mm (7 x 8 inches) with grooved beading on the edges to hold the wire. Pass about 1 metre of 28 swg enamelled copper wire through the hole and then wind 22 turns of wire around the grooved beading. Pass another metre through the hole; the two ends of the wire should be long enough to easily reach the electronics.

An Induction Balance Metal Detector



The schematic of an Induction Balance type of metal detector.

HOW IT WORKS

The heart of the circuit is the search coil, L1 and L2. These two coils, which are essentially identical, are arranged in the same plane with a small overlap in such a way that there is practically no inducative coupling between the two. There is minimum pickup when the fields generated in L1 are cancelled in L2 when in free air. Any metal brought into the electro-magnetic field of L1 will distort the field, causing pickup in L2.

Q1 is a straightforward Colpitt's oscillator working at a nominal 130 kHz. This type of circuit is very stable and the use of polystyrene capacitors also help with stability. The supply to this stage is separately decoupled by R4 and C1.

The pickup coil L2 is tuned by means of C4 and C5 and amplified by Q2 which feeds to the level control RV1. This controls the "free air" state of the circuit and is set to the point where the later stages are just operating. The signal is further amplified by Q3 (here it is still an RF signal) and is detected by D1 and D2. When no metal is in the vicinity of the search coil and with RV1 correctly adjusted, a DC voltage of about 500 mV appears across C8. R9 increases the effective input impedance of Q4 as seen by the detector stage.

Q4 is just held off by the voltage available but as soon as any metal distorts the electromagnetic field, L2 produces a larger RF signal, a higher voltage across C8 and a consequent fall (from 8 V) in the voltage at the collector of Q4. This voltage is also monitored by the meter in parallel with the load resistor of Q4. The fall in voltage is dependent upon the proximity and/or size of the metal near the search coil.

It is necessary to ensure that the DC voltage fed to the next stage is clean and R12 and C9 act as a filter to remove any residual AC even if this is at low frequencies.

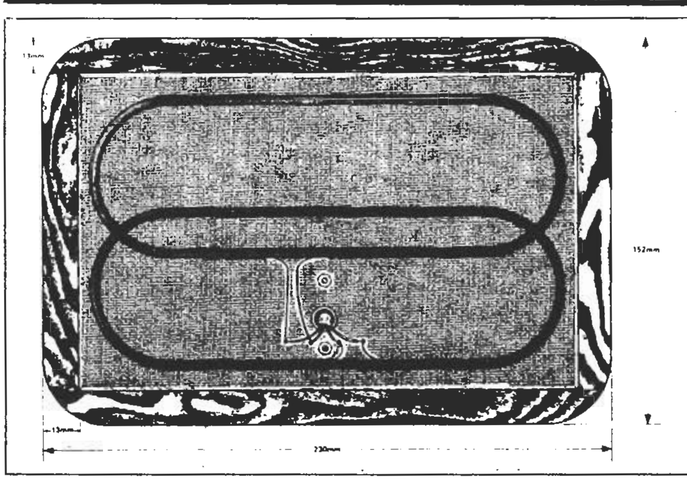
IC2 (the next but one stage) is a voltage controlled oscillator — but to operate this so that metal is indicated by a rising note, rather than a falling one, the voltage at the junction of C9 and R12 has to be inverted and this is achieved by IC1: in "no-metal conditions, there is about 2 V at the output of this op-amp which rises when metal is near. This stage quickly saturates to give about 7 V at pin 6. IC1 has unity gain.

IC2 is a voltage controlled oscillator. In "no-metal" conditions it gives about 70 Hz which rises to 500 Hz when metal is present, diode D3 gives a rapid recharge to C12 and affects the mark/space ratio of the output which results in lower battery consumption. R20 and C12 can be altered to give a different range of audio frequencies if desired.

The output is taken to a volume control and fed to the LM380 audio power amplifier which in turn feeds the speaker.

The levels of signal around Q2,3,4 are all dependent upon transistor gain, temperature and supply voltage, but this doesn't matter because the level control RV1 is adjusted until Q4 just begins to conduct.

Current drain for the complete circuit is in the order of 50 mA.



The search coil. This is L1 and L2 which are made from two coils originally wound on a 140 mm former and then squeezed into the shapes shown.

Winding The Coils

The search head is the key to the whole operation; be prepared to spend some time experimenting.

The housing of the coils is not important; a rectangular shape is used for ease of construction. The coils L1 and L2 should be sandwiched between two pieces of hardboard or plywood separated by two pieces of wood about 6 mm thick.

To wind the coils, you'll need a cylinder about 140 mm (5½ inches) in diameter. Using 32 swg enamelled copper wire, trap one end onto the former with tape and wind 40 turns as close together as possible. Remove the coil and wrap tape around it at intervals to keep it from spreading.

Two identical coils are required. They should be glued into the housing as shown in the drawing.

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