System Design and Assessment Notes

Note 9

LABORATORY EMP SUSCEPTIBILITY TESTING OF BLACKBOXES: SOME PROBLEMS AND SUGGESTED SOLUTIONS

by
R. C. Keyser
Gulf Radiation Technology
A Division of Gulf Energy & Environmental Systems Company

Supported by
Air Force Special Weapons Center
under
Contract F29601-70-C-0029

March 1972

ABSTRACT

Discussions of two problem areas relating to blackbox susceptibility testing, using direct-drive simulation, are presented. The first is on the problem of simulating with sufficient accuracy realistic signal distribution within complex cables. A program to determine the simulation accuracy for a matrix of possible variables is suggested for consideration. The second is on the problem of fault isolation and suggests the limited use of analysis combined with special fault detectors to aid in the unambiguous detection of failures.

1. INTRODUCTION

This paper addresses some of the problems of laboratory EMP susceptibility testing at the blackbox level, using the technique of simulating bulk cable currents previously observed during full-system field illumination. This approach has been used extensively in past assessment programs and has been a useful assessment tool. However, during the course of these programs, questions have been raised as to the accuracy of this technique and these remain unanswered. It is the purpose of this paper to suggest a program for resolving these questions.

In the real-life case, the blackbox is mounted in an airplane, missile, etc., and is connected to a network of cables which are driven by one or more points of entry (POEs). Susceptibility testing of the box in such a real-life situation provides the ultimate in realism, but is generally impractical, if not impossible, due to the complexity of box interactions, inadequate diagnostics, inability to obtain necessary simulator field levels, etc. In addition, it is usually the most expensive approach, since testing costs generally increase as the level of assembly increases while the amount of useful data obtained generally decreases.

At the other extreme, the lowest level of assembly at which testing can be used is the circuit level. This is the ideal level in some respects, since ultimately it is the noise voltage which appears across the circuit input* that will cause circuit or system failure. It is also a convenient level to use since failures are unambiguous and circuit analysis can be used to help predict failures (assuming adequate models are available for high-frequency characteristics, breakdown characteristics,

---

*The word "input" in the context of circuit malfunction means any pair of wires, not just the actual input wires.

etc., of the components which make up the circuit). This prior analysis can aid greatly in understanding the characteristics of the noise waveform which are important to producing the circuit failure — i.e., rise time, area under the pulse, etc. The overriding problem with working at the circuit level, however, is the extreme difficulty of determining what the noise input to the circuit really is. If the particular input which results in first failure of the circuit is conductively coupled to the blackbox interface, the input pulse shape may be little changed from that which appeared at the interface, and accurate measurements may be practical. If, on the other hand, the critical circuit input is coupled nonconductively to the interface, then the input pulse shape may be altered significantly, there may be more than one path exciting the input, etc. Thus, the characteristics of the internal coupling network of the box become very important. Unfortunately, these are generally very complex and difficult to determine in sufficient detail to allow an accurate and complete analytical assessment of vulnerability. The unit-to-unit variation may also necessitate use of several models to represent a number of boxes supposedly of the same configuration.

Susceptibility testing at the blackbox level represents an intermediate step between the two extremes, and has probably been the most widely used approach. As generally practiced, this involves making measurements of the bulk cable current (i.e., the vector sum of all the individual wire and internal shield currents in a cable) at the system or blackbox interface connectors while illuminating the complete vehicle with an appropriate field, and then reproducing this same bulk cable current waveform on the cables, usually one at a time, in the laboratory. The amplitude is then increased until a failure is produced, and the corresponding current becomes the "failure threshold" for that particular blackbox interface cable. This approach, while offering improvements in diagnostics over full-system tests and improvement in realism and completeness over circuit-level tests, still suffers from many inadequacies and possible inaccuracies.

Some of the areas of concern with "direct-drive" simulation, as this approach is called, are:

1. A different distribution of voltages and currents on the cable interface for direct drive versus real drive — a demonstrated fact and probably the most serious source of error.
2. Assumes common-mode current — a very serious error source, if differential mode drive of a cable occurs in real life. If, in fact, the drive is really common-mode, this is not a problem.
3. Generally does not simulate multiport drive of a blackbox — a potentially serious problem when nonconductive paths between more than one interface connector and a given circuit exist, also a demonstrated fact.
4. Wave shapes difficult to duplicate — a serious problem to the extent that circuit failure thresholds are wave-shape-dependent, which is reasonably expected to be the case.

The problems listed above, and possibly others not listed, all relate to the problem of simulating in the laboratory the exact (or at least acceptably accurate) distribution of vector currents and voltages on all the interface connectors as occur in a real-life field illumination. A problem of a different sort is being able to actually diagnose blackbox failures.

The problem of diagnosing failures may, at first glance, appear to be rather simple. In fact, there are frequently some rather serious difficulties in doing so. Some of these are as follows.

1. Observing that a failure has occurred — the normally available system/blackbox outputs may not be adequate to detect, within an acceptable time after occurrence, that a failure has occurred.
2. Identification of the responsible circuit — even if a failure symptom is detected, it will frequently be the case that more than one circuit could have caused the symptom. Identifying unambiguously the guilty circuit may then be extremely difficult, if not impossible.
3. Determination of coupling path — most circuits will be susceptible through more than one coupling path. Again, identifying the guilty path unambiguously may be very difficult.

The use of available test connectors (which are not normally connected in the operational configuration) or other special diagnostic connections to alleviate these problems unfortunately alters the coupling network and may result in altered threshold levels.

The overall susceptibility testing problem must, therefore, be addressed in two parts, with the dividing line between the two at the interface connectors.

2. SUSCEPTIBILITY TESTING PROBLEMS

2.1 CURRENT SIMULATION

As noted previously, the usual parameter to be measured during both field illumination and laboratory direct-drive simulations, as a measure of simulation accuracy, is bulk cable current (BCC). This current is the vector sum of the individual currents which are flowing on all of the conductors passing through the current probe being used for the measurement. But it is not at all difficult to show that an almost unlimited number of very different distributions of current on the several conductors can produce the same vector sum. Therefore, a priori, we know that identical BCC is not a sufficient condition to guarantee the accuracy of the simulation. But now a very legitimate question to ask is: Is there anything special about the way real POEs drive cables, the way simulators drive cables, and/or the properties of the cables and terminations themselves which inherently will result in an acceptably accurate simulation, or which can be used in an appropriate manner to produce an acceptably accurate simulation?

Consider, for example, that in any practical cable there will be coupling between wires, resulting in crosstalk. The degree of coupling will be a function of cable construction, certainly, but will nevertheless always exist, and only the values of coupling parameters will be different for different cables. Now, at a point between the common-mode POE which excites a given cable and the cable termination, and sufficiently remote from both, the common-mode voltages are expected to be nearly equal for all wires. The point of this example is that for such a case the method of driving the cable is unimportant (except that it must be common-mode); therefore, any direct-drive simulation method would be adequate.

The critical length of cable which must exist between the POE direct-drive point and the box under test, in order to produce this desirable situation, will be a function of several parameters, e.g., the frequencies involved, the cross-coupling parameters of the cable, the initial uniformity of signal distribution at the POE/direct-drive point, termination impedances, cable routing, etc. In a great many practical installations, the length of a real cable combined with the values of its controlling parameters will be such that the rather idealistic uniform distribution of common-mode signals will not exist at any point. Then the manner of exciting the cable for direct-drive simulation becomes very important to producing an accurate simulation.

Recognizing, then, that an arbitrary nonuniform signal distribution will generally exist on a cable at the point of BCC measurement, the question is: How can we determine what that distribution is and how can we reproduce it in the laboratory? The simplest answer to this question is to simply apply a brute-force approach; i.e., measure the vector current in each conductor in the cable individually and then force these same vector currents to flow in the simulation, using as many generators as are required to accomplish this task. Unfortunately, this approach destroys the primary advantages of the BCC technique, which are fewer required measurements and minimum disturbance of the system being assessed. It is also not possible to use this brute-force approach for past assessment programs where all of the available data are in the form of BCC measurements.

What is needed, then, is a thorough study of the sensitivity of signal distribution on cables to the pertinent parameters such as distance from POE/direct-drive point, termination impedances, cable parameters, method of cable excitation, etc. In particular, the study should address the problem of designing better techniques for measuring cable signals and then properly reproducing them in the laboratory. Due to the difficulties previously discussed, these new techniques are expected to be somewhat more complex than pure BCC measurements but less complex than making measurements on every wire. But the important point is that these new techniques will have a sound, experimentally verified theoretical basis, and well defined limits of applicability and accuracy.

A technique that is considered a prime candidate for meeting the requirements of maximum simplicity, consistent with acceptable accuracy, is the grouping of wires for both the field illumination measurements and laboratory simulation driving. For example, it is reasonable to expect that, if a POE excites a short cable with a relatively uniform common-mode voltage distribution, the interface current distribution will be dominated by termination impedances. Thus, it would be reasonable to group wires for this case according to termination impedances and then measure the bulk bundle currents (BBC) and simultaneously reproduce these in the laboratory simulation. As another example, if a POE excited a group of wires in a short cable preferentially, then it would be appropriate to bundle and excite these same wires preferentially in the simulation. But whatever the governing criterion, an important element to the success of this technique is a priori knowledge of which criterion (or criteria) is correct. This knowledge can be gained from the sensitivity study previously mentioned. The result of this study would be a set of validated techniques of field measurements and laboratory simulation based on wire-grouping.

The preceding discussion of grouping illustrates but one possible approach to improving the current simulation side of the susceptibility testing problem. As the sensitivity study progresses, other such schemes may suggest themselves and these should also be investigated.

The following paragraphs, broken down into specific study areas, outline a possible plan to accomplish this study.

2.1.1 Method of Cable Drive

A cable may be excited by three different, basic mechanisms — electric field coupling, magnetic field coupling, and conductive coupling. Real POEs may involve one or more of these mechanisms, and the mix may vary if more than one mechanism is present. It is the purpose of this part of the study to:

1. Characterize the reasonable range of POE types as to their basic coupling mechanisms and the mix of mechanisms which may exist for each. POEs in which one mechanism clearly dominates (by, say, 20 or 40 dB) would be identified.
2. Characterize the various direct-drive schemes that are used (i.e., capacitive coupling via a foil wrap, inductive coupling via transformers or distributed wire coupling, and conductive coupling) as to their basic coupling mechanisms.
3. Derive for 1 and 2 above equivalent generators which can be used with conventional circuit analysis codes to excite lumped-parameter cable models.

The program to accomplish tasks 1, 2, and 3 should be an iterative program of analytical predictions verified and improved by experiment.

2.1.2 Cable Parameter Study

The cross-coupling parameters of the cables used in actual systems and in laboratory simulation will be important in determining the signal distribution on these cables and the way in which this distribution changes with distance. It is the purpose of this part of the program to determine the limits on these parameters in order to ensure that the sensitivity studies do not extend into impractical areas. Among the cables expected to be studied are the following examples.

1. A cable with maximum crosstalk should be examined. This cable would have no shielding of the conductors, and the conductors would be arranged so that they are parallel throughout their length, in order to maximize crosstalk. "Fat" and "thin" wire versions of this cable should also be examined, since different coupling parameters will be maximized by these different cases. It is anticipated that these cables would have to be specially constructed, since normal commercial practice is to minimize, not maximize, crosstalk.
2. A cable with minimum crosstalk should be examined. This cable would have all shielded conductors, spiral conductor lay, etc., in order to minimize crosstalk. It is expected that this cable (or cables, if needed) could be purchased rather than fabricated. That is, the best obtainable commercial cable construction is expected to accurately represent the best real-system cables.

The determination of cable parameters would be done experimentally, based on available experience in cable-modeling. The parameters would be determined on a per-unit-length basis, and models for any arbitrary length of cable can then be created.

2.1.3 Termination Impedance Study

This is expected to be a brief study. Its purpose is to determine the range of parameters to be expected in the terminations. The study would be in two parts, the first part devoted to actual circuit inputs and the second to "transmission line" characteristics of the interior wiring of the blackbox. The former is necessary principally to determine any nonlinearities and the latter to determine the true nature of "shorts" and "opens" (neither of which really exists at high frequencies).

2.1.3 Sensitivity Study

With knowledge of drive functions, cable parameters, and termination characteristics gained from the previous studies, all of the data required to perform an overall sensitivity study are available. This study is expected to utilize the capabilities of modern computer codes to solve large network problems.

The manner of performing this study would be to determine the signal distribution at the defined interface point of the model for the matrix of variables which have been identified. The exact nature of this matrix is yet to be defined, and is expected to be time-varying during the course of the study. The problem is, of course, to reduce the matrix to as small a size as will accomplish the desired task. With the number of variables already discussed, the number of solutions required is potentially very large, with resulting high cost. The variables matrix must include, but not necessarily be limited to: cable cross-coupling parameters, cable conductor-return circuit parameters, cable overall length, termination impedances, drive-point coupling mechanism(s), and frequency.

Particular emphasis should be given through the sensitivity study to detecting and understanding patterns of signal distribution, since these can be used to establish correct criteria for the grouping of wires in a cable for field measurements and laboratory drive. Another important element of the study of grouping should be establishing the tradeoff between accuracy of laboratory simulation and simplicity of grouping — i.e., the fewest possible groups. For example, the study may show that using three bundles will give distribution agreement within a factor of ±5, using five bundles gives agreement within ±2, etc. That is the sort of information which the engineer preparing a test plan can put to immediate practical use, thus taking the results of the study out of the realm of the abstract in which so many past efforts have ended. In fact, the whole emphasis of this study should be geared toward practical application of the results. The ideal result would be a preliminary "user's manual" which would outline various ways to simulate field excitation by laboratory direct drive and the expected error range of each simulation technique. The results of the sensitivity study would also, conversely, bound the errors on past direct-drive tests in order to provide a measure of the uncertainty limits of past assessment programs.

2.2 FAILURE IDENTIFICATION AND ANALYSIS

The impetus for improving the technique of laboratory simulation of cable currents is to ensure that accurate susceptibility testing of systems or blackboxes can be performed. The reasons that laboratory tests are needed to supplement full-scale system-level testing were mentioned earlier: (1) the need to produce threat (or greater by a margin of, say, 2 to 10 X) cable currents, and (2) the need for more exhaustive tests with better diagnostics than are available in the field. The problem of obtaining the required currents is a matter of equipment design primarily, and will not be discussed in this paper.* The problem of testing and diagnostics, however, will be discussed in the paragraphs that follow. Throughout these discussions, it will be assumed that the problem of simulating correct interface signal distributions has been solved, and that multiport drive will be necessary.

Having solved the problem of how to simulate accurately the real-life excitation, the question then arises as to just how the testing should be conducted, what use can be made of analysis, how failures can be detected

---

*It should be noted, however, that pulsers capable of being externally triggered (i.e., synchronized with equipment under test) up to 400 kpps with outputs of 10 amps into 50 ohms with 8-nsec rise/11-nsec fall times and 25-nsec minimum pulse duration are commercially available.

and isolated, etc. Answers to these questions will be proposed in the following discussion.

Before proceeding, however, let us consider how the nature of the blackbox to be tested will affect the test procedures used. It is clear that the complexity of the box function and internal makeup will strongly affect the relative ease or difficulty of performing adequate susceptibility testing. By far the most difficult problems are presented by a digital computer. The principal characteristics which are responsible for these problems are:

1. Digital computers are susceptible to transient upset as well as permanent damage. By their nature, transients are much more difficult to detect and isolate.
2. A limited number of outputs are available for normal observation, and in general, each of these may be altered by a large number of internal circuits. Thus, an output state change does not identify a specific circuit failure.
3. A digital computer may exist in a very large number of possible internal states, and it is easy to show that the state of a given circuit can affect the sensitivity of itself and of other circuits, as well as the detectability of an upset.

Because it is the most difficult to test, the digital computer will be used as the basis for the following discussions. The ideas discussed can then be applied as necessary to simpler testing situations.

One of the questions asked above was "What use can be made of analysis?" A carefully proportioned combination of pretest predictive analysis and post-test diagnositic analysis would make optimum use of this tool. The predictive analysis would be applied in the form of circuit analysis to determine upset and damage thresholds of the interface circuits only. These are selected for the predictive analysis because (1) they represent a relatively small subset of the total circuit types, thus minimizing the analysis tasks, (2) their coupling paths from the interface are conductive and are, therefore, not expected to significantly alter the signals reaching the circuits, and (3) the circuit threshold predictions combined with signal distribution data can provide very useful data on expected BCC thresholds for purposes of test planning. In particular, since upset of the interface circuits is expected to be the lowest-level failure, the predicted failure level of these can be used to set the lower limit of BCC that will be required. (The test should, of course, start at some margin, say a factor of 3, below the lowest predicted threshold.) The diagnostic analysis is just what the name implies; it would be used only after a failure has been observed as an aid to locating unambiguously the guilty circuit. It combines circuit analysis (again for upset and/or damage thresholds) with analysis of an identified radiative coupling path.

A second important question that was asked was: "How can failures be detected and isolated?" This is basically the diagnostics question and is a sticky one indeed for transient upset. (Permanent damage can be detected by ordinary diagnostics which are designed to detect just this type of failure, i. e., defective components. The only requirement is that enough time be allowed between noise pulses for the diagnostic routine to be run and the failure flagged.) The three characteristics of digital computers previously mentioned give the whole problem of locating specific failures of logic circuits a "looking for the needle in a haystack" appearance. Consider, for example, characteristics 1 and 2, the limited number of available outputs to monitor a very great many more internal elements and the transient nature of upset failures. For a given output, there may be several logic paths which could have caused a state change, even within one clock interval after the noise pulse. As the number of clock intervals between noise pulse and error indication increases, the number of potential logic paths which could cause that failure increases also.[*] To help identify unambiguously the guilty path, a special logic state indicator[†] with memory could be constructed. In application, the box would be opened, several of these detectors attached at appropriate locations determined by examination of the possible guilty logic paths, the box resealed and again tested. In retesting, careful note would be taken of the threshold level to see if any change occurred due to the presence of the detector. After again observing the failure, the box would be reopened and each detector interrogated to see if it had been disturbed. Thus, the guilty path could be located unambiguously. A second application of the detectors would be used to identify the exact circuit in the path where the failure is occurring. Finally, the diagnostic analysis could be used to locate the coupling path by which the energy reaches the circuit.

The problem of characteristic 3, the many possible logic states, is probably the most difficult of all. It will almost always be completely impossible to inject a noise pulse into every possible state. For example, there are 2^N possible states in a computer with N active memory elements — i. e., flip-flops (the state of magnetic memory is not expected to have any effect on thresholds) — and for N = 200 (a very small computer), $2^N > 10^{12}$ states. About the best approach that can be suggested is to

---

[*] This indicates that the diagnostic program should be carefully written to minimize the number of clock intervals that can occur before the error is flagged. That would tend to at least reduce the size of the "haystack" somewhat.

[†] This could be really a very simple device, consisting of only a quad 2-input gate IC and a Zener power supply if required. Such an IC would be wired as a set-reset flip-flop capable of accepting either positive or negative logic signals as required. Power would be derived from the normal power buss. The size would be quite small, somewhat larger than a flatpack IC package. Leads should, of course, be kept very short to minimize the unavoidable coupling path alteration, and lead attachment is probably the biggest problem.

apply as many pulses as possible and then, assuming a normal threshold distribution, thresholds near the lowest possible will be observed. Then the probability of being in a lower threshold state at least becomes acceptably small. An exception to the above approach is the existence of states which are of long duration, e.g., a non-compute or standby mode which may be critical. These may exist for a sufficient length of time that the probability of receiving a noise pulse during this time is significantly greater. Such special modes should be identified and thoroughly tested independent of the tests for normal operation.

Based on the above discussion, a suggested procedure for susceptibility testing of blackboxes might consist of the following steps.

1. Using circuit analysis and component burnout data, predict the thresholds for upset and damage of conductively coupled interface circuits only.
2. Combine the thresholds predicted in (1) with signal distribution data to obtain BCC thresholds for upset and damage of interface circuits.
3. Use the upset threshold BCC divided by a factor of 3 as the lower limit of BCC required for the test.
4. The upper limit of BCC will be the criteria level multiplied by a factor of 3, or the point at which failure occurs, whichever is higher. That is, test to first failure, even if well above criteria.
5. Conduct the test by introducing noise pulses simultaneously on all of the wire groups as required to produce the correct signal simulation. Start at the lowest level as determined in (3) above and increase the level in steps (say, 3 dB) until first upset is observed. (The diagnostics program should be designed to detect I/O failures and internal failures independently.)

6. Continue to increase the level (but in smaller steps, e. g., 1 dB) and observe and record as a function of level each upset failure, up to a level of 1/3 the predicted interface burnout threshold.
7. Analyze functionally to determine the possible causes of each observed upset failure.
8. Using diagnostics previously discussed, determine which of the possible causes was, in fact, responsible for each failure.
9. Continue the tests at higher levels approaching interface circuit burnout, still using small steps. At each level, run both the I/O and internal diagnostic routine before going on to the next level. (Smaller steps are required for burnout testing since it is not possible to overshoot the threshold and then go back to determine it more accurately.)
10. Observe and record failures as a function of level, as before. Internal upset failures are diagnosed as before.
11. If 3X criteria has not been reached, continue on to this level.

This completes the "normal" mode susceptibility testing. If special modes have been identified, these should now be tested in the same manner, after repairing all permanent damage failures. The procedure used is basically the same except that the noise pulse generators will have to be synchronized to place the pulse in the desired proper time location — i. e., during occurrence of the special mode.

3. SUMMARY

This paper has presented a two-part approach to resolving some of the existing problems of laboratory susceptibility testing.

Section 2.1 addressed the problem of obtaining an acceptably accurate simulation of field drive in the laboratory. The suggested study program is strongly oriented toward technology due to the nature of the problem to be solved, and is one which is urgently needed in order to satisfactorily put to rest the question of the accuracy of the BCC approach. This question has been raised repeatedly by agencies and contractors engaged in EMP assessment programs, and will continue to be raised until a satisfactory answer is obtained.

Section 2.2 suggests not a study program but rather a procedure which may be used for diagnostic testing of blackboxes. A selective use of analysis is also suggested as an adjunct to the test program.

Acknowledgment

The author is grateful to Dr. R. L. Mertz, Deputy Division Manager of Gulf Radiation Technology, for his helpful suggestions and criticism.