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Tech-notes

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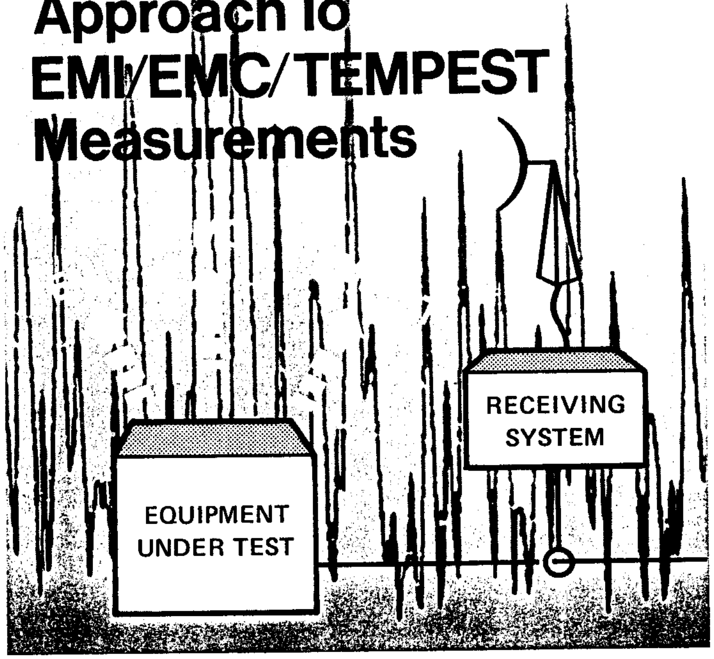
A Modern Receiving System Approach To EMI/EMC/TEMPEST Measurements



Since the early 1940's, the growth of the electronic and communication technologies has given rise to many specialized fields of test and measurement which support these technologies in electronic systems. Examples of some closely related, but distinct, fields of specialization are electromagnetic interference (EMI), electromagnetic compatibility (EMC), TEMPEST, and electromagnetic pulse (EMP). The techniques and disciplines incorporated within each field are intended to insure the survivability of electronic equipment, subsystems, and systems in an adverse electromagnetic environment. A second, but equally important objective, is to insure the equipment, subsystems or systems themselves do not degrade the electromagnetic environment.

Accomplishing the desired EMI/EMC objectives requires a specialized knowledge of the electronic processes, electromagnetic environment and the test techniques required for the prediction of electromagnetic effects. However, the user or designer of electronic equipment can benefit from a general knowledge of these fields.

This issue will present an introduction to EMI, EMC, TEMPEST and EMP fields of test. It will also describe characteristics required of measurement instruments, and explain why these characteristics are needed.

A description of terms such as EMI, EMC and Frequency Management, relevant to the specialized fields of test and measurement can be found in the Glossary of Terms on page 11.

In order to demonstrate the meaning and importance of EMI, EMC, TEMPEST, and EMP, consider the following hypothetical situation. Assume that a "black box" exists in a subsystem within the aircraft shown in Figure 1. In this example, further assume that the aircraft is to perform a reconnaissance or electronic warfare mission. It is not necessary to state the specific purpose of the black box, or the aircraft's mission in this particular example.

The black box selected in this example must do two things:

1. It must survive in the electromagnetic environment within the aircraft's structure.

2. It must not contribute any degradation to the environment within the aircraft, or degrade the power and signal busses to which it is connected.

The process of assuring that both of these conditions are achieved is commonly referred to as the EMI/EMC process.

EMI Test—First Step Leading to System Level Electromagnetic Capability

The term electromagnetic interference (EMI) refers to the prediction, measurement and suppression of electromagnetic interference. The term EMI is normally used at the black-box level. However, it may be extended to the subsystem or system level as well. The measurement and suppression of EMI is normally referenced to tolerable interference levels (limits) of military specifications such as MIL-STD-461A.

Ideally, the control of electromagnetic interference begins with the initial design of circuitry within the black box. At a very early stage of the circuit design, potential interference sources can be identified and steps taken to eliminate them. An alternative is to contain the interference source by shielding, filtering, and other interference control techniques. However, it is impossible to eliminate all potential sources of interference. For example, it is impossible to eliminate signals which are necessary to the function of the black box, such as the local oscillator in a receiver or a clock in a digital system.

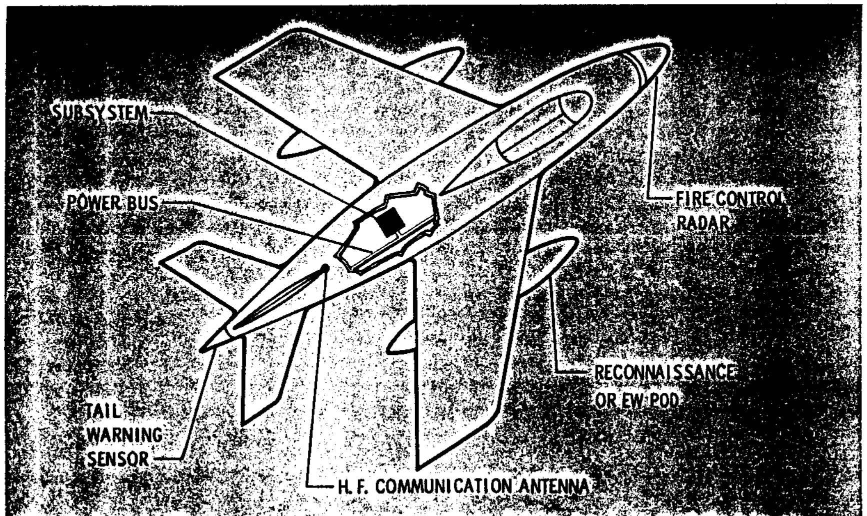


Fig. 1. A simplified example of the subsystem (black box) as installed in an aircraft used in reconnaissance or electronic warfare missions.

Since all sources of interference within a given piece of equipment cannot be entirely eliminated, it is necessary to perform a qualification test to determine potential interference levels which may emanate from the equipment. This emanation may occur as radiation or conducted interference on power and signal lines connected to the equipment. A simplified qualification test set up is shown in Figure 2. The equipment under test (EUT) is placed on a bench (normally covered with a copper ground plane) within a shielded enclosure. The shielded enclosure insures the normal (ambient) environment at the location of the test will not interfere with the measurement of interference generated by the EUT.

Sensors required to measure both conducted and radiated interference from the EUT (the black box) are connected to test instrumentation to measure interference levels. These sensors normally consist of RF current probes which encircle power and signal lines. Appropriate antennas are used to cover the entire frequency range of interest.

While the equipment under test is installed in the shielded enclosure, an additional test, the susceptibility test, is performed. This susceptibility test is the first step in assuring system level compatibility. It consists of using very high-power signal generators and antennas to bombard the EUT with high-level radio frequency energy. The objective is to determine if the EUT is susceptible to particular signals or external interference levels generated in the environment around it. It is a means of determining whether or not the EUT will survive in a dense electromagnetic environment which may be present at a particular final installation.

The EMI and susceptibility tests are only the first steps in the overall objective of insuring electromagnetic com-

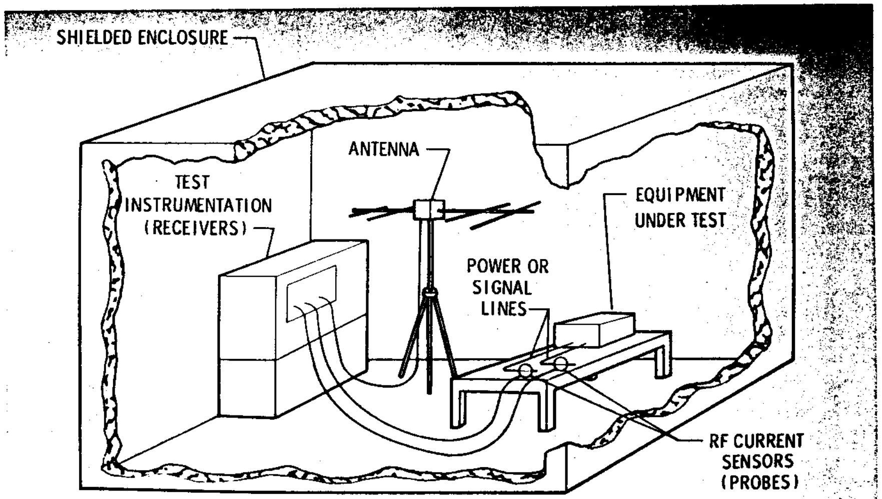


Fig. 2. A typical qualification test set up for the measurement of interference generated by Equipment Under Test (EUT).

patibility of a *complete system*. Electromagnetic *compatibility* is the final objective of the EMI/EMC process. Electromagnetic interference measurements and susceptibility tests performed to specification limits such as those specified in MIL-STD-461A are merely aids to this end.

Once the EMI and susceptibility test have been performed, and the EUT (the black box) has been found to meet the specification limits, the EUT must be installed in the final configuration and a system-level test must be performed.

System Electromagnetic Compatibility—EMC Testing

The black box used in the example of Figure 1 is, of course, only one of many such boxes that are installed in the aircraft. The only way to insure that all such boxes will operate in the presence of each other is to perform an overall system-compatibility test.

This test is the actual exercising of all subsystems in the aircraft, in all possible modes, and monitoring the effect on all other system components. Various military specifications govern this EMC test. For example, MIL-E-6051D is the specification governing such tests for the U.S. Air Force.

The exercising of all equipment, in all possible modes, while monitoring the effect on all other subsystems is a formidable task on a modern aircraft. However, such is the requirement to insure electromagnetic compatibility.

TEMPEST Test

The objective of the TEMPEST field of test and measurement is to totally eliminate any undesired radiation from the equipment of interest. Since only a small amount of additional information on the TEMPEST field can be discussed, this article will combine the TEMPEST test with the EMI test. Those interested in the TEMPEST field must refer to the appropriate government agencies.

The EMP Field of Test

The electromagnetic pulse, or EMP, is normally the electromagnetic result of a nuclear explosion. The effects of EMP upon solid state circuitry can be disastrous. The electromagnetic pulse resulting from a nuclear explosion can destroy semiconductor devices or otherwise disrupt the operation of equipment within the field of the electromagnetic pulse. Hardening of devices and circuits to minimize the EMP effects is normally accomplished using EMP simulators (for obvious reasons). The test is somewhat related in nature to the susceptibility test performed on equipment to determine its resistance to electromagnetic interference.

Related Fields of Test and Measurement

The terms electromagnetic interference and electromagnetic compatibility are normally used in the sense previously described. However, there are related fields of test and measurement which are very often included under the broad definition of EMC. For example, not only must unintentional electromagnetic radiation be controlled, but intentional radiation must be controlled to insure that it does not interfere with the reception of other signals within the frequency spectrum.

Frequency management is one field directly related to the control of intentional radiation. An excellent example of frequency management is the assigning of frequencies to various electromagnetic emitters such as radio and television stations, military and civilian radar, and other navigational equipment. Communication signals, radar signals, and other such intentional radiation sources must frequently operate in close proximity. It is imperative, therefore, that these emitters be assigned frequencies that result in an overall electromagnetic compatability of the environment.

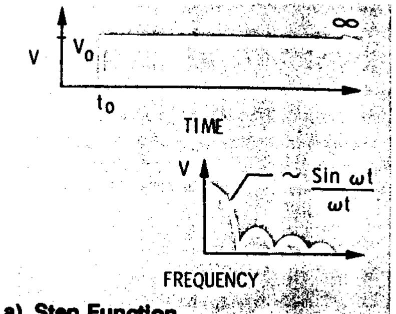
Clearly, then, the EMI, EMC, TEMPEST, and frequency management processes are merely steps in an escalating chain of events leading to the overall compatibility of the system. Ultimately, the electromagnetic environment is a complex geographical area including, perhaps, an entire continent. The example of the black box installed in an aircraft could be expanded to include a squadron of such aircraft, and then to all other electromagnetic users within a geographical area where the aircraft may operate. With today's supersonic aircraft, this geographical area could encompass a very large part of the world.

Signal Sources of Electromagnetic Interference

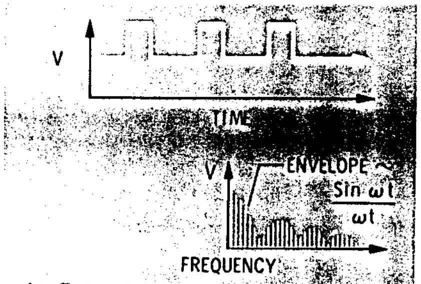
Requirements for instrumentation used in the measurement of electromagnetic interference, or signals present in a TEMPEST test, require user familiarity with the characteristics of signals encountered in these tests. A few of these signals are illustrated both in the time and frequency domain as shown in Figure 3. All of the signals illustrate the *broadband* characteristics of signals encountered in the measurement of electromagnetic interference.

Figure 3a illustrates how a simple switch closing can generate interference in very high-frequency radio equipment. As shown, the voltage is zero for any time before t_0, and a constant potential value V_0 after t_0. The voltage rise from zero to V_0 occurs in nearly zero time. In the frequency domain, the voltage step produces a signal with very broad frequency characteristics. The actual signal has a characteristic proportional to $\frac{\text{Sin}\ \omega t}{\omega t}$. The result is a signal source that can cause interference to the surrounding circuitry.

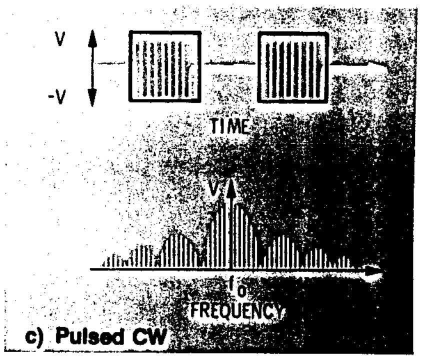
Figure 3b illustrates a repetitive signal which can produce continued interference. The frequency character-



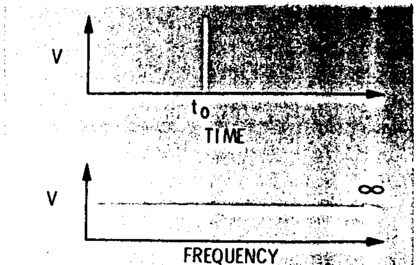
a) Step Function



b) Pulse Train



c) Pulsed CW



d) Impulse

Fig. 3. Time-domain and frequency spectra waveforms of signals encountered in the measurement of electromagnetic interference.

istics of this pulse train are similar to that of the single voltage step function. However, in this case, the frequency domain representation of the pulse train consists of harmonics spaced at regular intervals from the fundamental frequency of the pulse train to, theoretically, infinity. The amplitude envelope of the individual harmonic components is again proportional to $\frac{\sin \omega t}{\omega t}$. For very-narrow pulses (that is, pulse widths which are very narrow in relation to the period of the pulse train), this spectrum can be very broad.

Figure 3c is an example of a radar or digital radio-type signal generated within the equipment and unintentionally radiated. This pulsed-CW signal is a composite of a continuous-wave signal which is modulated, or gated, by a pulse. In this case, the frequency domain is identical to that of the pulse train illustrated in Figure 3b, with one exception: the spectrum is "double-sided" and is centered about the CW signal frequency, f_0.

Figure 3d is an example of a single-impulse signal. It consists of a single pulse of, theoretically, zero width, finite height, and finite area within the pulse. When the impulse is translated into the frequency domain, a spectrum results which is continuous and constant in amplitude from zero frequency-to-infinite frequency (theoretically). Although the impulse, as defined here, cannot be exactly reproduced in practice; there are many signals generated by electronic equipment which do approximate the theoretical impulse function. Lightning generated in thunderstorms also have impulsive signal characteristics.

When the undesired signal encountered is a narrow-band type signal, filtering or other techniques can be used to simply eliminate it. However, if the undesired signal occupies a relatively large segment of the frequency spectrum, it is often impossible to entirely eliminate it without suppressing desired signals as well.

The instrumentation normally used in the measurement of these unwanted signals are receivers, sensors (current probes, antennas, and other transducers that transform electromagnetic energy into a voltage for the receiver input), and generators or ancillary equipment. Since the receiver has the characteristics required for the measurement of signals present, it is the dominant piece of instrumentation in the electromagnetic interference or TEMPEST test procedure.

Receiver Characteristics for Measurement Applications

The previous examples of signals encountered in a hypothetical electromagnetic interference test also establish the characteristics required of a receiver for EMI/EMC/TEMPEST measurement applications. Some of the features common to all measurement applications and required of EMI/EMC/TEMPEST receivers are listed in Table 1. Most of the required receiver characteristics are established by the nature of the signals encountered in the EMI/TEMPEST environment. However, the receiver characteristics of an extremely large dynamic range, RF preselection, ability to handle large amounts of data, and the IF and video outputs for external displays are requirements of a system nature.

An extremely large dynamic range and RF preselection are both related to the impulsive type signal encountered. In order to measure both low-amplitude, fast-rise-time signals and large amplitude impulsive signals, the instantaneous linear measurement range of the receiver must be very large. The fast-rise-time signal precludes any available time for attenuator switching. Therefore, the measurement of a peak-amplitude signal requires an instantaneous linear measurement range that is very broad.

The requirement for RF preselection is imposed by the nature of the impulsive-type signals. The receiver will essentially integrate (sum) energy present in the spectrum over the bandwidth of the receiver front-end. If no filtering is present between the antenna terminals and the first active devices in the receiver, the receiver front-end will overload and produce spurious readings which are not representative of the signal level itself. The flat response of an impulsive type signal shown in Figure 3d will result in a front-end overload if no filtering is provided in the receiver front-end. This simple example readily illustrates why wide-open front-ends, such as those used in common spectrum analyzers, are unsatisfactory for electromagnetic interference measurements.

The ability to acquire large amounts of data, and the provision for various IF and video outputs for external displays are a direct result of the quantity of data that must be acquired in the course of a normal EMI/TEMPEST test. In an EMI test, the frequency range of interest may encompass all of the spectrum between 20 Hz to 18 GHz. Therefore, a continuous scan, from the low-frequency limit to the high-frequency limit, is the only practical means of acquiring the required amounts of data. A minor change in the equipment under test may require the scan to be repeated. Many repetitions of the scan in a single test are not uncommon.

The IF and video outputs for external displays are requirements consistent with the objectives of the EMI test. In the course of the EMI test, the receiver must scan a very wide frequency range and must analyze, as rapidly as possible, the characteristics of the signal being measured. In addition, the test may require that the signal be recorded for later analysis using off-line techniques such as analytical programs within a digital computer.

Measurements That Add to Receiver Requirements

Where the objective of the measurements is to totally eliminate any undesirable radiation, the receiver must exhibit features in addition to those listed in Table 1. These features include increased sensitivity, wider bandwidths, and a larger number of bandwidths.

Increased sensitivity is the direct result of a test requirement to detect the presence of *any* signal present. The wider bandwidth requirement is related to the nature of the signals encountered in such tests. The larger number of available bandwidths allows the user to optimize the receiver bandwidth for a particular type signal. The ideal is the "matched-filter"

BROAD BANDWIDTHS
CALIBRATED MEASUREMENT CAPABILITY
WIDE FREQUENCY RANGE
ABILITY TO MEASURE BOTH NARROW AND BROADBAND SIGNALS
ABILITY TO CAPTURE AND MEASURE FAST NARROW PULSES
NARROWBAND AND BROADBAND SENSITIVITIES
EXTREMELY LARGE INSTANTANEOUS DYNAMIC RANGE (WITHOUT SWITCHING ATTENUATORS)
RF PRESELECTION
ABILITY TO ACCURATELY ACQUIRE LARGE AMOUNTS OF DATA
IF AND VIDEO OUTPUTS FOR EXTERNAL DISPLAYS

Table 1. EMI/EMC/TEMPEST Receiver Characteristics

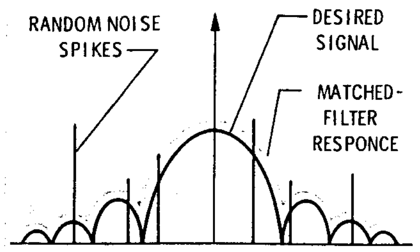


Fig. 4. The matched-filter response to pulse-type signals.

response shown in Figure 4; however, it is not achievable in most practical situations.

The pulse-type signal illustrated in Figure 4 can be used to show the advantage of the matched-filter response. For example, if noise is present in the frequency range occupied by the desired pulse-type signal, then the noise will have a detrimental contribution in the reconstruction of the pulse-type signal at the receiver output. However, by constructing a matched-filter response identical to the spectrum of the desired signal, the contribution at the receiver output by the desired signal will be maximized, and the contribution from noise or other undesired effects will be minimized. While this capability (or an approximation to it) is desirable in any receiver, increased sensitivity makes it mandatory.

An example of a receiver that has application to EMI/EMC/TEMPEST measurements is shown in Figures 5 and 6. The receiving system, the WJ-8940A, consists of a digital control unit, a tuner/synthesizer unit, and an IF/demodulator unit. Combined, the three units comprise a receiving system that meets or exceeds all of the requirements established for measurement of electromagnetic interference and related applications. Key features of the WJ-8940A Receiving System are listed in Table 2.

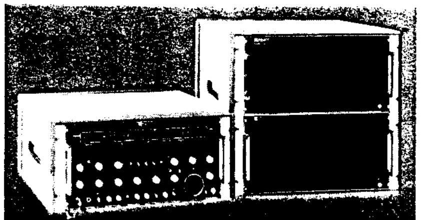


Fig. 5. The WJ-8940A Receiving System consisting of Digital Control Unit, Tuner/Synthesizer Unit and IF/Demodulator Unit.

Current Trends—System Approach to EMI/EMC/TEMPEST Measurements

The WJ-8940A Receiving System is an example of state-of-the-art instrumentation for the measurement of electromagnetic interference. It also includes characteristics imposed by current trends toward a *system approach* to such measurements. While the basic characteristics required of EMI/EMC/TEMPEST measurement receivers can be related to the characteristics of the signals involved, the reasons for a system approach to these measurements are not so readily apparent.

The basic reasons for adopting a system approach toward EMI/EMC/TEMPEST measurements are more closely related to: 1) the sheer volume of data which must be acquired, 2) the trends in EMI/EMC/TEMPEST qualification tests, and 3) in the required data reduction, correction and final data formatting which must be accomplished in performing the test functions. The increasing trend toward production type testing (using sampling techniques) places considerable strain upon the user of manual data gathering techniques. In addition, manual data reduction is a formidable task which may consume a larger number of man hours than the actual test itself. It is, therefore, becoming increasingly apparent that acquisition, reduction, and data formatting must be combined into one continuous task. The use of a system is essential if the volume of testing required is to be economically feasible.

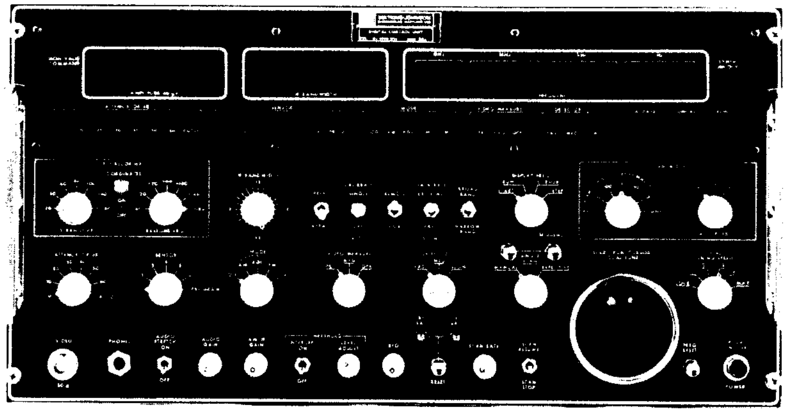


Fig. 6. The WJ-8940A Receiving System's Digital Control Unit.

Implementing the System Approach

The implementation of the system approach to data acquisition (measurements) places additional requirements on the receiver design for EMI/EMC/TEMPEST measurements.

The receiver must be designed *from the outset* for system application. A receiver designed for manual measurements is rarely, if ever, adaptable to system application. Adapting a manual receiver is a difficult process at the

WIDE BANDWIDTHS (50 MHz)

WIDE RANGE OF BANDWIDTHS (17 BANDWIDTHS ARRANGED IN A 1, 2, 5 SEQUENCE
FROM 200 Hz TO 50 MHz)

INTERNAL AUTOMATIC CALIBRATION WHICH NORMALIZES RECEIVER GAIN OVER THE ENTIRE
FREQUENCY RANGE

LARGE INSTANTANEOUS DYNAMIC RANGE:

100 KHz IF, 110 dB
21.4 MHz IF, 90 dB
160 MHz, 60 dB

AUTOMATIC DIGITAL READOUT OF SIGNAL AMPLITUDE IN dB μV AND dB μV/MHz

AUTOMATIC (AUTO-RANGING) ATTENUATOR PROVIDING 60dB ATTENUATION IN 10 dB STEPS

SIX SENSOR (ANTENNA OR PROBE) INPUTS WITH MANUAL OR AUTOMATIC SELECTION AT
APPROPRIATE FREQUENCIES

CAPABILITY TO SYNCHRONIZE THE DETECTOR SAMPLING PERIOD WITH AN EXTERNAL
PULSE TRAIN INPUT

SIGNAL INTERCEPT FUNCTION WHICH STOPS THE RECEIVER SCAN WHEN A SIGNAL EXCEEDS
A PRESET THRESHOLD

AUDIO STRETCH WHICH ALLOWS THE OPERATOR TO HEAR NARROW PULSES

BUILT-IN SCAN CONTROLS

BUILT-IN SYNTHESIZER FOR FREQUENCY ACCURACY

BUILT-IN CONTROLS FOR XY COORDINATE PLOTTING

Table 2. Characteristics of the WJ-8940A Receiving System

very least. However, once the receiver has been designed for direct application to a system (such as an automatic RF data acquisition system using a digital computer), integration into a system is a relatively straightforward task. Thus, the system designer is free to concentrate his efforts toward the development of computer programs or other important functions necessary to implement the system approach.

Conclusion

This article has illustrated the EMI/EMC/TEMPEST procedure by use of a typical example. Although the example is somewhat simplified, the overall process describes the actual test steps necessary to bring a basic equipment item from design, through qualifications, to the final objective of electromagnetic compatibility. As part of this objective, we have provided an outline to the characteristics required of receivers for EMI/EMC/TEMPEST measurement applications.

Editor's Comment

We have presented in this issue an overview of some specialized fields of test and measurement. We hope to devote a future issue of Tech-notes to the technical details of instrumentation, test procedures, and design requirements for the EMI/EMC/TEMPEST process.

Author: Kenneth Bach

Mr. Bach joined the Watkins-Johnson CEI Division in 1975 and is currently Section Head, Applications Engineering. Ken's responsibilities include assisting W-J customers and potential customers in the design of receiving systems, and in solving receiving system requirements with state-of-the-art digital control and IF demodulator equipment. His previous responsibilities at CEI included work in the development of EMC/TEMPEST equipment and system requirements.

Ken earned his BSEE at the University of Maine in 1963, followed by his MSEE degree in 1965. In addition to his extensive managerial experience, Ken was an instructor in the Electrical Engineering Department at the University of Maine. He is a member of the IEEE and ETA Kappa Nu.

Glossary of Terms

EMC—Electromagnetic Compatibility—The process of insuring all electronic equipment within a system or subsystem works in harmony without mutual interference.

EMI—Electromagnetic Interference—Any radiated or conducted energy of an electromagnetic nature, which is undesirable, or unnecessary to the normal functioning of a particular equipment.

EMP—Electromagnetic Pulse—A high-level pulse of particular characteristics generated as a result of a nuclear explosion.

EUT—Equipment under test.

Frequency Management—The process of assuring orderly and efficient utilization of the electromagnetic spectrum.

MIL-E-6051D—USAF specification governing EMC tests for systems.

MIL-STD-461A—Tri-Service specification governing requirements for EMI testing.

RFI—Radio Frequency Interference—an obsolete term replaced by "EMI".

TEMPEST—A test similar to the EMI test but with much more stringent requirements.