Distributed RF Instrumentation System

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New technology addresses the shortcomings of traditional network and spectrum analyzers.

Introduction

A new generation of instrumentation systems is now available for conducting RF measurements and tests. These systems are designed to overcome the shortcomings inherent in traditional network and spectrum analyzers. Some systems combine digital signal processing and electromagnetic technologies. One in particular, an automated system for sensing and processing electromagnetic radiation, has been developed under contract to the Air Force Phillips Laboratory (AFPL). The setup offers distributed multi-channel network and spectrum analyzer functionality which can be customized to automate specific RF applications such as pre-certification of electronic components and shielding effectiveness measurements.

This article describes the advantages of such a system and discusses how it differs from traditional network and spectrum analyzers.

The system was designed to overcome the shortcomings of traditional network and spectrum analyzers. Some of these differences involve:

- Low capital and operational costs for an equivalent number of data channels and recorded data rates
- Use of spread-spectrum excitation signals for measuring transfer functions
- Radiation emission detection capabilities in a noisy urban environment
- Localization of EM source and identification of propagation path
- Lower weight and increased portability
- Elimination of interference with nearby electronics or transmitters
- Automated EM test applications

A New Design

This particular system is the result of an innovative application of dual technologies, patents for which are in process.

SPREAD SPECTRUM EXCITATION (SSE)

In addition to the familiar narrowband CW mode of operation, the system has a SSE mode which uses wideband random (white noise) or pseudo-random excitation signals to estimate the EM shielding effectiveness of systems. The system SSE mode of operation includes calculation of the important coherence function. A valid transfer function estimate requires that the excitation (input) and test point (output) signals be highly correlated (a coherence function near one). The system automatically uses the coherence measurement either to increase the number of samples averaged or to increase the transmitter power output until the desired coherence is achieved over the band of interest. The theory behind SSE is discussed in the next section of this article.

DISTRIBUTED INSTRUMENTATION SYSTEM

The system has a distributed and expandable architecture. All modules are time and frequency synchronized, and perform as a single cohesive instrument.

The system uses an innovative modular architecture for RF measurement systems. The system modules can be spatially distributed; up to 2-km spacing is possible. The system can address an unlimited number of modules. The digital fiber optic link provides complete EM isolation while transporting the control signals as well as the recorded data. Driven by a runtime LabView interface, the system allows for full customization and the integration of other general purpose interface bus (GPIB) instrumentations. The flexible design architecture provides high-fidelity test data at a low cost.

Currently, there are three types of system modules:

- Digital Interface Controller — interfaces a computer with the system network
- 1 GHz Waveform Synthesizer — synthesizes a 3 MHz wide modulated waveform centered about any carrier frequency in the range of 10 kHz to 3 MHz
- 1 GHz Receiver — records and digitizes 3 MHz wide signals centered about any carrier frequency in the range of 10 kHz to 3 MHz

All modules are configured and controlled from the system software. Once the network is up and running, there is no need to make manual adjustments to the receiver or waveform synthesizers. This setup not only adds

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to the accuracy of the measurements, but also saves valuable engineering time.

The Theory Behind SSE

Using traditional fast Fourier transform (FFT) techniques, it is easy to compute the power spectral density (PSD) of a digitized data sequence. However, it is difficult to determine the accuracy of these estimates because no quantitative indicator is given as to the quality of the estimates. Stochastic processing is superior to traditional FFT techniques because it allows signals to be extracted from noisy or noise-limited data and provides a measure of the data quality.

SSE processing consists of time-sliced, coherent, cross-correlated transfer function averaging. The stochastic process gives a measure of the quality of the PSD estimates, known as the coherence function, which is used to ensure that estimates are derived from correlated data and not from system-generated artifacts or noise. Since a correlation process is used, a minimum of two independent receivers are required and they must gather the data simultaneously.

Stochastic processing exploits the stationary random nature of an electromagnetic excitation source to estimate PSDs. It improves confidence in the estimate by using cross-correlation to reject uncorrelated noise, such as noise due to the measurement system itself. The error bars of a stochastic measurement system are determined ultimately by the number of samples and desired frequency resolution. Very tight confidence bounds can be achieved by increasing the sampling window. Low power sources can be used which eliminate the necessity of using interference-generating and relatively high power sources.

A key element of stochastic processing is the use of a coherence function which determines the degree of correlation between a source and a test point. This is a direct result of cross-correlation, and provides the noise immunity. An overview of the processing theory follows.

We attempt to model a system by its impulse response h(t) by

$$y(t) = h(t)*u(t) + e(t)$$

where

$y(t)$ = output due to some input $u(t)$
$e(t)$ = additive noise
$*$ = convolution

In the frequency domain, this becomes

$$Y(\omega) = H(\omega)\, U(\omega) + E(\omega)$$

To make a stochastic estimate of the transfer function $H(\omega)$, we estimate spectral densities and compute the following ratio:

$$\hat{H}_c(\omega) = \frac{S_{yu}(\omega)}{S_{uu}(\omega)}$$

where

$H_c(\omega)$ = estimate of $H(\omega)$ based on the cross spectral density $S_{yu}(\omega)$
$S_{uu}(\omega)$ = estimated power spectral density (PSD) of the input $U(\omega)$

We compute the square of the coherence of the estimate, $\gamma_{yu}^2(\omega)$, as:

$$\gamma_{yu}^2(\omega) = \frac{|\hat{H}_c(\omega)|^2}{|\hat{H}_a(\omega)|^2} = \frac{|\hat{S}_{yu}(\omega)|^2}{\hat{S}_{uu}(\omega)\hat{S}_{yy}(\omega)}$$

where the estimate of the magnitude-squared of $H(\omega)$ is given by:

$$|\hat{H}_a(\omega)|^2 = \frac{\hat{S}_{yy}(\omega)}{\hat{S}_{uu}(\omega)}$$

$\gamma_{yu}^2(\omega)$ is unity for a perfect correlation and zero if the input and output are completely uncorrelated. Thus, we use $\gamma_{yu}^2(\omega)$ to reject estimates of $H(\omega)$ in the regions where $\gamma_{yu}^2(\omega)$ is low. Note that $U(\omega)$ is assumed to represent a stationary sequence, that is, its statistical moments do not vary in time. Therefore, $U(\omega)$ can be a broadband noise source or a traditional sinusoid (i.e., CW source).

The Welch method with no overlap (also referred to as the Bartlett method) is used to estimate the cross-correlations. With this method, a discrete Fourier transform (DFT) of a window of input and output digitized waveforms are computed. The results are multiplied by their own complex conjugates to obtain an estimate of auto-spectra. The DFT of the input is multiplied by the complex conjugate of the DFT of the output to obtain an estimate of the cross-spectral density. The window length and sampling interval determine the frequency resolution and bandwidth of S_{yu}.

Multiple estimates of S_{yu} are averaged to obtain an overall estimate. The error variance of the estimate is inversely proportional to the number of windows. It is given by

$$\sigma_s^2 = \frac{\sigma_{so}^2}{N_w}$$

where

N_w = number of windows
σ_s^2 = error variance of the averaged estimate
σ_{so}^2 = error variance of one estimate

Depending on the length of the data record and desired frequency resolution, the error variance can be made arbitrarily small.

The SSE Theory in Practice

A system is excited with a spread spectrum-type signal that has dominant frequency content over a wide, continuous frequency band (wideband). The bandwidth of this excitation signal is several thousand times larger than a CW tone. Therefore, one spread spectrum pulse can excite the system with the equivalent of thousands of CW tones. By comparing the frequency spectrums, it is apparent that one spread spectrum pulse has the spectral content of many CW pulses. This advantage greatly decreases the time required to make transfer function measurements. Interference with other electronic devices is considerably reduced, because the excitation signal is at a much lower power density per Hz. Because the excitation is over a continuous band, as opposed to CW, which changes frequency in discrete steps, vital transfer function information is not missed.

Low-power excitation measurements are possible because of the excitation signal duration and the transfer function processing method used. A high-power short duration pulse has the equivalent average power of a low-power, long duration pulse. Because this excitation signal has a duration comparable to CW durations, which is much longer than an impulse duration, measurements can be made at low power. As part of the transfer function processing, a coherence function is computed. The coherence is an indicator of the correlation between any two measurements (typically input and output). Since noise is uncorrelated by definition, the coherence function allows measurements that are corrupted by noise to be identified and rejected, as well as identifying good quality data. Therefore, excitation power levels can be reduced without compromising measurement quality.

Environmental (ambient) signals can be used as the system excitation, which is a feature that is unique to stochastic processing. Transfer function measurements that can be made without actively producing excitation signals are the best type of non-interference tests because no external signals are produced. The coherence function makes ambient excitation feasible because of the noise reject capability.

Network Analyzer Applications

The system has proven to be a better alternative for traditional network analyzers for a variety of applications. The following is one such application.

SHIELDING EFFECTIVENESS MEASUREMENT SYSTEM

Nuclear Electromagnetic Pulse (EMP) Hardness Surveillance tests currently conducted using a network analyzer-based system can be streamlined with the system. Due to its distributed architecture, the system can place recording instrumentation at each test point location, as opposed to the more traditional technique wherein test point signals are transmitted to a central location for recording. The technique dramatically improves the dynamic range of the system, especially for weak signals, and avoids troublesome analog data link contamination of the data.

Figure 1 shows the successful comparison of shielding effectiveness measurements made using a distributed system versus a network analyzer-based system. This verification experiment was conducted at DSWA's ARES facility in January 1997 on a ALCM cruise missile. Each ALCM test point was simultaneously instrumented using both systems, and the comparison was successfully made for several test points over the entire 1-GHz bandwidth.

Spectrum Analyzer Applications

The system's features makes it a more complete field measurement tool compared to the traditional spectrum analyzers. Several applications are described.

AUTOMATED IEC1000-4-3 INSTRUMENTATION SYSTEM

The system software automates IEC1000-4-3 testing. The standard test specification has been programmed in the system software. As a result, running the test (calibration and equipment under test) has become a much easier task. Advantages include:

- *Ease of Use* (from the EMC engineer's point of view). New systems are available which preclude a steep learning curve and are often EMC engineer-unfriendly.
- *Reduced Hardware Components.* A single system can replace a number of discrete modules such as: signal generator, power meters, data acquisition system, amplifier/antenna selector, digital fiber optics data link, and control computer. Thus, it greatly simplifies control software development, improves system reliability, and significantly reduces maintenance and system calibration costs.
- *Reduced Test Duration.* A system is capable of completing IEC-4-3 calibration and EUT testing in about 1 to 2 days (which includes production of a preliminary test report).
- *Future Expansion.* One system can be reused to perform conducted immunity (IEC-4-6) as well as radiated emission testing. This capability dramatically reduces overall EMC instrumentation capital costs as well as labor training costs. Further, the system software can easily be expanded to include other standard certification testing such as EC, FCC and more.

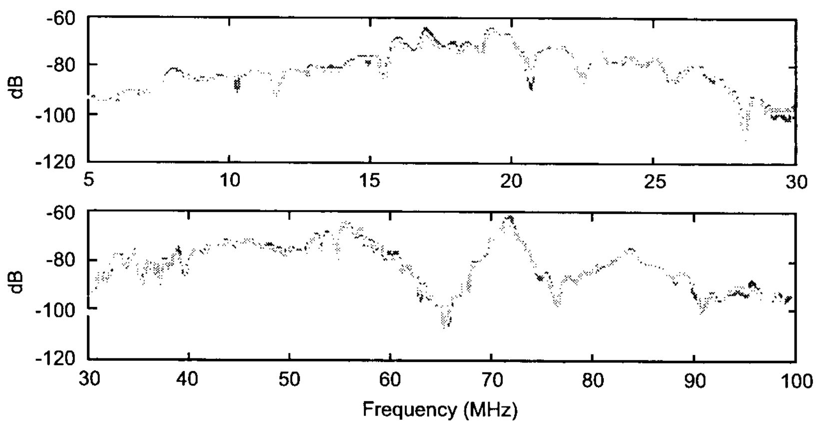

Figure 1. *Shielding Effectiveness Measurement of ALCM Cruise Missile at Two Different Frequency Bands Measured by the System and a Network Analyzer-based System. The two results are in perfect agreement over all frequencies.*

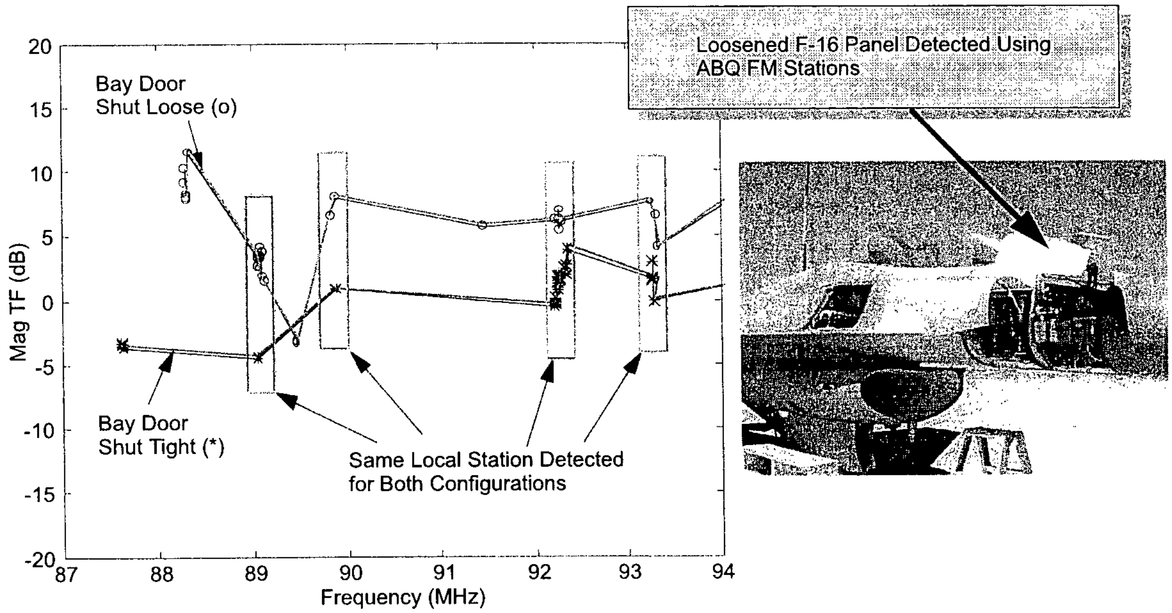

Figure 2. *The System Successfully Determined the Degradation Caused by a Loosened Equipment Bay Door by Monitoring the Albuquerque FM Bands.*

HARDNESS SURVEILLANCE SYSTEM USING AMBIENT MAN-MADE RADIATORS

During the May 1996 test series at the AFPL Leslie facility, a test point inside a F-16 avionics bay was monitored as the preprogrammed receivers scanned the Albuquerque FM band. A coherence function near unity was observed at the center frequencies of several local FM stations. Estimates of the shielding effectiveness at these frequencies were consistent with the results of the earlier active test. To demonstrate hardness surveillance test capability, the same test point was monitored with the equipment bay door shut tight and then loosened (to simulate degradation). As seen in Figure 2, several FM stations were detected (using the coherence function) in both configurations. At every common station frequency, approximately 8 dB of degradation was measured with a loosened equipment bay door. The system, therefore, can be used as a low cost, practical in-situ hardness surveillance system. It can continuously scan for local man-made signals, and for those detected, compare the resultant shielding effectiveness estimate with stored baseline values.

Conclusion

The new generation of instrumentation systems for RF measurement combine the latest in digital signal processing and electromagnetic technologies to provide EMI/EMC engineers with a complete RF test measurement and analysis system. Features to look for in instrumentation systems are modularity, spread spectrum excitation, and computer automation. These advantages will make newer systems more powerful, yet cost-effective, alternatives to traditional network and spectrum analyzers.

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