Misc.

D-Notes

A Coincident-Current Magnetic Memory Cell for the Storage of Digital Information*

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Summary—A small, ring-shaped, ferromagnetic core with properly "rectangular" B-H characteristics may be operated so that its flux polarity reverses only when the correct combination of two or three magnetizing windings are coincidentally excited. Such cores may then be used as memory devices and assembled into a two- or three-dimensional memory system with storage-cell selection at the intersection of two or three space co-ordinates. Only a core which retains a large percentage of remanent flux of the proper polarity, in spite of repeated "nonselecting" disturbances, can be used as a coincident-current magnetic memory unit. Repetitive pulse-pattern testing designed to obtain quantitative data on the operation of such units, in the form of defined "information-retention ratios" and "signal ratios," indicates that only a few core materials are satisfactory.

Introduction

A SCHEME for storing binary information in a three-dimensional array of small ferromagnetic cores and selecting the desired core by exciting the proper three co-ordinate lines has been presented by Forrester in a recently published article.[1] Operation in such an array imposes certain requirements on the ferromagnetic cores which can best be stated after a simple outline of the storage scheme.

Basic Core Operation

A stored binary digit may be represented by the direction of the magnetic flux within a core which has a "rectangular" hysteresis loop. The digit may be sensed, or read, by applying a large magnetizing force of fixed arbitrary polarity and observing the voltage induced in a sensing winding.

Fig. 1 shows a hysteresis loop for a core which might be suitable as a cell in a three-dimensional system; the loop is determined by symmetrical cyclical excitation of amplitude H_M.

Assume, at the start, that the core's state is at the point $-B_R$. The application of a magnetizing force of $+H_M/2$ moves the operating point to x; upon removal of the magnetizing force, the operating point returns along the dashed line to a point just above $-B_R$.

The path traveled during the application and removal of the *full* H_M is quite different; the operating point moves to y, and then to $+B_R$. The core reverses its magnetization and the flux undergoes a large change.

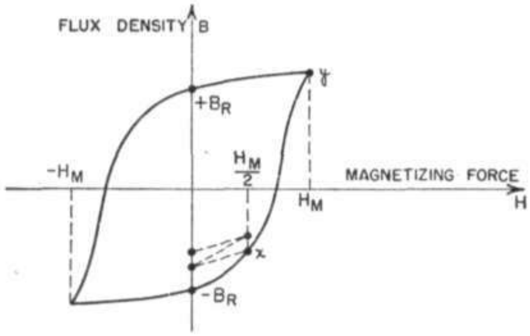

Fig. 1—Paths of operation of a magnetic memory unit.

Two- and Three-Dimensional Selection

If nine such cores are arranged in a two-dimensional array, as in Fig. 2, and currents of magnitude $I_M/2$

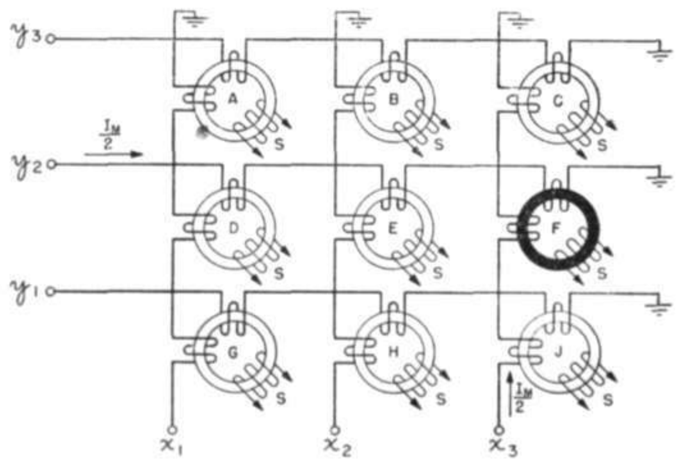

Fig. 2—A two-dimensional array of cores.

(where I_M results in a magnetizing force of H_M per core) are caused to flow coincidentally in selected lines x_3 and y_2 as shown, core F is the only core in the array which has the full magnetizing force, H_M, impressed. Cores, D, E, C, and J have $H_M/2$ impressed; cores A, B, G, and H have no impressed magnetizing force. Each core is, in this arrangement, a coincidence device, and the only core whose magnetization is significantly affected is the one at the junction of the selected lines. (The output signal may be taken from the sensing windings, S, after suitable mixing.)

The extension to three dimensions may be accomplished by stacking two-dimensional arrays, like the

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[1] J. W. Forrester, "Digital information storage in three dimensions using magnetic cores," *Jour. Appl. Phys.*, vol. 22, pp. 44–48; January, 1951.

ones of Fig. 2, along a z axis, with corresponding x lines connected in common and corresponding y lines connected in common. In this arrangement the application of $H_M/2$ to an x line and a y line results in the selection of a line of cores parallel to the z axis. All of these cores, except a desired one, may be "unselected" by the application of *minus* $H_M/2$ to the cores in each z plane, except the one containing the desired core.

Greater Selecting-Current Ratios

Variations on the selection scheme described above have been devised which impose less stringent requirements on the core. It is possible for the core to have to discriminate between currents which bear 3:1, 5:1, or greater ratios to each other;[2,3] advantage may be taken of these greater current ratios to reduce switching times, increase signal-to-noise ratios, or relax some of the hysteresis-loop requirements. The cost is an additional increase in the electronic equipment surrounding the system for each increase in the H ratio.

The discussion that follows is concerned with core requirements for operation with a 2:1 selecting-current ratio. A core that operates satisfactorily with a 2:1 ratio will have a high margin of reliability at greater ratios.

Information-Retention and Signal Ratios

The ONE-to-ZERO output-signal ratio is an important criterion by which to judge a simple magnetic binary storage unit. However, this ratio is insufficient for judging a coincident-current unit of the type described, and a set of new criteria have been set up for that purpose.

Information Retention

Refer back to Fig. 1 and let an "undisturbed ONE" be defined as the $-B_R$ flux-state of the core and an "undistured ZERO" as the $+B_R$ state. Let a "read" pulse of H be arbitrarily fixed at $+H_M$ so that reading a ONE results in a large flux change and a correspondingly large output pulse, and reading a ZERO gives a small output pulse. A ZERO is, then, "written" by an $+H_M$ pulse also, and a ONE is written by an $-H_M$ pulse.

Recall that selecting one core in a two- or three-dimensional array results in the application of $H_M/2$, called a "nonselecting" pulse, to cores elsewhere in the array. The application of repeated nonselecting *read* pulses to a core containing a ONE tends to run the state of that core up along the B axis, as indicated by the dashed lines in Fig. 1, disturbing or destroying its information. When the hysteresis loop is properly rectangular and all parameters correctly adjusted, the operating point moves up the axis only to some asymptotic position not far above the point $-B_R$. This is the situation for a core which operates satisfactorily in the coincident-current scheme.

A core which contained an undisturbed ONE and has been subjected to a large number of nonselecting read pulses is considered to hold a "disturbed ONE." By the above reasoning, the disturbed-ONE output is usually lower than the undisturbed-ONE output.

In an analogous manner, repeated nonselecting write-ONE pulses will run the core's operating point from $+B_R$ downward, *increasing* the size of a ZERO output pulse so that a disturbed-ZERO output is usually larger than an undisturbed-ZERO output.

Signal Ratios

Since nonselecting disturbances may reduce the output signal from a core containing a ONE and increase the output from a core containing a ZERO, the ratio of the disturbed-ONE output to the disturbed-ZERO output, called the "*disturbed-signal ratio*," is a critical measure of a core's performance as a coincident-current memory unit. This ratio approaches infinity in the ideal case, and should be much greater than one if reasonable discrimination between the binary digits is to be obtained.

The application of a nonselecting pulse to a core results in a voltage output, called a "nonselecting output," that is, a form of noise. The ratio of a disturbed-ONE output to a nonselecting output, called the "*nonselecting signal ratio*," is another important criterion of operation. Like the disturbed-signal ratio, it approaches infinity in the ideal case and should be much greater than 1 for satisfactory operation.

Hysteresis Loop Shapes

The two ratios mentioned above are functions, largely, of the shape of a core's B-H loop. The values of the ratios approach the indicated ideals as the rectangularity of the hysteresis loop increases.

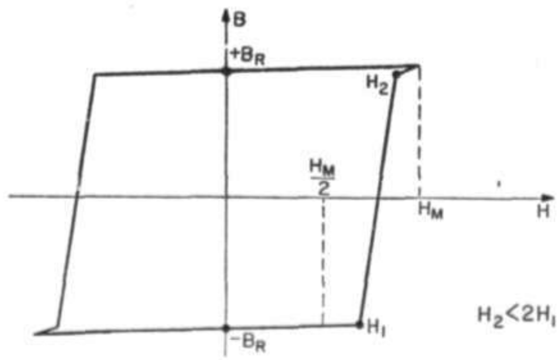

Fig. 3—An idealization of a B-H loop.

From the idealized hysteresis loop of Fig. 3, some necessary conditions for coincident-current operation

[2] "Ferromagnetic and Ferroelectric Cores," Summary Report No. 26, Section 3.4, Digital Computer Laboratory, M.I.T., Cambridge, Mass.; Second Quarter, 1951.

[3] R. R. Everett, "Selection Systems for Magnetic Core Storage," Engineering Note E-413, an internal document of the Digital Computer Laboratory, M.I.T., Cambridge, Mass.; August 7, 1951.

may be stated. A loop must exist for which the following relations hold true:

$$H_M > H_2,$$

$$\frac{H_M}{2} < H_1,$$

where H_1 and H_2 are the points at which the B-H curve changes direction abruptly. Combining these gives one general requirement on the hysteresis loop shape,

$$H_2 < 2H_1.$$

Experimental results give qualitative support to this general requirement.

Experimental Results

Cores were tested to ascertain signal ratios, B-H characteristics, and response times. Where possible, the testing was accomplished repetitively and at a high rate, and results were presented on an oscilloscope.

Test Technique

Previous considerations lead directly to the magnetizing pulse patterns desired for signal testing. Two of these patterns are illustrated in Fig. 4; mode *a* con-

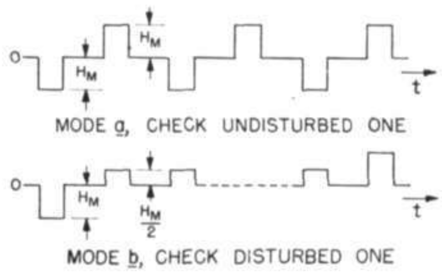

Fig. 4—Core-testing pulse patterns of H.

sists of alternate-polarity, full-amplitude pulses for checking an undisturbed ONE; mode *b* checks a disturbed ONE by interspersing a large number of half-amplitude, nonselecting pulses between the negative (write-ONE) pulse and the positive (read) pulse. The response to the nonselecting pulses may also be observed during mode *b* operation. Other modes check for undisturbed and disturbed ZEROs. (Pulse amplitudes, lengths, spacing, and the number of intervening nonselecting pulses are independently variable.)

Core B-H characteristics were generally observed at low frequencies by the usual methods.

Response times were taken to be the lengths of the disturbed-ONE output pulses, and the length of the test pulses was kept somewhat larger than this.

Optimum Results

Many cores were tested. The problem was well bracketed by two of them, one metallic, the other a magnetic ferrite.

The best metallic core, made by Allegheny Ludlum of one-mil "Silectron" tape, has excellent signal ratios; its response time, during the reading of a ONE, is about 25 microseconds.

Scope traces for this core, for the disturbed-ONE mode and the disturbed-ZERO mode, are shown in Fig. 5; arrows point to the pertinent output pulses. The

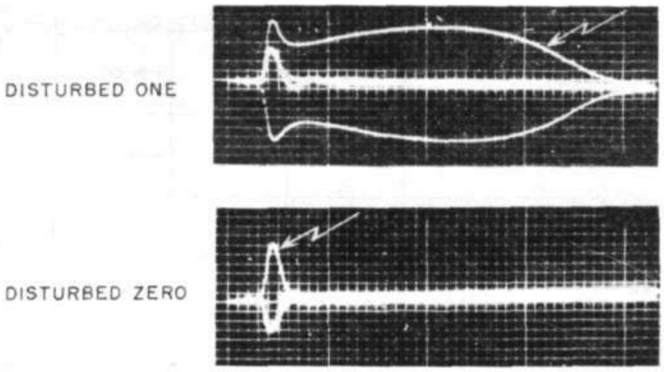

Fig. 5—Coincident-current test results, best metallic core.

disturbed-signal ratio and the nonselecting signal ratio are both obtainable from these traces. (The time scale is 5 microseconds per large division.) The negative trace in the upper photograph is the core output when the ONE is written; the heavy center trace combines the large number of nonselecting outputs which follow the writing; and the final disturbed-ONE output shows as the large positive pulse. The positive trace in the lower photograph is the output from the read or write-ZERO operation; the interspersed nonselecting write-ONE pulses merge in the heavy negative trace.

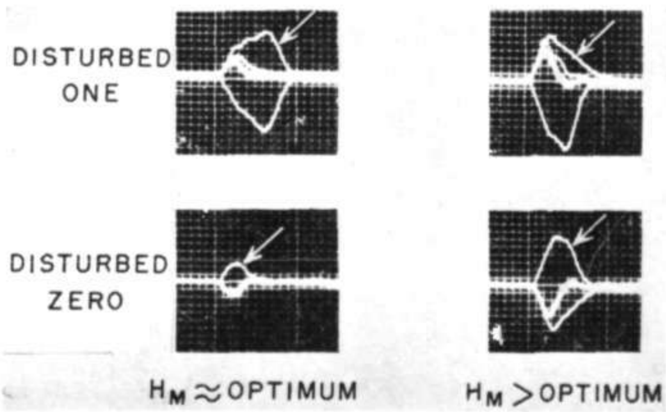

Fig. 6—Coincident-current test results, best ferritic core.

A very promising material for high-speed work in this field is magnetic ferrite. Good results were obtained with a General Ceramics and Steatite core, which has fair signal ratios and a response time near one-half microsecond.

Fig. 6 shows scope photographs for this core under two conditions. The first column was taken for H_M

adjusted to optimum amplitude. The second column was taken with too large an H_M amplitude, resulting in an increased disturbed-ZERO output and a decreased disturbed-ONE output. This led to an unsatisfactory disturbed-signal ratio close to one in value.

CORE CRITERIA	BEST METALLIC CORE	BEST FERRITIC CORE	IDEAL
DISTURBED-SIGNAL RATIO	13	6	$\rightarrow \infty$
NON-SELECTING SIGNAL RATIO	16	$3\frac{1}{2}$	$\rightarrow \infty$
RESPONSE TIME	25 μ SEC	$\frac{1}{2}$ μ SEC	$\rightarrow 0$

Fig. 7—Core comparisons.

The table in Fig. 7 summarizes the important test results for the two cores. H_M was adjusted to the optimum value in each case. The test results are compared to the ideal values shown in the third column of the table. The signal ratios are found from the voltage-time areas of the output pulses; this gives a rather pessimistic, but fundamental, measure of a core's characteristics.

The signal ratios of the metallic core are probably as good as are needed for proper operation of large arrays. Those of the ferrite are too low.

On the other hand, the response time of the metallic core, while sufficiently low for many purposes, is too long for the high-speed memory of a computer like M.I.T.'s Whirlwind I, where a memory access time of a few microseconds is desired. The ferrite's response time of one-half microsecond is as fast as can be used today.

Conclusion

Summarizing, a small ring-shaped, ferromagnetic core with properly rectangular B-H characteristics may be operated so that its flux polarity reverses only when the correct magnetizing windings are coincidentally excited. Such cores may then be used as cells in a three-dimensional memory system with cell selection at the intersection of three space co-ordinates.

This scheme promises to make available compact, reliable, and long-lived digital-computer storage which contains, inherently, its own selection mechanism. Selection is made along space co-ordinates only, and high operating speeds are possible.

Further development work at M.I.T. is being aimed toward improving core materials, and toward assembling large numbers of these cores into a high-speed memory system.

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