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In the village of Blunham, Bedfordshire.

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OCTOBER 1958

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'When a Subject is proposed to your Thoughts, consider whether it be knowable at all, or no; and then whether it be not above the Reach of your Enquiry and Knowledge in the present state; and remember that it is a great Waste of Time to busy yourselves too much amongst Unsearchables....

'Consider again whether the Matter be worthy of your Enquiry at all; and then, how far it may be worthy of your present Search and Labour according to your Age, your Time of Life, your Station in the World, your Capacity....

'Consider whether the Subject of your Enquiry be easy or difficult whether you have sufficient Foundation or Skill, Furniture and Advantages for the Pursuit of it. It would be Madness for a young Statuary to attempt at first to carve a Venus or a Mercury, and especially without proper Tools. And it is equally Folly for a Man to pretend to make great Improvements in Natural Philosophy without due Experiments.

'Consider whether the Subject be any ways useful or no, before you engage in the Study of it: Often put this question to yourselves Cui bono? to what purpose?

....There are many subtle Impertinences learnt in the Schools, many painful Trifles even among the Mathematical Theorems and Problems, many Difficiles Nugae, or Laborious Follies of various kinds, which some ingenious Men have been engaged in. A due Reflection upon these Things will call the Mind away from vain Amusements, and save much Time."

Watts on the Mind

A SPRING PASSAGE OF 'ANGELS' AT MALVERN IN 1958

by E.W. Houghton and F.W. Coultas

Summary

Circumstantial evidence has been given to show that the large movement of 'angels' observed from Malvern on 29th and 30th March, 1958, could be explained by a passage of migratory birds. Equivalent echoing areas of some of these targets were evaluated for three sets of conditions and found to be:-

(i) For the largest target, 1.6 sq. metres.

(ii) For the average large target, 0.18 sq. metres.

(iii) For a target to give 80% painting on the PPI at far range, 0.07 sq. metres.

The echoing area of most of the targets, however, was less than 0.07 sq. metres. An air-speed range of 18 to 47 knots was calculated from the measured ground speeds of many of the echoes and from wind speeds reported from Gloucester (see Appendix 1). The maximum height measured was 9500 feet, but most of the echoes lay below 4000 feet.

1. Introduction

A radar watch was kept for 'angels' from 0830 to 0900 hours each morning from the beginning of March. The aims of this exercise were threefold:-

(i) To widen our knowledge of the nature of these 'angels' which might reasonably be deduced as bird echoes.

(ii) To estimate equivalent echoing areas.

(iii) To provide data for Dr. Lack's work on bird migration.

To further these ends, we confined our observations to the peak months of the Spring passage of birds in and through the United Kingdom.

No continuous movements of 'angels' were detected until March 27th, when during that morning a chain of scattered echoes were seen moving North by West. By the morning of March 29th, there was a regular passage of echoes heading East by North and ENE. These were large 'steady' echoes travelling at different ground speeds in the range 38 to 63 knots and at heights from 4000 to 7000 feet. Target density was low enough in the SE bearing sector to enable a count to be made, and an average of 3 to 4 echoes passed through the sector each 15 minutes. By the evening of March.29th the echo density had increased so that there were large patches of echoes on the plan position indicators. Unlike previous 'angel' displays, this show consisted of a carpet of echoes bobbing up and down about near noise level while among these echoes a considerable number of larger 'steady' echoes moved. The whole carpet of echoes, in height layers up to 7500 feet, headed N by E. The ground speeds of individual echoes were measured and found to lie in the range 40 to 62 knots. On the morning of March 30th, the 'angel' display had reached a very high density. Some very large amplitude echoes were present and heights up to 8000 feet were recorded. In the evening, the echo density had fallen, and this decrease continued until the equipment was shut down. Many high elevation targets were detected during this phase and one was flying at 9500 feet. The equipment was run again from 1930 to 2200 hours on April 1st, but by this date the plan position indicators were clear except for a few scattered 'angels'.

At this point we should like to advance some reasons why we have considered these 'angels' in passage to be birds:-

(i) The main headings of these targets lay in the bearing arc 67-79 degrees while the wind direction lay from 210 to 240 degrees, so consequently the targets must have been boring obliquely into the wind (i.e., powered flight).

(ii) The air speeds of the echoes fall within the air speed range of 'flocking' birds known in the UK, viz. 15 to 53 knots.

(iii) The life time of the larger echoes was greater than the tracking period.

(iv) Targets measured at the same time and altitude differed in air speed.

(v) Ground speeds of all targets measured exceeded wind speeds (i.e., this is a specialised case because wind and target headings were in the same quarter, but it again indicates powered flight).

(vi) Though the air speeds and the altitudes of different targets were dissimilar, each target maintained a relatively constant air speed and altitude.

(vii) Masses of discrete echoes were moving on the same heading.

(viii) Target headings coincided with known routes for visible migration and March is considered to be a peak month for bird migration.

(ix) Most of the targets had estimated equivalent echoing areas considerably less than other known space vehicles.

As far as we are aware, prolonged powered flight does not occur in atmospheric phenomena (i.e., air bubbles, differences in refractive indices, etc.), and so we are left with birds and insects. The equivalent echoing areas of insect swarms known in the UK have always been assumed negligible at centimetric wavelengths, but as far as the authors are aware this has not been proved by experiment. Relatively little is known about the prolonged flight and speed of insects, though immense flights of butterflies do reach us from the Continent. These immigrations may occur early in the year and on March 22nd, 1935, hundreds of Small Tortoiseshell (Aglais urticae) were found on Flamborough Head(1). However, the bird is superior to the insect in power and area. Also if insects were effective centimetric targets we should expect their echo densities to increase in Summer instead of at the peak periods of bird migration in Spring and Autumn.

2. The Radar

Observations were made using a centimetric radar fitted with a number of aerial beams stacked in elevation and rotated continuously in azimuth. This aerial system permits a large volume of sky to be 'illuminated' and for many targets to be measured in range, bearing and height each revolution of the aerial.

We found it advisable to define watching ranges, heights and bearings in accordance with radar performance and siting, because of the heavy traffic of 'angels'. There were two main zones on the plan position indicators associated with loss of radar information. One of these regions is a cut-off zone from bearing 150° to 330° due to the proximity of the Malvern Hills, while the other is a region of permanent echoes produced by ground reflections from hills, trees and buildings.

Most of our observations were made in the bearing sectors 330° to 60° and 100° to 150° and the amount these sectors were affected by 'angels' is recorded in Appendix 2. With a few exceptions, the 'angels' were heading approximately ENE or E by N.

The heights of a large number of targets were measured each watch and the maximum heights taken have been recorded in Appendix 2. Only strong echoes were measured, but these were available in abundance, especially in the region of interest above 4000 feet. The maximum height of 9500 feet was recorded on the evening of March 30th on a target travelling ENE at a ground speed of 40 knots, when the main drift of 'angels' at that time was E by N.

3. Characteristics of 'Angel' Targets

The ideal radar target is a metal sphere as it scatters radio energy isotropically. Such a target presents the radar with the same aspect ratio at all times and consequently the received signal does not vary with changing target aspect. The effective scattering area of a propeller driven aircraft on the other hand, however, changes violently with aspect and fluctuations of signal strength of 10:1 are common. Two kinds of fluctuation can be recognised on the received signal from a propeller aircraft - very rapid changes associated with the rotation of the propellers as reflecting surfaces (i.e., propeller modulation) and slower deep fading with changes of aircraft aspect. Single bird targets, because of their shape, should produce changes of signal strength with aspect and by movement of their wings, provided that all parts of their surface scatter radio waves equally (i.e., a condition approached at near optical wavelengths). If this condition was realised it might be possible to classify single birds into wing beat groups. Qualitative experiments conducted during World War II on single Herring Gull (Larus argentatus) targets with an S band accurate position finding radar, indicated that the relative signal fluctuations were less than those for aircraft, and it was not possible to detect wing beat modulation. As a part of the same investigation, multiple bird targets were examined and found to have two main fluctuation components:-

Large changes with aspect of flock (i.e., depending on positioning of the flock with respect to the radar), and

Rapid beating associated with the positioning of each bird with respect to its neighbour.

The amplitude variation of this rapid beating was greater for Herring Gull formations than it was for Mallard (Anas platyrhynchos) flights.

The scanning radar is not the ideal set to examine in detail the fluctuations of a single target, because it samples target information only periodically, but very rapid changes (e.g., propeller modulation) can be seen if there are sufficient pulse returns per target. In our case this condition was satisfied and both rapid fluctuations and aspect changes slower than the aerial scanning rate could be observed. A feature of near receiver noise level 'angel' targets seen during the evenings of March 29th and 30th was a bobbing up and down fluctuation. This could have been the result of flock behaviour (i.e., large changes of position of birds in the flock, or changes in flight direction). Alternatively, it could be that the sky was so packed with flocks that the radar ceased to resolve them as discrete targets. For reasons which are not clear unless it is just a question of bird species and flock behaviour, 'angel' targets in the morning were usually steadier. This phenomenon has been noticed at other times. Many of the larger echoes were as steady as those from aircraft targets. When examined closely on the elevation display many, but not all, large signal targets appeared to have a high frequency fluctuation component.

Target speed is a valuable parameter for sorting out identity and all echoes measured during March 29th and 30th were travelling at airspeeds known for British birds. The highest airspeed measured was 47 knots approximately, the lowest 18 knots approximately. A wide variety of speeds were encountered each watch, as can be seen from the ground speed limits given in Appendix 2.

4. Equivalent Echoing Areas

Three kinds of target merited attention:-

(i) Large targets at far ranges.

(ii) Steady targets at far ranges.

(iii) The general mass of targets bobbing up and down about average peak noise level at far ranges.

Mean tangential (S + N)/N ratios for two or more consecutive azimuth scans of the aerial were measured on large and steady targets at far ranges using the elevation display. Echoing areas were then calculated from measured S/N ratio, from measured range and the known radar parameters. The difference between 80% painting on the PPI and a tangential S/N of 1:1 had been measured on a previous occasion and found to be 4dB (i.e., for relating elevation display loss with PPI visibility factor for 80% painting).

On this basis the equivalent echoing areas for large and steady targets were from 0.2 to 1.6 sq. metres.

Another estimate of echoing area was made by looking for those PPI targets at far ranges which painted on two or more consecutive scans of the aerial. The detection probability for these targets was then taken as equivalent to 80% painting. The large number of echoes that painted in this way had an estimated equivalent echoing area of 0.07 sq. metres.

Errors for the first estimate are of three kinds:-

(i) In measuring tangential S/N.

(ii) In measuring the ratio of tangential S/N to 80% PPI painting.

(iii) In evaluating the PPI visibility factor and 80% painting.

The total error from these causes may affect the value of EEA by a factor of 4, while errors in the second estimate are mainly due to item (iii) and may change the EEA by a factor of 2 or 3.

5. Discussion

Amongst a crop of ideas and suggestions that an investigation such as this engenders, there are two suggestions that might have a radar application, and a number related to bird study using radar.

Most aircraft targets have larger echoing areas than any 'angel' measured at present, and therefore target echoes could be sorted out on this basis alone. The commonly used PPI systems, however, are useless for this task because amplitude limiting is provided at a signal to noise ratio of 2 or 1.5:1 in order to obtain optimum range performance. One solution would be to divide the PPI screen into two areas, an outer ring for optimum range performance and an inner circle capable of detecting amplitude changes. This facility could be realised by video mixing a range-gated linear receiver and a range-gated 'log' receiver, and then feeding the mixed output to an 'unlimited' PPI display. Should subsequent measurements confirm this record that passage 'angels' usually fly at relatively constant heights, then they could be used, when present in large numbers, as echoing sources to investigate the low cover diagram of a sited radar.

We shall not dwell here on the use of the volumetric radar, which, though admirable for plotting 'angel' measurements on a grand scale cannot be used directly to bridge the gap between the observed 'angels' on the PPI display and migratory birds. A most satisfactory way of relating 'angels' on the PPI display to birds on flight would be to site an accurate position finding radar fitted with optical binoculars (moving in synchronism with the radar) in a position where it could simultaneously track, both optically and electrically, numbers of individual birds and flocks of birds each day. For obvious reasons, it would be convenient at first to view large birds - for example, sea-birds, duck, geese, etc. It might be of interest to make a list of subjects that could be studied using such a radar, e.g.:-

(i) Scattering area with aspect (individually and in flocks); presence of wing modulation; fluctuation with flock pattern; polarisation; speed range; height range; flight times with respect to sunrise, sunset and weather.

(ii) Use of radar as an early warning or "putting on" instrument for optically viewing high flying birds, especially against a clouded sky.

(iii) Investigation of echo enhancement devices for marking migratory flocks so that they can be explicitly identified on a scanning radar.

(iv) It has been reported that birds react evasively to a radar beam directed at them(2). It is obvious that this phenomenon should be further investigated.

6. Acknowledgments

We are indebted to Squadron Leader N. J. Gardiner, RAF, O/C Radio Introduction Unit, RRE Malvern, and the RAF servicing team attached to the unit, who maintained the equipment during the exercise; also to Dr. Matthews, Assistant Director (Research) of the Wildfowl Trust, for information on migration from the New Grounds, and to Capt. A. F. Davenport, REME (TA) for reports on 'angels' in another area.

7. References

(1) E.B. Ford, Butterflies, London: Collins (1945).

(2) H. Albert Hockbaum, Travels and Traditions of Waterfowl, Oxford University Press.

APPENDIX 1 - WEATHER CONDITIONS

Reported from the Meterological Office, Air Traffic Control, RAF, Gloucester

March 29th, 1958

Time.	Wind Direction	Wind Speed (knots)	Temperature (°C)	Height (ft)	Remarks
0700	200°	9	+ 10	Surface	Surface: Continuous slight drizzle.
	230°	30	+ 5	2500	Visibility 2.5 n.m.
	230°	30	0	5000	Cloud conditions: $\frac{7}{8}$ Stratus, base 700 ft., tops 1000 ft.; 8/8 Strato-Cumulus, base 2500 ft. in layers to 7000 ft.
	230°	27	- 3	7500	
	230°	27	- 8	10000	
1900	160°	5	+ 10	Surface	Surface: Dry but cloudy.
	230°	20	+ 5	2500	Visibility 7 n.m.
	230°	30	- 1	5000	Cloud conditions: 5/8 Strato-Cumulus, base 2500 ft., tops 4000 ft.; 2/8 Alto-Cumulus, base 10000 ft., tops 12000 ft.; small amounts of Cirrus.
	230°	20	- 4	7500	
	230°	23	- 8	10000	

March 30th, 1958

Time	Wind Direction	Wind Speed (knots)	Temperature (°C)	Height (ft)	Remarks
0700	Variable 080°-240°	4	+ 8	Surface	Surface: Dry but cloudy.
	220°	15	+ 7	2500	Visibility 2.5 n.m.
	210°	15	+ 1	5000	Cloud conditions: $\frac{3}{8}$ cloud base 600 ft., tops 1000 ft.; $\frac{7}{8}$ Strato-Cumulus, base 1000 ft., tops 4000 ft.
	210°	12	- 3	7500	
	210°	17	- 8	10000	
1900	Calm	-	+ 10	Surface	Surface: Dry but cloudy.
	220°	5	+ 7	2500	Visibility 7 n.m.
	230°	10	0	5000	Cloud conditions: $\frac{1}{8}$ Strato-Cumulus base 5000 ft., tops 6000 ft.; $\frac{5}{8}$ Alto-Cumulus base, 8000 ft.. tops 9000 ft.; 6/8 Alto-Stratus, base 12000 ft.
	240°	10	- 2	7500	
	240°	10	- 8	10000	

APPENDIX 2 - RESULTS OF OBSERVATIONS

Date	Time	Approx. Bearing Sector (Degrees)	Measured Height (ft)	Ground Speeds (knots)	Headings	Density	Remarks
29.3.58	0640 to 0815	340-10 120-150	4000-5500 4000-7000	38 to 63	E.N.E. E.by N.	Individual echoes increasing to light echo density	Large 'steady' echoes. Rain cloud echoes in Azimuth Sector 80° - 120°.
	1900 to 2200	330-40 100-150	4000-7500 4000-6500	40 to 62	E. by N.	Heavy	A dense carpet of echoes bobbing up and down near noise level. Among the echoes were a considerable number of large signal echoes. Bulk of echoes were below 5500 ft.
30.3.58	0630 to 0830	330-60 100-140	4000-8000 4000-5500	27 to 59	E. by N.	Very Heavy	A denser display than on the evening of March 29th. Many of the large signal echoes were fairly steady and these large targets were usually flying above 4000 ft.
	1915 to 2245	340-30 100-130	4000-9500 4000-6000	23 to 49	E.N.E. E.by N.	Heavy decreasing to medium	Less dense than the evening of March 29th.

TRANSFER OPERATIONS IN A TRANSISTOR COMPUTER

by G. Ord and P. L. Lewis

Summary

The operations of transfer, exchange, shift and count are discussed and a basic circuit is developed enabling any of these operations to be completed in under 200 millimicroseconds. The circuit uses a delay cable of 60 millimicroseconds delay and switching is done using bidirectional transistor switches.

1. Introduction

In the arithmetic and control sections of most types of high speed computers it is necessary to store digital information in registers where it is readily transferable from one register to another. In order to store numbers these registers are made up of 1-digit stores and although it can be considered that the transfer of information is from one register to another, the detailed transfer is from one 1-digit store to another. Usually the digits are in corresponding positions in two different registers, but sometimes (e.g., for multiplication by two) it is necessary to alter the positions of the digits in a register, and then, as well, the transfer is between digit stores. For these reasons the various operations involving transfer type operations will be discussed with reference to 1-digit stores only.

One of the most important factors governing the design of the basic 1-digit store, and also of the transferring circuits, has been the speed at which it is required to receive and transmit information - the aim has been to do so at a rate of 5 Mc/s. Another factor, though not an essential one, has been the requirement that the transmitting digit store retain its information as well as transmit it. A third factor which has been taken into account is the simplification which can be made in purely arithmetic circuits (those that perform adding and subtracting) if two forms of the stored digit are available - the digit and its inverse. The one-digit store has therefore been based on a symmetrical bistable circuit of the Eccles-Jordan type. However, it is not proposed to discuss the circuit in detail (see Ref. 1,3,4), only some features affecting its speed of operation and some of the types of operations which are required to take place between 1-digit stores. These operations are:-

(a) Transfer from one 1-digit store to another, retaining the information in the transmitting store as well. This will henceforth be understood when we use the term "transfer".

(b) Exchange the contents of one 1-digit store with the contents of another, i.e. A to B and B to A. In a computer another process which is allied to this is 'shifting' which takes place when B is transferred to C as A is simultaneously transferred to B. In both exchange and shift a 1-digit store is transmitting its own information and receiving information from elsewhere at the same time.

(c) Count the input pulses applied to a 1-digit store so that the flip-flop is only turned over and back once for every two input pulses. This facility is used when the register of which the 1-digit store is a part, is required to count incoming pulses in the ordinary sense. It is also very useful when the register forms part of an adding circuit.

As each of these operations is effected by a transistor used as a bidirectional switch this will also be discussed.

2. The Basic Circuit

This is shown in Figure 1. The transistors shown in dotted lines are there only to set the bistable circuit into one direction or the other. If the emitter followers T3 and T4 are removed and

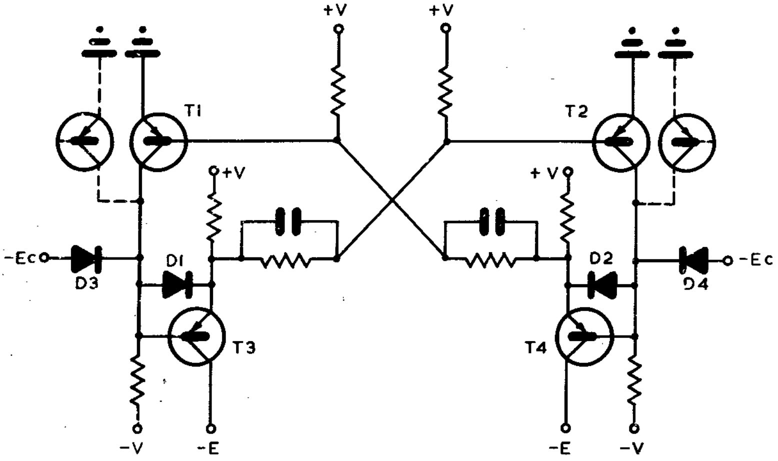

Figure 1 Basic digit store circuit

a short circuit placed between the collector of T1 and the circuit connected to the emitter of T3, and similarly with the opposite half of the symmetrical circuit, it will be seen that the circuit becomes the Eccles-Jordan flip-flop. The emitter followers' in the cross couplings are included to increase the speed of the circuit changeover and also to enable load currents to be taken from the circuit. In large signal operation, however, the emitter followers with a capacitive load become momentarily open circuit when a large positive voltage is applied to their bases; they can provide a high current output only in the one direction. Under these conditions the base to emitter voltage of T3 exceeds the forward conducting voltage of D1 which is turned on and current to the load is now provided via the low collector impedance of T1, which is very low in the bottomed state. Thus the total impedance is the sum of the forward impedance of the diode (perhaps 20 Ω depending on current) and the satúrated collector impedance of the transistor (10-20 Ω). This is small so long as T1 is saturated and in the design of the flip-flop it is necessary to allow an extra amount of current to the base of T1 so that T1 remains saturated under all conditions of load.

The diodes D3 and D4 limit the negative voltage excursion of the collectors of T1 and T2 and so enable the changeover to be faster in the negative direction. However, when T1 (T2) is turned on, before the collector voltage can move positively, some of the holes stored in D3 (D4) must be removed and thus D3 and D4 do delay the positive voltage movement. With low hole storage diodes of the GEC EW 78 type, this delay is only about 10 - 15 millimicroseconds when 3 - 4 mA have been passing through the diodes previously in the forward direction.

By not allowing T1 and T2 to saturate(2), either by conditional negative feedback paths through diodes or by emitter resistances, it is possible to prevent the hole storage in T1 and T2 which delays the negative voltage movement at T1 and T2 collectors. In circuits similar to that shown, an improvement in delay of 30 millimicroseconds can be achieved by these means but as the total safe turn-over time is 150 millimicroseconds it was thought better to use less complicated circuits.

3. The Transistor as a Switch

If a current is removed from the base of some types of alloy transistor (say by a current sink) irrespective of the potentials of the collector and emitter, then hole current flows from emitter to collector of a p.n.p. transistor if the emitter is positive with respect to the collector, and current flows in the reverse direction when the emitter is negative with respect to the collector. The transistor under these conditions is a bidirectional device. If the current withdrawn from the base is great enough to saturate the transistor when either the named emitter is acting as emitter or collector, the transistor will be bottomed irrespective of the direction of current flow. In the forward direction under such conditions the voltage drop across a transistor such as the 2N 240 (Philco surface barrier switching transistor) for an I_c of 5 mA and an I_b of 0.5 mA is less than 0.1 volt with an impedance R_c less than 20 Ω. In the reverse direction the figures are V_c less than 0.1 volt for $I_c = 2.5$ mA and $I_b = 0.5$ mA, impedance R_c approximately 30 Ω. Therefore for some switching applications the transistor emitter-collector path can be considered a short circuit. Even if the transistor is not saturated it can be considered as a resistance in series with a switch and thus capable of passing current in either direction.

The 2N 240 transistor is not specifically designed as a symmetrical transistor, but from the examination of a number of specimens the reverse current gain is sufficient to make the transistor useful in a number of symmetrical circuits. At lower frequencies specifically symmetrical transistors are available.

4. Transfer between 1-Digit Stores

In the process of transfer from one 1-digit store to another, the receiving store must be made to conform to the transmitting store, preferably without altering the condition of the latter. If the stores differ it is necessary to change the receiving store either from 1 to 0 or from 0 to 1. If unidirectional gates are used this means that two gates need to be used, one to set the receiving store from 1 to 0 and the other from 0 to 1. A variation of this method is to clear the receiving store into one state (say 0) and then on transfer it is only necessary to change the state of the store if the other state is required (say 1). Thus, only one gate is required but in addition there needs to be the facility for clearing the receiving store.

Only one gate is needed if it can be a bidirectional one(5). With this type of gate, current is passed from the transmitting to the receiving store in one polarity if the stores differ 0 to 1 and in the other polarity if they differ 1 to 0. A diagram of the arrangement is shown in Figure 2. Only a simplified form of the circuit is shown and the bidirectional gate is represented by a switch and a series resistance which will certainly be less than 1000 Ω. The tapping on the emitter follower load arranges that

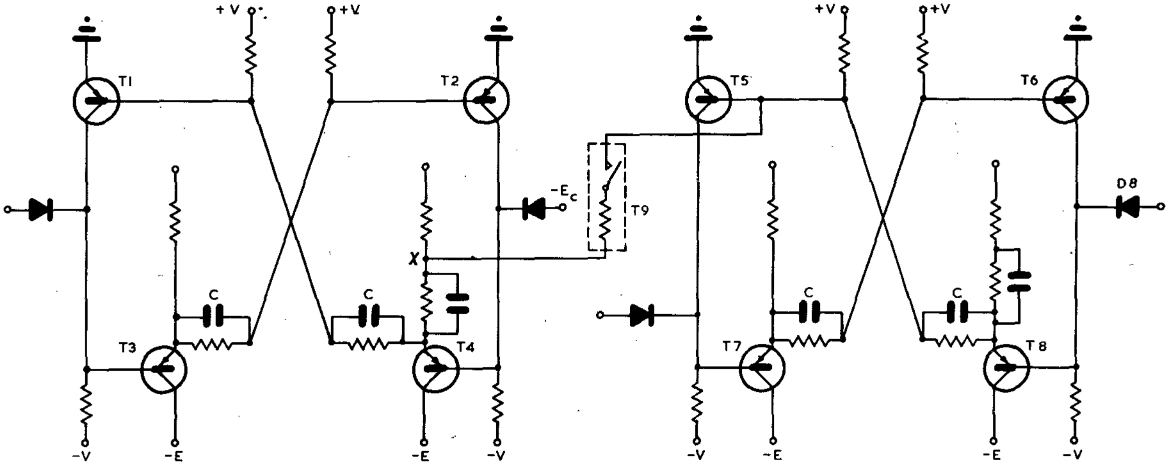

Figure 2 Skeleton circuit showing transfer

positive bias is given to the waveform available at the emitter of the emitter follower T4. If both stores are in the same configuration the closing of the switch will not alter the configuration of either store. If T1, T2 are on and off respectively, and T5, T6, off and on, the potential at T4 emitter is approximately $-E_c$ volts (say -4 volts) and X is a little more positive. The base of T5 is a fraction of a volt positive with respect to earth and as the base is non-conducting the impedance at this point is determined by the cross coupling networks and is relatively high. When the switch is closed the base potential of T5 attempts to move in a negative direction, turning on T5. The impedance at the base is now much lower (say 100 Ω) but current is still withdrawn from the base so long as the switch is closed. The T5, T6 store will now become on, off, in conformity with the T1, T2 store and then the switch is opened.

If T1, T2 are off, on and T5, T6 on, off the potential at T4 emitter is just slightly positive with respect to earth and the point X more so. T5 base voltage is approximately -0.4 volts.

On closing the switch, current flows from X to T5 turning off T5. The potential drop from T4 emitter to X is arranged to be sufficient to feed current into the base T5 even when T5 base has been turned off. Thus T5, T6 conform to T1, T2.

Figure 3 shows the waveforms which are obtained when an input pulse of 1.5 mA peak amplitude and 70 millimicroseconds duration is applied to the base of the switch transistor. Before the pulse is applied it is presumed that T5 (Figure 2) is conducting and that it is to be made non-conducting. The delay of 30 millimicroseconds before waveform V_cT5 (Figure 3) moves negatively is due to hole storage in the transistor. There is also a delay before the collector T6 begins to move, some of this being due to the voltage threshold which has to be overcome at the base of T6 and some due to the hole storage in D8, Figure 2. The changeover is complete in about 100 millimicroseconds but when there is heavy loading of the circuit on the emitter followers the edges are slower, and the changeover is complete in approximately 140 millimicroseconds.

It will be noticed that the regenerative action of the flip-flop is only beginning to occur at about the end of the input pulse and thus the condensers C are providing some memory of the past state of the circuit and helping to change it over into its new condition.

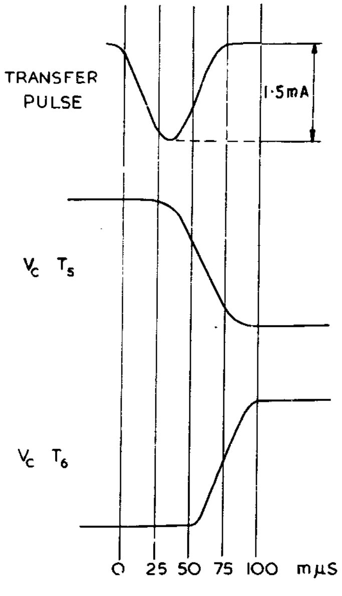

Figure 3 Waveforms for transfer

When the circuit is being turned over in the reverse direction the action is slightly slower.

5. Exchange between Stores

The difficulty about exchanging the contents of two stores is that either store is sending and receiving information simultaneously, altering the contents of another store while it itself is being altered. Obviously the solution to the problem is to memorise the incoming information temporarily during the sending operation and then to make the remembered incoming information set up the store. The temporary memory can, of course, be another and similar store but this is expensive in equipment.

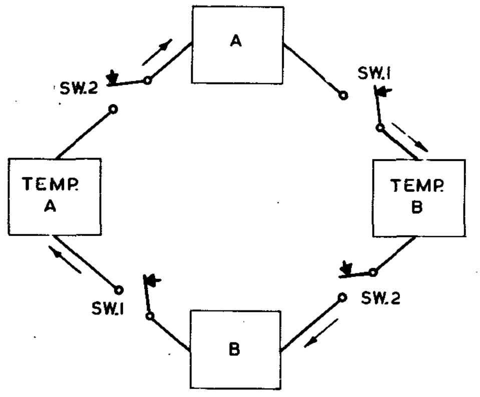

Figure 4 Exchange using temporary memories

In the first phase of the operation (see Figure 4), operation switches SW1 are closed, information flows from A and B to Temp B and Temp A respectively. In the second phase switches SW2 close and the transfer is from Temp B and Temp A to B and A respectively.

Another and more economical scheme is to use a delay line as a temporary memory, (see Figure 5(i)). When the switches SW are closed information flows into the delay line. The switches are opened before the information starts to alter the digit stores. The switches can either be before or after the delay line as in Figure 5(i) or 5(ii), the only difference being that in the circuit of 5(i), the changeover takes place after the information has passed through the delay, whereas in the circuit of 5(ii) the changeover takes place immediately the switches are closed, but then the delay time must be allowed to elapse before the switches can be closed again for a subsequent exchange.

6. Shifting

This is a very similar process to exchange. Store n receives information from n - 1 and passes its own information on to store n + 1 (instead of back to n - 1, see Figure 6). It is possible to use the delay line not only to shift information 1 digit at a time but any specified number of digits if extra switches are included. It is also possible to use the same delay line for exchange and shift as is shown in Figure 7. The waveforms of the circuit when used for exchange or shift are very similar to those obtained when transferring. However, an allowance of 60 millimicroseconds must be made for information to travel down the delay line before the gate may be opened again.

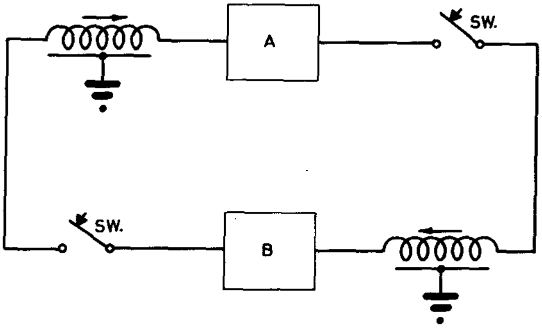

Figure 5 (i)

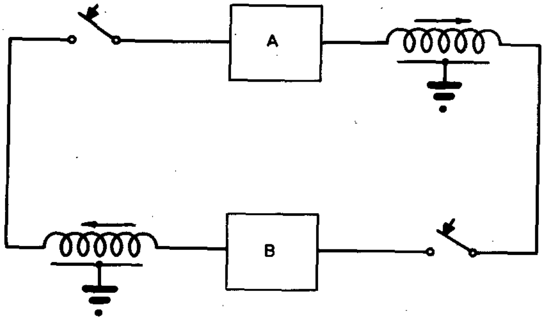

Figure 5 (ii)

Exchange using delay lines

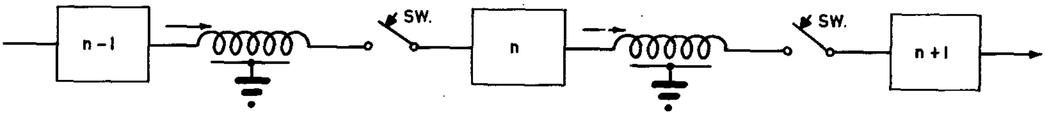

Figure 6 Shifting

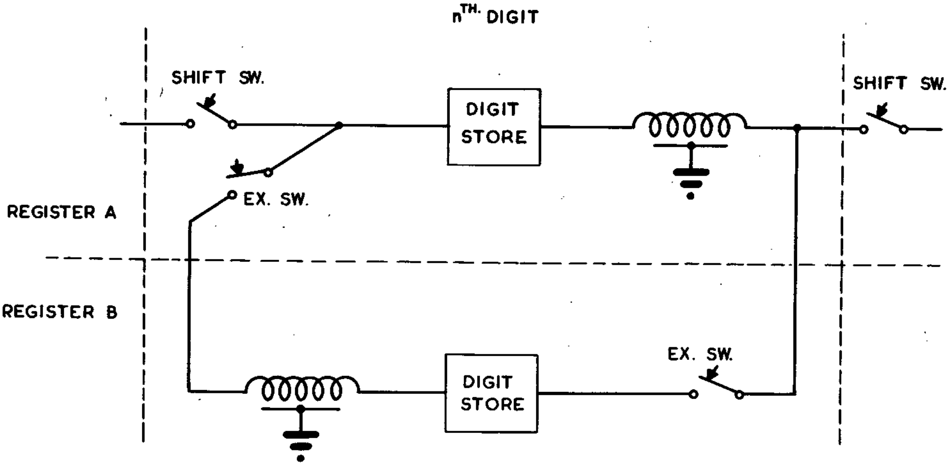

Figure 7 Exchange and shift

7. Counting in one Store

This process is also known as scaling or halving. In essence it is "exchange" within a store but with the difference, compared with the normal process of exchange, that the present state of the store is exchanged with the inverse of the present state. This corresponds exactly to the logical definition of a binary counter which is a device which should remember the state it is in at present and on the receipt of an impulse should change over to the inverse state(5). A schematic diagram is shown in Figure 8. Before the counter switch is closed it is considered that information from the output has had time to reach the end of

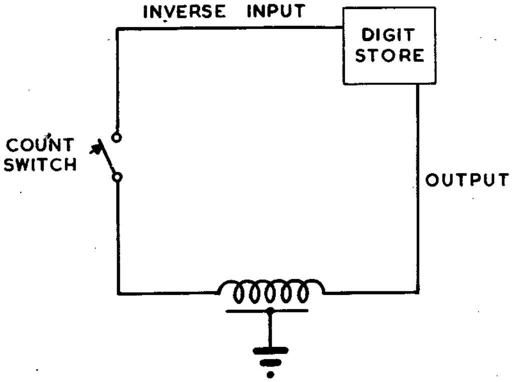

Figure 8 Count

the delay line. When the counter switch is closed this information flows into the inverse input of the bistable circuit and changes it over, but before the information about the new state of the circuit can reach the end of the delay line, the switch is opened. As far as practical details are concerned, the mode of operation is exactly the same as for exchange.

In many applications of counting circuits it is desirable to follow one counter with several more, to enable division to be done by 2^n and thus it is necessary to drive one counter from the output of the previous one. In the circuit shown the maximum voltage swing is approximately 0 to -4 volts. This is a little on the small side if only passive elements are used to form a 70 millimicrosecond gating pulse, from the emitter follower output, large enough to drive the next stage. It will probably be necessary to do some amplification. However, it is unlikely that a cascade of counters will be built up in this way at these speeds, either with or without the amplifier, as the propagation time through several stages will be too long. In order to cut down the propagation time it is necessary to go to the length of using logical circuits of the kind discussed by Richards(6). Figure 9 shows the simplest of these types. The gates G1, G2, G3 are controlled by the previous counters and allow the input pulse to be applied to several stages very nearly simultaneously (there is some delay in the gates). If this type of counter system is used it is not difficult to use the counter circuit discussed above.

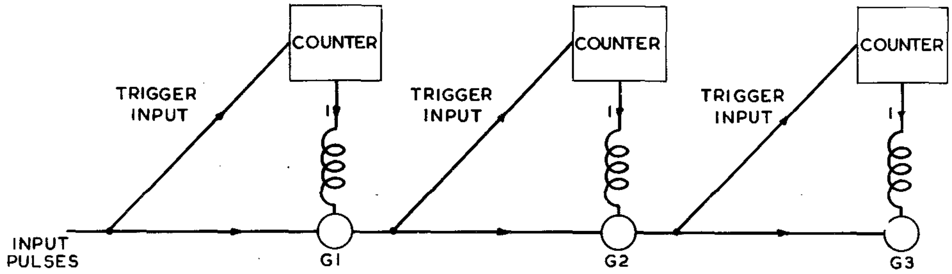

Figure 9 Cascade counter for fast propagation

As a point of interest, if the counter gate is permanently open any change of state will keep the circuit changing over continuously: the circuit acts as a square wave oscillator. Using longer lengths of line a square wave oscillator has been produced, the half period determined by the length of delay line and with edges of approximately 30 millimicroseconds.

8. Complete Circuit

A more detailed circuit of a 1-digit store is shown in Figure 10. The delay line is fed from a tapping on the emitter follower load which not only gives a positive DC voltage shift but makes the voltage swing applied to the switching transistor smaller and this eases the problem of providing the constant current drive from the base. The 1K resistance terminates the delay line in its correct impedance. Transistor T11 is operated when exchange is wanted, T12 when shift (there could be several gating transistors giving different orders of shifts at this point), T9 when transfer, and T10 for a count.

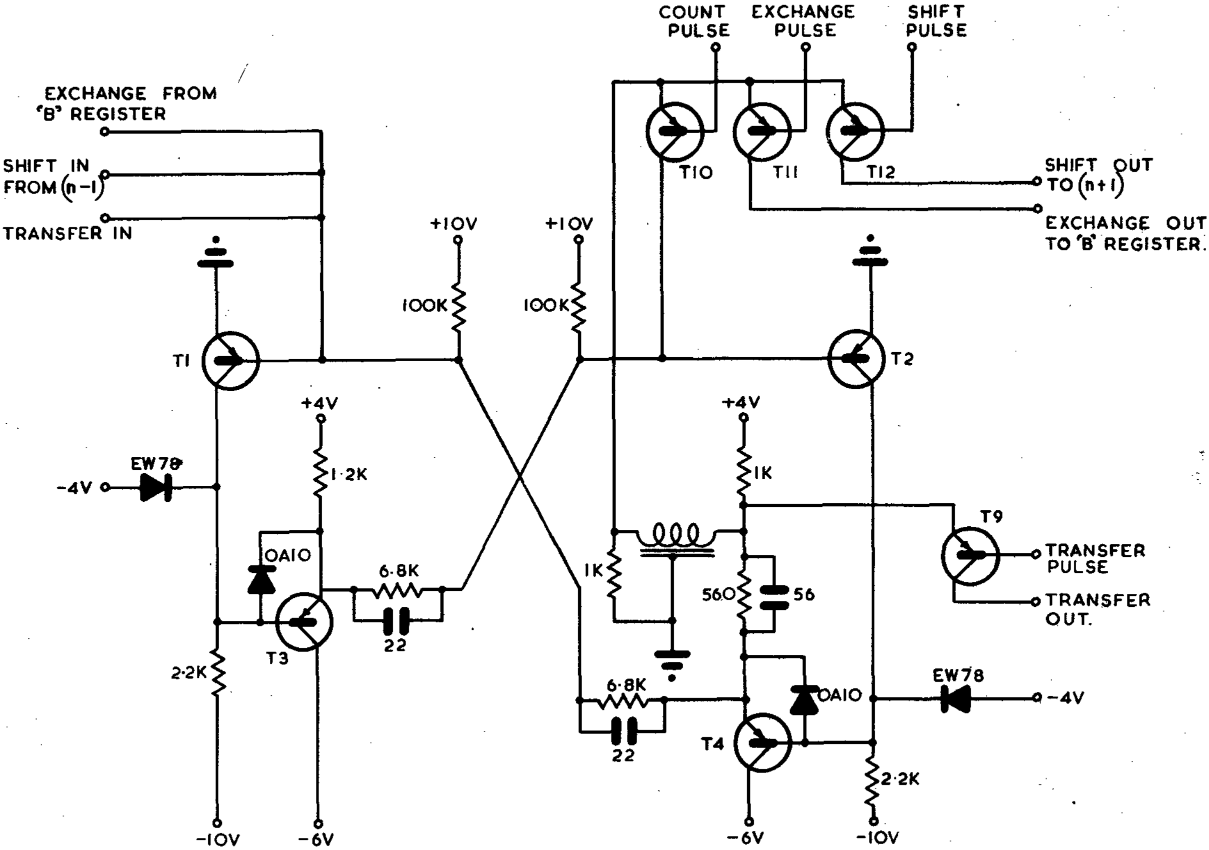

Figure 10 Complete circuit for a 1-digit store

9. Conclusion

The processes of exchange, shift and count have been shown to be similar, and even the transfer operation (A to B) can be considered to be half of an exchange operation (A to B and simultaneously B to A). If a transfer operation is carried out in this way the delay line is included in the transfer path. Thus the fundamental circuit for all the operations is substantially the same, the various processes required determining only the positions of the switch transistors. The four processes are only wanted in one or two registers of a computer but most registers need three of them.

It is thought that by using slightly improved circuits with more components and better transistors in certain positions, it will be possible to achieve switching speeds up to about 10 Mc/s. However, the circuits described rely on transistors being used near their saturated (bottomed) condition and in the inverse direction, and this sets a limit to their speed of operation. The present trend in the development of most high frequency transistors (fco greater than 100 Mc/s) is to produce graded base transistors which lose their high frequency response at low collector volts, are not reversible, and which have a very limited maximum reverse voltage between emitter and base. Such transistors cannot be used in the ways which have been described previously and require quite different circuit techniques(7).

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A WIRED SUBROUTINE STORE USING FERRITE CORES

by D. A. H. Brown

1. Introduction

The unit to be described is a special subroutine store which supplements the high speed store (Williams Cathode Ray Tube Type) of TREAC. Before the installation of the subroutine store, the high speed store was required to carry all the three parts characteristic of any digital computer programme, namely (i) the master programme peculiar to the computation required, (ii) subroutines which may be used in many programmes, such as taking a square root or finding the sine of an angle, and (iii) the data to be operated on. The subroutine store is confined to removing item (ii); all the common subroutines are wired into the subroutine store as a pattern of 0 and 1's stored in a matrix of ferrite cores. This frees the very considerable amount of high speed storage space normally occupied by the subroutines.

The principle of having frequently used subroutines made available to the computer from a special store is not new; it has been described by Renwick (1956) who used four wires to set a special set of ferrite cores into four different 0/1 patterns corresponding to sets of instructions. The density of use of the cores in his system is therefore 4 bits/core. The TREAC store has raised this to 64 bits/core.

2. Terminology

In describing the ferrite core subroutine store and its operation, it is necessary to distinguish various terms. They are set out here for reference; their meaning will be made clear later.

(a)	Subroutine	The sets of instructions needed to complete a definite mathematical operation, such as taking the square root of a number or finding the sine of an angle.

(b)	Master Wire	The wire which threads all the 480 cores of the matrix.
(c)	Setting Wire	Any one of the set of 64 wires which traverse some, but not all, of the cores of the matrix.
(d)	Read Wire	One of the 32 vertical wires each threading a set of 15 cores corresponding to any one instruction.
(e)	Output Wire	One of the 15 horizontal wires corresponding to one of the 15 digits of an instruction.

3. The Ferrite Core Subroutine Store

The ferrite core subroutine store has been constructed as a matrix of 480 cores of the 2 mm type (FX 1508 in D2 material) arranged as 32 words of 15 digits. The 15 digits are dictated by the form of the instruction in the RRE computer, which is 5 function digits plus 9 address digits; one extra digit is now required in order to specify whether the next instruction is to be taken from the high speed or core store.

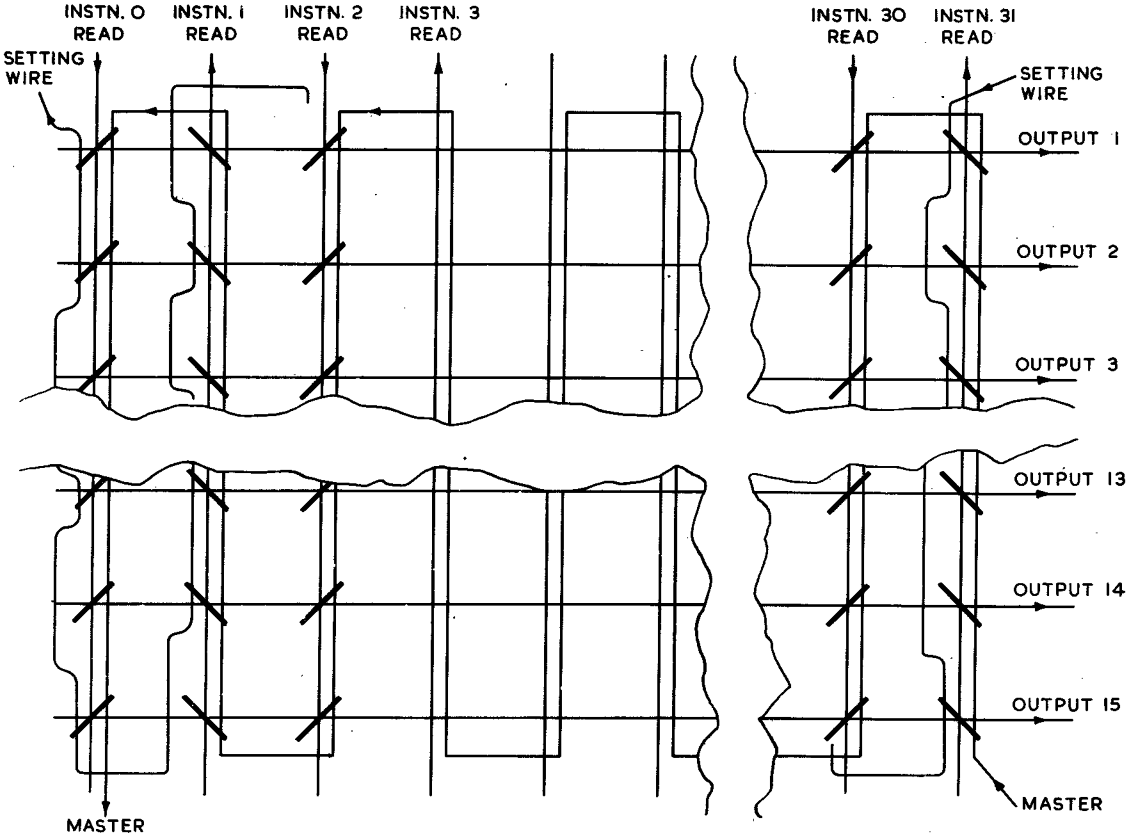


Figure 1 Matrix arrangement

The cores are arranged as shown in Figure 1 as 32 vertical columns of 15 cores. The various wires are indicated in Figure 1 where the arrows indicate the polarities of the currents used; the read and output wires require return wires (not shown) which run back outside the cores; each read and output wire has its own separate return. The master wire threads all the 480 cores of the matrix. There are 64 setting wires, each of which threads some only of the cores.

The sequence of operation to enter any chosen subroutine is:- (i) pulse master wire (1A, 5µsec.) - this sets all cores to 0 state; (ii) pulse the required setting wire (1A,5µsec.) - this sets certain cores over to 1 state thereby setting up a 0/1 pattern in the matrix; (iii) read out required instruction by pulse (1A,2µsec.) on read wire. In stage (iii) the output lines give a negative pulse whose amplitude is determined by whether a 0 or 1 was stored in the particular core. A little consideration will shown that, with the arrows in Figure 1 representing the direction of conventional positive current, a negative pulse always occurs at the output and that the inclination of the cores to left and right in alternate columns is necessary to achieve this if the master and setting wires are to run up one column and down the next in the obviously convenient manner. The direction of the read out current must then similarly alternate in adjacent columns.

The columns of wires are spaced $\frac{1}{2}$" apart and therefore occupy $15\frac{1}{2}$" horizontally, while the output lines are spaced $\frac{3}{8}$" and occupy $5\frac{1}{4}$" vertically. The setting and master wires are each of 46 SWG copper wire, this choice being dictated by the necessity of using relatively fine wire in order to get a large number of wires through each core. With the matrix dimensions given this means that the master and setting wires each have resistances of 40 to 50 ohms. The read and output wires are of 36 SWG and form a stronger framework for the cores to rest on. The wires have self-fluxing insulation as this eases considerably the making of the numerous joints.

It is shown in Appendix 1 that, when the master or a setting wire is pulsed, there is a simple relation between the resistance of the read circuit and the time taken to switch the storage cores. The read circuit comprises each read wire with its return and connections to the switch matrix (Sec. 5) output winding. The resistance of this circuit has been set at 2 ohms by careful choice of the length and gauge of the return wires and the connecting wires.

Figure 2 shows how each setting wire is wired in practice. Above and below the columns of wires are sets of 64 small tags arranged 8 x 8 at $\frac{1}{8}$" spacing, 17 sets above the wires and 16 below. Each instruction runs from the appropriate tag at the top to the corresponding tag at the bottom and then back up the next column and so on. In this way initial mistakes in wiring require only the alteration of the incorrect instruction and not the complete replacement of the whole setting wire.

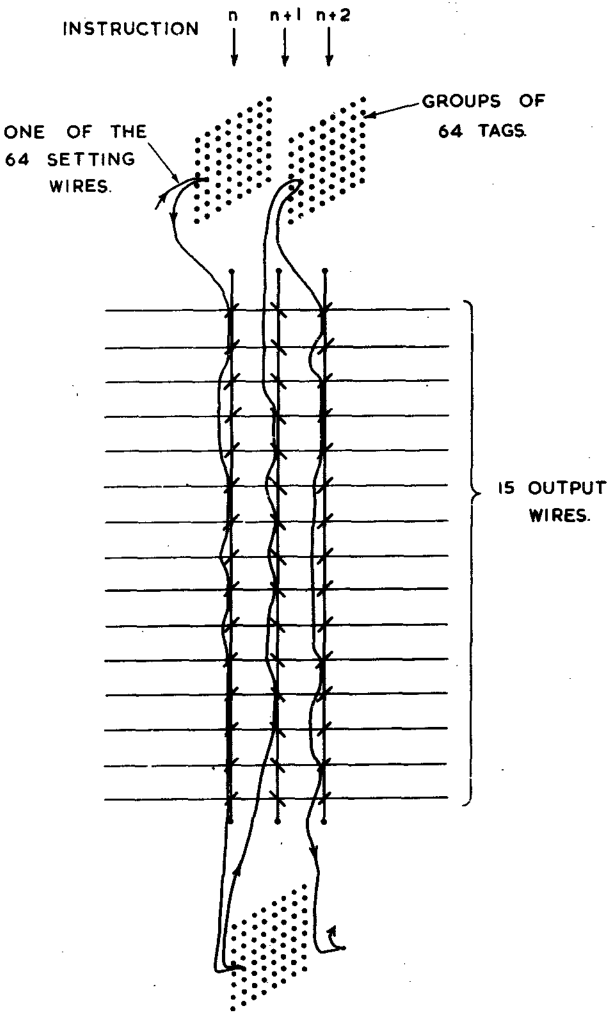


Figure 2 Setting wire detail

The terminology may be now explained in a little more detail. A chosen subroutine does not usually have exactly 32 instructions; some are shorter and some longer; consequently a subroutine, if longer than 32 instructions, may require the use of two or more setting wires, while for short subroutines, two may be stored in one wire. It is therefore not correct to call the setting wires "programme wires", since they do not in general correspond to complete subroutines.

The main engineering problems concern the selection of the required setting and read wires and these selection systems will now be dealt with.

4. Setting Wire Selection

The requirement here is to select one of the 64 wires and to pass a current of 1A into it; because of insulation requirements between the various wires, the potential should not stray far from earth. The system chosen is shown in Figure 3, and uses switching valves in series on an 8 x 8 matrix principle. One of the eight "catcher" valves (C1 - C8) has its grid at earth potential (say C5) while the other seven have their grids below -100V. One of the driver stages D1 - D8 is now turned on (say D3). The arrangement of diodes in series with each setting wire constrains this current to flow via wire 34 and out at C5, and no other route is possible.

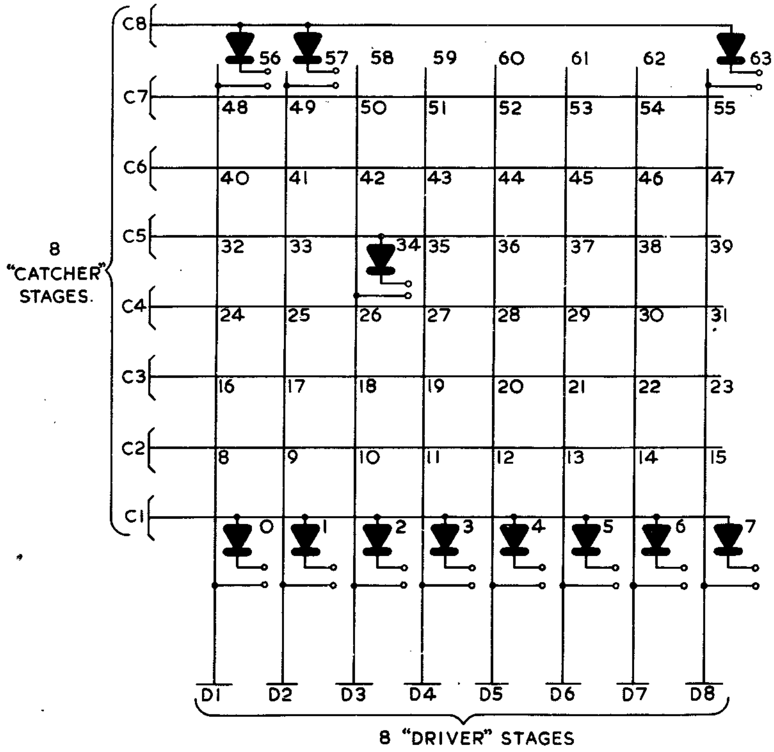


Figure 3 8 x 8 diode matrix for setting wire selection

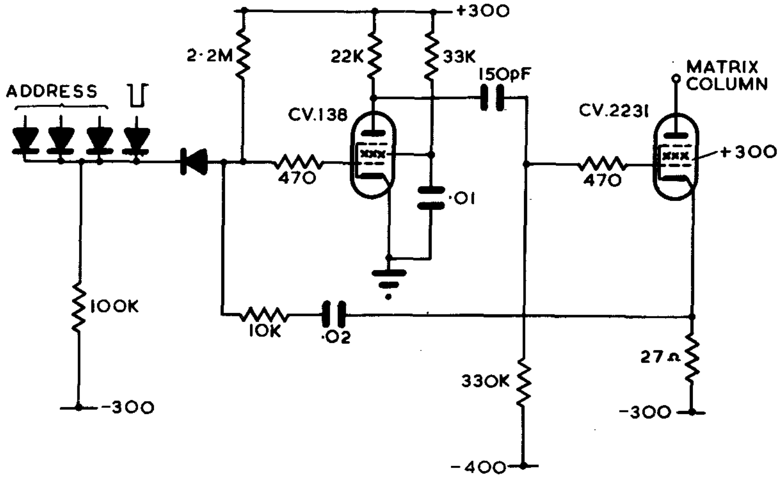


Figure 4 (a) "Driver" Circuit

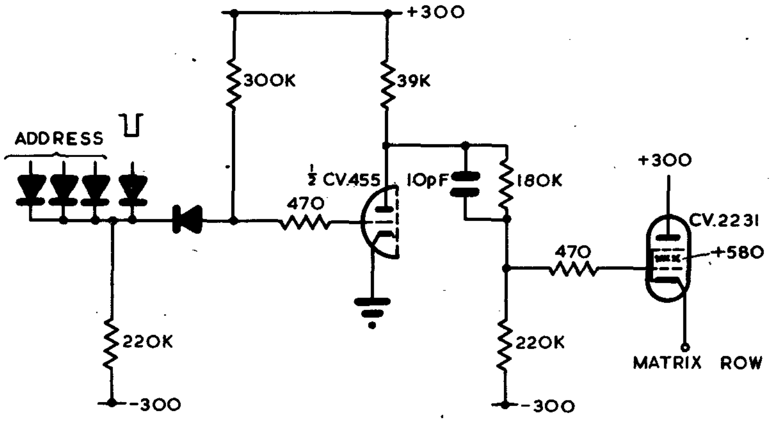


Figure 4(b) "Catcher" Circuit

The circuits of the driver and catcher stages are given in Figures 4(a) and (b). The driver has a current of 1.2A turned on by feedback action when the current in R is released into the virtual earth at the CV138 grid; approximately 0.2A of this current is lost in the screen circuit of the driver and the rest flows in the setting wire. This loss of current in the screen circuit means that the current in the setting wire is not accurately defined but as the screen/anode division ratio is determined by electrode geometry, which is not likely to change greatly with age, this does not seem a serious limitation. The pulse length is 5µsec.

The silicon junction diodes produce a voltage drop of less than 2V at 1A after an initial transient spike of about 6V falling to the steady 2V in 0.5µsec. The peak power dissipation in the diodes is therefore 2W while the rated mean dissipation is 150mW. The limitation which these figures set to the maximum rate of pulsing is not of importance in the RRE computer.

The system described requires the full 1A current to flow in the valves and it may be thought that a system using pulse transformers to step down the current would be preferable. This may be so, but it would entail an alteration of the present pulsing scheme in order to obtain balanced current; this would not be difficult if the setting wires were first pulsed simultaneously with the master pulse, the current being in a direction to aid the master pulse, and then, when the master pulse had finished, the setting wire current were reversed. As an alternative to a balanced current scheme, the setting wire current could be unidirectional if a diode system were used to allow the magnetising current built up in the transformer to discharge. A large transformer ratio could not be used because of the resistance of the setting wires; taking this as 50 ohms with a 1A pulse means that the secondary voltage would be 50V; if 150V is taken as the maximum primary voltage which could conveniently be used, a three to one step down of current is the best that could be achieved. A more important objection to pulse transformers at the time of designing the equipment was the consideration of the back e.m.f. to be expected from (at worst) 480 cores changing state simultaneously (though none of the subroutines finally used require more than approximately half this number to be switched); at 0.1V from each one an extra 48V of back e.m.f. was expected; this, together with the 50V ohmic drop, requires 100V of secondary output; this is so large that any appreciable current transformation ratio would produce an impracticably high primary voltage requirement. In fact it is now realised that the back e.m.f. need not be quite as high as 48V and a two or three to one current transformation might be achieved.

5. Instruction Selection

A balanced current may flow in the read wires and a pulse transformer scheme has been used. It involves a 4 x 8 matrix of square loop ferrite cores (FX 1396 in D1 material); these cores are used in pairs at each position and each pair has three windings connected as shown in Figure 5; there are 37 turns of 30 SWG on the bias windings, 25 turns of 36 SWG on the drive windings and 5 turns of 36 SWG on the output windings.

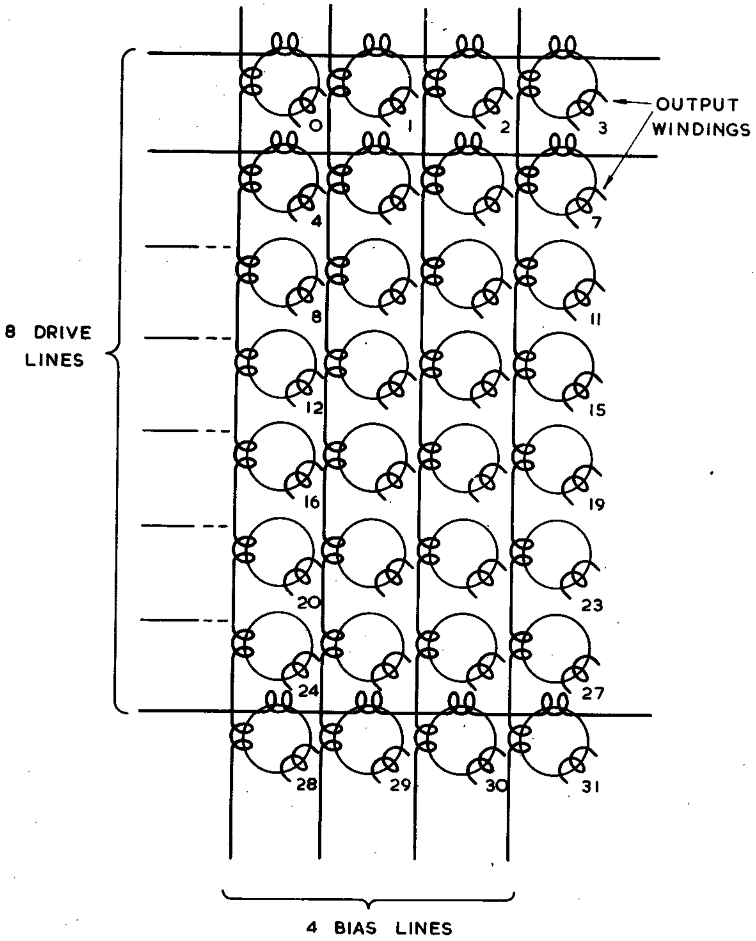


Figure 5 Core switch matrix for instruction selection

The eight bias windings on one column are in series and carry a steady current of 200 mA interrupted only by a 2µsec. pulse. The four drive windings in each row are in series and are pulsed for 2µsec. with 300mA. The 32 output windings are connected to the 32 read wires.

The effect of the d.c. bias is to keep the switch cores normally in one state of magnetic saturation. The m.m.f of the bias winding (200mA and 37T = 7.4AT) is very nearly the same as that of the drive winding (300mA and 25T = 7.5AT), and the small difference between them of 0.1AT is very much less than the coercive m.m.f. (1.4AT for these cores). Any instruction is selected by removing the bias from the column containing the appropriate switch core and simultaneously applying the drive to the corresponding row. The selected core is switched to its opposite magnetic state. The seven unselected cores in the column are brought to H = 0 only and do not switch, while the three unselected cores in the row have the bias m.m.f. cancelled by the drive m.m.f. and also come close to H = 0 but do not switch. The design of the windings is considered in Appendix 2.

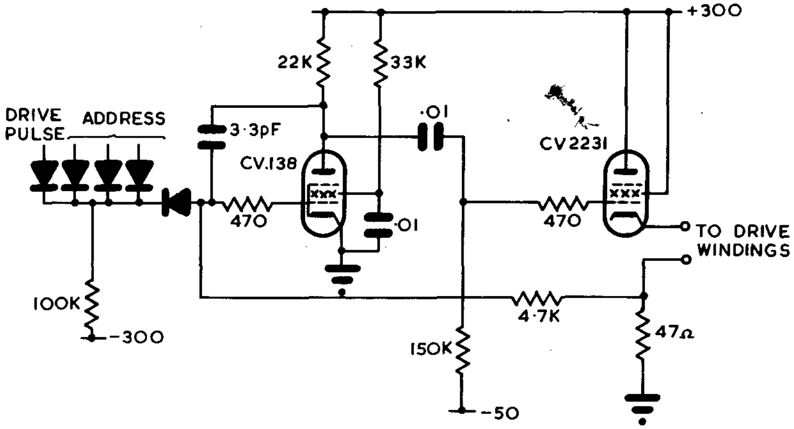


Figure 6(a) Core switch matrix drivers

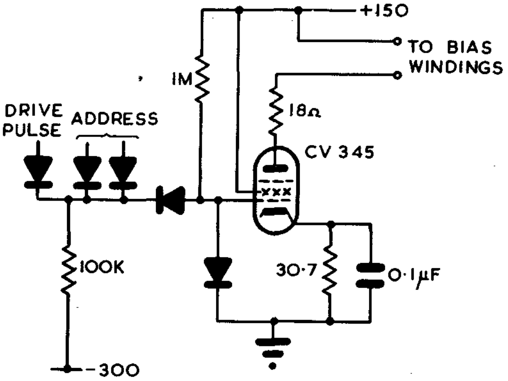


Figure 6(b) Core switch matrix bias valves

The circuit diagrams of the bias valves and the driver valves of the switch matrix are given in Figures 6(a) and (b). The system of having 200mA standing current in each of the four bias valves is wasteful and has been used in the interests of simplicity Other schemes using a pulsed bias would be more efficient though involving more complicated pulsing.

6. Amplifier and Discriminator

The amplifier and discriminator circuits are shown in Figure 7 and are conventional. The digit output is taken directly into a pulse transformer which gives a step up of about 12:1 (design value 15:1), the secondary being connected to an amplifier. A small amount of negative feedback is used on the amplifier, though the loop gain is only about 2. The positive output from the amplifier is about 15V for a 1 and only 3V for a 0. It is applied through a d.c. restoring circuit to the grid of a cut off valve, and only the 1 output is sufficient to drive this valve into conduction. The negative output from this valve is taken by a White Cathode Follower for distribution to the computer.

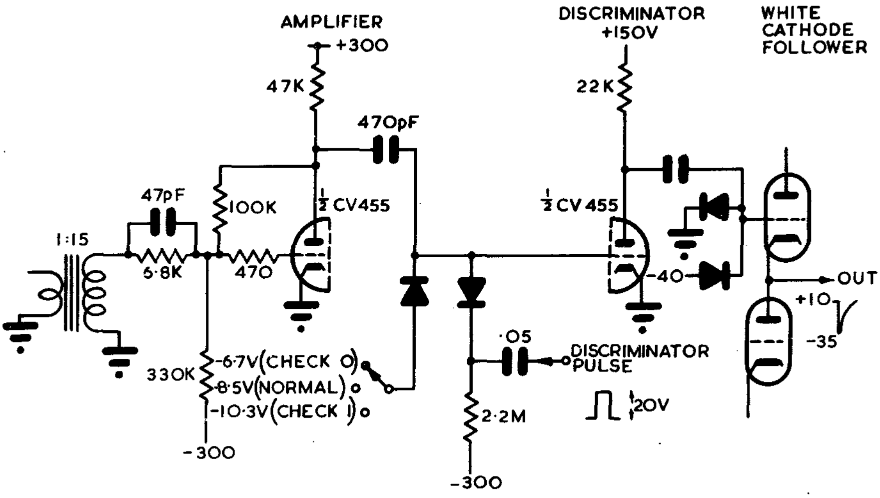


Figure 7 Amplifier and discriminator

The pulse transformer specification is:

Primary: 12T, 30SWG, 0.075 ohm. Secondary: 180T, 44SWG, 24 ohms. Primary and secondary wound side by side on former $\frac{1}{2}$" O.D.; both windings are $\frac{1}{3}$" wide and are spaced 1/16" apart; secondary is single wave wound; core is 60 pairs of E/I 0.004" Radiometal, Type 500T. The turns given are now thought to be generous, and a 9/135 turn winding would probably be sufficient.

A marginal check has been applied to the discriminator level, which is normally at -8.5V. A range of about ±2V on this has been thought to be a suitable variation and the discriminator gives no output from a stored zero when the level is changed to -6.7V and the amplitude of a stored 1 shows no reduction at -10.3V. This has been useful for checking the system operation.

7. Wiring and Testing

The 64 setting wires store 30720 bits of information on the 480 cores and it is inevitable that some mistakes will be made in wiring. A testing unit was therefore set up so that, before installation in the computer, each setting wire could be pulsed and the contents of the 32 wires read out sequentially; the sequence of 0's and 1's as displayed on an oscilloscope could then be compared with the wiring schedule and any discrepancies noted. (The extra equipment needed to do this consisted of a single multivibrator and five binary dividers). This revealed that of the 2048 instructions stored, 57 had a mistake. These mistakes were corrected and checked again before installation. After installation one further error has been found which seems to have eluded even the extensive pre-installation check.

Several practical points of wiring the matrix were not foreseen and led to difficulties which could be avoided by more careful attention to its mechanical design.

First, during wiring both short circuits between wires and breaks in wires occurred. The breaks could easily be found and repaired. The short circuits were almost invariably caused by the wires rubbing against other tags on the end fixing arrays of 64 tags arranged 8 x 8 (Figure 2); it was usually sufficient to ease the wire away from such a rubbing spot. If the matrix were repeated it would be very desirable to constrain the wires to follow definite paths over insulating pins or through insulating channels so that they could not rub against any metal parts.

Secondly, where a core in the matrix has many wires missing it, so that most subroutines are 0 in this position , and only a few "1"s, the wires passing outside it soon build up in number as wiring progresses, and obscure the core; it is then difficult to find the core and pass a "1" wire through it. This could be avoided if a small channel or a pin were provided next to each core so that wires not threading a core could be kept out of the way.

Lastly, the brown paxolin of the matrix background makes a very poor contrast to the brown enamel covering of the wire so that it is difficult to find the end of the wire and to follow its path. A background in sharp contrast to the wire colour is required.

In order to make daily servicing and fault finding easier, a switch has been incorporated in the installation. In the "Test" position of this switch the C.R.T. store controls the machine and reads out the instructions as numbers into the accumulator. This test facility, which essentially uses the C.R.T. store to test the core store, has been found useful. A simple daily test takes all the instructions as "numbers", adds them up and compares with the known answer. Also, a programme in the C.R.T. store allows any one selected wire to be pulsed and its 32 instructions to be read out repetitively; this was a considerable help during installation, and promises to be useful for servicing.

8. Acknowledgments

Mr. R. H. A. Carter has given advice on the installation of the system in the computer. The very considerable task of wiring the matrix was patiently done by Mrs. A. Summers. I should also like to thank Mr. P. Bounds for constructing and testing the units.

9. Reference

W. Renwick, "Magnetic Core Matrix Store with Direct Selection using Magnetic Core Switch Matrix", I.E.E. "Ferrites" Convention, Proc. I.E.E., 104 B, Supplement No. 7, p. 436 (1957).

APPENDIX 1

READ CIRCUIT RESISTANCE AND MASTER PULSE LENGTH

The cores of the matrix are threaded by several distinct sets of wires - setting wires, master wire, read and output wires There are consequently transformer effects to be considered as mutual inductance links all these circuits.

It is simplest to start by considering the master pulse. During this pulse the setting wires are effectively open circuit and no current can flow in them.

The output wires of the storage matrix are connected to the pulse transformer primaries which, because of their inductance, have a high impedance for short pulses, so that the current in these output wires will be negligible. Consequently the only mutual effect of importance is that between the master pulse and read circuit. During the master pulse the essential circuit to be considered is that of Figure 8.

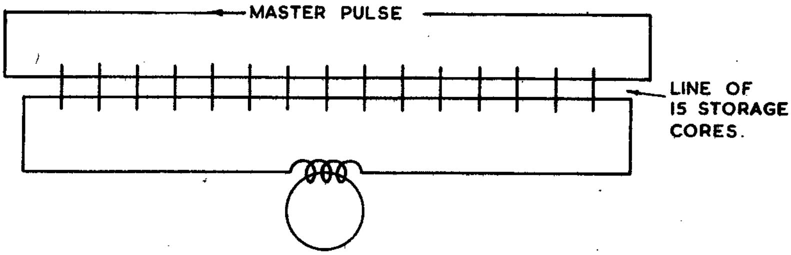


Figure 8

The switch matrix core is held hard over in one magnetic state by the bias so that (ideally) though current may flow in its winding no flux change will take place; only the circuit resistance is important. Let I_1 be the master pulse current, I_2 be the induced current in the read circuit, and R be the resistance of the read circuit. Then the equations governing the transition of the storage cores are

$$I_1 - F_c = I_2 \qquad (1)$$

$$15\frac{d\phi}{dt} = I_2 R \qquad (2)$$

These assume that the hysteresis loop of the storage cores is square with coercive m.m.f. F_c (amps). If the saturation flux is Φ_s (webers) then the time required for the transition of the storage cores from one state to the other is simply

$$\tau = \frac{15 \quad 2\Phi s}{R(I_1 - F_c)} \qquad (3)$$

This shows that if R = 0 the cores will take an infinite time to change state and clearly R should be made large. Exactly the same conditions apply during the pulse in the setting wire.

For $\Phi_s = 4 \times 10^{-8}$ webers, $I_1 = 1A$, $F_c = 0.4$ A, equation (3) gives a required $R\tau$ product of 2 ohms - μsec. In practice, R = 1 ohm and $\tau = 3\mu$sec. has been found to produce complete reversal in most cores but some have seemed to be anomalous in requiring longer pulses; the theory can therefore be considered only as a guide to design. To cover these anomalous cases and to give that factor of safety which is desirable if reliable working is to be achieved, the final choice is R = 2 ohms, $\tau = 5\mu$sec.

The resistance of the read circuits has been set at 2 ohms by choosing carefully the length and gauge of the wires connecting them to the switch matrix.

APPENDIX 2

DESIGN OF WINDINGS ON SWITCH MATRIX

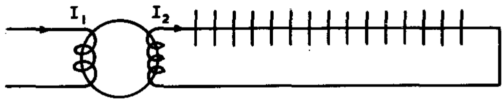


Figure 9

During read out, both master and setting wires are open circuit and the output wires are high impedance. The simplified circuit is then that of Figure 9 in which the switch matrix drives the 15 cores of an order. Clearly we have

$$N_1 I_1 - F_{cs} = N_2 I_2 \qquad (4)$$

$$N_2 \frac{d\phi_s}{dt} = I_2 R + \frac{n d\phi}{dt} \qquad (5)$$

Here N_1 is the number of primary turns on the switch matrix core, N_2 the turns on the output winding, I_1 is the drive current, I_2 the read current, R the resistance of the read circuit, F_{cs} is the coercive m.m.f. of the switch matrix cores, ϕ_s is the flux in the switch core, ϕ the flux in the storage core and n the number of storage cores being switched (which may be $0 \leqq n \leqq 15$).

Taking the worst case of $n = 15$ and $d\phi/dt = 0.1V$, then with $I_2 = 1A$ and $R = 2$ ohms, equation (5) requires a switch matrix output voltage of 3.5V. Assuming that this must be maintained for 2µsec. (which is on the safe side since the storage cores will have switched and ceased to produce any back e.m.f. well within this time) then the total output of the switch matrix secondary must be 7V-µsec = 700×10^{-8} webers. A pair of FX1396 cores (8mm dia.) have a saturation flux of 76×10^{-8} webers and a total flux change available of twice this, 152×10^{-8} webers. Therefore $N_2 = 5$ turns is appropriate and gives again a small safety factor.

Equation (4) with $N_2 = 5$, $I_2 = 1$, and $F_{cs} = 2A$ requires a drive of 7AT. In practice it appears that F_{cs} must be rather larger than the quoted figure and a drive of 7.5AT has been used. The drive winding then is 25 turns with a pulse current of 300mA. The bias winding is 37T with 200 mA d.c.

SOME GYRO MECHANICS

by A. L. Quartley

1. Introduction

As a means of providing an angular space reference, the gyro has a simple elegance which immediately captures the imagination. Since Foucault's experiments to demonstrate the earth's rotation with a gyroscope in 1852,(1) much engineering endeavour has been directed towards making a practical gyro which succeeds at least in part in exploiting the latent possibilities of the device in this role. Today, after all the development work behind the maritime gyro compass and more recently gyros used in aircraft, the problem of making a gyro space reference which is sufficiently free from drift to provide accurate navigational information over usefully long periods is still largely with us.

At RRE, some simple experiments have recently been conducted in order to solve a specific gyro problem. They cannot be regarded as an attempt to grapple with the more general gyro problems, but they have yielded a certain insight into the behaviour of practical gyros, which the present account goes some way towards describing.

2. The Characteristic Behaviour of a Gyro

When first experienced, the response of a gyro when one tries to turn it about an axis lying in the plane of spin of its rotor is quite astonishing. It refuses to move in the direction in which the torque is applied, and persists instead in moving in a plane at right angles to this. This unexpected response depends on an acceleration force which is as fundamental as the centrifugal force we associate with a rotating mass, but as it does not fall within our everyday experience, it appears as a strange phenomenon when first encountered. An attempt is made in what follows, first to illustrate the conditions in which this acceleration arises, and to make it account for the behaviour of a gyro, and then to deal with the equations of motion of a practical gyro with a view to discussing some of the practical difficulties which have to be overcome by those seeking to make gyros of high performance.

3. The Acceleration upon which Gyro Behaviour Depends

First consider a point P moving at uniform angular velocity around the circumference of a circle of radius r and centre O (Figure 1). If $\dot{\theta}$ is the angular velocity of P with respect to a line XOX', and YOY' is a further line drawn at right angles to XOX', then the instantaneous position of P in these co-ordinates is

$$z = x + jy$$

$$= r\,(\cos \dot{\theta}t + j \sin \dot{\theta}t)$$

This may be conveniently written in polar form as

$$z = re^{j\dot{\theta}t}$$

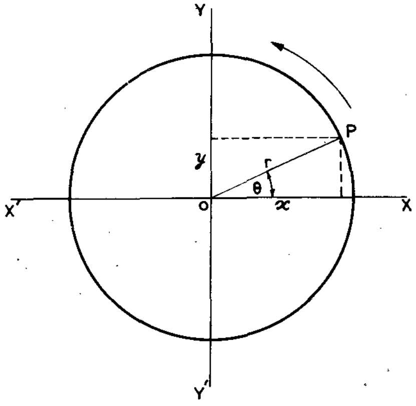


Figure 1 The acceleration at point P moving on a circular path.

If we wish to know the tangential velocity of P on its path round the circumference of the circle, we differentiate z with respect to time and get

$$\dot{z} = jr\dot{\theta}e^{j\dot{\theta}t}$$

which indicates that P has a velocity $\dot{\theta}_r$ at right angles to r, i.e. in the direction of rotation. Further, if we now wish to find the acceleration of P we differentiate once more with respect to time and get

$$\ddot{z} = -r\dot{\theta}^2e^{j\dot{\theta}t}$$

which tells us that P has an acceleration $\dot{\theta}^2r$ inwards towards the centre of the circle. This is of course the centripetal acceleration which, when acting on a mass yields a force reaction radially outwards, and is described in engineering parlance as centrifugal force.

Next consider the case where P not only spins around O, but also moves radially outwards with a constant velocity v, so that r may now be written as

$$r = vt$$

The locus of P, instead of being a circle, will now be a spiral (Figure 2). The instantaneous position of P expressed in the same polar form used in the previous example is now

$$z = vte^{j\dot{\theta}t}$$

and, differentiating twice with respect to time in order to find the accelerations, we obtain

$$\ddot{z} = (2jv\dot{\theta} - vt\dot{\theta}^2)\,e^{j\dot{\theta}t}$$

We thus see that, whereas in the previous example we had a centripetal acceleration alone, we now have an additional acceleration $2v\dot{\theta}$ which operates at right angles to this and in the direction of rotation. This new term is called the Coriolis acceleration, and it becomes evident as soon as we consider a point having velocity along a line while the line is itself rotating.

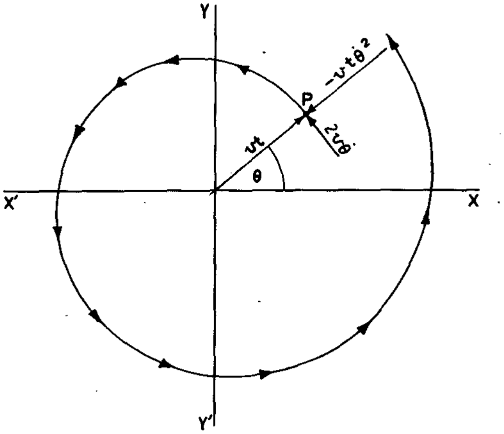


Figure 2 The acceleration at point P moving on a spiral path

4. Coriolis Acceleration and the Rotor Wheel of a Gyro

Everyone knows that a gyro employs a wheel which spins on an axis through its centre. Figure 3(a) illustrates such a wheel, spinning with angular velocity ω. If P is a point on this wheel at a fixed radius r, the velocity of P at any instant in a direction tangential to its path is ωr. If we now suppose that, while it is spinning, the axle of the wheel also turns about a vertical line YY' with a velocity $\dot{\theta}$, then if P is in the position shown (where it lies on YY') it will clearly be subject to the same conditions as point P illustrated in Figure 2. It will have a velocity ωr (corresponding to v) along a line which is rotating at angular velocity $\dot{\theta}$ about YY'. For the direction of rotation shown, P will thus be subject to an acceleration $2\omega r\dot{\theta}$ acting into the page. In Figure 3(b), which shows a side view, the acceleration operates in a clockwise direction. Further, if an exactly similar point P' is situated diametrically opposite to P, it is clear that it will have a velocity ωr in the opposite direction to P and will thus be subject to an acceleration $2\omega r\dot{\theta}$ acting out of the page (Figure 3a), or in Figure 3(b) again in a clockwise direction.

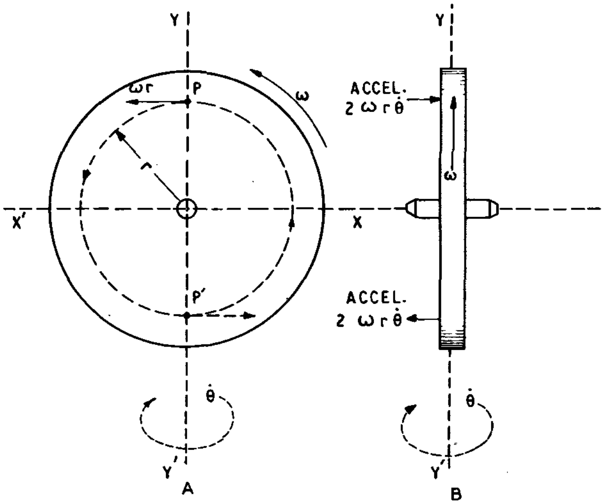


Figure 3   Coriolis acceleration acting on points P and P' situated at a particular position on the rotor wheel

5. Reaction Forces necessary to balance Coriolis Acceleration Forces

In a practical gyro wheel, a mass m (say) is associated with the points P and P', and force is equated to mass times acceleration. A force $2m\omega r\dot{\theta}$ must then be applied to each point in the direction indicated by the accelerations shown in Figure 3(b). This argument implies that in order to turn the axle of the spinning wheel about the axis YY' a couple must be applied about axis XX'. The couple must be equated to the sum of the acceleration forces acting on all the points like P and P'.

In Figure 4, the wheel is again viewed as in Figure 3, but P is now in any arbitrary position making an angle ωt with respect to axis XX'. This position may be defined on axes XX' and YY' as

$$x = r\cos\omega t$$

$$y = r\sin\omega t$$

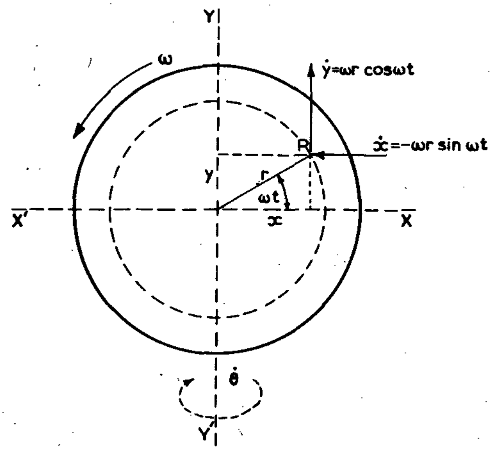


Figure 4 Coriolis acceleration acting on points P and P' situated at an arbitrary position on the rotor wheel

The components of the velocity of P referred to these axes are thus

$$x = -\omega r \sin \omega t$$

$$y = \omega r \cos \omega t$$

If as before the axle of the wheel turns about YY' with a velocity $\dot\theta$ it may be seen that the component $\dot{y}$ does not yield a Coriolis acceleration, because it lies parallel to YY'. Thus for movements of the circle about YY' the Coriolis acceleration is due solely to the horizontal component of the velocity of P, and we may write it as

$$-2\omega r\,\dot\theta \sin \omega t$$

We can now find the total couple or torque to be applied about one axis (XX') of the spinning wheel in order to sustain an angular velocity $\dot\theta$ about the other axis (YY') at right angles to it.

Figure 5 represents an infinitely small element of the wheel illustrated in Figure 3, having say a uniform thickness b, and a density ρ. The mass of this element is then

$$m = \rho b r \, d\alpha \, dr$$

and if it is subject to the conditions depicted in Figure 4 the acceleration acting is

$$-2\omega r\dot\theta \sin \alpha$$

Hence the applied force required to balance the product of mass and acceleration is

$$f = 2m\omega r\dot\theta \sin \alpha$$

$$= 2\omega r^2\dot\theta \rho b \sin \alpha \, d\alpha \, dr$$

The turning moment thus applied about XX' is, for this element,

$$fr \sin \alpha$$

$$= 2\omega r^3 \dot{\theta} \rho b \sin^2\alpha \, d\alpha \, dr$$

Hence for an annular ring of radius r, width dr and thickness b, the turning moment is

$$2\omega r^3 \dot{\theta} \rho b \, dr \int_0^{2\pi} \sin^2\alpha \, d\alpha$$

$$= 2\pi\omega r^3 \dot{\theta} \rho b \, dr$$

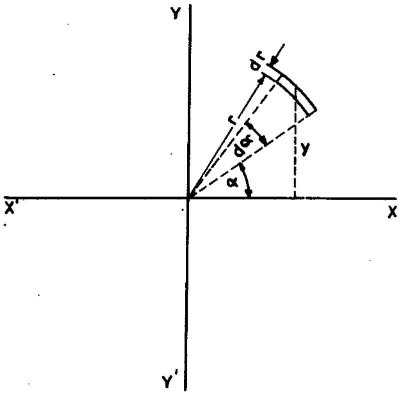


Figure 5 **Infinitely small element of wheel**

Thus for a disc of radius r and thickness b, the total torque applied is

$$\tau = 2\pi\omega\dot{\theta}\rho b \int_0^r r^3 dr$$

$$= \tfrac{1}{2}\pi\omega\dot{\theta}\rho b r^4$$

and if the mass of the disc is written as M, then

$$\tau = Mr^2\omega\dot{\theta}/2$$

Those readers who are familiar with the expressions giving the moment of inertia of various geometrical figures about significant axes will recognise that $Mr^2/2$ is the moment of inertia of a solid wheel about its axis of spin. This is seen to be the case if one considers an elementary ring such as would result if $d\alpha$ of Figure 5 were made equal to 2π. The moment of inertia of this ring about its axis of spin will then be

$$mr^2 = 2\pi\rho b \, r^3 dr$$

Hence the moment of inertia of the solid disc about the same axis is

$$I = 2\pi\rho b \int_0^r r^3 dr = \pi r^4 \rho b/2 = Mr^2/2$$

Thus for the gyro wheel here considered, the relation between applied torque about one axis and the resulting angular velocity about an axis at right angles is

$$\tau = I_s \omega_s \dot{\theta}$$

where I_s is the moment of inertia about the spin axis, and ω_s is the angular velocity of spin.

When such a torque is applied to a gyro, the velocity with which it turns about the axis at right angles is termed the "velocity of precession", and the relation arrived at above is a general one for all gyros whatever the geometry of the rotor. This relation is a key to understanding why a gyro is so effective as an angular space reference.

6. Frictional Effects

The ideal angular space reference, if set up to indicate a line at any position A in space, will, if moved bodily to another position B, indicate a line which lies exactly parallel to the line through A, even though the platform upon which it is carried may have performed many angular manoeuvres during its passage from A to B.

Figure 6 shows a schematic illustration of a gyro wheel spinning in bearings mounted on gimbal frames E and G which are pivoted orthogonally both with respect to each other and to a supporting platform, at pivot points LL' and HH'. If the supporting platform turns through an angle about either the vertical or horizontal axis, friction in the pivot bearings between frame G and the platform, or between frames E and G will tend to make the respective frame turn with the platform.

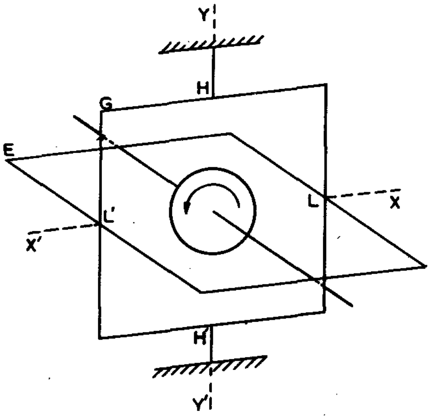


Figure 6 Gyro wheel in gimbal frames

Friction in this context is somewhat complicated, as the word is used to cover several effects, all of which oppose the free turning of a shaft in its bearing. Three such effects are: Coulomb friction, "stiction" and viscous friction. The first of these is that which offers a resistance to motion proportional to load and is exemplified in the inclined plane experiments of elementary mechanics. The second is more difficult to describe, but is loosely of the relaxation kind encountered in the bowing of a violin, while the third is proportional to velocity and is equivalent in dimension to electrical resistance. It is because the latter lends itself to mathematical expression in linear equations that it is so often used to represent the whole friction family when an analysis is being made. This approach, although sometimes not entirely realistic, does make possible a simple assessment of the sensitivity of a device to frictional effects. With this in mind, and using the relation between applied torque and precession velocity obtained earlier, the behaviour of a gyro as a space reference device in this practical situation may be examined as follows.

The platform upon which the gyro is carried is assumed in Figure 7 to have turned through an angle α in the direction indicated. If the outer frame G moves in the same direction through an angle θ due to frictional coupling, then the torque acting on frame G is

$$F(\dot{\alpha} - \dot{\theta})$$

where F is the coefficient of viscous friction in pivots HH'.

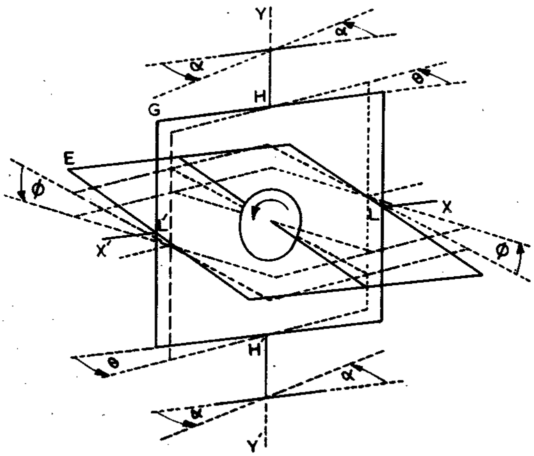


Figure 7 Response of gyro to angular displacement of platform

If the spin momentum of the gyro wheel is $I_S\omega_S$ in the direction shown, this friction torque will cause a precession ϕ about axis XX' such that

$$F(\dot{\alpha} - \dot{\theta}) = I_S\omega_S\dot{\phi}$$

As there will also be friction in the pivots LL', this precession about axis XX' will encounter a resistance $F\dot{\phi}$ acting to oppose ϕ and, by so doing, provide the torque about axis XX' which causes precession θ

about YY' such that

$$F\dot{\phi} = I_s\omega_s\dot{\theta}$$

Thus $$\dot{\phi} = \frac{F(\dot{\alpha} - \dot{\theta})}{I_s\omega_s}$$

and $$F\dot{\phi} = \frac{F^2(\dot{\alpha} - \dot{\theta})}{I_s\omega_s} = I_s\omega_s\dot{\theta}$$

Hence $$\dot{\theta} = \frac{F^2\dot{\alpha}}{I_s{}^2\omega_s{}^2 + F^2}$$

$$\dot{\phi} = \frac{FI_s\omega_s\dot{\alpha}}{I_s{}^2\omega_s{}^2 + F^2}$$

Assuming $I_s\omega_s$ is much greater than F and integrating, we obtain

$$\theta = F^2\alpha/(I_s\omega_s)^2$$

$$\phi = F\alpha/I_s\omega_s$$

The error in the angular reference line indicated by the gyro will thus be a fraction of the angle turned through by the platform if $F/I_s\omega_s$ is a fraction. Further, this error is independent of the speed at which the platform is turned. For a given pivot friction, the greater the spin momentum in the rotor, the smaller is the error, and the more accurate the reference provided by the gyro. In practice the upper limit to the spin momentum is set by the ability of the wheel to withstand the stresses arising from centrifugal force, so that after this limit is reached for a particular wheel design, further improvement depends on reducing the pivot friction. In a simple instrument gyro of the pattern used in, say, an "artificial horizon" type indicator, the ratio of friction to spin momentum will be approximately 1:500, thus providing a reference good to 1:25 x 10^4 in the plane turned through by the supporting platform and 1:500 in the plane at right angles to this. Gyros fitted with air floated or magnetically suspended pivots often work at friction to spin momentum ratios of the order 1:10,000.

7. The Equations of Motion for a Practical Gyro

Because the torque applied in one plane causes precession in a plane at right angles, it is necessary when building up the equations of motion which will completely describe a gyro to consider simultaneously torques which may operate in both planes. A convenient preliminary approach which is useful in establishing the signs of the torque reactions is as follows. Consider the torques applied about the two axes of the gyro wheel shown in Figure 8(a). These are τ_θ causing precession ϕ, and τ_ϕ causing precession θ. These torques may be considered as the components of a single torque such that

$$\tau = \tau_\theta + j\tau_\phi$$

as shown on the Argand diagram in Figure 8 (b). The response of the gyro to τ_θ will be a precession velocity

$$\dot{\phi} = \tau_\theta / I_s \omega_s$$

along the j-axis, whereas the response to τ_ϕ will be a velocity

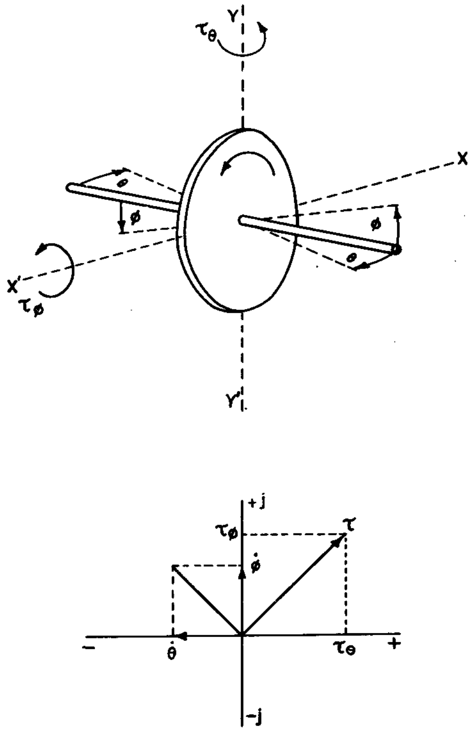
$$-\dot{\theta} = \tau_\phi / I_s \omega_s$$

along the negative real axis. Thus, consistent with the vector sense of the diagram, we may write

$$\tau_\theta = I_s \omega_s \dot{\phi}$$

$$\tau_\phi = -I_s \omega_s \dot{\theta}$$

In the practical gyro it is necessary to consider also those torque reactions arising from the accelerations of the moments of inertia of the wheel and its supporting frames about the axis to which the torque is applied, together with the viscous friction torque discussed earlier.



Figures 8(a) and (b) Gyro wheel and Argand diagram

Taking these terms into account, the complete simultaneous equations of motion for the two axes thus become

$$\tau_\theta = I_1 \ddot{\theta} + F_1 \dot{\theta} + S \dot{\phi} \qquad (1)$$

$$\tau_\phi = I_2 \ddot{\phi} + F_2 \dot{\phi} - S \dot{\theta} \qquad (2)$$

where I_1 and I_2 are the moments of inertia of the gyro about the YY' and XX' axes, F_1 and F_2 the coefficients of viscous friction at the gimbal frame pivots, and S the spin momentum ($I_s\omega_s$) of the rotor wheel. These equations are often referred to as the Euler equations, since a gyro is a particular case of the dynamics of a system having three orthogonal axes of rotation, the equations of motion of which Euler formulated and solved in the year 1736(2).

8. The Transient and Steady State Response

Assuming an external torque to be applied about axis YY', and writing equations (1) and (2) in operational form, we have

$$\tau_\theta = I_1 p^2\theta + F_1 p\theta + Sp\phi \qquad (3)$$

$$0 = I_2 p^2\phi + F_2 p\phi - Sp\theta \qquad (4)$$

where

$$S = I_s\omega_s$$

whence from (4)

$$S\theta = (I_2 p + F_2)\phi \qquad (5)$$

Substituting for θ in (3) and rearranging, we obtain

$$\phi = \frac{S\tau_\theta}{p(F_1F_2 + S^2)} \quad \frac{1}{p^2 \dfrac{I_1 I_2}{F_1F_2 + S^2} + p \dfrac{I_1F_2 + I_2F_1}{F_1F_2 + S^2} + 1} \qquad (6)$$

The precession ϕ is thus expressed as a function of the time integral of the applied torque, multiplied by an oscillatory quadratic term. Solving for p in this latter expression we obtain

$$p = \frac{I_2F_1 - I_1F_2}{2I_1I_2} \pm \sqrt{\frac{(I_1F_2 + I_2F_1)^2 - 4I_1I_2(F_1F_2 - S^2)}{4I_1{}^2\, I_2{}^2}} \qquad (7)$$

If, for simplicity, $I_1 = I_2 = I$ and $F_1 = F_2 = F$, then

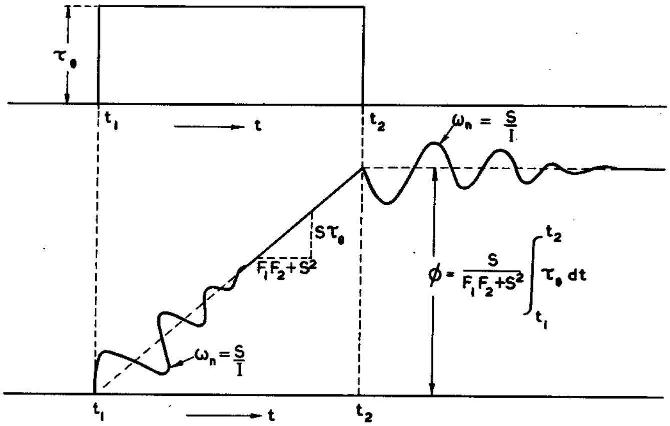
$$p = -(F/I) \pm jS/I \qquad (8)$$

Thus ϕ is a damped oscillation given by

$$A \exp(-Ft/I)\,(\cos(St/I) \pm j \sin(St/I)) \qquad (9)$$

S/I is called the nutation frequency (ω_n) of the gyro, and is that frequency at which the gyro will ring if given a sharp blow or a step function of torque; F/I is the damping factor of this oscillation. As an example, if τ_θ were a pulse such as that depicted in Figure 9(a), the precession ϕ about XX' would be as illustrated in Figure 9(b). This is, however, only half of the picture, as oscillatory motion about the other axis has also to be considered. The physical meaning of this oscillation will be discussed later.

Returning now to equation (6), and considering the case where τ_θ is a sinusoid, it may be seen that the quadratic will exhibit



Figures 9(a) and (b) Rectangular torque pulse and response of gyro resonance at a frequency given by

$$\omega_o^2 = (F_1F_2 + S^2) / I_1I_2 \tag{10}$$

where ω_o is the undamped natural period of the gyro. At this frequency the quadratic reduces to

$$\frac{(I_1F_2 + I_2F_1)}{F_1F_2 + S^2} p \tag{11}$$

which is the damping term. Substituting for $F_1F_2 + S^2$ from equation (10), the expression (11) may be written p/ω_oQ where

$$Q = \frac{\omega_o I_1 I_2}{I_1F_2 + I_2F_1} \tag{12}$$

This is the resonant amplification of the gyro at frequency ω_o, and is equivalent to the Q of an electrical resonant circuit. Where the approximations

$$I_1 = I_2 = I$$

$$F_1 = F_2 = F$$

can be legitimately made, together with the extremely close approximation

$$\omega_o = S/\sqrt{(I_1I_2)}$$

Q may be written

$$Q = S/2F \tag{13}$$

Equation (6) then becomes

$$\phi = \frac{\tau_\theta /p\, S}{p^2/\omega_o^2 + p/(\omega_oQ) + 1} \tag{14}$$

It was stated earlier that in some gyros the ratio of friction to spin momentum may be of the order of 1:10,000, which will yield a Q of 5000. In general it can be said that all gyros which have good space reference qualities tend to display an extremely high Q resonance at their natural undamped frequency, which for the low damping under discussion here is of course virtually the nutation frequency. It is of interest to note that the gyro is, however, an unusual device with regard to damped and undamped frequency, as the latter contains a friction term while the former does not (see equations (9) and (10)). At resonance we have, from equation (14)

$$\phi = \tau_\theta \omega_o Q/(p^2 S) \tag{15}$$

and from (5)

$$\theta = (I_2 p + F_2)\,\phi\,/\,S$$

If Ip is much greater than F and $I_1 = I_2 = I$, we find

$$\begin{aligned}\theta &= Ip\phi/S \\ &= \tau_\theta Q/pS \end{aligned} \tag{16}$$

Writing $\tau_\theta = \tau \sin \omega_o t$, we finally obtain

$$\phi = -(Q\tau \sin \omega_o t)/\omega_o S$$

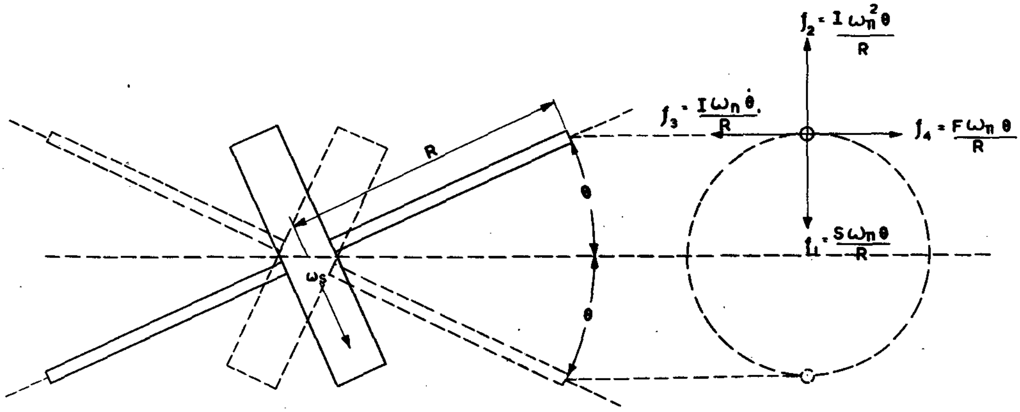
$$\theta = (Q\tau \cos \omega_o t)/\omega_o S$$

Since ϕ is about axis XX', while θ is about axis YY', and these are at right angles, it is seen that θ and ϕ are the cartesian components of a circular oscillation, which indicates that the shaft of the rotor of the oscillating gyro describes the surface of a cone in space, or alternatively the tip of the shaft can be said to trace the locus of a circle. This, of course, will be true only if the moments of inertia - and to a far less extent the frictions - are the same about the two axes. Where these are unequal, the locus will be an ellipse.

8. The Physical Meaning of Nutation

The movement of a gyro when it is made to ring at its nutation frequency resembles that of the resonant oscillation just described, except that the locus of the tip of the rotor shaft becomes a spiral because the amplitude of the oscillation decreases with time. It is physically obvious why a weight attached to a spring has oscillatory characteristics, but it is less obvious why a gyro should behave in a similar manner. The explanation is, however, quite straightforward, and may be expressed simply in terms of a dynamical balance between the centrifugal torque produced by the circular oscillation of the rotor inertia on the one hand, and the torque arising from the precession of the rotor around the circumference of this same circle on the other.

Figure 10(a) shows a gyro rotor having spin momentum S, nutating about a horizontal axis with an amplitude θ.



Figures 10(a) and (b) Nutating gyro wheel and locus of tip of shaft

Figure 10(b) shows the circle described by the tip of the rotor shaft during a cycle of the oscillation. If the angular frequency of nutation is ω_n, the tangential velocity of the end of the shaft will be $\omega_n\theta$, and thus the torque required to precess the rotor at this velocity is

$$\tau_1 = S\omega_n\theta$$

If R is the length of the shaft measured from the centre of the rotor, this torque may be thought of as a force reaction

$$f_1 = S\omega_n\theta/R$$

acting on the tip of the shaft in a direction pointing radially inwards towards the centre of the circle. If the moment of inertia of the rotor about any axis in a plane perpendicular to the spin axis is I, the motion of the shaft and rotor must produce a centrifugal torque

$$\tau_2 = I\omega_n^2\theta$$

which in turn may be regarded as a force

$$f_2 = I\omega_n^2\theta/R$$

operating radially outwards from the tip of the shaft. These are the forces which, when equated, define the frequency at which the gyro nutates. Thus,

$$I\omega_n^2\theta/R = S\omega_n\theta/R$$

or

$$\omega_n = S/I$$

Where viscous friction of coefficient F is active at the pivots of the general system, this will generate a force

$$f_4 = F\omega_n\theta/R$$

tangential to the path of the nutation, and in the direction which will oppose the motion. To overcome this friction, the momentum in the plane of nutation ($I\omega_n\theta$) must decrease at a rate which will provide a force equal and opposite to the friction force. Since both I and ω_n are constants, this rate of change must be produced by a decrease in θ such that

$$I\omega_n\dot{\theta}/R = F\omega_n\theta/R$$

The radius of the circle in Figure 10(b) will thus decrease exponentially with time.

9. Gyros used in Servo Loops

In some tracking applications which require an angular space memory, a gyro is often used as the main element in a position controlled servo. Here, error signals are arranged to generate a torque in motors fitted to the gyro which cause it to precess in a direction which will cancel the error. It is in such applications that the resonant frequency response has a particular significance. For example, if in such a position servo an error signal of magnitude θ is fed into an amplifier, which in turn drives torque motors to produce a torque

$$\tau = G\theta$$

then from equation (14) the open loop transfer function of the servo is

$$\frac{\theta_o}{\theta} = \frac{G}{pS} \frac{1}{(p/\omega_o)^2 + (p/\omega_o Q) + 1}$$

which for a harmonic input of $\omega = \omega_o$ becomes

$$\theta_o/\theta = -GQ/\omega_o S$$

Thus, where Q may be measured in hundreds, or in some cases even thousands, the value of G (for all practical values of ω_o and S) which will keep the loop gain less than unity (and hence the system stable) at this frequency would be hopelessly low for any practical application of the servo over its useful frequency range. For this reason it is customary to stabilise such a loop by purposely introducing further lags, with the object of producing sufficient phase change to ensure that the gyro resonance occurs within a quadrant of the Nyquist diagram which is well away from the negative real axis.

10. Some Factors affecting the Behaviour of a Gyro as a long term Space Reference

As with other devices which are used to measure what may be called "DC" changes over a long period of time, drift in the reference line indicated by the gyro is the basic problem. Many of the individual sources of such drift are of course well known and understood. The first and most obvious is simply a mass out of balance in the gimbal frames, which in limiting conditions poses problems concerned with temperature and distortion under acceleration. Where the friction forces at the gimbal pivots alter in magnitude with direction of movement, this will also produce drift when angular manoeuvres are made. This latter effect is a gross example of the general problem of drift arising from non-linear characteristics, which yield a DC output in the presence of both noise and fluctuating signal. Thus, pitching or yawing of the platform upon which the gyro is carried, mechanical vibration and any electrical noise which might be fed to torque motors (where these are used) can all produce drift if some non-linear coupling exists.

An inherent non-linearity is present in all gyros which are mounted on simple gimbal frames(3). This occurs because angular displacement of the inner gimbal carries the gyro wheel in a direction which in the limit brings its spin axis in line with the outer gimbal pivots. Intermediate positions of the inner gimbal between the normal and this pole position will thus yield a varying relation between torques generated at the outer gimbal pivots and the velocity at which the gyro precesses.

Many other peculiarities of a more subtle nature than those here mentioned undoubtedly contribute to produce drift. Work done at RRE has revealed that an unsuspected mechanical feedback may operate in the most simple "two degree of freedom" gyro in a way which can make it oscillate continuously at its own nutation frequency, or alternatively exhibit a far higher Q at resonance than measurements of the friction would indicate. This effect, depending as it does on forces generated within the rotor bearings, may at its simplest be regarded as yet another possible source of noise.

It is a salutary thought - and yet one which is in a way peculiarly flattering to those engaged on technological problems - that so much time and effort are still being concentrated on a piece of apparatus which, in its essentials, comprises a wheel, two frames, and three pairs of bearings!

11. Acknowledgments

In conclusion, the author would like to thank in particular Mr W.H.B. Cooper who first introduced him to the Coriolis approach used in this article, and also Mr P.H. Hammond with whom, as well as Mr Cooper, he has had many interesting discussions on the whole topic of gyros.

12. References

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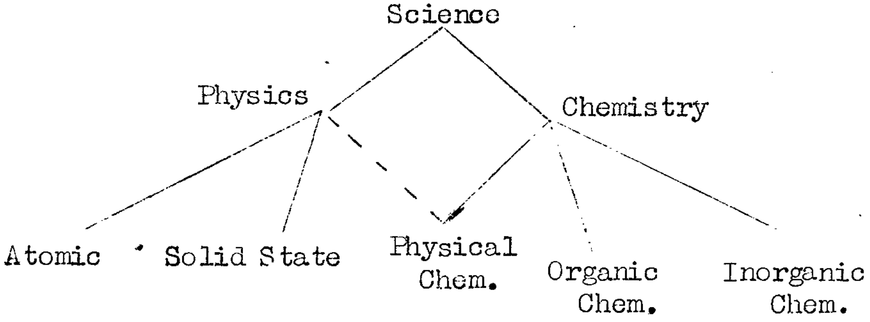
LIBRARY RETRIEVAL

By S. Whelan

1. Introduction

Undoubtedly the simplest form of retrieval system is the ordinary alphabetical index. Where small collections of documents are involved, such a scheme works moderately well - most office filing systems are of this kind. However, such a method is of little use when dealing with large collections (say 50,000 documents), for then each letter of the alphabet will have coded under it a large number of documents and to retrieve any one document from the sub-collection associated with any one alphabetical letter will need some further retrieval system and, hence, some modifications of the original alphabetical index is necessary. As the library grows (and libraries do!) the modifications superimposed on the original (relatively simple) system will be such as to complicate the system and lead to more sophisticated retrieval methods such as the Universal Decimal System (UDC). Despite apparently superficial differences, all such methods have one thing in common. They treat the subject matter of the library (field of knowledge) as being capable of subdivision into a tree-like structure; thus, e.g.:-

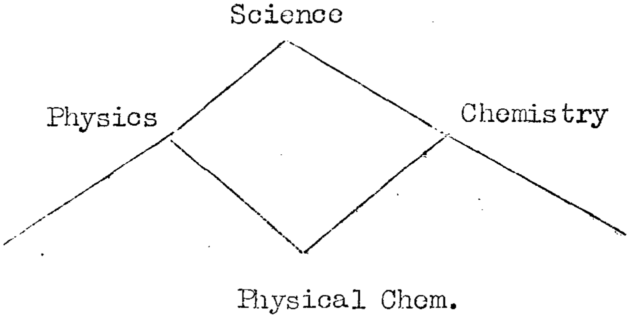


Such a subdivision is essentially arbitrary and becomes more so as the library grows. After only two subdivisions we are in difficulty straight away. How, for example, are we to classify a document on Physical Chemistry? Do we classify it under Physics or under Chemistry? Does it deal with Physics in Chemistry or Chemistry in Physics? At the very start, a decision of some sort is forced upon us. This would not be too bad if, having made the decision according to some principle or other, we could be certain that when a similar decision is to be made in the future, it will be made in conformity with the same principle.

Unfortunately there is no procedure which can guarantee such conformity. Indeed there cannot be, for it would be impossible for any principle or procedure to take account of all the consequences inherent in arbitrariness.

Various subterfuges are introduced to overcome such difficulties but they end by making the system they were designed to correct unwieldy and, in some cases, unmanageable. The net result is that, sooner or later, such systems fail to retrieve wanted information and, very often, a high percentage of the library's documents are effectively lost. As far back as 1945, Dr. Vannevar Bush (Atlantic Monthly, 176, pp. 101-108, (1945)), when reflecting on this matter remarked, "Even the modern great library is not generally consulted...... our ineptitude at getting at the record is largely caused by the artificiality of systems of indexing".

The question arises, therefore, as to whether there is any other structure which will enable us to code Physical Chemistry under both Physics and Chemistry, which is logically where it ought to be coded instead of under either. The answer is that there is such a structure - a lattice, thus:-



The notion that library language is a lattice occurs in the writings of Fairthorne(1) and Mooers(2) and the researches of the Cambridge Language Research Unit have established that a thesaurus is also a lattice, where thesaurus is taken to mean the grouping of words of similar or related meaning into notional families after the manner of Roget. In other words a thesauric or lattice classification is not arbitrary.

2. Thesaurus

By 1955 RRE felt that Retrieval Research for the most part was doing little more than invent systems which, while certainly an improvement on existing systems, did not materially differ from them and, in any case, were not sufficiently fundamental. It was this consideration together with the intrinsic merits of the scheme which decided RRE to adopt what is essentially a thesaurus approach and to embark on a pilot experiment designed to test this approach. The RRE scheme consists in choosing a limited number of basic or elementary terms (100-200, say) which, both singly and in combination, cover the subject matter of the library documents. These terms should be as fundamental to the library as possible - indeed its ultimate constituents. They need not even be dictionary words, but it follows that they will be as exclusive as possible. The exclusion property follows from the lattice property of the thesaurus but it can also be argued from first principles. For, if an additional term is added to a list of thesaurus heads and if this additional term can be accounted for by a combination of one or more existing heads then, clearly, it is not a head. Choosing these heads (terms) is not easy; nor is it clear on what general principle it should proceed - still less is it clear whether the process could be mechanised by, e.g., machine searching of dictionaries. Obviously synonyms and near synonyms would be grouped in the same head, as would also words of cognate meaning such as - e.g. - "export" and "import". In this way we avoid the risk of non-retrieval of, e.g., a document on "Imports to Y from X" when the enquirer wants documents on "Exports from X to Y". We can always choose heads to ensure that the system discriminates to any extent we wish and the RRE scheme further ensures that the frequencies of recurrence of the heads are contained within certain limits (referred to as bandwidth). Clearly "electromagnetics" is far too general a head for a library dealing with electromagnetics.

Furthermore the thesaurus must be constructed before embarking on the experiment. Indeed the system would not be thesauric if the terms (heads) are allocated after reading documents. This latter scheme would be more like Uniterm.

The following more or less random sample of terms used in the RRE experiment shows the scheme to be a thesauric one:-

No.	Head	(Synonyms, Cognate words etc)
2	Add	(gain, superimpose, sum, application, join, towards)
10	Calculate	(compute, analog, digital, count, enumerate, numerical, determine, estimate, value, error)

No.	Head	(Synonyms, Cognate words etc)
28	Generate	(excitation, construct, make, produce, prepare, design)
37	Macro	(large, excessive, increase, amplify, wide)
73	Star	(solar flares, prominences, eclipse, meteors, sun)

Should the library extend in some unforeseen way either by storing books on some completely new subject or books on a subject not new, but which the library did not hitherto deal with, then it is always possible to add to the list of heads. The RRE scheme uses 75 heads. In practice, assuming one has a fair knowledge of the library to be coded, it is not difficult to discover the first 20-30 heads. To arrive at more is usually a difficult procedure. Another possible way is to make a library lattice, which is what the members of Cambridge Language Research Unit have done. Either way the task is not easy.

When the list of terms is complete they are then placed in some convenient order (RRE uses the alphabetical order). It is to be remembered that there is no essential significance - beyond one of mere convenience - attached to this ordering of the terms amongst themselves. When ordered, the terms are now numbered from zero upwards. This list of numbers (heads, terms) is now used to code the documents for storage and subsequent retrieval.

3. Coding, Storage and Retrieval

The document to be stored is given an accession number, read and abstracted.

(a) Coding. To facilitate the operation of the scheme, (even by persons unacquainted with its basic principles), an alphabetic dictionary of terms which occur in the reports and in the library requests has been compiled. These terms give reference to as many of the listed thesaurus heads as is necessary. Consequently, when a report is abstracted, the numbers associated with the heads which cover its subject matter are noted. This may be done either by reference to the list of heads or, more easily, by reference to the dictionary.

(b) Storage. Metal plates (about 14in. square), capable of being punched with 10,000 holes each, are used for storage. There are as many plates as there are thesaurus heads and the coordinate position of a hole in a plate represents the accession number of the document being stored. If, for example, the document to be stored has an accession number 509 and the heads number 5, 17, 24, 36, 61, 83 cover its subject matter, then the plates corresponding to heads 5, 17, 24, 36, 61, 83 have each a hole punched in the 509th position.

(c) Retrieval. To make retrieval easy and speedy all the plates are stored together and each plate has a tag on it which is easily visible and identifiable and which bears the number of the thesaurus head to which it corresponds. A request for a document is broken down into the heads which cover its subject matter (again, either by using the list of heads or by means of the dictionary), and the plates (heads) which apply to the document in question are then pivoted about one end, thus bringing them simultaneously in register in front of a parallel beam of light; clearly the document having the hole (and hence the accession number) common to all the plates is the document sought after. More sophisticated means for reading the coordinate positions of holes easily suggest themselves.

4. Experimental Results

A first experiment on a very small (randomly chosen) document-sample (110 reports) gave 100% success and encouraged us to increase the sample to 1000 documents. These 1000 documents consisted of documents currently received at the RRE library. The fact of currency eliminated bias in choice and so the sample can be regarded as sufficiently random.

Several lists of questions were prepared to test the scheme. The lists were prepared in the following way. A list of the titles of the documents in the sample was handed to members of the library staff who were asked to compile requests similar to the requests the library usually receives. The requests were to have no more vagueness or precision than the usual library request. Typical questions asked were on such subjects as: Butterfly Circuits, Brightness of the Atmosphere, Properties of Oxide Cathodes, etc. (see Appendix 1, which gives a sample extract from the experimental results).

In all cases where the request was moderately specific the document in question was retrieved without any unwanted or irrelevant material. As the precision of a request decreases, giving way to vagueness, then the document or documents in question are still retrieved, but so also are other documents in descending scales of relevance corresponding to the increasing scale of vagueness. This, of course, is what one would expect a thesaurus retrieval system to do and it becomes more clear when one regards the thesaurus as a lattice. For a thesaurus system will always retrieve something and this something will be what is most relevant to the request(3).

The interesting result is that the relevant material is always retrieved. In the RRE scheme the worst proportion of relevant to less relevant materials was found to be of the order 1:3 and this only in cases of extremely vague requests. In no case did the system fail to retrieve the wanted material. While perfection is not claimed for the RRE thesaurus, it gives an amazing degree of success (see Appendix 2).

5. Conclusions

The research makes clear that the thesaurus approach to information retrieval is the most promising approach made so far. The theoretical and experimental fact that it always retrieves the material most relevant to a request is the best guarantee of this approach. It means that none of the library's material is ever 'lost', as indeed a fair proportion of it is when other retrieval systems are employed.

From our studies we are convinced that any further research on retrieval will have to proceed along thesauric lines if any worthwhile results are to be obtained. Nor is there any objection to extending the scheme to cope with the largest libraries. A larger thesaurus (lattice) will, of course, be necessary and obviously the scheme would have to employ digital computers but the rules for finding the elements of a lattice are precisely the rules which computers are designed to obey.

6. Acknowledgments

Acknowledgments are due to Mr. P. M. Woodward of RRE for many useful discussions, especially on the subject of the thesaurus heads; to Dr. A. M. Uttley of the National Physical Laboratory, Teddington, for discussions on the thesaurus heads and for having designed and constructed the retrieval equipment; and to members of the RRE Library staff, notably Miss K. Duncan and Mr. C. K. Moore for their assistance especially in working out lists of questions. Above all, thanks are due to Mr. B. W. Hodlin of RRE for having suggested the research, for having supervised it throughout its various stages and finally for reading, and making many helpful criticisms of this paper.

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1. R. A. Fairthorne, Essentials for Document Retrieval, R.A.E. Library Memorandum No. 23 (April 1955).

2. C. N. Mooers, Proceedings of the Third London Symposium on Information Theory, 1955, C. Cherry (editor), London, Butterworth (1956).

3. M. Masterman, Potentialities of a Mechanical Thesaurus, Cambridge Language Research Unit (1956).

APPENDIX 1

Question	Degree of precision	No. of reports retrieved	No. of relevant reports	No. of irrelevant reports	No. of relevant reports in sample	Ratio of irrelevant to relevant reports
Luminescence of Metallic Salts	Precise	1	1	0	1	0
Post War Structure of Ferromagnetism	Very Vague	3	1	2	1	2
Butterfly Circuits	Vague	1	1	0	1	0
Technical Writing	Vague	4	1	3	1	3
Earth Conductivity	Vague	2	1	1	1	1
High Vacuum Techniques	Vague	3	1	2	1	2
Frequency Converter	Very Vague	35	9	26	9	2.88
Metrology	Very Vague	27	12	15	12	1.25
Welding Techniques	Vague	24	6	18	6	3
Potential Divider	Vague	7	2	5	2	2.5

APPENDIX 2

No. Head (Synonyms, Cognate words etc.)

1. Acoustics (tune, resonate
2. Add (gain, superimpose, sum, application, join, towards
3. Air (meteorology, climate, climatology, cloud, wind, storm, gas, sky
4. Angle (phase, angular, corner
5. Anti (opposed to, prevent, prevention, not, non-
6. Array (shape, pattern, matrix, arrangement, structure, lattice
7. Attenuation
8. Auto (automatic, self
9. Bend (reflection, refraction
10. Calculate (compute, analog, digital, count, enumerate, numerical, determine, estimate, value, error
11. Change (alter, different, alternate
12. Characteristics (properties, parameters
13. Circle (wheel, rotate, ring, annular, cyclic
14. Component (element, part, factor, unit
15. Constant (stable, stability, permanent
16. Control (servo, feed-back
17. Defence (flight, military, gunnery, attack, tactics, tactical, strategy
18. Electric (current, conductivity
19. E.M. above 10 cms (Above 3000 Mc/s))
20. E.M. 10 cms. - 1 cm (3000 - 30,000 Mc/s))Electromagnetic
21. E.M. 1 cm - 1 mm (30,000 - 300,000 Mc/s)) Waves
22. E.M. below 1 mm. including IR and beyond)
23. Equal (equation, equate
24. Equipment (apparatus, instrument, set, machine, mechanical
25. Explode (bomb, burst, blow-up, projectile, weapon, missile
26. Foreign (various countries
27. Function (purpose, use
28. Generate (excitation, construct, make, produce, prepare, design
29. Ground (land, sea, horizon, earth, cosine
30. Height (elevation, sighting, perpendicular, vertical, sine
31. Infrared
32. Integral (differential
33. Jam (interference, RCM
34. Limit (finite, test, trial
35. Line (linear, direct, length, axis
36. Locate (find, position, scan, plot, search
37. Macro (large, excessive, increase, amplify, wide
38. Magnetic (magnet, magnetostriction, solenoid
39. Material (metals, non-metals, mass, resins
40. Measure (correct, adjust, assess, calibrate, verification