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SUBJECT: TESTING THE MAGNETIC-CORE MEMORY SYSTEM IN A COMPUTER

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Abstract: A working memory has a "safe" operating region in a multidimensional space whose coordinates consist of the significant operating parameters of the memory. Errors occur only with excursions of the operating point outside the safe volume; such excursions result from failure of the surrounding equipment to remain perfectly stable. The optimum operating point is determined by the nominal settings of all the parameters which permit operation with a minimum of errors. Reliability is then defined as the ratio of the number of memory cycles to the number of errors. This is, to a very close approximation, the reciprocal of the probability of the operating point to drift from its optimum setting into the region outside the safe volume.

The specific problems of finding an optimum point and evaluating the reliability of the 32 x 32 MTC memory have been facilitated by reduction of the number of significant variables to two: the driving current and the common bias of the sensing gate tubes. Optimum conditions were 475-ma X, Y, and Z driving currents (1/2 I_m) and -30-v gate-tube bias. Since the probability distributions of the variables are not known, reliability can only be evaluated by optimizing the adjustments of the system and maintaining count of its errors.

I. General Problem

A system affected by n parameters will in general operate as long as these variables are set to correspond to some point within a "safe" volume in an n-dimension space whose coordinates are these parameters. If the system is a computer memory, the shape of the operable volume in the n-dimension space will depend upon the computer's program. This volume will henceforth be called a "shmoo."

Memory-test programs are usually cyclic and do not work on "live" incoming data. This type of program always "does the same thing" to the memory. A practical program dealing with input data that may be continuously changing is, from the memory's point of view, like a very large number of programs. The word program will now be considered from the memory's point of view, so that it refers to a given information pattern stored and acted upon at certain PRF's.

The surface of a shmoo for a given program may be obtained by varying a parameter between the lower and upper bounds over which operation is possible, while the other variables are fixed. This is repeated for many values of the "fixed" variables. Then a new parameter is picked as the one to be varied over operation limits, and the process is repeated.

Two shmoos corresponding to two programs will most probably overlap in the n-dimension space and share a common volume. If a volume exists that is common not only to two shmoos but to every possible shmoo, then the memory is a working memory. Operation within the common volume is error free. Errors occur only upon transient excursions of the operating point outside the common volume; such excursions result from failure of the surrounding equipment to remain perfectly stable.

Let us define the nominal optimum operating point as that point in the n-dimension space at which, for the given surrounding equipment, a minimum number of errors occur on a long-term basis (allowing many programs to be worked). The problem is to find this point and, at this point, to determine the reliability of the memory. The stability of the surrounding equipment and the tolerances of the memory itself are both involved in this problem.

A. Experimental variables

If the memory operation is a function of only two variables, a two-dimensional shmoo may be simply obtained for a given program. If operation depends upon 3 variables and data is taken for 5 points of each variable, 5 two-dimensional shmoos are needed. If, on the other hand, operation depends upon n variables and each is varied over 5 points, $5^{(n-2)}$ two-dimensional shmoos are needed to specify the operating space for each program.

Among the variables affecting the 32 x 32 MTC memory are the X and Y read-and-write driving-current magnitudes (128 of them); digit-plane driving-current magnitudes (17 of them); rise time and pulse duration of these currents; strobe time; sensing-amplifier gains (17 of them); sensing-gate-tube bias; and temperature. Hence the total number of variables lies between 10 and 170 depending upon how one weighs and counts. At any rate, $5^{(n-2)}$ experiments per program for an almost infinite number of programs is staggering.

B. Optimum settings and reliability

Assume for a while that the information concerning these variables is available. How can it be used to determine an optimum operating point in multidimensional space and to allow the calculation of a figure of reliability?

It will be assumed that the number of errors made on a long-term average basis will be proportional to the number of excursions of the operating point outside the common volume. This assumption, that errors are just as likely to occur as a result of crossing the safe surface at one point as at any other, must be made in the absence of specific prior knowledge of the programs (and their respective shmoos) to be handled by the computer. Each parameter may be described statistically in terms of a probability distribution that peaks at the nominal setting. For given settings of the n parameters, the probability of the operating point being at a given point in the n-dimensional space is the product of the n distribution amplitudes. This over-all probability function, a scalar field, is the joint probability of the n independent parameters. The problem of finding an optimum point is one of maximizing the probability that the operating point will be within the safe volume. The surface of the safe volume may be approximated by some equation while the distributions of the parameters may be approximated by analytic functions. The maximizing done on a formal basis will only require differential calculus, but will involve the lengthy procedure outlined below.

"safe" n-dimensional volume
in space whose coordinates
are the independent variable

$P(v_1 - v_1^0)\ P(v_2 - v_2^0) \cdots P(v_n - v_n^0)$ is the probability of the operating point being at any point $p(v_1, v_2, \cdots, v_n)$ when the variables are nominally set at $v_1^0, v_2^0, \dots v_n^0$.
The probability of being within the safe volume is:

$$P \equiv \iint_{v_1 v_2} \cdots \int_{v_n} P(v_1 - v_1^0)\, P(v_2 - v_2^0) \cdots P(v_n - v_n^0)\, dv_1\, dv_2 \cdots dv_n .$$

P is only a function of $v_1^0, v_2^0, \dots v_n^0$ and is to be maximized. The optimum point is now found from the simultaneous equations:

$$\frac{\partial P}{\partial v_1} = 0 \quad ; \quad \frac{\partial P}{\partial v_2} = 0 \quad ; \quad \cdots\cdots \quad ; \quad \frac{\partial P}{\partial v_n} = 0$$

A more practical and no less precise procedure is that of trial and error. Here again knowledge of the n-dimension shmoos and of the statistics of the parameters is necessary. How a trial and error process may be instrumented in the absence of such precise knowledge will be considered below.

II. An Engineering Answer for the 32 x 32 MTC Memory

A. Finding optimum point

1. Reduction of number of variables.

To make the first important reduction, let all the driving currents be identical in magnitude (1/2 I_m) and let this magnitude be a single variable. The X and Y currents should be identical by symmetry, and a limited amount of experimental data shows that the Z current magnitudes are best when they are the same as for X and Y. This is not sufficient, however, to justify the lumping of all currents into a single variable. It is necessary in addition to show that all the currents simultaneously undergo the same transient excursions from the nominal $1/2\ I_m$. The X and Y currents would exhibit this as a result of power supply transients. However, the Z driver circuits are not the same as the X and Y circuits and so would not experience the same transients. Also, variations may exist among the Z driver units and among the X and Y driver outputs due to driving-tube differences. Actually the currents do not behave as a single variable. Although the biggest strain on the memory comes from read-and-write driver currents wandering in opposite directions, the circuitry is such that this possibility is remote; the next biggest strain comes from all drivers drifting in the same direction. Assuming a single driving-current magnitude thus leads to an approach that is nearly the most conservative.

The memory performance varies considerably with termperature. This will not be considered as a variable, however, because it is fixed by the temperature of the air-conditioned memory space.

The 17 sensing-amplifier gains will not be considered as experimental variables. They are not quantities that could fluctuate rapidly; their sensitivity to power-supply fluctuation gives only second-order gain variations. These gains are subject to long-term variation, however, but this would doubtless be eliminated by system tune-up at sufficiently close time intervals. If shmoos are taken and the gain (all 17 identical) noted, the shmoo that will result from a different gain can be simply calculated from the first shmoo if one knows the gate-tube threshold. It follows at any rate that complete information is obtainable from data taken at fixed gain settings.

Operation of the memory depends upon current-gate durations only when these gate widths are less than the time necessary to switch the memory cores. The read-and-write gate durations may be eliminated as variables if they are made sufficiently long.

As long as the current gates are of sufficient durations, rise time on write is not important. Experiment shows also that varying the read rise time between 0.5 and 1 μsec has no effect upon margins. Hence it is no longer necessary to consider rise time as a variable.

2. Observe properties of remaining variables.

There are three remaining variables: driving-current magnitude, strobe time, and gate-tube bias. The significance of the single driving-current magnitude has already been discussed. Next to be considered are the special characteristics of strobe time.

All times are measured with respect to some start pulse which initiates the read gate into the read switch. The time of strobing is fixed relative to this pulse by delay-line amplifiers. The strobe time could be pin-pointed if it were not for the fact that, for the particular driving circuits used, the time after the start pulse when the X and Y read currents begin flowing in the selected memory lines depends fairly critically on power-supply voltages. The strobe time turned out to be a significant variable whose value hardly needed to be changed over wide variations of the other variables. For each driving-current magnitude of an experimental run, the strobe time was adjusted to give maximum bias limits. This procedure lead to the result that the strobe time needed only to be increased by 0.05 μsec as the driving currents were lowered from 500 ma to 350 ma. The strobe time was set at 1.20 μsec with read current - rise times at 0.5 μsec thereafter.

The gate-tube bias is the last remaining variable. Gate-tube bias limits give a measure of the size of the smallest ONES and the largest ZEROS. The differences between these limits, very significant quantities, are the differences between the ONES and ZEROS outputs and are proportional to sense-amplifier gain.

3. Two-dimensional reduction.

Now the problem of finding the optimum operating point is two dimensional. For a given program, let the bias limits be plotted against driving-current magnitude where the strobe time has been optimized. This gives a single two-dimensional shmoo per program (See Fig. 1). When a sufficient number of shmoos have been taken for the various programs, the overlap region may be found, as shown in Fig. 2.

Fig. 1

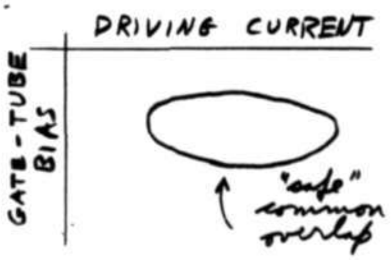

Fig. 2

The two-dimensional safe-overlap region together with the characteristics of the driving currents and gate-tube bias are sufficient to determine the optimum point. The gate-tube-bias probability distribution should not only include the variations in the bias potential applied to the gate tubes but also should take account of any stray noises appearing on the outputs of the sensing amplifiers that are generated within the sensing amplifiers. These distributions may be measured but not very simply. They may best be estimated and at the same time the optimum point should be selected. The decision as to where to operate for a minimum of errors is not difficult in two dimensions and can be made with as close an accuracy as the shmoos can be measured in the first place.

B. Reliability

Reliability may be conveniently defined as the number of operations divided by the number of errors. This is a statistical measure — a long-term average. Reliability is then the ratio of the probability of the operating point being inside the safe volume to the probability of the point being outside the safe volume. This is very nearly the reciprocal of the probability of being outside the safe volume.

In a reliable system such as a magnetic-core memory, it may be assumed that appreciable simultaneous excursions of two or more variables from their nominal settings is a very much rarer situation than that of a single variable deviating from nominal. Therefore, not much conservatism will be lost if it is assumed, that excursions of the variables are mutually exclusive events. From the optimum point, each of the parameters may be varied separately over finite ranges before the system fails. The error probability is then the sum of the probabilities of each variable being outside its safe range. The reciprocal of this sum is the reliability. These probabilities are difficult to obtain, but a feeling for the system reliability may be achieved from knowledge of the allowable ranges of the variables at the optimum point. These ranges at least give a basis for critical comparison of various magnetic-memory systems and of the merits of the various adjustments of a given system.

III. Experimental Determination for the 32 x 32 Memory in MTC

The procedures described above will be illustrated for the 32 x 32 magnetic-memory installation in the Memory Test Computer.

Fig. 3 shows two shmoos taken on the MTC memory-test programs MP11 and MP28-2 (the "inchworm"). MP11 places all ONES or all ZEROS in a memory plane and operates on the memory at a low PRF. Most of the computer time is spent in toggle-switch storage and the arithmetic element. This program placed less strain on the memory system than the high-speed program MP28-2 which had about the poorest margins of all those tried. The safe overlap region for the 32 x 32 memory in MTC was roughly the shape of the shmoo of MP28-2. The placing of the optimum point was easy here because the tolerable ranges of both current and bias were maximum and balanced at the same point. For this special case, no knowledge of the variations in current and bias was necessary because the best operating point biaswise also turned out to be the best operating point currentwise.

At the optimum operating point, if each variable is allowed to change while the others are fixed, the reliability of the memory alone is indicated by the following tolerances:

Driving currents	±15% at 475 milliamperes	85 F
Gate-tube bias	±30% at -30 volts	
Strobe time	±15% (+0.2 μsec) at 1.20 μsec	
Read-rise time	Noncritical 0.5 - 1.0 μsec	

As yet, the probability distributions of these variables have not been measured. Monitoring these variables for deviations may give information leading to equipment changes with subsequent improvement in reliability. The reliability may only be measured at present by keeping count of errors made over known numbers of memory cycles.

Only observations of the existing system have been considered thus far. Some recommendations may be made now for improving the 32 x 32 MTC memory installation. The time when the X and Y driving currents begin flowing in the memory lines after the initial cycle start pulse depends fairly critically upon the -300-v supply. Reducing this sensitivity will improve reliability. It is believed that the margins on all programs could be made as good, if not better, than those of MP11 by improving the filtering and shielding in the sensing circuits and making changes in the sensing amplifiers to reduce PRF sensitivities. Photographs of voltage waveforms on the sensing windings show that the sizes of ONES and ZEROS changed negligibly with program. Delta noise is not a serious problem here, and hence operating margins should not be greatly affected by the nature of the program.

A considerable amount of experimental work was done by R. L. West and F. R. Durgin of IBM. Their results are given in the IBM report "An Experimental Evaluation of the MTC Memory System" and justify many of the simplifications made here in arriving at a practical solution to the memory-adjustment and evaluation problem.

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