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THE EFFECT OF CORE MATERIALS ON MAGNETIC AMPLIFIER CIRCUITS

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INTRODUCTION

A series of new type, fast-response, magnetic amplifier circuits were recently developed at the Naval Research Laboratory as a direct result of a new theoretical approach to the magnetic amplifier problem (1,2). This type of amplifier was used to demonstrate the effects of core materials.

The operation of the new circuits depends upon the ability of the magnetic core material to remain at any given flux-density level, up to saturation, in the absence of an applied mmf. Many core materials, which are generally considered superior for use in conventional magnetic circuits, do have the property of remaining at or near any existing flux level when applied mmf's are removed. However, one core material which is considered superior for use in magnetic amplifier circuits will not remain at an arbitrarily chosen flux level (saturation and below) in absence of an applied mmf. For this reason, this and similar core materials are theoretically inappropriate for use in the new type magnetic amplifier circuits and are found to exhibit relatively poorer performance.

This paper demonstrates experimentally the magnetic characteristics which commercially produced core materials exhibit during their use in magnetic amplifiers. In addition, the effect and relative importance of rectifier leakage upon the operation of the new type circuits is observed when core materials having different loop widths are used and compared.

EXPERIMENTAL DETAILS

Core Materials

The core material of core "A" is a 50% nickel-iron alloy which has been grain oriented, annealed in pure dry hydrogen, and has been given drastic cold reduction.

The core materials of core "B" and "C" are 4% silicon steels which have been grain oriented. Each of the two materials was produced by a different manufacturer.

The material of core "D" is 4% molybdenum, 79% nickel, and 17% iron. This material is not grain oriented but has been heat treated to obtain high permeability.

Choice of Circuit

The single-core amplifier circuit shown schematically in Figure 1 was chosen for these experiments because of its simplicity and because it is the basic circuit of the series of new

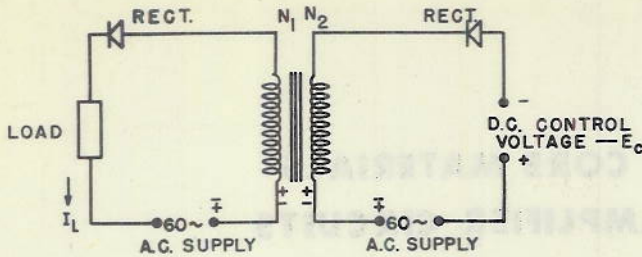


Figure 1 - Basic single-core magnetic amplifier circuit

size of wire, the rectifier current ratings and load resistance were kept the same. A direct comparison of the four core materials is made for the given set of circuit parameters tabulated in Appendix A. The cores are toroidal in shape and of wound tape construction for which the tape width is one-half inch for cores "A," "B," and "D," and five-eighths inch for core "C."

The control-voltage waveform is that of a continuous series of half sinusoids. Since the control voltage is obtained by full-wave rectification of the 60-cycle ac supply through a variable voltage transformer, the control-voltage waveform is made the same as that of the ac supply to the control circuit and 180° out of phase with it during the reset half cycle.

HYSTERESIS-LOOP CHARACTERISTICS

The hysteresis loops for the various core materials (Figures 3 and 4) were obtained with the circuit of Figure 2 in which the ratio of R_1/R_2 is the same as the turns ratio of the power winding to the control winding, N_1/N_2 . Thus, the signal to the horizontal amplifier of the cathode-ray oscilloscope is proportional to the total magnetizing force (the integrator draws negligible current from the search coil). The major hysteresis loops of the four core materials (Figure 3) were obtained by short-circuiting the dc control-voltage terminals. In each figure of Figure 4 is shown a set of three superimposed minor loops, corresponding to control-voltage settings of zero, an intermediate value, and a value just below the knee of the transfer characteristic for each material. At a larger control-voltage setting (fifty volts), the minor loops disappear when using core "B"; those for cores "A" and "C" get quite small but do not disappear; while those for core "D" exhibit practically no change in shape as control voltage is varied. It may be noted that in all four cases, a control-voltage setting of fifty volts is practically equivalent to open-circuiting the control circuit, since with this setting the net voltage in the control circuit is always blocked by the control-circuit rectifier (2).

A pronounced bulging and sharpening of the second-quadrant knee is shown for the minor loops of cores "A," "B," and "C," while this effect is negligible for core "D." When this phenomenon was noted, special precautions were applied to make sure that the measuring techniques did not affect the result. It was found that the major part of this bulging is a characteristic of the core when operating in the magnetic amplifier circuit used in these experiments. As can be seen in Figure 4, the cores exhibit dynamic characteristics quite different from those which are obtained with small constant values of dc-bias mmf and reduced ac applied voltage (3). This is probably due to the fact that the peak values of mmf are larger (by a factor of more than 1000) in actual amplifier operation.

CORRELATION OF LOOP CHARACTERISTICS TO TRANSFER CHARACTERISTICS

A scrutiny of the measured transfer characteristics (Figure 5) reveals discrepancies from the characteristics of the predicted ideal amplifier of the theory (1). There are three

amplifier circuits, some of which are more complex. The circuit includes a two-winding transformer, a pair of rectifiers, a load, a control-voltage source, and a 60-cycle ac supply.

Test Conditions

In the case of the tests on the core materials reported herein, the magnetic path length, the number of turns, the

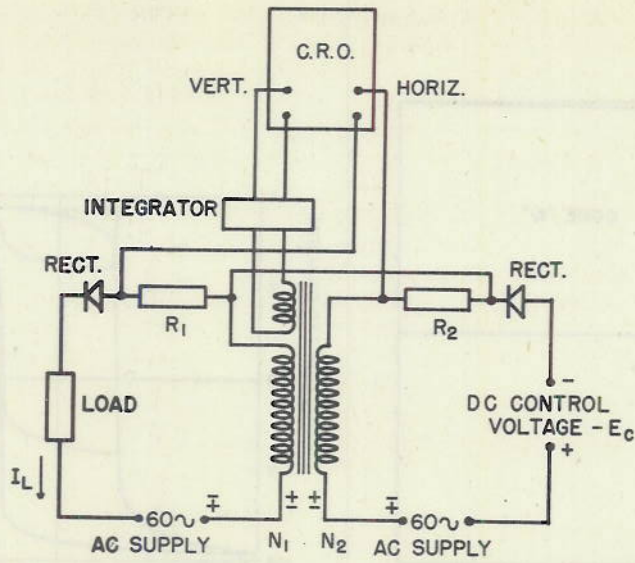


Figure 2 - Test circuit used for obtaining hysteresis loops of the four core materials

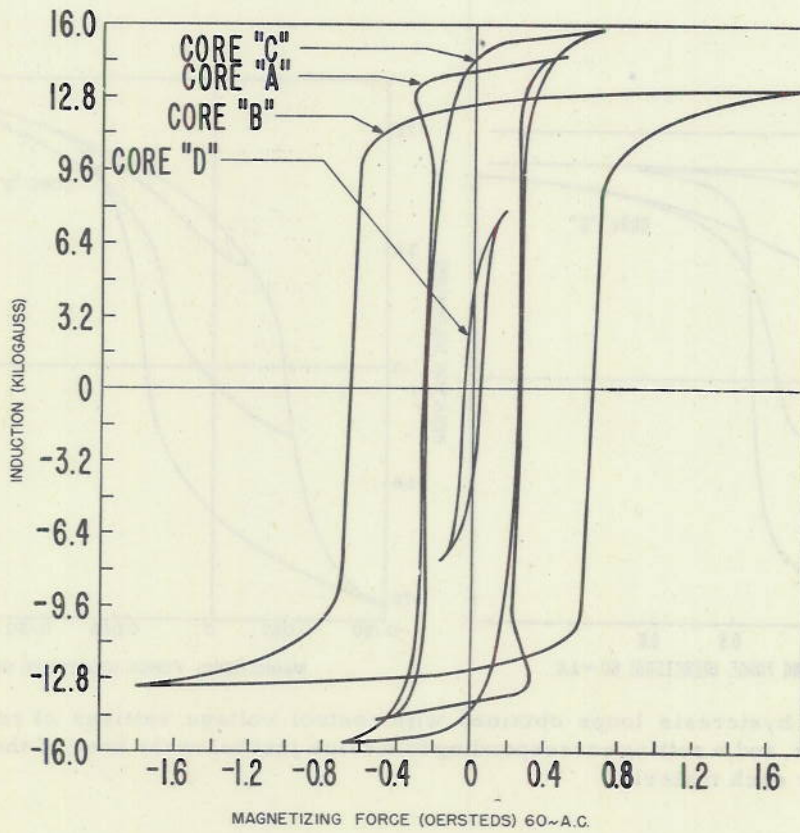


Figure 3 - Major hysteresis loops obtained by short-circuiting the dc control-voltage terminals

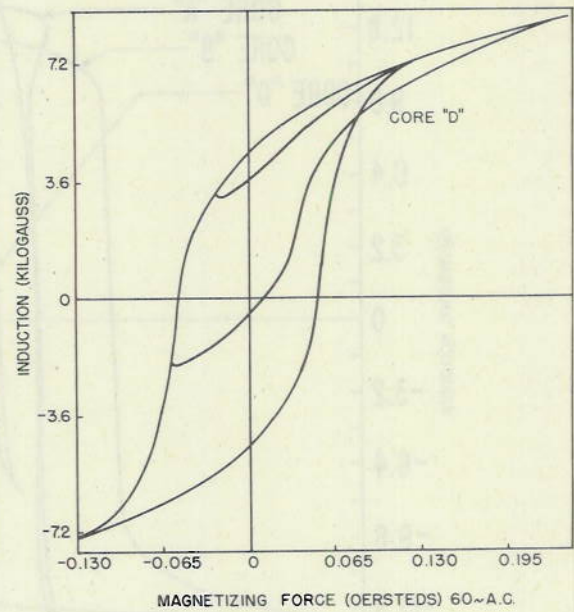
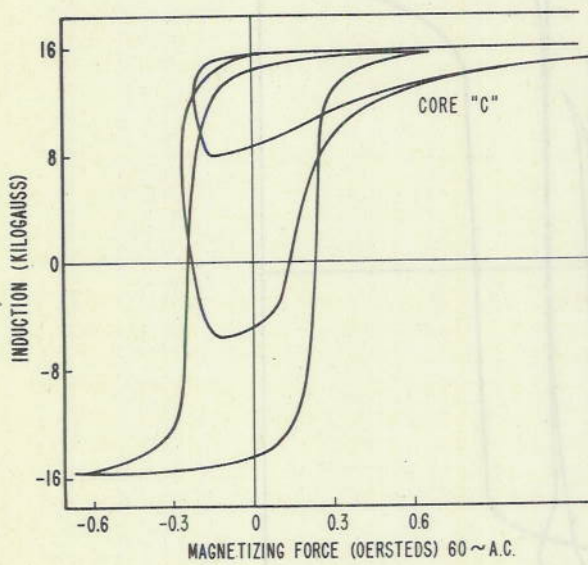
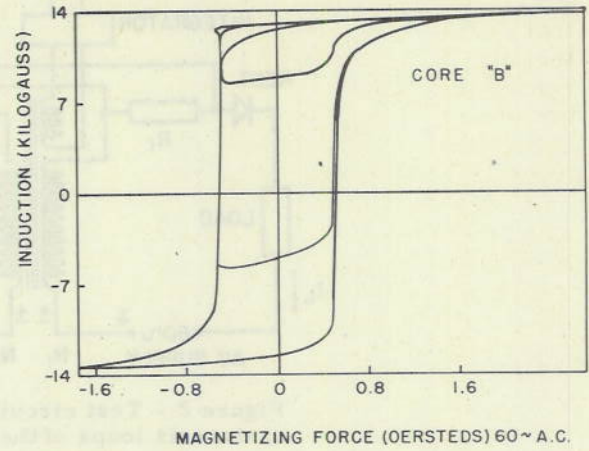
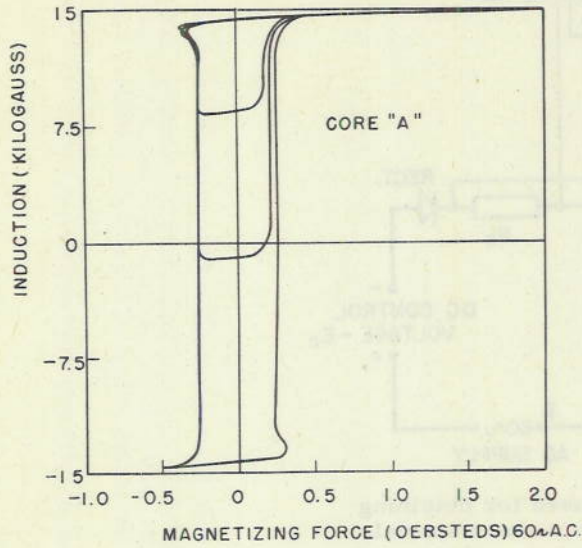


Figure 4 - Minor hysteresis loops obtained with control voltage settings of zero, some intermediate value, and a setting corresponding to a value just below the knee of the transfer characteristic for each material

major reasons for the experimental transfer characteristic to deviate from the theoretical transfer characteristic. First, matching of ac supply voltages in the power and control circuits is quite critical. A slight error in the ratio of ac supply voltage of the power circuit to that of the control circuit will shift the transfer characteristic. If the ac supply voltage in the control circuit is too large, the shift will be to the left and if the ac supply voltage is not large enough, the shift will be to the right. Second, operation of the new circuits depends upon the maintenance of flux at saturation level without need of an applied mmf. If this condition is not met, the amplifier will reset without regard to the control voltage (1). This uncontrolled reset will prevent the amplifier from having complete half-cycle conduction and consequently the power handling capacity will be reduced. Third, but not least, is rectifier leakage. Leakage through the load-circuit rectifier will produce an mmf which aids the mmf derived from the control-circuit current. If the rectifier leakage (times the turns ratio) tends to exceed the control-circuit current requirements for core magnetization, reset will be accomplished without regard to the control voltage. This also results in a reduction of power handling capacity and loss of linearity of the transfer characteristic. With the use of improved rectifiers, the effect of leakage can be minimized and core materials with narrower loops can be used with a consequent higher gain factor and without loss of power handling capacity or transfer characteristic linearity.

An ideal transfer characteristic is assumed to be one which exhibits a linear relationship of average load current vs. average control voltage with the load current ranging from zero to some maximum value called saturation. It is assumed that the control voltage is derived from a voltage similar in wave shape and of the same phase as the ac supply voltage to the control circuit (2). Ideally, independence of supply frequency and voltage, rectifier leakage, and core hysteresis-loop width is implied (1). This is considerably more independence than can generally be obtained in conventional circuits where control current is used as the independent variable.

The transfer characteristic for core "B" most nearly approaches the ideal for the following reasons: First, the hysteresis-loop width is large. This results in larger magnetizing current requirements and consequently greater rectifier leakage can be tolerated without loss of linearity of the transfer characteristic. Second, the hysteresis loop is nearly rectangular and thereby high residual induction is obtained.

The transfer characteristic for core "A," which is next best with the given conditions imposed, exhibits a rounding off at the knee. Since, by inspection of the minor loops for core "A" in Figure 4, it can be seen that there is no appreciable loss of induction at remanence, it is deduced that the load-circuit rectifier leakage is greater than half the width of the hysteresis loop. This deduction is born out by the oscillographic records

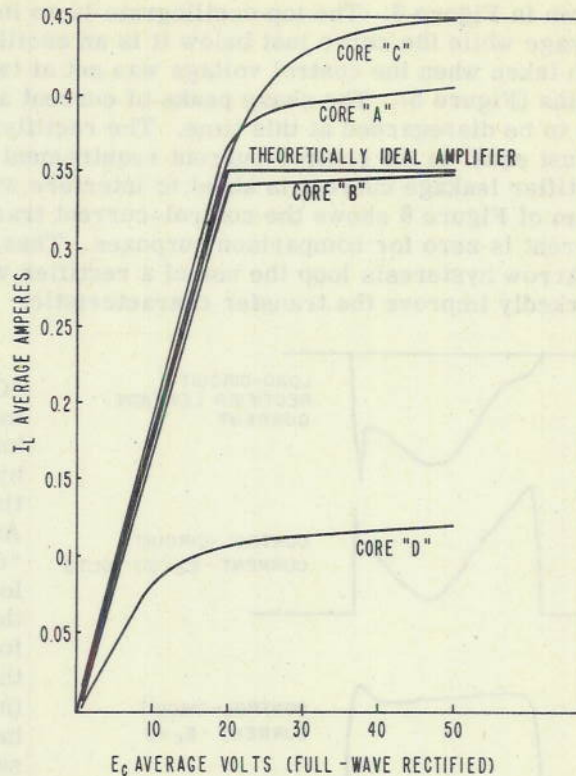


Figure 5 - Measured transfer characteristics of the core materials using the circuit shown in Figure 1

shown in Figure 6. The top oscillogram is an indication of the load-circuit rectifier leakage while the curve just below it is an oscillogram of the control-circuit current, both taken when the control voltage was set at twenty volts, the point where nonlinearity begins (Figure 5). The sharp peaks of current at the extreme right of the oscillograms are to be disregarded at this time. The rectifier leakage current (top trace in Figure 6) is just equal to the control-current requirement at one point; in other words, the peak rectifier leakage current is about to interfere with the controlled reset. The third oscillogram of Figure 6 shows the control-current trace when the load-circuit rectifier leakage current is zero for comparison purposes. Thus, it can be seen that since core "A" has a narrow hysteresis loop the use of a rectifier with less leakage in the load circuit would markedly improve the transfer characteristic.

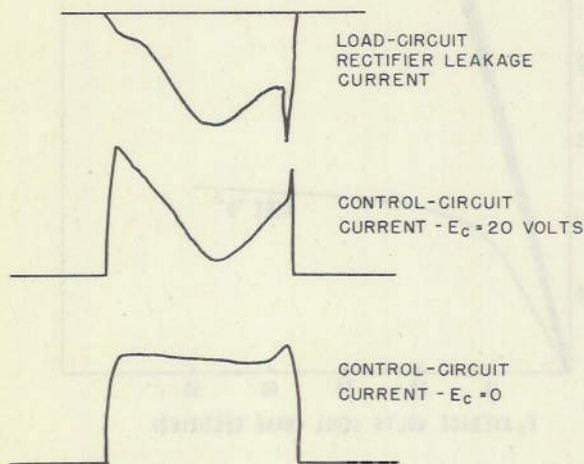


Figure 6 - Oscillograms for core "A" indicating (a) load-circuit rectifier leakage, (b) control-circuit current, and (c) control-circuit current when the load-circuit rectifier leakage is zero

The transfer characteristic for core "C," third best of the group, shows an even more pronounced rounding at and above the knee. The rounding effect can be caused by one or both of two things: Loss of induction at remanence and rectifier leakage. An inspection of the minor loops for core "C" in Figure 4 shows only a very small loss of induction. In fact, it is to be noted that remanence induction is slightly higher for the minor loops. It has been suggested that since the core material is relatively thick for this sample, eddy currents may have a prominent effect on the loops. The same rectifier was used in all cases and rectifier leakage increases with voltage. Therefore, it is concluded that rectifier leakage is the major contributing factor since a supply voltage greater than that used for core "A" was employed. This conclusion is borne out by the two transfer characteristics obtained using core "C" (Figure 7); one is a replot of the transfer characteristic shown in Figure 5, while the

other, which approaches an ideal characteristic, was obtained when a rectifier with less leakage current was used. In this latter case the rectifier leakage never reached the current value necessary for magnetization.

The transfer characteristic for core "D" deviates drastically from an ideal characteristic. Ideally, all four transfer characteristics would have the same slope below the knee since the same load resistance was used. Also, the saturation values of load current would be in proportion to the applied (supply) voltages. In the case of core "D" the slope of the transfer characteristic below the knee is much less than expected and the saturation value of load current is only about one half the value it should be ideally. An inspection of the minor hysteresis loops for core "D" in Figure 4 reveals an obvious reason for the discrepancy, loss of induction at zero applied mmf. This marked deviation of remanence from peak induction affects the transfer characteristic throughout its range. An important secondary reason is rectifier leakage, which will reduce the induction further since the loop is quite narrow and slopes down quite markedly throughout the second quadrant. Even a low value of mmf due to rectifier leakage will accomplish uncontrolled reset. A considerable loss of power handling capacity results and for these reasons core "D" is considered an inappropriate core material for use with the new magnetic amplifier circuits.

It appears, from the experimental data presented, that the relatively poorer core material of core "B" (wider hysteresis loop) obtains the most nearly ideal transfer characteristic. It may be well to note that control current is proportional to hysteresis-loop width and therefore the amplifier which employs cores with narrower hysteresis loops will have an inherently higher gain factor (1). To maintain a nearly ideal transfer characteristic while employing narrower-loop core materials, it is necessary to use rectifiers with less leakage (Figure 7).

CONCLUDING REMARKS

The comparisons of the four core materials are based on experiment. The parameters contained in the circuit were not theoretically ideal. The major non-ideal element, other than the cores, is the load-circuit rectifier. Since theoretically ideal rectifiers have not as yet been produced, it is necessary to include the effects of nonideal rectifiers to be realistic. Fortunately, with proper choice of rectifiers, commensurate with the core materials used, an ideal transfer characteristic can be approached. Since the control-circuit current is equal to the magnetizing current minus the load-circuit rectifier leakage current times the turns ratio, the criteria for selecting an appropriate rectifier to obtain an optimum transfer characteristic is only that the leakage must not exceed the magnetizing current requirement (Figures 5, 6, and 7).

The basic circuit used is new and unconventional, but it is believed that, with its inherent one-cycle response and high gain factor, it is sufficiently important to be used for this investigation. Although the results of this investigation can be used in the general field of magnetic amplifier design and analysis, it is well to note that the specific points of comparison made in this paper apply directly to the circuit (and its operation) given in Figure 1.

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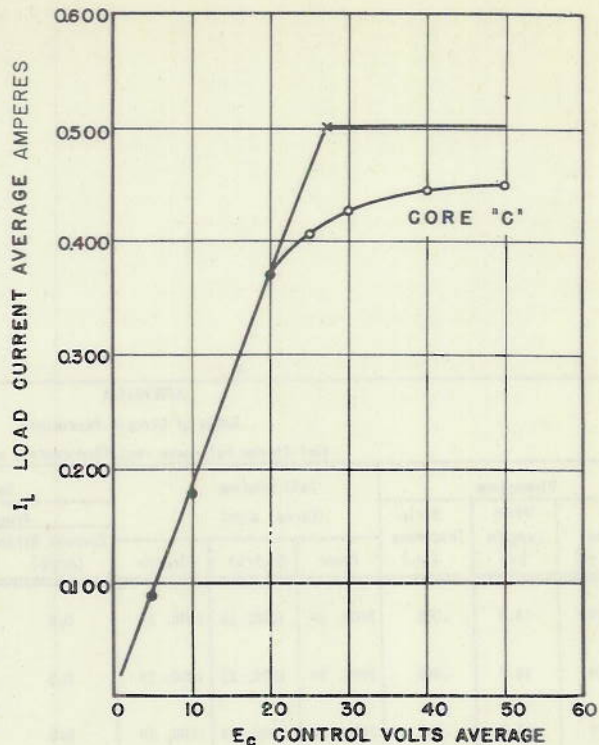


Figure 7 - Transfer characteristics of core "C" showing the effect of rectifier leakage; (o) replot of the curve shown in Figure 5, (x) improved transfer characteristic obtained when a rectifier with less leakage was used

APPENDIX A
 Table of Circuit Parameters
 (Unfiltered full-wave rectified control voltage)

Core	Dimensions			Coil Winding (turns, size)			Rectifiers			AC Supply Voltage (volts)		Resistance (ohms)	
	Area (Sq. cm)	Mean Length (cm)	Strip Thickness (in.)	Power	Control	Search	Power		Control	Power Circuit	Control Circuit	Load	Control Source
							Current Rating (amps)	Voltage Rating (volts)					
Core "A"	0.720	18.0	.002	2000, 24	1000, 29	1000, 29	0.5	68	1N39	57	29	25	75
Core "B"	0.658	18.0	.002	2000, 24	1000, 29	1000, 29	0.5	68	1N39	47	24	25	75
Core "C"	0.720	18.0	.012	2000, 24	1000, 29	1000, 29	0.5	68	1N39	67	34	25	75
Core "D"	0.733	18.0	.002	2000, 24	1000, 29	1000, 29	0.5	34	1N39	28	14.25	25	75

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