UNIVERSAL HIGH-SPEED DIGITAL COMPUTERS: A MAGNETIC STORE

By Prof. F. C. WILLIAMS, O.B.E., D.Sc., D.Phil., F.R.S., Member, T. KILBURN, M.A., Ph.D., Associate Member, and G. E. THOMAS, M.Sc.

SUMMARY

The elements and organization of an experimental magnetic storage system are described. A rotating wheel is used to give high transfer speeds and relatively short access time to data which are transferred directly to the high-speed cathode-ray tube store of a digital computer. The wheel is run in synchronism with the fundamental frequency of the computer under the control of a servo mechanism. A plated layer of pure nickel is used as the recording medium. A low-impedance type of head combined with a new method of digital representation have been employed for the storage of data.

A complete storage system of this type with a capacity of 3 000 numbers, each of 40 binary digits, has been incorporated in the Manchester University computer.

(1) INTRODUCTION

The magnetic storage system here described was designed as an integral part of a particular computing machine, although in modified form it has proved of more general utility. It is thought better to describe what has been done in connection with the computing machine, and explain why it was done, rather than to attempt any more general treatment. There are two reasons for this view; first, that since the equipment was designed to fill a specific urgent need, some aspects of the problem have not been pursued with the relentlessness that would be appropriate to a purely academic investigation; secondly, that the possible modifications and alternatives to suit other particular circumstances are legion and their full discussion would greatly lengthen the paper.

(2) THE FUNCTION OF A STORE IN A COMPUTING MACHINE

(2.1) The Concept of an Intermediate Store

In the computing machine proper,[1] and many others of its class,* calculations are performed by transferring numbers to and fro between a rapid-access store and a computing unit in a manner set out in a table of instructions. The main requirement of the rapid-access store is that access to a particular piece of information contained therein shall be possible in a time comparable with the time taken to perform an elementary computation, such as is called for by a single instruction. There is no theoretical objection to supplying the whole storage capacity of the machine in this form. The practical objection lies in the fact that available rapid-access stores are somewhat complicated, expensive, and suffer from the defect that a failure of power supply results in a loss of stored information.

The alternative to a rapid-access store of the full capacity appropriate to the type of problem to be solved is a smaller rapid-access store, backed by a slower-access store of greater capacity. The rapid-access store can be reloaded at appropriate intervals from the slower-access store, and an opposite transfer

* See References.

Dr. Williams is Professor of Electrical Engineering, and Dr. Kilburn and Mr. Thomas are in the Electrical Engineering Department, at the University of Manchester.

of information can convey computed results from the rapid-access store to the slow store. The essential difference between high- and low-speed stores, which makes such an arrangement attractive, is that, when access time requirements have been reduced for the backing store, the method of storage actually employed may be selected from a larger range. Just as access time for the rapid-access store should be comparable with the time of an elementary computation, so access time to the backing store should be comparable with the average time taken to use up a single loading of the rapid-access store. Thus an infinite array of alternatives presents itself, ranging from a very large rapid-access store coupled to a slow-access store with long access time, down to a very small rapid-access store coupled to a slow-access store with relatively short access time. Furthermore, there is no reason why the slow-access store should not in turn be backed up by an even slower-access store, such as punched cards or paper tape, or even pencil and paper, books of tables and a keyboard. It is therefore appropriate to label the first backing stage of storage as "intermediate," forming a balance between the high-speed rapid-access nucleus storage of the machine and the slow-speed slow-access type of storage, such as punched tape.

The objective in the present case was to find a sound engineering balance between the rather complex high-speed store and the complexity of the intermediate store. Since a small high-speed rapid-access store requires rapid access to the intermediate store, these two factors are mutually opposed, and, as is usually the case in practical engineering, the compromise adopted was determined by the practical circumstances and the readily available materials. It is therefore necessary at this stage to outline the storage requirements of the desired intermediate store.

(2.2) Representation of Numbers and Instructions

The numbers in the high-speed store are represented in binary form; each number has 40 digits and each digit, 0 or 1, is represented externally to the store by the presence or absence of a voltage pulse. The individual digits of a number occur serially in time on a single wire, the least significant digit occurring first. The time interval between digits of successively high significance is 10 microsec and is determined by a train of clock pulses, usually called *dash pulses*, derived from a crystal oscillator. The interval between successive 40-digit numbers is marked by a 5-pulse (50-microsec) gap defined by the *black-out waveform* (so called because in the high-speed store the cathode-ray tube beam is "blacked out" during this period) and consisting of five successive "zero" pulses. This configuration of digit spacing is illustrated in Fig. 1. Instructions are represented in exactly the same way as numbers, two being contained in one 40-digit sequence; they require no separate discussion here.

(2.3) The Rapid-Access High-Speed Store

The rapid-access store is made up of units, each comprising one cathode-ray tube and its associated amplifier and gate. A unit stores 64 numbers, or 128 instructions, or a mixture.
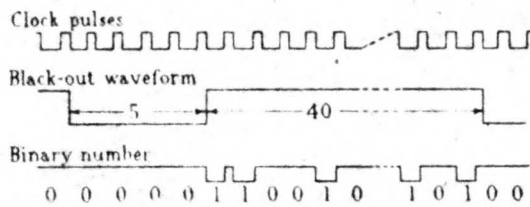
Fig. 1.   Representation of a binary number.

Associated with a set of such units there are the necessary time-base units and waveform generators. These are of such complexity that it would be uneconomical, even if practicable, to operate with a single-unit rapid-access store. When used in conjunction with an intermediate store, a convenient arrangement is to reload the rapid-access store one whole unit at a time. On the assumption that access will be necessary to each word in a unit at least once during its "life" in the rapid-access store, a reasonable access time for the intermediate store would be 64 times that of the rapid-access store where the unit size of transfer is one word of 40 digits; the access time is therefore 450 microsec. The rapid-access store contains words represented in serial form, and access to these words can be had only one at a time; therefore the fastest method of reloading a unit of 64 words is to do it serially, one word following another, separated only by the black-out period. It will therefore be advantageous to have output from the intermediate store in serial blocks of 64 words. If this output can be arranged to operate in the computer time scale (i.e. 10 microsec per digit with the digit intervals properly phased relative to the clock pulses), then direct connection between output of (or input to) the intermediate store and the input to (or output from) the rapid-access store will be possible. Furthermore, if correspondence in time between word 1 in the rapid-access store and word 1 in the intermediate store can be maintained, no other identification of words within a block of 64 (called a "track" for reasons that will be apparent later) will be necessary; it will be necessary only to identify or label the blocks of 64 as track 1, 2, 3, etc., in the intermediate store. The various units in the rapid-access store, to which any track may be routed at will, may be designated unit 1, 2, 3, etc., provided that it is understood that there will be many more tracks than units, and that any track may be routed to any unit.

It is worth stressing here that any system which is not run in synchronism with the digit frequency of the remainder of the machine will require an additional storage means, probably a "staticisor," which can accept information at one rate and transmit it at a different rate. Also, if "word synchronism" and "track-unit" synchronism are not employed, some system of identifying digits in a word, and words in a block, will be required.

(2.4) Survey of Possible Intermediate Stores

A store of unlimited size can in principle be made by using punched cards or punched paper tape; all that is needed to extend the store is more cards, or more tape. These are, however, ruled out as intermediate stores, as defined above, by their relatively high access time and slow speed. For example, it would take about 1 min to punch one trackful of information on paper tape, whereas a unit of the rapid-access store can be read out in 28 millisec. These paper stores are highly developed for teleprinter and business machines, and they have their role to play in computers, both for the ultimate input and output mechanism, and for the permanent recording of programmes, tables, results, etc. They are in fact admirable for the slow-speed store which backs up the intermediate store and which, by the

arguments given before, can have slower access the larger the intermediate store is made.

Other well-known recording schemes are the gramophone disc, photographic methods, and magnetic recording. The authors had no knowledge of disc recording and doubted whether it could approach the 100-kc/s frequency response required. The processing aspect of the photographic technique was a severe disadvantage. Magnetic recording on the other hand had already been proposed[3-6] and some aspects investigated.

The various methods of magnetic recording may be divided into two classes: the tape-wire class, and the coated-drum class. The feature of synchronism was considered to be very important, both because of the simplification of identity problems, and because it offered the highest possible reloading speed, and therefore the minimum of rapid-access store for a well-balanced machine. It was felt that synchronism would be more easily obtained with a rigid rotating drum than with somewhat elastic tape or wire fed from one reel to another, or even formed into a loop. These views were based on the expectation that about 80 digits could be stored per linear inch of the magnetic recording material. A superficial speed of the recording surface of about 70 m.p.h. would be required, combined with positional control of the surface, accurate to ± 0.001 in under the recording head. These limits are set to ensure simultaneity of digit occurrence in the intermediate and rapid-access stores.
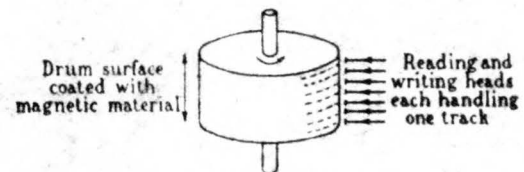

Fig. 2.—Magnetic drum.

The arrangement envisaged is illustrated in Fig. 2. A drum with its cylindrical surface coated with magnetic material describes a revolution in the time occupied by the transfer of sixty-four 40-digit words. With due allowance for the 5 digits lost in the intervening black-out periods this time is

$$(40 + 5) \times 64 \times 10 \text{ microsec} = 28.8 \text{ millisec.}$$

This corresponds with a rotation speed of 2 080 r.p.m., which is a convenient speed for an induction-motor drive. The diameter, on the assumption of a packing density of 80 digits/in, is approximately 11½ in.

Rotation of the wheel moves the magnetic recording material under a vertically disposed set of recording heads; each head controls the magnetic pattern impressed on the peripheral track immediately beneath it on the wheel. Experience indicated that about 30 heads can be used per inch parallel to the drum axis, so that for a 2-in depth of surface 64 tracks might be arranged. A drum of these dimensions has therefore a total storage capacity of 64 tracks, each holding 64 words of 40 digits —a total of some 163 840 binary digits made up into 4 096 words of 40 digits. So far as our limited experience went, this appeared an adequate size, bearing in mind that additional drums could be installed and paper tape could be used for further backing up. The identity of individual tracks could, of course, be established by selection of the appropriate individual head associated with the desired track; full synchronization ensures word and digit identity.

A solution along these lines appeared so advantageous that effort was concentrated on testing its practicability to the exclusion of all other alternatives. The particular problems which arose are enumerated in the following Section.

(3) THE PROBLEM OF A MAGNETIC-DRUM INTERMEDIATE STORE

(3.1) Synchronization

The entire proposal fails if synchronism between drum rotation and the rapid-access store cannot be achieved with the required degree of accuracy. With 80 digits/in, each digit occupies about 0·012 in; for reasonable safety positioning to $\pm 0·001$ in was sought, thus allowing some latitude for variation in the mechanical position of the heads, and for reasonable duration stability of any necessary gating waveforms. Synchronism with the clock waveform of the machine can be achieved in two ways, according as the drum or the rapid-access store is the master. Thus, the clock waveform could be recorded on a track on the wheel, as could a version of the black-out and other waveforms. These recorded waveforms could then drive the rapid-access store and hold it in synchronism. The only requirement on the rotation speed of the wheel would be that it should be smooth and lie within limits acceptable to the rapid-access store.

Alternatively, the rapid-access store can be driven by a master oscillator, preferably crystal-controlled to ensure stability. The problem then is to control the rotation of the wheel by some servo action which monitors the phase relationship between one or more waveforms recorded on, and derived from, the drum and the corresponding waveforms derived from the crystal-controlled rapid-access store. This arrangement is the more general, in that two or more similar drums can supply one rapid-access store and also because some rapid-access stores, such as the mercury delay line,[2] have an inflexible time-scale of their own. This was the arrangement investigated and a description of the manner in which reliable synchronization was obtained has been given elsewhere.[7] So far as this paper is concerned, fully synchronous rotation will be assumed without further discussion.

(3.2) The Recording Surface

Several varieties of wire and many magnetic powders have been used for sound recording, but at the time of these experiments the authors were confident in the satisfactory operation of nickel plating only for digit storage at high repetition rates. It had been used by other workers in the computer field.[4, 8] There appeared to be no definite information about the thickness to be employed, and so the first tests were made with a commercially plated wheel without any particular specification other than a request for a thickness of about 0·001 in. It was a fortunate accident that a pure nickel surface was prepared, as subsequent experience with cobalt-nickel mixtures yielded much poorer magnetic characteristics.

Powders were not readily available and have not been tested; but it is believed that some may be superior to nickel, though it is also thought that this superiority may be marked only if the surface is run in contact with the magnetic head. This procedure cannot be adopted, because the resulting friction would vitiate the accuracy of synchronization, and because the wear would reduce the useful life of the wheel and its recorded data. Nickel plating is more resistant to accidental damage, such as is caused by rubbing during the setting-up of the heads, which run normally with about 0·001 in clearance from the nickel surface. For these reasons pure nickel plate, 0·001 in thick, has been used throughout and all the experiments described relate to this material. It is known to suffice; it is not known to be the optimum.

(3.3) The Method of Recording

Of the various magnetic recording patterns available, the one resulting from the use of a narrow transverse gap for both the writing and reading heads appears to have found favour for acoustic recording. Compared with the longitudinal-gap variety

it seems likely to yield a higher digit packing factor, since a gap can easily be made narrower than its length. The high digit repetition rate required demands a high digit packing density, even at the expense of a low track packing density; otherwise the superficial speed may become excessive. Hill-and-dale recording using a single sharp magnetized edge near the surface has not been tried. In its transverse form it might yield excellent results, but longitudinally it would suffer the same defect as the longitudinal gap. For these reasons, transverse-gap recording has been used, once again because experiment showed that it was adequate rather than necessarily optimum.

After this decision a suitable head had to be designed. Both Bigelow[3] and Booth had used a single straight wire placed close to the plating, without an iron circuit, and they had obtained successful results. The wire must be very fine, of 0·001–0·002-in diameter, and it is therefore very fragile. Furthermore, the current density required for writing is very high, and, if numerous digits are to be written in succession, there is a danger of fusing. Another type of head used by Booth[8] consists of a single wire threaded through a magnetic circuit which has a defined air-gap. The advantages over the single wire alone are that the wire can be thicker, since the gap defines the recording field, and that the arrangement is more robust. The head actually employed is a development of this arrangement.

(3.4) Method of Representation of Digits

In order to establish the two necessary states in each digit cell of the magnetic medium, a method of representation was developed which facilitated the use of standard current amplifiers and the single-wire type of head construction. In Fig. 3, plot 1
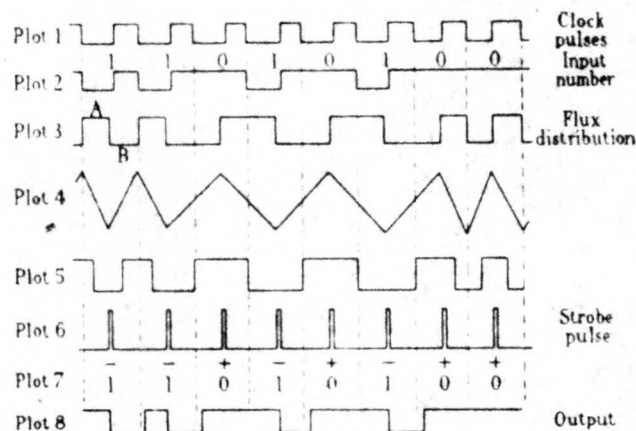

Fig. 3.—Digit representation waveforms.

represents the 100-kc/s clock waveform of the computer. Plot 2 on the same time-scale represents a number 11010100. A negative pulse of 6 microsec duration represents a 1, and a steady zero level a 0. The magnetic flux distribution desired on the recording material is illustrated in plot 3. There are only two levels of flux intensity, corresponding to saturation of the material in either direction. A "1" is represented by a digit cell saturated for its first half to level A and for its second half to level B; a 0 is represented by the inverse. To generate such a flux distribution on the moving magnetic material, a "write" current of the same shape as plot 3, with the abscissa in the time scale, must be passed through the "write" head.

The waveform described is of an essentially balanced nature, for in any digit cell the two levels of the waveform occupy equal time periods. The maximum degree of unbalance that can occur is represented in Fig. 4, where a succession of 0's change
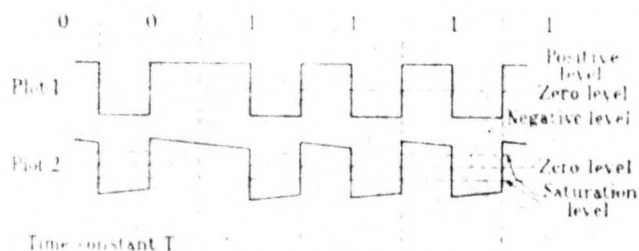
Fig. 4.—Transformer decay characteristics.

to 1's. The positive level in the latter half of the last 0 is extended into the first half of the first 1, so that a positive level of twice the usual length is obtained. The succeeding 1's are again balanced. In exactly the same way the transition from 1's to 0's produces a negative level of twice the usual length.

The effect of this in a transformer of decay period T, where T is greater than the digit period, is illustrated in plot 2. On the assumption that the decay of level is linear with respect to time, the double level at change-over will produce a fall of double the usual amount. This displacement will be compensated in the following cycles in the case illustrated. If the 0–1 transition were immediately followed by a 1–0 return, then the shift would be immediately compensated by the extra positive shift due to the double-length negative level.

The shift for a single transition, as illustrated, is the maximum that can occur, for a similar double-length positive level will not be produced until 0's are again succeeded by 1's; this implies an intermediary change from 1's to 0's and the resultant compensating shift in the opposite direction. In the case of "write" transformers, it is therefore only necessary to make T extend over several digit periods, and to ensure that the two saturation levels of current lie below the minimum transformer current as in Fig. 4.

The writing current required in the writing head can therefore be obtained by standard transformer matching with a relatively low current source as will be described in Appendix 10.1.

The induced voltage obtained on circulation of the established flux pattern past a "read" head of identical construction to the "write" head is of the form illustrated in Fig. 3, plot 4. The practical form of the waveform obtained is illustrated later in Section 4.4, and a theoretical justification of this waveform is given in Reference 9.

Plot 5 is obtained by taking positive and negative values of plot 4, without regard to magnitude, and corresponds with electronic squaring of plot 4. This curve is very similar to the "write" waveform, except that it is of reversed phase and its transitions are delayed; during repeated 1's or 0's the delay is one-quarter of a digit period. Plot 6 is a narrow strobe pulse delayed one half-digit period after the clock pulse, and it is used to gate plot 5 so as to deliver 1's only when plot 5 is negative during the strobe. Thus the original number is recovered (see plot 7) and can be reconstituted in standard form as in plot 8. This result is admirable in all respects save one, namely that it is half a digit period too late to be fed back into the rapid-access store. This defect is readily overcome by using a separate head for reading, advanced appropriately against the direction of rotation of the wheel. The necessary advance is about 0·007 in and a suitable construction of such a double head is described in Section 4.2. The writing of a single digit occupies a total time of one digit period, which cannot begin until the input information becomes available at the beginning of a digit period. The mark that really represents the state of the digit cell is the direction of the reversal that takes place half-way through the digit period, when a peak is produced in the induced "read"

voltage. This accounts for the delay mentioned above. Examination of plots 5 and 6 shows that the strobe could be advanced nearly one-quarter of a digit period without loss of sense. However, if this were done, the timing of plot 5 would be extremely critical, and, since this is derived from the drum, its timing depends entirely on the accuracy of synchronization. A maximum latitude of ¼ digit period is obtained with a strobe ¼ digit wide and delayed by half a digit period; or, in the practical case, with the reading signal advanced one half-period.

The general conclusions which have been reached as regards this method of representation of digits are: that it makes possible a considerable degree of latitude in synchronization; that it enables a digit packing density to be employed equal to that achieved with any other system; and that both writing and reading signals are of a sufficiently narrow frequency range to permit the use of transformers.

(4) EXPERIMENTAL APPARATUS
(4.1) The Magnetic Drum

The wheel developed for the original experiments and for subsequent use in the computer is illustrated in Fig. 5. It is of 11½-in diameter and 2 in deep at the rim, and was machined from a centrifugal casting in bronze. The central hub contains a 3-phase induction motor consisting of an internal stator secured to the massive base-plate at the bottom and by the gantry at the top of the axle. The squirrel-cage rotor is secured internally to the hub of the wheel and rotates on two sets of thrust ball bearings at the bottom and top of the fixed stator axle. The 36-in perimeter of the wheel accommodates the 2 560 digits contained in one unit of the rapid-access cathode-ray tube store. There are a further 320 digit positions corresponding to the 64 black-out periods of the 64 numbers; these positions are wasted. The wheel rotates at a speed of 2 080 r.p.m., constrained to nearly 1 000 r.p.m. slip from the synchronous speed of 3 000 r.p.m. by the eddy-current braking coils which are mounted above the horizontal surface of the wheel. Each digit is therefore scanned in the required period of 10 microsec, and the complete unit of 2 560 digits may be read in one revolution period of 28·8 millisec.

The recording heads are held in close proximity to the external rim of the wheel, which is plated with a 0·001-in layer of pure nickel. The right-angle brackets employed to support the heads are illustrated in Fig. 5; they may be adjusted relative to the recording surface by means of the micrometer adjustments laid in the base plate. A working separation of 0·001 in is maintained between the head and the recording surface; variation of this separation, due to eccentricity of the wheel or to vibration of the mountings, will produce modulation of the amplitude of the pick-up signal. In order to eliminate these defects, the wheel has to be turned to an accuracy of less than 0·001 in in the 11½-in diameter—an operation which limits the width of the rim in the present case to 2 in. If the diameter is reduced, then it is possible to extend the width of the recording surface. To ensure absence of vibration the massive base-plate and rigid mounting is employed, while the wheel is dynamically balanced on high-quality bearings. The wheel constructed in this manner is found to be almost vibrationless and to run smoothly for long periods without attention.

(4.2) Multiple Recording Heads

The principle of the single-wire type of head design of Dr. Booth was found to be satisfactory and to lend itself readily to the particular design requirements of our system. As has been explained in Section 3.4, it is necessary to supply separate heads
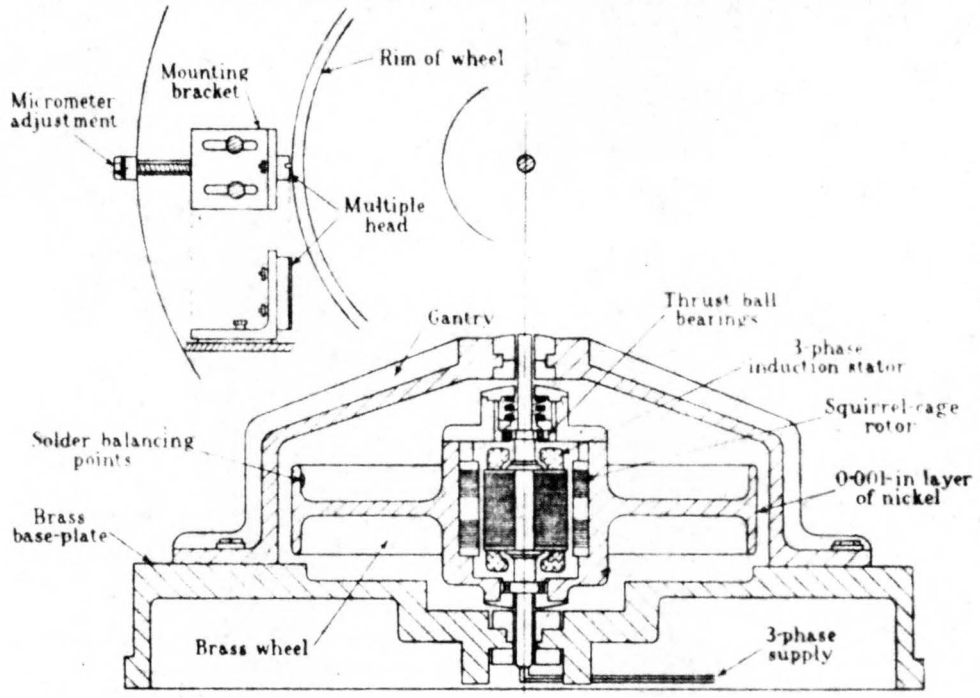
Fig. 5.—Magnetic wheel.

for the processes of reading and writing, with the reading head advanced by at least 0·007 in relative to an identical writing head. This separation between reading and writing heads must be accurately controlled and, when a number of double heads are used, the separation must be constant within the limits ± 0·001 in.

The small-iron-path principle of the Booth head was employed in the construction illustrated in Fig. 6. A single "double-head" unit consists of a central lamination B of Radiometal, to both sides of which are pressed cupped laminations A and C. A single wire is threaded through each of the triangular cups formed between A and B and between B and C. Two thin paper separating pieces prevent actual contact of the three pole-pieces and define a gap of width 0·001 in in the actual recording face of the head. The two gaps in the recording face satisfy the dual requirement of a reading and writing head. If the writing current is passed through the right-hand wire, flux will flow in the closed magnetic circuit formed by the B pole-piece and the C pole-piece. At the gap in the circuit, a fringing field of flux will be produced, which, owing to the sharp edge presented by the C pole-piece to the B pole-piece at this point, will be a considerable proportion of the total flux which passes between the two pole-pieces. This fringing flux will assume a path in the magnetic medium which is moving past the writing gap, and a magnetic pattern will be recorded.

The flux produced by this recorded pattern will couple with the magnetic circuit formed by the pole-pieces A and B around the left-hand wire. The extent of this coupling will again depend on the characteristics of the air-gap in the magnetic circuit. Flux developed in this circuit will induce a voltage in the reading wire and a signal approximating to the time derivative of the flux distribution in the magnetic circuit will be obtained. If the magnetic medium is assumed to move from left to right, the reading gap may be considered as phase-advanced with respect to the writing head. The amount of this advance is controlled by the width of the central pole-piece B. In practice, a separation of 0·015 in is required, and it is obtained by using a single lamination B of the required thickness.

The outer pole-pieces A and C are only 0·005 in thick, so that an extra brass boundary-piece 0·02 in thick is added to protect the assembly, which is securely clamped at the base of the laminations. In order to multiply the construction, each of
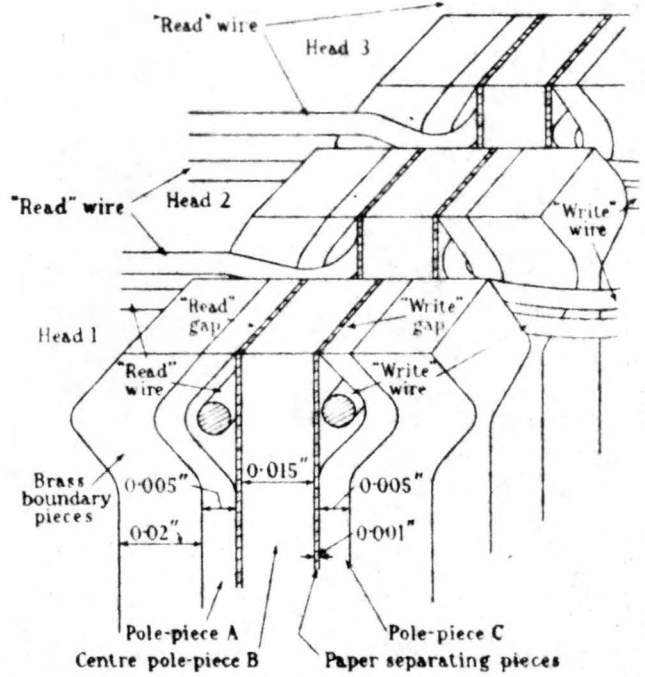

Fig. 6.—Multiple head.

the five components is cut before assembly with a series of equidistant slots, so that each has the form of a comb with a series of teeth equal in number to the number of heads it is required to fashion in one block. The five slotted laminations are assembled in the correct order, and separate wires are

threaded through both the "read" and "write" sides of the total number of heads formed. These wires are brought out through the spaces between adjacent heads as illustrated in Fig. 6.

The width of the recording surfaces on the wheel is 2 in and a series of multiple heads based on the design described above have been constructed in blocks 2 in long. As experience was gained, the number of heads per block was increased from 9 to 32. The latest development is a block of 32 heads, each head being separated from its neighbour in the block by a distance greater than the width of one head. It is therefore possible to interleave the tracks of two blocks of heads on one wheel, giving a total storage capacity of 64 tracks per wheel. Fig. 7 gives a
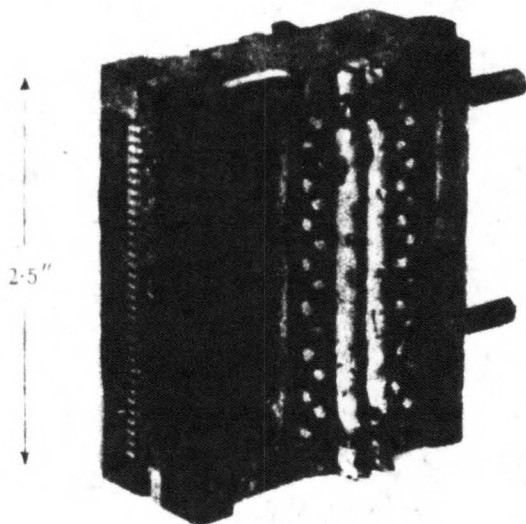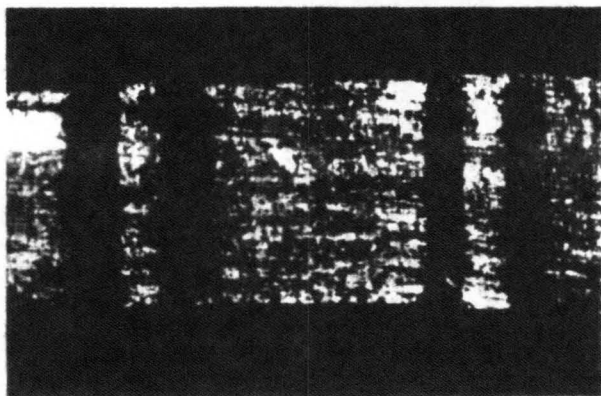

Fig. 7.—32-unit multiple head.

Fig. 8.— Single unit of multiple head (scale 70 : 1).

general view of one complete block of heads while Fig. 8 is a close-up of the recording face of one head in which the reading and writing gaps can be clearly distinguished. As can be seen from this photograph the width of this head is less than 0·015 in, the separation between the two gaps.

In the models of the 32-head construction so far tested, mechanical failure in the complicated wiring connections is restricted to 2 units in the 32; it therefore seems possible that,

when the design has been further standardized, a reliable form of construction can be achieved with these dimensions. The magnetic properties of the separate head units are entirely satisfactory, as the amplitude of the pick-up signal is high above the noise level. It would therefore appear that the limit in size reduction has not yet been reached. A further decrease in scale seems possible, though the problem of multiplicity of connections in such a small space, and the percentage of head failures in the composite construction, merit consideration relative to that of an individual type of head assembly.

The specially designed mounting brackets illustrated in Fig. 5 are employed to ensure that the recording face of the head is held parallel to the 2-in recording surface. A clearance of 0·001 in is maintained between head and wheel.

When it is required to interleave two blocks of heads, vertical adjustment of one of the blocks is necessary. This adjustment is obtained by means of a vertical micrometer attached to the upright face of the mounting bracket.

(4.3) Writing and Reading Apparatus

A block schematic of the equipment is given in Fig. 9. Signals from the rapid-access store enter at A with a waveform
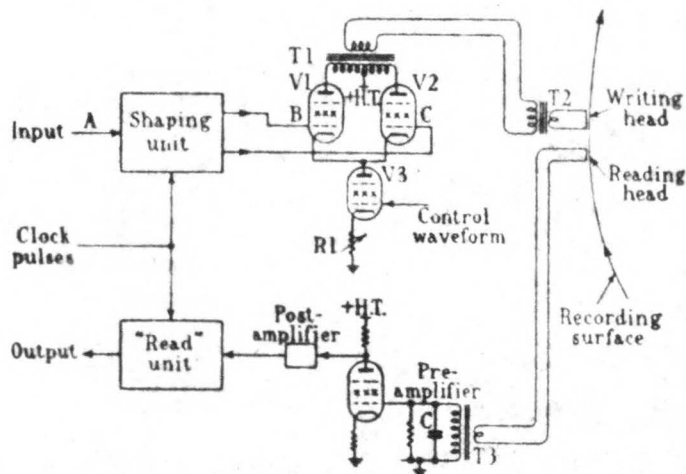

Fig. 9.—Schematic of "write" and "read" paths.

The "read" unit consists of an amplifier, a limiter, and a strobing unit.

as illustrated in Fig. 3, plot 2; this is operated on by the clock pulses (plot 1) to yield the waveform of plot 3 at B and a paraphase version of it at C.* Both these waveforms are of amplitude 90 volts centred on + 55 volts. The control waveform on the grid of V3 can have either of two values: 0 volts or − 50 volts. In the latter case no current flows in V3; therefore no current flows in either V1 or V2, and the "write" unit is inoperative no matter what enters at A.

When the tail valve is turned on, a current defined by R1 flows in V3 and traverses V1 and V2 according as one grid or the other is the more positive. Thus the defined current is shuttled back and forth between V1 and V2, according to the waveform at B (and C), and a current having this waveform traverses the whole of the primary of the transformer T1. This current is sensibly devoid of a d.c. component. The inductance of T1 is such as to yield a fairly good "current transformer" action, and so a current of similar waveshape, but about 60 times the magnitude, flows in the secondary and is supplied to the single-turn head via T2. Two transformers rather than one are used because the head impedance is very low (0·01 ohm) and

* Details of the shaping unit will be found in Appendix 10.1.

requires to be stepped up so as to compare with the lead impedance. T2 is mounted very near the head; T1 cannot be mounted in that position for a variety of reasons, one of which is that the primary of T1 is at too high an impedance to tolerate the lead capacity as a shunt.

The reading head is also of very low impedance, but here any loss in the leads can be made up at small cost by additional gain in the amplifier; therefore only one transformer is used, namely T3 situated in the pre-amplifier unit. This transformer is broadly tuned to 100 kc/s, because it has been found experimentally (as might be expected from the waveshapes in Fig. 3, plot 4) that such restriction of frequency response does not impair the utility of the signal, and at the same time reduces noise, increases the signal at the first grid, and permits some control of the timing of the zeros of the output wave by variation of C. Tuning must not be sharp—a response not more than 5 db down 0 150 kc/s is satisfactory. From the pre-amplifier

to one word by applying the appropriate waveform to the grid of V3. For this to be possible it is necessary that, when V3 is switched off at the end of a word, all significant transient currents in the head should die away before the end of the ensuing 5-digit black-out period. The push-pull layout and the nature of the waveforms help greatly here but, to make quite sure, the transformer decay time-constants are set at a figure less than 50 microsec and greater than 10 microsec, which is the greatest duration of unidirectional current-flow. These transients prevent writing in blocks of less than one word. There is no corresponding problem on the reading side, as the output may be gated at will by the outward transfer gate.

(4.4) Experimental Results

The oscillograms in Fig. 10 were taken with an experimental set of recording heads, with the reading head spaced 0·5 in from
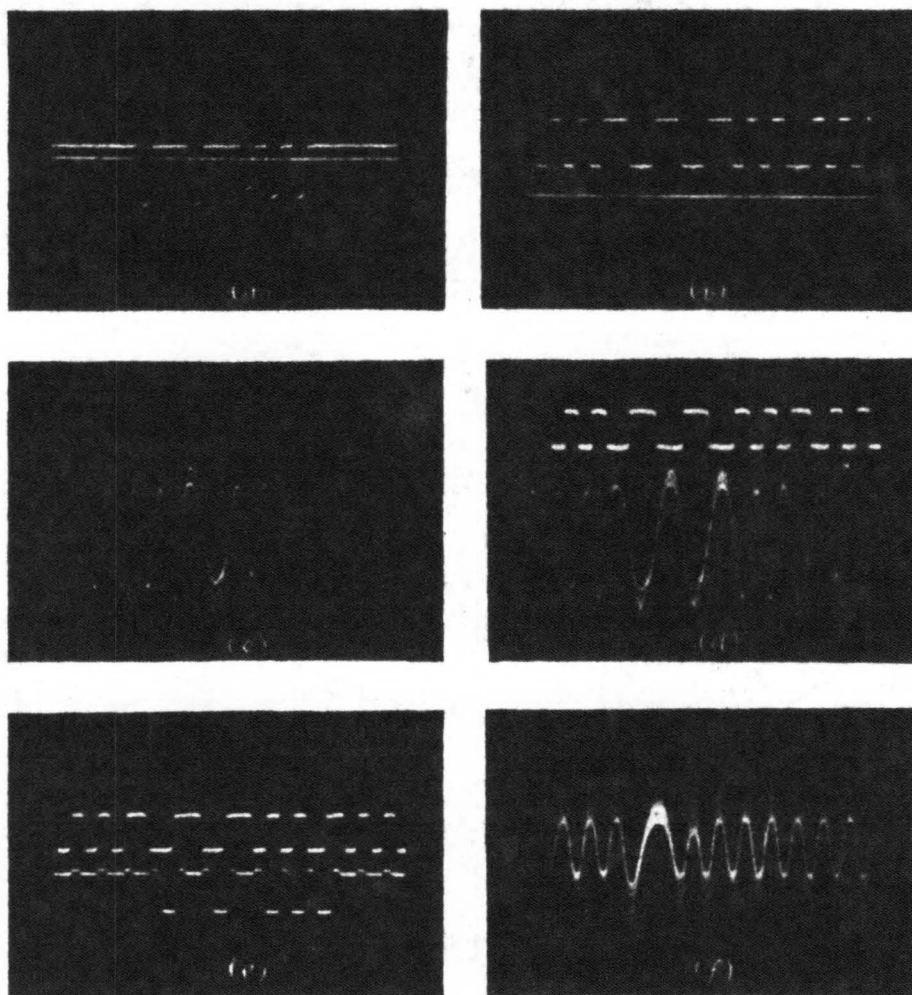

Fig. 10. —Oscillograms.

the signals pass through a post-amplifier (concerned with track selection, see Section 5.2) to the amplifier proper, where the output has a waveform similar to Fig. 3, plot 4, and of amplitude about 20 volts peak to peak. The signal is then limited to yield the form of plot 5 and gated to yield plot 8. Details of the limiter and gate and of T3 will be found in Appendix 10.2

With the equipment, signals from the rapid-access store can be recorded in blocks of any length up to 64 numbers and down

the writing head. The reading head was placed after the writing head so that it was possible to read immediately what had just been written by the writing head. Owing to the large writing currents employed, particular care had to be taken over the screening between the two heads. By employing this construction it is possible to run the wheel at various speeds and, so long as the speed is maintained constant, a steady reading signal can be observed

Two test patterns were employed for testing the recording properties at various speeds. The first consisted of a single 1 in a series of 0's, while the second was the number 001010111000. The pulse train representing this number is illustrated in (a); this was fed into the "write" waveform generator, where the waveform of trace (b) is produced.

Trace (c) is an oscillogram of the "read" signal at the final amplifying stage in the "read" unit; the recorded pattern is a single 1, as can be observed from the single 50-kc/s change-over cycle. The outline of the signal is blurred because this is a photograph of 64 identical words recorded on the 64 spaces corresponding with one track; the blurring is due to cyclic amplitude modulation, probably because of the eccentricity of the drum. The amplitude of the signal at the minimum portions of the modulation cycle is 26 volts.

Trace (d) is the reading signal obtained with the test number; it may be compared with plot 4 of Fig. 3 and it is seen to possess 50-kc/s and 100-kc/s components of approximately equal amplitude. The squared waveform is displayed alongside the reading signal. It may be seen that the amplitude modulation of the reading signal does not injure the squared version.

Trace (e) displays the squared version of the reading signal and the final reading output which correspond with plots 5 and 8 in Fig. 3. A negative level in the squared signal at the beginning of a digit period releases a negative pulse.

Traces (c) and (d) were taken while the wheel was running in synchronism with the computer at a speed of 2 080 r.p.m. The digit packing density at this speed is equal to 80 digits/in. In order to test the effect of increase of digit packing density, the wheel may be run at half-speed and the same recording apparatus employed. Trace (f) is an oscillogram of a single 1 recorded in a succession of 0's while the wheel is run at half-speed, and therefore the pattern is stored at a digit density of 160 digits/in. The shape of the waveform is similar to that of trace (c), which is an identical pattern stored at 80 digits/in; the amplitude, as would be expected, is, however, of only half the magnitude of trace (c).

The practicability of this increase by a factor of two in the digit packing density has since been fully tested in the magnetic store of a later machine which employs a working density of 166 digits/in.

These results do not exhaust the possibilities of experimental investigation but they suffice to prove the workability of the system. Other points that have been checked are that the new information can be written in a single rotation over old information, without prior demagnetization, and that single words, or every alternate word, can be changed without erasing the adjacent words, or any part of them.

Track separation has also been investigated. Early experiments used tracks 0·25 in wide and with 0·1-in separation. These figures have been progressively reduced to 0·015 in wide with 0·015-in separation. There is still no sign of crosstalk between tracks or of any tendency to damage the tracks on either side of the one being written on. Thus the fundamental limit has not been reached, but the difficulty of making the heads and arranging the leads is now exerting a limiting effect.

With the double type of head construction described, reading cannot take place during writing operations on the same or any other track (when multiple heads are used) owing to the coupling effects. Experiments with separate reading and writing heads, as stated in the first part of this Section, have, however, proved that with adequate screening it is possible to approach the two heads to within 0·5 in of one another without interference. This separation corresponds to a delay of about one 40-digit word if a packing density of 80 digits/in is used, and therefore makes a single-word regenerative loop possible between a reading and writing head situated on one track.

(5) TRACK SELECTION
(5.1) Writing-Head Selection

A selection system for use with 64 reading and writing heads was built and tested in the practical magnetic storage system to be described in the next Section. The selection of the writing head on the selected track is performed by a relay tree of 14 relays with which it is possible to connect 1 of the 64 writing heads to the common writing unit. The time of setting of the relay tree extends the time of a writing operation to 60 millisec. of which 30 millisec are allowed for the relays to come to rest and 30 for the actual transfer. It was decided to employ relays and a common writing unit in place of 64 distinct writing units, which would require 192 valves. The increased selection time was preferred to the disadvantages of the large number of extra valves needed with electronic selection.

In practice the relays have proved very reliable, as precautions have been taken to avoid the movement of contacts passing current and so reducing wear. Duplication of contacts was also carried out to reduce intermittent failures.

(5.2) Reading-Head Selection

Each reading head is coupled to a pre-amplifier, as described in Section 4.3. The selection of a track is performed by gating the outputs of the 64 pre-amplifiers connected to the reading heads. The pre-amplifiers are grouped in four blocks of 16 each. The output of each block is taken to a group of 4 post-amplifiers; the output of this block is fed to the common reading unit. The 16 valves in each pre-amplifier block have a common anode load, and all the valves except one are biased on their suppressor grids to -100 volts, so that only one selected valve draws anode current. The suppressor voltages are controlled by a bank of decoding valves incorporated in the magnetic control circuits.

The four signals of the four tracks selected by the blocks of pre-amplifiers are fed to the post-amplifiers, which are of exactly similar construction. One of the post-amplifiers is allowed to draw anode current and the selected signal is fed from the common anode load to the reading unit. The suppressor switching of these initial stages results in a surge of 2 millisec duration at the final anode. A delay in selection of this duration has to be incorporated in the time of a reading transfer to cover this irregularity. In the practical system the existing delay of 30 millisec incorporated in the writing transfer is employed so that both reading and writing transfers occupy the same time. The circuits of the pre- and post-amplifiers are given in Appendix 10.2.

(6) PRACTICAL SYSTEM

A magnetic store was built in to the existing computing machine to produce a large-scale computer.[10] It was decided to furnish a maximum intermediate storage capacity of 64 tracks, with each track containing 2 560 digits. This store was to work in conjunction with a rapid-access cathode-ray tube store of total capacity 5 120 digits, divided between 4 cathode-ray tubes. The block schematic of the organization of the stores is shown in Fig. 11. The rapid-access store is divided into two units, each unit containing two cathode-ray tubes. The intermediate store consists of two 12-in magnetic wheels of identical design to those previously described. Although it is possible with the dimension of head used to contain 64 tracks on one wheel, it was decided to use two wheels to furnish data on the properties of a multiple-wheel system. Each wheel has thus 32 tracks on its surface. The intercoupling between intermediate and rapid-access stores is so arranged that the contents of any track may be transferred to either of the two stores and that the track may be further organized in either of the two tubes in each store.
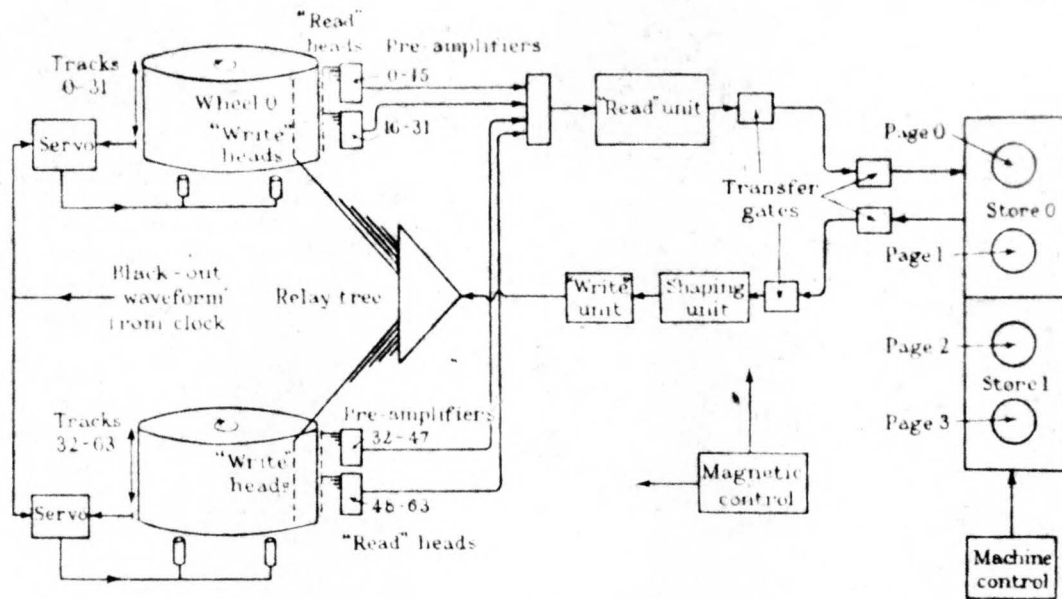
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Fig. 11.—Schematic of magnetic store.

Each wheel has a separate servo system as indicated. The reading and writing circuits are, however, common to both wheels, and the circuits for reading, writing and selection are identical with those already described. There are two channels for information between the magnetic and the rapid-access store: the inward transfer channel along which information gated by the outward transfer gate of the magnetic store travels to the cathode-ray tube store and is admitted through the inward transfer gate; and the outward transfer channel which has two gates to carry out the inverse functions. Transfers are labelled relative to the rapid-access store, which is the working nucleus of the machine.

The unit of transfer is one track of information, and the time of transfer of this unit is 28 millisec, the period of revolution of the wheel. Control of all transfer is entirely automatic and is accomplished by the addition of a magnetic control unit to the existing main control unit of the machine. A new series of instructions, known as "magnetic instructions," is introduced to motivate the magnetic control, exactly as ordinary machine instructions are fed to the main control. The difference between the two types of instructions is mainly one of time, ordinary machine instructions take only $1 \cdot 8$ millisec apart from multiplication, while a magnetic transfer occupies 56 millisec. From the arguments already stated in Section 2, this disparity of time is balanced because magnetic instructions are demanded at only infrequent intervals.

In order to facilitate servicing, a unit was built into the transfer system which enabled every digit in one of the rapid-access stores to be checked against the corresponding digit on a selected track. A non-equivalence was indicated in a binary counter which could count up to 15 successive non-checks. By repeatedly checking a track against a tube over a period of time, intermittent faults could rapidly be detected in either store. A test programme was also constructed to check the actual mechanics of the various possible transfer operations. By applying these maintenance techniques it was possible to run the machine for an extended period with little attention to the magnetic store.

The magnetic store itself, excluding control circuits, contains 131 pentodes and 35 diodes, while the extra control circuits include 140 pentodes and 193 diodes.

(7) CONCLUSIONS

The magnetic system outlined in the previous Section was incorporated in a pilot, but full-scale, computing machine, which was run continuously for a period of 9 months. The maximum capacity ever employed at one time was 47 tracks, a total capacity of 120 000 digits. During the period of test, information was stored for six months without renewal on certain tracks in spite of the fact that during this period the bearings were replaced in the wheel concerned.

The method of synchronous control has been shown to allow great flexibility in the organization of the storage system.

A nickel recording medium has been tested practically and has been found to store digital information with no deterioration and with a packing density of 80 digits/in. Experiments have indicated that a packing density of double this value is practicable.

A low-impedance single-wire double-head has been developed to meet the requirements of the storage system. The head width has been reduced to $0 \cdot 015$ in and still found to function satisfactorily. A multiple form of construction has been designed with which it is possible to employ 64 tracks in a total width of 2 in.

The phase-modulation method of digital representation has been developed to facilitate the use of single-wire heads. It has been found to operate satisfactorily with high digit-packing densities.

(8) ACKNOWLEDGMENTS

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(10) APPENDICES

(10.1) Writing Waveform Generator (Fig. 12)

The unit consists essentially of a flip-flop circuit which may be triggered by a repetitive trigger on the anodes and also by a series of gated trigger pips on both control grids. A special waveform known as "digit square wave" is generated external to the unit. This waveform is shown in Plot 1. It has a period of 10 microsec and its front edge may be moved relative to the beginning of the digit period as defined by the clock of the computer. Thus in Plot 1 the separation L microsec may be
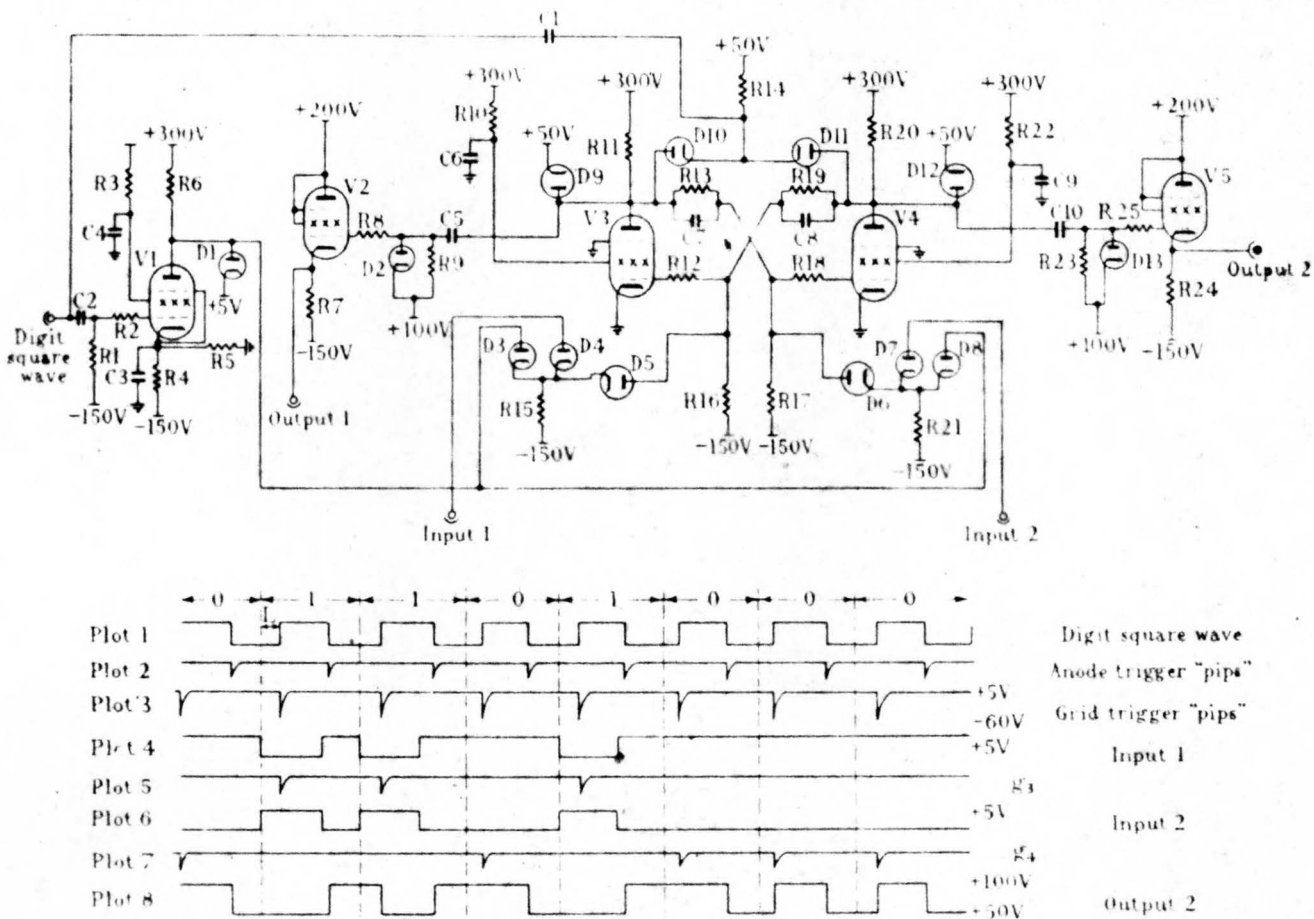

Fig. 12. — Writing waveform generator.

R1	= 10 kΩ	R15	= 47 kΩ	C3	= 10 μF
R2	= 470 Ω	R16	= 470 kΩ	C4	= 0.1 μF
R3	= 15 kΩ	R17	= 470 kΩ	C5	= 0.001 μF
R4	= 3 kΩ	R18	= 470 Ω	C6	= 0.1 μF
R5	= 15 kΩ	R19	= 100 kΩ	C7	= 33 μμF
R6	= 33 kΩ	R20	= 47 kΩ	C8	= 33 μμF
R7	= 5 kΩ	R21	= 47 kΩ	C9	= 0.1 μF
R8	= 470 Ω	R22	= 15 kΩ	C10	= 0.001 μF
R9	= 220 kΩ	R23	= 220 kΩ		
R10	= 15 kΩ	R24	= 5 kΩ	V1	= CV138
R11	= 47 kΩ	R25	= 470 Ω	V2	= CV173
R12	= 470 Ω			V3	= CV138
R13	= 100 kΩ	C 1	= 100 μμF	V4	= CV138
R14	= 1.9 kΩ	C 2	= 100 μμF	V5	= CV173

controlled between 0·2 microsec and 6 microsec. The width of the square wave may also be controlled and a true 50 : 50 mark/space ratio obtained. This waveform is now employed to generate two sets of repetitive trigger pips. Considering the anode trigger pips first, the square wave is differentiated with a 100-$\mu\mu$F condenser and 1 900-ohm differentiating circuit and the negative spikes are applied to both anodes of the valves V3 and V4 by the diodes D10 and D11. The diodes D9 and D12 remove the positive spikes and limit the flip-flop circuit's swing: the triggering waveform is then as shown in Plot 2. The action of these trigger pips on the flip-flop circuit will produce a halving waveform of 20-microsec period.

The differentiated digit square wave is also applied to V1. V1 is normally cut-off by the 20-volt positive bias on the cathode. The positive spikes of the differentiated grid waveform turn on the valve for a small period and the valve "bottoms." The anode voltage is caught at + 5 volts and, when the valve "bottoms," a 60-volt negative spike is produced as shown in Plot 3. These trigger pips occur mid-way between the anode trigger pips and they are applied to the grids of the valves V3 and V4 by the two diode gates.

Consider the gate attached to V3. The gate consists of an "and" gate in diodes D3 and D4 which is coupled to the grid of V3 by the diode D5. The anode of D3 is fed with repetitive trigger pips. D4 is fed from input 1 by the waveform shown in Plot 4. This is the output 1 from the inward transfer gate and represents the information which it is desired to reinterpret. For a digit period containing a 0, the anode of D4 is held at − 5 volts and no trigger pip passes through the gate. For a 1, however, the anode is taken to − 20 volts for 6 microsec and, when the anode of D3 goes negative, the cathode will follow and a negative pip will be applied to the grid of V3 through D5. Thus, owing to the variable delay L, the edge of the digit square wave and the trigger pip produced by this edge may be orientated relative to the digit pulse.

In the case of the gate attached to V4 an exactly similar action occurs, but the gating waveform applied to the anode of D7 is shown in Plot 6 to be the inverse of that applied to the other gate, and a trigger pip on the grid of V4 is obtained for every pip that was "gated out" on V3. The complete set of trigger pips applied to the flip-flop circuit are now shown in Plots 2, 5 and 7.

The resultant output waveform is illustrated in Plot 8 for output 2, derived from the anode of V4. In order to trace the formation of this waveform, consider the first trigger pip shown in the plots drawn. This pip is applied to the grid of V4, so that the anode of V4 must rise to its positive level at this instant; 5 microsec later a common anode trigger pip is applied and the flip-flop circuit reverses its state so that the anode of V4 falls to the negative level. The next grid trigger pip is applied to the grid of V3, which is however already "topped," so that no change takes place. The complete formation of Plot 8 may be traced in this way from the sets of trigger pips drawn. Fig. 10, trace (b), is a record of this output waveform derived from the input data shown in trace (a).

This output waveform is identical with that required for the phase-modulation method of digital representation which it is desired to use. The phase of the waveform obtained is delayed by a time L microsec from the input information. This delay may be controlled between 0·2 microsec and 6 microsec by varying the phase of the digit square wave, for the trigger pips may be gated anywhere in the 6-microsec extent of the negative pulse representing a 1. It is useful to be able to introduce a controlled delay into the writing path which is required to compensate the excess phase advance in the reading path.

The anode waveforms of both valves, V3 and V4, are d.c.

restored below + 100 V and applied to the grids of two powerful cathode followers V2 and V5. The two phases of the output signal are then fed to the writing unit.

(10.2) Pre-Amplifiers (Fig. 13)

A pre-amplifier is employed to raise the voltage level of the pick-up signal to a larger amplitude as near the head as possible.
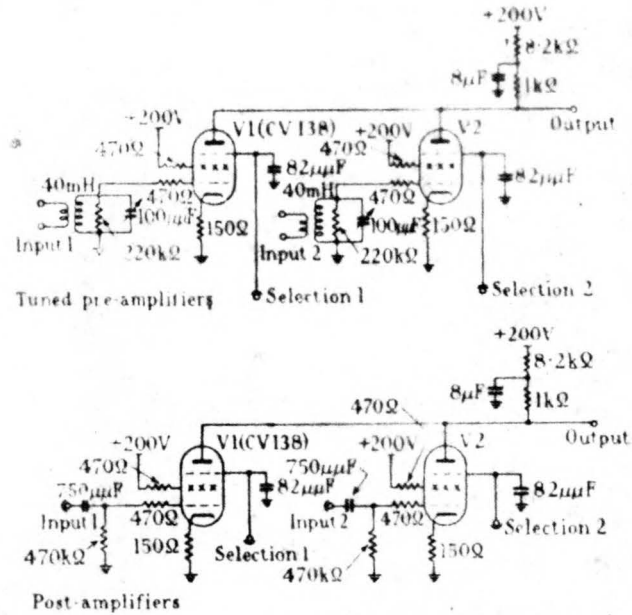

Fig. 13. Schematic of pre-amplifier and post-amplifier.

It is also convenient to employ the pre-amplifier for selection purposes. The signal from the reading head is fed to the primary of a step-up transformer; the output amplified voltage is then applied to the control grid of a miniature pentode. The anodes of the pentodes associated with each track are made common and taken to an anode load of 1 000 ohms which is decoupled from the h.t. supply. The suppressor grids of all the valves are taken to − 150 volts, except for the valve associated with the track which it is required to select. This suppressor is connected to earth, and current is allowed to flow to the anode of the valve concerned. The output signal obtained at the common anode point is an amplified inverted version of the pick-up signal of the selected track. The input transformer consisted of a 1-turn primary coupled to two 175-turn wave-wound coils on 25 laminations of type 500T Mumetal laminations. Separate screen voltage supplies were attached to each screen grid. Cathode bias was supplied by a 150-ohm resistor and a 10-μF by-pass condenser. The anode load employed was reduced to 1 000 ohms so that it was capable of driving a considerable length of connecting cable to the next unit. It was found in practice that, owing to structural irregularities in the heads, the phase of the reading signal from various heads differed slightly, and some degree of compensation could be attained by placing a small condenser of 10 to 50 $\mu\mu$F on the input grid of the pre-amplifier.

The principle of individual phase adjustment was incorporated in the design illustrated in Fig. 13. The input transformer has a large turns ratio and is tuned on its secondary winding with a 100-$\mu\mu$F variable condenser. The inductance of the secondary is 40 mH and the tuned circuit has a high effective impedance at resonance. It is clamped with a 220 000-ohm resistor so that a measure of phase control is obtained by variation of the tuning

capacitance. The coil is well screened in a dust-core coil former. Switching is controlled by the suppressor voltages. The screens are fed from a common · 200-volt line so that no heat-dissipating screen resistors are employed and a miniature form of construction is facilitated. A 1 000-ohm common anode load provides a suitably low impedance for driving the connecting lead to the post-amplifier which follows.

The design of the post-amplifier illustrated in Fig. 13 follows the same lines. The coupling to the grid is a simple a.c. coupling of suitably large time-constant to pass the maximum frequency (100 kc/s). Selection of any unit may again be performed on the suppressor and a low anode load is employed to drive the signal along the cable to the reading unit.

and a measure of phase control is also obtained by variation of the 100-$\mu\mu$F tuning condenser. The signal is further amplified in V2 to 20 volts amplitude and the signal fed to the clipping stage V3. The pick-up signal derived from the standard test pattern is illustrated in trace (c) of Fig. 10.

The bias resistor of 4 700 ohms in the cathode of V3 establishes a positive potential on the cathode. Consider the anode-connected end of the 47 000-ohm grid resistor of V3 to be taken negative. The grid will tend to go negative and therefore the anode voltage will rise positively. This positive rise will be transmitted back to the grid through the 100 000-ohm feedback resistor and 0·1 μF condenser, so that the change of grid voltage will be compensated and the grid voltage will be held within
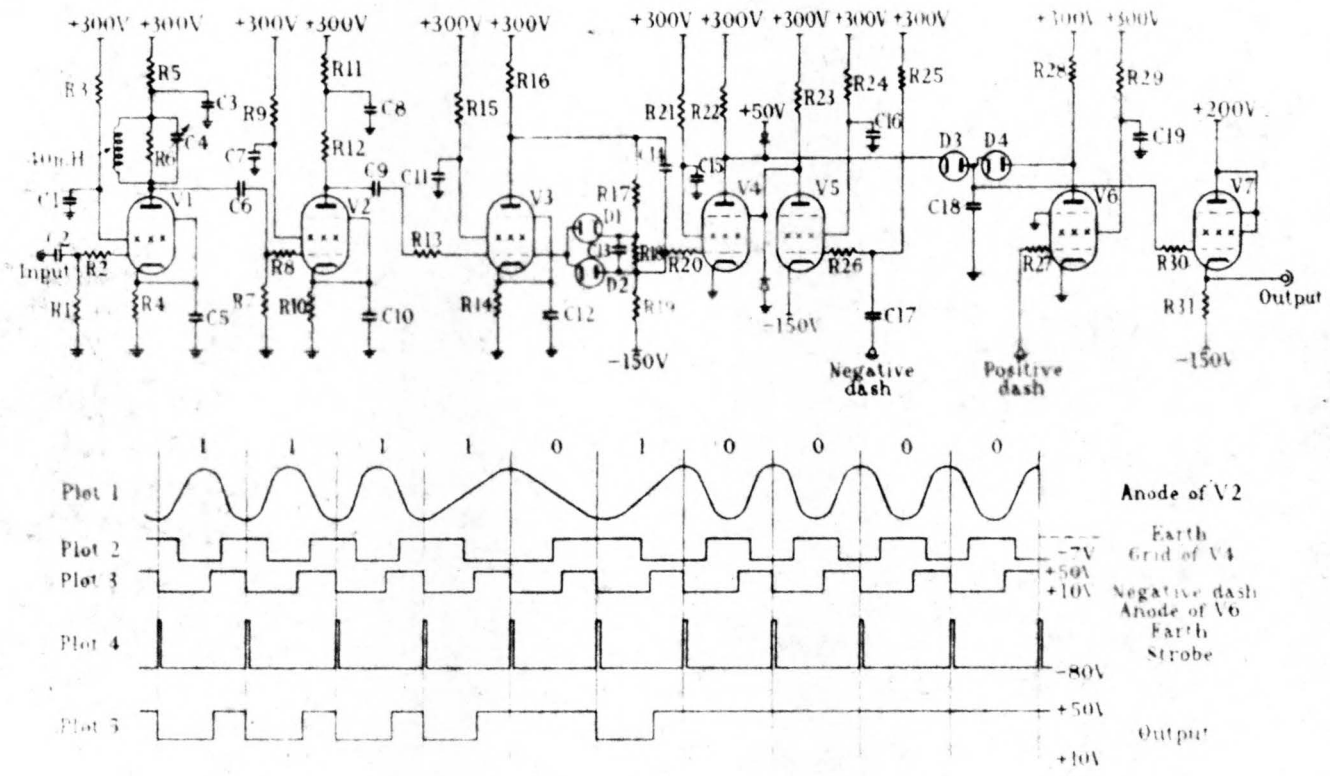

Fig. 14. Reading circuit.

R1	27 kΩ	R21	15 kΩ	C9	0·25 μF
R2	470 Ω	R22	47 kΩ	C10	10 μF
R3	22 kΩ	R23	22 kΩ	C11	0·1 μF
R4	220 Ω	R24	22 kΩ	C12	10 μF
R5	8·2 kΩ	R25	150 kΩ	C13	0·005 μF
R6	10 kΩ	R26	470 Ω	C14	0·1 μF
R7	27 kΩ	R27	470 Ω	C15	0·1 μF
R8	470 Ω	R28	47 kΩ	C16	0·1 μF
R9	22 kΩ	R29	27 kΩ	C17	56 μF
R10	220 Ω	R30	470 Ω	C18	56 μF
R11	8·2 kΩ	R31	22 kΩ	C19	0·1 μF
R12	47 kΩ				
R13	47 kΩ	C1	0·1 μF	V1	CV138
R14	4·7 kΩ	C2	820 μμF	V2	CV138
R15	22 kΩ	C3	8 μF	V3	CV138
R16	47 kΩ	C4	100 μμF	V4	CV135
R17	100 kΩ	C5	10 μF	V5	CV173
R18	4·7 kΩ	C6	820 μμF	V6	CV138
R19	100 kΩ	C7	0·1 μF	V7	CV138
R20	10 kΩ	C8	8 μF		

(10.3) Reading Unit (Fig. 14)

The first two stages of the unit amplify the input signal from the post-amplifier, which may or may not be incorporated in the unit, to a signal of 20 volts amplitude at the anode of V2. The form of the reading signal at the anode of V2 is shown in Plot 1. The anode load of V1 consists of a heavily damped 100-kc/s resonant circuit. This circuit filters out any high-frequency pick-up which may have entered in the previous stages,

the grid base of the valve. A current will therefore flow through the 47 000-ohm resistor from the grid to the anode-coupled end. This current must flow through the diode D2, so that the anode of D2 will be held at the grid potential, which approximates to the cathode potential of V3. Therefore, when the applied voltage at the anode of V2 goes negative about a mean level, the output voltage is held slightly positive. When the input voltage is positive, exactly the same feedback action occurs and the diode

D1 is conductive. The cathode of D1 is therefore held at cathode potential. The potential at the tapping point will be 7 volts more negative owing to the constant voltage drop across the 4 700-ohm component in the chain. Therefore, when the voltage at the anode of V2 is positive relative to the mean level, then a voltage of 7 volts is produced at the output. This effect is illustrated in plot 2. The slope of the change-over edges of the waveform is finite owing to the non-ideal characteristics of the diodes D1 and D2.

This waveform is applied to the grid of V4. The suppressor is switched by a fine strobe pulse generated in V5 from a negative dash pulse. A negative dash pulse of the form shown in plot 3 is differentiated with a 56-$\mu\mu$F condenser and 150 000-ohm resistor returned to 300 volts. The narrow negative spike produced is applied to the control grid of V5 which cuts the valve off for a very short period of less than 1-microsec duration at the beginning of the digit period. A positive-going pulse is produced on the anode and applied to the suppressor grid of V4, being caught by a germanium crystal at earth potential. V4 is therefore allowed to pass anode current for only a short period at the beginning of each digit period. If the control grid of V4 is positive when the strobe is applied, V4 is "bottomed" for the duration of the strobe. If the grid is negative, the anode remains at + 50 volts, caught by the crystal. A negative spike produced on the anode of V4 pulls the potential of the 56-$\mu\mu$F condenser down to + 10 volts through the diode D3. The condenser remains at this potential until it is pulled back to + 50 volts potential by the negative-dash waveform generated in V6. The condenser voltage is fed to the grid of the cathode follower V7. The resultant action of the strobing mechanism is that a positive level at the grid of V4 during a strobe instant produces a 6-microsec negative pulse at the output, while a negative level leaves the output signal unchanged. The resultant output signal obtained for the test patterns employed is shown in plot 5.

It is desirable for the strobe pulse to lie in the centre of the positive and negative levels of the squared signal as illustrated in plots 2 and 4. There is a 2 5-microsec tolerance on either side of the strobe when the system is adjusted in this fashion, so that any temporary displacement of the phasing, such as that caused by a writing operation, will be covered.

[The discussion on the above paper will be found on page 120.]