Height selection and frequency measurements of signals originating from biological preparations

by

Charles J. Roemmélé

Gatty Marine Laboratory,

University of St. Andrews,

Fife, Scotland.

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Tm 5751

CERTIFICATE

I certify that Charles J. Roemmélé has fulfilled the conditions laid down in the regulations for a degree of Master of Science, under Ordinance No. 51 of the University Court of the University of St. Andrews, and that he has accordingly qualified to submit this thesis for the degree of Master of Science.

DECLARATION

I hereby declare that the work recorded in this thesis has been carried out by myself, and it is of my own composition. I further declare that it has not been submitted in any previous application for a higher degree.

CURRICULUM VITAE

I was educated at the Academy, Glasgow, and attended the Heriot--Watt and Dundee Technical Colleges. At the termination of this course I obtained a Higher National Certificate in Electronic Engineering. I have since been elected a Member of the Institution of Electronic and Radio Engineers and as such I am classed as a Chartered Engineer.

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Finally, I would like to thank my wife, Penny and my mother, Dr. M.E. Roemmélé for their continuous and unstinting encouragement, without which I could not have completed this work.

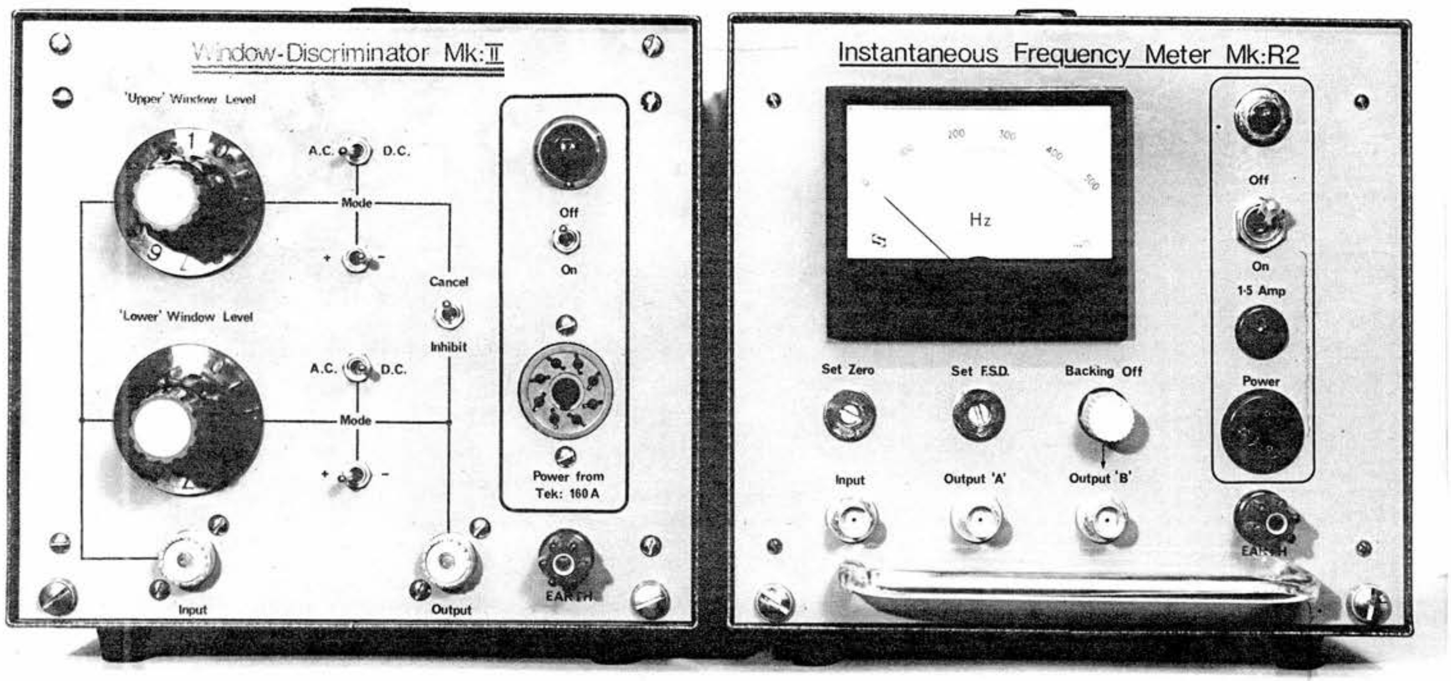


Fig. 1 Photograph of MK:2 Discriminator
and MK:R2 Frequency Meter.

INTRODUCTION AND DISCUSSION

One of the recognised methods for a detailed study of the electrical activity of a sense organ is to dissect a single sensory nerve fibre and record the frequency and distribution of action potentials that appear during a period of appropriate stimulation. In many preparations a detailed dissection is difficult and in many cases impracticable. There is then a need for an alternative method of extracting information from a group of nerve fibres. Since each individual nerve fibre is characterised in extracellular methods by a constant potential amplitude that differs from that of all other units represented in the collection of fibres, an all embracing method of selecting out single units can be achieved by signal voltage selection and measurement of the frequency of these unit potentials.

When a nerve containing many axons is stimulated by any method a large number of action potentials appears along it. The problem is to analyse which potentials emanate from which fibres and what the discharge patterns are. It is necessary therefore to have some device which discriminates between signals just appearing above instrumentation noise and the largest voltage signal present, so that the firing of single units can be followed experimentally if desired. This is possible for the reason explained above.

The device then has (a) to be able to select signal voltages that lie between any two variable and choosable threshold or window values, (b) to follow and display the instantaneous frequency (i.e. reciprocal of time intervals) of potentials under investigation, so enabling small changes in frequency to be compared relatively easily. The visual difference when measuring long time periods is not as defined as when measuring frequency.

Given that these two conditions should be followed an approach using electronic instrumentation techniques was sought. These will be dealt with purely as an electronic/electrical problem to be solved and as such will concentrate on the voltage window threshold section first.

When a signal voltage of any shape and form is present and is available for height analysis it is relatively easy to design and build a voltage threshold device such as the Schmitt Trigger (Ref: O.H. Schmitt) (Fig. 20 Appendix I). This will produce an output signal only after a predetermined level at its input has been reached or passed. Once the threshold has been passed, the Schmitt will stay in its unstable state until the input signal falls below the level at which the device first changed from its quiescent state to the unstable one. There is a slight amount of backlash i.e. the two transitions do not both occur at the same input level (See description Appendix I). This system works extremely well except when attempting to analyse small signals interspersed amongst larger ones. Difficulties arise due to the fact that large signals trigger off the threshold device before the smaller ones, so presenting at the output a pulse signal indicating the total of both large and small signals thereby presenting an integrated output without discrimination. It can be seen therefore that some method of rejecting or discriminating against the larger signals is required yet allowing the smaller ones to pass on unhindered, or at least giving an output signal proportional to its original height. It is necessary therefore to have a device that has two thresholds which can be programmed, thus ensuring that

a) Signals between and only between these two predetermined levels will be passed on unhindered and

b) Signals either below the lower threshold and/or signals above the higher threshold are inhibited therefore enabling the analysis of small signals in the presence of larger ones to be studied more easily. Easy manipulation of these two threshold levels enables the research worker to raise or lower these two levels to encompass whatever signal he is wishing to follow.

Some workers in the Nuclear and Electronic Research field, including Van Rennes, have devised window discriminator systems but have relied on the very rapid rise time and short pulse duration time (0.5µs) of radiation detector signals so that they can use a coincidence gate device. A coincidence device is one in which signals will cancel each other out <u>providing</u> they are absolutely coincident in time with each other. This inhibits any signals that lie outside the thresholds. Unfortunately most electrically propagated signals originating from preparations of nerve tissues have rise and fall times of 500μs or longer and duration times that are usually not shorter than 1ms; coincidence detectors have been tried by the writer (and J. Houk et al. and W. Bradley et al.) but as the period of the lower threshold output pulse will always be longer than the upper threshold one there was always this difference in output widths from the Schmitt triggers. Thus when applying these pulses of different widths to a coincidence device it produced two outgoing narrow pulses which consisted of the difference between the pulse widths at the start and completion of the original signal waveform. G.O. Plumb used the technique of starting an oscillator and setting bi-stables when the input passed through successive threshold levels. When the oscillator ceased after 500μs a pulse was generated if the signal had passed between any two levels and it also reset the system. However, as the signal width had to be shorter than this allowed time it therefore strictly limited the performance of this whole device. Another design by R. B. Stein set successive bi-stables on the rising phase as before and during the falling phase produced an output pulse if the signal had passed through more than one threshold level. A disadvantage of this device is that one module is required for each size of spike to be discriminated and as each module is made up of six integrated circuits it does not appear to be an economic design. A further disadvantage is that he utilised the internal amplifier of a C.R.O. and when the amplitude gain was varied the relative setting of the discriminator would have to be reset. Even moving the trace on the screen will necessitate further re-alignment. A further design by E. H. Ramey also used the internal amplifier of a C.R.O. to programme the discriminator and the use of a varying time interval before resetting his logic placed an additional limitation on the device. It is necessary therefore to have a system that will produce an output waveform only if the signal has passed through the lower gate and <u>not</u> the upper one. It is therefore prerequisite that the system has to have a memory so that it will or will not open the final gates, and that it does not have a long or varying time interval before resetting.

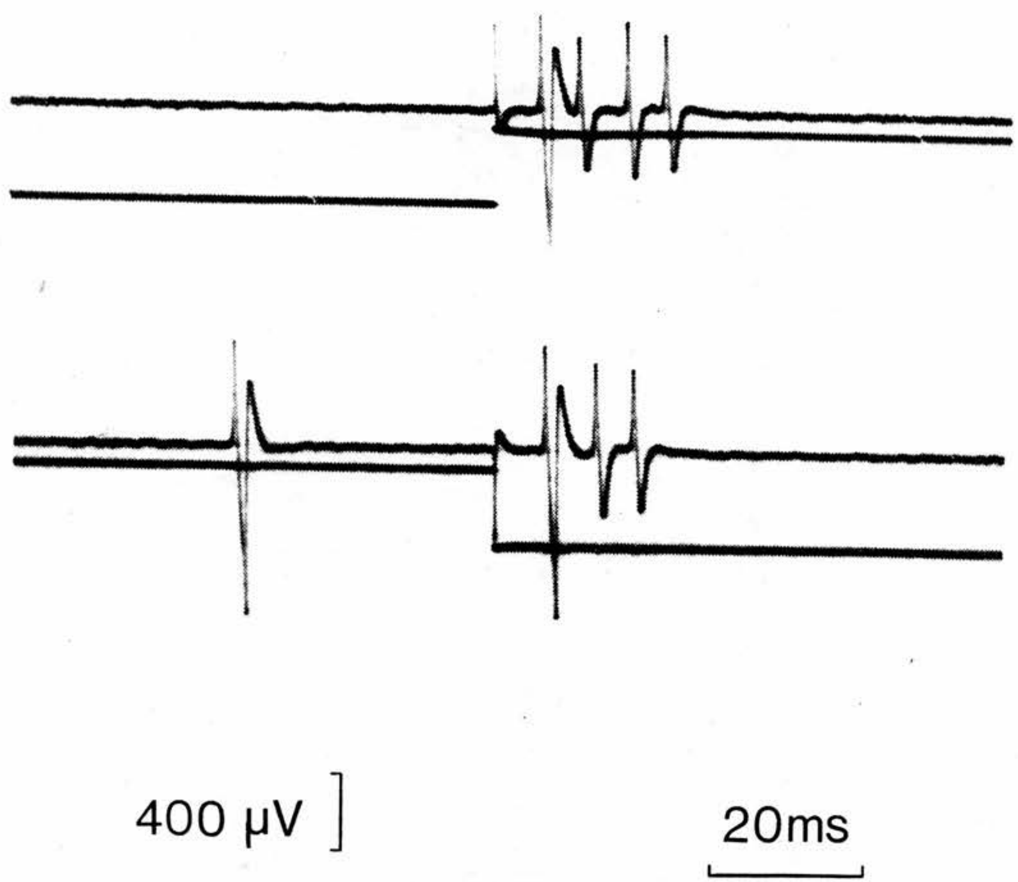


Fig. 2. An example of a typical extracellular action potential. The first and third traces are action potentials whereas the second and fourth are stimulating potentials (Ref. M.S. Laverack)

DEVELOPMENT AND DESCRIPTION

If one looks for a moment at the general shape of an action potential (Fig. 2) one finds that it is roughly triangular in shape both on the positive going part and also on the negative going part (Figs. 2 and 3). Thus the signal voltage rises and falls in an approximately linear fashion. If the lower and upper threshold levels (hereinafter known as L.T.L. and U.T.L.) are adjusted so that the leading edge of the signal passes through both, the upper trigger will snap-over a finite time after the lower. If one wants this signal to be rejected (as it has passed both levels) one has to have a system that stores the information from the L.T.L. until it either receives or does not receive information that the same signal has also passed the U.T.L. (F.J.M. Farley). Taking a case when the signal does pass the L.T.L. but does not pass the U.T.L. it has to be arranged that this information might or might not be required to be presented as an output signal pulse. It is necessary therefore to insert into the instrument some way of releasing the information that the signal has not passed through the U.T.L. This, of course, is due to the fact that one cannot preconceive what voltage height the incoming signal might be at relative to the settings of the two threshold levels.

If however one looks at the trailing edge of the signal (Fig. 3) one finds that the width of the upper Schmitt pulse will always be narrower than that of the pulse from the lower. This information can be used by observing that the cessation of the Schmitt pulse from the

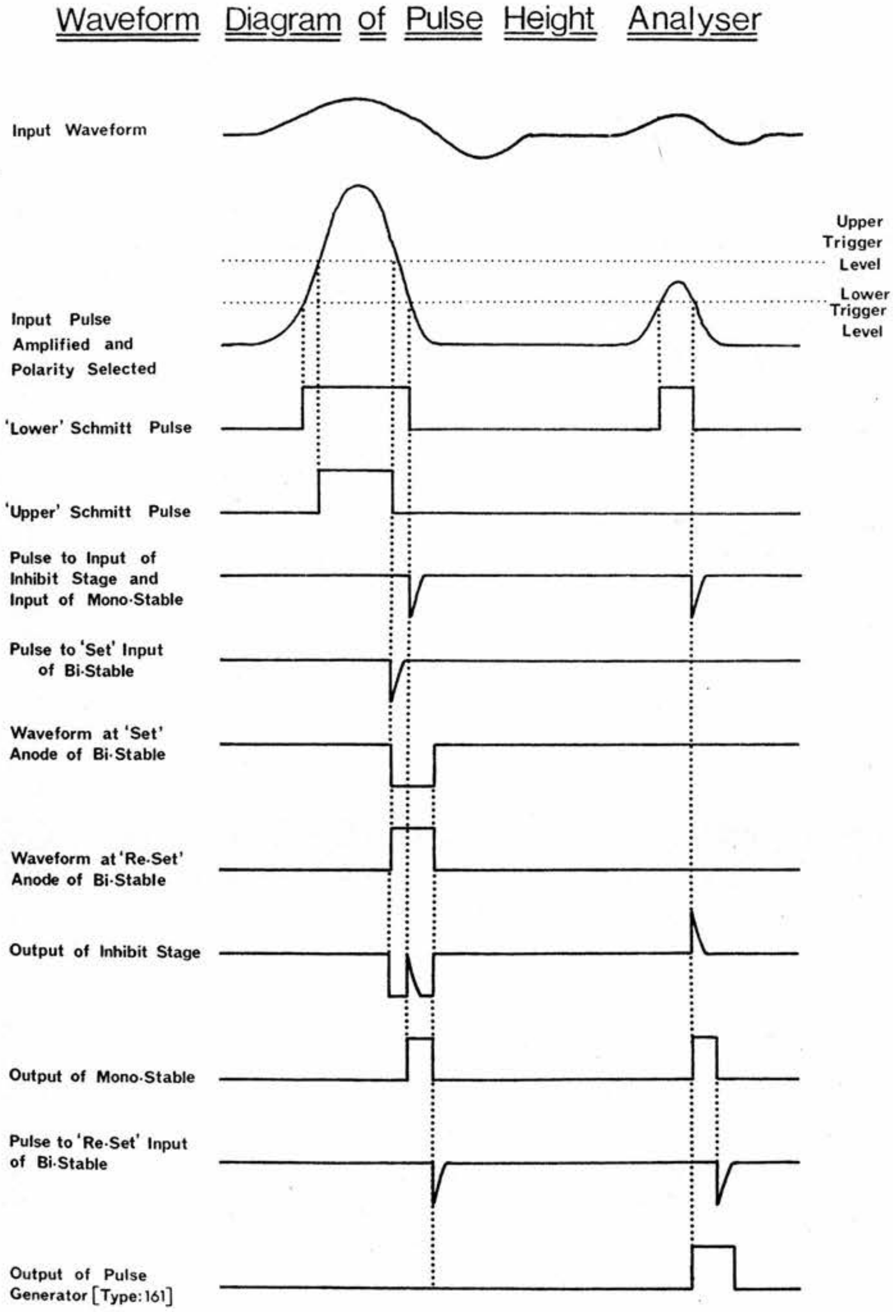

Waveform Diagram of Pulse Height Analyser
Input Waveform
Upper Trigger Level
Lower Trigger Level
Input Pulse Amplified and Polarity Selected
'Lower' Schmitt Pulse
'Upper' Schmitt Pulse
Pulse to Input of Inhibit Stage and Input of Mono-Stable
Pulse to 'Set' Input of Bi-Stable
Waveform at 'Set' Anode of Bi-Stable
Waveform at 'Re-Set' Anode of Bi-Stable
Output of Inhibit Stage
Output of Mono-Stable
Pulse to 'Re-Set' Input of Bi-Stable
Output of Pulse Generator [Type: 161]

Fig. 3.

U.T.L. is a finite time before the cessation of the Schmitt pulse from the L.T.L. It is therefore possible to use the information from the U.T.L. to inhibit the pulse coming from the L.T.L. or, providing that there has been no signal from the U.T.L., allow the L.T.L. pulse to be passed on unhindered.

A description of how the inhibitor section of the R.1 discriminator functions follows using Figs. 3 and 4 as guides. Taking the case when an input signal passes through the L.T.L. but not the U.T.L., the sequence of events within the inhibitor is as follows:-

> The L.T.L. Schmitt trigger output produces a square wave whose duration is proportional to the level at which it passes through the sensitivity level of the trigger (Fig. 3). Once this pulse has been produced it is differentiated by the input capacitor (330pF) and resistor (47KΩ). This differentiated signal is then clipped by the diode (OA8I) and fed to the pentode section of the output valve. This valve is held in the normal screen grid bias condition by the voltage appearing at the anode of the D type bi-stable multivibrator M 8162 (See Appendix II). The same clipped spike is also fed to the anode of the mono-stable valve M 8162 which then passes into the unstable condition for a time determined by the setting of the gate width

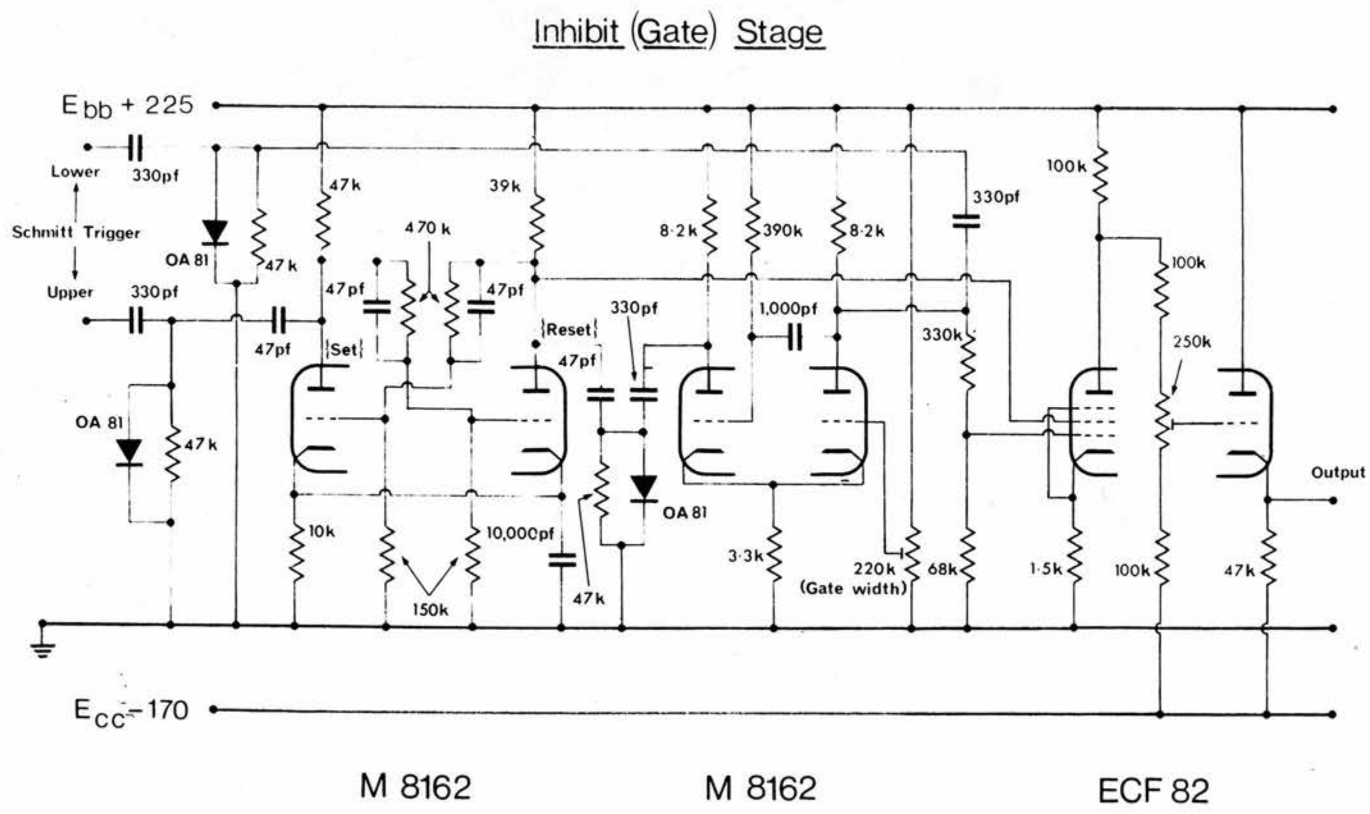


Fig. 4. Circuit diagram of Inhibit stage of the window discriminator.

potentiometer. The output from the M 8162 mono-stable is also differentiated and clipped. This is fed to the reset anode of the bi-stable which does not change its logical state as it is already in the set condition due to the biasing arrangement of its anode loads (Appendix II). The pentode section inverts and amplifies this pulse which is then fed to the output triode, the cathode of which in the quiescent state is set at zero volts, this being controlled by the d.c. level potentiometer (250 KΩ). The signal pulse appearing at the cathode of this valve is 40 V (Fig. 5) and it is fed to the input of a Tektronix type:161 pulse generator. The reason for utilizing an outside pulse generator is that an output of any height, width or polarity can be selected by the operator to his own choice. This is therefore a system which, provided that the gate is not closed, will allow the signal from the L.T.L. to pass.

Taking however the case when an input signal passes through both the L.T.L. and U.T.L. the sequence of events within the inhibitors is as follows:-

The Schmitt trigger stages of both the lower and the upper threshold levels will produce output square wave pulses, the widths of which

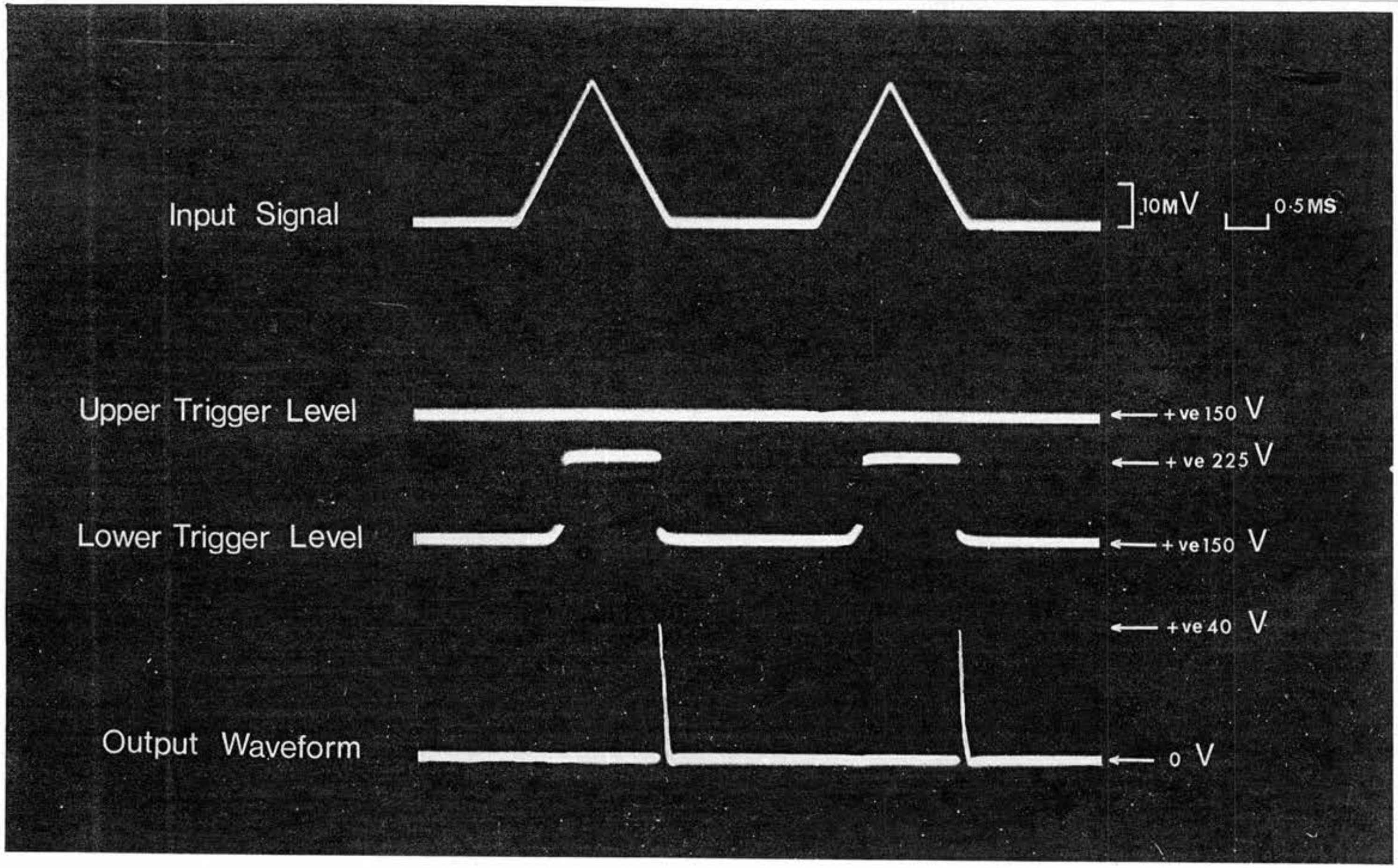


Fig. 5
C.R.O. trace photograph of the voltage waveforms within the inhibit stage.

will be different as previously explained (Page 9). The output pulses are differentiated and clipped, but in this case the spike from the trailing edge of the U.T.L. Schmitt is fed to the set anode of the bi-stable which then changes its state. In changing its state it alters the bias conditions of the pentode placing this valve into the hard ON state, this negative going condition being passed to the output valve. The spike appearing from the trailing edge of the L.T.L. is applied to the control grid of the pentode where it is amplified and passed to the output valve. The initial spike from the L.T.L. is passed to the mono-stable stage which moves into its unstable state as before, but in this case the negative going spike from the shaping network does have an effect at the reset anode of the bi-stable whereupon the bi-stable resets into its original state and awaits the arrival of the next pulse or pulses from the two different levels. The signal appearing at the output consists of a positive 40 V spike pulse enveloped in a negative 40 V pulse (Fig. 6), this output being fed as before to a Tektronix type:161 pulse generator which will not trigger

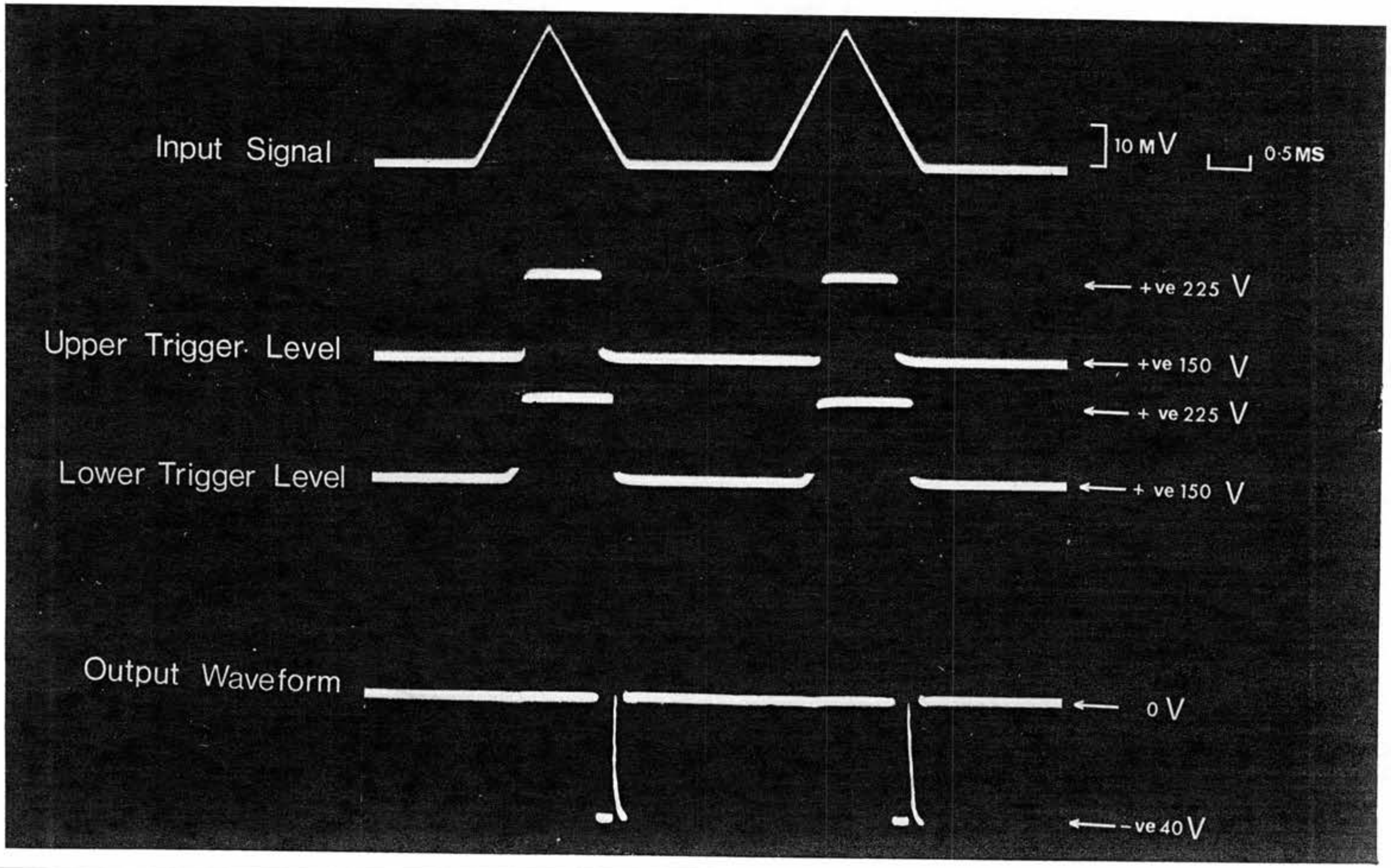


Fig. 6
C.R.O. trace photograph of the voltage waveforms within the inhibit stage.

if set to a position that is covered by the operating instructions as set out in Appendix VI.

When neuronal signals appear from a biological preparation they are usually between the order of 10μV and 20mV. Before any kind of height analysis can be made voltage amplification has to take place. Amplification is necessary because signals originating from biological preparations are small in comparison to the trigger settings of the Schmitts. In most laboratories there are, as part of their normal complement of equipment, various types of voltage amplifiers which can transform small signals into larger ones thus enabling the small signals to be routed and displayed on a C.R.O. or other display device with comparative ease. When this amplified signal is fed to the C.R.O. for observation the same signal is fed to the input terminal of the window discriminator if height analysis is required. The output to the 161 at the rear of the discriminator is also fed to the other channel of the C.R.O. thus enabling the worker to observe simultaneously the signal before and after passing through the window discriminators (Fig. 3 and Fig.19).

A stage by stage description of the analyser follows:

When the pre-amplified signal is fed into the instrument it appears at the top end of a ladder-type selector (Fig. 7) which sets the upper and lower threshold levels. This consists of a two-pole ten way switch and a potentiometer

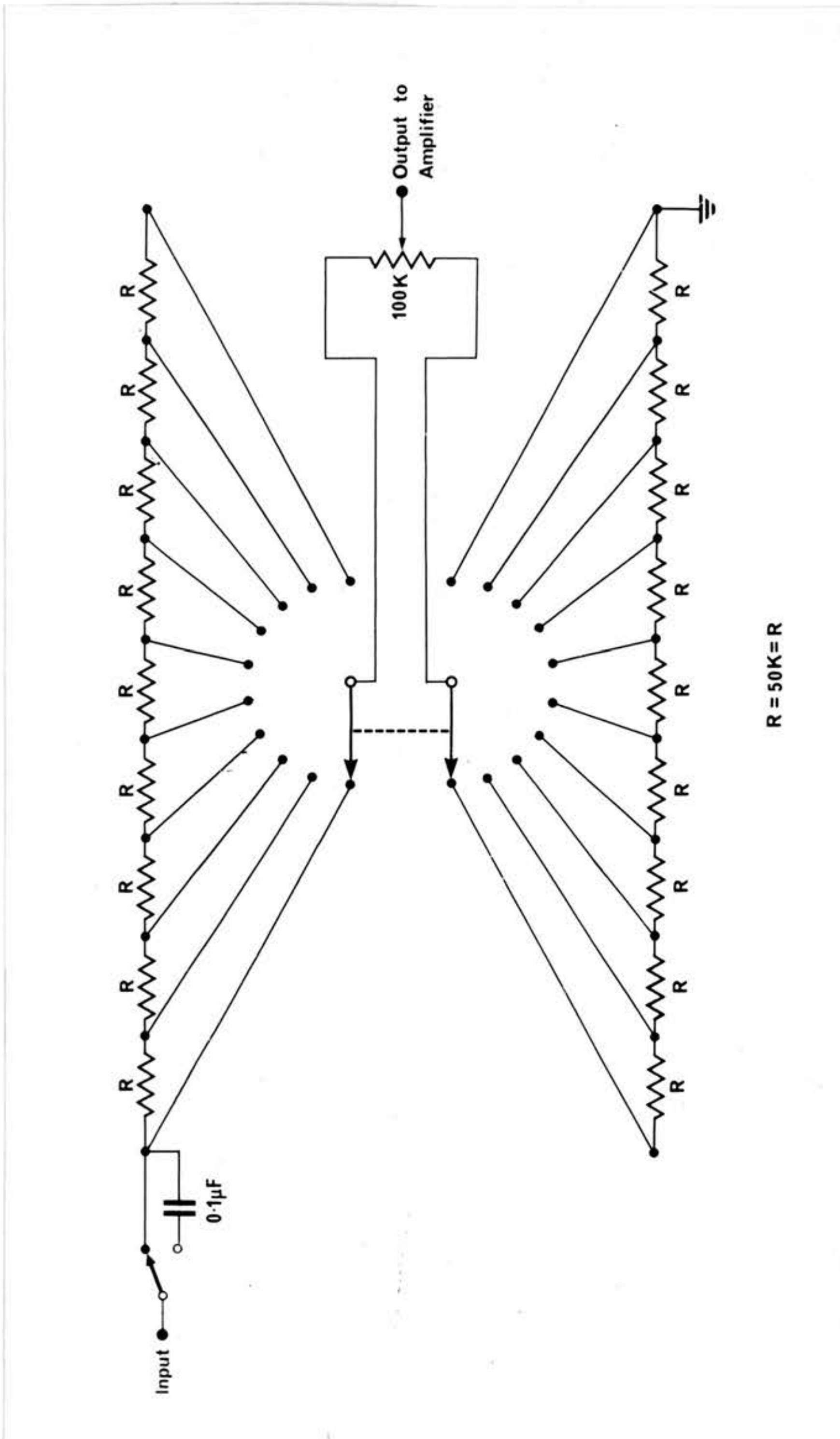

Output to Amplifier
100K
R
R
R
R
R
R
R
R
R
R
R
R
R
R
R
R
Input
0·1µF
R = 50K=R

Fig. 7

mounted in tandem to it. The ten positions of the switch are numbered from 0 to 9 and the potentiometer is so connected to the chain of resistors that at any position the sensitivity of the potentiometer is the same whether at the top or bottom of the array. Although this arrangement might appear complicated in comparison to a helical potentiometer, it is very much easier and less confusing to rotate a ten position switch through 360 degrees than attempting to rotate a circular dial and knob through 3,600 degrees. The reason that the variable resistor has a value twice that of each step is that it gives an overlap above and below each setting thereby reducing the need of unnecessary changing of the switch position. Due to random movements of some preparations base line shift can occur thereby disturbing the threshold settings of the discriminator. To overcome this, capacitor coupling can be inserted if required giving the whole discriminator a time constant of 0.05 seconds. This time is dependent only on the attenuator as the rest of the device is directly coupled, thus ensuring that the voltage height is the only variable.

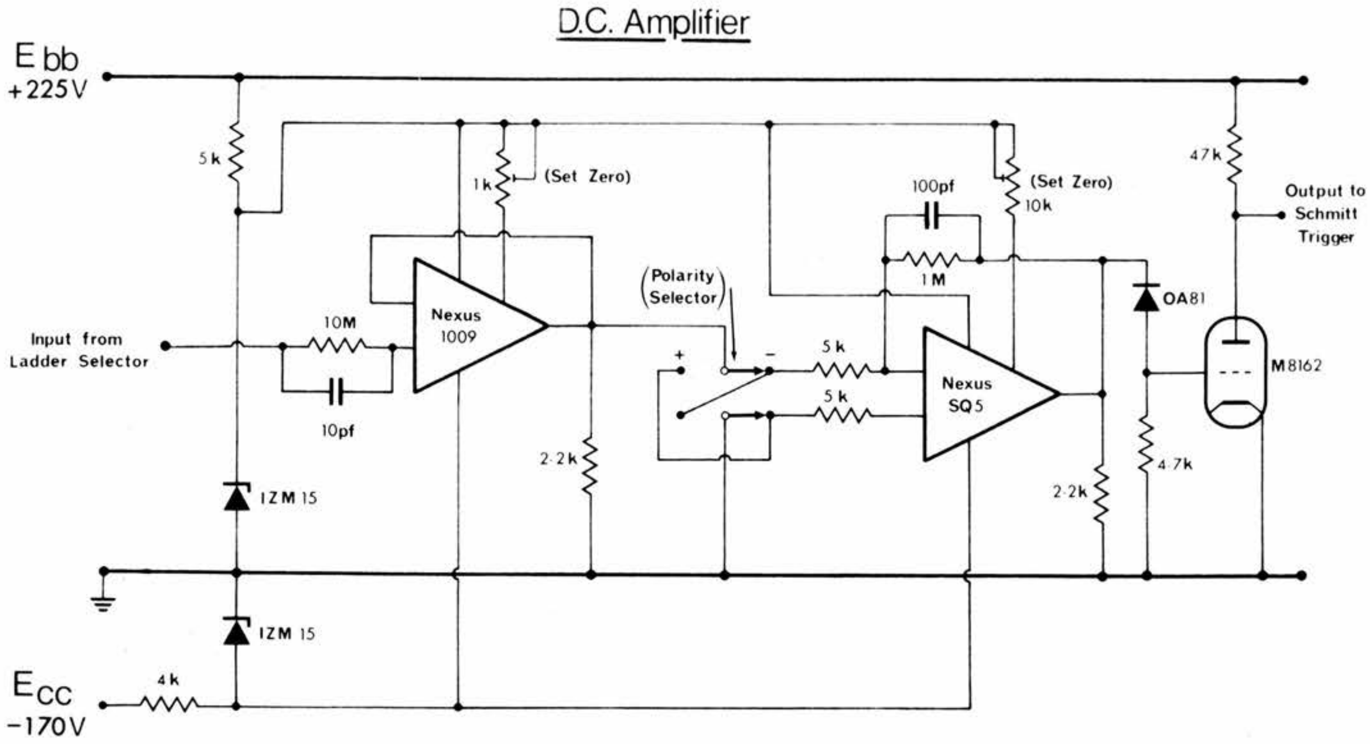

D.C. Amplifier
E bb
+225V
5 k
1 k
(Set Zero)
100pf
(Set Zero)
10k
47k
Output to
Schmitt
Trigger
Input from
Ladder Selector
10M
10pf
Nexus
1009
(Polarity
Selector)
+
−
5 k
5 k
1 M
Nexus
SQ5
OA81
M8162
2·2k
2·2k
4·7k
IZM 15
IZM 15
Ecc
−170V
4 k

Fig. 8.

The output of this attenuator is then fed to the d.c. amplifier (Fig. 8) where it is amplified by approximately 10,000 times. A facility whereby the polarity of the signal can be changed is available at the front of the panel. This is necessary as a biological signal is bi-polar in extracellular conditons. A description of this amplifier is given in Appendix II. The output of the amplifier is then fed to the Schmitt trigger stage (Fig. 21), the backlash of which is set by the 250 KΩ potentiometer. The analysis of this device is given in Appendix I. A block diagram of the whole discriminator is given in Figs. 9 and 10.

Block Diagram of Window System

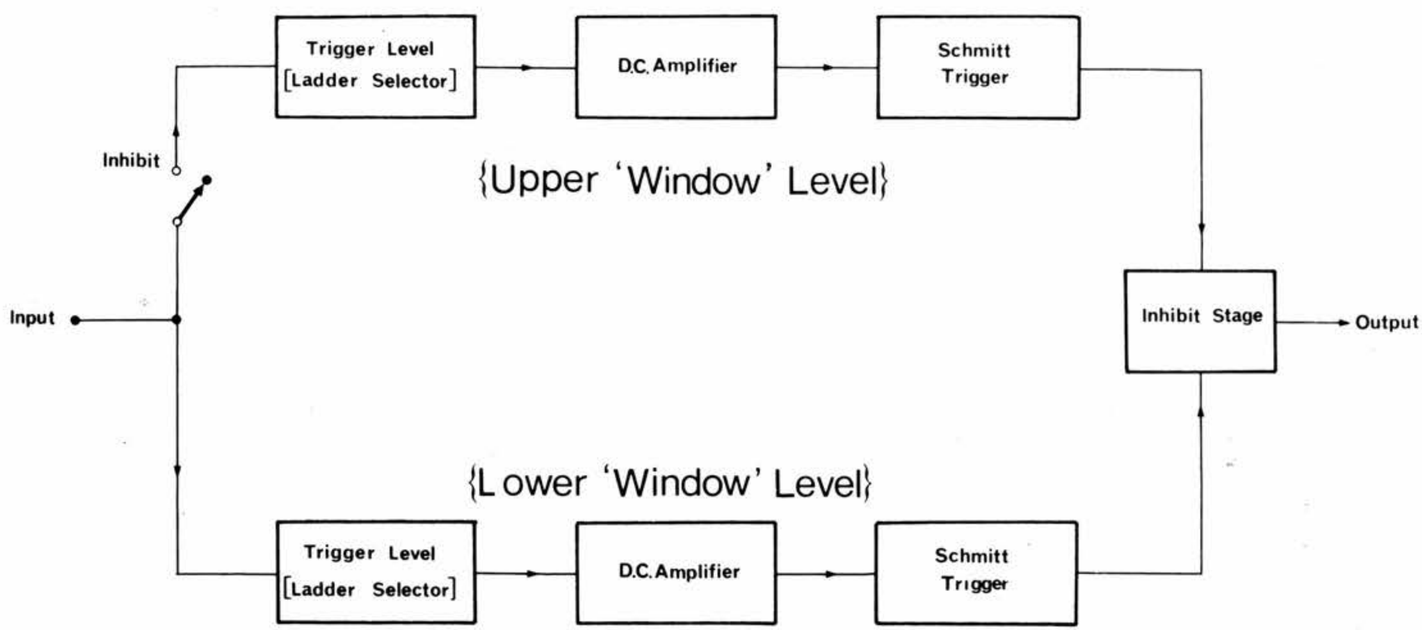


Fig. 9.

Block Diagram of Inhibit (Gate) Stage

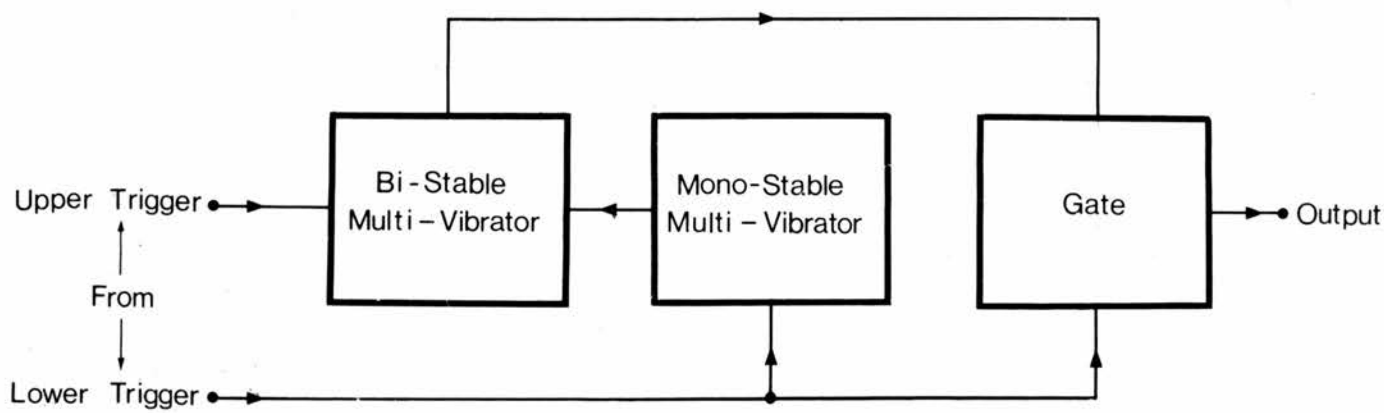


Fig. 10

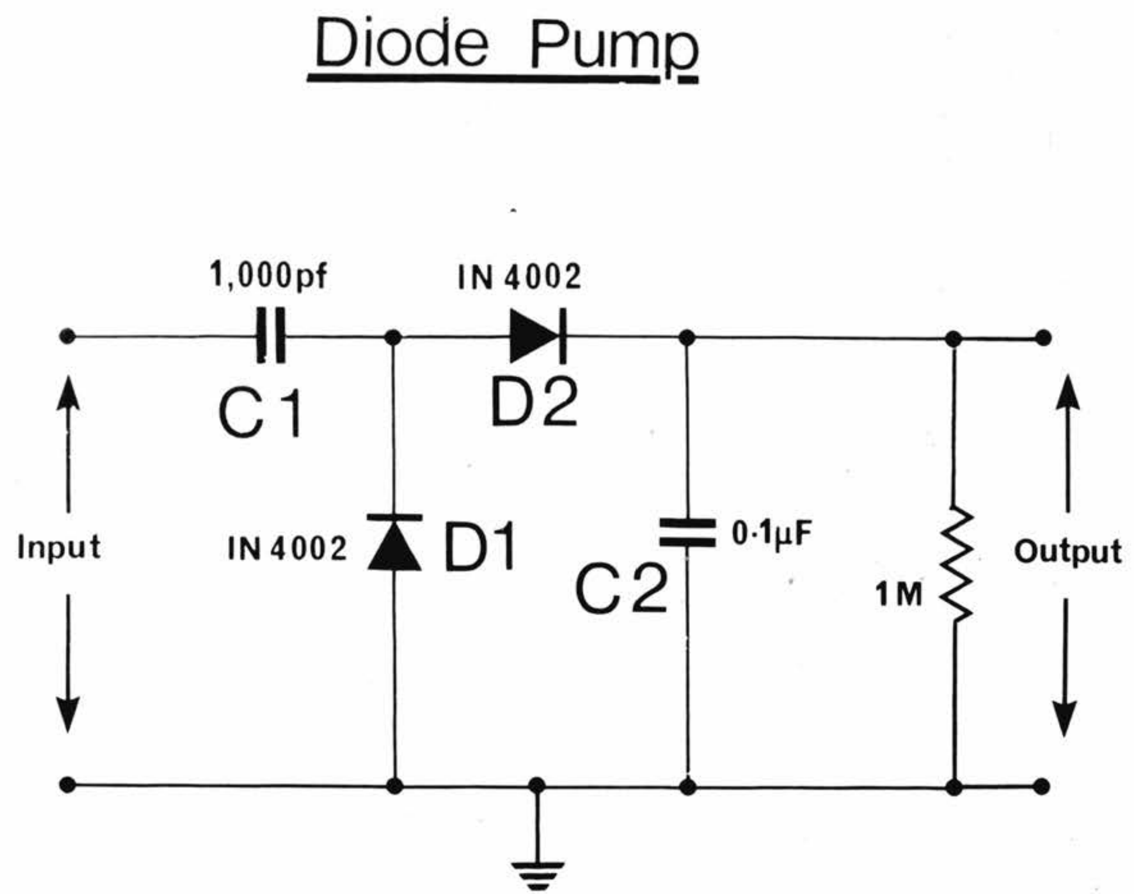


Fig. 11
Circuit of Ratemeter Mk: 1.

INTRODUCTION ON FREQUENCY MEASUREMENT

As previously discussed, it is of assistance to the further understanding of neuronal pathways if the method of signal height analysis is used. It is also of assistance if the steady and varying frequency of nerve discharges can be determined relatively easily.

Various electrical/electronic instruments have been designed and built (Ref. A.F. Huxley and J.E. Pascoe; MacNichol and Jacobs; R.S. MacKay) such that a voltage is produced at the output proportional to the frequency of the input or inversely proportional to the time interval between signal pulses, but as will be shown there are features in my design that are an improvement on these instruments.

One of the most simple and convenient ways of obtaining a voltage signal from a train of pulses is to use a diode pump integrator device (Fig. 11); an elegant analysis was given by J.B. Earnshaw. The linearity of this device is shown in Figure 12. The upper sections of Figure 12 show the output voltage of the diode pump in relation to step changes in input frequency from which the two lower graphs were drawn. A disadvantage of this device is that it will produce an output voltage only after a certain number of pulses have passed. This is due to the fact that this device integrates the signal with respect to time and therefore a small and rapid change in input frequency can be lost. The form of the input signal to this ratemeter is ideally one in which the amplitude (E) and duration (T) are constant. To achieve this the input is fed from a Tektronix pulse generator 161. This generator is the output stage of the window discriminator and therefore

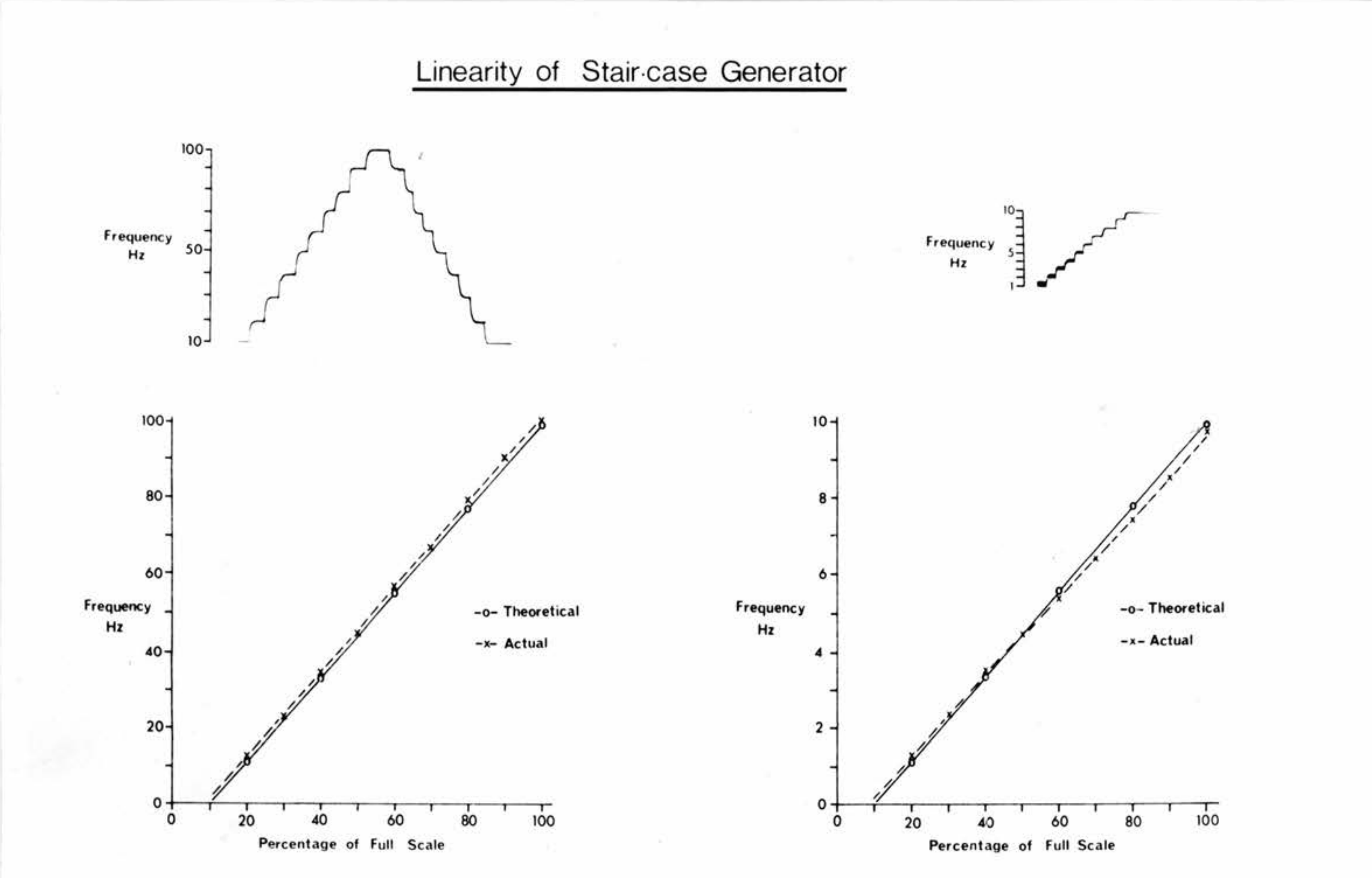


Fig. 12
Linearity of Diode Pump

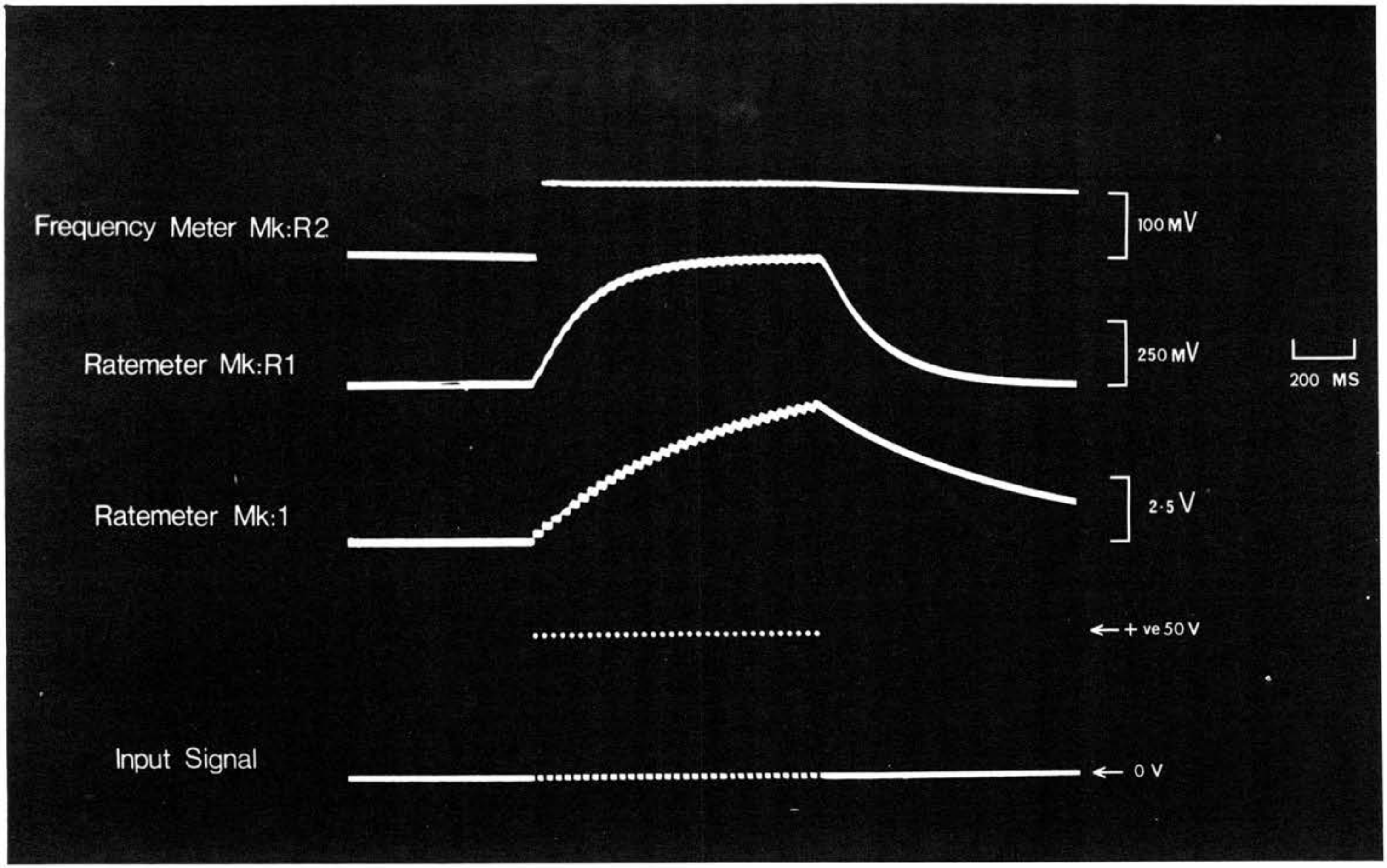

Frequency Meter Mk:R2
Ratemeter Mk:R1
Ratemeter Mk:1
Input Signal
100 mV
250 mV
2·5 V
← + ve 50 V
← 0 V
200 MS

Fig. 13

the discriminator is compatible with this particular type of ratemeter.

Referring to Figure 13 and in particular to the voltage output of the diode pump designated in the figure Ratemeter Mark I, it can be seen that there is a ripple on the rising output voltage. It is also noticeable that a final d.c. steady voltage has not been reached even at the conclusion of the train of input pulses. To overcome this disadvantage an improvement to the basic pump was required. The improvement consisted of adding a stage of smoothing to the output of the Mark I. The resulting circuit (Mk: R1) is shown in Figure 14 and the improvement in the response at the output to the same input as before can be seen; although the amplitude at the output is lower than that of the Mark I it is not considered a disadvantage in comparison to the reduction of ripple. The basic outline of this improvement to the diode pump was given by B.H. Brown.

It can be seen that an instrument that will produce at its output a very rapid change of d.c. voltage for a small change of signal frequency at its input would be the ideal solution, but by definition a device cannot integrate if a rapid response is desired.

To detect an instantaneous change in signal frequency it is necessary therefore to measure the change in latency between the two previous signal pulses. This interval can be presented as a voltage proportional to time or inversely proportional to frequency. Referring to Figure 13 and in particular to the signal which originates from Frequency Meter R2, it can be seen that an instrument was designed to

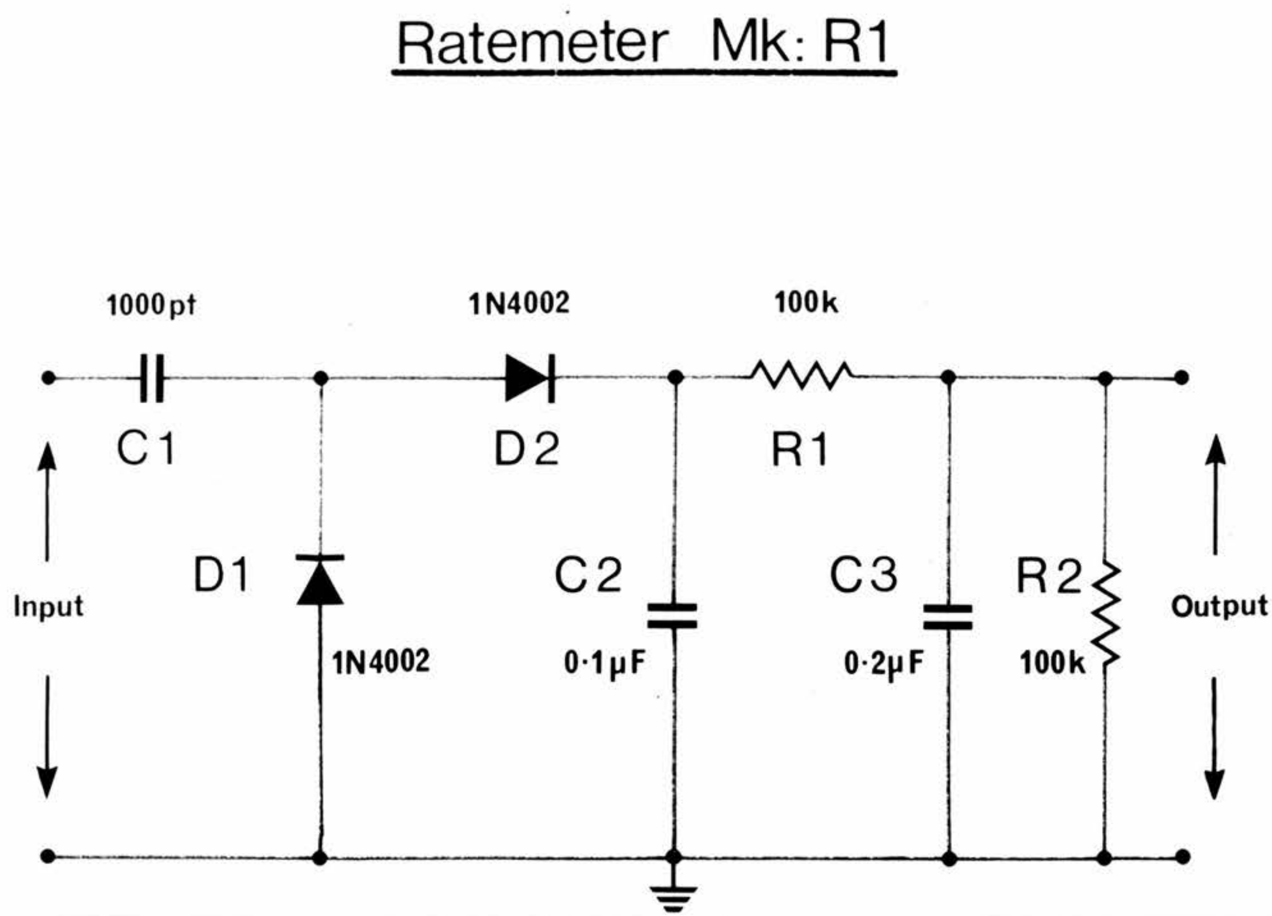

Ratemeter Mk: R1
1000pt
C1
1N4002
D2
100k
R1
Input
D1
1N4002
C2
0·1μF
C3
0·2μF
R2
100k
Output

Fig. 14

display instantaneously a voltage that was proportional to frequency.

DISCUSSION

To develop and design an instrument to display on a C.R.O. and/or pen recorder seemed to be necessary if a small and rapid change of frequency was to be detected relatively easily. To present the period between pulses and the result in terms of frequency is not difficult and in fact since 1950 more than six developments have been published.

The method of obtaining the inverse of time interval between pulses (i.e. the frequency) and the manner of output presentation are the major differences between the various designs of previous workers. One of the designs (Ref. J. Houk et al.) uses the technique of linearly charging a capacitor from a constant current generator and at the receipt of the next pulse the capacitor is discharged and the charging restarted. During the period of charging the voltage across the capacitor is followed on a C.R.O. screen and the height is therefore a direct measure of the time interval between the two foregoing pulses. In the device by M. McDonald and W.J. Perrin the period of charging is followed on a slow speed pen recorder. As the final result of these designs is an envelope shape of time interval (or period between pulses) it is only satisfactorily workable as a measure of time if the recorder or time base of the C.R.O. is run at an extremely slow speed.

In an elegant design by Andrew and Roberts (Ref. A.M. Andrew and T.D.M. Roberts) they showed that by using a six diode biased network an approximation to the hyperbolic charging of a capacitor could be achieved. The reasoning behind the hyperbolic charging of a capacitor is that when the next pulse enters the system the voltage across the capacitor will be directly proportional to frequency at the point at which this occurs. Their design was a complicated one and showed that the technique of using a diode biased network was the most accurate way of generating a hyperbolic function. The final accuracy of their instrument was to within 1.0% up to a frequency of 100 Hz. At the time of their work vacuum tube valves were the active devices used but over a period of time the characteristics will vary thereby reducing the reproducibility of the system.

A slightly different approach was to charge a capacitor in a linear way and obtain the rectangular hyperbolic function of it. The authors (Ref. E.F. MacNichol and J.A. Jacobs) fed the output to a six diode biased amplifier which transformed the linear charging voltage to the function required. The use of extremely accurate high value resistors (1% tolerance) did not make this instrument any more stable in accuracy due to the inherent variation of resistance value with temperature change. The further use of the particular type of valve d.c. amplifier was to a large extent the reason for the lack of accuracy which was to 10% over a range of frequency of 25:1.

A method by which two separate capacitors were alternately charged and discharged was shown by Tove and Czekajewski (Ref. P.A. Tove and J. Czekajewski) but as they used a method of charging which gave only an accuracy of 10% over a certain section of the scale of their instrument

I did not consider it to be any improvement over the design by MacNichol. The reason for utilizing two separate capacitors was that they alternately switched a moving coil meter across the capacitors so enabling a reading of capacitor voltage to be taken. By monopolising one of the capacitors by the meter they had to have another capacitor for charging purposes over the period of time between pulses. The capacitors used were 100µF and as the charge across them must have been considerable at long time intervals high current devices had to be used to discharge them quickly and in fact in their earlier design relays were used for this task.

A design by R.S. Kay showed that by utilizing an eight zener diode discharging network, highly accurate measurements of frequency could be achieved, thus improving on the design accuracy of Andrews. As will be pointed out, the continuous indication of changes in frequency is the prime consideration of a frequency measuring system in electrophysiology and not a high degree of accuracy. The output of his instrument could be used only on a C.R.O. because the display of information by a brightening pulse lasted for only 100µs. If therefore there is a long time period between signals, there is no indication that this period is steadily lengthening. This in my opinion is a fundamental drawback of his device.

J.D.Gasking and J.A.Humphrey, and H.Ludwig and Ng.Yan-Kit described a digital method of displaying changes in frequency and the final accuracy was 2% over a frequency range of 2Hz to 65Hz. Although this method of display was relatively novel, there was no continuous indication of increasing period after the interval of the two preceding impulses had been read and displayed.

A ratemeter design by J.M. Neilson changed information of period (time interval) to frequency by utilizing an invertor. The technique of inversion was achieved by modulating the pulse width of a free running oscillator using a voltage which was obtained from linearly charging a capacitor during the previous period between pulses. The mean d.c. level of the oscillating signal was achieved by passing it through a low pass filter. Although an accuracy of 1% on full scale deflection was claimed the frequency range covered was very small, i.e. 16 to 1, the major reason being the use of the filter. A more serious drawback was that there was no continuous indication of lengthening interval if the period of the next signal pulse was longer than the preceding one.

I used the principle of discharging a charged capacitor through a diode resistor network utilizing only passive devices, the equations for which were derived from an article by McDonald and MacKay (Ref. R.D. McDonald and Ref. R.S. MacKay). A sample and hold technique (Ref. H. Rouhof and Ref. J.M. Pope et al.) was then used to transfer information from the discharging capacitor to another, termed the holding capacitor. Instead of using diode resistor networks for discharging a capacitor, the following workers have used either the emitter to base junction of a transistor (Ref. D.G. Green) or a Quadratron (Ref. J.M. Pope et al.)

but R.S. MacKay and the makers of the Quadratron have shown that these are extremely temperature dependent and should be used only in a thermostatically controlled oven. I would prefer not to use an oven in an electronic design on the grounds of unnecessarily complicating the instrument.

Having studied the various designs of the aforementioned I came to the conclusion that none offered all the following salient points though some offered two or three of them:

a) Wide frequency range (5 Hz to 500 Hz) and linearly accurate to 5% of reading thereby ensuring that the instrument could be used in a variety of electrophysiological research work.

b) An output signal voltage that gives an indication as to what (in terms of frequency) is taking place at all times.

c) That the output falls below the bottom and rises above the top level of the calibrated scale with frequencies that are lower and higher than the instrument is designed for, thereby removing any likelihood of a spurious reading should the input signal fluctuate wildly.

d) Stability and ease of operation in the event of long term experiments.

e) Economy and simplicity of construction, thereby ensuring that a replacement of a unit is easy in case of failure.

f) That the linearity of the reading rarely requires a high degree of accuracy as biological results are not repeatable to within

5% so enabling point a) above to be followed.

An appraisal of these points led me to design an instrument that followed all of them and as such a description of the Frequency Meter R2 (i.e. Instantaneous Ratemeter) follows.

Block Diagram of Instantaneous Ratemeter

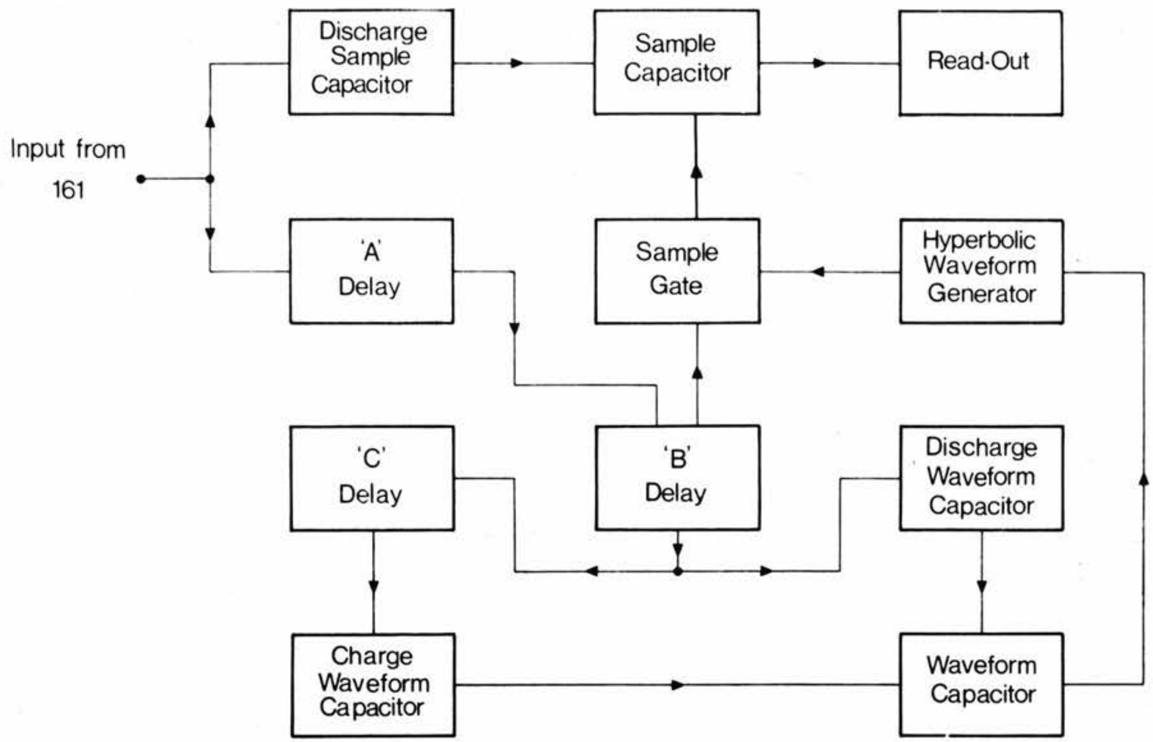


Fig. 15/1

DEVELOPMENT AND DESCRIPTION

To measure the time interval between signals and convert it to frequency requires the use of a rectangular hyperbolic generator as time is inversely proportional to frequency. In my design I charge a capacitor on receipt of an input pulse and after a delay start to discharge this capacitor through a triple diode resistor network (Ref. R.S. MacKay) thereby approximating to a hyperbolic curve and so obtaining a linearity of discharge to reciprocal of time of 5%.

At the instant that the next input pulse enters, the voltage at that point of time on the discharging capacitor (C1) (Fig. 16) is sampled by another, termed the sampling capacitor, this voltage being directed to a read out stage and presented on a C.R.O. and/or meter. Before sampling the first capacitor, the sampling capacitor (C2) is discharged completely, thereby ensuring that any voltage appearing across it is only the voltage that is sampled at that point of time on the first one (C1). After being sampled, the first capacitor is discharged and after a delay is re-charged to the full d.c. potential of the power supply; it is then hyperbolically discharged as previously. The sequence of events repeats itself as before on the entry of another input pulse.

With reference to Figures 15, 16 and 17 the sequence of events through the Frequency Meter R2 is as follows.

On receipt of a positive input pulse, ideally derived from the gate

Detail of hyperbolic discharging system

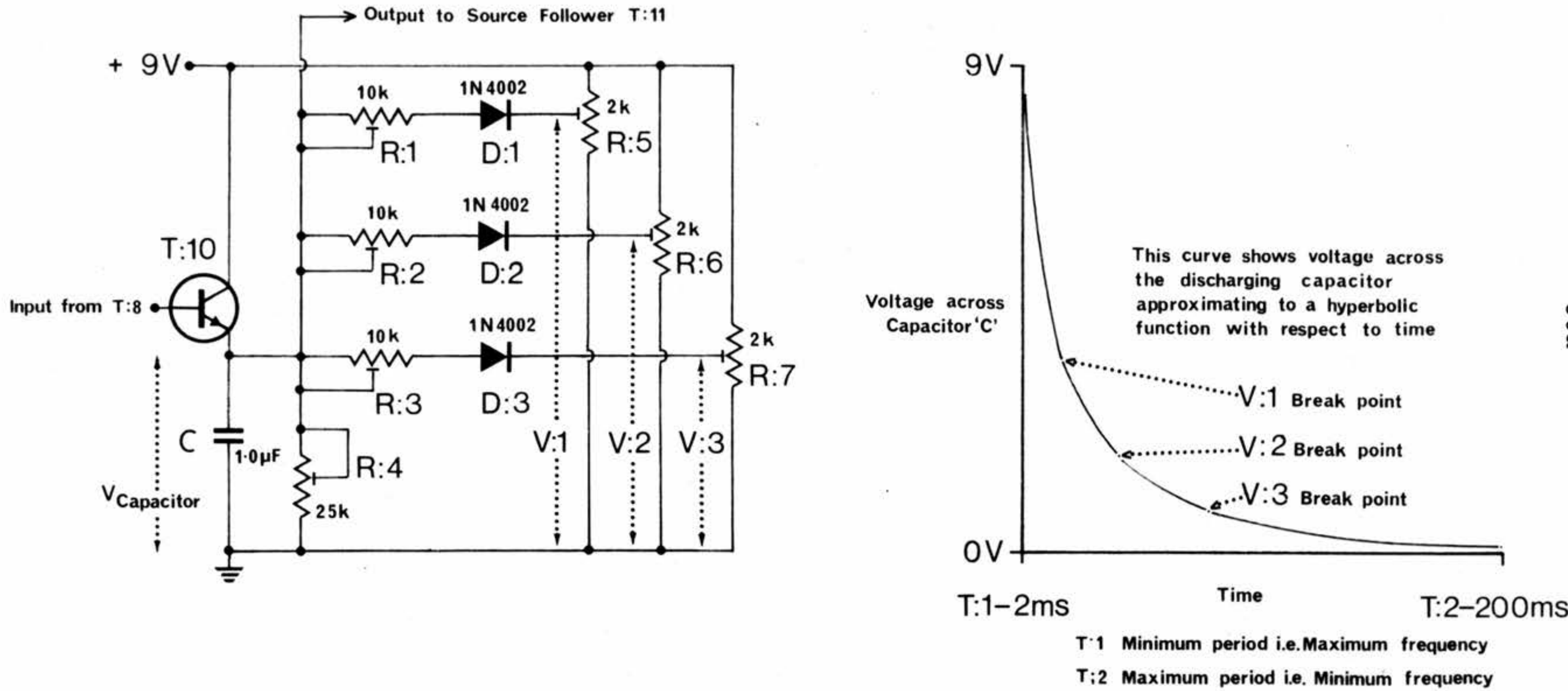
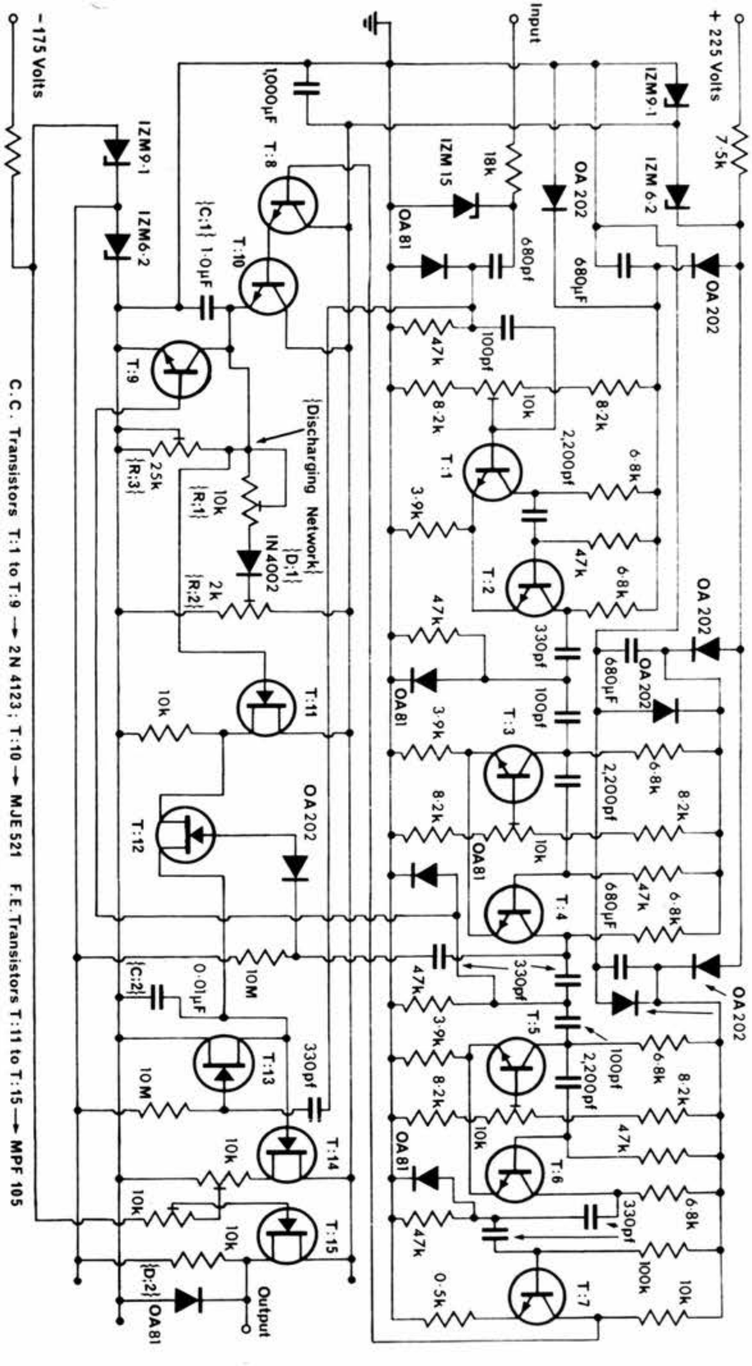


Figure : 15/2



Circuit Diagram of Instantaneous Ratemeter

Fig. 16

output socket of a Tektronix pulse generator type 161, the leading edge of this pulse is fed to a semi-conductor (T13) which is driven hard-on. Because this device is in parallel with the sampling capacitor it discharges this capacitor completely thereby eliminating any false reading on the next occasion that it is used. The same positive spike pulse is fed to a delay system designated 'A' delay. An analysis of the type of delay used is given in Appendix VII. There are two reasons for using a delay at this point; these are that

i) it allows enough time for the sample capacitor to discharge before anything else is undertaken within the system, and

ii) the time of A, B and C delays is such that the eventual non-linear discharge of the waveform capacitor starts after a period determined by the upper part of the frequency range of the instrument.

At the termination of the 'A' delay a negative going spike is directed to another delay system, designated 'B' delay. After being triggered, the output pulse signal from 'B' is directed to the sampling gate (F.E. transistor T 12) which when operated transfers to the holding or sampling capacitor a proportion of the voltage which is across the waveform capacitor at that moment of time. When the 'B' pulse ends it closes the sampling gate, so ensuring that no more information is transferred to the hold capacitor and also produces a negative going spike.

This signal spike is directed to two further stages of the

Waveform Diagram of Ratemeter

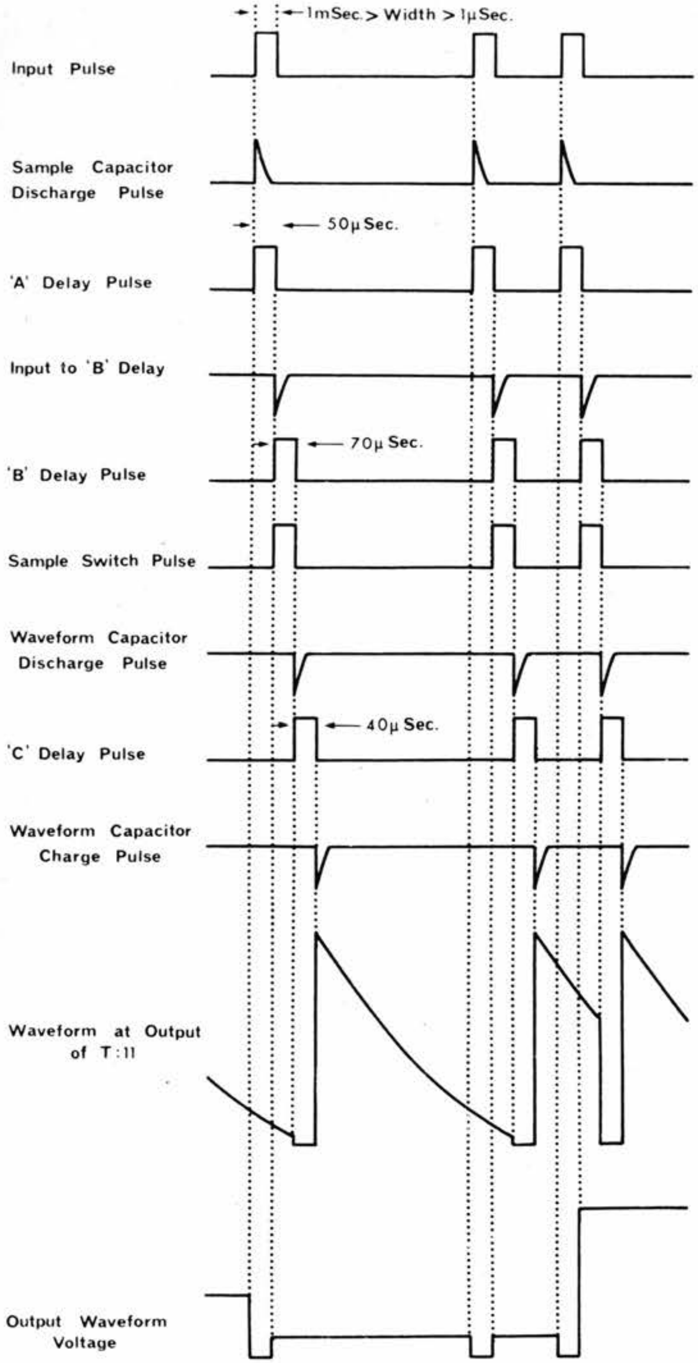


Fig. 17

instrument which perform the following functions:-

i) Energises a transistor (T 9 - Fig. 16) such that because it is in parallel with the waveform capacitor (C1) it discharges any previous charge on it so that it will not accumulate previous charges.

ii) Initiates another delay designated 'C' delay. The reason for this delay is that it allows time for the waveform capacitor to be discharged completely by T9 such that there is no accumulation of charge on this capacitor which otherwise would affect the reading across it.

At the completion of the 'C' delay pulse a differentiating network produces a negative going pulse which is amplified and inverted by T 7. This in turn is directly coupled to a 'Darlington' pair of transistors T 8 and T 10 which charge the 1.0μF waveform capacitor extremely quickly. Once the waveform capacitor (C1) has been fully charged, T 8 and T 10 cut off and the discharging network of R1, R2, R3 and D1 across C1 commences to discharge approximately to a hyperbolic waveform.

In Figure 16 only one biased diode resistor network (R1, R2 and D1) is shown but two more networks were added parallel to it. In the interest of clarity they were omitted from this drawing, but with reference to Figure 15/2 detail of the discharging network used has been drawn. R.S. MacKay showed that when discharging a capacitor (i.e. C1; Figure 16 and C; Figure 15/2) by different values of resistors (i.e. R1, R3; Figure 16 and R1,2,3 & 4; Figure 15/2) which were themselves switched out of the network by diode gates (i.e. D1; Figure 16 and D1,2 & 3; Figure 15/2), the potential across the discharging capacitor approximated to a hyperbolic curve, with an error of 6% if a three biased network was used. The readings displayed on the R2 instrument show that by using the same number of networks the percentage error is less than he stipulated. This is due to the fact that the break-points (i.e. cut-off points) on the discharge curve are not sharp but are gradual caused by diode characteristics rounding off the transition from one slope to another. These diode gates are activated when the voltage curve passes predetermined break-points which are set by potentiometers (i.e. R2; Figure 16 and R5,6 & 7; Figure 15/2). The discharge of the network was displayed on a C.R.O. with a hyperbola inscribed on the graticule. The break-points were then adjusted to the best visual match.

After the transfer of voltage information from C1 to C2 a field effect transistor (T 14) reads that voltage which is present on C2, and by virtue of the fact that it presents a very high resistance across this capacitor the voltage does not decay rapidly to zero. The decay time constant of C2 and the input resistance of the source follower (T 13) approximates to 60 seconds, thereby ensuring that after this interval the output voltage falls to a low potential and no ambiguous reading will result. This can be seen on the top trace of Figure 13 after the cessation of the input pulses. After the analogue signal has passed through the source follower (T 14) it is processed via two 10 KΩ potentiometers to the output stage (T 15). The first potentiometer controls the voltage excursion at the top end of the frequency range and the second one sets the output level at the lower end of the range. The output stage (T 15) is a source follower which, as it is analogous to a cathode follower, presents at the output a very low resistance which enables low input impedance chart recorders to be used at its output.

A copy of the instructions for using the Instantaneous Frequency Meter is given in Appendix VIII.

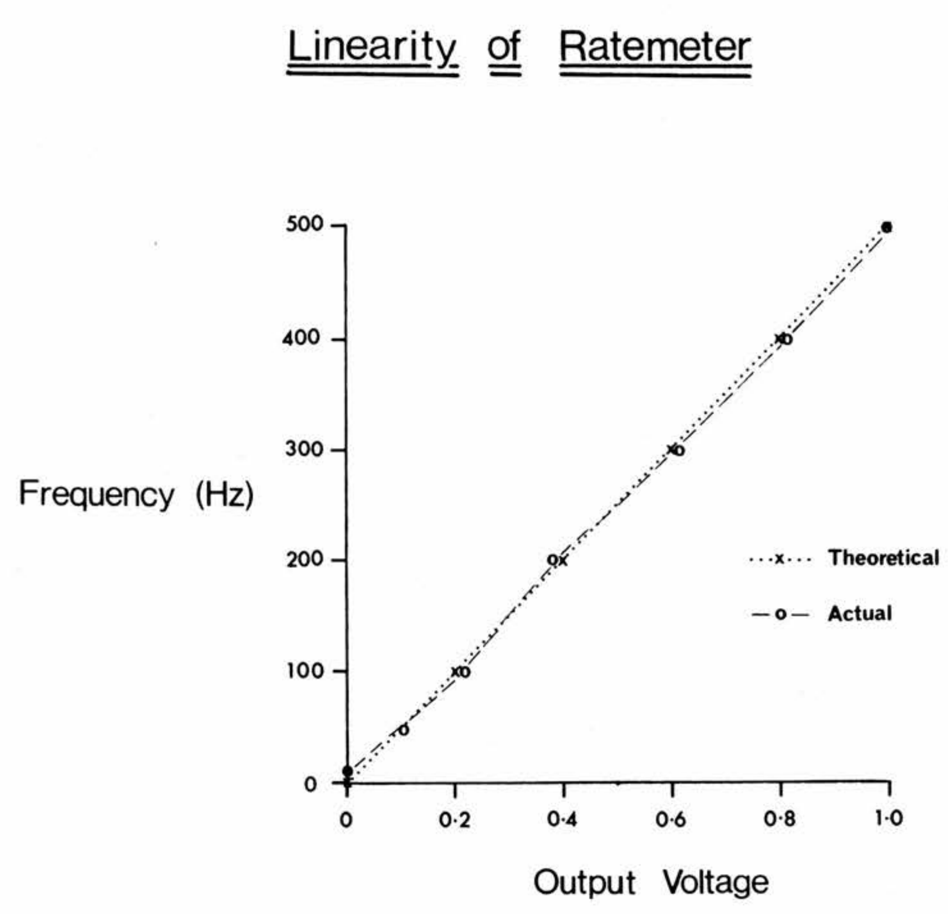


Fig. 18
Linearity of Frequency Meter

RESULTS AND CONCLUSIONS

With reference to Figure 18 which shows the linearity of the Frequency Meter it can be seen that the percentage error is not more than 5% over a frequency range of 100:1 so following point (a) of the design brief (Pages 33-34). On examination of Figure 13 it will be noticed that when the burst of input pulses is arrested the output voltage of the Mk:R2 instrument does not remain constant but starts to decay towards zero. This decaying voltage indicates that the period since the last pulse appeared is lengthening, and as such, follows point (b) of the brief which required that information on frequency is being constantly presented.

Referring to the first three traces of Figure 19, the first trace shows an extracellular recording from the eye withdrawal motorneuron in the optic tract of _Carcinus maenas_ (by courtesy of D.C. Sandeman) and it can be seen that the voltage height of the spike signals varies considerably; this is due to the fact that different types of cells are producing spikes during this period of observation. The second trace shows the signal from the pulse generator output of the window discriminator. The upper window level section of the discriminator is cancelled and the lower window level is so adjusted that it is triggered by all of the signals at that particular height. The gate output of the pulse generator is directed to the Frequency Meter and the third trace shows the frequency distribution of the voltage train. At one point in Figure 19 (arrowed) the third trace almost breaks

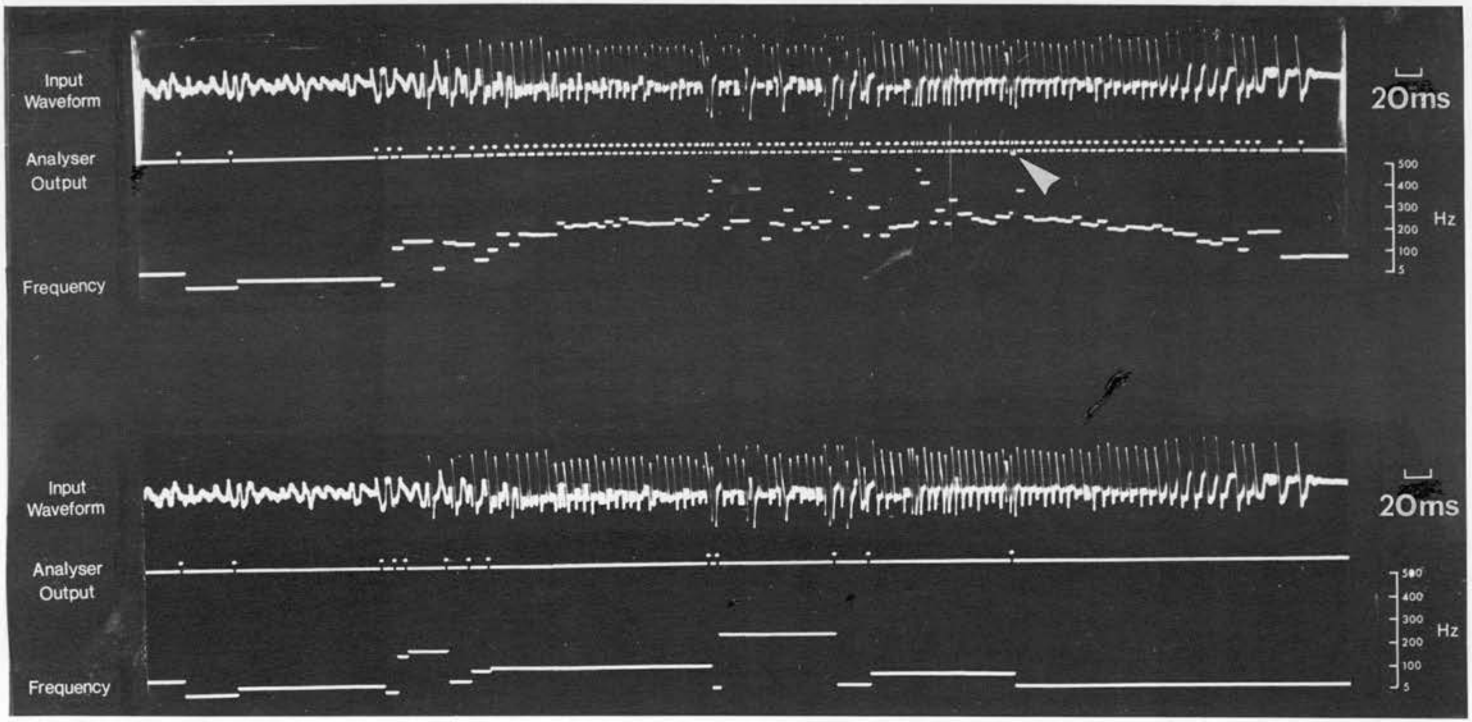


Fig. 19
Oscilloscope Recordings showing the output of the Discriminator and Frequency Meter (See text).

through the base line of the second trace; on looking closer at this 'bar' of information it can be seen that it is above the 500 Hz point of the scale, thereby indicating that the input frequency has passed above the upper design limit as in point (c) (Page 33). With regard to the fifth and sixth traces (Fig. 19), the fifth one shows the output when the inhibitory section of the discriminator is switched into the system. The attenuator was so adjusted that the discriminator inhibited the large input signals while permitting the smaller ones to pass through and trigger the output generator. The selected pulses were directed to the input of the Frequency Meter (F.M.) and the sixth trace shows the frequency distribution of the input signal that lay between the two levels of the analyser. The discriminator and ratemeter were also utilized by Shepheard (Ref. P.R.B. Shepheard) to follow electrically the output of motor nerves initiating the head movements of _Schistocerca gregaria_. In doing so he found that he could differentiate between axons which conveyed dissimilar signals. The ratemeter also showed, in his experiments, that the motor output frequency reached in each case was more or less the same for step changes in stimulus.

The F.M. and discriminator were designed to be powered from a power supply unit type 160A and the F.M. to have an input signal that was derived from a pulse generator type 161, the triggering of which was fed from the window discriminator. Both of these supplementary instruments are manufactured by Tektronix Limited.

The reasoning behind the use of these commercial instruments to feed the F.M. and discriminator was that there would be no difficulty in introducing them into the experiments as every investigatory set-up within the laboratory uses Tektronix equipment, therefore the condition of point (d) was fulfilled. As the F.M. and the discriminator use removable printed circuit cards in their construction, the replacement is made simple in the case of any malfunction and also the use of a very reliable external power supply substantially reduces the overall cost of construction. The further use of standard components in the design contributes towards an economic design as set out in point (e).

It will be seen therefore that two instruments were designed to:

a) select out and display a finite voltage signal which was enveloped in a large number of different voltages

b) display the frequency distribution of these potentials that were selected out as above.

These two criteria enable the source of a potential generator in a biological preparation to be ascertained relatively easily and as such the design can be seen to have been successful.

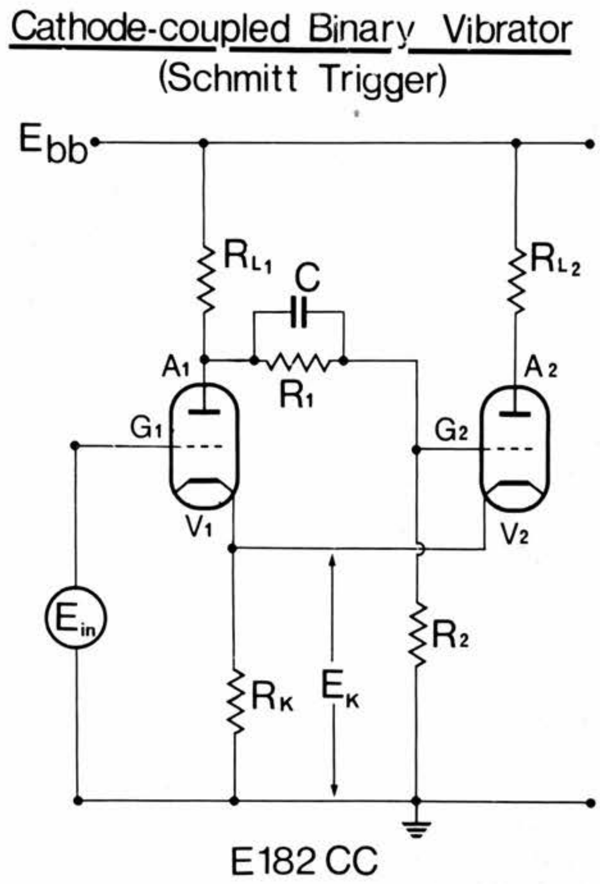


Fig. 20
Circuit diagram of Schmitt

APPENDIX I

Analysis of Schmitt Trigger

(Cathode Coupled Binary)

A Schmitt trigger (Ref. O.H. Schmitt) is a two stage regenerative circuit which changes from a stable state to a quasi-stable state when a voltage applied to its input exceeds a pre-set threshold value. When the voltage at its input falls below the value at which it changed its state, the Schmitt will reset back to the stable state and await the next input signal. The output from this trigger device is a positive square wave, the duration of which is governed by the changes in state.

With reference to Figures 20 and 21, consider that the input is 0 volts. It is possible to prove that the left hand side (L.H.S.) is cut off and that A 1 is at H.T. potential, i.e. the stable state. As the value of the resistances R 1 and R 2 is large, one can afford to neglect their loading effect on V1. The attenuation ratio of R 1 and R 2 is so adjusted that the grid-to-cathode voltage is negative two volts (-2V). It can be ascertained from the tube characteristics (see Figure 22) that IL2 = 7mA therefore the cathode-to-grid voltage of V1 = 7 x 15 = 105 V and valve V1 is therefore cut-off. The voltage at the grid of V2 is 105 - 2 = 103 V and the ratio of attenuation (α) is 103/225 = 0.45. The state of the Schmitt will not change until V1 comes out of cut-off and this will only happen when Ein = -7 + 105 = 98 V. The negative seven volts is derived from the fact that the anode to cathode voltage drop of V1 is 225 - 105 = 120 V; at this value cut-off

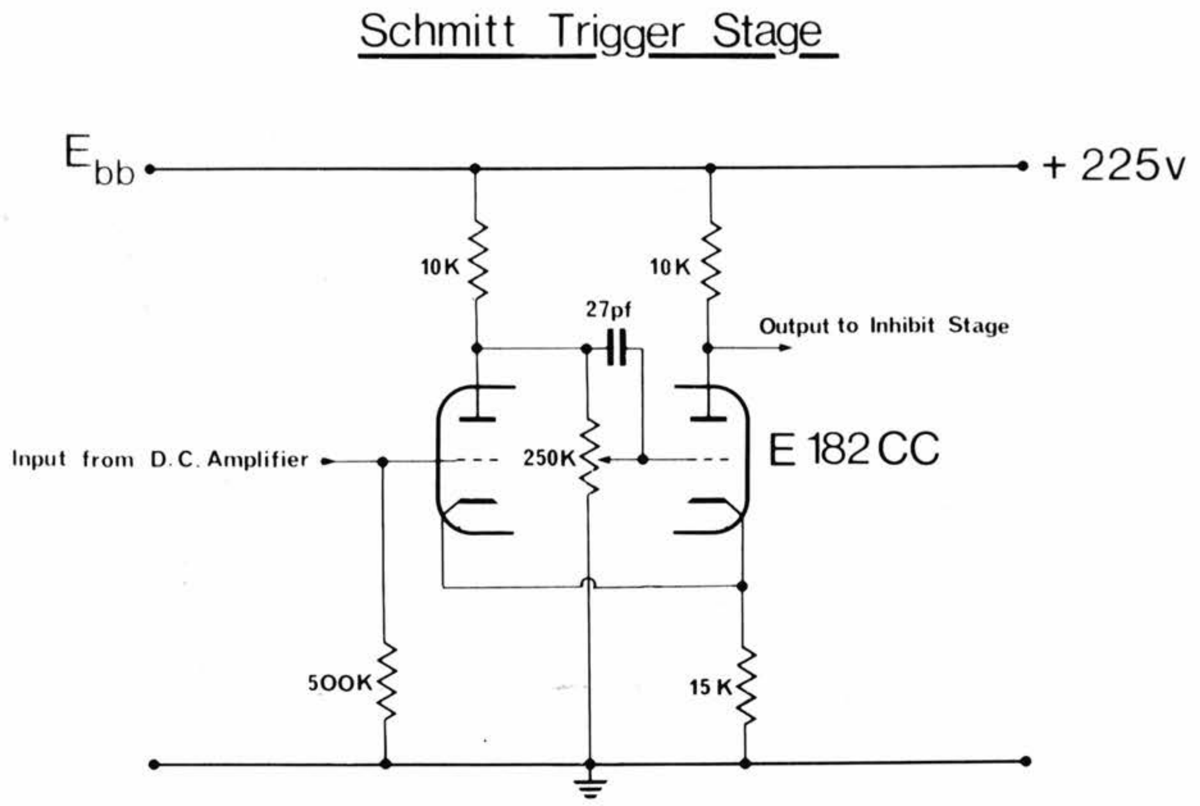


Fig. 21
Circuit diagram of Schmitt Trigger

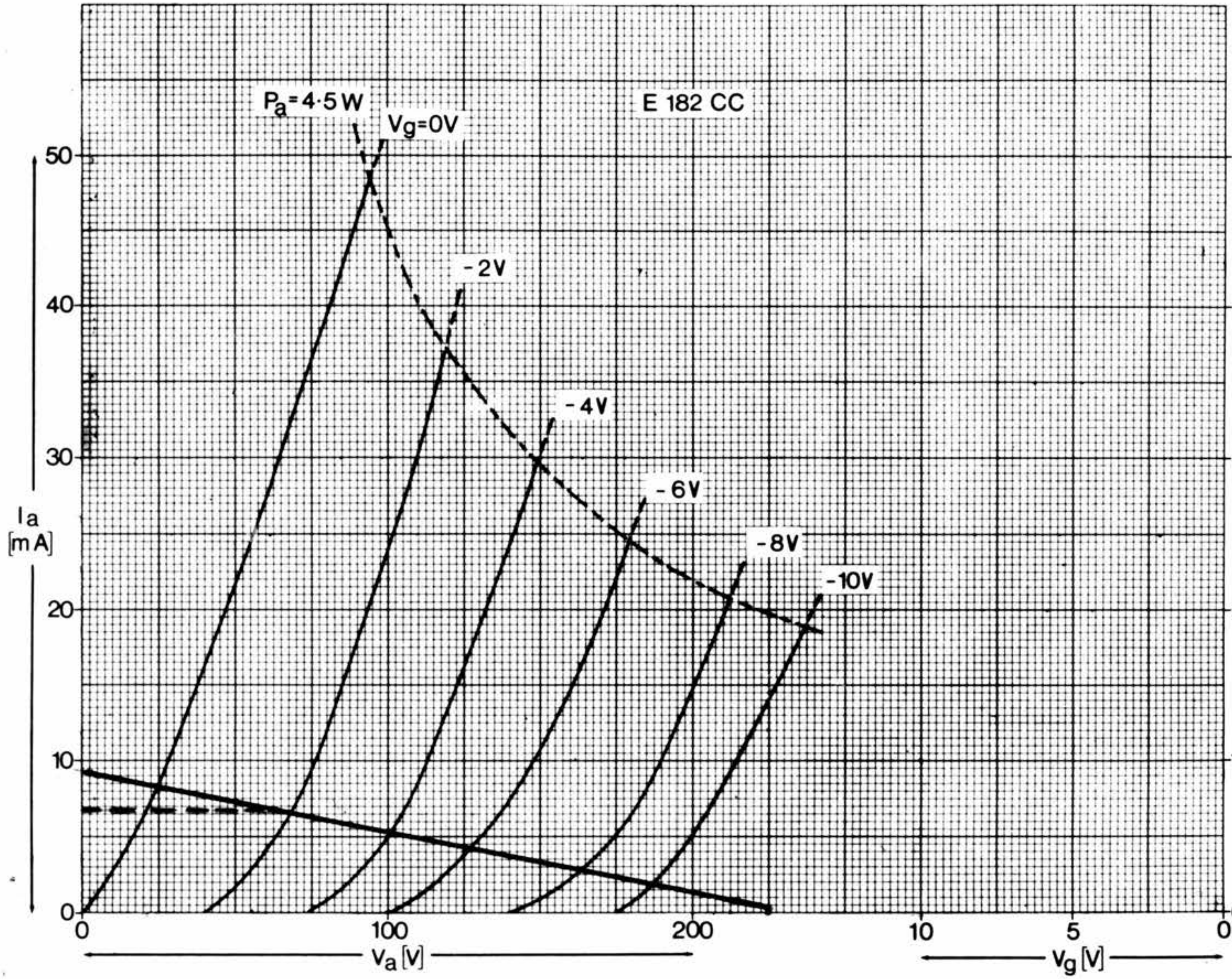


Fig. 22. Valve Characteristics of E182CC.

occurs at -7 V. When Ein reaches 98 V the voltage at the anode of V1 will fall taking G2 with it. The signal at G2 is transferred to V1 due to the fact that the cathodes are coupled together; this signal then appears at the anode of V1 in the same phase as at G2 and if the loop gain of the system exceeds unity a regenerative action will take place which will drive V2 to cut-off, i.e. the quasi-stable state. From Millman and Taub equation 5/10 Loop Gain $= \frac{\mu}{2} \times \frac{RL.\alpha}{RL + Ra} = 4.65$, therefore the loop gain exceeds unity.

As the loop gain is more than unity the Schmitt will move back into its stable state only if the input (E) is taken to a lower value than that which caused it to move into the quasi-stable state. This effect is known as backlash and is a function of the gain which is set by the preset potentiometer. The backlash in each Schmitt is set to the same value so that the upper Schmitt will always reset before the lower provided that the dial settings of the upper ladder selector are above the lower.

Assuming that V2 is cut off after Ein has risen above 98 V it is found from Millman and Taub equation 1 : 14 that IL1 =

$$\frac{Ein - Vgk}{Rk}$$

$$= \frac{98 - 2}{15} \text{ mA}$$

$$= \frac{96}{15} = 6.4 \text{ mA}$$

The voltage at grid 2 is $(225 - 6.4 \times 10^{-3}) \times 0.45 = 72.5$ V while the cathode voltage is $6.4 \times 15 = 96$ V; therefore the grid-to-cathode voltage of V2 is 72.5 - 96 = -23.5 V which proves that V2 is indeed cut-off.

The output pulse is taken from the anode of V2 and is a positive step, of value,

IL2 x RL i.e. 70 V.

(Derived from Millman and Taub).

APPENDIX II

Analysis of Amplifier Stage

In a biological preparation the amplitude of nerve potential appearing can vary from 10μV to more than 20mV. This is a variation of more than 2,000:1, and if these signals are to be processed using electronic instrumentation some form of voltage amplification has to be used.

An amplifying system that can be used in the Direct Coupled (d.c.) or Alternating (a.c.) mode was decided upon due to the fact that some signals are derived extracellularly and some intracellularly.

The first stage of the amplifier system (Fig. 8) uses an operational amplifier connected in the voltage follower configuration. This form of amplifier presents to the input a very high (typically 100 MΩ) impedance and one of the features of the voltage follower is that its gain is very nearly unity and is positive. A 10MΩ resistor was placed in series with the input of the Nexus 1009 operational amplifier (Fig. 8) so that, when the output of the ladder selector was traversed from the top to the bottom, i.e. from 500KΩ to 0Ω, the change in output voltage of the amplifier due to the variations of gate leakage current at its input would be minimised.

The output of the voltage follower is then fed to a changeover switch, the output of which is fed to either the invert or normal input of the following operational amplifier. The reason for the change-over switch is so that the operator can select positive or

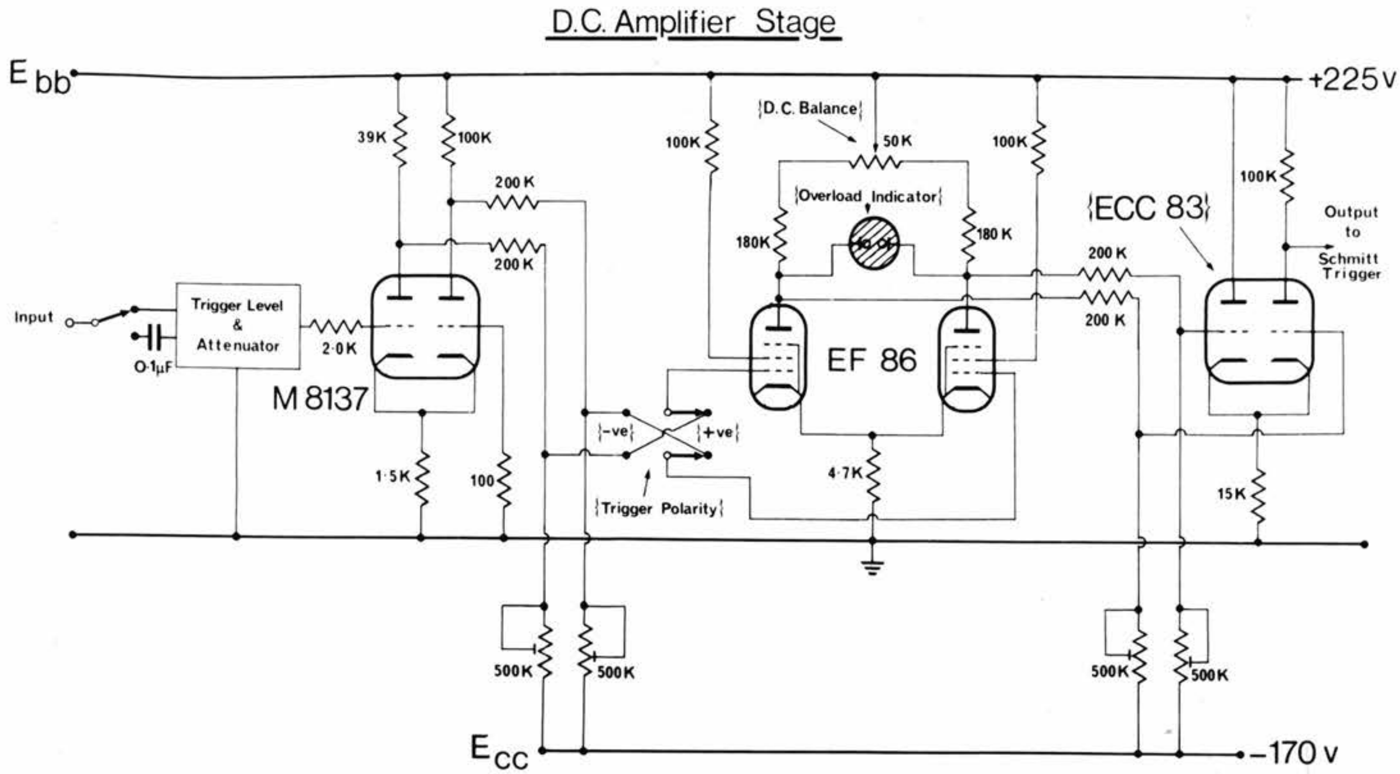


Fig. 23
Circuit diagram of valve type amplifier

negative parts of the input signal.

The output of the second operational amplifier is then fed via a polarity selecting diode to the third and final stage of the d.c. amplifier. The third stage is comprised of a valve (M 8162) with its quiescent anode potential set to 95 V. This level is just below the threshold level of the Schmitt trigger which follows the d.c. amplifier.

The total gain of the d.c. amplifier is approximately 10,000 and by the use of the selector switch and polarity diode (Fig. 8) either a positive or negative signal can be selected for processing.

A great amount of investigation was undertaken before this final form of amplification was decided upon. Amongst various types were completely valve types such as is shown in Fig. 23. Due to the reliance of d.c. stability on the heater potential in the first stages the valve type was superseded by the more stable solid state input amplifier, viz Nexus 1009 and SQ 5.

Voltage drift measured in the solid state amplifier was 50 $\mu V/^{o}C$ and the long term drift per day appeared to be 100 μV. These two drifts are relative to the amplifier input. The maximum temperature change noted was $\pm$ $5^{o}C$, the midpoint being $22^{o}C$. These figures compared very favourably with the drift of the completely valve type amplifier which was 5 $mV/^{o}C$. This was caused by the dependence of anode current on the stability of the heater potential and therefore the temperature. The 10 MΩ resistor at the input did not significantly affect the overall drift as the first operational amplifier exhibited a low voltage drift due to the inherent stability of a voltage follower. The discriminator operates with a differential of 500 μV between the two inputs over the range of input levels from 5 mV to 5 V. Since the setting up and operating instructions detailed a method of calibrating the discriminator an internal means of calibration was not considered necessary.

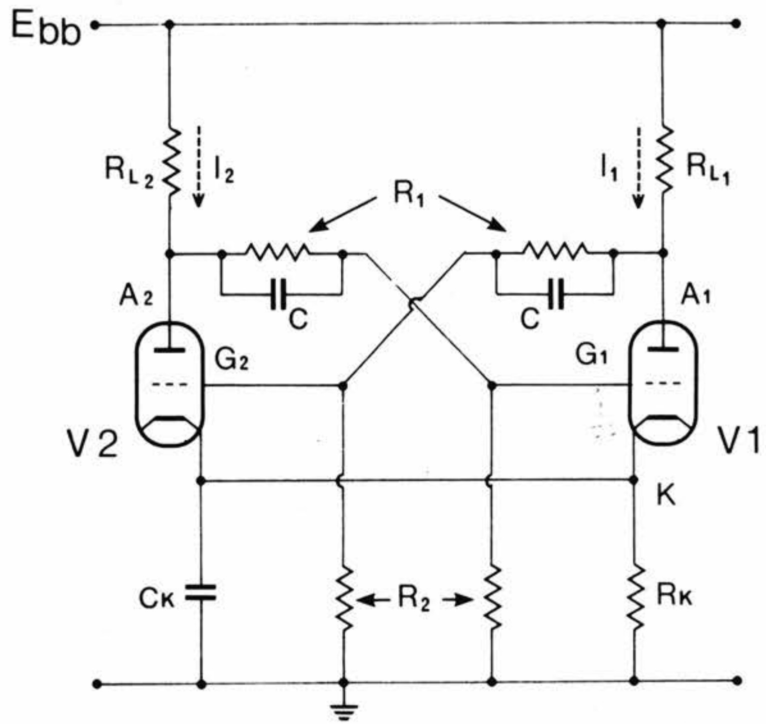
APPENDIX III

Analysis of Bi-stable Multivibrator

A bi-stable multivibrator is a two stage regenerative circuit that can exist in either of two completely stable states (Ref. Eccles and Jordan). The binary, as it is sometimes called, can be made to make a rapid transition from one state to another. The binary configuration is so arranged that there are only two outputs. The voltages at the output of each stage can be in two distinct but unequal voltage states, one of which is termed low and the other high. This stable state can be changed by a command signal injected into the binary whereupon the outputs change rapidly placing the output which was low to a high position and similarly the output which was high moves to a low state. The circuit can be so arranged, as it is in the final design, that the command trigger signal is injected at a point where, if the level is already at high it does not change and only if this level is at low will it change to a high state. One can then have a system which will reset to a high position only if it is at a low state but will not change if it is already at the high state.

If a command signal is then injected the circuit will or will not close depending on its state. This condition is dependent on whether it has previously received a set signal at the other inject point or not. One therefore has a gate system, the output of which can control the flow of signal information passing through another device such as an Inhibit Stage (See Appendix V).

Bi-Stable Multivibrator



M 8162

Fig. 24
Circuit of Binary Stage

The circuit of the self-biased binary is given in Fig. 24. The reason for utilizing a self-biased binary is that it

a) obviates the need of using a negative supply line with the resultant saving in economic conditions, and

b) complements the self-biasing of the mono-stable device (Appendix IV).

With reference to Fig. 24, it can be seen that it consists of two valves coupled so that the anode of $V_1(A_1)$ is directly connected to the control grid of $V_2(G_2)$ and the anode of $V_2(A_2)$ is directly connected to the control grid of $V_1(G_1)$.

The anode loads' RL_1 and RL_2 magnitude is of the order of that which is normally used in a conventional amplifier. It will be seen from Fig. 4 that RL_1 is not the same as RL_2, the reason for which will be explained further on. The signals applied to the two control grids are dependent only on the ratio of the coupling resistors R_1 and R_2. These resistors are usually, as in this case, made large enough not to load the amplifier output. In this design R_1 and R_2 lie in the range 100 to 470 KΩ and are of the same order of magnitude.

Usually the anode resistor loads are equal in as much as component tolerances allow and therefore the anode currents are relatively equal.

As outlined above, the anode resistors are <u>not equal</u> and in fact the value of RL_1 is 20% less than that of RL_2. The reason for this imbalance is to ensure that V_1 is always hard on and V_2 hard off when first applying the H.T. power. As the binary is guided into its proper logic state on first switching on, the sequence of switching within the entire inhibit stage will be assured. A short explanation follows which will verify the statement that V_1 is always On and Low and that V_2 is Off and High.

On first applying power to these valves there is nothing to stop both valves conducting equally, but on warm-up the anode of V_1 will approach the H.T. rail more quickly than that of V_2 due to the fact that RL_1 is less than RL_2. Once the grid of V_2 is brought more positive than V_{g1}, the cumulative amplifier action of V_1 and V_2 will ensure that V_1 is hard off and V_2 hard on. I have tested out more than 30 valves and not one has failed. It is also assumed that when ageing this imbalance will not be reversed. To assist this logic, resistors having a tolerance of 5% were used, so enabling the long term stability of this binary to be achieved.

Assuming that V_2 is cut-off and V_1 is clamped having a grid to cathode voltage of zero, the condition of V_1 is determined by drawing a load-line on the anode characteristics of the valve M 8162 (Fig. 25). The load-line is the line which passes through the supply voltage E_{bb} = +225V and has a slope inversely proportional to the resistor values $RL_1 + R_K$ therefore the Load Line = 39 + 10 = 49 KΩ. Where this line passes through the curve $V_g = 0$ of the characteristics, it shows that there is a quiescent valve current of 3.5mA, then the quiescent voltage at the anode of $V_1(V_{a1})$ is

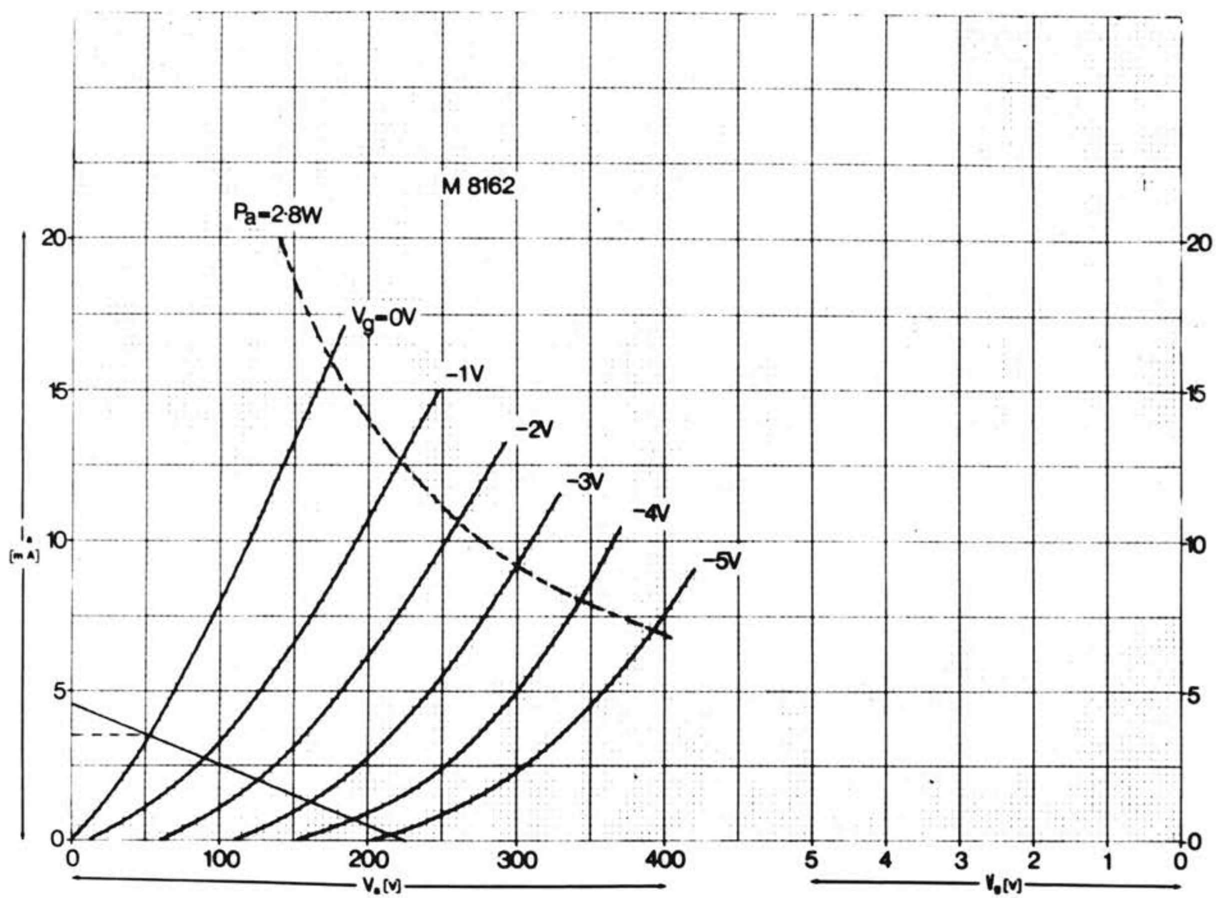


Fig. 25
Valve characteristics of M 8162

$$V_{a1} = E_{bb} - (RL_1 \times I_1)$$
$$= 225 - (39 \times 3.5)$$
$$= 225 - 136$$
$$= 89 \text{ V}$$

This figure of 89 V is true and is borne out by meter readings.

The voltage at the cathode (V_K) is the product of its value of resistor and the anode current I_1

therefore $V_K = I_1 \times R_K$

$$= 3.5 \times 10^{-3} \times 10^4$$
$$= 35 \text{ V}$$

The voltage at the control grid (G_2) of V_2 with respect to earth designated V_{g2e} is the product of the voltage at A_1 and the ratio of the resistors $\dfrac{R_1}{R_1 + R_2}$

therefore $V_{g2e} = V_{A1} \times \dfrac{R_1}{R_1 + R_2}$

$$= 89 \times \frac{150}{630}$$
$$= 21.1 \text{ V}$$

Then the grid to cathode voltage of V_2 is $21.1 - 35 = -13.9$ V. On looking again at the valve characteristics (Fig. 25), one finds that the cut-off occurs at -6 V, so V_2 is indeed cut-off as was assumed. To make absolutely certain that V_1 is clamped, the voltage at the grid of V_1 with respect to earth(V_{g1e}) will be calculated.

$$V_{g1e} = E_{bb} \times \frac{R_2}{RL_2 + R_1 + R_2}$$

$$= 225 \times \frac{150}{667}$$

$$= 50 \text{ V}$$

Since V_1 goes into a clamp or hard-on condition when the voltage on the grid is higher than that on the cathode, which as previously worked out was at 35 V, this value V_{g1e} shows that V_1 is indeed hard-on.

The voltage at the anode of V_2 is as follows:-

$$V_{A2} = E_{bb} - \frac{E_{bb} \times RL_2}{RL_2 + R_1 + R_2} = 210 \text{ V}$$

Then the voltage swing at the anode is:-

$$210 - 89 = 121 \text{ V}$$

In the calculations above various approximations have been made; these are:-

a) The loading on the valve of the coupling resistors (R_1 and R_2) are assumed to have a negligible effect on the performance, and indeed as they have a value which is a factor of ten above the anode loads, the loading can effectively be ignored.

b) In equating the voltage drop across the cathode resistor only the anode current was used and not the effect of positive grid current as well. Grid current is assumed to flow when it is driven positive, but as grid current usually is the order of micro-amps, no correction to the value of V_K was considered necessary.

Voltage levels in a binary very rarely have to be known with absolute accuracy so a more detailed calculation was not considered necessary. This view is supported by the approximate information given by the manufacturers of both passive and active components.

When the binary changes state, i.e. from one valve being hard-on and the other being hard-off to the first one being off and the second on, the current through R_K will vary and may drop to a low level. To overcome this possible malfunction during the transitory period, a capacitor (C_K) having a value of 0.01μF was parallel-coupled to R_K, so ensuring that at no time was the bias voltage at the cathode removed. The reason for using a capacitor value of 0.01μF was that the overall time constant of R_K and C_K was 100μs, and this was deemed long enough to hold the bias voltage during the change-over period which is of the order of 1μs.

The type of binary which is used here is triggered from one state to another by negative going spikes. These spikes are applied to the separate anodes by coupling capacitors and they are in turn coupled to the opposite valve grid by the resistor chains R_1 and R_2. The initiating spike signal can be attenuated by combination of R_1 and C_m (Miller Capacitance). To overcome this attenuating effect which at times negates the trigger pulse, such that the binary might not change its state, a compensating capacitor was inserted in parallel to R_1 assisting the propagation of the trigger pulse. This capacitor is known as a speed-up or commutating capacitor and its value, though not critical, is not usually more than 50 pF. The exact value was calculated using the formula:-

$$C \text{ coupling} = \frac{R_2 \times C_m}{R_1}$$

(Derived from Millman and Taub)

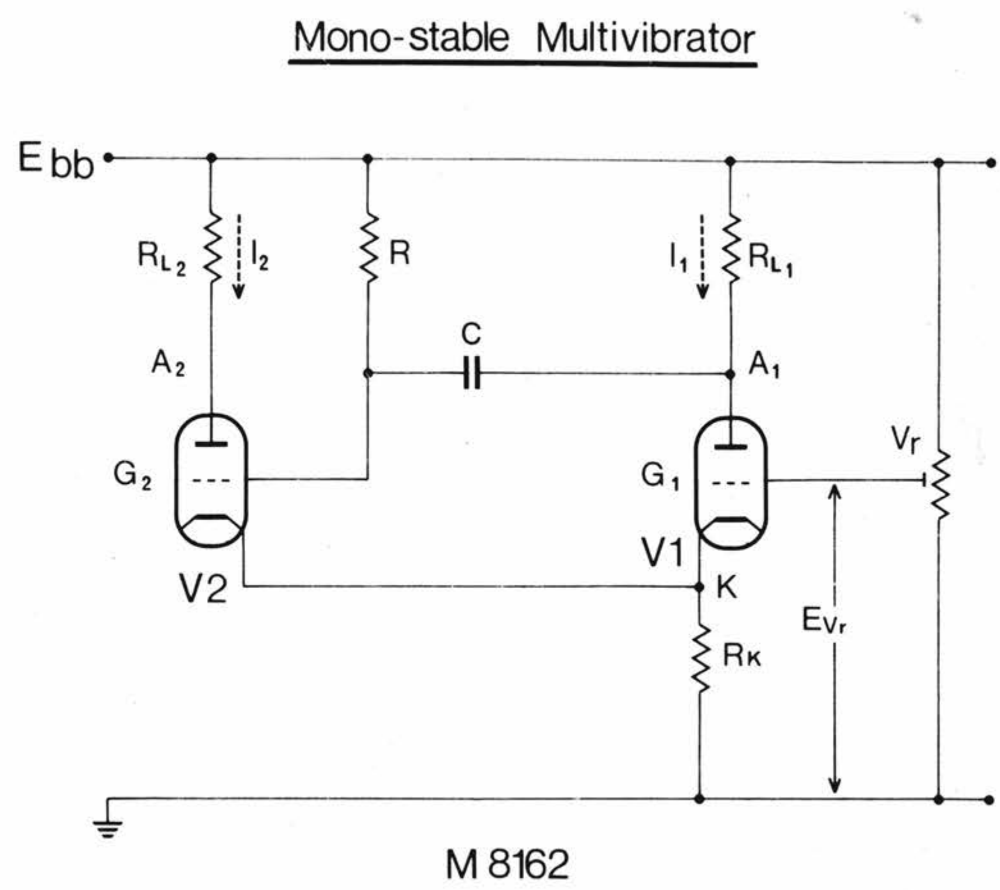


Fig. 26
Diagram of Delay vibrator

APPENDIX IV

Analysis of Mono-stable Multi-vibrator

A mono-stable vibrator (Fig. 26) is a two stage regenerative circuit that can remain in two states, one stable, the other quasi--stable. It is normally in the stable state and only moves over to the unstable state for a certain time 'T'. The time can be selected by the choice of components. After this time 'T', the mono moves back under its own volition to the stable state to await the next command signal. A triggering signal is required to induce a transition from the stable to the unstable state and this trigger signal is obtained from the differentiating network within the Inhibit Stage (Fig. 4), which is at the output of the lower Schmitt trigger stage. This mono therefore will produce a square wave voltage signal the duration of which can be controlled. This output voltage step is applied to another differentiating network, polarity selected to pass on only the negative signal spike. This negative signal spike is then passed on to the reset anode (Fig. 4) of the bi-stable which if it is in the high state will move down to the low state but only if it is high. It can be seen therefore that the mono system produces a delayed triggering signal only if it is itself triggered by the lower Schmitt trigger.

The circuit of the mono-stable as used is given in Fig. 4. The reason for using a cathode coupled (self biasing) mono is that the anode A_2 at which the output signal is taken off is not directly involved in the regenerative loop. The loading at this point therefore does not affect the interval at which the mono is set.

Referring to Fig. 26, it can be seen that it consists of two valves coupled so that

a) the anode A_1 of one is capacitor/resistor coupled to the other valve's grid G_2

b) the grid G_1 is coupled to a potentiometer V_R, the function of which is to set accurately the time interval of this device, and

c) the cathodes are coupled together and terminate to earth via a common resistor R_K.

The anode loads RL_1 and RL_2 are of equal magnitude and the anode A_1 is the one at which the negative trigger signal is injected. In the stable state V_1 is biased so that it is cut-off and V_2 is conducting. This situation will remain until a negative going signal is injected at A_1 and via C to G_2. After this trigger pulse has been applied, the state of V_1 reverses and it is so arranged that it conducts heavily. When V_1 starts to conduct V_2 is forced into a state of non-conduction, the voltage at its anode A_2 rising towards and reaching E_{bb}. V_2 is driven into cut-off by the same negative pulse that is applied to V_1. When V_1 abruptly changes to the conducting state, the voltage at the anode falls sharply and as the capacitor C (Fig. 26) is connected to it, the voltage on both sides of this capacitor falls by the same amount. This is due to the fact that the capacitor cannot charge instantly but only after a certain time.

The voltage at G_2 falls with V_{A1} and rises to E_{co} in a time:-

$$T = RC \log_e \frac{E_{bb} + I_1 RL_1 - I_2 R_K}{E_{bb} - E_{co} - I_1 R_K}$$

This equation is derived from Millman and Taub Equation: 6/5.

After V_{A1} changes abruptly, the voltage at G_2 will rise slowly governed by resistor R. A point will be reached where the voltage will be of a value (V_2 cut-off) at which V_2 will start to conduct. Once V_2 starts to conduct, regenerative action of V_1 and V_2 will ensure that the change back into the stable state is abruptly made.

(Derived from Millman and Taub)

APPENDIX V

Analysis of Inhibit Stage

An inhibiting co-incident stage is one in which, if an inhibit command is injected before a signal reaches the gate, the signal will not be passed through. On the other hand, if there is no inhibit command before the signal reaches the gate, the signal will be able to pass on unhindered. A device which will satisfy these conditions is a dual control grid valve and in this design a pentode (6U8) was used.

Further to the brief description of the whole device on Page 4, the window discriminator can have two states at its output. They are as follows:-

a) when an input voltage signal passes through two threshold values no output signal is produced

b) when an input voltage signal passes through the lower of the two threshold values only, an output signal is produced.

Taking the state at a) above and referring to Fig. 3 when an input signal is directed into the system and after amplification is of sufficient height to trigger off both the lower and upper Schmitt stages, the outputs from both the Schmitts are fed to their respective inputs of the gate stage (Fig. 4).

Referring to the waveform diagram (Fig. 3) and circuit diagram (Fig. 4), when the upper pulse(known as U.P.) enters it is differentiated and positively clipped to produce a negative spike which is fed to the set anode of the bi-stable. On receipt of this pulse the bi-stable will change state to a high condition. The voltage at the reset anode will rise towards E_{bb} and as it is directly connected to the screen-grid of the co-incident pentode valve, the pentode valve will be driven hard-on and the anode potential will fall to a low point. This fall is then fed into the final output cathode follower valve, the cathode follower being so adjusted that the output is normally at zero volts. When this fall in grid voltage is present the output falls to a negative value, typically negative 40 V.

A finite time after the U.P. has entered, the lower pulse (known as L.P.) enters and is differentiated and clipped to produce a negative spike also. This signal is fed to two input points within the system. Taking the first input point as the control grid of the pentode, this spike is amplified and inverted and the output of this is directly fed to the final output cathode follower. As was described above, the voltage at the output is at -40 V and as the amplitude of the spike is so arranged that it is not more than 40 V positive, the final output signal will not appear to rise above zero volts.

Taking the second input point as the input anode of the mono--stable stage, this input triggers this stage to produce at its output a narrow pulse typically lms. The output is fed to a differentiating and clipping circuit, the output of which is taken to the reset anode of the bi-stable stage.

On receipt of this pulse the bi-stable will change to a low condition. When it changes to a low condition, the voltage at the reset anode will fall to a low value. This is approximately 80 V and as this is connected to the pentode and triode valve the potential at the final cathode follower output will be reset to zero.

With reference to the state as outlined on Page 9, only a single square wave pulse will be produced and that by the lower Schmitt trigger valve. When the L.P. enters the gate stage it is differentiated and clipped to produce a negative going spike (Figs. 4 and 5) and is fed to the mono-stable and output stages. In this case, however, the output pentode valve has not been driven hard on and is biased such that it will amplify and invert this spike in a reasonable fashion.

The voltage at the final output of the cathode follower stage is in the quiescent state set at zero volts. When the positive going signal is applied to the input grid of the cathode follower it is reproduced at the output as a positive spike rising from zero volts.

The second path for the negative spike derived from the lower Schmitt is directed towards the mono-stable stage which produces a negative going spike from the differentiating network at its output; this is fed to the reset anode of the bi-stable. In this case, however, the bi-stable has not been placed in a set mode as there has not been a spike signal produced by the upper Schmitt. The design of the bi-stable is so arranged that it will not change its state if the reset anode receives a trigger pulse when that anode is at a low condition.

Similarly the bi-stable will not change its state if the set anode receives a trigger pulse when that anode is at a high condition.

APPENDIX VI

Instructions for using Discriminator Mk: II

This instrument has been designed to reject pulses that lie below or above two variable trigger voltage levels and to pass uninhibited pulses that lie between these levels. These two variable levels are designated lower and upper window levels respectively. The instrument is powered from a Tektronix power supply type 160A and the output from the discriminator (known as the DR/2) is fed into a Tektronix pulse generator type 161, so that the output pulse polarity, width and level can be selected at will. The DR/2 can be d.c. or a.c. coupled; in the a.c. mode the time constant is 0.05s, whereas in the d.c. mode the band width is flat to 10 KHz. It will also accept either negative or positive going signals with respect to earth and the sensitivity is such that it will accept signals as low as 5.0mV. Ideally the input to the DR/2 should be fed from the output of an E.S.G. amplifier or similar.

The following instructions should be observed so that the DR/2 is utilized to its fullest extent. Before switching on the 160A power supply,

1. Plug in the 8 pin octal power cord; one end goes to the front panel octal socket on the DR/2, the other goes to any vacant octal socket on the 160A.
2. Switch the inhibit/off switch to the off position and adjust both switch dials to zero.

3. Switch on the 160A and allow five to ten minutes for the whole system to warm up and stabilize.

4. Derive a bi- or mono-polar signal of not more than 500 Hz at an amplitude of 500 mV; connect this signal to the input of the DR/2 at the same time connecting it to the lower beam of the oscilloscope.

5. Connect a lead from the output socket of the DR/2 to the input socket of a 161 pulse generator. The controls of the 161 have to be adjusted as follows:-

   a) Trigger selector switched to positive pulse.

   b) Positive trigger bias control set to approx. 7 on dial.

   c) Pulse width switch and variable control set to 2 ms.

   d) Output pulse polarity switch to negative.

   e) Output pulse amplitude output to 5 V and connect a lead from the output socket of the 161 to the upper beam of the oscilloscope.

6. Select on the DR/2 the input polarity and mode; the input polarity can be judged by monitoring the signal on the lower beam of the C.R.O., as in section 4 above.

7. Rotate the lower window switch and dial (known as L.W.) until a pulse appears from the output 161; this signifies that the input pulse has passed through the lower window.

8. Switch the inhibit/off switch to the inhibit position then

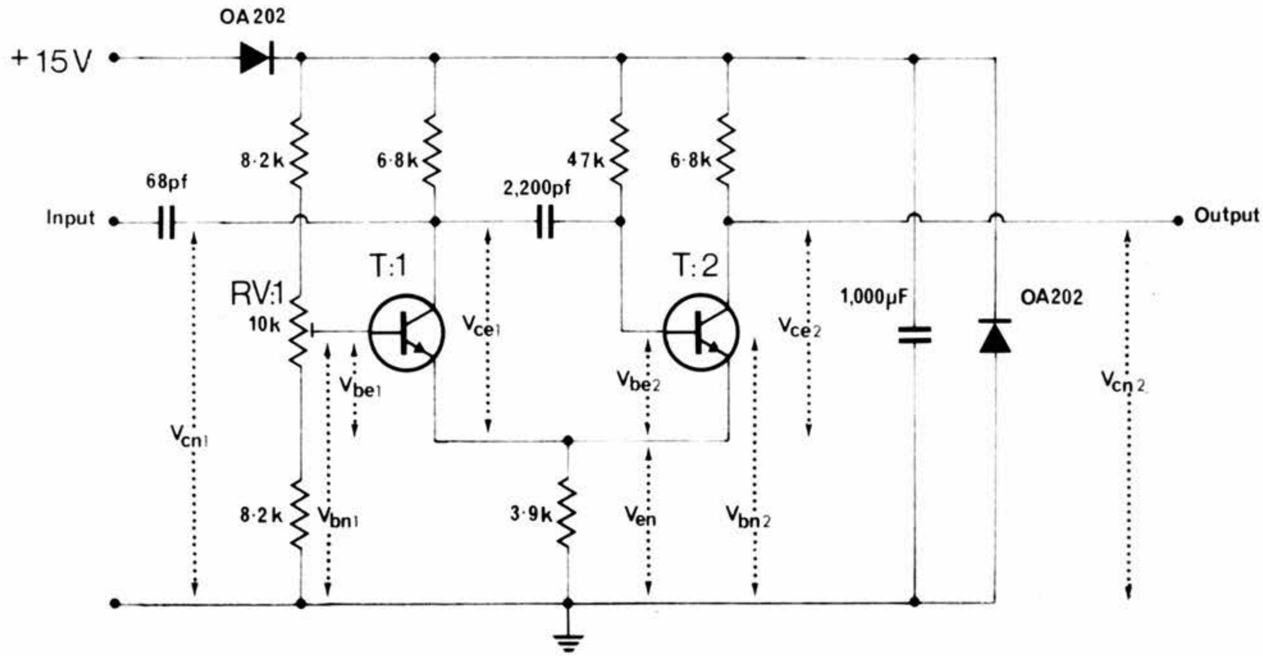
rotate the upper window switch and dial (known as U.W.) until the output pulse disappears. This signifies that the input pulse has passed through both levels and that the DR/2 is functioning correctly.

9. Remove the input test pulse and substitute the signal that is to be processed and by repeating steps (7) and (8), the desired signal levels can be rejected or accepted.

10. To test at any time whether the DR/2 is functioning correctly all that is required is for the inhibit/off switch to be placed in the off position and all the pulses that are passing through the L.W. will be displayed; on replacing the switch to the inhibit position only those pulses that lie between the two levels will be passed.

11. The L.W. and U.W. can be so adjusted that the DR/2 will discriminate between signals that differ in amplitude by 300 μV.

Emitter Coupled Multivibrator



T:1 & T:2 — 2N 3704 or 2N 4123

RV:1 Set Pulse Width

Fig. 27
Circuit Diagram of Transistor Delay

APPENDIX VII

Analysis of the Delay Circuit

The type of time delay circuit that was used in the frequency meter was the emitter coupled multivibrator (known as the mono). A mono is a two transistor stage regenerative circuit which can be in two states, one stable, the other quasi-stable. The mono is normally in the stable state and only moves over to the unstable state for a finite time 'T', the duration of which can be selected. After this time 'T', the mono moves back to the stable state without requiring a resetting signal.

To induce a transition from the stable to the unstable state, a triggering signal has to be introduced to the device and in the above design a narrow spike signal was used. This was injected (Fig. 27) at the collector of T1 which in its stable state is non-conducting. The output signal is taken from the collector of T2 which, as it is not directly involved in the regenerative loop, is the ideal take-off point. To ensure that T2 is hard ON and T1 is OFF, the left and right hand side (L.H.S.) and (R.H.S.) of Figure 27 is redrawn in Figure 28.

Taking Kirchoff's voltage law (K.V.L.) round the right hand side (R.H.S.) two meshes, we have

$$15 - I_{b2} \times (50.9) - 0.7 - I_{c2} \times (3.9) = 0 \qquad (1)$$

and $$15 - I_{c2} \times (10.7) - 0.3 - I_{b2} \times (3.9) = 0 \qquad (2)$$

$$14.3 - I_{b2} \times (50.9) - I_{c2} \times (3.9) = 0 \qquad (3)$$

and $$14.7 - I_{c2} \times (10.7) - I_{b2} \times (3.9) = 0 \qquad (4)$$

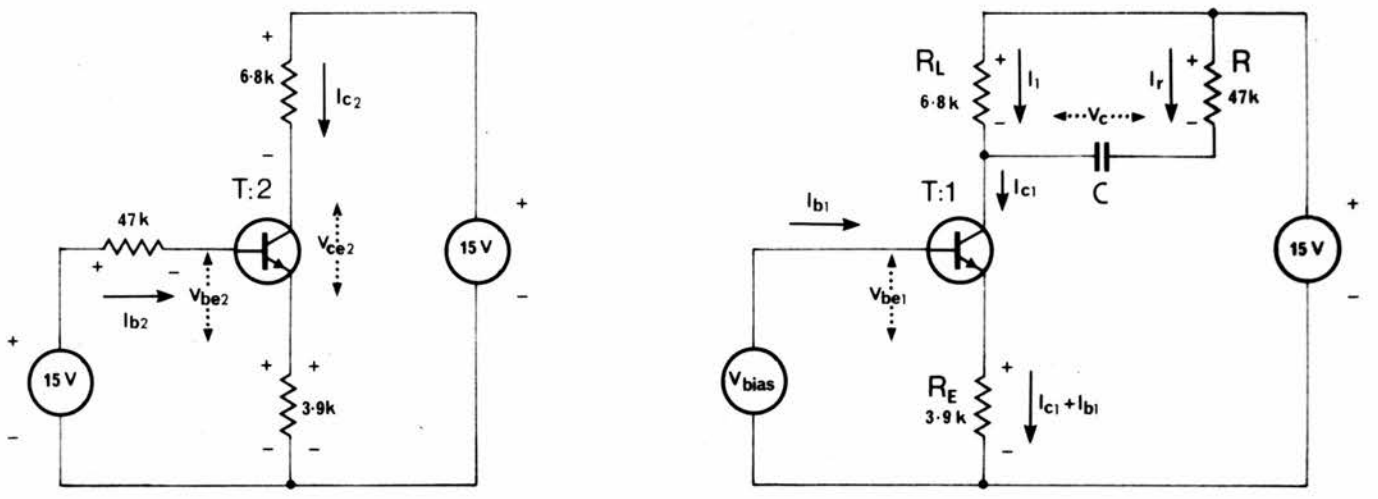


Fig. 28
L.H.S. and R.H.S. of Fig. 27

Solving by multiplying Eq. (3) by 10.7 and Eq. (4) by 3.9 and subtract

$$153 - 534.6 \times Ib2 - Ic2 \times 41.7 = 0$$

$$47.33 - 15.2 \times Ib2 - Ic2 \times 41.7 = 0$$

$$105.6 - 519.4 \times Ib2 = 0 \tag{5}$$

$$Ib2 = \frac{105.6}{519.4} = 0.16 \text{ mA} \tag{6}$$

Substituting in Equation (1) above this value of Ib2

$$15 - (50.9 \times 0.16) - 0.7 - Ic2 \times (3.9) = 0$$

$$14.3 - 8.14 = Ic2 \times (3.9)$$

$$Ic2 = \frac{6.2}{3.9} = 1.6 \text{ mA} \tag{7}$$

Then Minimum h_{FE} required $= \frac{1.6}{0.16} = 10$ (8)

With reference to Figure 27

In the stable state Vcn1 = Vcc = +15 V

and Ven = (Ic2 + Ib2) x Re

= 7.1 V (9)

Now Vbe1 = Vbn1 - Ven = 5.3 - 7.1 = -1.8 V (10)

Then T1 is biased <u>off</u>

Now Vbn2 = Ven + Vbe2 (Sat.) = 8.0 V (11)

and Vcn2 = Ven +Vce (Sat.) = 7.4 V (12)

therefore

V across 'C' = Vcn1 - Vbn2 = 15 - 8.0 = 7.0 V (13)

Assuming a trigger signal has been passed to the collector of T1 and T1 comes <u>hard on</u>

$$Ven = Vbias - Vbel = 5.3 - 0.6 = 4.7 \text{ V} \tag{14}$$

(where V bias is the setting of RV1 Fig. 27)

$$Icl + Ibl = \frac{Ven}{Re} = \frac{4.7}{3.9} = 1.2 \text{ mA} \tag{15}$$

Since $Icl + Ibl = Icl \times (1 + \frac{1}{h_{FE}})$

$$Icl = \frac{h_{FE}}{1 + h_{FE}} \times \frac{Ven}{Re} = \frac{10 \times 1.2}{11} = 1.1 \text{ mA} \tag{16}$$

$$Il + Ir = Icl = 1.1 \text{ mA} \tag{17}$$

and K.V.L. applied to RL_1, C & R (Fig. 28)

$$RL_1 \times Il + Vc - R \times Ir = 0 \tag{18}$$

Since the V across C at the time (t = +0) of triggering does not instantly change

$$6.8 \times Il - 47 \times Ir = -7.0 \tag{19}$$

Solving Eq. (17) and (19)

$$Il = 0.83 \text{ mA}$$

and $Ir = 0.25$ mA

Then at time T = +0, $Vcn2 = Vcc = 15$ V

and $Vcnl = Vcc - Il \times RL_1 = 15 - 5.6 = 9.4$ V

and $Vbn2 = Vcnl - V$ across 'C' $= 9.4 - 7.0 = 2.4$ V

Then T2 is indeed <u>hard-off</u>

The time of the pulse out can be approximated to

$$0.7\ CR = 0.7 \times 2,200 \times 47 \times 10^3 \times 10^{-12}$$

$$= 70\ \mu s$$

These equations were derived from J. Millman and H. Taub.

APPENDIX VIII

Instructions for using Instantaneous Frequency Meter Mk:R2

This instrument has been designed to display on a calibrated meter and/or an external read out device such as a C.R.O. or a pen recorder the relative frequency of the last two preceding events. This instrument is powered from a Tektronix power supply type 160A and the input of the instantaneous frequency meter R2 (known as the F.M.2) requires a positive pulse greater than thirty volts to trigger it; ideally the input should be fed from the gate output socket of a Tektronix pulse generator type 161.

The following instructions should be followed so that the F.M.2 is utilized to its fullest extent. Before switching on the 160A power supply unit

i) Plug in the 8 pin octal power cord, one end going to the front panel octal socket on the F.M.2 the other going to any vacant octal socket on the 160A.

ii) Switch on the 160A and allow five to ten minutes for the whole system to warm up and stabilize.

iii) Derive a positive going signal having a pulse width of 1 ms or less, and an amplitude of thirty volts or greater.

iv) Inject this signal into the input socket of the F.M.2; setting the signal frequency to 5 Hz adjust the pre-set control marked 5 Hz so that the output meter reads correctly. Reset the input frequency to 500 Hz and by adjusting the 500 Hz pre-set control, set the meter to read full scale.

v) Connect the signal that is to be processed to the input of the pulse generator in place of the signal generator and the frequency monitoring system is ready for use.

There are two output sockets on the front panel of the F.M.2, one is marked 'Output A' and the other 'Output B'; a description of these follows:

a) The output signal at 'A' is directly proportional to the frequency input; at a frequency of 5 Hz the output is zero and at 500 Hz the output is one volt, the output being linear between these two frequencies, the linearity of the output being subject to an error of 5%.

b) The function of output B is so that small changes in frequency can be observed; this is done by monitoring the signal differentially from 'A' and 'B' and backing-off the standing potential of 'A' utilizing the 'B' output.

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