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ROYAL AIRCRAFT ESTABLISHMENT
FARNBOROUGH, HANTS

TECHNICAL NOTE No: G.W.225

**A PULSE-OPERATED
AUTO-CORRELATOR**

by

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and D.E.VERRIAN

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ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

A Pulse-Operated Auto-Correlator

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and

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SUMMARY

A pulse-operated auto-correlator offers advantages over other forms of correlator in its comparative simplicity and its ability, under certain conditions of use, to provide a complete correlogram without the necessity of recording the input data.

The system involves the storage of information on a series of condensers connected to the contact banks of two uniselectors, the wipers of which can be rotated at the same speed but with any desired angular separation, equivalent to the required values of τ , the correlation interval. Theoretically the results obtained are accurate for a repetitive function if the sampling rate is more than twice the highest frequency component.

A test instrument has been built which demonstrates that the principle is sound, and provides the basis of a practical machine. The main difficulties requiring further investigation are listed in the conclusions.

LIST OF CONTENTS

	<u>Page</u>
1 Introduction	3
2 Basic Principles	3
3 Practical Circuits	6
4 Control Circuit	7
5 Test Results	7
6 Conclusions	8
Advance Distribution	9
Detachable Abstract Cards	

LIST OF APPENDICES

	<u>Appendix</u>
Operation of the Summator	I
Control Circuit Operation	II

LIST OF ILLUSTRATIONS

	<u>Figure</u>
Basic Principle	1(a)
Modified Circuit	1(b)
Storage Circuit	2(a)
Multiple Storage	2(b)
Overall Circuit	3
Summator	4(a)
Control of Relays M and N	4(b)
Control Circuit	5
Graph of $\frac{1}{\sin \frac{2\pi}{n}}$ against n	6

1 Introduction

The construction of correlograms from recorded data by graphical methods is both tedious and lengthy. An instrument operated from continuous inputs may be somewhat complicated and must be used in conjunction with a recorder.

A model pulse-operated machine has been constructed which, apart from the multiplying and integrating components (common to any auto-correlator), employs only relays and simple electronic circuits.

2 Basic Principles

The operation is based upon the storage of samples of the input signal on a number of condensers. If the number of stores available is adequate to "record" the entire signal, all the points on the correlogram may be obtained without the use of additional recording devices.

2.1 Defining the auto-correlation coefficient as:-

$$V_{\tau} = \lim_{A \rightarrow \infty} \frac{1}{A} \int_0^A f(t) \cdot f(t + \tau) dt$$

then for a sinusoidal function $y = \sin \omega t$

$$\begin{aligned} V_{\tau} &= \lim_{A \rightarrow \infty} \frac{1}{2} \left[\cos \omega \tau - \frac{1}{\omega A} \sin \omega A \cdot \cos \omega (A + \tau) \right] \\ &= \frac{1}{2} \cos \omega \tau \end{aligned} \quad (1)$$

Now if the input is sampled r times at intervals t' then:-

$$Y_r = \sin r \omega t'$$

and

$$\begin{aligned} V'_{\tau} &= \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{r=1}^n \sin r \omega t' \cdot \sin \omega (r t' + \tau) \\ &= \frac{1}{2} \cos \omega \tau - \lim_{n \rightarrow \infty} \frac{1}{2n} \sum_{r=1}^n \cos \omega (2 r t' + \tau) \end{aligned} \quad (2)$$

$\sum_{r=1}^n \cos \omega (2 r t' + \tau)$ represents the sum of a series of vectors having successive angular separations of $4\pi \frac{t'}{T}$ where T is the periodic time of the sine wave. For $t' \ll T$ the sum will tend to zero at each complete

cycle and hence the second term of the expression for V'_τ will be zero. For larger values of t' the same effect will be apparent until $t' = \frac{T}{2}$ when the angular separation becomes 2π and the vectors add. However for $t' < \frac{T}{2}$ (that is, more than 2 samples per cycle) the second term is zero and

$$V'_\tau = \frac{1}{2} \cos \omega \tau .$$

2.2 In practice of course neither A in Equation (1) nor n in Equation (2) will be infinite. An error will therefore be apparent of magnitude dependent upon the length of data available.

It can be shown that if m is the number of samples per cycle then the second term of Equation (2):-

$$\begin{aligned} &= \frac{1}{2n} \frac{\sin 2\pi \frac{n}{m} \cdot \cos \left(\omega \tau + 2\pi \frac{n+1}{m} \right)}{\sin \frac{2\pi}{m}} \quad (3) \\ &= \frac{1}{2} C \cos (\omega \tau + \phi) \text{ for specific values of } n \text{ and } m . \end{aligned}$$

Thus compared with the true auto-correlation coefficient the error has an amplitude of 100 C % and a phase angle ϕ .

'n' must be integer but 'm' may have any value (> 2.0). If $\frac{n}{m} = \text{integer}$ then Equation (3) becomes zero. In practice it will not be practicable to ensure this condition and in any case for a complex waveform 'm' varies for each frequency component and hence it is safest to assume that $\sin 2\pi \frac{n}{m}$ has its maximum value of unity. The magnitude of the error will therefore be determined mainly by the factor:-

$$C' = \frac{1}{n \sin \frac{2\pi}{m}} \quad (4)$$

Fig.6 shows the graph of $\frac{1}{\sin \frac{2\pi}{m}}$ plotted against m and for $m > 2$ it will be seen to have a minimum at $m = 4$ when $\sin \frac{2\pi}{m} = 1$. Hence the maximum error for a sampling rate of 4 per cycle will be $\frac{100}{n}$ % relative to unity, and will vary between this value and zero according to $\sin 2\pi \frac{n}{m}$.

As an example consider a sampling rate of 25 per second and a frequency of 4 cycles per second.

Then

$$m = 6.25 .$$

From Fig. 6:-

$$C' = \frac{1.2}{n}$$

and for a maximum error of 1%

$$\frac{1.2}{n} \cdot 100 = 1 \quad \text{or} \quad n = 120 \text{ samples.}$$

Hence the data length should be a minimum of $\frac{120}{6.25} = 20$ cycles.

However

$$\frac{n}{m} = \frac{120}{6.25} = 19.2$$

and

$$\sin 2\pi \cdot 19.2 = 0.94$$

Theoretically the error will therefore be reduced by the factor 0.94, but for 119 samples the factor will be 0.06 and for 121 samples 0.7. In practice it is thus better to assume the worst case - that is $\sin 2\pi \frac{n}{m} = 1$.

Now if there is a component frequency at 1 cycle per second, it will be seen that $m = 25$ and for $n = 120$

$$100 C' = \frac{4.1}{120} \cdot 100 = 3.4\%$$

To reduce the error at this frequency to 1% it would therefore be necessary to increase the number of samples to about 500.

Thus for repetitive functions which can be analysed into a series of harmonics the auto-correlation coefficient may be obtained by sampling provided that $m > 2$ for the highest frequency component, and the error can be reduced to a desirable maximum by choice of suitable sampling rates and/or length of data. This is not necessarily true for a random input but forms a useful guide; if the data under consideration is obtained from a system which rejects by filtering action any frequencies greater than $\frac{1}{2m}$, then the sampling rate must be greater than 10 per second, and the minimum length of data for a reasonable degree of accuracy can be estimated.

2.3 A simple circuit arrangement is illustrated at Fig. 1(a). Two uniselectors, controlled by a pulse drive so that they step round together, have their corresponding contacts connected to each other and to storage condensers. With the stored voltages proportional to instantaneous values of the data, the unisector wipers apply the two required potentials to a multiplier. Switching is arranged so that the multiplier output is connected to the summator (integrator) once each time the wipers come to rest on a pair of contacts. If the uniselectors are synchronised so that they are both connected to the same condenser at the same instant, the output of the summator, when all the condensers have been sampled, is a measure of the auto-correlation coefficient for τ equal to zero. By advancing one wiper so that it steps a fixed number of contacts in front of the other one, an output equivalent to another value of τ is obtained.

2.4 As shown in Fig.1(a), the arrangement is suitable for the case when there are an adequate number of condensers to store the whole input data without the use of an additional recorder. Provided that the leakage is negligible, readings for all the available values of τ can be obtained from successive revolutions of the wipers. A limit to the method is imposed by the number of contacts or condensers available. A modification by means of which the system can operate from a recording is shown at Fig.1(b); a second contact bank of the first uniselector is used and the wiring arranged so that a condenser charged at (e.g.) contact 4 is connected to the multiplier via contact 5 (i.e., one step later). The charge must be stored only until the second uniselector has passed the equivalent contact; the operating time may therefore be increased indefinitely using as many revolutions of the uniselector as desired - the limitation is that τ can be increased only to the equivalent of one revolution.

2.5 For an input lasting for, say, 30 seconds with a highest frequency component of 5 cycles per second, a minimum of 300 storages is necessary to obtain an auto-correlogram without employing a recorder. If however the data is recorded, a 50 contact uniselector can be used - with a sampling rate of 4 per cycle (20 per sec), 12 revolutions will be necessary, and the maximum value of τ will be restricted to $1/12$ th of the recording ($2\frac{1}{2}$ secs). If the input contains higher frequencies, measurements can be made by slowing down the replay speed of the recorder (or increasing the sampling rate), but the number of revolutions will be increased accordingly, reducing the maximum value of τ ; an alternative is to deal with the recording in several portions to obtain the value of τ required, averaging out the correlogram from the individual results.

3 Practical Circuits

3.1 The basic storage circuit is shown at Fig.2(a), the condenser being connected to the grid of a cathode-follower. The use of this arrangement for each store would be extravagant, and also has the disadvantage that grid current and additional leakage in the valve assembly increases the rate of discharge. A more suitable method is illustrated at Fig.2(b); each condenser is connected only to its appropriate uniselector contact. A single cathode follower in the wiper circuit suffices for all the condensers (see also Appendix I, paragraph 2.1).

3.2 The overall arrangement is shown at Fig.3.

3.21 With the multiple-bank switches Sc_1 and Sc_3 set to position 1, the data will be stored on the condenser as the wiper of contact bank A_B rotates. The maximum time available is equivalent to one revolution of the uniselector. The remainder of the circuit is inoperative during this cycle.

3.22 For correlation, Sc is moved to position 2. On depressing the "start" control relay C will operate its contacts, removing the zeroing earth from the summator and connecting the cathode follower and multiplier in circuit. After one revolution P operates, providing the output as a D.C. signal; relay C drops out and a new value of τ can be set up by advancing the wiper of A_B . This process is continued until the required number of points on the correlogram have been obtained.

3.23 With Sc at position 3 the circuit is set up for use with a recorder. On operating the "start" control the first value of the input signal is stored on condenser 1 via contact C of A_A . Meanwhile the inputs to the cathode followers are both zero from condenser 0. At the next step, the second value of the input is stored in condenser 2, and condenser 1 is connected to the cathode followers. This process may be

continued for as many revolutions of the uniselector as desired, because a new input to a condenser will automatically cancel the previous stored value. The whole process must now be repeated, commencing at the same point on the recording, but with wipers A_A and A_B (mechanically joined) advanced for a different value of τ .

3.3 Fig.4(a) shows the summator circuit. When relay M operates the contacts M_2 and M_3 close and the input voltage is stored on the condenser associated with cathode follower CF_2 . When M releases this voltage is maintained at the output but, via contact M_4 , is also stored at CF_1 . When M closes again, the previous output at CF_1 , together with the new input value are added in the amplifier AMP.1 and stored at the output. There is a sign reversal in AMP.1 and consequently a further reversal is required (AMP.2) to obtain the correct sign at CF_1 . In the operation M_4 must open before M_3 closes to prevent the loop from being closed; when M releases M_3 must open before M_2 and before M_4 closes. Further information on the summator is included at Appendix I.

3.4 The multiplier employed was of the diode squarer type, having an output range of 0 ± 60 volts for inputs of 0 ± 50 volts D.C. It was discovered during tests that a considerable error was introduced due to ripple on the multiplier output, which of course was not apparent when measuring the mean output on a D.C. meter. The summator however accepts the instantaneous value when contact M_3 (Fig.4(a)) opens and consequently extra precautions were taken to suppress the ripple.

4 Control Circuit

The control arrangements were designed to meet the following conditions.

4.1 Simple "START-STOP" buttons to operate for each of the three conditions of paragraph 3.2.

4.2 A "ZERO" reset, to restore the uniselectors to their home contacts and discharge all condensers.

4.3 Switches to preset the value of τ .

4.4 A "RESET τ " control to restore the uniselectors to their initial positions for a preset value of τ .

The basic circuit is shown at Fig.5 and a description of the operation is in Appendix II.

5 Test Results

5.1 To provide a simple test an input approximating to a sine wave was used. The amplitude was 30 volts and the equivalent sampling rate was 12 per cycle (or 30° per contact of the uniselector). A single cycle was an adequate data length for test purposes as under these conditions each cycle is merely a repetition of its predecessor; as $\frac{n}{m}$ equals unity $\sin 2\pi \frac{n}{m}$ is zero and the error is zero.

5.2 Typical results were:-

τ	Summator Output		A	B	$\cos \tau$
	A	B	117.7	114.4	
0	117.7	114.4	1	1	1
30	101.4	98.0	0.862	0.859	0.866
60	58.2	55.6	0.494	0.486	0.5
90	1.1	0.6	0.009	0.005	0

5.3 Although the values of $\cos \tau$ given by the two runs A and B agree closely with the theoretical values, it will be noted that the actual readings vary appreciably. It was discovered during the tests that these discrepancies were due to long term drift of the amplifiers and cathode followers.

6 Conclusions

6.1 Although the tests carried out were limited, they were adequate to demonstrate that the principle is sound and achievable in practice.

6.2 The following difficulties and sources of error were noted:-

6.21 Summator - drift of cathode followers. Although the actual drift may be small the effect on the summator output can be considerable as the error is additive every time the summator relay operates; moreover the linearity is upset. The most critical adjustment was found to be the zero setting of cathode follower CF_1 (Fig.4(a)).

6.22 Amplifier drift. Long term drift has an effect similar to that of a zero error. If consistent results are to be obtained drift-stabilised amplifiers should be used.

6.23 Multiplier. For many purposes a multiplier having a high percentage accuracy relative to the maximum output is satisfactory. When used in a correlator however, one input may be zero and the other large - or both may be small - and the accuracy relative to the true product for these inputs must be high, especially with regard to any change brought about by altering the signs of the inputs. Care must be taken to adjust the multiplier used to meet this requirement.

6.24 Condenser leakage. In the condensers associated with cathode followers as storage circuits it is shown in Appendix I that leakage due to negative grid current is the main difficulty. In the case of the condensers storing the input signal, the performance is adequate provided good quality condensers are used and care is taken in maintaining good insulation; a discharging effect however was noted due to the rotation of the uniselectors (connected to cathode followers) - this appeared to be due to the input capacity of the cathode follower (including the wiring), as the effect was most apparent when successive condensers were charged to potentials of opposite sign.

6.3 These investigations have not been carried out in sufficient detail to produce a practical instrument. The results however indicate that the principle is sound and that with more effort a comparatively simple, accurate and flexible machine could be built at a reasonable cost.

Attached:-

Appendices I and II.

Drg. Nos. GW/P/4054 to 4058.

Detachable Abstract Cards.

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CS(A)	
PDSR(A)	
DGTD(A)	
PDGW	- 80
DCD	
D Inst RD	
DG of A	
DWR(D)	
GWAB (Dr. R.C. Knight)	
TPA3/TIB	- 100
Director, RAE	
DD(E)	
DD(A)	
RPD	- 2
Radio	
Arm	
Patents	
Elec Eng	
IAP	
Instn	
Math Services	
GWTV	- 2
Library	

APPENDIX I

Operation of the Summator

1 Control of relay M

The pulse drive operating the uniselector relays is connected via auxiliary contact banks A_c and B_c (Fig.4(b)). At the beginning of the pulse the uniselector relays are energised but the wipers do not move and a circuit is therefore completed to relay M, which operates. As contact M_1 closes, relay N is energised and is held closed via N_2 . As N_1 closes M is de-energised and opens. At the end of the operating pulse N drops out and the wipers step forward one contact, resetting the circuit ready for the arrival of the subsequent pulse. This arrangement ensures that M operates after the beginning of the pulse and releases before the end of the pulse (i.e. whilst the wipers are stationary on the appropriate contacts). The duration for which M remains closed depends upon the operating times of relays M and N and upon the adjustments of contacts M_1 and N_1 ; during tests of the circuitry the duration was set to approximately 35 milliseconds. By inclusion of switch Sc_2 , the process can be halted if desired at the end of the uniselector revolution; at position 2, M will not be operated on contact 49, but relay P will be energised instead, connecting the summator output to a voltmeter (Fig.3). With Sc_2 in position 3, relay M is reconnected into circuit at contact 49 and the summing process can continue for subsequent uniselector revolutions.

2 Accuracy

2.1 The simple storage circuits are dependent for their accuracy upon the amount of condenser leakage and cathode follower drift. The former is not important in the summator circuit as the whole operation takes only a matter of seconds; by careful selection, condensers were obtained which showed negligible leakage over a period of 10 minutes. Drift due to negative grid current is however important; with contact M_3 (Fig.4(a)) open, so that the condenser is connected only to the cathode follower grid, a reverse grid current of $1\mu A$ will cause a change of potential of +1 volt per second on a $1\mu f$ condenser. By careful selection of the valve and adjustment of the cathode follower, a drift of 1 volt in $4\frac{1}{2}$ minutes was achieved; in this case such a performance should be satisfactory if the maximum possible range of the summator is utilized and the operating time is restricted to 30 seconds or so. It should be noted that the drift of CF_1 is not so important, as the condenser is isolated only for the short period (about 35 ms) that M_4 is open; for the remainder of the period between pulses the condenser is maintained at its correct voltage by the output of CF_2 .

2.2 The effect of gain of individual components and cathode follower zero errors can be very important. If gains a, b, c, d and e (Fig.4(a)) are used and there are zero errors x and y on CF_1 and CF_2 then (neglecting sign reversals in the amplifiers):-

$$Vo_1 = (V_1 + ex) ab + y \quad \text{as} \quad VL_1 = x$$

$$VL_2 = (Vo_1) od + x = [(V_1 + ex) ab + y] od + x$$

and

$$Vo_2 = [V_2 + e \{ (\overline{V_1 + ex} \cdot ab + y) od + x \}] ab + y$$

Put $ab = r$ and $cd = s$, and let it be assumed that the circuit has been adjusted for no output zero error and $V_{o2} = 2 V_{o1}$ when $V_1 = V_2$, then:-

$$2 [(V_1 + ex) r + y] = [V_1 + e \{ \overline{(V_1 + ex) \cdot r + y} \} s + x] r - y$$

which will be satisfied if the overall gain e.r.s is unity, and x and y are of opposite sign.

Then with $V_1 = V_2$ the summator will appear to be linear. For $V_1 \neq V_2$ this will not be so and in the case when $V_1 = -V_2$, V_{o2} will be $2(erx + y)$ instead of zero.

The complete circuit will be linear if x and y are zero and the total gain e.r.s is unity. In practice however it is preferable to have both r and es each unity as otherwise a zero error x may be overlooked. For example, let $y = 0$, $r = 0.9$, $s = 1$ and $e = \frac{1}{0.9}$. Then

$$V_{o1} = \left(V_1 + \frac{x}{0.9} \right) 0.9 = 0.9 V_1 + x$$

$$V_{o2} = 0.9 (V_1 + V_2) + 2x$$

and $2 V_{o1} = V_{o2}$ if $V_1 = V_2$, but $V_{o2} = 2x$ if $V_1 = -V_2$.

Thus for $x \neq 0$ the characteristic of the summator will be a diamond shaped "hysteresis" loop. Having initially adjusted the gains to unity, rapid checks can be made during operation by adjusting the output to zero with the "zero" switch operated and then applying inputs $+X$, $-X$, $-X$ and $+X$. V_{o2} and V_{o1} should be zero; any discrepancy can be removed by adjusting the zero control of CF_1 .

2.3 By taking reasonable care in the selection of components and lining up, an overall performance should be obtained having an error of less than 1% of the maximum output over the range +50 volts.

APPENDIX IIControl Circuit Operation1 "Start-Stop"

1.1 Operation of the "START" button energises relay C (Fig.5) which is self holding via contact C_1 . Contacts C_2 and C_3 connect the operating coils A and B of the two uniselectors to a pulse voltage whose frequency can be adjusted to meet the required sampling or operating rate. Additional contacts of C (Fig.3) remove earths from the multiplier inputs which are then connected to the wipers of unselector contact banks A_B and B_B , and also remove the "zeroing-earth" from the summator.

1.2 Operation of the "STOP" button merely releases relay C, stops the uniselectors and zeros the multiplier and summator. In positions 1 and 2 of the control switch S_C (Fig.4(b)), to meet the conditions of paragraphs 3.21 and 3.22, the uniselectors are required to stop at the last contact of A (not necessarily the last contact of B if $\tau > 0$). When C is operated contact C_4 (Fig.5) applies a positive potential to contact 49 of A_A ; when the wiper reaches this point relay L operates, releases C by the opening of contact L_3 and is itself released when C_4 reverts to its off position; a separate switch S_D is included to remove this facility when not required.

2 "Zero" Reset

On operating the "ZERO" button, relay D operates and holds via contact D_2 . Positive voltages are applied via D_1 to the homing contacts A_H and B_H of the uniselectors A and B, which commence to rotate automatically. The positive voltage on wiper B_A is ineffective until the home position (contact 0) is reached, whereupon relay F operates via D_4 and is held by F_2 . When F_1 opens the operating potential is removed from B_H and the unselector B stops. When D is operated, wiper A_B (Fig.3) is earthed so as to discharge all the condensers; for this to be effective unselector A must complete a second revolution when homing if it is further advanced than contact 1. This is achieved by a similar arrangement as for unselector B, by relay E connected to contact 0 of A_A , but the circuit is made ineffective until relay G, associated with contact 1, has operated. Thus if A_A is at rest on any contact from 2 to 49, on the operation D, D_3 will apply a positive voltage to A_A and the wiper will hunt round. On arriving at contact 1, G will operate via D_5 (holding via G_2) and contact G_1 will close the circuit to relay E which will operate the next time the wiper arrives at contact 0, and stop the unselector in this position. When both E and F are operated relay D is released (contacts E_3 and F_3) and relays E, F and G release (contacts D_3 and D_4) thus restoring all the relays to their off condition. Contacts D_5 and D_6 are to prevent false operation of other controls when D is operated and vice versa.

3 Preset τ

3.1 To simplify and speed up the operation of the correlator it is desirable that homing facilities be provided on the uniselectors so that the wiper of B returns to the zero contact and that of A to any selected contact equivalent to the required value of τ for the next run.

3.2 The homing facilities are provided by relays H, J and K (see paragraph 4 below) and the control of the value of τ by switches S_A and S_B . J responds to a positive voltage on wiper A_A (Fig.5) and is connected by the multi-position switch S_A so that the wiper halts at contact 0, 5, 10, 15 etc. as selected. In practice J is a slow operating relay and it is convenient to make connections from S_A to contacts 49, 4, 9, 14 etc. allowing the unselector an extra step before it stops.

3.3 Use is made of relay L (already employed in the STOP system - paragraph 1.2) to select individual positions between 0 and 5, 5 and 10 etc. If S_A is set to 5 and S_B to 2 (i.e. required value of $\tau = 7$), wiper A_A will stop at contact 5 under the influence of relay J, but as soon as H releases relay L is connected via H_5 to A_A and will operate from the positive voltage applied to contact 5 from S_B position 1. Contact L_1 steps A forward, but L_2 prevents B from being energised. L will drop out immediately A_A moves away from contact 5, but as the positive voltage appears on contact 6 from S_B position 2, L will operate again and A will move on to position 7. Contact 7 is isolated so that no further operation of L will occur and the wiper will remain at 7.

4 Reset τ

4.1 To reset τ to repeat a run, or to home the unselector to a new value of τ (paragraph 3 above), a homing circuit separate from the "ZERO" reset is employed as A is not normally required to return to contact 0.

4.2 Unselector B is always required to return to contact "0" so that relay F used for the ZERO-reset can also be employed for this purpose. On depressing the RESET τ control H operates and K is operated via H_6 . K_4 in parallel with D_4 connects F into circuit and the operation is exactly the same as in the case of the ZERO-reset.

4.3 When H operates, H_5 connects positive voltage to wiper A_A and the unselector A hunts round due to closing of contact H_4 . On the operation of J at the contact selected by S_A , A will cease to step round due to the opening of J_2 . H will release immediately J operates and to prevent premature halting of B, K is arranged not to release until F has operated (K_5 and F_4 in parallel with H_6).

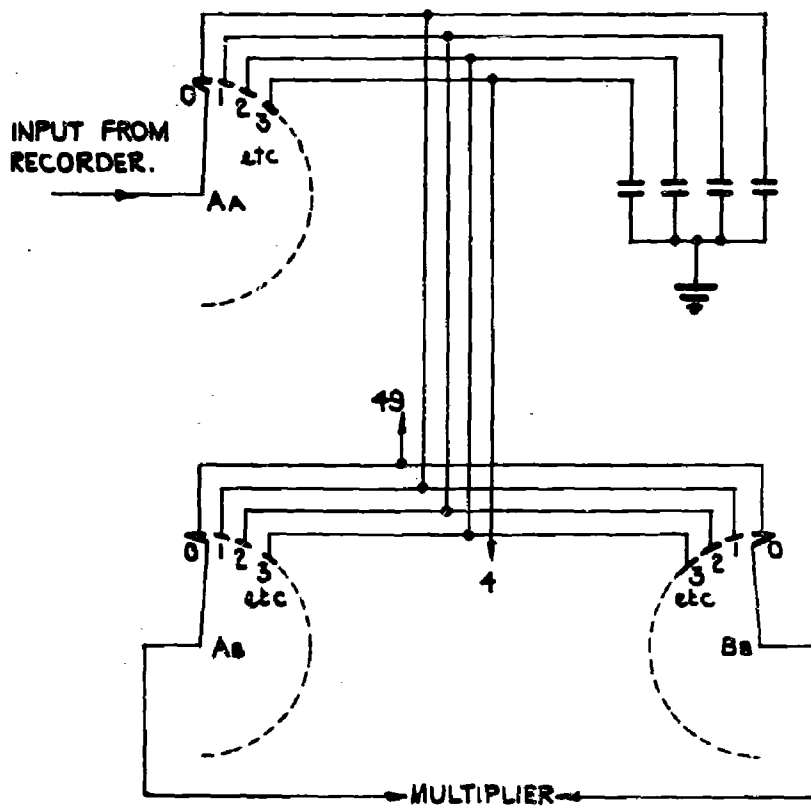
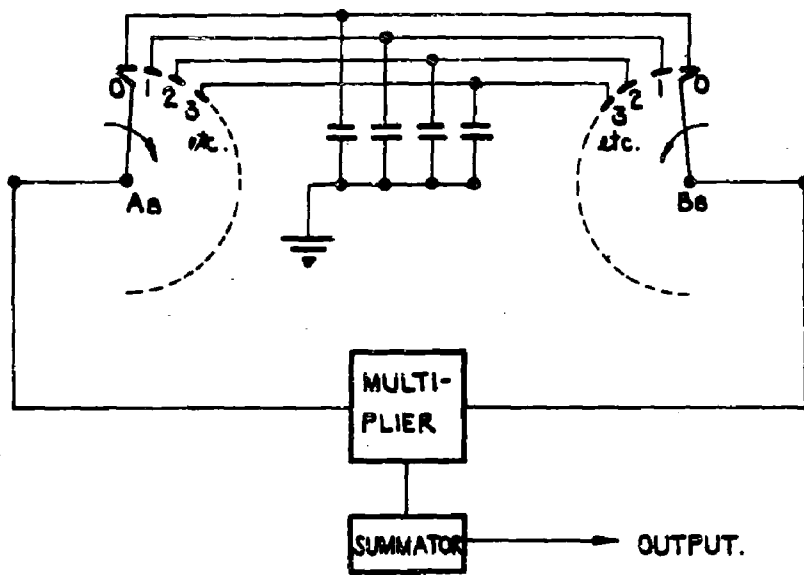


FIG. 2 (a & b) & 3.

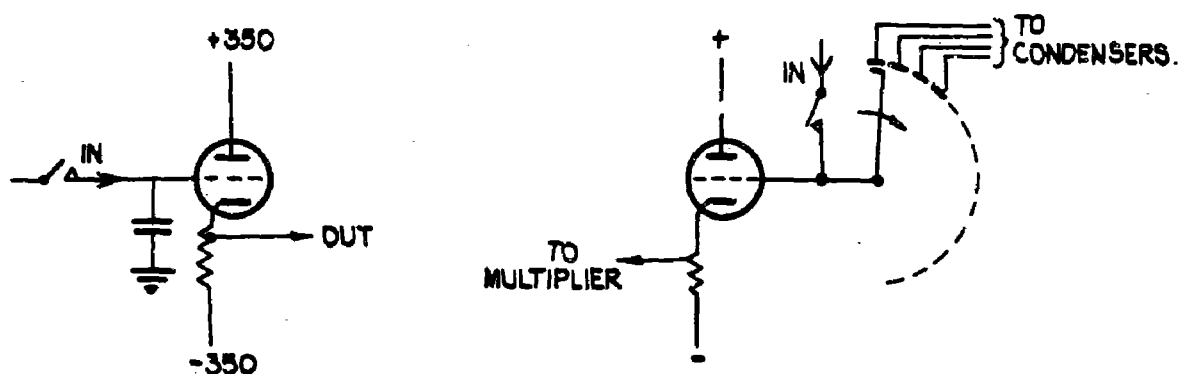


FIG. 2 (a). STORAGE. FIG. 2 (b). MULTIPLE STORAGE.

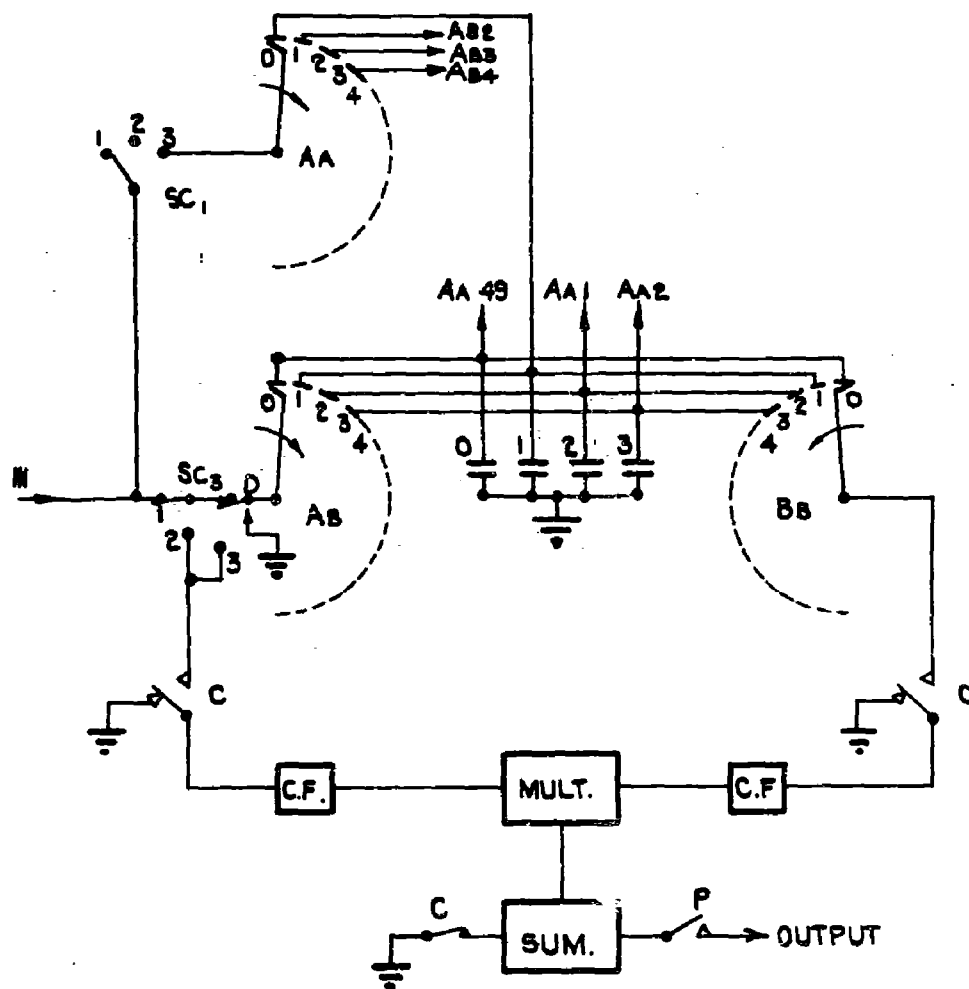


FIG. 3. OVERALL CIRCUIT.

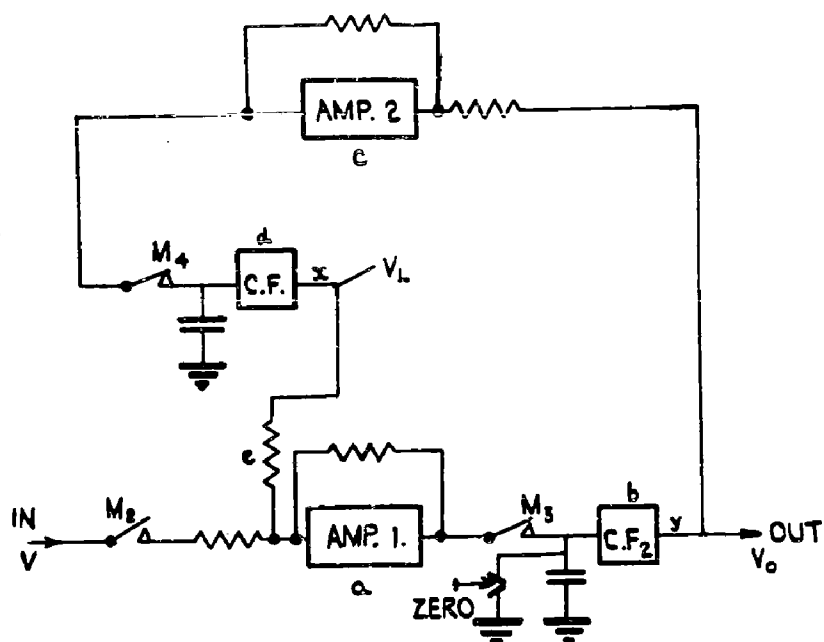


FIG. 4(a) SUMMATOR.

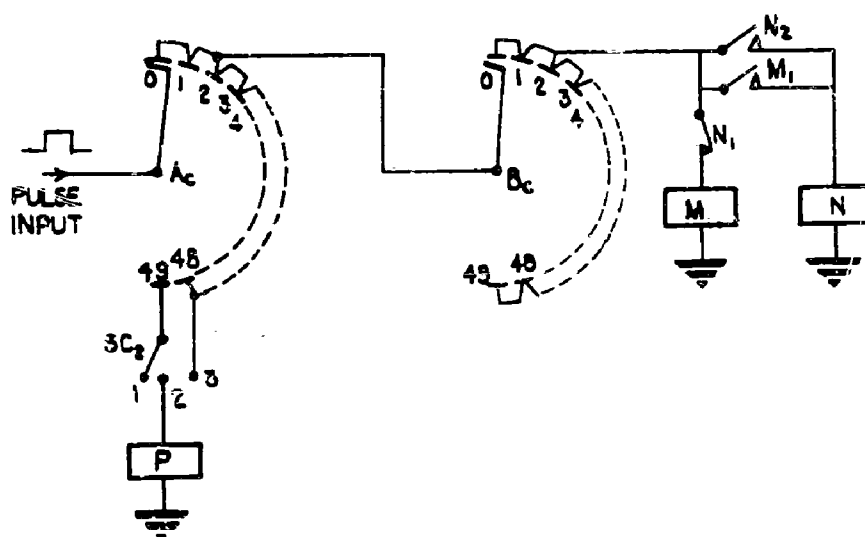


FIG. 4(b) CONTROL OF RELAYS M AND P.

FIG. 5

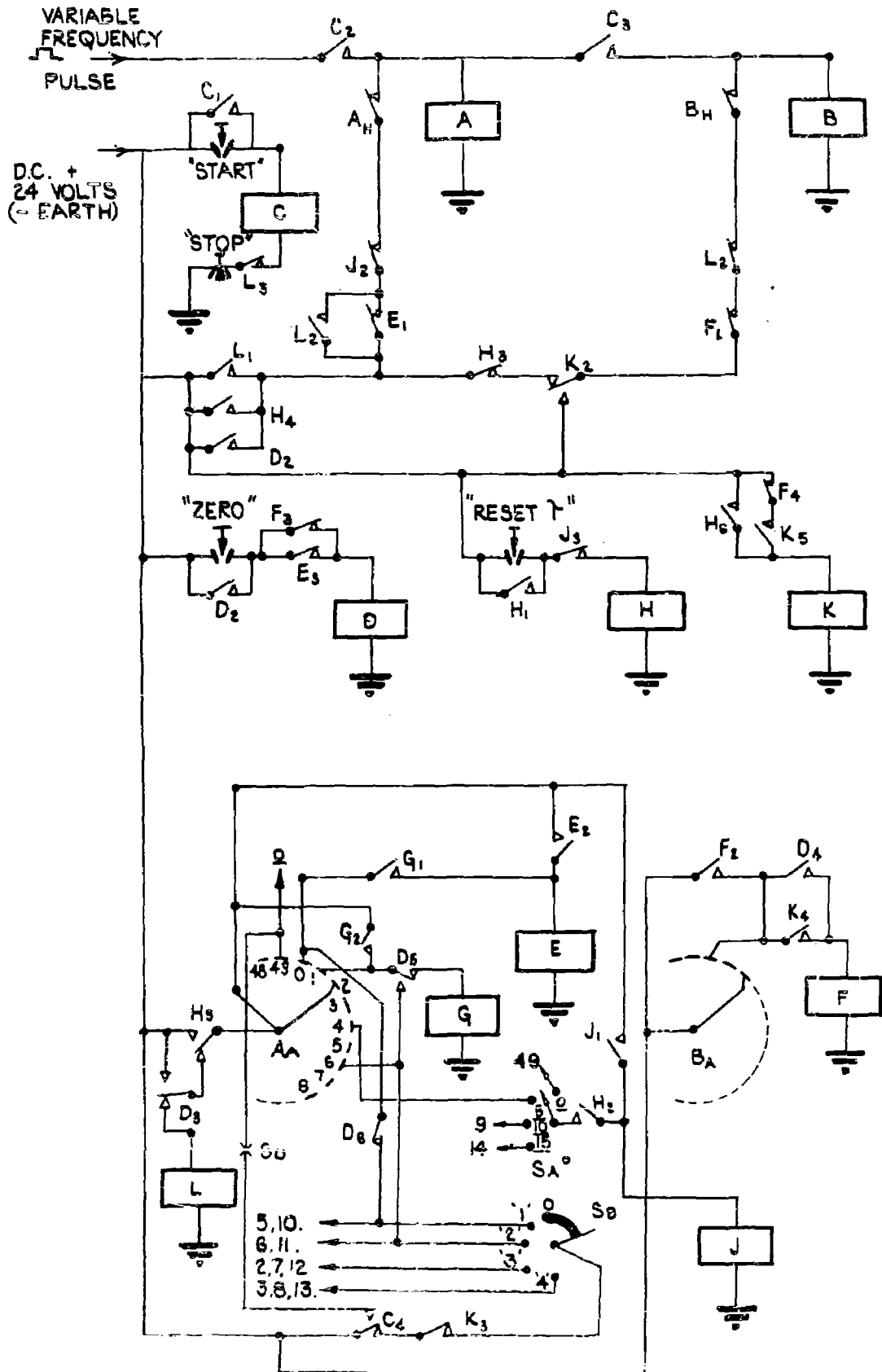


FIG. 5. CONTROL CIRCUIT.

FIG. 6.

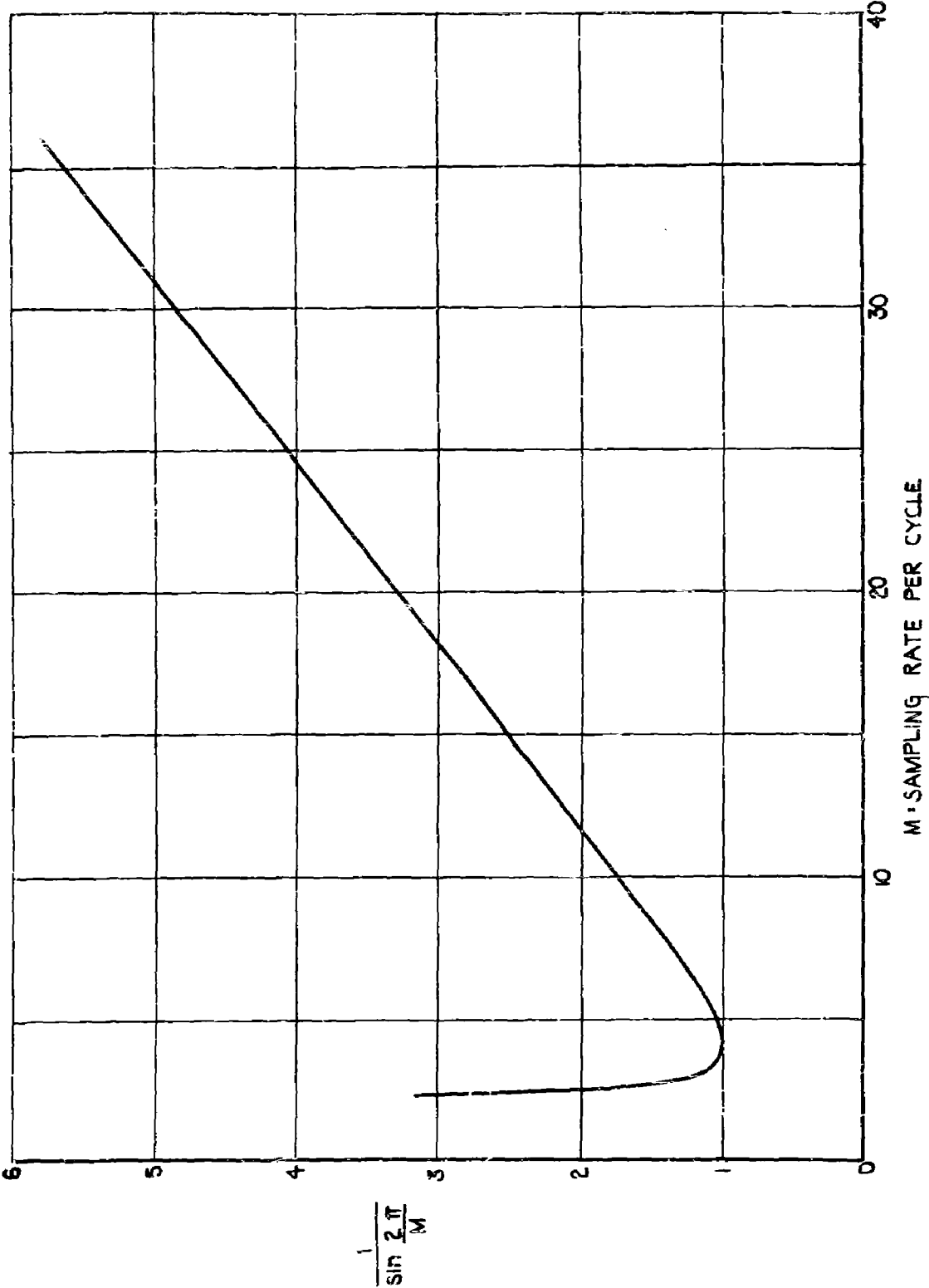


FIG. 6. GRAPH OF $\frac{1}{\sin \frac{2\pi}{M}}$ AGAINST M.

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