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Application of the variable reluctance head and the parametron to magnetic digital recording

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APPLICATION OF THE VARIABLE RELUCTANCE HEAD AND THE PARAMETRON TO MAGNETIC DIGITAL RECORDING

by

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I. INTRODUCTION

In this dissertation a new system for handling information in digital computer systems is described which makes use of two recently developed electronic devices. These devices are the variable reluctance read head and the parametron. Both devices have unique characteristics which make them especially suitable for this application. The variable reluctance head allows the reading of magnetically recorded information while the relative velocity of the head and record is zero, up to an upper limit which is as yet undetermined. The resulting information from the head is phase information which makes the parametron well suited. The parametron is capable of large amplification of the two distinct phases of read head output at extremely low cost.

Several forms of the head seem to be feasible, some of which are easier to construct mechanically than others. The horseshoe type is described and investigated experimentally.

The recording of digital information by magnetic systems is investigated in order to compare the conventional systems with this proposed system.

The proposed system, built around these new devices, is shown to be superior in several respects to the conventional systems. These advantages are:

1. Insensitivity to amplitude variations of the read voltage
2. Potential low cost
3. Simplicity of construction

4. A major improvement in noise rejection.

In addition several new possibilities are described.

In order to gain over-all perspective of the problem to which this system appears to have the largest application, some general information about magnetic digital recording is given.

II. BASIC DESIGN, ANALYSIS, AND EXPERIMENTAL RESULTS

In a large number of applications the rapidity of the computational aspects of the digital computer are practically worthless when taken alone. In order to take full advantage of the high speed inherent in the arithmetic, memory, and control sections requires judicious use and handling of information. This is especially true at the slow speed bottleneck -- input and output. The value of efficient and rapid input and output equipment is most easily distinguishable in some particular applications. One application in which input and output are a major factor in monopolizing computer time for nonproductive operation is that in which programs and data are changed frequently. Many such problems are run daily on any digital computer used largely for engineering type problems. It has been estimated that for the "Cyclone" in use at Iowa State University the average time used per run is approximately three to five minutes. This figure is exclusive of the production runs of the Atomic Energy Commission.

The engineering class of problems are extreme in the sense that the same program is seldom used often. However, an exception to this would be a program to reduce data from an experiment, for example wind-tunnel data reduction. Even in this case the program will probably have to be read in each time an experimental run is performed. This reasoning is evident in the fact that many newer computers designed principally for engineering problems use paper tape, apparently because of its inexpensiveness and ease of error correction. In addition, the input-output gear for handling paper tape, as well as the correction gear, is relatively inexpensive. The principal disadvantages of paper tape are that it is bulky for the amount of information stored and it is not especially durable. The durability is, of course, no major problem if the tape is not used often. Also considered a major disadvantage is the fact that it is slow in comparison to magnetic tape. At present, for example, paper tape readers up to 1,000 characters per second are available and magnetic tape can be read up to at least 62,500 characters per second.

As a logical result of the foregoing one may wonder why magnetic tape is not used more for problems where input-output time is a large share of the problem time. This may be accentuated by the fact that magnetic tape may be used many times by simply erasing and placing new information on it. The present reasons are several-fold. First, the magnetic tape provides no visual indication of what is on it. This means that if a magnetic tape typewriter is used, once the tape is removed the operator can no longer easily find an error and correct it. This would appear to necessitate a magnetic tape reader whose output would then drive a printer. This device is inherently very expensive. The reason is that the speeds of the magnetic tape reader and printer are incompatible. The magnetic tape must be moving sufficiently fast to cause a usable read voltage to be induced in the head feeding the following amplifiers and wave shaping circuits. This speed is much faster than can be tolerated at present by reasonably priced printers. The solution now is that a block of information is read from magnetic tape and stored in a buffer memory which is then interrogated electronically at a speed compatible with the printer. The memory and associated circuits make this device almost a small computer in itself. A second reason magnetic tape is now seldom used in engineering problems is that once the results are printed out from a given problem-run on magnetic tape the magnetic tape to printer problem must be faced again. A third reason is that tape correction equipment almost must be provided, which, in the present techniques, at least involves two tape handling units, which in themselves are expensive since they require rapid acceleration and deceleration of the magnetic tape.

Although all of the preceding statements refer to engineering problems, the philosophy applies to a much broader class of problems and situations. Another class of problems, which use magnetic tape and the digital computer, is one in which inventory, payroll, or similar records are kept on magnetic tapes. In the Other Systems Applications section it will be shown how this proposed system could effect a saving of computer time.

In the present magnetic tape and magnetic disc file systems of certain commercial manufacturers a check is made to determine whether the desired character has been written, on command. This check consists of looking for the inductive spike of voltage after the write winding has been pulsed. Hence this check is merely a check to determine if an open circuited head or drive line exists.

The basic concept of the variable reluctance read head has been explored previously (1,2). The circuitry used here is different to the extent that in the previous work sinusoidal signals were used throughout. Also, conventional amplification was used. Such a device is presently in use at the installation of the Impérial Chemical Industries Ltd. Middlebrough, England. A modified version of the variable reluctance read head is commercially available from the New Electronic Products of London, England. No details on this head have been obtained to date. It is believed that this head is similar to that reported by Kilburn (1), and suffers from the fact that it is incompatible with conventional digital magnetic tape recording techniques.

One of the basic devices employed in the development of this system is the parametron. The basic concept of the parametron, as a computer element, appears to have been advanced simultaneously by J. von Neumann (3) and several Japanese, notable Eiichi Goto (4), in 1954. As indicated by Wiggington (5) these efforts were quite similar in concept, but appear to have no direct connection. Since the parametron idea was first advanced, the development has proceeded at a tremendous pace. Of significant importance is an article by Sterzer (6) in which a parametron system is described with 60 decibels gain and repetition rates of 100 megacycles.

A. The Read Head

The basic shape of the read head used in this experimental work is that of a horseshoe. A fundamental picture of this read head is shown in figure 1. The underlying idea is that the interrogate winding induces a local field in the vicinity of the hole which saturates that area of the horseshoe, thereby increasing the reluctance seen between the pole tips. The saturated area will take the form of a toroid, centered at the hole. For this reason it is clear that the hole should be centered in the width of the horseshoe.

In order to utilize the head to read magnetic records the idea is as follows. A magnetic dipole placed between the pole tips induces a flux in the soft magnetic material. The direction of the flux depends upon the orientation of the dipole. The interrogate winding is then energized, thereby reducing the flux since there is an increase in reluctance of the path. The read winding in figure 1 will then have a voltage induced due to the change in flux linkages. The information is carried, then, in the phase of the read voltage. For these investigations pulse techniques were employed. A typical read output is shown in figure 2. Both dipole orientations are shown. The most desirable magnetic material for use in the read head would be one whose B-H curve has the general characteristic shown in figure 3.

It should also be pointed out that the same head, as shown in figure 1, can serve as a write head simply by energizing the write winding. Another possibility would be to apply current to a separate write winding or, alternatively, the center wire of the interrogate winding could be opened and the interrogate winding used to write.

The particular head used for the experimental investigations was made of what was deduced to be a type of Hypersil. The B-H curve for the material was investigated and the shape is shown in figure 4.

The horseshoe was mounted on a brass backplate. The reasons will

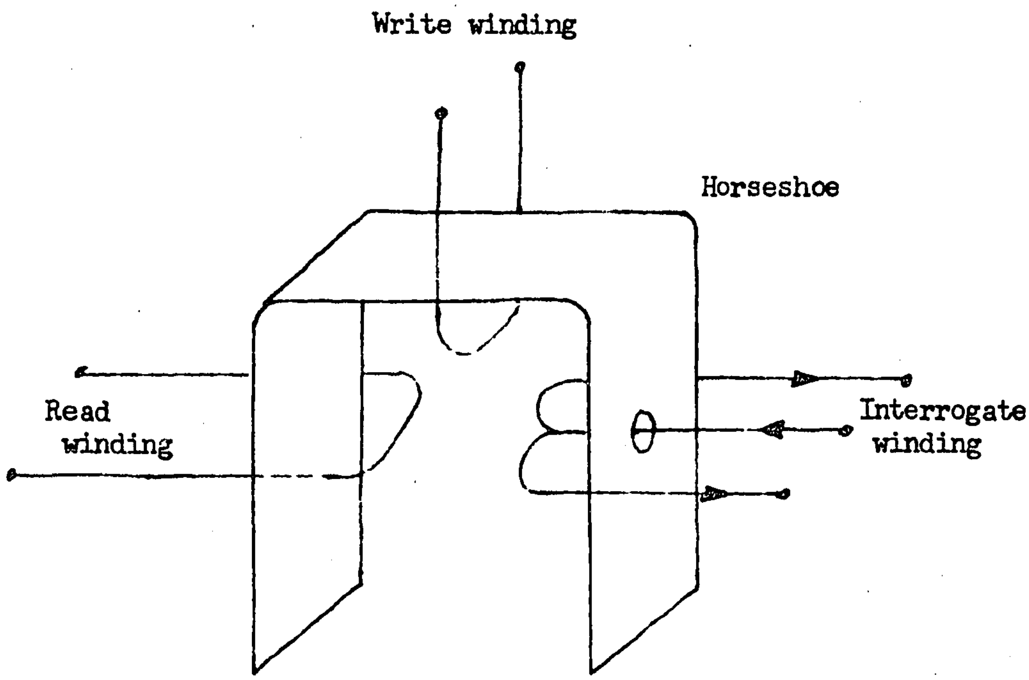

Figure 1. Basic read head

Read head

Interrogate current

Read head

Interrogate current

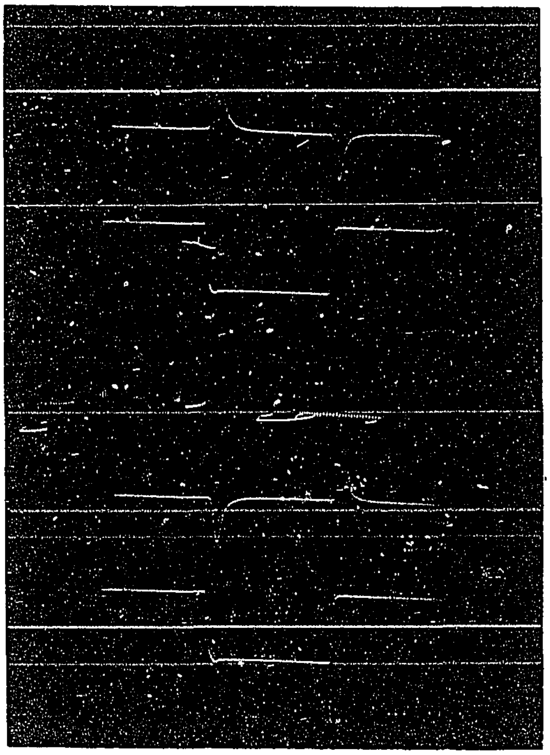

Figure 2. Typical read winding output showing both polarities

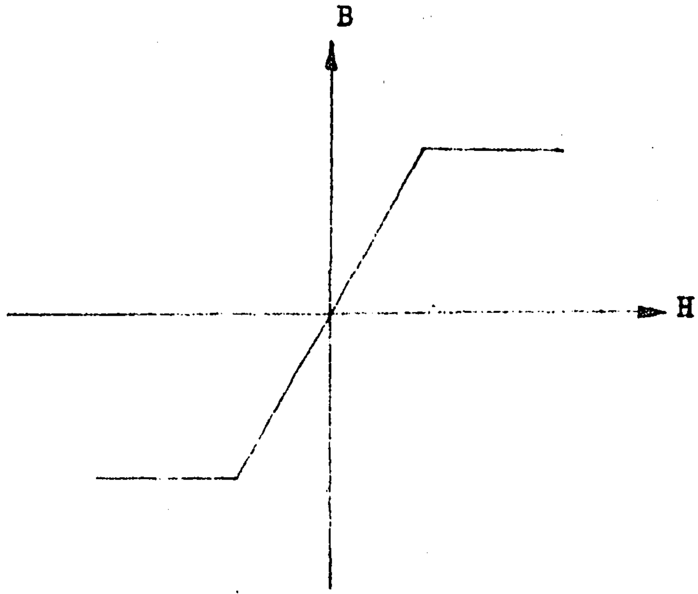

Figure 3. Ideal B-H curve for read head

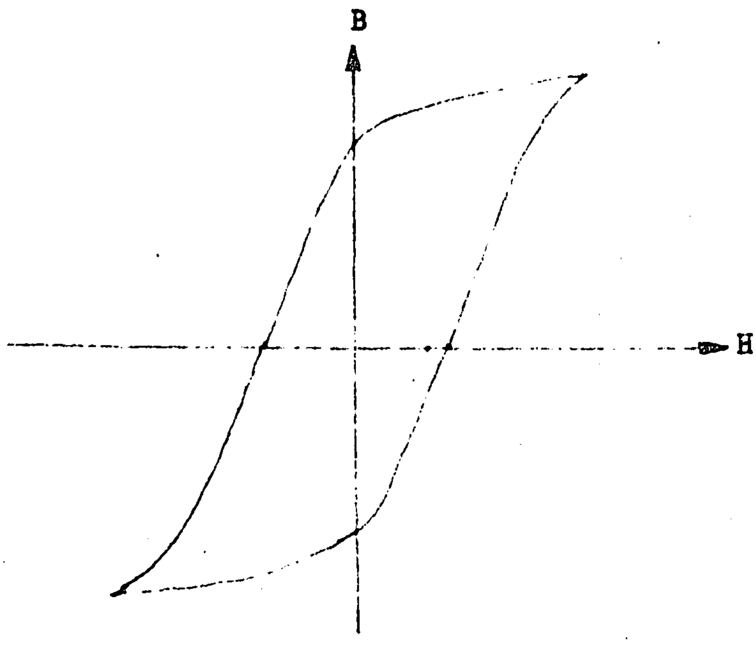

Figure 4. Hypersil B-H curve

become apparent. First a piece of the Hypersil was cut which was approximately:

42 mils wide

235 mils long

2 mils thick.

The one side of the horseshoe was affixed to the brass backplate as a supporting structure with epoxy glue. Then a 20 mil diameter hole was put through the middle of the Hypersil and then on through the brass backplate. Two number 32 enameled copper wires were inserted through the hole from the Hypersil side and soldered to the brass on the back. The interrogate lines thus formed were then brought directly away from the sides of the head and up to the top being affixed to the brass. The lines were insulated from the brass except where soldered on the back. The lines then form what is known as a strip-line which serves to contain the field and reduce the noise induced elsewhere. Next, a 15 turn coil of number 39 enameled copper wire was wound at the top of the horseshoe. For these investigations this winding was used for both read and write. The rest of the Hypersil was then pulled over in front and a five mil shim placed between the two pole tips of the horseshoe which were then faced off to a smooth surface.

The required interrogation pulse in this head was about one ampere peak and a 3:1 pulse transformer was used. The current required then from the driver was approximately one third ampere. The particular pulse driver used in the experimental investigations is described later in this section. A pulse of approximately 160 milliamperes appeared to be sufficient into the read winding to write on the magnetic tape with the tape flush against the head.

One experimental difficulty was experienced with this particular head. As can be seen from figure 4 the remanent magnetic flux density after writing, using the read winding, caused a voltage to be induced which was sufficient to bias the phase of the output. This flux was approximately as large as the flux captured by the head from the magnetic tape. In order to circumvent this problem for the investigation the following was done. A spot of each polarity was written on the magnetic tape. The head was then demagnetized with a permanent magnet. In order for this system to be practically applied, a solution to this problem must be found. The English group mentioned in the Introduction (1) has solved it in their system apparently by using two heads spaced one gap-space apart. However, a better solution appears to lie in the area of vacuum deposition of Permalloy, with the easy direction along the length of the horseshoe. A fringe benefit of this method should be good uniformity of the resulting heads.

Another read head was also fabricated of Permalloy. The small amount of available Permalloy was, however, only one-eighth mil thick and the output voltage from the head was correspondingly low.

For schematic diagrams a standard symbol for the read head is adopted and shown in figure 5.

B. Parametron

In the most elementary possible terms the parametron is a resonant

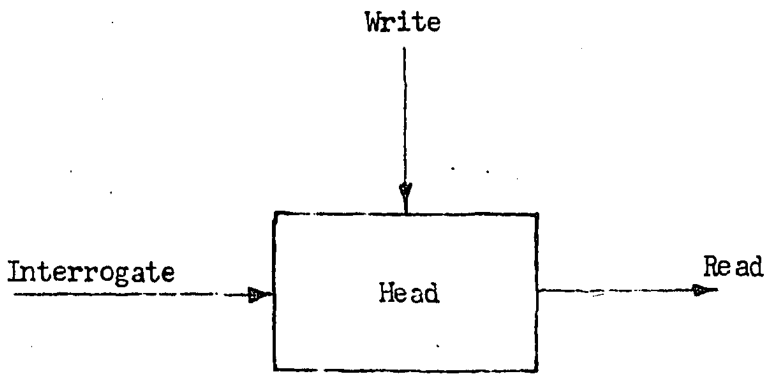

Figure 5. Schematic symbol for read head

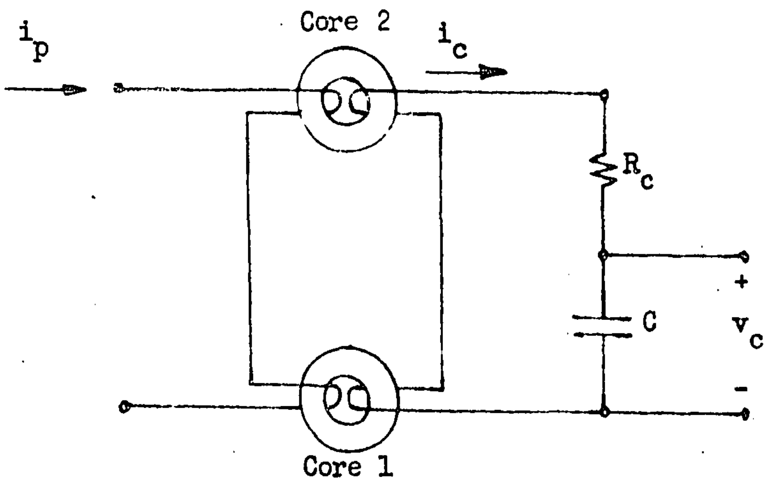

Figure 6. Circuit for graphical analysis

circuit in which either the inductance or the capacitance varies periodically. Neither the capacitor nor inductor variable method seems to exhibit a marked advantage over the other.

The parametron is a special case of the parametric amplifier. The parametric amplifier consists of two tuned circuits coupled through a nonlinear reactance which varies with a pump voltage, or current. The conditions of the tuned circuits must be such that the sum of the resonant frequencies of the two tuned circuits be equal to the pump frequency. The parametron is a special case in which the two tuned circuits are combined into one. Hence, the resonant frequency of the one tuned circuit must be half that of the pump. It is this fact that makes it very useful in application to binary systems. The frequency is fixed, but the phase is quantized to one of two phases which differ by 180 degrees. These two phases can then be used to represent either a "0" or a "1", in binary notation. The representation of information by the phase of a signal is commonly referred to as phase-script. Pulse-script denotes signals representing pulse information. Conversion between phase-script and pulse-script is very conveniently done.

As with most oscillatory circuits the initial conditions are very important to the build-up of oscillations. In particular, for the parametron a small voltage induced in the tuned circuit in one of the two second subharmonic phases, prior to application of the pump, will govern the final phase of the oscillation. The final amplitude reached after application of the pump is normally much larger than the small initial voltage. This gain may be of the order of several thousand. Goto (7) quotes a personal source in which amplification of 100 decibels is reported.

Since the differential equations which describe the operation of the parametron are inherently nonlinear, a complete and accurate analysis is not easily made. A more detailed analysis will be pursued later, but a rather simple, intuitive, explanation due to Goto will be considered first.

For a simple LC resonant circuit with resistance, capacitance, and inductance in parallel assume that the inductance varies with the pump according to

$$L = L_o(1 + 2a \text{ Sin } 2\omega t). \qquad 1$$

Also assume that the current in the inductor is sinusoidal and can be broken into a sine and cosine term, such as

$$I = I_s \text{ Sin } \omega t + I_c \text{ Cos } \omega t. \qquad 2$$

The resulting voltage across the inductor is then the time rate of change of LI.

$$\begin{aligned} V_L = {} & L_o\omega[I_s \text{ Cos } \omega t - I_c \text{ Sin } \omega t] \\ & + 3aL_o\omega[I_s \text{ Sin } 3\omega t + I_c \text{ Cos } 3\omega t] \\ & + aL_o\omega[-I_s \text{ Sin } \omega t + I_c \text{ Cos } \omega t] \end{aligned} \qquad 3$$

Since the circuit is tuned to ω, the second term in equation 3 will be greatly attenuated and hence the inductor voltage will consist of the first and the third terms. The first is easily observed to be the normal voltage leading the current by 90 degrees in time phase. The third term, however, yields a voltage which appears as would a negative resistance, $-aL_o\omega I_s$ Sin ωt. If this equivalent negative resistance is sufficiently large, and can overcome the actual resistance of the inductor, the circuit is seen to exhibit oscillation. Accordingly, a buildup of oscillation will occur until a further nonlinearity of the circuit causes limiting.

1. Mathematical analysis

A detailed analysis becomes significantly more difficult. A gross inspection of the problem yields that the coefficients of the governing differential equations are not constant, but periodic. If, as in the previous discussion, a variable inductor is assumed which varies sinusoidally with time it is clear that even this is an approximation to the variation of L with time. This is in turn most easily seen from the fact that for the parametrons used in this investigation, the inductance varies as the slope of the B-H curve at a point determined mainly by the pump current. Hence, this approximation is valid only for a linear hysteresis curve.

For a parallel RLC circuit the governing differential equation is seen to be

$$\frac{d^2\lambda}{dt^2} + \frac{1}{RC}\frac{d\lambda}{dt} + \frac{1}{LC}\lambda = 0. \qquad 4$$

The transformation $\lambda = z \exp(-t/2RC)$ yields the differential equation

$$\frac{d^2z}{dt^2} - \left(\frac{1}{4R^2C^2} - \frac{1}{LC}\right) z = 0. \qquad 5$$

If

$$L = L_o(1 + 2a \text{ Cos } 2\omega t)$$

and

$$1/L = (1/L_o)(1 - 2a \cos 2\omega t), \qquad 6$$

for a sufficiently small a, equation 5 becomes

$$\frac{d^2z}{dt^2} - \left(\frac{1}{4R^2C^2} - \frac{1}{L_oC} + \frac{2a}{L_oC} \cos 2\omega t \right) z = 0. \qquad 7$$

Now let $x = \omega t$ and the result is

$$\frac{d^2z}{dx^2} + \left(\frac{1}{\omega^2 L_o C} - \frac{1}{4\omega^2 R^2 C^2} - \frac{2a}{\omega^2 L_o C} \cos 2x \right) z = 0. \qquad 8$$

Let us now define $\theta_o = (1/\omega^2 L_o C) - (1/4\omega^2 R^2 C^2)$ and $\theta_1 = a/\omega^2 L_o C$, which reduces equation 8 to a form which is identical to that of a classical differential equation (8).

$$\frac{d^2z}{dx^2} + (\theta_o - 2\theta_1 \cos 2x)z = 0 \qquad 9$$

This differential equation is known as Mathieu's equation. Mathieu's equation is a special form of Hill's (8) equation which has the form

$$\frac{d^2z}{dx^2} + (\theta_o + 2\theta_1 \cos 2x + 2\theta_2 \cos 4x + \cdots)z = 0. \qquad 10$$

Hill's equation may be solved by assuming a solution of the form

$$z = e^{\alpha x} \sum_{r=-\infty}^{\infty} b_r e^{irx} . \qquad 11$$

Substitution of equation 11 back into Hill's equation results in the recurrence relation for all integral values of r

$$(\alpha + 2ir)^2 b_r + \sum_{k=-\infty}^{\infty} \theta_k b_{r-k} = 0. \qquad 12$$

It can be shown that α, in order to satisfy Hill's equation, must satisfy the infinite convergent determinantal equation 13.

$$\begin{vmatrix} \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \frac{(i\alpha+4)^2-\theta_0}{4^2-\theta_0} & \frac{-\theta_1}{4^2-\theta_0} & \frac{-\theta_2}{4^2-\theta_0} & \frac{-\theta_3}{4^2-\theta_0} & \frac{-\theta_4}{4^2-\theta_0} & \cdots \\ \cdots & \frac{-\theta_1}{2^2-\theta_0} & \frac{(i\alpha+2)^2-\theta_0}{2^2-\theta_0} & \frac{-\theta_1}{2^2-\theta_0} & \frac{-\theta_2}{2^2-\theta_0} & \frac{-\theta_3}{2^2-\theta_0} & \cdots \\ \cdots & \frac{-\theta_2}{-\theta_0} & \frac{-\theta_1}{-\theta_0} & \frac{(i\alpha)^2-\theta_0}{-\theta_0} & \frac{-\theta_1}{-\theta_0} & \frac{-\theta_2}{-\theta_0} & \cdots \\ \cdots & \frac{-\theta_3}{2^2-\theta_0} & \frac{-\theta_2}{2^2-\theta_0} & \frac{-\theta_1}{2^2-\theta_0} & \frac{(i\alpha-2)^2-\theta_0}{2^2-\theta_0} & \frac{-\theta_1}{2^2-\theta_0} & \cdots \\ \cdots & \frac{-\theta_4}{4^2-\theta_0} & \frac{-\theta_3}{4^2-\theta_0} & \frac{-\theta_2}{4^2-\theta_0} & \frac{-\theta_1}{4^2-\theta_0} & \frac{(i\alpha-4)^2-\theta_0}{4^2-\theta_0} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{vmatrix} = 0 \tag{13}$$

In application to parametron studies the most common situation is to have the θ's given, in which case α must be determined.

Hill's determinantal equation can be symbolized by $\Delta(i\alpha) = 0$. It has been found (9) that

$$\Delta(i\alpha) = \Delta(0) - \frac{\sin^2 \frac{1}{2}\pi\alpha i}{\sin^2 \frac{1}{2}\pi\,\theta_0}, \tag{14}$$

and therefore α is a root of the transcendental equation

$$\sin^2 \frac{1}{2}\pi\alpha i = \Delta(0)\,\sin^2 \frac{1}{2}\pi\,\theta_0 \,. \tag{15}$$

It can now be seen that Mathieu's equation is solved by the same line of attack, and is, furthermore, a simplification, in that all θ's greater than θ_1 are zero. Also, note that θ_1 in Hill's equation is the negative of θ_1 in Mathieu's equation. Hence $\Delta(0)$ becomes

$$\begin{vmatrix} \text{---} & \text{---} & \text{---} & \text{---} & \text{---} & \text{---} & \text{---} \\ \text{---} & 1 & \frac{\theta_1}{4^2-\theta_o} & 0 & 0 & 0 & \text{---} \\ \text{---} & \frac{\theta_1}{2^2-\theta_o} & 1 & \frac{\theta_1}{2^2-\theta_o} & 0 & 0 & \text{---} \\ \text{---} & 0 & \frac{\theta_1}{-\theta_o} & 1 & \frac{\theta_1}{-\theta_o} & 0 & \text{---} \\ \text{---} & 0 & 0 & \frac{\theta_1}{2^2-\theta_o} & 1 & \frac{\theta_1}{2^2-\theta_o} & \text{---} \\ \text{---} & 0 & 0 & 0 & \frac{\theta_1}{4^2-\theta_o} & 1 & \text{---} \\ \text{---} & \text{---} & \text{---} & \text{---} & \text{---} & \text{---} & \text{---} \end{vmatrix} = 0. \qquad 16$$

In order to correlate these seemingly diverse pieces of information consider now the method of solution of a physical problem.

If R, L, and C are given, θ_o and θ_1 may be determined for equation 9. Armed with θ_o and θ_1 find $\Delta(0)$. Read (10), for example, has represented $\Delta(0)$ by a 7 x 7 matrix and arrived at approximate answers by solution on the "Cyclone" digital computer. Once $\Delta(0)$ is known, the transcendental equation 15 can be employed to determine α. To determine the total solution equation 12 must be employed to find the b's for equation 11. Having found the α one is now able to determine the stability, and if unstable, the rate of growth of a signal of small proportions in the resonant circuit. If α is real and greater than zero we can observe an exponential growth of z with x, where $x = \omega t$. One must also account for the transform from λ to z and hence instability will occur for the circuit if

$$\alpha\omega - \frac{1}{2RC} > 0. \qquad 17$$

Furthermore, the rate of growth will be proportional to

$$e^{\left(\alpha\omega - \frac{1}{2RC}\right)t}. \qquad 18$$

Since complete textbooks (11) have been written on the solution of Mathieu's equation, additional, more complete, information should be obtained from these sources. Also of considerable aid is the set of tables prepared by the National Bureau of Standards (12) which give certain of the coefficients for a form of the solution similar to equation 11.

2. Graphical analysis

Under an extreme idealization of the B-H curve a graphical technique can be developed for analysis of the type of parametron used in this experimental investigation. This method of analysis was first described by Lavi and Finzi (13).

The approximation for the B-H curve is such as to make it perfectly square, but with small coercive force. A circuit similar to that used by Lavi and Finzi is shown in figure 6. Assuming one turn coils around the cores and square wave current pump the describing equations are

$$\frac{d\varphi_2}{dt} = \frac{d\varphi_1}{dt} + R_c i_c + v_c \qquad 19$$

$$F_1 = i_p + i_c \qquad 20$$

$$F_2 = i_p - i_c \tag{21}$$

$$i_c = C\frac{dv_c}{dt}. \tag{22}$$

The states of the cores are then defined to be

1. Unsaturated -- u state $(F = 0)$
2. Saturated -- s^+ $(F > 0)$

   s^- $(F < 0)$.

Lavi and Finzi also observe that the mode (v_1, v_2) cannot appear, except for the trivial case $i_p = 0$. One further assumption is that of eliminating s^-, whereupon the transition from (u_1, s_2^+) to (s_1^+, u_2) must be through (s_1^+, s_2^+). The first step in the analysis is to investigate each mode independently.

In the mode (s_1^+, u_2) the resulting equations are

$$\frac{d\varphi_1}{dt} = 0 \quad \text{and} \quad F_2 = 0 \tag{23}$$

$$i_p = i_c \quad \text{and} \quad F_1 = 2i_p \tag{24}$$

$$\frac{d\varphi_2}{dt} = R_c i_p + v_c(t) \tag{25}$$

$$v_c = v_{su} + i_p \frac{t - t_{su}}{C} . \tag{26}$$

In equation 26 v_{su} and t_{su} are the voltage across the condenser and time, respectively at the start of the (s_1^+, u_2) mode.

In the mode (u_1, s_2^+) the equations 19 through 22 become

$$F_2 = 2i_p \tag{27}$$

$$\frac{d\varphi_1}{dt} + R_c i_p + v_c(t) = 0 \tag{28}$$

$$v_c(t) = v_{us} - i_p \frac{t - t_{us}}{C} . \quad 29$$

For the mode (s_1^+, s_2^+) the resulting equations which describe the circuit are

$$v_c = v_{ss} e^{-\frac{t - t_{ss}}{R_c C}} \quad 30$$

$$\frac{d\varphi_1}{dt} = \frac{d\varphi_2}{dt} = 0 \quad 31$$

$$i_c = - \frac{v_{ss}}{R_c} e^{-\frac{t - t_{ss}}{R_c C}} .$$

To facilitate following through the graphical analysis assume initial conditions $t = 0$ at $\varphi_1 = \varphi_s$, a mode (s_1^+, u_2) exists, and therefore, v_c is increasing along with $\frac{d\varphi_2}{dt}$. At a later time $t = t_2$ the mode (s_1^+, s_2^+) is reached, whereupon, from t_2 to $t = T/2$ v_c decays exponentially with a time constant of $R_c C$. In the second half cycle the mode (u_1, s_2^+) exists with the boundary conditions $\varphi_1(T) = \varphi_2(0)$ and $v_c(T) = - v_c(0)$.

Lavi and Finzi report good correlation with experimental results up to three megacycles. An extension of these concepts to buildup appears to necessitate including the saturated inductance of the coils which has been omitted. This study is believed by the author to warrant further investigation in detail, with a view to possible computer mechanization of computation. The basic algorithm of parametron operation should not be extremely difficult to obtain.

3. Experimental results

The parametrons used in the experimental investigation were constructed of square-loop ferrite cores. These cores are the type normally used in digital computer memory arrays. Specifically, they were the S-3 type produced by the General Ceramics Company. These cores have a coercive MMF of approximately 0.262 ampere turns. It is felt that although the experimental results verify the feasibility of the system, better parametrons would significantly improve the performance. A better parametron would be one without the square-loop characteristic and more like figure 3.

For purposes of this investigation it was deemed advantageous to keep the frequencies involved low. This allowed many parts to be built using common laboratory snap-leads, usually without noticeable stray pickup. In the last configuration the pump frequency was approximately 50 kilocycles. A difficulty was experienced in going to higher frequencies because of the large switching time of the S-3 cores.

A detailed sketch of the parametron used is shown in figure 7. Each core has wound on it two 15 turn coils of number 30 enameled copper wire. The capacitor was 0.1 microfarad.

In the first experiments the variable inductor was replaced by a fixed 32 microhenry coil and the pump was supplied from the Hewlett-Packard 211A square wave generator through a 4:1 pulse transformer. The square wave generator output and the parametron output are shown in figure 8. The pump frequency in this case was 84 kc.

Undoubtedly these parametrons would be unsuitable for a good,

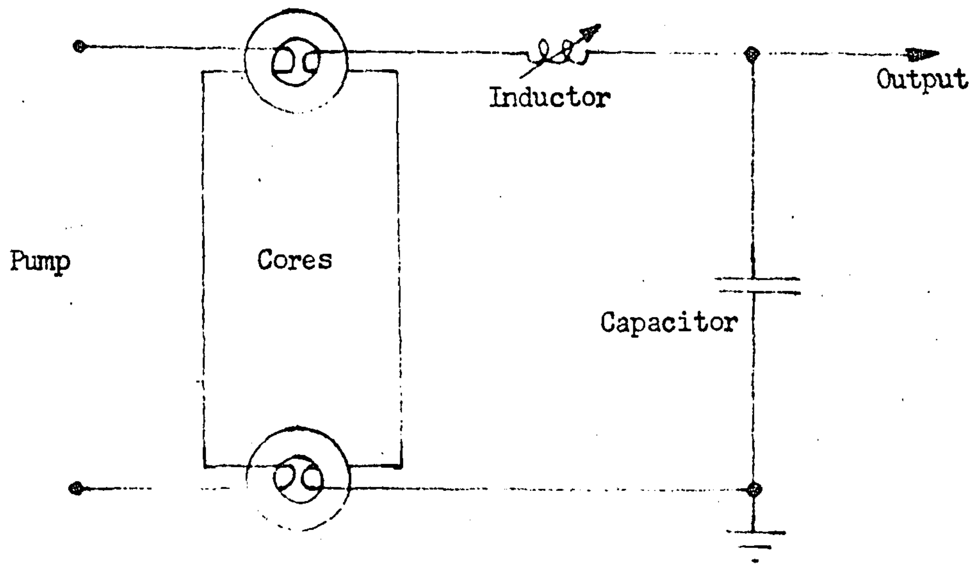

Figure 7. Experimental parametron

Parametron output

Pump voltage

Parametron output

Pump voltage

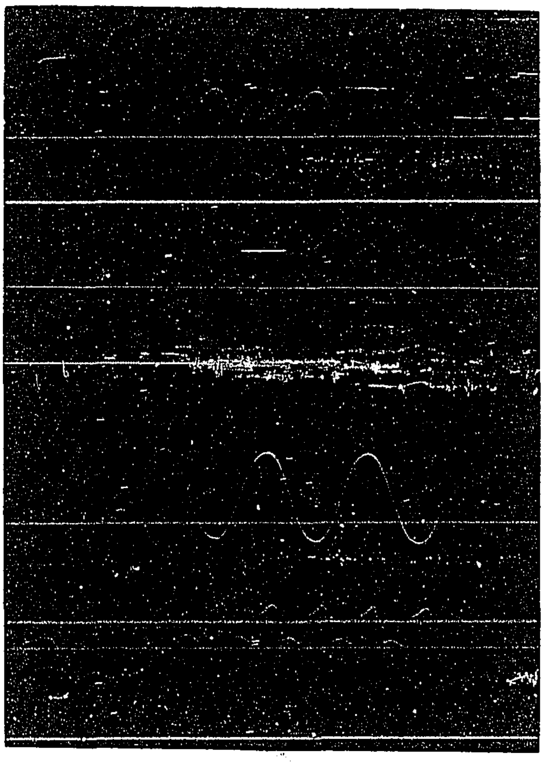

Figure 8. Typical parametron output showing both polarities

operating system. However, it is of interest to note some of the reported parametron characteristics referred to in the Introduction. Sterzer reports a variable capacitance parametron produced from strip line with a 60 db gain and a rise time of between 6 and 7 db per nanosecond and a fall time of 1.5 nanoseconds. This, with Goto's reported gains of 100 db, should allow operation under the worst possible combination of operating conditions, for example a one-turn vacuum-deposited read winding.

It is of extreme importance to note that a variation of pickup voltage amplitude from the read head of as high as 50 percent should not have any great effect on the performance. The reason is that the parametron is relatively insensitive to amplitude variation as long as it is sufficiently large to establish a particular phase in the output after the pump is turned on.

Several methods for gating the parametron were tried and the best, by far, for this experimental configuration, was shorting the pump winding of the read parametron. Another method that should be investigated is connecting the pump windings in parallel, rather than in series as was done, and opening the pump winding of the read parametron.

C. Circuits

The experimental circuits used were very basic and straightforward.

A tunnel diode oscillator and a single transistor amplifier were used to drive the two parametrons in series on the pump windings. The circuit of the oscillator amplifier is shown in figure 9.

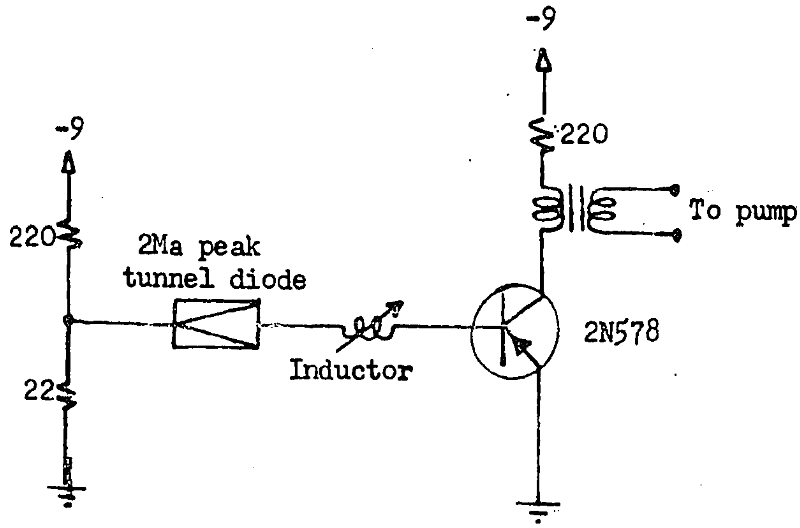

Figure 9. Tunnel diode oscillator and amplifier

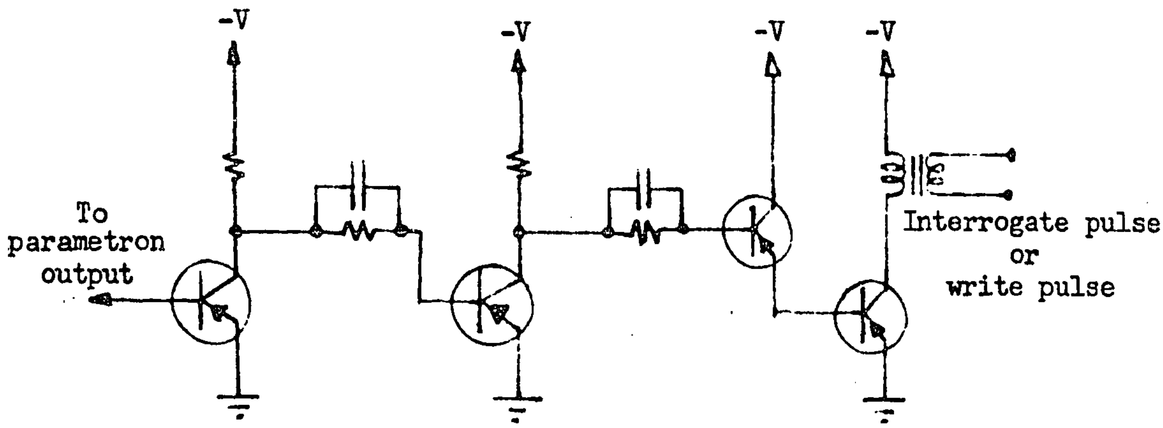

Figure 10. Clipper -- amplifier

No serious deterioration of operation of the standard phase parametron was observed by coupling directly from the parametron output to the base of a transistor amplifier. The general schematic of the amplifier is shown in figure 10. The clipper-amplifier consists of one stage of voltage amplification and then three stages of current amplification to reach the current pulse levels required of the interrogate pulse or the write pulse. This design could doubtless be simplified. It is included here principally for completeness and as an example of one possible way to accomplish the desired effect. The only place where any real experimenting with circuits was done was in the gating of the read parametron. After considerable experimentation the optimum combination of those tried was found to be the series connection of the pump windings and shorting the read parametron pump to kill the oscillation. Also of some importance was the method of coupling the read voltage from the read head into the parametron. The optimum method was found to be connecting through a pulse transformer whose secondary was placed in series with the parametron resonant circuit.

D. Complete System

The complete system is shown in figure 11. This system was used for this basic investigation. The purpose of the study was to prove the feasibility and get estimates of performance to compare to theoretical predictions.

In figure 11 the switch diverts the current pulse from the interrogate winding to the read winding, which then serves to write on the

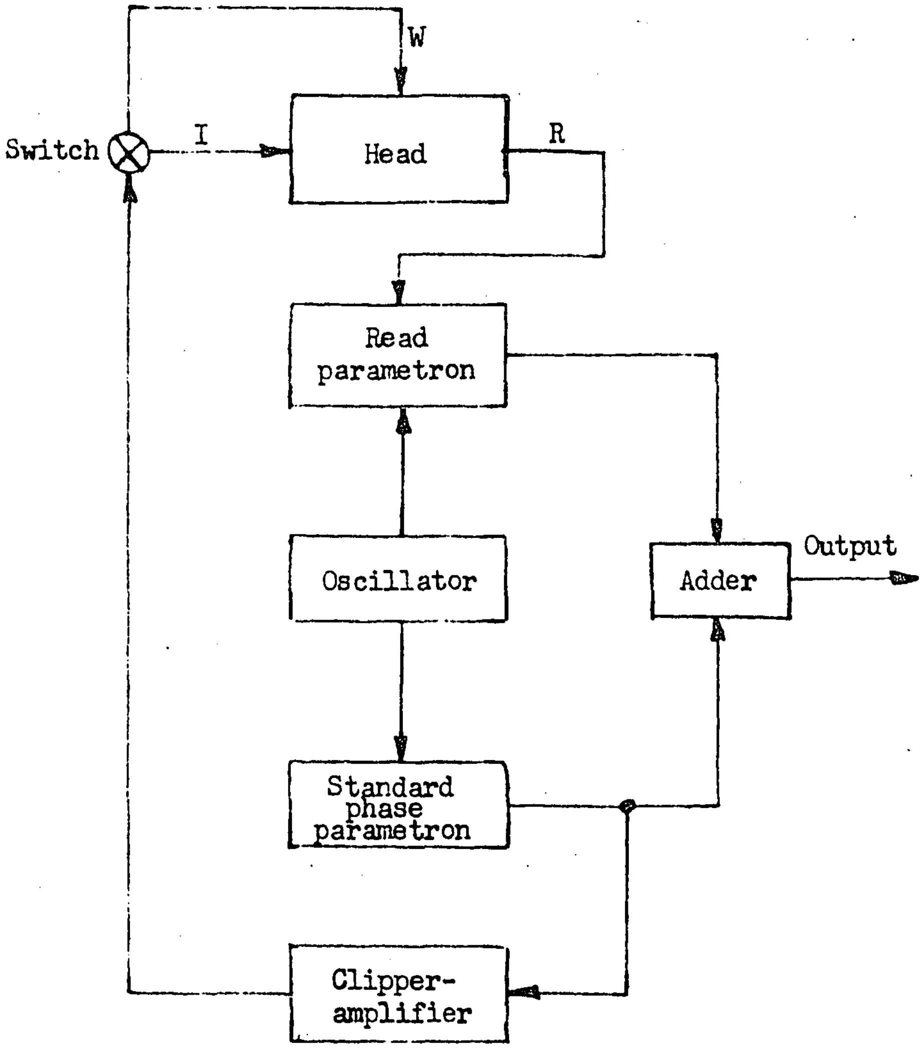

Figure 11. Complete experimental system

magnetic tape. The summing amplifier was actually the Tektronix 561 scope preamplifier which provided an "add" position. However, a simple alternative is to have a single transistor amplifier with two base resistors -- one to each parametron output. One or both of the base resistors should be variable to allow for small variations in the two parametrons. Hence, if the two parametrons are in-phase a large collector current or voltage swing will be experienced. If they are 180 degrees out of phase no output swing will be observed. The collector could then be used in several ways. One would be to use it into a punch solenoid for punching paper tape or punched cards. Another could be to run a Flexowriter or similar printing equipment. Yet another scheme would be to drive a neon or indicating light.

The output voltage from the read head was run through a 10:1 pulse transformer which was in turn in series with the parametron secondary. With the pump shorted out on the read parametron a voltage at the parametron output of approximately 10 millivolts peak to peak was observed, whose phase was dependent upon which spot on the magnetic tape the read head was positioned over. With the short removed the signal grew to approximately 1.2 volts.

III. COMPARISON WITH PRESENT DIGITAL COMPUTER MAGNETIC RECORDING TECHNIQUES

A. General Discussion

The following analysis will give support to the following statements.

The proposed scheme will give rise to a system which is considerably less susceptible to noise.

The proposed scheme offers radical advantages over standard magnetic tape readers in two important ways. First, the acceleration and deceleration of the tape is not important. That is, the read voltage is relatively independent of the tape velocity. Secondly, the associated electronics is simplified.

The proposed system can be used for any data rate from zero up to at least those presently commercially available.

According to the analysis results the standard magnetic record reading head has a rather severe alteration of voltage spectrum for variation of head-to-recording spacing. Also, very wide variations in amplitude of the output voltage are experienced, approximately 20 to 1 for a spacing of 1/2 to 2 mils with a 2 mil wide bit. This has a large implication on magnetic disc recording where "run-out" of the disc causes wide variations in head-to-disc spacing. In contrast, the proposed system is practically insensitive to amplitude variations. The only requirement is that a flux larger than stray flux is captured by the read head. It is also of interest to note that the peak output voltage from the variable reluctance read head varies only approximately three to one over the same separation variation of 1/2 to 2 mils and a 2 mil bit.

B. Analysis of the Present Read System

In order to arrive at an analytical expression from which to work, the following assumptions are made. The field intensity about the magnetic recording is assumed to vary inversely with the distance from each end. This assumes, then, that the ratio of recording width to pole separation is large, and hence analogous to the electrostatic problem using fine lines of charge. Also, it is assumed that the flux in the head is directly proportional to the component of magnetic field intensity parallel to the bit orientation for the undisturbed free space field.

The geometry and definition of symbols are shown in figure 12. For this configuration and under the above assumptions the magnetic field intensity described is given in equation 32.

$$H_x(x) = 2As \frac{[(y^2+s^2) - x^2]}{[x^4 + 2(y^2-s^2)x^2 + (y^2+s^2)^2]} \qquad 32$$

In equation 32 the symbol A is the assumed arbitrary proportionality constant. If A is taken to be numerically one-half and s to be one, a plot of $H_x(x)$ for various y values is given in figure 13.

A plot of the slope of figure 13 should then be proportional to the voltage induced in the existing form of read head moving at constant velocity (or constant record velocity if the head is stationary). Since

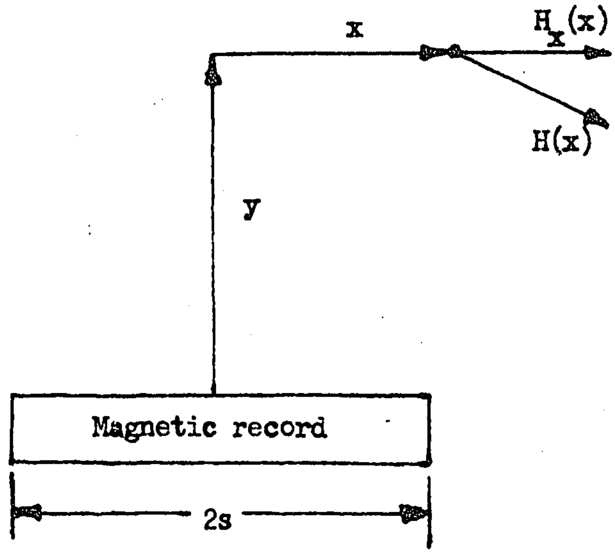

Figure 12. Dimensions for obtaining $H_x(x)$

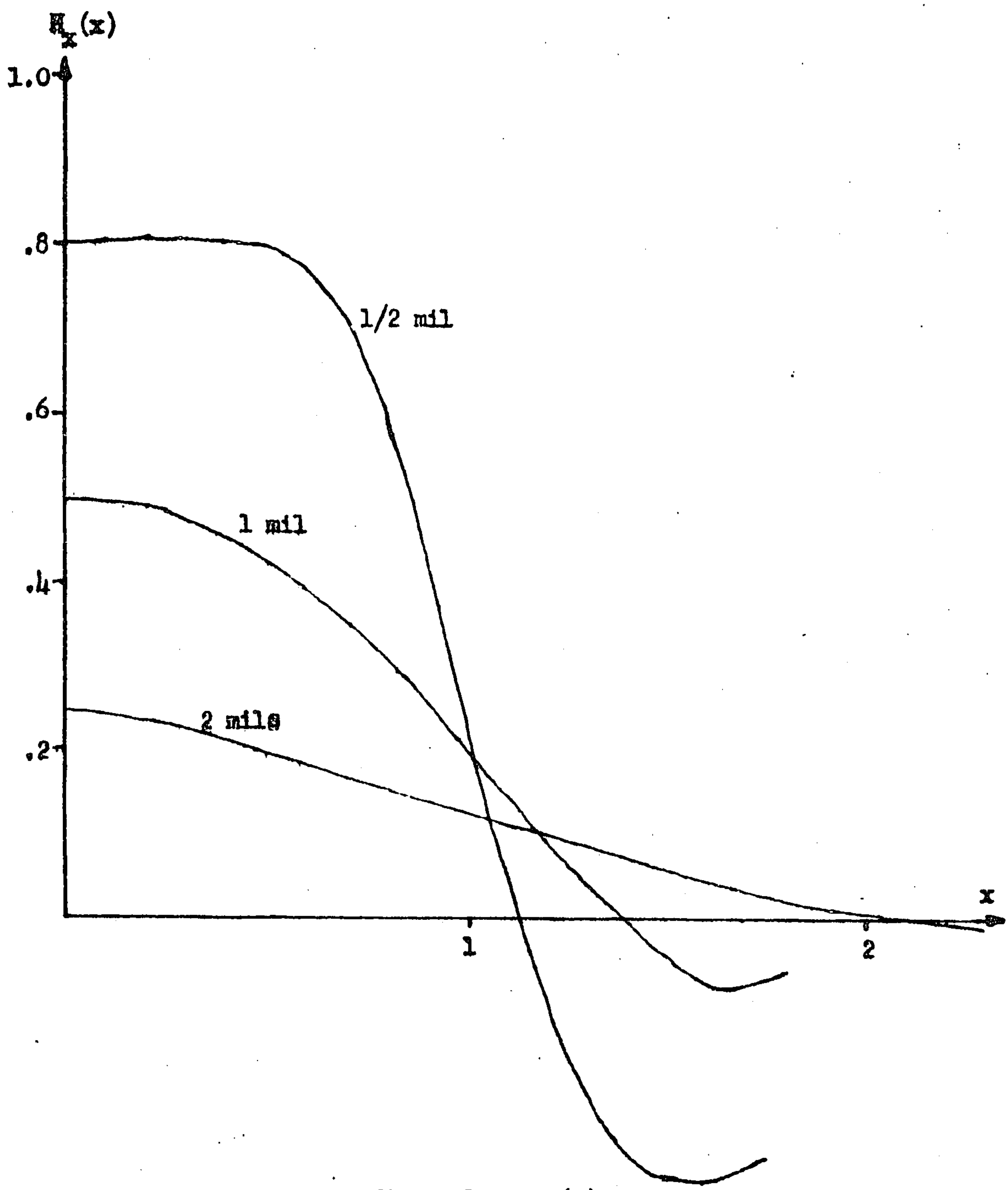

Figure 13. $H_x(x)$ for different head-to-recording spacings

such a curve is seen to be symmetrical about the origin only one side is given in figure 14. It may also be easily seen that for a constant velocity the abscissa is directly proportional to time t.

Since all of the preceding derivation rests rather heavily on the indicated assumptions, exact, time consuming, solution to obtain the frequency spectrum of the voltage hardly seems justified. For this reason the voltage pulses were approximated by the dotted straight lines. Bearing in mind the symmetry about the origin, these approximated waves were analyzed by taking the Fourier Transform of them. The resulting $|E(j\omega)|$ is plotted in figure 15. Since the limiting cases are of most importance only the upper and lower curves are considered.

On the basis of voltage magnitudes only, from the unnormalized curves of figure 15, it appears that an approximate bandwidth of at least 50 kilocycles to 600 kilocycles will be required. From figure 14 it may be seen that the read voltage magnitude varies approximately 20 to 1 for a spacing fluctuation from one-half to two mils. In view of this fact, an amplitude sensing system could have severe troubles if spacing variations occurred while reading, for example in a magnetic disc system. This factor is very important in this proposed system since only phase is sensed over several cycles of sampling, and the only requirement is that a signal of sufficient magnitude is present.

During the time in which this phase of the investigation has been carried out the electronic digital computer at Iowa State University, the "Cyclone", has been undergoing modifications. For this reason a more exact solution has been postponed. When this valuable computational aid

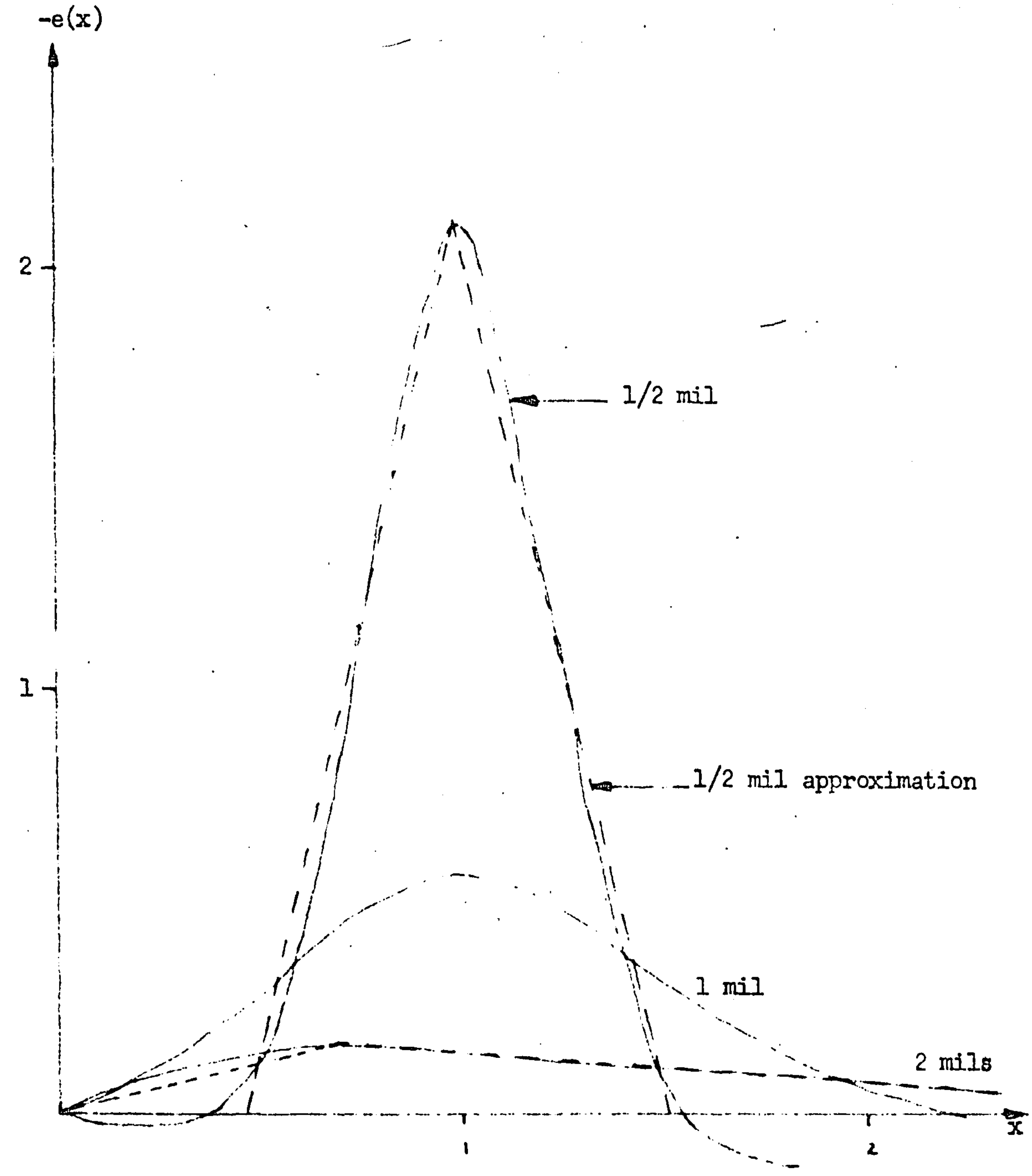

Figure 14. -e(x) and approximations

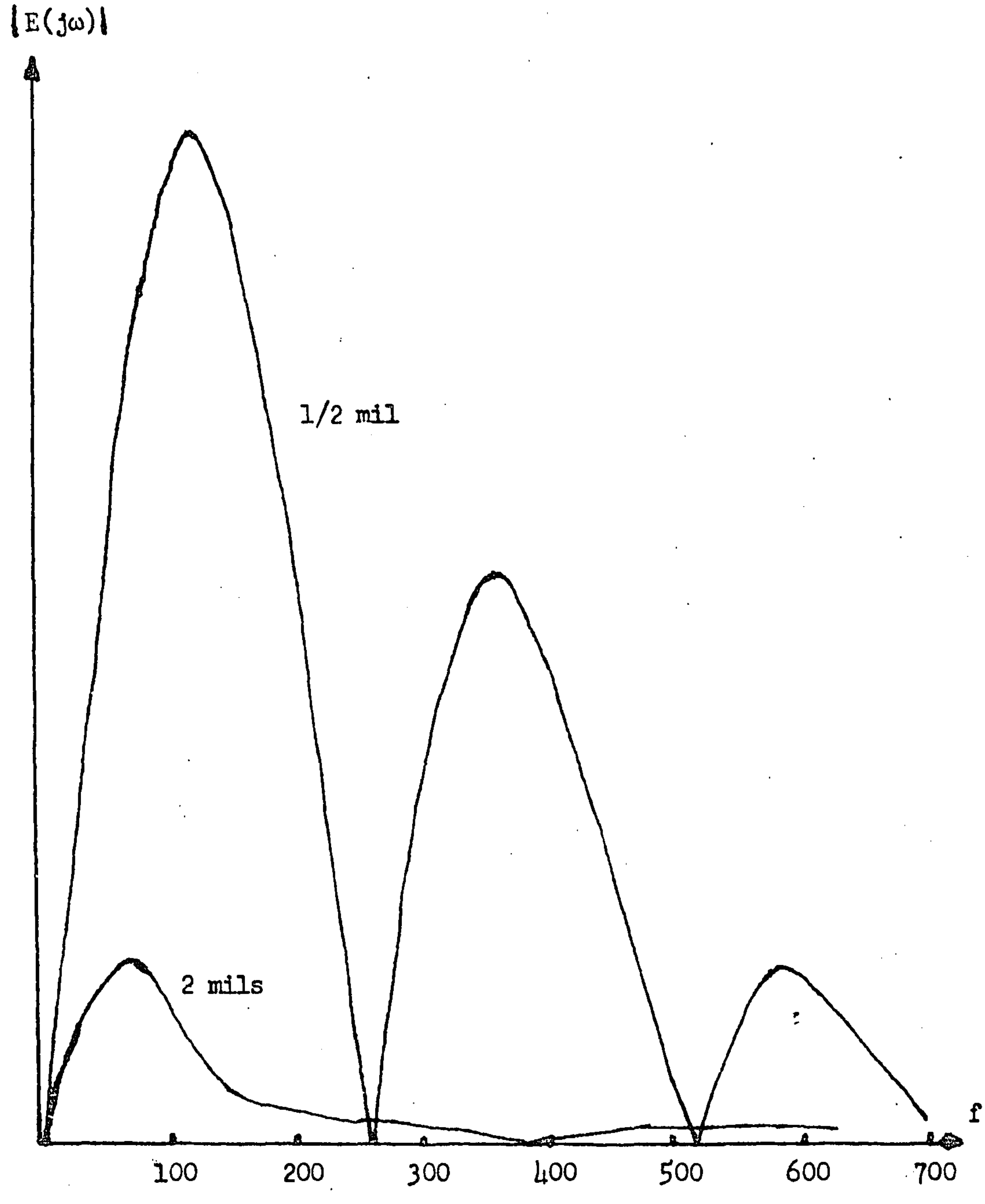

Figure 15. Frequency spectrum of read voltage

returns to normal use it is anticipated that this phase of the investigation will be explored more fully. With the aid of the "Cyclone" it should become feasible, for example, to make a more accurate determination of bandwidth on the basis of power. This should allow an exact statement of signal to noise ratio improvement utilizing the more exact curves, rather than the straight line approximations in figure 14.

In the curves of figure 14 the abscissa can be related from mils to microseconds. Specifically, for a recording character rate of 100 kilocycles with a two mil bit (s = 1 mil) a resulting scale factor of two microseconds per mil is derived. It should also be noted that a relation of the proportionality between the magnitudes can be obtained. The frequency spectrum plots given in figure 15 are on a proportional basis from figure 14, and hence specific magnitudes cannot be found, only relative sizes.

C. Analysis of the Parametron Read System

In contrast to the previously described system it will be shown that this system is radically less sensitive to noise. It should be observed that the voltage spectrum of a pulse of voltage is proportional to $(\mathrm{Sin}\ \frac{\omega\tau}{2} / \frac{\omega\tau}{2})^2$ and hence has most of its energy confined to lower frequencies. This is important since most noise encountered in this type of equipment is not thermal noise but induced from extraneous pulses.

From a rough theoretical analysis it can be seen that the rise time, or build-up time, of the tuned circuit due to the excitation of the read head allows a Q of up to ($\pi f_o T$), where f_o is the read frequency and T is the build-up time to the 63 percent point. Specifically, at a 100 KC character rate a period of 10 μsec would be available for reading. This period could be handled with 5 μsec for build-up and 1 μsec for parametron build-up. This would leave 4 μsec for utilization of the information. It should also be pointed out that this does not take full advantage of the system. Conceivably these times could be reduced by at least an order of magnitude with presently existing hardware as discussed earlier. For example, in the work done by Sterzer repetition rates exceeding 100 mc are reported. Also Pohm et al. (14) report that magnetic film parametrons can be operated considerably in excess of 2.5 mc repetition rates with pump supplied at approximately 100 mc. It is interesting to note from the preceding information that a Q in the resonant circuit, for the 100 KC character rate, of roughly 30 would yield good results. A Q of 30 at 2 mc corresponds to a 60 KC bandwidth. It is very important that this is centered at 2 mc and only 60 KC wide. This is in direct comparison to the approximately 600 KC wide conventional system which runs from 50 KC to 600 KC. The improvement in the noise rejection should be much greater than the 10 to 1 bandwidth reduction would indicate. As indicated earlier this is due to the fact that pulse energy is concentrated at lower frequencies.

IV. SYSTEM DESIGN PROPOSAL FOR HIGH-SPEED DIGITAL COMPUTER INPUT-OUTPUT

The overall hardware required for a complete magnetic tape system are:

1. Tape typewriter
2. Computer tape input
3. Computer tape output
4. Magnetic tape printer.

All four of these devices are similar in concept to paper tape in both handling and use.

The tape typewriter is currently available from commercial manufacturers. The only possible improvement offered by the variable-reluctance head and parametron scheme would be to read all of the material typed on the tape exactly one character position away from the write position. This information could then be used to either actuate the associated typebars or provide a neon lamp visual bit display for operator comparison. The read system is exactly like the tape printer system to be discussed except that a timing track is unnecessary, since timing is provided by operation of the keys by the typist. A further advantage would be provided since a read-without-type could be provided to locate a record to be altered.

Computer tape input and output, the second and third parts of the system, could follow conventional lines in existing installations. As indicated previously, considerable cost advantage can be obtained by use of the variable-reluctance head and parametron system. In particular, a much less expensive tape unit could be developed, the reduction in cost coming through the relaxation of mechanical requirements over standard tape units. The tape output is made up of the mechanical equipment to move the tape and a write head which cannot conceivably be improved by the proposed system.

Fourth, and most important, is the magnetic tape reader. As presently envisioned, electronic speed is not a problem. The subsystem to be described here involves the use of a timing track, although a system can be developed which would eliminate this requirement. The only additional requirement is odd tape parity and a logical "or" of all levels to trigger the gating. This necessitates increased electronics and hence cost which would have to be balanced by the user. No major changes in concept are required over this described system, however. The timing track consists of a bit at the location of each recorded character on a separate track. This bit is sensed by a variable reluctance head. Once the signal exceeds a chosen signal level the read circuitry is reset for the next sequence of operations.

The read circuitry operation consists merely of allowing proper build-up in the parametron resonant circuit and then turning on the pump followed by gating the parametron output, after conversion from phase-script to pulse-script, to the printer. The tape then could be accelerated at any convenient rate and reach a steady-state constant velocity, whose resulting character rate is compatible with the chosen printer. The entire read system is shown in figure 16. The peak rectifier, Schmitt trigger, and single-shot multivibrator simply gate the

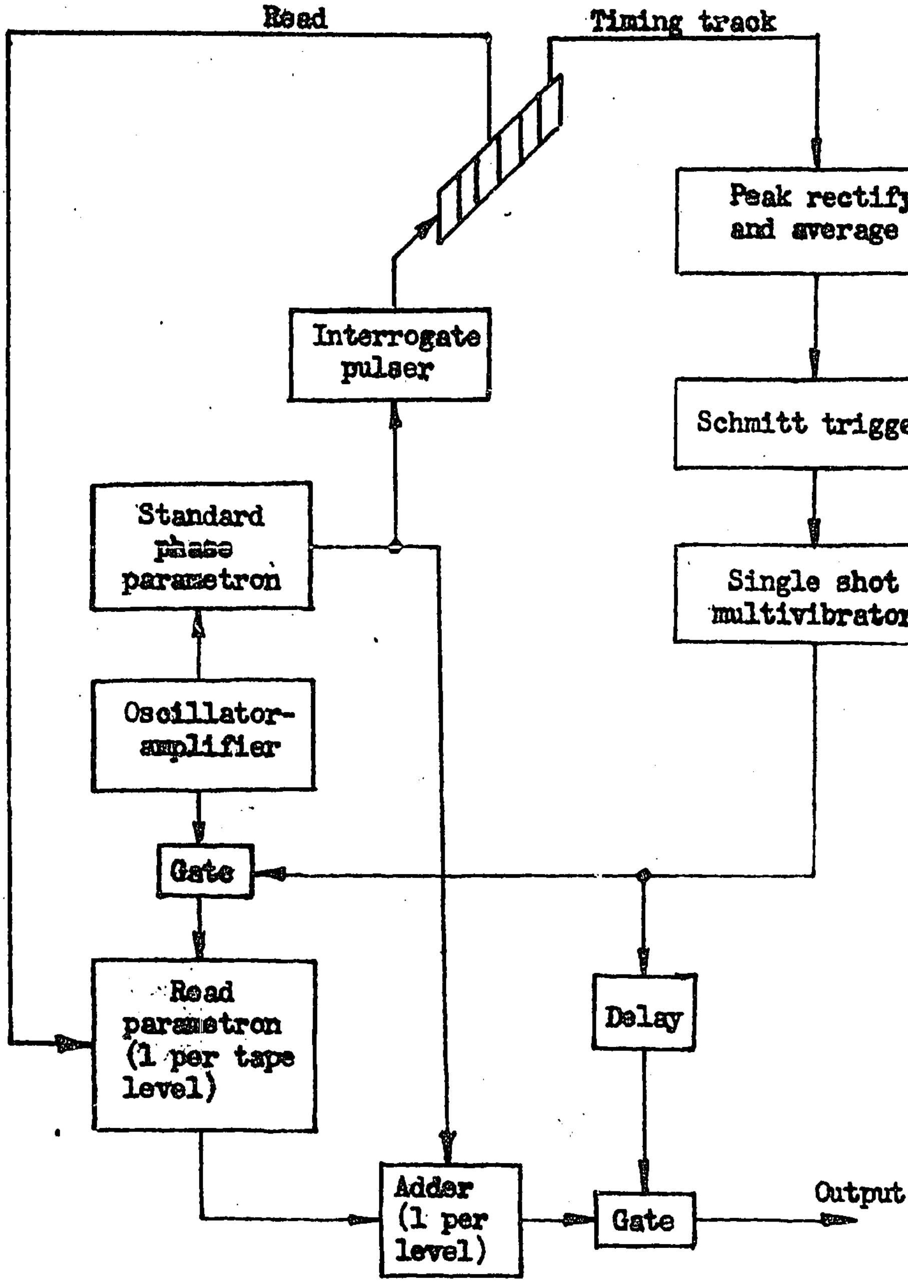

Figure 16. Read system

pump to the read parametron and gate the pulse-script information out of the adder to the printer. The remainder of the system is described earlier. Since this is a read system only, the write feature of the heads has been omitted.

Magnetic tape editing equipment can also be constructed along these same lines. The fundamentals of operation are exactly the same as the above described systems. In use the editing equipment should be almost identical with that now used on paper tape.

V. OTHER SYSTEMS APPLICATIONS

In the light of the foregoing description it can now be seen that the major contribution here is to demonstrate how a combination of recently developed components can lead to a simple realization of a digital magnetic recording system. This system is shown to be compatible with existing magnetic recording systems.

In the Introduction a method of checking was described which is used in commercial digital magnetic recording systems. By employing the variable reluctance read head and parametron system the character written could be read back directly from tape or disc. This system would allow 100 percent checking so that even flaws on the tape or disc surface could be detected and bypassed. The concept of 100 percent checking should open new doors in reliability of input-output equipment. Although somewhat less important, is the fact that this checking does not require additional heads, the same heads being used for read and write.

Another valuable application of the proposed system is in conversion equipment. Many types of conversion equipment are now in use for conversion between magnetic tape, paper tape, and punched cards. Equipment is presently available for every conversion of the three media. Due to the massive electronics to make the magnetic tape read speed compatible with the other two, this conversion is relatively expensive. Due to the tape speed independence of the method a drastic cost saving could be made in this conversion equipment.

In reference to the Introduction another area of application is seen to be in searching magnetically recorded records without the computer. An inventory record could be found, for example, with a magnetic tape reader similar to that described in Section IV.

Yet another application is that of telephone line data transmission. A very simple system is envisioned in which computer output, at a centralized location, is made on magnetic tape. This tape is read with this technique and sent over lines to a remote magnetic tape, card, or paper tape station. The receiver station could make use of it in an infinite number of ways -- print out, input to another machine, etc.

Another idea hinted at previously is the use of such a system for magnetic tape editing without the necessity of a digital computer for supervision and coordination.

Although one seems to be limited only by his imagination it can be observed that since reading is almost independent of tape speed the requirement of acceleration and deceleration of magnetic tape units becomes less important and a radically less expensive tape unit should develop.

VI. SUMMARY

A novel method for reading magnetically recorded data is presented. Contrary to conventional amplitude sensing magnetic read systems this system is phase sensitive. This method, in addition to being virtually amplitude insensitive, is also independent of the relative velocity of record and read head. A further advantage is offered in the electronic implementation by very low cost and simple devices. One of the most important devices is the parametron, which offers phenomenally large voltage gains at very low cost. One of the most important advantages of the proposed system is the reduction in noise sensitivity over conventional systems.

The combination of the variable reluctance read head and the parametron opens up a host of new possibilities for digital computer applications. One very important possibility is an inexpensive tape unit. The main simplification is in the mechanical problems of starting and stopping magnetic tape rapidly. This develops because the read voltage is independent of tape velocity. Not to be overlooked, however, is the simplified electronic circuitry involved.

Many applications are envisioned, some of which are described, in which it is profitable to read magnetically recorded data slowly in order to be compatible with an electromechanical device. One of these is a magnetic tape printer. Others are a magnetic tape transceiver for use over a transmission line of limited bandwidth and a magnetic tape to paper tape or magnetic tape to punched card converter.

The advantage of amplitude insensitivity leads to a very large capacity disc file. At the present state of the art a billion character disc file looks feasible.

One of the practical problems not yet completely answered is a magnetic material for use in the read head, and less importantly in the parametron, whose B-H curve shows low residual flux density, linear relationship of B to H, and sharp saturation at some level of magnetic field intensity. However, this characteristic appears to be practically obtainable with evaporative deposition of magnetic thin films. This is not, then, thought to be a major problem, but additional research in this direction should be undertaken.

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