Cover Feature

TRANSISTORISED A.C. MILLIVOLTMETER Part 1

by H. Smith and D. L. Woolley, B.Sc.

This article is the first of a 2-part series which gives full constructional details of an easily-built a.c. millivoltmeter having a range from 10mV to 100V full-scale deflection, together with a flat response up to 200 kc/s on the volt ranges and up to 400 kc/s on the millivolt ranges. The meter is unaffected by external fields and has a very high input impedance

THE MILLIVOLTMETER DESCRIBED IN this and next month's issue has 9 ranges from 10 millivolts to 100 volts full-scale, and it can also be used to measure decibels, having an overall range from -46dB to 40dB, 1 volt representing 0dB. The frequency response of the millivoltmeter is flat between 20 c/s and 200 kc/s, and an extended high frequency response up to 400 kc/s is obtained on the millivolt ranges. The frequency responses for volt and millivolt ranges are shown in Fig. 1.

In order not to present an appreciable load to any circuit under test, the input impedance has been made as high as possible. Although the impedance varies slightly with frequency, it is not less than 680 kΩ on the 3 to 100 volt ranges. The 1 volt range, together with the millivolt ranges, uses a pre-amplifier having a high input impedance of the order of 1 MΩ.

Most of the millivoltmeter components are mounted on a printed circuit board, designed so that it may easily be reproduced; the remaining larger components are mounted, together with the printed circuit board, within a metal case built in units made from sheet aluminium and brass angle section. As the millivoltmeter is battery driven and as its components are fully screened by the metal case, there is no deflection on the meter due to mains hum on any range. Noise produced by the amplifier is very low and produces no deflection on any range.

A calibration control is provided on the front panel of the instrument so that all the ranges may be calibrated easily. This process is described fully in next month's issue.

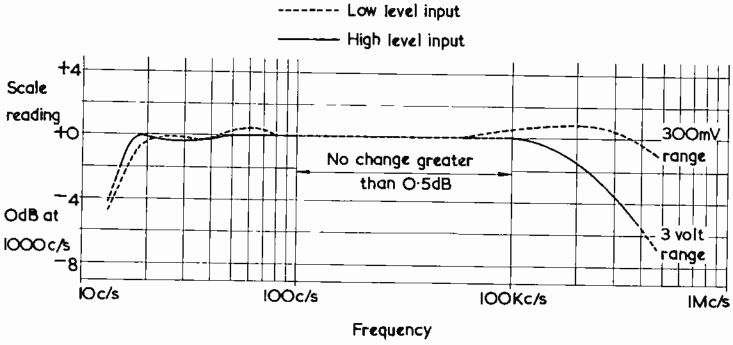

Fig. 1. The measured frequency response of the millivoltmeter

Circuit Description

The circuit of the millivoltmeter is shown in Fig. 2. To the right of the dotted line are the attenuator networks and the main amplifier. The alternating voltage (the signal) to be measured is fed into the base of TR$_3$ via isolating capacitor C$_2$ (to bar direct current from the millivoltmeter) and a potential divider formed by R$_{17}$, the base input impedance of TR$_3$ and the appropriate resistor, R$_8$ to R$_{11}$, switched in by S1.[1]

TR$_3$ amplifies the signal, which is then directly coupled to the base of TR$_4$. After further amplification the signal is fed via C$_6$ into a full wave bridge rectifier, formed by crystal diodes D$_1$ to D$_4$, which produces a direct current to operate the meter, M$_2$. Finally the signal is fed back to the emitter of TR$_3$ where, as will be described shortly, it controls the overall gain of the amplifier. TR$_3$, TR$_4$ and their associated components form a direct coupled amplifier which has good temperature stability, since each transistor has direct control over the base bias conditions of the other. (For example, if the collector-emitter leakage current of TR$_3$ increases as a result of a rise in temperature of this transistor, the collector current increases, the voltage drop across R$_{18}$ increases and the base bias voltage on TR$_4$

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[1] Ideally, R$_{19}$ is in parallel with R$_{17}$, assuming C$_7$ to have negligible impedance compared with R$_{19}$, and so forms part of the attenuator.

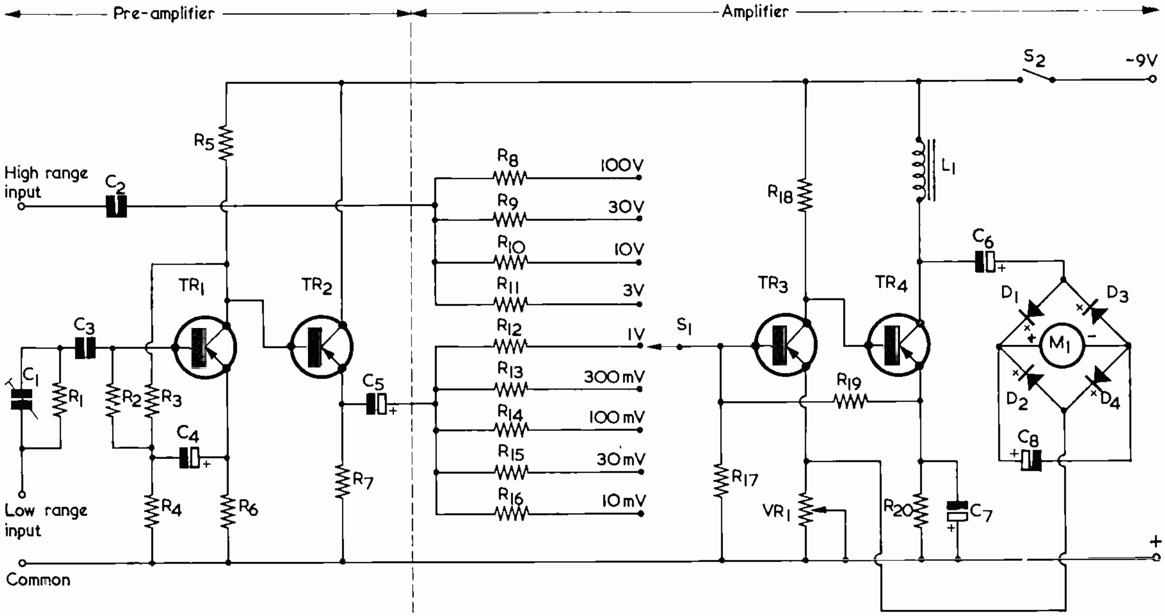


Fig. 2. The millivoltmeter circuit diagram. If desired, S_2 may be combined in a 3-way switch which enables the battery voltage to be checked, and this point is discussed in the second article in this series

General Note.

It should be noted that some of the components listed here are discussed at length in the second part of this article, and that the reader should not attempt to obtain them before reading this second part. The components concerned are the range resistors R_8 to R_{16}, R_{21}, the switches, the aluminium panels and the meter.

Resistors

(All fixed values ½ watt 5% high stability. See text)

R_1	1 MΩ	
R_2	47 kΩ	
R_3	47 kΩ	
R_4	10 kΩ	
R_5	22 kΩ	
R_6	2.2 kΩ	
R_7	2.7 kΩ	
R_8	22 MΩ	
R_9	6.8 MΩ	
R_{10}	2.2 MΩ	
R_{11}	680 kΩ	
R_{12}	220 kΩ	
R_{13}	68 kΩ	
R_{14}	20 kΩ	Range resistors
R_{15}	3.3 kΩ	
R_{16}	1 kΩ	
R_{17}	4.7 kΩ	
R_{18}	5.6 kΩ	
R_{19}	22 kΩ	
R_{20}	150 Ω	
R_{21}	Battery check meter resistor	
VR_1	50Ω potentiometer, wire-wound	

Components List

Capacitors

(see text)

C_1	50pF air-spaced trimmer
C_2	0.47μF 400V wkg.
C_3	0.47μF 400V wkg.
C_4	50μF electrolytic 15V wkg.
C_5	50μF electrolytic 15V wkg.
C_6	8μF electrolytic 15V wkg.
C_7	100μF electrolytic 15V wkg.
C_8	1,000μF electrolytic 15V wkg.

Inductor

L_1	Choke. 10 henry, 50mA. D.C. resistance less than 500 Ω.

Semiconductors

TR_1	OC44
TR_2	OC45
TR_3	OC42
TR_4	OC76
$D_{1,2,3,4}$	OA81

Switches

S_1	1-pole 11-way, wafer switch, ceramic insulation
S_2	s.p.s.t. switch
S_3	(alternative to S_2) 3-pole 3-way wafer switch

Meter

M_1	Moving coil meter. F.S.D. 500μA, d.c. resistance 100Ω

Battery

9-volt battery type PP9 (Ever Ready)

Miscellaneous

3 knobs
3 input terminals. Type L1001/1W (Belling-Lee) or similar
Printed circuit board and etching materials
Battery clips
Aluminium panels (Obtainable cut and bent to size from H. L. Smith & Co. Ltd.)

becomes more positive, or less negative. Such a change causes a decrease in the collector current of TR_4, hence a decrease in voltage drop across R_{20}. This decrease in voltage is passed by the potential divider R_{19} and R_{17} to the base of TR_3 which becomes more positive, thus reducing the collector of TR_3 and so counteracting the original current increase).

Unfortunately, the gain of each transistor will increase with temperature rise and, although the no-signal conditions of the amplifier will remain stabilised, the overall gain of the amplifier will vary with temperature. However, the signal fed back from the bridge network is out of phase with the incoming signal component at the emitter of TR_3 and so can be considered as

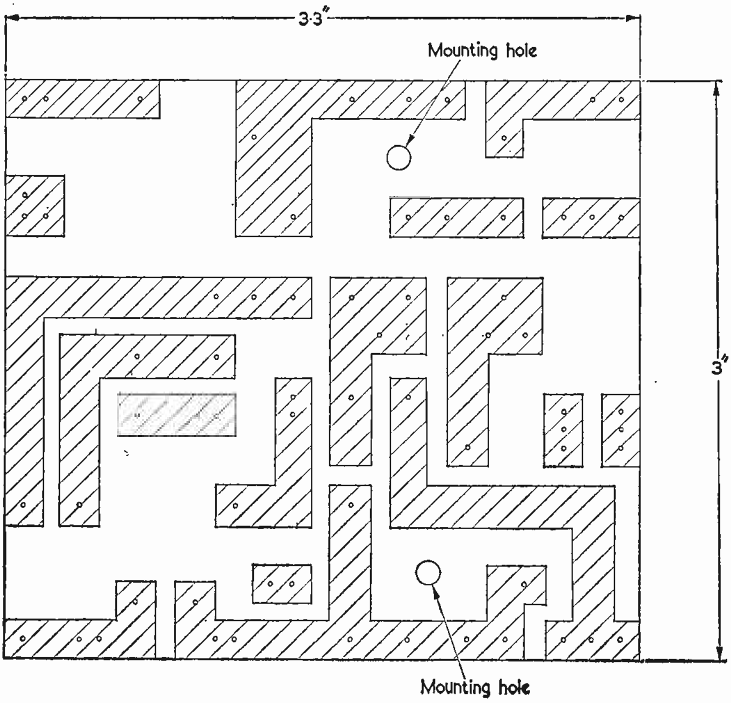


Fig. 3. The conductor side of the board. This is reproduced full size and may be traced. Copper sections are shown shaded

negative feedback. In fact, the feedback loop can reduce the amplifier gain by a factor of 10 times. Thus any change in gain of the amplifier with temperature or frequency change is automatically controlled, as is any non-linearity of the bridge circuit. By adjusting VR_1, (the calibration control) the amount of negative feedback can be varied and thus the overall gain of the millivoltmeter can be controlled.

Although a resistor could have been used instead of L_1 as the load for TR_4, the fact that this transistor consumes about 7mA makes the maximum value for such a resistor, to avoid cut-off in TR_4, about 1 kΩ. Such a value would have reduced the gain of the amplifier considerably. The impedance of the choke is high, even at low frequencies and thus the gain of the amplifier is high also.

The moving coil meter, M_1, has an f.s.d. of 0.5mA and an internal resistance of 100Ω. However, because of the feedback loop it is possible to use any convenient meter with an f.s.d. between 200 μA and 1mA, and any value of internal resistance between about 1 kΩ and 50Ω. The more sensitive the meter, the greater will be the amount of feedback required and the better will be the frequency response of the millivoltmeter. If a very sensitive meter is used, the range resistors R_8 to R_{16} will have to be increased in value, for the calibration control may then not have enough range.

Capacitor C_8 damps the meter movement considerably and enables voltages at very low frequency to be measured. Also, C_8 controls the sudden kick of the meter pointer caused by current surges on switching the millivoltmeter on and off.

To the left of the dotted line is the pre-amplifier. On the millivolt ranges, the signal is fed, via C_1, R_1 and isolating capacitor C_3 to the base of TR_1. C_1 is used to increase the high frequency response of the circuit, and it bypasses R_1 to an increasing extent at the high frequencies. TR_1 acts as a voltage amplifier, its base bias circuit, consisting of R_2, R_3 and R_4, increasing the input impedance at the base.

TR_2 and R_7 form an emitter follower circuit having a high input impedance (presenting a negligible load to TR_1) and a very low output impedance that is unaffected by the switching in of range resistors R_{12} to R_{16}. The overall gain of the pre-amplifier is near unity, its main purpose being to increase the input impedance on the millivolt ranges. Experiments have shown that temperature changes have very little effect on the pre-amplifier. In a series of tests, the gain was found to vary by approximately 1% for a temperature rise of 10°C.

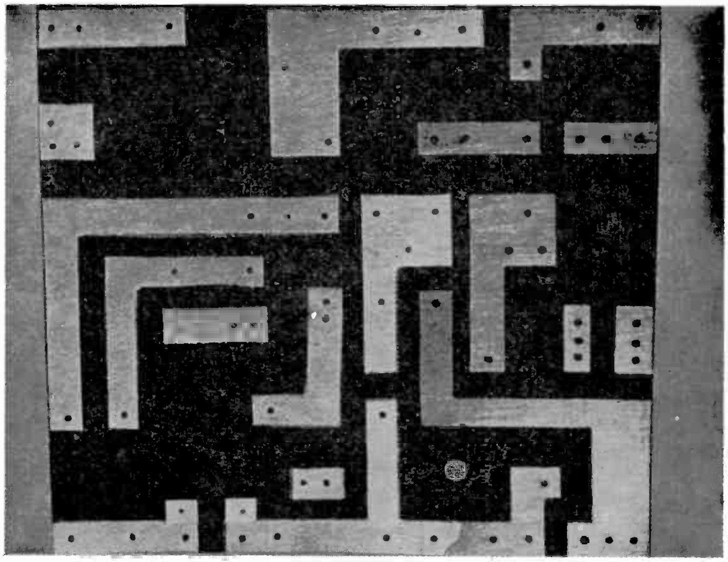
It will be noted that the conventional large value bypass capacitor which might normally be expected to be connected across the supply lines is not included in the present design. Such a capacitor is usually required because, as the battery ages and nears the end of its useful life, its internal resistance increases. The battery may then cause unwanted common coupling at audio frequencies between different parts of the circuit, giving rise to unstable amplification. To keep the impedance of the supply circuit as low as possible at all frequencies it is common practice to bypass the battery with a large electrolytic capacitor of say 100μF or more. The effect of such a capacitor was tried with the present design, using an old battery with a series resistor to accentuate any internal resistance effects. None were noticeable, and so a bypass capacitor was not employed.

If, nevertheless, it is desired to use a bypass capacitor, one of 100μF at 15 volts working should be wired across the positive and negative battery leads on the printed board.

Preparation of the Printed Board

The first stage in the preparation of the printed board is to cut a piece of copper laminated board to the correct size; i.e. 3 by 3.3ins. Probably the best tool to use for cutting the board is an Eclipse Junior hacksaw, as the saw teeth are fine and do not tend to chip the brittle laminate. All saw cuts should be made from the copper side of the board as there is then no tendancy for the saw teeth to break the bond between the insulating and copper laminates. An ordinary steel woodworking block-plane, set very fine and well sharpened, can be used to plane the sawn edges of the board in order to produce straight edges and right-angled corners, the board being held edge upwards in a woodworking vice.

The board should now be cleaned with fine steel wool and placed in Ferric Chloride etching solution for about 10 to 20 seconds, but no longer. After washing the board and drying it with a soft cloth, the copper surface will now be a dull, salmon-purple colour. This surface will



The copper side of the printed circuit board after etching

take pencil marks easily, whereas the original shiny surface is very difficult to mark. With the aid of a sharp HB pencil and a small ruler marked in tenths of an inch, the printed circuit design may now be copied from Fig. 3 (which is reproduced to scale) directly on to the board. Only the outlines of the copper strips to be left unetched need be drawn.

A resist has now to be applied to the copper surface in order to protect the actual circuit from the etching solution. Any oil-based or cellulose-based paint will act as a resist but Brushing Belco is recommended as it dries fairly rapidly and has been used by the authors very successfully on many occasions. The paint, in any chosen colour, should now be painted over all the copper areas that are to remain unetched, using a No. 2 or similar fine water colour brush. Care must be taken to apply a fairly thick, hole-free layer, avoiding the areas of copper to be etched.

If painting has been concluded satisfactorily it is possible to etch the board almost immediately, as the paint recommended need not dry fully before it resists the action of the etching solution. However, for those who find if difficult to paint a good straight edge, the best policy is to leave the paint to dry hard overnight and touch-up the design with a sharp pen-knife and ruler. The uneven edges and rounded corners may be cut straight and the surplus paint easily removed.

The etching solution has already been mentioned. It is prepared by dissolving Ferric Chloride crystals in water, a suitable ratio being:—

250gm. of Ferric Chloride to 500cc. of water; i.e. about 8oz. of Ferric Chloride to 1 pint of water.

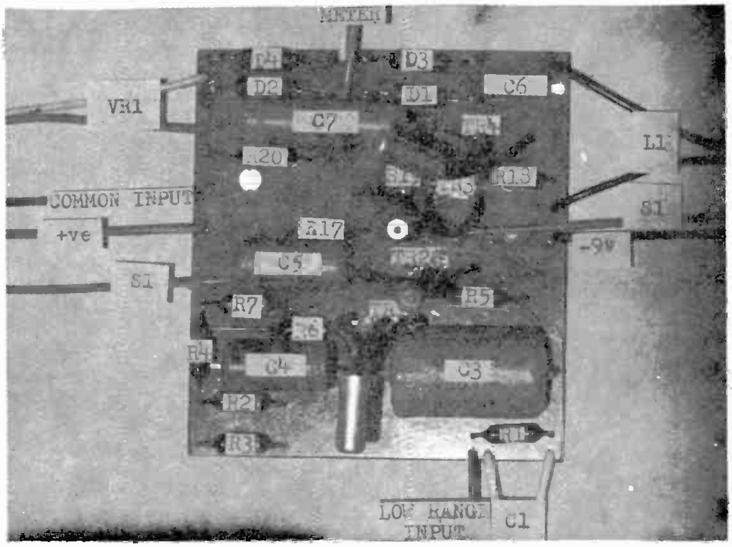
This ratio produces a strong solution which dissolves copper rapidly. Weaker solutions do the job equally well, but take a longer time. At normal room temperature the strong solution will take only 10 to 15 minutes to etch through the copper normally used on laminated boards. The solution may be used over and over again, but it takes a longer time to etch through the copper as it becomes more exhausted. If the board is actually floated on the surface of the Ferric Chloride solution, copper side downwards, the etching process is completed speedily. Care must be taken to avoid air bubbles, which adhere to the surface and prevent etching.

When all the unprotected copper has been dissolved, the board should be removed from the etching solution, washed in tap water and dried. Although the paint could now be removed, it is better to leave it in situ as a protection for the copper whilst the holes are drilled in the board. A No. 55 twist-drill or one of similar size is used to drill all but the mounting holes, drilling being carried out with a hand drill or mounted power drill. A piece of wood should be used to back-up the laminate to prevent chipping as the drill breaks through the board. All drilling should start from the copper side of the board. The two mounting holes in the board should be drilled with a No. 30 or ⅛in drill.

The paint should now be removed with acetone or cellulose thinners and the board cleaned carefully with fine steel wool.

Mounting Components on the Printed Board

As the millivoltmeter is a piece of test equipment, it is desirable that its components have good stability so that the overall characteristics of the instrument vary as little as possible with time. Therefore, every component used in the prototype instrument was bought



The components mounted in position on the board

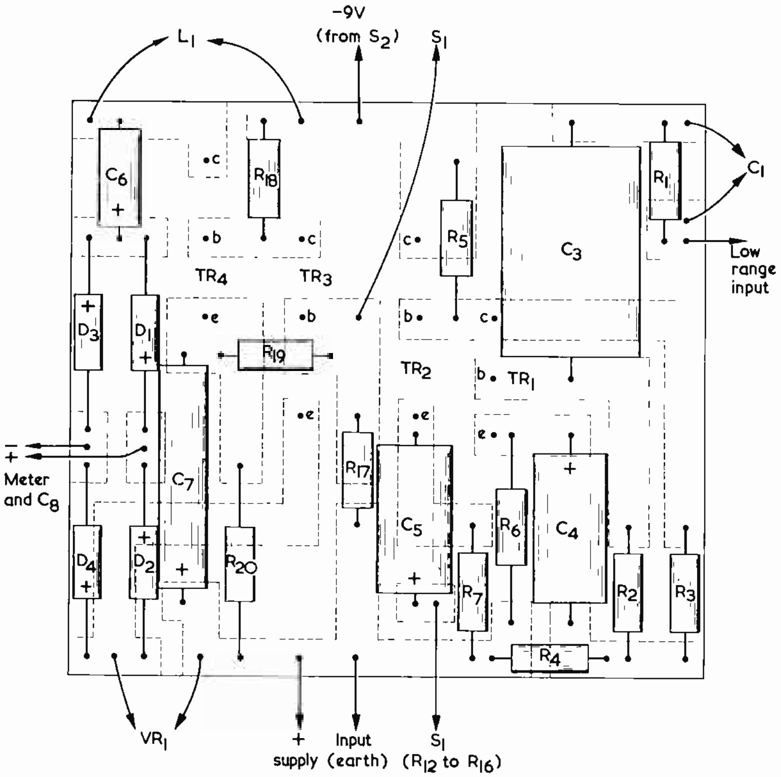


Fig. 4. The component side of the board with components mounted. Also shown are lead-out wires to the circuit external to the boards

new, and tested before being mounted on the printed board or within the metal case. All resistors are of the ½ watt, 5% tolerance high stability type available from Radiospares Ltd. The electrolytic capacitors are also Radiospares types, but the non-electrolytic capacitors are Mullard polyester components.[7] Each of the four Mullard transistors was tested for emitter-collector leakage and current gain before being soldered into the circuit.

Work may commence with the printed board, and the resistors should be soldered in place first of all. Before each one is fitted into position, its leads should be lightly scraped in order to make sure that they are clean, and then bent carefully to the correct shape to fit the relevant holes on the board. When bending the leads, they should not be bent sharply near to the body of the resistor as the protective coat on the resistor may be damaged. On the copper side of the board the leads should be about ⅛in long and bent over flat against the copper. The printed board component layout is shown in Fig. 4.

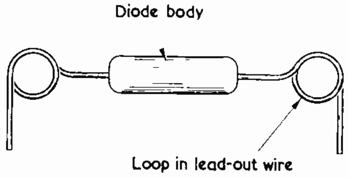


Fig. 5. The diode lead-out wires may be formed in a loop to increase the distance between the solder joint and the diode body

Capacitors, lead-out wires to the circuit external to the board, diodes and transistors should next be mounted on the printed board, in in that order. Care must be taken to connect electrolytic capacitors the correct way round. There are fourteen lead-out wires and, since many of these will be twisted together later on, it is a good policy to adopt a colour code of some kind. If single stranded p.v.c. insulated wire is used it may be obtained in many different colours and it also keeps its position when twisted together. Each lead-out wire should be cut to an initial length of about 12ins, as it is very easy, during the final wiring, to cut the leads to the correct length.

The diodes are sensitive to heat and if loops are made in their leads as shown in Fig. 5, the heat given by the soldering process will have a long route to travel before it reaches the diode envelope. There is no reason to shorten the transistor leads which should, therefore, be left full length. They should be insulated with p.v.c. insulation taken

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[2] It should be noted that Radiospare components may only be obtained through retailers. For reasons which are clarified in the second part of this article the range resistors, R_8 to R_{16}, are specified at the somewhat wide tolerance of ±5%. It is possible to employ different values for these resistors or, even, a different quantity, and these points are also discussed in the second part.—EDITOR.

from the lead-out wires. Provided that an excessively long time is not taken to solder each transistor lead, there should be no need to use a heat-shunt. If the soldering iron is at the correct temperature and cored solder is employed, it should be possible to make a really sound joint in less than five seconds.

(To be concluded)

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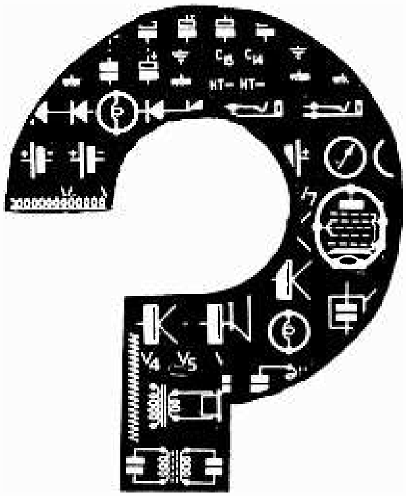
understanding radio

Miller Effect, and the Triode Oscillator

By W. G. Morley

IN THE LAST ARTICLE IN THIS SERIES WE CONCLUDED our discussion on the triode as voltage amplifier and examined some practical triodes, as are encountered in commercially manufactured radio and audio amplifying equipment.

We now turn our attention to a further factor which has to be considered in relation to the triode, this being Miller Effect, after which we shall introduce the subject of the triode as oscillator.



Inter-Electrode Capacitance

Since the electrodes of a triode valve are in fairly close proximity to each other, it follows that a capacitance exists between them. Capacitances also exist between the leads and pins connecting to the electrodes, these capacitances being in parallel with the capacitances existing between the associated electrodes themselves.

In conventional voltage amplifier triodes the inter-electrode capacitances are quite small and are normally less than some 2.5 pF. These small capacitances have negligible effect on circuit operation in some applications, but in others they are of importance and have to be taken into account. Inter-electrode capacitances are identified by the small letter "c" followed by suffix letters designating the electrodes concerned.[1] Thus, the expression c_{a-g} represents the capacitance between anode and grid, c_{g-k} the capacitance between grid and cathode and c_{a-k} the capacitance between anode and cathode. Also of importance is c_{k-h}, which represents the capacitance between cathode and heater. With directly heated triodes, inter-electrode capacitances to the filament are referred to as c_{g-f} and c_{a-f}, the letter "f" (for filament) replacing the letter "k" (for cathode). More complicated expressions for inter-electrode capacitances may also be encountered, two typical examples being c_{g-h+k} and c_{g-all}. The first of these expressions refers to the capacitance given with the grid as one "plate" of the effective capacitor, and the heater and cathode joined together as the other. The second (which is usually applied to valves having more complicated electrode structures than the triode) refers to the capacitance between the grid as one "plate" and all the remaining electrodes joined together as the other. Modern practice has introduced two further expressions, these being c_{in} and c_{out}. The expression c_{in} stands for the capacitance between the input electrode (the grid) and all other electrodes except the output electrode (the anode) joined together. The expression c_{out} refers to the capacitance between the output electrode (the anode) and all other electrodes except the input electrode (the grid) joined together.

The expressions for inter-electrode capacitance just given will be found in the specifications for their products which are issued by the valve manufacturers. It may be noted, in passing, that the capacitance figures quoted by manufacturers normally apply, unless otherwise stated, to the valve when it is cold (i.e. no heater or filament supply applied).

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[1] The small "c", instead of a capital letter, is used because the capacitance is *inside* the valve. See the footnote on page 325 of the December 1965 issue.