where $A_w \equiv (T_w - T_0)_{max}$, and the phase lag angle is

$$\varphi = \sin^{-1} \frac{-\omega/\lambda}{[1 + (\omega/\lambda)^2]^{1/2}} \tag{5}$$

For the purpose of evaluating λ in Eqs. (2–5), the convection coefficient h may be determined from experimental data of Ref. 1, which gives the Nusselt number as a function of the Reynolds number for flow across wires. For the iron-constantan thermocouple response results presented in Figs. 1–4, values of ρ = 486 lb/ft^3 and c = 0.12 Btu/lb°F were used. It is seen from Eq. (2) that the thermocouple time constant is simply the inverse of λ.

Results

The results of the analysis were compared to experimental data obtained for the response of a 30-gage (d = 0.010-in. diameter) iron-constantan thermocouple subjected to a step change in air temperature. The step change in air temperature was achieved by thrusting the thermocouple, which was initially in thermal equilibrium with the ambient environment, into a uniform stream of hot gas at 230°F issuing from a 4- × 4-in.^{2} duct. The output of the thermocouple was monitored on an oscilloscope and the thermal response was documented with an oscilloscope camera. Data were obtained for hot air flow velocities of V = 100, 200, and 300 fps.

Figure 1 shows the comparison of the theoretical calculations with the experimental data for a step change in air temperature from T_{g_1} to T_{g_2} at $t = 0$. The dash curve is the theoretical calculation given by Eq. (2) with the numerical value of λ calculated as described previously for the actual conditions of the experiment. The experimental data are represented by the symbols, each of which is an average of duplicate data which were within 2% of each other for all data points measured. Although continuous traces of the experimental data were obtained, the agreement between the experimental data and the theoretical calculations is too close to allow definition of two discrete curves. As a result, points were measured from the continuous trace experimental data at 100-msec time intervals for the comparison shown in Fig. 1.

The near perfect agreement of the calculated curves and the experimental data must be considered somewhat fortuitous. In reviewing the various inputs to the analysis in detail, one may have expected disagreement between the analysis and the experimental data in the neighborhood of 10–20% if the anticipated differences between the analysis and the experiment had accumulated in a more unfavorable way. Even with an unfavorable accumulation of differences, however, the analysis must be considered as a good indication of the actual thermocouple response.

Figures 2–4 show some numerical results of the analysis which are of particular interest for the response of thermocouples within the inlet to a jet engine. The results given are for iron-constantan thermocouples of various wire gage sizes oriented normal to an airstream with a velocity of 400 fps at standard pressure and temperature. The curves are also considered indicative of the response for other wire orientations and indicative of the response for chromel-alumel thermocouples since the response depends only upon the value of λ, which for chromel-alumel thermocouples is within a few percent of the value for iron-constantan thermocouples for the same wire size and flow conditions. The data of Fig. 2, which give the response to a step change in air temperature, indicate a time constant of approximately 100 msec and a 99% rise time of approximately $\frac{1}{2}$ sec for the 30-gage (d = 0.010-in. diameter) thermocouple wire used in recent exhaust gas ingestion tests performed by Norair and others.

Figures 3 and 4 show, respectively, the attenuation factor A_w/A_0 [Eq. (4)] and the phase lag angle φ [Eq. (5)] as a function of frequency for a gas temperature which varies sinusoidally with time. From Fig. 3, it is seen that flat response for the 30-gage (0.010-in. wire) is limited to frequencies of less than a few tenths of a cycle/second while at 15 cps the input signal is attenuated 90%.

Reference

[1] Landenburg, R. W. (ed.), *High Speed Aerodynamics and Jet Propulsion: Physical Measurements in Gas Dynamics and Combustion* (Princeton University Press, Princeton, N. J., 1954), Vol. IX.

Aerospace Ground Equipment Reduction by Built-In Testing

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Background and Problems

THE cost of avionics and aerospace ground equipment (AGE) for a modern military aircraft is becoming a greater percentage of the total program cost with each passing year. This is not just the original cost of the avionics and the AGE to provide the necesssary support. It is also the ownership costs, which include maintenance, spare parts, facilities, and the training of personnel to keep the aircraft on flight status.

The military normally uses AGE at three levels of maintenance: organizational (flight line), intermediate (field shop), and depot. This also represents the order of urgency for rapid turnaround of equipment to maintain a mission-ready aircraft.

In addition to the problems of space and the training of personnel, there are the problems of time and equipment. The AGE that checks a complicated avionics system must provide an accuracy and reliability that inspires confidence with the human interface. The complexity of avionics subsystems is also increasing, which has a direct effect on AGE. This complex equipment requires months of training for the technician to reach the required skill level to perform the necessary maintenance. With the more complicated systems, this means less time of the technician's enlistment is spent in the actual work for which he was trained. The reenlistment rate of these highly trained technicians is also somewhat less than desired, since the knowledge gained in this training is just what industry is looking for. Providing increased space for these men and their equipment is also of concern to the military. This is especially true on aircraft carriers, where AGE quantities, if not restricted or replaced by other functions, can cause a reduction in the quantities of aircraft that could be carried otherwise.

Present testing techniques, if continued without improvement, could completely overwhelm operations at the organizational maintenance level. Even if the properly trained technicians were available, they could be required to wait their "turn" to get the aircraft. A means must be provided to reduce or eliminate organizational and intermediate level AGE and the associated long-term technician training programs.

Approach

Microminiaturization techniques applied to advanced avionics systems now make it more feasible to employ built-in self-test and fault-isolation circuits commonly known as BIT.

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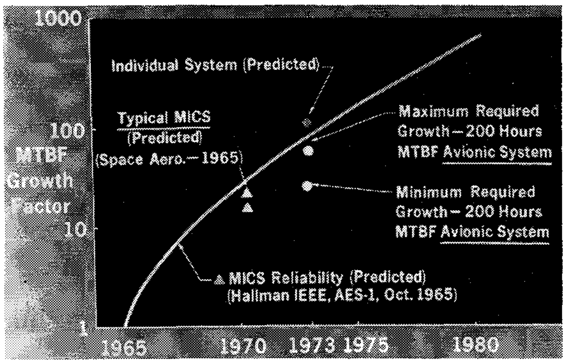

Fig. 1 Prediction of avionics reliability growth.

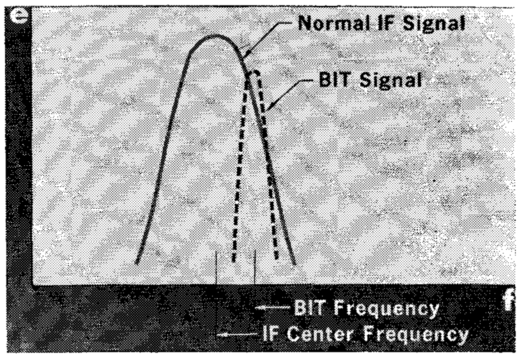

Fig. 3 BIT check through IF by low-level signal insertion.

Such techniques would not have been as practical a few years ago because of size and weight restrictions. It is necessary to have BIT designed into the avionics system concurrently with the avionics design, and preferably by the same design group. The engineering test specialist within this avionics group knows best how a circuit or subsystem should be tested. Anyone further removed from the design effort or attempting to add BIT later would have difficulty achieving equivalent results.

It is also necessary to know just how far and to what extent BIT will be used. Each function within a system presents a problem of its own and must be considered on an individual basis. If this approach is not taken, the ridiculous situation could be reached where you would need a BIT tester for the BIT. The BIT for each function must be analyzed and the probability given for its ability to correctly indicate a fault when it occurs. Once the fault is indicated, the probability of correctly locating the faulty card, module, or line replaceable unit (LRU) must be ascertained.

Another great asset of BIT is reliability through microminiaturization. Since the BIT circuitry will be integrated with the same techniques as the avionics it is checking, it will enjoy the additional reliability afforded by the techniques.

The addition of BIT will also reduce interference and coupling between wires and cable bundles in aircraft used for testing. This is possible by the comparative ease of emitter-follower addition to LRU outputs or test points, which in turn permits low-impedance cable runs between LRUs, and between LRUs and test panels or indicators.

Several reliability growth predictions due to microminiaturization have been estimated using conventional 1965 design techniques as a base (Fig. 1). These techniques are generally predicted to increase the mean-time-between-failure (MTBF) rate by 100 times in the 1970–1975 time period, where complete compatibility to microminaturization is possible. Figure 1 also shows the predicted growth factor required in 1973 to provide a complete avionic subsystem capable of 200 hr MTBF.

Some proposed BIT techniques have been suggested as possible applications to aircraft avionics subsystems. One example is an approach to the test of a ultra-high frequency (UHF) receiver (Fig. 2). In this situation, a test is proposed that gives an "end-to-end" test without disturbing incoming signals. In normal operation, it must be assumed incoming signals may be received at any time. The BIT design must be integrated to perform on a strictly noninterference, but reliable, basis. A 5- or 6- kHz signal of a few milliseconds duration recurring at 1-, 5-, or 10-sec intervals could be injected into the set at a low level to simulate voice signals. By using this frequency to modulate a carrier to the mixer, the mixer, intermediate frequency (I.F.) amplifier, second detector, and audio amplifiers can be checked. The test signal could be set at a low level to prevent interference during reception of a normal transmission and could be of such a short duration that it would be inaudible to the pilot.

In another application, I.F. amplifiers could be checked by low-level BIT signal insertion beyond the normal "roll-off" or "skirt" of the I.F. pass band (Fig. 3). A special BIT detector could be utilized at the output on either a continuous or intermittent basis as required. The BIT signal would be so small and "far away" that normal I.F. operation would be unimpaired. It should be pointed out that these tests are not diagnostic routines, but functionally integrated tests that give confirmation of normal operation.

There are areas of BIT where microcircuits can provide only a portion of the testing. One example is in the "plumbing" end of radar systems. Another suggestion proposed dithering signals for insertion into critical servo loops with a BIT monitor (Fig. 4). The amount of the dither would be set for the particular circuit involved and be capable of detection by only the BIT circuitry. The normal function and reliability of the servo loop must be undistributed. Another type of check is possible by sending a single Fourier-analyzed pulse through the system. This could be an in-flight action by the pilot, should he question the servo operation. In other applications, a microminiaturized testing circuit can be utilized for the in-flight measurement of a straight mechanical func-

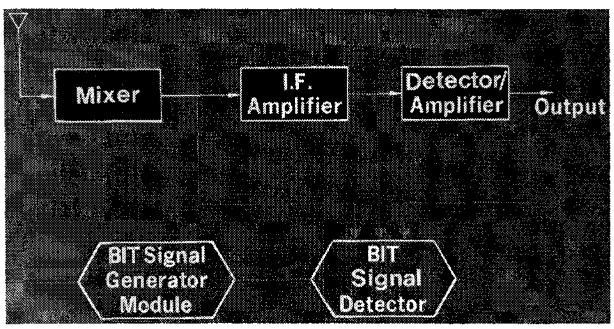

Fig. 2 A proposed end-to-end check of a UHF receiver by BIT.

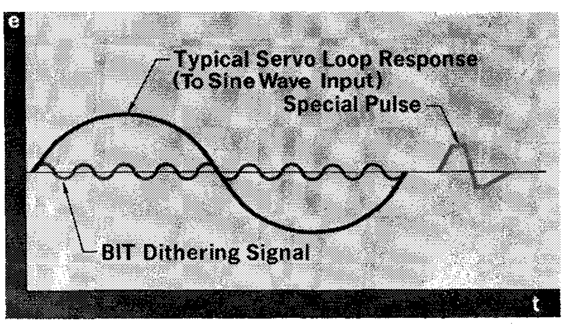

Fig. 4 Servo application of BIT utilizing special pulses and dithering signals.

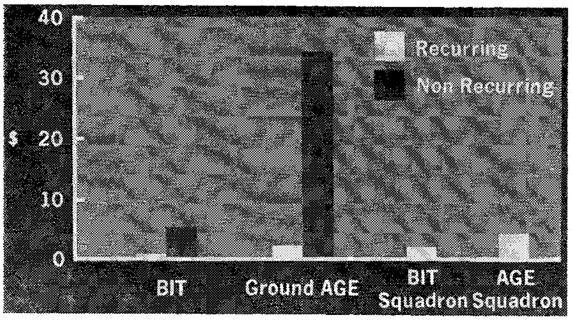

Fig. 5 Cost comparison of BIT vs ground AGE for one fighter squadron at organizational level.

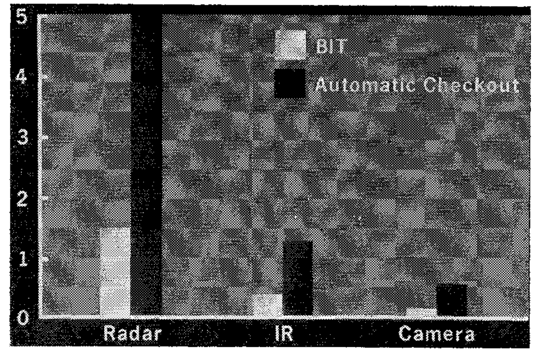

Fig. 6 Comparison of original cost of BIT vs automatic check out for three selected systems.

tion. This type of testing is similar to that being used on some commercial airlines for onboard measurement of engine parameters.

Operations

The question may arise for the necessity of BIT with the high-reliability figures quoted for microcircuits. If an avionics system is predicted to fail only once every several hundred hours, would it be less costly to exclude BIT and withhold the aircraft from flight status during avionics repair? The answer is that BIT would still pay better dividends and cost less. It will reduce fault-isolation time, which is a large portion of mean-time-to-repair (MTTR), and allow service by a technician of lower skill level. Take the case of an equipment with a 1000-hr MTBF. Prediction of just when the failure will occur during the 1000-hr period is very difficult, to say the least. It could occur in the first hour of operation.

BIT can provide continuous in-flight status. A malfunction can be brought to the pilot's attention. Even some in-flight intermittent faults can be retained by proposed indicators, for further investigation when the aircraft has landed and the power removed. A continuous "no go" indication will permit the pilot to rely on other backup equipment for the particular mission at hand, proceed to an alternate target, or about the mission entirely depending upon the mission and the particular equipment that has failed. It will also enable the pilot to give advance notice of this trouble to his base on the return flight so the proper maintenance team can be alerted.

BIT, in addition to the proper monitoring of other non-electronic equipment, could practically eliminate organizational level AGE. In most instances, it will be possible to pinpoint the trouble to the faulty LRU or module. A new or repaired module can be installed without a harmonization requirement. This will be a great advantage to Navy carrier aircraft and to an operation that requires a maximum dispersion of aircraft. It will also assist intermediate and depot operations, since the BIT portion contained within the card of LRU can be used to assist in bench testing. This will be particularly helpful in a field operation with a system such as the Navy versatile avionics shop tester (VAST).

Summary and Conclusions

Realization of the full potential of an aircraft requires that all subsystems be capable of extended periods of operation with a minimum of maintenance. Rapid turnaround requirements, limited carrier space facilities, and extended periods of deployment necessitate the use of new and faster techniques requiring a minimum ground crew and minimum AGE.

Microminiaturization with its significant increase in reliability, over-all cost reduction, and BIT integration provides an excellent means to attack this maintenance problem. BIT shows an estimated savings when compared to normal AGE at the organizational level (Fig. 5). A savings is indicated for both recurring and nonrecurring costs. It is also noted that BIT is a winner in an original (nonrecurring) cost comparison with automatic checkout equipment for three selected aircraft subsystems (Fig. 6).

The success of any plan depends in a large measure upon the unified thinking that must be put into configuration control and coordination of the over-all program. Accuracy and reliability must be maintained to insure confidence in the new approach. BIT must be designed concurrently with the original avionics subsystem design. Such an integration will probably not be immediate on all airborne systems. It could be accomplished as a gradual mix as new equipments are added to the inventory. It would be logical that the more complicated avionics subsystems would be the first to be BIT-integrated and microminiaturized. These are the avionics systems that now require the more complex AGE testers that represent a costly investment.

Training personnel to operate a BIT or VAST routine will take less time and equipment and permit additional technicians to be available at a lower skill level. The technician can be trained in ground BIT sequence operation. He will not be required to know details of the avionics subsystem under test. This will also follow at the intermediate level of maintenance. Eventually it is very possible that the only maintenance required will be BIT at the flight line and repair at the intermediate level.