Marginal Checking as an Aid to Computer Reliability*

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Summary—**Deteriorating components, particularly crystals and vacuum tubes, cause reduction of safety margins and are a principal source of error in digital computing and pulse communication.**

Marginal checking varies voltages in logical circuit groups, inducing inferior parts to cause failure, while a test program or pulse transmission detects and localizes potential failure. In a digital computer, this can be automatically accomplished with the computer itself acting as the detector.

In one trial on a 400-tube prototype system the application of this type of preventive maintenance for half an hour per day improved reliability 50 to 1. Results of preliminary tests on a full computer are discussed.

I. INTRODUCTION

ELECTRONIC digital computers will be used to solve real-time problems and must be reliable. For example, when the modern computer becomes the nerve center of an all-weather air traffic control system, the plane pilot must know the system is operating, and will continue to operate, without error. Such reliability can be guaranteed only by detecting imminent failures and preventing their occurrence.

In order to obtain "computer reliability," a much higher degree of performance is required than in ordinary means of communication. The basic difference is the high concentration of information used in a computer compared with the concentration of information in speech, television, or radar. Interruptions in circuits of the latter type can occur at frequent intervals, with little loss of intelligence. An occasional intermittent tube does not void the sense from a radio, ignition noise does not completely void television, nor does an arcing magnetron nullify the plot on a radar screen.

This criterion is not good enough in computer applications. The usual method of transmitting intelligence in a computer is to supply high-frequency pulses to particular circuits at specified times. A single pulse occurring at the wrong time can invalidate the usefulness of the whole effort. This single-error limitation is due to the presence of a memory in a computer. Memory remembers the errors as well as the information to be processed, and once an error becomes imbedded in the memory it can be propagated into all subsequent calculation.

The necessary reliability can be approached by combining good design with the best available components, and utilizing marginal checking as an additional aid.

Marginal checking differs from ordinary checking by not only answering the question, "Are all circuits functioning?" but also, "How much *longer* will the circuits function?" Good equipment starts with wide safety margins, but age and wear reduce these safety margins, leading to eventual failure. Marginal checking assures adequate safety by testing the system frequently enough so that only slight deterioration can occur between tests.

II. THE MARGINAL CHECKING SYSTEM

A. Magnitude of the Problem

Most of the large-scale digital machines under development utilize many thousands of vacuum tubes, crystals, resistors, condensers, and coils. The vacuum tube is the least reliable component of this group, and the crystal rectifier, though better than the tube, is still a weak link in the chain of reliability. Failures in the resistors, condensers, and coils are not frequent, and these elements do not threaten computer reliability to such an extent.

What may be expected of a system using present-day vacuum tubes and crystals? A few assumptions will serve to indicate the problem. If a typical computer has 5,000 cathodes and 10,000 crystals, suppose the tubes will last on an average of 5,000 hours, and the crystals, 10,000 hours. Every 30 minutes one of these aging components may cause a failure. Furthermore, some of these failures will not be steady but will cause marginal operation and thus be very difficult to locate. In a typical 8-hour day this may cause 16 shutdowns. Even if a trouble-location technique is well developed, so that the period of shutdown is short, the efficiency of the machine will be very low. One might ask if a periodic replacement program could be followed which would eliminate many of these component failures. Unfortunately, early failure in groups of new tubes is quite high, so that wholesale replacement on simply a time basis would increase the failure rate.

B. Features of Marginal Checking

The preventive maintenance techniques called marginal checking use performance margins to establish life expectancy of components, so that those with low margins can be removed during a testing period.

Three features of this marginal checking scheme make it very practical for use in large electronic systems:

(1) The checking system can detect imminent failures before they become real failures and cause computational error.

(2) This detection can isolate the failing component to a specific tube, crystal, or resistor.

(3) Such isolation can be so rapid that it consumes only a small percentage of total machine time.

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1. Conversion to Real Failures: The conversion of imminent failures to real failures during test periods is the important key in this marginal checking system. Such checking is possible in computers and also in many other pulse systems due to the on-off nature of the circuitry used.

In a computer, information passes from one place to another as the presence or absence of a pulse on a transmission line. It is not necessary that the pulse be of any particular amplitude to get this information to its destination but only that the pulse be large enough to affect the detector. If the presence of a pulse means a 1 and the absence a 0, then a pulse which is too small to affect the detector has the same effect as no pulse at all and so a 0 is recorded.

a. A Simple Computer Channel

Fig. 1 gives a typical basic block diagram often encountered in pulse systems. Gate tube *A*, when open, allows pulses to pass along a channel to a flip-flop. If the pulses are large enough and the flip-flop in proper condition, each pulse will cause a reversal of the flip-flop from a 1 to 0 or vice versa.

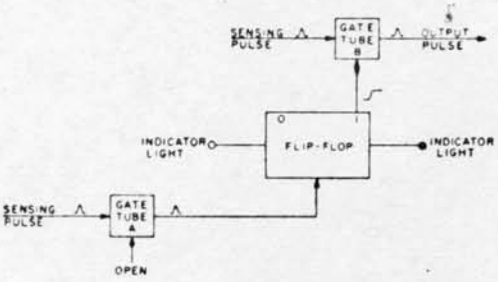

Fig. 1—A typical computer channel.

Two sorts of trouble may develop. First, the gate tube may deteriorate and cause the pulse amplitude to be reduced to a point where the flip-flop will not switch or, second, the flip-flop may refuse to switch because one of its components has deteriorated.

b. Checking the Gate Circuit

The margin of performance in the gate tube (*A*) can be checked by lowering the voltage on the screen of the tube by inserting a negative voltage in series with the screen lead as shown in Fig. 2 (a schematic for gate tube circuit). The pulses emerging from the tube will be lower than they were before the deviation.

If both the flip-flop and gate as shown in Fig. 1 have adequate margins then this marginal checking of the gate circuit will make no difference. This can be detected by another gate tube (*B*) which opens and closes according to the action of the flip-flop. If a sensing pulse is applied to gate tube *B* in Fig. 1, it will pass through to indicate that the flip-flop has switched and opened the channel. In the diagram shown this should occur for every other pulse passing through gate tube *A*.

A low margin in gate tube *A* will interrupt this sequence and no check pulse will emerge from gate tube *B*. From such a test it can be determined whether or not the gate circuit is nearing an unsafe condition. The circuit shown in Fig. 2 has a nominal screen voltage of 90 volts. A typical margin would be minus 20 volts from this value.

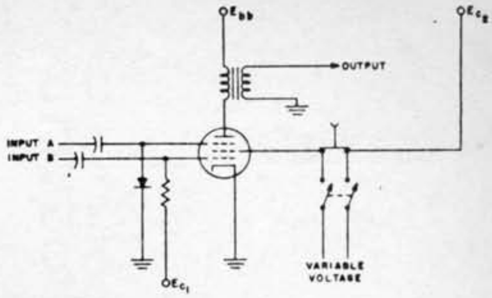

Fig. 2—Marginal checking of gate circuit.

c. Checking the Flip-Flop

This first check assumed that the flip-flop was performing normally and acting as a detector for the arrival of pulses. To check this assumption the following test can be made on the flip-flop circuit.

Fig. 3 is a simplified schematic of a flip-flop. One tube must have the ability, when conducting, to hold the other tube in a nonconducting state. The circuit is completely symmetrical. Tube deterioration shows up as a reduction in plate current in one tube with a consequent reduction of bias available to the opposite tube. The large cathode resistor allows considerable aging before the condition becomes intolerable but eventually tube deterioration will become so extreme that instability will occur and the flip-flop will favor one side. Then, whenever it is ordered to change sides by an incoming pulse the circuit will either fail to switch or fail to hold its new position after switching takes place.

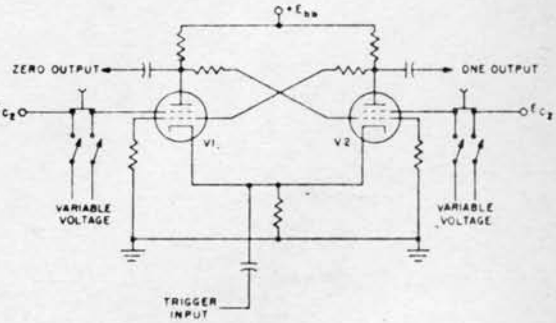

Fig. 3—Marginal checking of flip-flop circuit.

This unfavorable condition can be detected before it leads to failure by feeding the two screen circuits of the flip-flop separately, as shown in Fig. 3, and selectively raising the screen voltage of the normally off tube about 30 volts (nominal value 120 volts). Raising its screen voltage also raises its number 1 grid cutoff voltage. The normally on tube must have a safe margin of plate current available if it is able to hold the tube being checked

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off under these extreme conditions. If the on tube is weak it will fail to hold off the opposite tube and a spurious switching operation will result. The detection of this condition can be automatic by using the sensing pulses and gate circuits shown in Fig. 1.

d. Testing Crystals in a Clamp Circuit

A third type of conversion which will pick up aging crystals is of considerable interest. Fig. 4 shows a clamping circuit which couples the plate of a flip-flop to a gate tube. Proper operation of this circuit depends on the back resistance of the crystal staying at a high value so that proper clamping action will be available during the period between the voltage pedestals used for clamping. If the crystal deteriorates, the voltage at the grid of the gate circuit will appear as shown at the right of the diagram. Serious deterioration will result in the opening of the gate circuit when it should be closed.

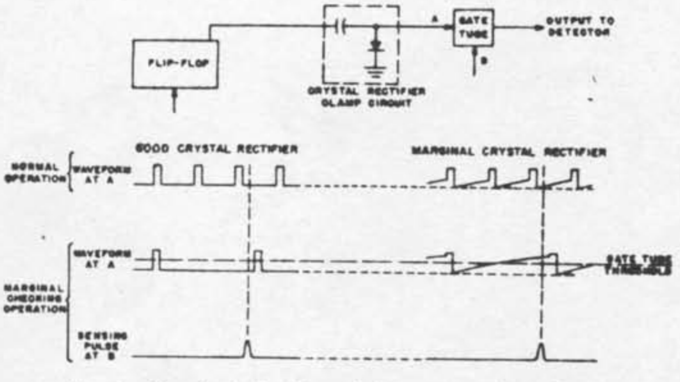

Fig. 4—Marginal checking of clamp crystal rectifiers.

To convert this imminent failure to a real one, a change in the timing of the clamping period is used. A good crystal will operate when a much longer period is allowed, but a deteriorating unit will not hold the bias that long and a failure will result. Values of 16 microseconds and 64 microseconds have been used effectively in this circuit. If a sensing pulse to the gate tube under control of this clamp circuit is inserted near the end of this longer wait period it will be rejected by a good crystal and passed by a deteriorating one. This scheme can then be automatized.

2. Localizing Failures: Once an imminent failure has been converted to a real failure by any one of the methods noted above, the problem of detecting the fault and localizing it to a particular source can be very time-consuming if it is not approached in an orderly manner. Fault isolation can be solved if the computer is divided for marginal checking into small logical sections. To simplify the trouble-location scheme, sections should be chosen so that at a given time only one fault can exist.

The logical design of a computer separates it into many channels, all starting at the pulse source and dispersing throughout the system to a destination.

Fig. 5 shows two of these typical channels separated into four sections. The vertical lines indicate how these channels may be broken for purposes of marginal checking and isolation of faults. In each case a pulse starts from the distributor along its channel and arrives at its destination with enough energy to change the condition of a flip-flop circuit in the destination section. If each section is subjected to voltage variation and the sequence still functions, the channel can be said to have adequate margins.

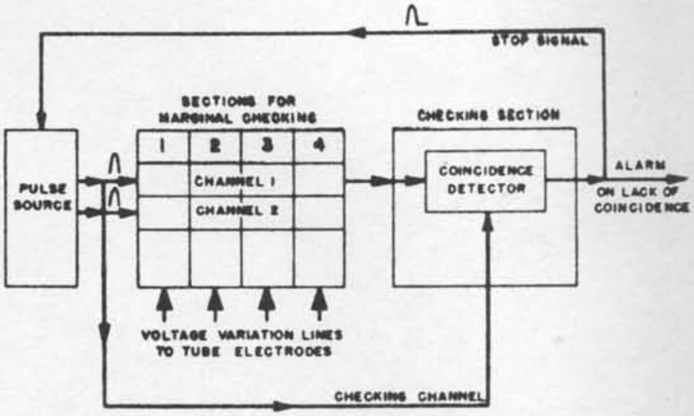

Fig. 5—Computer marginal checking.

The addition of a checking section to these channels allows the checking routine to be carried out automatically by the computer. An error-sensing pulse checks that the information arriving at the checking section via the channel under test is the same as that arriving by a separate checking channel. If the two pieces of information disagree, an alarm is sounded and immediately the pulse distributor is stopped.

Knowing the stopping point of the distributor, the channel at fault is isolated. In addition, knowledge of the section under voltage variation isolates the tube in the channel. The operator can usually find such troubles in a few minutes during such a test routine.

These channels are not used simultaneously but in a time sequence so tubes of the same type, but in different channels, may be grouped in the same section for voltage variation and no loss in isolation results.

3. Automatic Marginal Checking: The whole sequence of sending pulses through each of the channels has been automatized in the Whirlwind Computer system sponsored by the Office of Naval Research, at the Massachusetts Institute of Technology.[1] Some 200 sections are used. The computer program sends the pulses through each of the channels in a fraction of a second. Successive sections are selected by telephone switching apparatus and subjected to voltage variation at 5-second intervals. In this way the whole system can be completely checked in about 15 minutes.

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[1] The Whirlwind Computer is an electronic digital machine capable of performing at very high speed; i.e., 13,000 multiplications per second.

At present it appears that establishment of adequate margins once each day will be an excellent guarantee that the next 24-hour period will be completely free from error.

It is evident that the basic principles of marginal checking discussed in this paper are simple; but the system must be carefully designed to reap advantages of the checking in an economical way. Too many checking circuits complicate the equipment; not enough will fail to give unique indications and will not isolate defective components.

III. CONCLUSION

The most significant information about marginal checking is its performance record. Over a period of eight months, a 5-binary-digit prototype arithmetic element at MIT has been running a test problem over and over 24 hours a day. This test system contains about 400 vacuum tubes and 1,000 crystals, and marginal checking is done manually for a period of $\frac{1}{2}$ hour a day and deteriorating components are removed. This equipment has made several runs of three weeks without computational error which represents 2.5×10^{10} correct solutions of the problem, and about 10^{13} correct flip-flop reversals in 25 flip-flop circuits. The average run without error has been eleven days, which represents approximately a 50-to-1 improvement in the results obtained before marginal checking was installed. A run of forty-five days without error was made in early 1950. During this forty-five-day period, 12 tubes, 7 crystals, and 4 resistors were located during marginal checking periods and replaced because of low margins.

When one begins to work with larger systems, there is reason to believe that, with marginal checking, errors will not increase in proportion to the extra equipment involved. A high percentage of the remaining errors are caused by power failure, lightning, and external disturbances independent of the number of vacuum tubes in the system.

A measure of the success of marginal checking in improving the performance of the Whirlwind Computer is shown in Table I.

At present, 3,900 tubes and 11,000 crystals have been running for about 3,300 hours. 32 registers of test storage, made up of toggle switches and flip-flops, allow the solution of several problems which thoroughly test the computer.

During these installation tests, 187 tubes have been removed, 109 of which have been located by marginal-checking techniques. The majority of tube failures with deteriorating characteristics have been due to the formation of an apparent resistance on the cathode sleeve or in the cathode coating. This defect has been called interface resistance.

Obvious tube faults have been due to gas, broken pins, internal short circuits, and open welds. Many of these have been located by the built-in checking system of the computer without the aid of marginal checking.

Of the 272 crystal failures, 223 were located by the marginal-checking technique. The most serious fault has been a drifting of back resistance to a lower value by a factor of 2 to 10 with the continued application of voltage. The cause of this is not well understood but 1 to 10 per cent of new crystals exhibit this tendency after voltage has been applied for a period of 30 to 60 seconds. A few obvious faults have been due to completely open or short-circuited crystals.

About a dozen tubes and a few crystals have been intermittent. The on-off intermittent is the most difficult fault to locate in electronic circuits. Marginal checking does not aid in isolating this type of failure and this represents one limitation in the system. Complete failure such as filament burnout also cannot be predicted. However, in 3,300 hours of operation, only two tubes have exhibited such failure.

Some of the by-products of marginal checking have proved invaluable in testing the Whirlwind system. Many low performance margins have been found which were due to design weaknesses and not to deteriorating components.

Refinements have been made in the design to reduce noise level and improve timing of pulse sequences and frequency response. These improvements have all been possible earlier in the program than usual, due in a large measure to marginal checking.

TABLE I

TUBE AND CRYSTAL FAILURES*

	Tubes	Crystals
Number in use	3,900	11,000
Total failures	187	272
Obvious faults	76	7
Deterioration of operating characteristics	111	265
Failures located by marginal checking	109	223

* Note—Majority of tubes and crystals were in operation for 3,300 hours.

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The following references have been published by Project Whirlwind, Servomechanisms Laboratory, Massachusetts Institute of Technology, under Contract N50R160 for the Office of Naval Research. They are available at the Library of Congress, Naval Research Section, upon request.

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