EQUIPMENT RELIABILITY AS APPLIED TO ANALOGUE COMPUTERS*

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Introduction

I would like to preface my discussion of equipment reliability in analogue computers by introducing you to the M.I.T. Flight Simulator. The operation of this analogue computer is the source of much of the information for this paper.

In December, 1945, the Dynamic Analysis and Control Laboratory at the Massachusetts Institute of Technology began the design of a simulator to aid in the study of problems associated with aircraft and guided missiles. The development of the Simulator has been sponsored by the Bureau of Ordnance, Department of Navy, under Contract NOrd 9661. Portions of the Simulator have been used continuously since December, 1948, for obtaining solutions to a number of important dynamic problems; and in February, 1952, it was established as a computing facility available for general use.

FIGURE 1 shows an isometric view of the present arrangement of the M.I.T. Flight Simulator and Analogue Computer. The Simulator consists of two main sections: first, a Flight Table as shown on the ground floor, and second, the Generalized Computer as shown on the middle floor. Also shown is a portion of the electronics shop on the top floor. Either section can be operated independently of the other, or both sections can be operated together. The Flight Table section, which is precabled, has been arranged to solve the differential equations characterizing the motion of an aircraft in space. The main feature is a gimbal-mounted flight table that can test aircraft control-system elements which are sensitive to angular motion. The Generalized Computer section is an arrangement of a-c and d-c types of computing elements that can be interconnected to solve a variety of nonlinear differential equations with time-varying coefficients. The Generalized Computer section is constructed in rows, each row containing sufficient computing equipment to be operated as an independent computer when desired. The computing equipment consists of integrators, summing circuits, coefficient potentiometers, and automatic sequencing equipment for operating the computer. There is one basic d-c high-gain drift-stabilized amplifier used throughout the D-C Generalized Computer. Appropriate input and feedback networks are utilized to represent the various types of necessary mathematical operations. A 400-cps suppressed-carrier signal is used throughout the A-C Generalized Computer section of the Simulator and in the Flight Table section. The a-c integrators are of the electromechanical type, using a high-precision induction tachometer to form a velocity servo. Provision is made for connecting a maximum of five output units to the motor shaft through suitable gearing. These output units may be linear or nonlinear potentiometers or resolvers. The one basic amplifier circuit* used throughout the A-C Generalized Computer has a gain of 10 with a stabilization factor of at least 1000 at 400 cps. Since 1950, 174 of these basic amplifiers have been operated in the computer and throughout this paper this type of amplifier will be taken as a typical example of a computer component. Appropriate input-resistor networks make up the summing amplifiers, the repeater amplifiers, and the coefficient amplifiers.

First, it might be well to examine the meaning of the phrase "equipment reliability." As used in this paper, equipment reliability is a measure of the stability of electronic-component characteristics. If the characteristics of a vacuum tube, for

* Presented at the meeting of the Association, Sept. 9-11, 1953.

* J. C. Nowell, *Redesign of a 400-Cycle Multiple-Loop Feedback Amplifier*. Thesis (B.S.), Mass. Inst. of Tech., Dept. of Elec. Engr., May, 1948.

example, are required to remain exactly constant, then a vacuum tube cannot be considered reliable. However, if the requirements are only that the filaments are emitting electrons and that no elements are short-circuited, a vacuum tube can be considered relatively reliable. These two extremes are mentioned to point out the basic concept that reliability is a function of the arbitrary limits of acceptability placed upon the characteristics of the component or element in question. The computer amplifier.

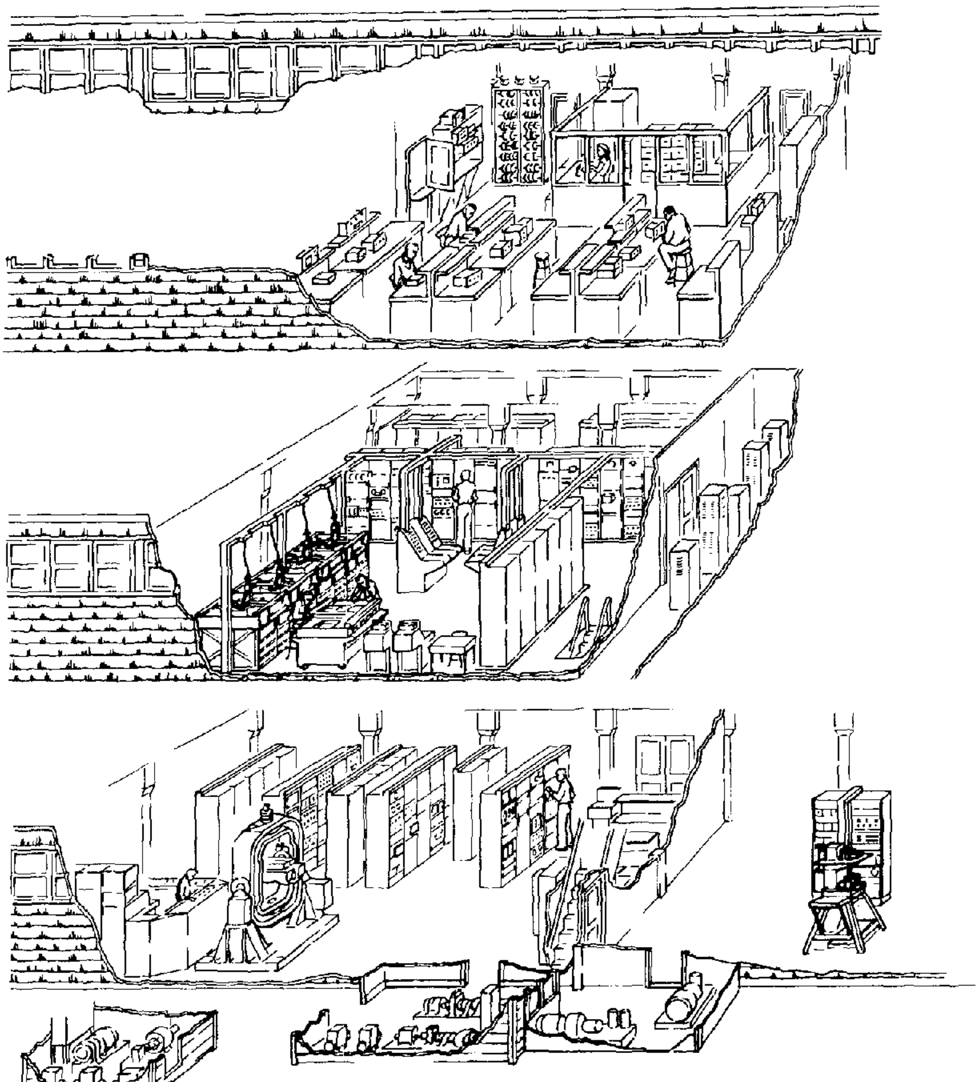


FIGURE 1

MIT FLIGHT SIMULATOR

with very stringent limits of acceptability, must use essentially the same electronic elements as the radio amplifier, for example, in which the limits of acceptability are relatively lax. However, in the computer amplifier these elements are designed into the circuit in such a way that their inherent reliability is acceptable. In addition, computing equipment must be designed for ease of maintenance.

Component Maintenance

The primary objective of a maintenance program is more than the correction of failures. Since component failures have such a direct effect upon the operating efficiency of a computer installation, the maintenance program must have the objective of improving the reliability.

The various maintenance programs which are possible vary from breakdown maintenance at one extreme to periodic maintenance at the other. In each of these instances the maintenance can be accomplished with the equipment in place, or with the equipment removed for maintenance then replaced, or with tested equipment substituted. Each of these programs requires obvious variations of the design and packaging of the computing equipment.

Early in the design of the M.I.T. Flight Simulator and Analogue Computer, the conclusion was reached that some form of maintenance by substitution would be required, and as the use of the M.I.T. Flight Simulator approached 100 per cent, the decision was made that a periodic maintenance program by substitution was mandatory for most of the components.

In planning a program of periodic maintenance, certain decisions must be made. First, a component failure must be defined; second, the measurements to be made at each maintenance check must be determined; and third, the length of the maintenance cycle must be specified.

The definition of a component failure of analogue equipment is not as simple as operate-nonoperate, but generally a failure should be considered to take place when the response of the unit falls below that required by design specifications. After the definition of a failure has been determined, the maintenance specifications must be established. The amount by which the maintenance specifications are more stringent than the design specifications determines to a large extent the per cent of component failures occurring during service.

The number and type of measurements to be made at each maintenance check are important. For example, the gain measurement of the computer amplifier is not a sufficient check. The following seven checks have been found to be very valuable:

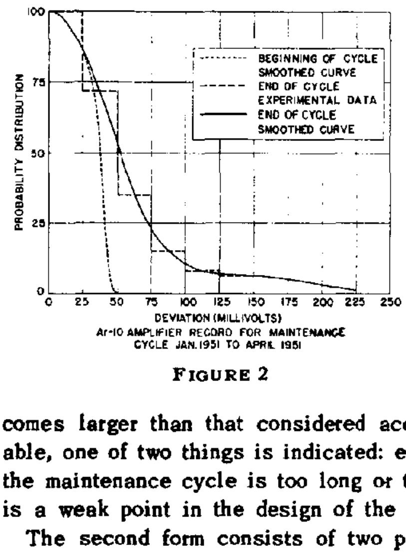
1. The noise level.
2. The maximum undistorted output, that is, linearity range.
3. The output balance, that is, the plus and minus outputs equal and opposite.
4. The overload-indicator circuits.
5. An open-loop gain test with rated filament voltages.
6. An open-loop gain test with a filament-voltage reduction; this gives a form of marginal test of the emission characteristics of each of the tubes in the circuit.
7. The closed-loop gain.

When a computer amplifier can satisfy each of the previous tests, the probability is very high that it will be a serviceable amplifier for the entire maintenance cycle.

The determination of the length of cycle is complex and involves both technical and economic factors. Therefore, cycle-length optimization is discussed as a separate topic later in the paper.

Experience has indicated the importance of keeping a complete maintenance record on each component. As a result of attempts to interpret maintenance records, it was found that a beginning-of-cycle maintenance test as well as an end-of-cycle maintenance test was worth while. In this way an accurate record is kept of the history of the component during the entire maintenance cycle. The importance of analyzing these maintenance data cannot be overemphasized.

Two forms of maintenance-data summaries have been developed to allow a quick evaluation of the maintenance program. The first form indicates at a glance the status of the maintenance program. This form contains the following six headings: unit designation, number of units, length of cycle, per cent of cycle passed, per cent of units tested, and per cent of units retested. As long as the per cent of units tested is equal to or larger than the per cent of cycle passed, the maintenance program is being kept up to date. If the per cent of units retested be-



Ar-10 AMPLIFIER RECORD FOR MAINTENANCE CYCLE JAN. 1951 TO APRIL 1951

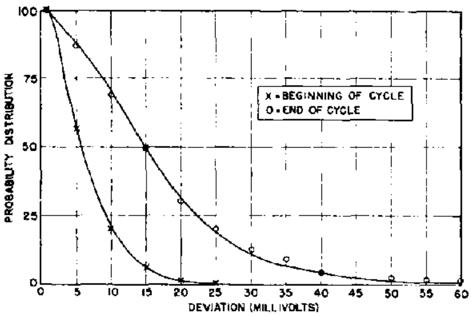
FIGURE 2

comes larger than that considered acceptable, one of two things is indicated: either the maintenance cycle is too long or there is a weak point in the design of the unit.

The second form consists of two parts. Part I of this summary consists of two tables: The first table is identical to the one just described; the second table is a summary of the units rechecked, giving the type of failure vs. the number and type of components having failed in this way. Part II of this summary consists of 2 plots of the probability distribution of gain error as a function of the gain error in millivolts. One is for the beginning-of-cycle test and the other is for the end-of-cycle test. To demonstrate the value of such curves, FIGURE 2 shows the probability distribution of gain error for the standard a-c computer amplifier. Curves of the beginning-of-cycle maintenance data and the end-of-cycle maintenance data are superposed for the Ar-10 amplifier for the maintenance cycle from January 1, 1951, to March 30, 1951.* The data were recorded at 25-millivolt intervals; therefore, the beginning-of-cycle maintenance calibration was not as valuable as it might have been with a smaller interval. Though crude, much was learned from these plots. For example, they show that 55 per cent of the amplifiers were beyond the maintenance tolerance of 50 millivolts of error in 50 volts, indicating very little marginal checking that would anticipate failures before they actually happen. The fact that the maintenance specifications were the same as the failure specifications also predicted a large number of failures during the maintenance cycle. The 50-millivolt limitation was desired but is obviously unrealistic. Therefore, a failure was defined as a gain error greater than 100 millivolts. The amplifiers, thus defined as failing, were then analyzed to determine the cause of their failure. This analysis of the 26 amplifiers (15 per cent) showed a total of 39 defects. Forty-six per cent of these defects were in tubes, 26 per cent were in condensers, 26 per cent were in precision resistors, and 2 per cent were miscellaneous. As a result of this analysis, four steps were taken: First, a filament-reduction form of marginal test was incorporated. Second, the voltage rating of a particularly weak condenser was increased. Third, a new source was found for standard resistors. Fourth, new quadrature-trim condensers were added which allowed the maintenance specifications to be tightened appreciably. FIGURE 3 shows the beginning-of-cycle maintenance and end-of-cycle maintenance data plotted for the period of December 1, 1952, through the end of Feb-

* T. F. Jones, Jr., *The Propagation of Errors in Analogue Computers.* Thesis (Sc.D.), Mass. Inst. of Tech., Dept. of Elec. Engr., 1952.

ruary, 1953. For these data, the measuring interval has been reduced to 1 millivolt. Furthermore, the maintenance specifications are one half the failure specifications, with the result that only 1 1/2 per cent of the amplifiers were failures, or approximately three amplifiers. The three amplifiers which failed do not give a sample worth analyzing. In the earlier data only 45 per cent of the amplifiers remained within the maintenance specifications during the cycle, but currently 80 per cent are remaining within the maintenance specifications, indicating appreciable improvement from marginal checking. The data for the cycle from December 1, 1952, through February, 1953, demonstrated



Ar-10 AMPLIFIER RECORD FOR MAINTENANCE CYCLE NOV. 1952 TO FEB. 1953

FIGURE 3

that 66 per cent of the 174 amplifiers had no element failures, 31 per cent required tube changes, and 3 per cent had miscellaneous defects. Of the tube difficulties, approximately one half the tubes were removed because of low emission and the other half, because of noise level; therefore, until there are major improvements in tube-characteristic stability, the next major emphasis must be placed upon cycle-length optimization.

Cycle-Length Optimization

The length of the maintenance cycle involves many factors. These factors affect the costs which help to determine the optimum maintenance cycle. The two fundamental costs involved are the cost per month for preventive maintenance and the cost per month in machine hours lost in locating trouble. If these two fundamental costs are defined as C_M and C_L, respectively, the total cost is given by the relation

$$C = C_M + C_L$$

The factors which make up the maintenance cost C_M for a particular component are

k_N = number of components to be maintained
H = time in hours required to maintain a single component
k_H = cost per hour for labor
T = maintenance-cycle period in months
B = fraction of components failing in service in time T.

These factors are related as follows:

$$C_M = \frac{Hk_H k_N(1 + B)}{T}$$

Similarly, the factors of C_L are as follows:

k_{MV} = cost per hour for machine time
T_L = average time in hours for locating a single trouble.

Therefore

$$C_L = \frac{k_N B T_L k_{MV}}{T}$$

and finally,

$$C = C_M + C_L = (k_N k_H)\frac{H}{T} + k_N k_H(H + \frac{k_{MV}}{k_H} T_L)\frac{B}{T}$$

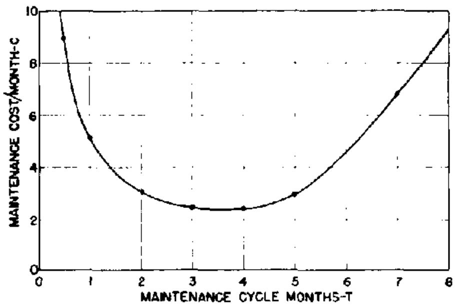
$$C = k_N k_H \left[\frac{H}{T} + \frac{B}{T}(H + \frac{k_{MV}}{k_H} T_L) \right]$$

The length of the maintenance cycle T which minimizes the total maintenance cost C can be determined analytically only if B is a known analytical function of T. Since this relation seldom exists, its fundamental forms will be derived.

Primarily there are two types of failures, those failures which are randomly independent of age and those randomly distributed about the average life of the component. If each "average-life" type failure is repaired and put back into service at the time of the failure, the new average-life distribution is no longer synchronized with that of the original group. After many average-life cycles, failures of this type will also occur randomly in the group of equipment, that is, in the same manner as those that, on an individual basis as well as a group basis, fail randomly. Now, random failures in a group of equipment give a linear B(T) curve with a slope equal to the equivalent average rate of failure from both types. Therefore the coefficient B/T in the cost equation is constant, and the cost asymptotically approaches a minimum as T approaches infinity, thus indicating that breakdown maintenance is optimum. Actually, other factors involving waiting-line theory apply as T approaches infinity. The cost equation derived assumes only one failure at a time.

In the above discussion the assumption was made that only the failure was repaired and if maintenance was performed it was limited to a checking process incapable of predicting an impending failure. If, however, a maintenance program is set up that, on the basis of time or variations of specific physical conditions, can predict an impending failure, the B(T) curve will be a delayed linear curve. Now the failure of B is essentially zero up to the value of T in the region of average predictability, at which time the value of B rises sharply and assumes a slope again equal to the equivalent average rate of failure for the group of equipment. This change in shape of the B(T) curve appreciably reduces the total cost out to the value of T in the region of average predictability. For larger values of T the cost again increases approaching the previous minimum. Except for the special case of very limited predictability, a distinct minimum is produced in the amount of the total cost, thus indicating that maintenance with predictability is clearly optimum.

The parameters k_N, k_H, and k_{MV} of the cost curve are essentially fixed, and H and



MAINTENANCE COST VS CYCLE LENGTH FOR Ar-10

FIGURE 4

T_L are the other two principal variables. For a given B(T), the level of the cost curve is determined primarily by H, and the slope of the cost curve for $T > T_{Min}$ is determined primarily by T_L. The value of effort directed toward reducing either of these parameters therefore can be calculated. FIGURE 4 shows a plot of a typical cost curve for the Ar-10 amplifier previously discussed.

There are many ramifications of reliability and optimum maintenance programs. This presentation represents only an introduction to this broad field in an attempt to initiate an organization of the information available.