SWITCHING CHARACTERISTICS OF LOGIC CORES

By

HENRY F. EBERTSHAUSER, JR.

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

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Thesis Approved:

Paul A. McCollum
Thesis Adviser

Ingvard Imsthe

Robert MacVicar
Dean of the Graduate School

PREFACE

With the advent of electronic computers, a number of new devices of magnetic character, some of which are still in the very early stages of development, have come into prominence. These include ferrite cores, ferromagnetic or tape-wound cores, thin films, transfluxors, paramistors and the like.

Even today, one finds magnetic drums being used in computer storage systems; ferrites are used in matrix-type storage arrays for high speed read-in and read-out. Ferromagnetic cores are used in shift registers and to perform various other logic functions. Thin films present promise in high speed memory circuits.

All of this has come about because of the non-linear characteristic of magnetic materials which man has learned to control and utilize to his benefit. But man's ever present desire for high speed of operation has presented new and interesting problems in the field of magnetics.

With high speed pulse drives, these magnetic devices no longer follow the hysteresis loop with which man has been accustomed to working, namely that obtained with sinusoidal and relatively low frequency drive. Instead, with rapid rise and fall times, the hysteresis loop is distorted and the energy loss becomes much greater. Irregularities appear in the loops which are presumed to be caused by nucleation of the domain walls.

If man could but understand the exact origin of magnetic fields and forces, that is: the basis for the formation of domain structures, the forces behind the motion of boundary walls, or some of the other questions that have their basis in the structure of the atoms which make up our universe, his ability to explain what he has observed in solid state magnetics would be greatly enhanced.

Man has long strove for the answers to these questions, but to no avail. A single breakthrough might mean years of labor and research saved. It is to this end for which man is working, but while this is being done, progress in everyday life must be continued and man therefore learns to utilize what he has and measures his understanding in his ability to relate his new found knowledge to things which he supposes to be true.

ACKNOWLEDGEMENT

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The author is most grateful also to Magnetics, Inc., for the bobbin cores tested in this study.

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HFE

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CHAPTER I

INTRODUCTION

The problem of analyzing magnetic core characteristics is one which often faces the engineer in modern electronic equipment design. Since much work has already been accomplished in the analysis of magnetic circuits involving solenoids and other magnetic cored elements, this would appear to be a rather simple problem. However, the electronics industry in conjunction with modern manufacturing processes has recently opened an entirely new field of magnetics. The manufacture of square-loop magnetic cores for the computer industry is a striking example of the fruits of these developments. Although data representing operating characteristics are available from the manufacturer, it would be most advantageous to a design engineer to have available characteristic curve plots analogous to the curves utilized in vacuum tube and transistor circuit design.

The means of measuring magnetic core characteristics evolves to a choice of method of measuring flux density and magnetic intensity along with the ability to measure a time rate of change of flux density. The instruments which might be used are the ballistic galvanometer, wideband a-c amplifiers incorporating a Miller integrating circuit, or d-c (direct coupled) amplifiers. Since the cores involved are very small, .075 to .2 inches outside diameter being typical, the parameters measured will be exceedingly small and some amplification will be necessary.

In order to facilitate measurement of these parameters, wide band d-c amplifiers might be used. Since the magnetic flux is the integral of the time rate of change of voltage, an operational amplifier is necessary. The d-c amplifier is well suited for this because of its versatility for purposes of amplification and integration merely by substitution of the proper elements in the feedback loop.

The characteristics measured in actual operation may not agree with those obtained experimentally due to factors such as loading. Therefore, all factors must be considered when characteristic curves for cores are evaluated. Included in this thesis is a discussion of core parameters, measuring techniques and the problems encountered when attempting to measure these characteristics.

CHAPTER II

MAGNETICS

In developing the theory of any device, it is of fundamental importance to have some understanding of the origins of its characteristics and the way it operates. A brief description of the basis for magnetic theory in addition to some of the means of determining and controlling the characteristics of certain types of magnetic materials will be examined.

Magnetic Materials

In the study of the magnetic properties of any substance or material, one must nearly always concern himself with a hysteresis curve. This curve or loop is obtained for a given material when the value of H is changed in a cyclic manner from a maximum value in one sense to an equal maximum in the other. Since the value of B obtained in this manner as a function of H is also a function of the past history of magnetization within the material, it is necessary to traverse the loop several times in order to obtain a stable value for the hysteresis loop or B-H curve as it is commonly called.

As with any curve or response function, it is possible to write a mathematical equation which will permit computation of B for a particular value of applied H. In the case under consideration, this equation is of the form:

$$B = u_o H \ (1 + k) \tag{2.1}$$

where B = magnetic flux density in webers per square meter

u_o = permeability of free space, 4×10^{-7} in rationalized mks units (weber per ampere-meter)

H = free space value of magnetic intensity in ampere-turns per meter

k = magnetic susceptibility

The factor $(1 + k)$ is referred to as the relative permeability of the material, sometimes referred to as u_r. Substituting u_r into Eq. (2.1) gives

$$B = u_o u_r H \tag{2.2}$$

This linear equation defines two classes of magnetic materials depending on whether the sign of k is positive or negative. Materials designated as diamagnetic have a k of the order of 10^{-5} and the sign is negative. Paramagnetic materials have a value of k associated with them of approximately the same magnitude, but of opposite sign (+).

A third group of materials represents the one with which this study is concerned. This group bears the name ferromagnetic. The relative permeability assigned to ferromagnetic materials has a value greater than unity. Unfortunately, the relationship between B and H is non-linear and some care must be exercised in assigning a particular value of permeability to a ferromagnetic material. However, it is this same non-linearity which makes magnetic cores so useful in the fields of computers and controls.

Hysteresis Loops

The hysteresis loop normally obtained through the use of a sinusoidal drive current of low frequency is not a suitable measure for determining the losses and operating characteristics for all modes of operation. Since the losses under any particular operation are dependent on the frequency and amplitude of the drive input, it becomes necessary to evaluate the B-H loop at many frequencies in order to determine the actual hysteresis loss. This loss is proportional to the area enclosed within the loop.

Furthermore, since present day computers use pulse type sequencing systems, it becomes necessary to analyze magnetic characteristics on the basis of pulse type inputs with varying rise times and under conditions of various drive amplitudes and pulse repetition rates (commonly referred to as "rep" rate).

Before discussing the various types of B-H loops which might be anticipated, it is necessary to present a basis for the discussion since various terminologies may be confusing to some.

If a B-H loop is considered, the following might be typical

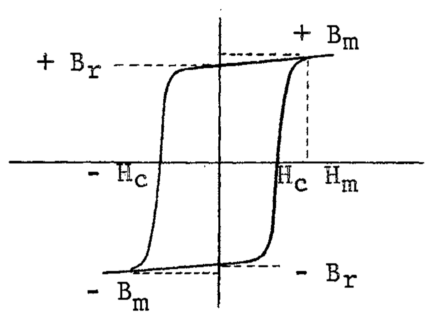


Figure 1

where B_m = saturation flux; note that since the knee of the curve has already been passed at this point, it would be possible by using higher drive currents to drive the loop to a value above

B_m; therefore, B_m must be the flux density corresponding to a minimum value of H at which a complete switch of the core will occur (a complete switch corresponds to a change in flux within the core from B_r in one direction to B_m in the opposite direction).

B_r = residual flux.

H_c = coercive force of the core; it is that value of drive below which no switch occurs.

It should be noted that for drive currents corresponding to values of H between H_c and H_m a partial switch of the field within the core will occur.

Since the various points on the curve lend themselves to more material considerations of the characteristics of core materials for digital use, several of these might be noted at this time.

(a) The value of H_c as determined on the B-H loop can be identified with the noise level which may be sustained by the core. Random pulses or noise of values less than H_c will not cause switching or any variation in the output voltage of the core.

(b) Values of drive greater than H_c but less than H_m will cause partial switching of the core which will cause a variation in the voltage output depending in a non-linear fashion on the drive input.

(c) It might also be mentioned at this time that the value $\frac{B_r}{B_m}$ is defined as "squareness ratio" and also carries considerable weight as a noise characteristic. The amount of voltage output produced when a core is driven from remanence (B_r) to saturation in the same sense (B_m) can result in incorrect read-out or sensing of the core. If the factor $\frac{B_r}{B_m}$ could be made equal to unity, this source of noise would disappear.

Square-Loop Materials

The factor $\frac{B_r}{B_m}$ as a noise characteristic of cores suggests the production of a magnetic material with as nearly a square loop as possible. Actually, square loop materials have been identified since the mid 1930's having been discovered through the application of a magnetic field during the heat treating cycle of magnetic alloys.[1] It was discovered that randomly directed magnetization in magnetic domains can be oriented during the anneal so as to produce a high degree of orientation in the direction of the applied field.

Ferrite cores, however, do not respond to this type of anneal due to their low Curie temperatures. Since ferrite domains do not align readily, this suggests a random type of orientation in the finished product. Therefore, if such a spatial relationship exists, these cores will exhibit a value of H_c greater than that which would be encountered were the domains oriented parallel to the easy axis of magnetization. There has been some study on the effect of core radial thickness versus domain orientation in ferrites and it is felt that perhaps the minimizing of radial thickness would contribute to improved parallel domain orientation.

In contrast to the disadvantage of requiring larger drive currents, ferrite cores have an advantage in low eddy current losses. Since the ferrites are manufactured by a process resembling powder metallurgy, the individual grains are insulated from each other by the binder material. Control of grain size in this case will therefore exhibit some control over eddy current loss.

To reduce the eddy current loss in tape-wound (ferromagnetic) cores, it is necessary to reduce the tape thickness or gauge of the material to a minimum. However, in the case of tape-wound cores, it will be shown later that tape thickness varies inversely with H_c. Therefore, there is an optimum gauge for any particular use or desired output from the core upon which both eddy current loss and minimum drive requirements depend.

Origin of Domains

If a magnetic anneal is used at some time during the processing of magnetic tape for logic cores, the domains will be oriented either parallel or antiparallel to the easy axis of magnetization. These domains or regions are made up of magnetic dipoles which are aligned even in the absence of an external field.

Figure 2 below shows a ferromagnetic material which is assumed to be saturated in the direction indicated.

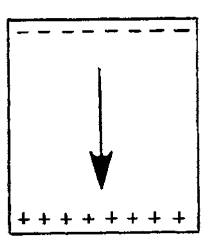


Figure 2

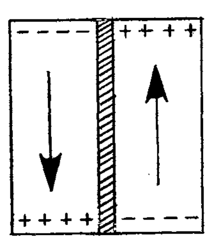


Figure 3

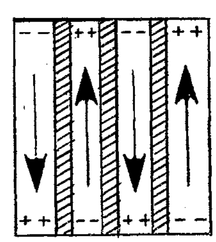


Figure 4

The value of magnetic energy for the configuration assumed in Figure 2, where the material is assumed to consist of a single domain, magnetized as shown, is given by

$$1/8\pi \int H^2 dV \qquad (2.3)$$

This energy term is quite large as a result of the magnetic poles at the surface of the material. Ridenour shows this term to be of the order of $M_s^2 \sim 10^6$ ergs/cm^3 where M_s (saturation magnetization) is the spontaneous magnetic moment per unit volume.[2]

However, this energy can be reduced by changing the dipole distribution in Figure 2 to a configuration with a greater number of poles as shown in Figure 3. In this instance, the magnetic energy is reduced by 1/2. To generalize, the magnetic energy is reduced to a factor of $(\frac{1}{2})^n$, where n is the final number of subdivisions which have occurred. This process of subdivision could be carried on until the amount of energy reduced by a given subdivision is less than the required amount of energy necessary to establish the transition layer between the domains.[2]

This transition layer, or Bloch wall as it is known, has associated with it a 180° transition from a magnetic field in one direction to a magnetic field in an antiparallel direction. Since the field energy favors parallel or antiparallel orientation, it will require energy to establish this boundary layer. This layer is presumed to have a finite thickness as a result of a balance between the exchange energy, which tends to make the wall as wide as possible, and the anisotropy energy which tends to make the wall as thin as possible. The arrangement of atoms and electron spins within the 180° wall is such as to produce a gradual change in the spin vector from one magnetic orientation to the opposing one.

In some ferromagnetics, domains of closure exist also. These might appear as in Figure 5, in contrast to the butt end configuration shown previously.

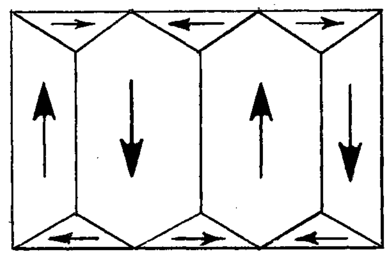
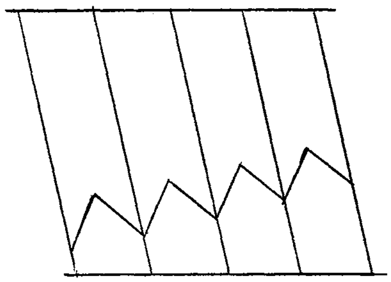


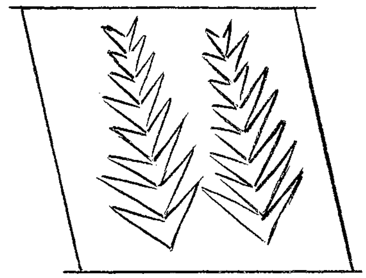
Figure 5. Domains of Closure

For example, in iron, the axis of easy magnetization is along the cube edges, while in nickel, the preferred axes are the body diagonals. Therefore, it is possible to have a magnetic material in which basic domains exist along with closure domains. These closure domains serve to complete the flux path within the material. In the presence of an external field, these domains must be magnetized along different preferred axes. The closure domains will tend to be elongated and this gives rise to the result known as magnetostriction.

A sketch of Bitter figures shows the effect of the existence of domains in the case of iron and silicon iron in Figure 6.[2]



Iron



Silicon

Figure 6. Sketch of Bitter Figures Showing Evidence of Existence of Domains in Iron and Silicon

Magnetism by Domain Growth or Rotation

There are two methods by which magnetization is assumed to take place. These include domain growth (or an increase in the volume of a domain) or domain rotation.

If a single crystal of a ferromagnetic substance could be isolated, the domains might be oriented along the preferred axes as shown in Figure 7.

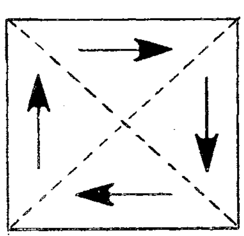


Figure 7

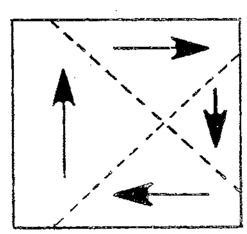


Figure 8

If an external field is then applied which is of sufficient intensity to cause some shift or alignment, the domain which was oriented parallel to the direction of the external field might increase in volume as shown in Figure 8. In this way, an increase in magnetic field strength has been attained through domain growth.

Correspondingly, the same increase in field strength could have been attained by domain rotation. In this case, the presence of an external field causes a change in overall orientation of all domains not in line with the external field. An example of this is shown in Figures 9 and 10, where Figure 9 indicates the domain orientation in the absence of any external field.

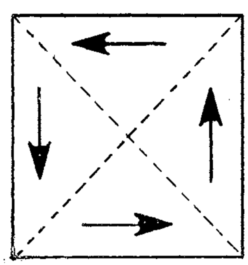


Figure 9

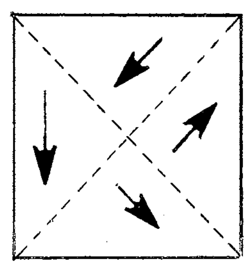


Figure 10

Studies of the origins of magnetism with regard to domain growth or rotation through the use of Bitter figures have shown that weak external fields cause the magnetic energy of a body to increase through domain growth while strong fields generally cause domain rotation.[2]

CHAPTER III

SWITCHING CHARACTERISTICS

The final criteria, which determines whether a simplifying assumption in analysis is valid or not, is how accurately the model follows the characteristics of the product.

In general, the creation of a directed magnetic field distribution is affected markedly by eddy currents. It is for this reason that transformer cores as well as logic cores are laminated. However, for core tapes of less than 1 mil thickness, it has been determined that a reasonable estimate of switching response can be ascertained even though eddy current effects are neglected. It would be logical to assume then that two conditions exist, namely: one in which eddy currents are the predominant retarding force to a change in magnetic field and another in which eddy currents are relatively insignificant. These will be examined.

One Mil Tapes

In the solution for tapes of 1 mil thickness (or greater), several simplifying assumptions may be made. The first which will be considered is that of loop squareness. In the following, a perfectly square loop material will be considered as shown in Figure 11.

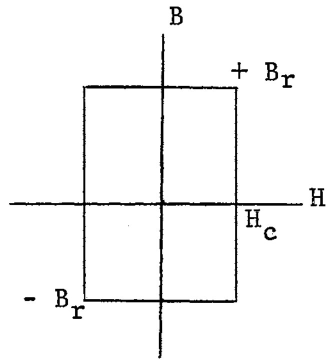


Figure 11. Square Hysteresis Loop Showing H_c and B_r

This will not lead to a completely correct solution, but it simplifies the work considerably and can be corrected after the initial problem has been solved. To further simplify the mathematics involved, the curvature of the tape will be neglected and the propagation of a TEM (transverse electromagnetic) wave into the material will be considered. Magnetization will be assumed to proceed by the formation of a single domain wall of negligible thickness at the inside edge of the tape which will move outward in the Z direction. This will give a fairly accurate result.

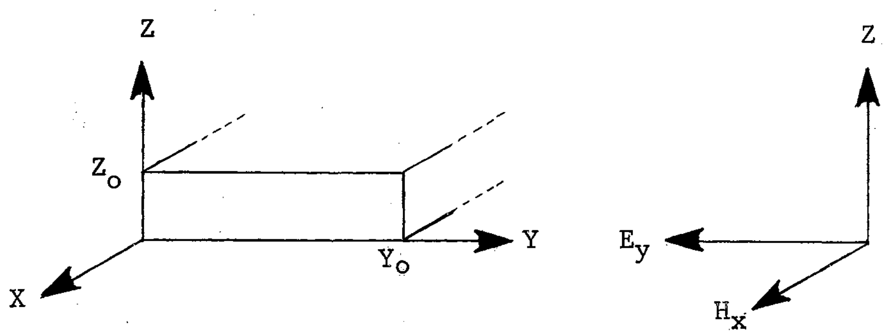


Figure 12. Butt End of Magnetic Tape Showing Axes and Assumed Location of External Field Vectors

The tape for the cores under consideration has a thickness of Z_o (1 mil or greater) as shown in Figure 12, with a width of Y_o. If R (radius of the core) is much greater than Z_o or Y_o, the value of H may be determined by

$$H = \frac{NI}{2\pi R} \tag{3.1}$$

If a single turn winding is used, this reduces to $H = \dfrac{I}{2\pi R}$

The magnetic flux is defined as

$$\Phi = \int_S B \cdot n \, da \tag{3.2}$$

where S = the surface area across which the flux is computed

n = unit normal vector to da

da = element of surface area

Therefore, the flux enclosed by the surface in question may be expressed as

$$\Phi = B_r Z Y_o - B_r \left(\frac{Z_o}{2} - Z \right) Y_o \tag{3.3}$$

$$\frac{\partial \Phi}{\partial t} = B_r Y_o \frac{\partial Z}{\partial t} + B_r Y_o \frac{\partial Z}{\partial t} \tag{3.4}$$

$$\frac{\partial \Phi}{\partial t} = 2 B_r Y_o \frac{\partial Z}{\partial t} \tag{3.5}$$

From Maxwell's equations, considering the TEM wave as shown in Figure 12,

$$\frac{\partial E}{\partial Z} = - \frac{\partial B}{\partial t} \tag{3.6}$$

$$E Y_o = - 2 B_r Y_o \frac{\partial Z}{\partial t} \tag{3.7}$$

$$E = -2B_r \frac{\partial Z}{\partial t} \tag{3.8}$$

From Maxwell's equations, also

$$\frac{H}{Z} = -\sigma E \tag{3.9}$$

where σ = conductivity, giving

$$\frac{1}{\sigma} \cdot \frac{\partial H}{\partial Z} = 2B_r \frac{\partial Z}{\partial t} \tag{3.10}$$

But the partial of H with respect to Z may be expressed by

$$\frac{H_{drive} - H_c}{Z} \tag{3.11}$$

Substituting for the partial of H and integrating

$$\frac{H_{drive} - H_c}{\sigma Z} = 2 B_r \frac{\partial Z}{\partial t} \tag{3.12}$$

$$Z = \sqrt{\frac{H_{drive} - H_c}{\sigma B_r} t} \tag{3.13}$$

When $Z = Z_o/2$, the flux will appear to be completely reversed since the greater portion will now be in the opposite direction. Substituting $Z = Z_o/2$ into the equation for Z:

$$\frac{Z_o}{2} = \sqrt{\frac{H_{drive} - H_c}{\sigma B_r} t} \tag{3.15}$$

Solving for t

$$t_s = \frac{Z_o^2}{4} \cdot \frac{\sigma B_r}{(H_{drive} - H_c)} \tag{3.16}$$

This equation shows that the switching time in thick tapes is inversely proportional to the difference between the drive and the coercive force of the core.

The voltage characteristic can be obtained through the use of Faraday's Law

$$V = \frac{d\phi}{dt} = 2\, B_r Y_o\, \frac{\partial z}{\partial t} \qquad (3.17)$$

where

$$Z = \sqrt{\frac{H_{drive} - H_c}{\sigma B_r}\, t} \qquad (3.18)$$

giving

$$V = Y_o \sqrt{\frac{B_r\,(H_{drive} - H_c)}{\sqrt{\sigma t}}} \qquad (3.19)$$

Therefore, the voltage output of the so-called "thick tape" is proportional to the square root of the difference between the drive and the coercive force of the core. Thus a curve of voltage output versus time would have the characteristic appearance, as shown in Figure 13:

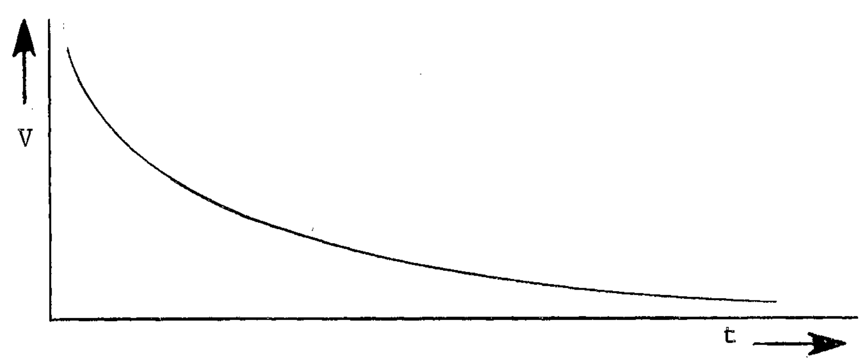


Fig. 13. Voltage Output of Thick Tape Neglecting Variation in Flux Density

Chen and Papoulis[3] have shown this to be somewhat in error. In the previous discussion, B has been assumed constant for H greater than H_c, which accounts for the smooth voltage curve. In actuality, B increases for H greater than H_c, and the curve of voltage versus time should look like that in Figure 14, where the knee occurs at the time when the change in flux direction has reached the center of the core.

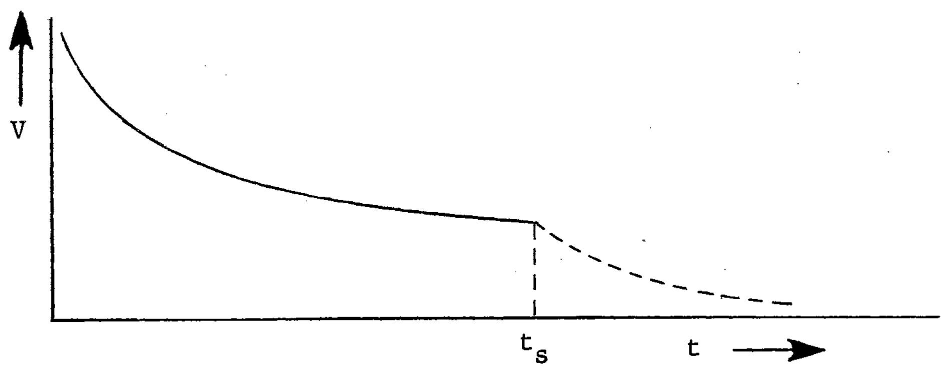


Figure 14. Voltage Output of Thick Tape Allowing for an Increase in Flux Density with Increasing H

Thin Tapes

In the previous discussion, magnetization reversal was assumed to take place through the motion of a domain wall retarded only by the effect of eddy currents within the tape. However, there are several other factors which impede wall motion. F. J. Friedlander[4] explains some additional factors which retard domain motion as:

(1) spin relaxation damping

(2) inclusions or imperfections in the crystalline structure which impose a frictional force impeding wall motion

(3) inertia effects which impede the acceleration of a wall

(4) the fact that walls have a finite thickness and have an energy associated with them which may also impede wall motion

In a thin tape, where eddy currents may be neglected as the main impediment to infinite wall acceleration, the problem of analysis becomes one of increasing perplexity. Since it is necessary for domains to be present and either grow in field strength in a given direction or to change field strength through rotation in order for magnetization reversal to take place, some regard must be given to the creation of domains in the material.

If the tape is so processed as to have a hysteresis loop as square as possible, no nucleation of domains will take place as the external drive is reduced from H_m to - H_c (see Figure 1, page 5). If nucleation were to take place during this change in external field strength, a rounding of the corners of the hysteresis loop would be evidenced and the ratio B_r/B_m would decrease. Thus, although some nucleation must be present, it must be kept to a minimum during the period of field alteration from H_m to - H_c to maintain the loop as square as possible. This, then, is a designing criteria for the establishment of a square loop material.

However, the existence of domains is necessary in order for magnetization reversal to take place. Therefore, some nucleation must take place or be in evidence at the time the external field is applied to cause a switching of the core. That some nucleation is caused when the external field is changed from H_m to - H_c is evident in the change of the shape of the output pulse when a core is prepulsed in the reverse direction by a field equal to - H_c prior to the application of a pulse of sufficient field strength to completely switch the core to $-B_m$.[6] The contrast between the output voltage pulse when the core is not prepulsed and when it is prepulsed with an external field equal to - H_c prior to complete magnetic reversal may be seen in Figure 15.

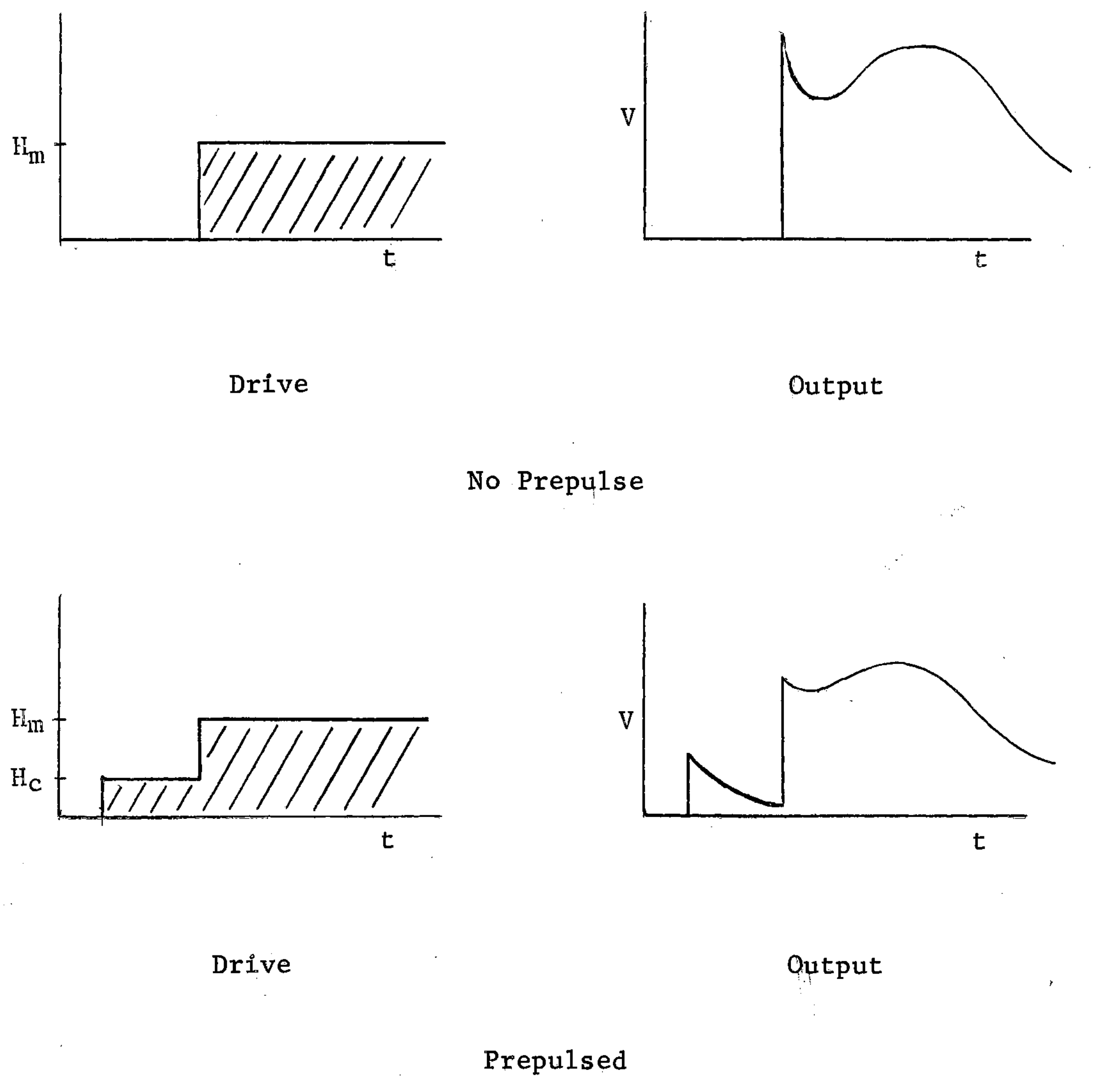


Figure 15. Variation of First Peak of Voltage Response Curve With and Without Prepulse of H_c

These domains occur at inclusions or imperfections through-out the crystal structure of the material rather than merely at the surface as was the assumption for thick tapes. Because of the change in appearance of the core output as seen in Figure 15, the first peak is attributed to the creation of domains within the tape. An oscillogram indicating the voltage output of a 1/8 mil tape-wound core showing the primary and main voltage peaks is seen in Figure 16.

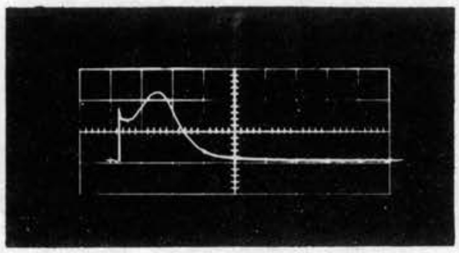


Figure 16. Oscillogram Showing Actual Voltage Output of a 1/8 Mil Tape-Wound Core

This is the voltage output of a 1/8 mil core driven by a step current driver from + B_r directly to - B_m (no prepulse). The core consisted of 29 wraps of 4-79 Mo-Permalloy. Driving field was 0.637 amp-turns/inch. Time scale: 1 microsecond/div. Voltage scale: 0.05 volts/div.

Theoretically, in 1/2 mil tapes, the retardation caused by spin relaxation damping is approximately equal to that caused by eddy currents. In thinner cores (1/4 and 1/8 mil), spin relaxation appears to be the main damping force to wall motion.[5]

Most papers assume a wall velocity proportional to a $f(B)\,(H-H_c)$ where the function of B is not a constant as was assumed for thicker tapes. It is rather a variable depending in some manner on the number of domains present, the thickness and shape of the wall, whether circular or ellipsoidal, and the distance a wall may travel before colliding with another wall.[5]

Magnetization reversal in thin tapes then appears to be concerned with the microscopic analysis of the crystalline and atomic structure of the material itself and as such does not lend itself easily to a model which will approximate the system response.

CHAPTER IV

STANDARD CHARACTERISTICS OF CORES

Frequently, in the development of a system component, new characteristics are found which are better able to predict the operation of the element in the circuit. The use of magnetic cores in the logic and storage systems of computers is just such an example of this. The operation of magnetic amplifiers which are merely a "big brother" to the logic core is generally predicted either through the use of the static hysteresis loop or through a low frequency dynamic loop.

The performance of logic cores in computer circuits can better be predicted through the use of characteristics such as "switching time (T_s)", "squareness ratio (B_r/B_m)", and the relationship between NI (mmf) and switching flux. In technical literature, switching flux and switching time are generally given as maximum and minimum limits over a specified range of operation. The ratio B_r/B_m is essentially a constant for a particular alloy and might be interpreted as a figure of merit for the alloy.

Switching Time

Switching time is defined as the time lapse between the 10% amplitude points of the output voltage response when the core is switched from residual (B_r) to saturation (B_m) in the opposite direction. It is also sometimes designated as the time lapse between the 10% amplitude points of the output flux response. This is generally given in micro-seconds.

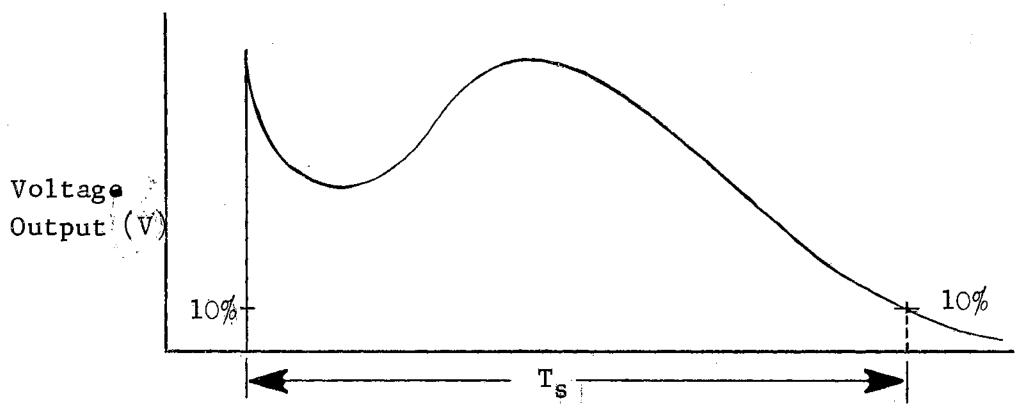


Figure 17. Switching Time as Measured Between 10% Points on the Voltage Output Curve

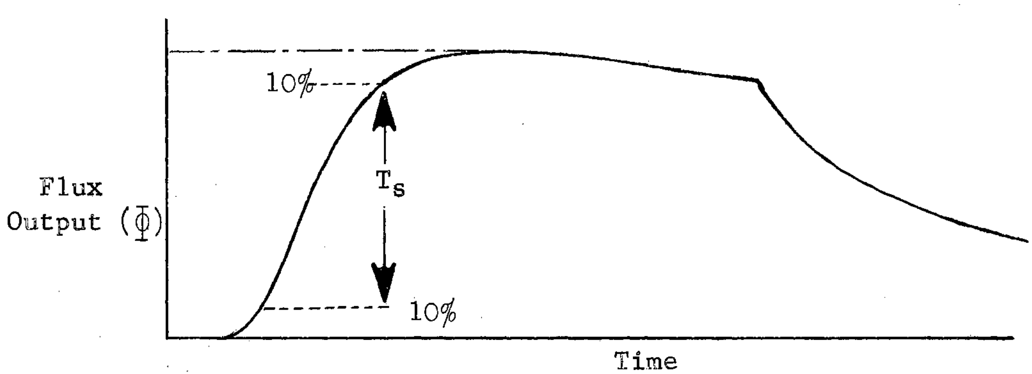


Figure 18. Switching Time as Measured Between 10% Points on the Output Flux Versus Time Curve

Squareness Ratio and Pulse Threshold

Squareness ratio (B_r/B_m), as has been mentioned previously (see Chapter II, pages 6, 7), is the ratio of residual flux to saturation flux.

The curve of NI (mmf) versus switching flux can be readily determined by subjecting the core to various drive amplitudes and plotting the flux response against drive amplitude.

From a plot of $1/T_s$ versus NI, by extrapolation, it is possible to determine a value, which might be designated H_o. This is the value of mmf below which no switching will take place and occurs at the value of $1/T_s = 0$. This value corresponds closely, but is not equal to H_c and is designated as "pulse threshold".

No switching will occur for pulses of amplitude less than H_o and it is therefore an excellent measure of the noise immunity of the core.

From graphs of the above characteristics, $1/T_s$ versus mmf, NI versus mmf, and the values of H_o and B_r/B_m, it is possible to make quantitative calculations of core performance under varying drive and load conditions much easier than through the use of the B-H curve.

CHAPTER V

AMPLIFIER CONSIDERATIONS

D-c amplifiers which are utilized in performing mathematical operations, such as summing, integrating and differentiating are generally referred to as operational amplifiers. Such a basic amplifier may be represented by the system in Figure 19.

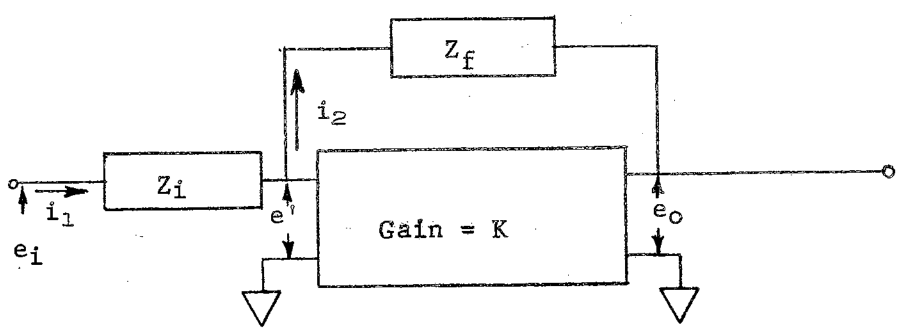


Figure 19. Amplifier Block Diagram

The gain of the amplifier in the figure may be expressed as

$$K = - e_o / e' \qquad (5.1)$$

where the minus sign indicates an odd number of phase reversals.

If the current into the first grid circuit of the amplifier is negligible, that is: $i_1 = i_2$, the current equations may be written

$$\frac{e_i - e'}{Z_i} = \frac{e' - e_o}{Z_f} \tag{5.2}$$

Since $e' = - e_o/K$,

$$\frac{e_i - e_o/K}{Z_i} = \frac{e_o/K - e_o}{Z_f} \tag{5.3}$$

which can be arranged to give

$$e_o/e_i = - Z_f/Z_i \left[1 + 1/K \left(1 + Z_f/Z_i\right) \right] \tag{5.4}$$

which for K much greater than $1 + Z_f/Z_i$, becomes

$$e_o/e_i = - Z_f/Z_i \tag{5.5}$$

This is the general equation for the operational amplifier.

If Z_f and Z_i are pure resistances, amplification or attenuation will result depending on the values chosen for the two resistances. On the other hand, a reactive element may be placed in the feedback loop and a different type of operation will result.

Suppose Z_f is a capacitor. Its Laplace transform impedance is 1/Cp. If Z_i is a resistor, the equation for the amplifier becomes

$$e_o/e_i = - 1/RCp \tag{5.6}$$

The amplifier thus becomes a linear integrator with an amplification introduced by the factor R times C in the denominator. If RC is less than 1, amplification results.

These are the general systems necessary for ordinary amplification of voltage output and integration to measure flux output of magnetic cores.

A typical circuit might be set up in the following fashion.

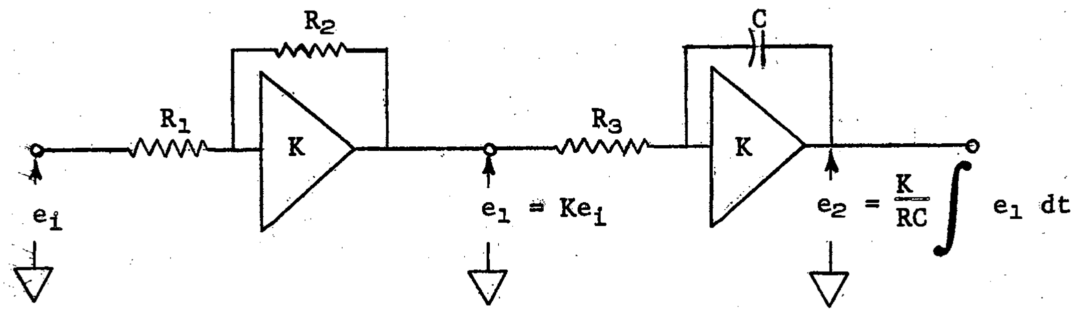


Figure 20. Operational Amplifier Circuit for Measurement of Switching Time, Voltage Response and Flux Output

The voltage from e_1 to ground represents the amplified voltage output of the core undergoing switching and as such represents a measure of switching time in addition to output voltage. The voltage from e_o to ground represents the flux output of the core amplified by the ratios R_2/R_1 and $1/R_3C$. However, R_3C can be made unity since sufficient amplification can be obtained from the first stage.

There are several problems encountered when using d-c amplifiers which must be taken into consideration. These are the problems of zero adjustment and drift, frequency response, and noise pickup.

Zero Adjustment and Drift

Frequently, an operational amplifier is designed with dual inputs, thus making it a differential amplifier. These are constructed so as to have a residual potential difference between the two input grids to the first stage. The feedback connections may be arranged such that these grids will be maintained at nearly equal potential, but in the situation where only one input is to be utilized, direct biasing of the other grid to give 0 volts DC between the output and ground is necessary. Such is the case under consideration.

In order for zeroing to be accomplished, the active input should be grounded if possible, and the bias adjusted on the second grid. A DC VTVM may be used between the output connection and ground to check the reference level. The GAP/R Model K2-W operational amplifier requires about 1.3 volts to bias the second grid and this voltage may be battery supplied or tapped off of the B^+ supply. The arrangement given in the GAP/R literature indicates biasing may be accomplished through the use of the following circuit.

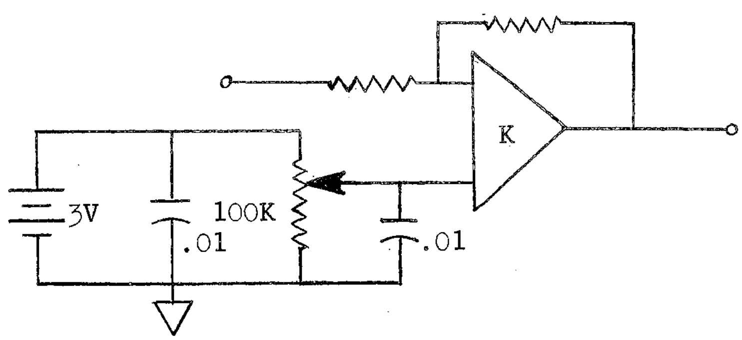


Figure 21. Direct Biasing of Operational Amplifier

It was the experience of this author that control of the grid voltage was not critical enough for the purpose for which the amplifier was intended. The amount of bias and the accuracy with which it must be adjusted are a function of the feedback arrangement around the amplifier. Since a gain of 100 was attempted, the control had to be made more critical.

This was accomplished by using a 250K potentiometer and a 5K helipot as shown in Figure 22.

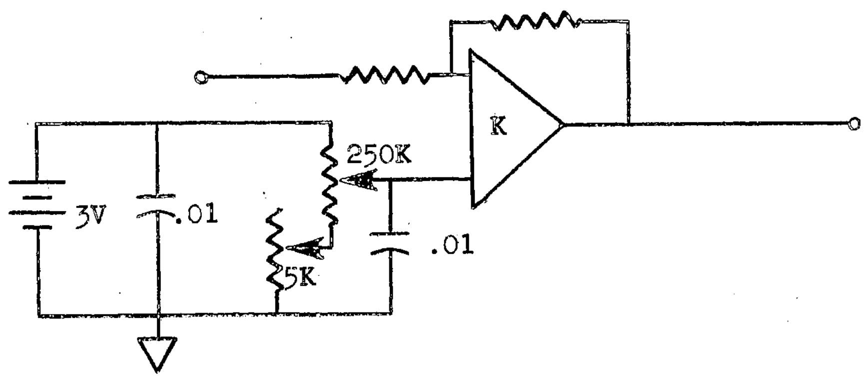


Figure 22. Modified Biasing Arrangement for Critical Control

In this manner, the 250K potentiometer had almost the full 3 volts of the battery supply across it, while the 5K helipot offered a total adjustment of less than 0.06 volts. This gave a control of 0.006 volts per turn on the helipot and made possible a very accurate adjustment of the bias on the unused grid.

The drift under the above condition was very slight. In order to increase the accuracy further, the amplifier was zeroed just prior to checking any switching operation on the core. Since an external trigger was used to supply a single switching or reset pulse to the core, there was no loss of accuracy due to amplifier drift.

Kepco 615B power supplies were used for all voltage requirements of the amplifier, thus reducing another factor which might have caused drift.

Frequency Response

The input pulse to the core for both reset and switching had a maximum rise time of 0.18 microseconds and was generally of the order of 0.05 microseconds. The top of the current pulse was flat to within 5% of the maximum amplitude of the pulse. In order to keep the decay time of the pulse from interfering with measurements of voltage and switching time, the input pulse width to the core was maintained at greater than 20 microseconds. The cores utilized were of such a size and construction as to have a switching time of less than 20 microseconds under any conditions anticipated, therefore, an input drive of this duration was deemed sufficient.

Since a d-c amplifier was used, low frequency amplification and reproduction of the input pulse presented no problem. The upper frequency limit of the system was the only necessary consideration.

The frequency response necessary to reproduce any periodic wave may be analyzed by means of a Fourier series. If a square pulse is used, the frequency spectrum is a plot of $\frac{\sin X}{X}$, where the fundamentals and harmonics appear at frequencies of 1/T, 3/T, 5/T, etc., where T is the period of the wave. Figure 23 shows a typical square wave with its associated frequency spectrum.

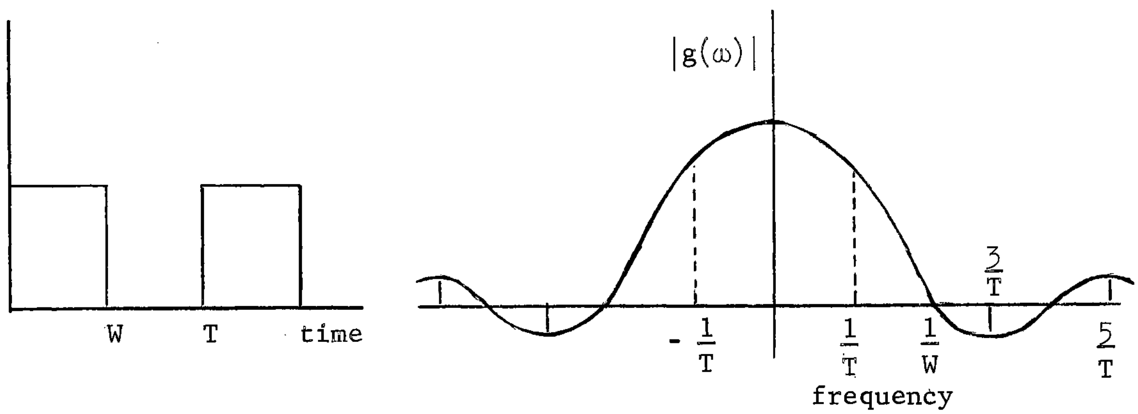


Figure 23. Square Pulse and Associated Frequency Spectrum

If the length of the pulse is kept constant, but the period is doubled to 2T, the envelope of the frequency spectrum retains the same shape but the fundamental frequency is now 1/2T. As T is made larger, the fundamental frequency, therefore, approaches zero in the limit, but the zeros of the envelope remain the same (envelope shape is preserved). Thus, the density of the frequencies present between zero and f = 1/W, the location of the first zero in the frequency spectrum, increases. W is the pulse width as shown in Figure 23.

If T becomes infinitely large, the frequency distribution becomes a continuous distribution, and an infinite number of frequencies occur between 0 and 1/W. The Fourier series must be replaced by its limit, which is the Fourier integral.

$$g(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} f(t)\, e^{j\omega t}\, dt \qquad (5.7)$$

For example, if a square pulse of current is applied at a time $t = -t_o/2$ and is stopped at $t = +t_o/2$, the Fourier integral may be evaluated as

$$g(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} I_o \, e^{-j\omega t} \, dt = \frac{I_o t_o}{2\pi} \left[\frac{\sin \frac{\omega t_o}{2}}{\frac{\omega t_o}{2}} \right] \qquad (5.8)$$

The frequency spectrum varies again as the function $\frac{\sin X}{X}$ where $X = \omega t_o/2$. The frequency spectrum obtained with the square pulse retains the characteristic shape, although the rep rate has gone to zero. There are an infinite number of frequencies between zero and 1/W and most of the energy of the pulse is concentrated in this band. Therefore, a bandwidth of 1/W is sufficient to reproduce the pulse. (A complete analysis may be found in "Transformation Calculus and Electrical Transients" by Goldman or in "Engineering Electronics" by Ryder).

For the specified pulse width of 20 microseconds, a bandwidth equal to $1/20 \times 10^{-6}$ or 50 Kcps is necessary. The GAP/R Model K2-W amplifier has a bandwidth of 100 Kcps which is more than sufficient.

This analysis was based on the width of the driving pulse applied to the core and not on the pulse output of the core. The pulse outputs of the cores examined, undergoing a switching operation from remanence to saturation in the opposite direction, were of the order of 2 to 10 microseconds. This places a bandwidth requirement of $f = 1/2 \times 10^{-6}$ or 500 Kcps on the amplifier. The GAP/R bandwidth is insufficient for this and some distortion resulted. This is not the only cause of distortion, however, as shunt capacitance to ground in any part of the circuitry may be another prominent factor, especially in high impedance circuits.

Shunt Capacitance

The effect of shunt capacitance on a square pulse, or any pulse for that matter, would be to delay the rise and fall times and thereby cause a stretching or increase in pulse width.

In coupling the core as closely as possible to the amplifier and in arranging circuit components, some shunt capacitance would almost invariably be present. The effect of the distortion caused by insufficient bandwidth and possibly shunt capacitance was noted when the output of the core was directly coupled to the scope amplifier which has a bandwidth of 30 Mcps. The apparent switching time was reduced by a factor of five. Therefore, the combined result of insufficient bandwidth of a single GAP/R amplifier stage and the possibility of shunt capacitance to ground because of improper location of circuit components and leads cause an error of a factor of five in the evaluation of core switching time.

Noise

Noise pickup may be encountered in any of the leads or carbon resistors utilized in the circuit. Since any noise would be amplified along with the signal from the point of its insertion in the circuit, the core jig was designed and located so as to reduce the noise introduced to the first stage. To accomplish this, the leads to the amplifier were made as short as possible by locating the core jig on the amplifier chassis. Noise introduced at a later point in the circuit would have less effect and could be neglected in the interpretation of the output.

The core jig consisted of a square section of plexiglass with terminals at each of the four corners. With the input and sense windings crossing at right angles in the center of the core, no observable transmission effect was noted between these windings when the core was removed from the circuit. All other leads were coaxial cable with the outside sheathing grounded. Noise pickup at the input to the amplifier was effectively reduced in this manner.

CHAPTER VI

CORE TESTING AND EVALUATION OF EXPERIMENTAL RESULTS

To demonstrate that characteristic curves which would relate core performance to various load and drive configurations are obtainable, the circuit shown in Figure 24 was constructed. The input drive to the core consisted of a single positive or negative pulse generated by a General Radio Co., Type 1217A Unit Pulser and amplified by a Type 1219A Pulse Amplifier (also manufactured by General Radio). These two units in tandem are capable of generating square pulses of current with a maximum rise time of .18 microseconds with the top of the pulse flat to within 5% of the maximum pulse amplitude.

A Tektronix oscilloscope, Type 545, with a 53/54L plug-in vertical preamplifier was used to display the core characteristics. When this scope is adjusted for a single trace upon the application of an external trigger, it also makes available for use a step voltage (which is synchronized with the sweep) of approximately 30 volts which lasts for the duration of the trace.

To achieve some degree of synchronization between the horizontal trace on the oscilloscope and the output pulse from the core, a differentiating circuit was placed across the step voltage from the scope and the output (taken across the resistor) was used to trigger the Unit Pulser. In this manner, a single drive pulse was available, which was delayed approximately 0.5 microseconds from the start of the sweep on the scope.

The output of the Type 1219A pulse amplifier depends on the nominal input impedance to the circuit. Therefore, some means was necessary to calibrate the unit to determine the exact drive available to the core. This was achieved by means of a decade switch with carbon resistors calibrated to 1% accuracy which was placed in series with the core drive. The voltage output across the resistor for a particular setting on the pulse amplifier was measured on the scope and the current pulse was thereby calibrated. This calibration was accomplished on several different days at various times and an average value of the pulse for the setting on the decade switch and pulse amplifier was noted. To further increase the accuracy of the measurements, the pulse amplitude was checked just prior to taking any pictures of the core characteristics.

"Core jigging" consisted of a single turn drive and a single turn sense winding which crossed at right angles inside the core bobbin. A single turn was used to simplify changing cores as much as possible and to simplify the mathematics involved when loading was considered.

A complete diagram of the circuit is shown in Figure 24.

Magnetics, Inc., of Butler, Pennsylvania, furnished the bobbin cores for this study. The cores supplied were of various diameters, ranging from 0.050 to 0.125 ID, with varying tape thicknesses of 1/8 to 1 mil, but all were rated at 20 maxwells output flux.

With this set of cores, it was possible to compare switching times and voltage outputs under load and drive conditions against the factors of tape thickness and effective diameter of the cores. In addition to

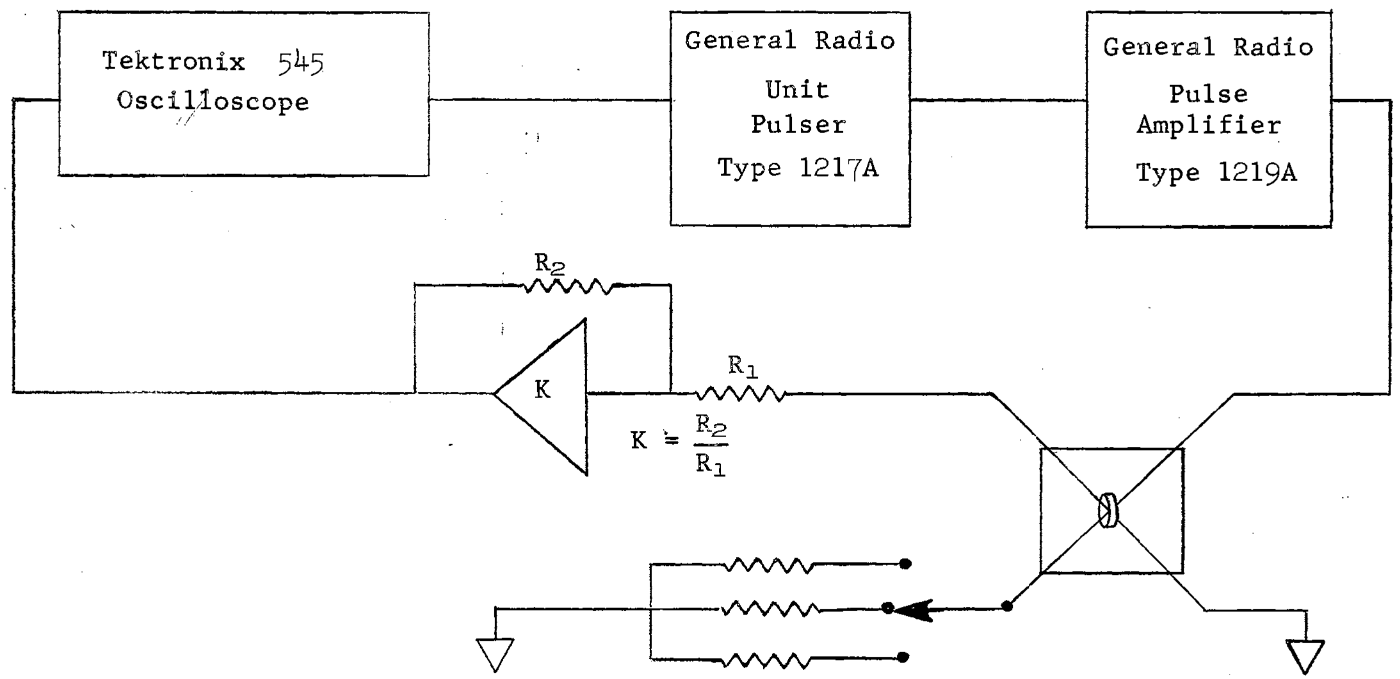


Figure 24. Test Circuit Diagram

furnishing the cores for the study, Magnetics evaluated the cores under a drive condition of 0.5 oersteds (open circuit secondary), which gave an approximate response time which might be anticipated.

It was not anticipated, however, that the frequency response of the GAP/R K2-W amplifier would be insufficient for satisfactory testing. This became evident when response times of the order of 5 times as great as those which had been expected were encountered. This may have been due to insufficient bandwidth of the amplifier or partly to shunt capacitance as explained in the previous chapter. The core output was then fed directly into the 53/54L preamplifier on the 545 scope. With the vertical scale set to the maximum gain, this gave sufficient amplification to the output pulse so that it could be observed and photographed directly from the scope.

Output Voltage Under Load

The voltage output of a core undergoing switching is a non-linear function of time as demonstrated in Chapter III. If the sense winding is closed through a resistor of small size, sufficient current will be caused to flow in the winding which will set up a field in opposition to the driving field. Since this secondary circuit will absorb power which should go to the core, the voltage output of the core will necessarily decrease, and in conjunction with this, an increase in switching time will occur.

Chen and Papoulis[3] have shown that loading effects on "thick" cores can be predicted with a fair degree of accuracy. However, this author knows of no model which will predict the effects of loading on cores with tape wraps of 1/2 mil or less. This results because of the inability to satisfactorily devise a model which will predict the voltage output of a thin core under a non-prepulse condition. Even the analysis of loading on "thick" cores becomes rather unwieldy because the secondary current is not a linear function of time as it is in the drive circuit. Experimental observations of thin cores can be made, however, and characteristic curves presented which may lead to knowledge which is not otherwise available at this time.

To analyze the response characteristics of a core under loading, measurements of voltage and switching time for various driving fields were made on a core with 7 1/2 wraps of 1/2 mil 4-79 Mo-Permalloy. The graph of $1/t_s$ versus driving field is shown in Figure 25.

The value of switching time for the highest drive condition was obtained by increasing drive slowly while continuously resetting and switching the core until no difference was noted between the time when the flux in the core was changed from $- B_r$ to B_m and when it was changed from $+ B_r$ to B_m. At this value of drive, no valid measurement of switching time could be ascertained. The driving field was then decreased slightly and the value of switching time read at this point.

These curves are representative of the characteristic curves of switching time and output voltage versus driving field which might be obtained for a logic core. It must be remembered that these curves are drawn for a single turn sense winding. Since the current in the secondary is directly proportional to the number of turns, the value of resistance in this winding must be increased in the same proportion to the number of turns to eliminate the effects of core loading.

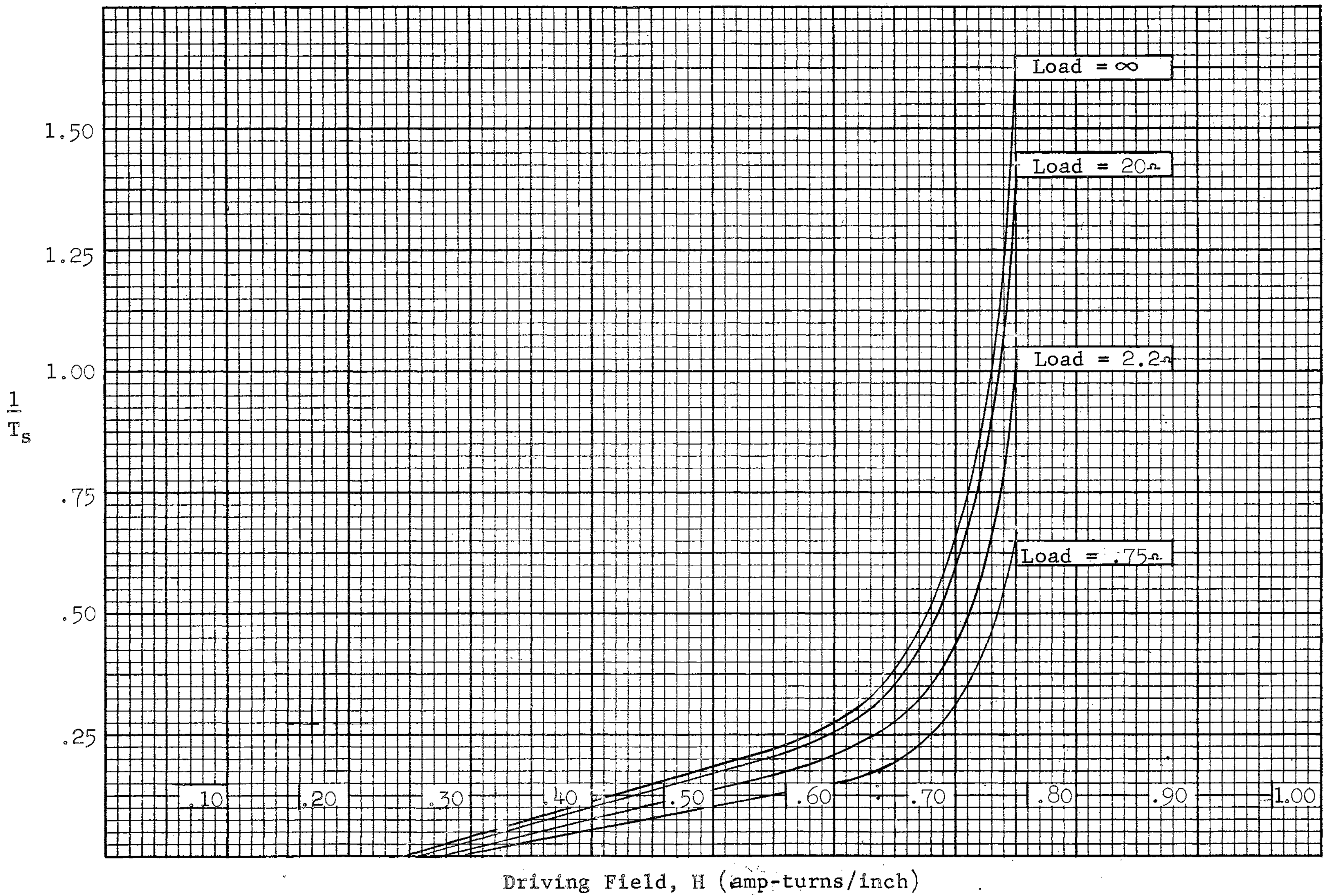


Figure 25. Switching Time Under Load Versus Driving Field

If the linear portion of the graph for an open circuit sense winding is expanded as in Figure 26, pulse threshold or H_o may be determined for this particular core.

Also shown is the relationship of output voltage to driving field in Figure 27, page 44.

Voltage and Switching Time in Relation to Diameter

In an attempt to analyze variations in these characteristics which might have been caused by core diameter, a set of plates was made consisting of four traces each for bobbins of 0.050, 0.086, 0.110, and 0.125 ID under various load conditions. These cores consisted of 29 wraps of 1/8 mil 4-79 Mo-Permalloy with a tape width of 1/16 inch. A group of cores consisting of from 3 to 6 units of each type were tested and the traces were made from a core representative of the group. All cores tested in any one group were very similar in response. Therefore, it is felt that the information presented will be fairly accurate.

The cores were reset by a large negative pulse prior to switching under a controlled positive pulse of 0.637 ampere-turns/inch for the purpose of recording the data.

The observed response is shown in Figures 28, 29, 30 and 31 on the following pages.

One observation in this series of tests should be mentioned at this time: the height of the first peak (presumably caused by nucleation of domains) increased rapidly with decreasing diameter. In the 0.050 ID core, the height of the first peak was measured to be 0.18 volts while the main voltage pulse was only 0.06 volts. As the diameter increased the difference was considerably less. For instance, in the core with

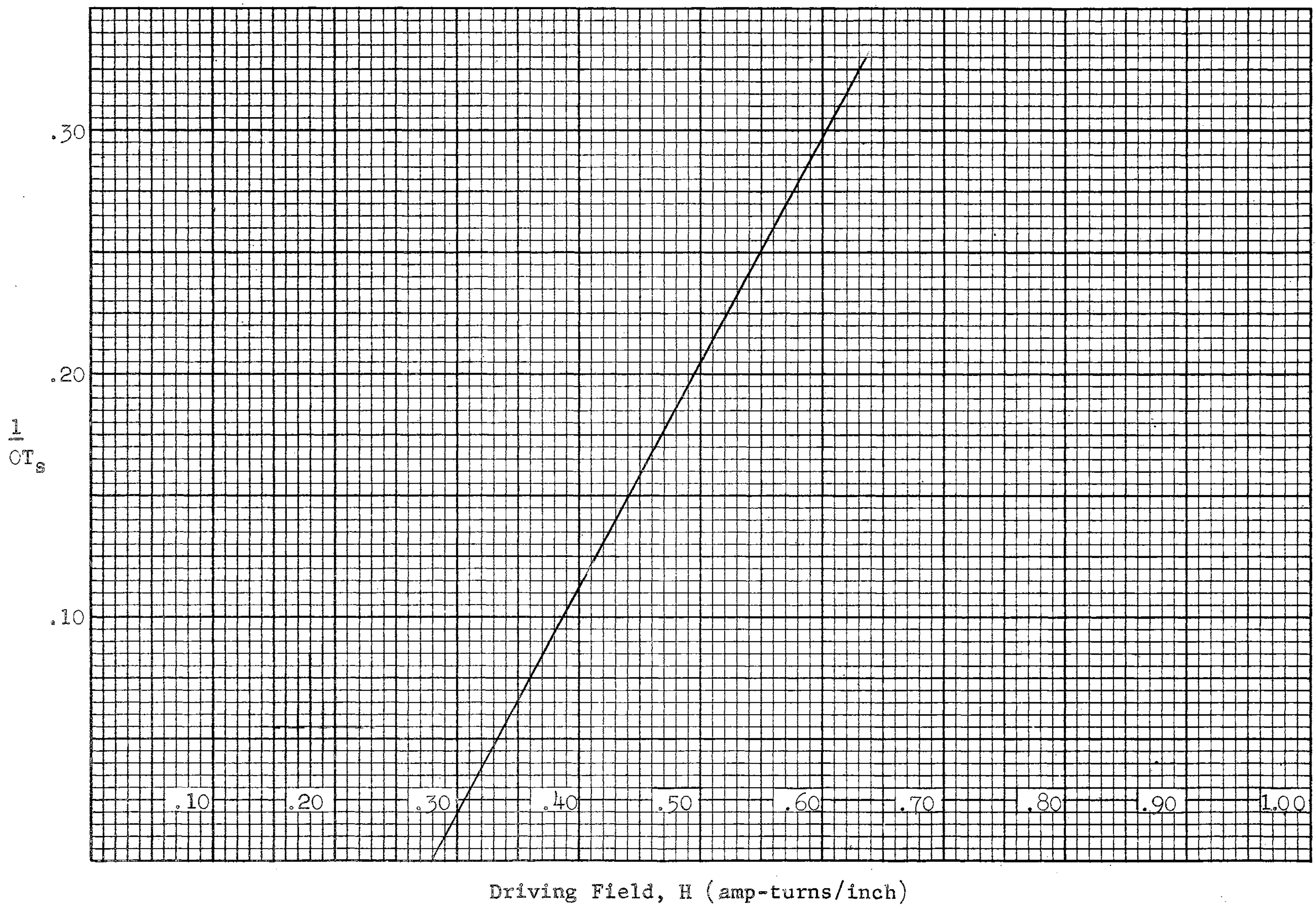


Figure 26. Open Circuit Switching Time Versus Driving Field

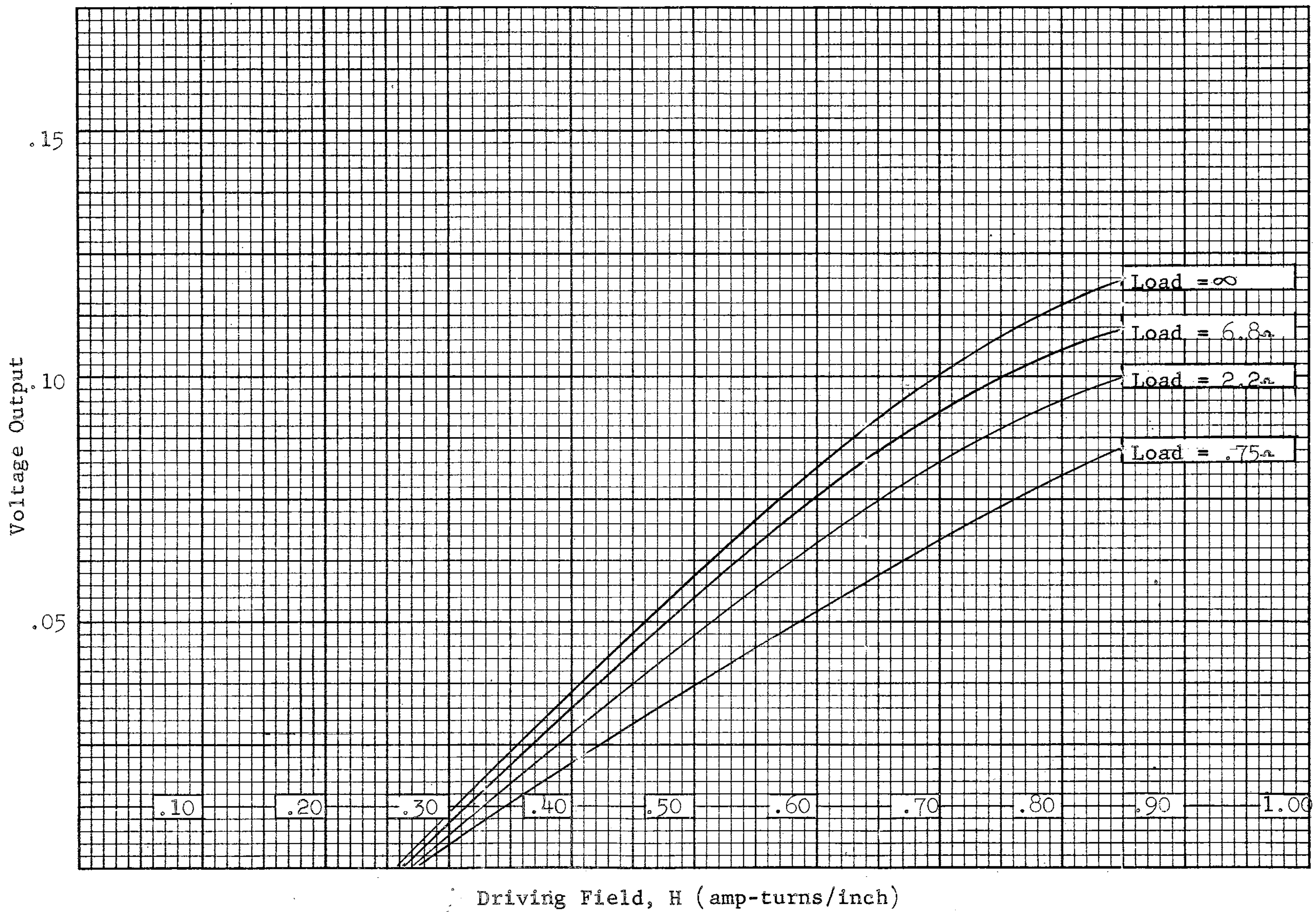


Figure 27. Voltage Output Under Load Versus Driving Field

Loading = 0.75 ohms

Loading = 2.2 ohms

Loading = 6.8 ohms

Open Circuit Secondary

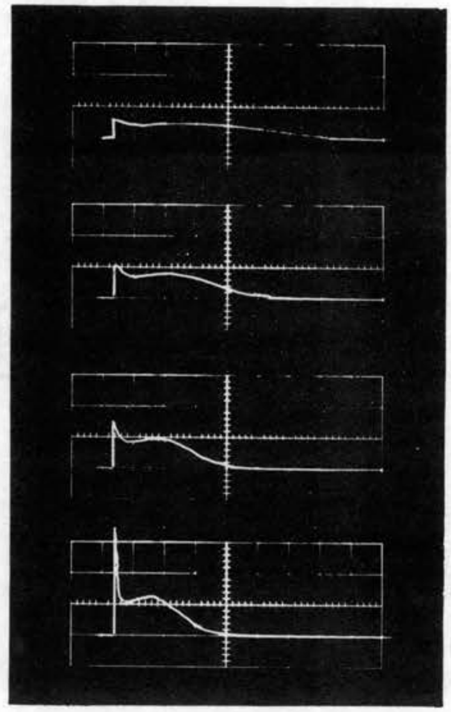


Fig. 28. Voltage Output of A Loaded Core. Core Dia. 0.050 in. ID, 0.0286 in. Effective Radius

Core: 29 wraps of 1/8 mil 4-79 Mo-Permalloy, 1/16 inches wide. Driving field: 0.637 amp-turns/inch. Time scale: 1 microsecond/division. Voltage scale: 0.05 volts/division.

In calculating the driving field for this core, the assumption was made that the effective radius was much greater than the height or width of the tape. Since the effective radius departs from this assumption to a greater extent with this core (this was the smallest core tested) than any other, one would expect some inaccuracy in the value of the driving field. This might account for the fact that the voltage output under all load conditions was the least of any of the cores tested.

Of particular note is the high value of the primary peak. This was only present in the 1/8 mil wrapped cores with 0.050 ID. All other cores experienced similar first peaks but not of such extreme height.

This core also showed the largest variation in switching time (open circuit secondary, t_s = 3.5 microseconds; 0.75 ohms load, t_s = 6.5 microseconds).

Loading = 0.75 ohms

Loading = 2.2 ohms

Loading = 6.8 ohms

Open Circuit Secondary

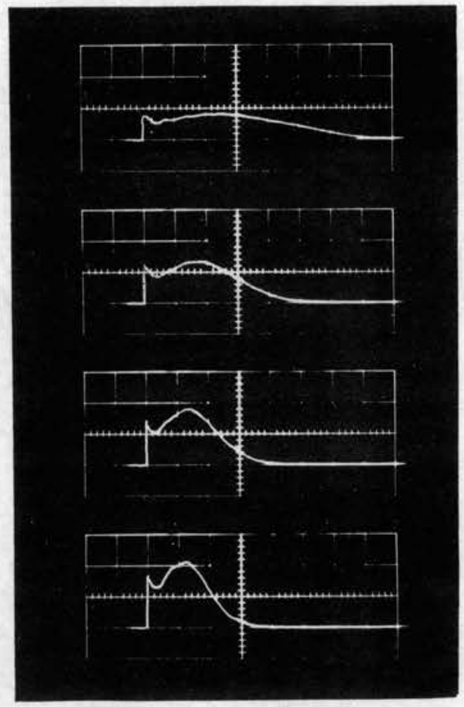


Fig. 29. Voltage Output of A Loaded Core. Core Dia. 0.086 in. ID, 0.0448 in. Effective Radius

Core: 29 wraps of 1/8 mil 4-79 Mo-Permalloy, 1/16 inches wide.

Driving field: 0.637 amp-turns/inch. Time scale: 1 microsecond/division.

Voltage Scale: 0.05 volts/division.

Loading = 0.75 ohms

Loading = 2.2 ohms

Loading = 6.8 ohms

Open Circuit Secondary

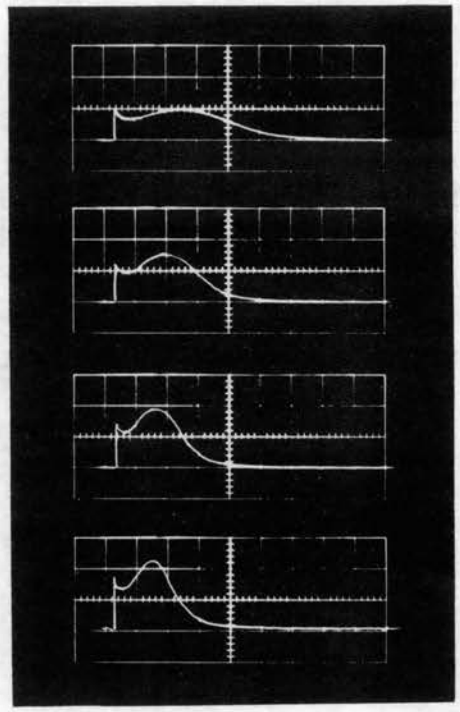


Fig. 30. Voltage Output of A Loaded Core. Core Dia. 0.110 in. ID, 0.0568 in. Effective Radius.

Core: 29 wraps of 1/8 mil 4-79 Mo-Permalloy, 1/16 inches wide.

Driving field: 0.637 amp-turns/inch. Time scale: 1 microsecond/division.

Voltage scale: 0.05 volts/division.

Loading = 0.75 ohms

Loading = 2.2 ohms

Loading = 6.8 ohms

Open Circuit Secondary

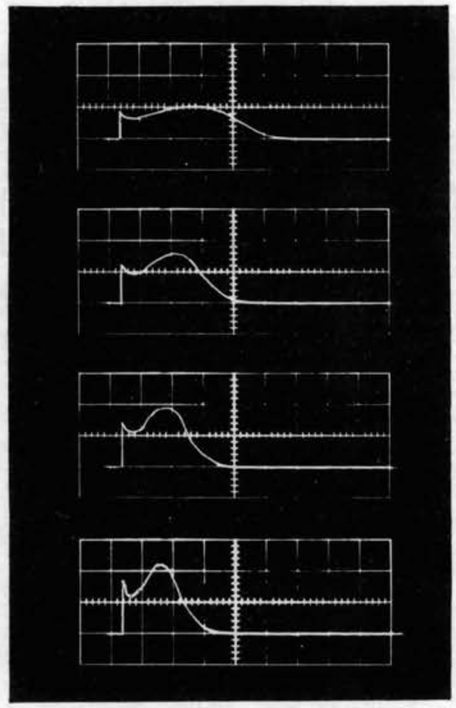


Fig. 31. Voltage Output of A Loaded Core. Core Dia. 0.125 in. ID, 0.0643 in. Effective Radius.

Core: 29 wraps of 1/8 mil 4-79 Mo-Permalloy, 1/16 inches wide.

Driving field: 0.637 amp-turns/inch. Time scale: 1 microsecond/division.

Voltage scale: 0.05 volts/division.

0.125 in. ID, the first peak was 0.08 volts compared with the main peak of 0.11. In all cases, the main voltage pulse was higher than the first peak except in the 0.050 ID core. Here, the first peak was considerably higher under all load conditions.

Response With Varying Tape Thickness

To determine if tape thickness had any marked effects on core response, a group of cores was chosen which had the same inside diameter. Any diameter could have been chosen. However, the 0.050 ID was eliminated since its characteristics varied from the remainder of the cores in previous testing. Cores with an ID of 0.086 were chosen and a set of photographic plates were made.

The attempt was made to hold the driving field constant at 0.637 amp-turns/inch, but this failed when the core consisting of 4 1/2 wraps of 1 mil 4-79 Mo-Permalloy would not switch under this low a value of driving field. To get a trace which at least resembled in size the traces of the other cores with thinner wraps, a drive of 1.556 amp-turns/inch was used. This prohibits to some degree, at least, any attempt to draw a correlation between these cores. However, this value of driving field was too great for the rest of the cores in the group, so both drives were used.

The traces for these cores are shown in Figures 32, 33, 34 and 35.

Loading = 0.75 ohms

Loading = 2.2 ohms

Loading = 6.8 ohms

Open Circuit Secondary

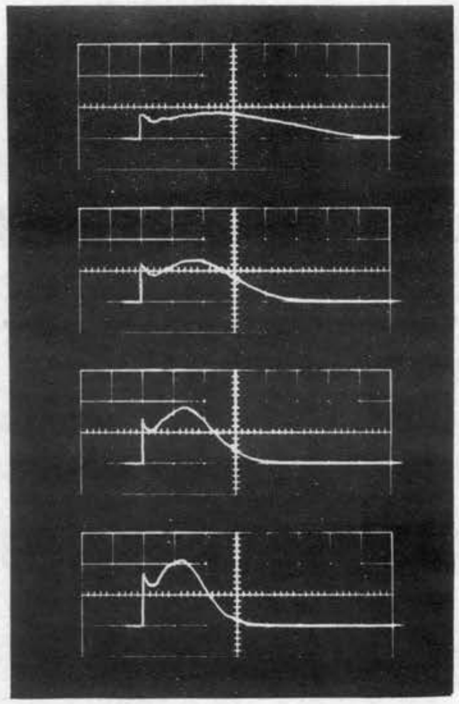


Fig. 32. Voltage Output of A Loaded Core. Core Dia. 0.086 in. ID, 0.0448 in. Effective Radius.

Core: 29 wraps of 1/8 mil 4-79 Mo-Permalloy, 1/16 inches wide.

Driving field: 0.637 amp-turns/inch. Time scale: 1 microsecond/division.

Voltage Scale: 0.05 volts/division.

Loading = 0.75 ohms

Loading = 2.2 ohms

Loading = 6.8 ohms

Open Circuit Secondary

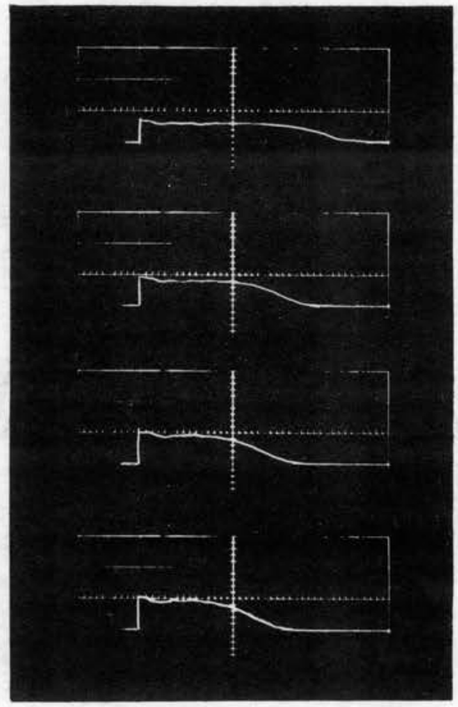


Fig. 33. Voltage Output of A Loaded Core. Core Dia. 0.086 in. ID, 0.0448 in. Effective Radius.

Core: 14 wraps of 1/4 mil 4-79 Mo-Permalloy, 1/16 inches wide.

Driving Field: 0.637 amp-turns/inch. Time scale: 1 microsecond/division.

Voltage scale: 0.05 volts/division.

Loading = 0.75 ohms

Loading = 2.2 ohms

Loading = 6.8 ohms

Open Circuit Secondary

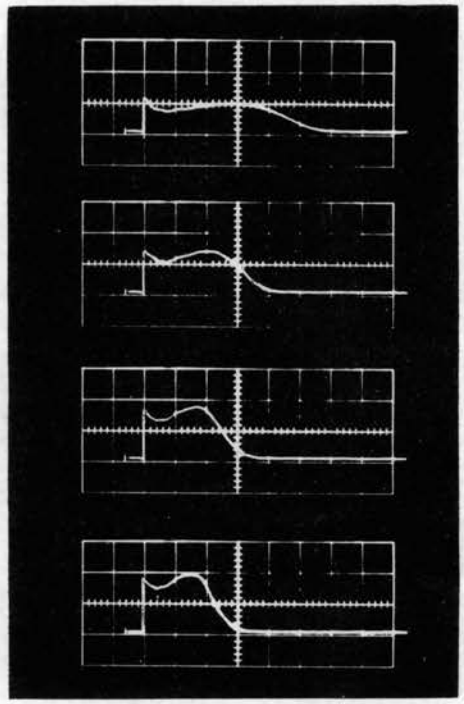


Fig. 34. Voltage Output of A Loaded Core. Core Dia. 0.086 in. ID, 0.0448 in. Effective Radius.

Core: 7 1/2 wraps of 1/2 mil 4-79 Mo-Permalloy, 1/16 inches wide.

Driving field: 0.637 amp-turns/inch. Time scale: 1 microsecond/division.

Voltage scale: 0.05 volts/division.

Loading = 0.75 ohms

Loading = 2.2 ohms

Loading = 6.8 ohms

Open Circuit Secondary

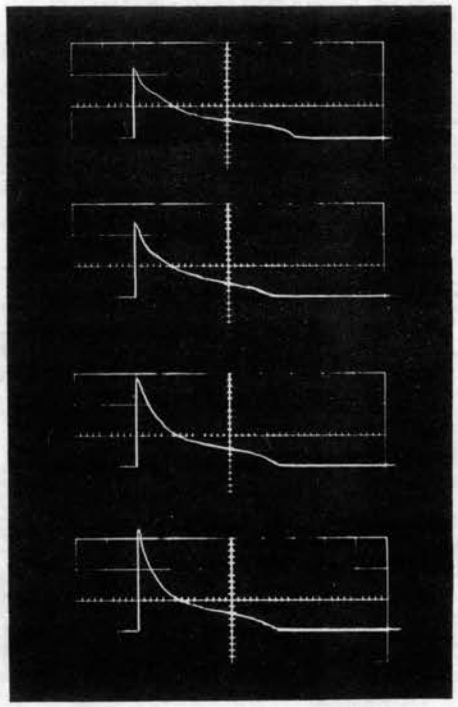


Fig. 35. Voltage Output of A Loaded Core. Core Dia. 0.086 in. ID, 0.0448 in. Effective Radius

Core: 4 1/2 wraps of 1 mil 4-79 Mo-Permalloy, 1/16 inches wide.

Driving field: 1.556 amp-turns/inch. Time scale: 1 microsecond/division.

Voltage Scale: 0.05 volts/division.

CHAPTER VII

SUMMARY

The purpose of this study was to determine the feasibility of using d-c amplifiers to measure core characteristics and to evaluate, if possible, some of the effects of loading against thickness of tape wrap and core diameter.

This was accomplished by attempting to utilize the GAP/R K2-W operational amplifier in recommended circuits. The problem of stability was solved by making the bias control extremely critical and zeroing the amplifier before each test. The frequency response necessary for single pulse drive and reset was evaluated and for cores of the diameter tested, the necessary response was of the order of 500 Kcps. The core response is in the order of 2 to 3 microseconds which places a large bandwidth requirement on the amplifier. The GAP/R K2-W used as a single stage of amplification is deemed unsuitable for this purpose due to its 100 Kcps bandwidth. This does not rule out all use of d-c amplifiers, however. The GAP/R K2-X, manufactured by Geo. A. Philbrick, Inc., has a bandwidth of 250 Kcps and it is entirely within reason that a d-c amplifier of sufficient bandwidth can be designed.

Cores of various diameters ranging from 0.050 to 0.125 inches inside diameter with tape thickness of 1/8 to 1 mil were tested and the observations recorded through use of the 53/54L Preamplifier and the Tektronix 545 oscilloscope. These results are presented in a set of

characteristic curves for a core of 0.086 inches ID with 7 1/2 wraps of 1/2 mil 4-79 Mo-Permalloy.

A set of photographs of core response for a constant drive of 0.637 amp-turns/inch was made on cores varying from 0.050 to 0.125 inches ID. These cores all consisted of 29 wraps of 1/8 mil 4-79 Mo-Permalloy. The only variable then was core diameter.

Diameter was found to have very little effect with respect to voltage response and switching time. The core of 0.050 showed some deviation but this could easily be due to the error in the assumption that core radius (for the purpose of computing driving field) is much greater than tape thickness or width.

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VITA

Henry F. Ebertshauser, Jr.

Candidate for the Degree of

Master of Science

Thesis: SWITCHING CHARACTERISTICS OF LOGIC CORES

Major Field: Electrical Engineering

Biographical:

Personal Data: Born in Duquesne, Pennsylvania, November 17, 1929, the son of Henry F., Sr., and Clare Ebertshauser.

Education: Attended grade school in Duquesne, Pennsylvania and graduated from Duquesne High School in May of 1947. Attended Carnegie Institute of Technology from 1947 to 1949. Attended Baylor University night school at various times from 1952 to 1956. Received the Bachelor of Science Degree at Oklahoma State University in January 1960. Completed requirements for the Master of Science Degree in May 1960.

Professional Experience: Entered the United States Air Force in 1951 and was commissioned in 1952. Present rank is that of Captain. All military service has been in combat and operations or in instructing radar operation and fundamentals. Also served as Armament Systems Officer in the Arctic with radar equipped fighter interceptor squadron.

Professional Organizations: Eta Kappa Nu, IRE.