Analyzing Broadband, Free-Field, Absorber Measurements

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Abstract: We present and analyze a method for free-field evaluation of broadband absorber in a non-ideal testing environment. Using broadband, short-impulse TEM horns, a frequency-rich spectrum (equivalent pulse length < 0.5 ns) illuminates a sample of the material under test and the reflections are recorded. Unwanted reflections from the sample edges, room environment, antenna and other systematic events are mathematically removed by a combination of time gating, background subtraction and systematic deconvolution. The result is an estimate of the reflection characteristics of the center at the sample. We also present an uncertainty analysis of the measurement technique. Keywords: RF, Compliance, Absorber, Ferrite, Reflection.

Introduction
There has been a large proliferation of various absorber systems for low-frequency RF testing facilities. New compliance standards require more complete RF testing and the lack of year-round open area test sites (OATS) requires the building of indoor facilities. Since these facilities are generally a few wavelengths in size at their lower frequency limits of operation, careful optimization of the absorber system is necessary. In response to this, we have refined a technique, previously used in large facilities and with large areas of absorber,[1,2] This method can characterize RF absorber across a broad frequency range (30 - 1200 MHz) using a small sample of material (~2m square) in a non-ideal (ordinary large room) environment. The sample is illuminated with the energy from the horns; the only qualification that the measurement zone (Fig. 1) is defined by the length of the impulse response of the material, the duration of the equivalent input pulse, and the size of the sample holder. The sample can still be illuminated with the energy from the horns; the only qualification being that it must be spatially separable from the desired response. The measurement zone must be free of obstructions and must be at least large enough that when the sample holder is moved for the background measurement, the reflections from the sample holder are not included in the time range of the sample.

Measurement Methodology
The system consists of a moveable sample holder and a broadband, coherent radar system. Broadband CW energy is transmitted and received using phase-linear, TEM horns. First, the sample and the measurement environment are illuminated. Then, the sample is moved out of the "measurement zone" and the response of the system to the measurement environment is made. The difference between the two measurements is the response of the sample, the sample holder and a residual response of the shadow region behind the sample.

Note that the measurement zone (Fig. 1) is defined by the length of the impulse response of the material, the duration of the equivalent input pulse, and the size of the sample holder. The sample can still be illuminated with the energy from the horns; the only qualification being that it must be spatially separable from the desired response. The measurement zone must be free of obstructions and must be at least large enough that when the sample holder is moved for the background measurement, the reflections from the sample holder are not included in the time range of the sample.

A traditional background subtraction is then employed, using the two previous measurements, to remove the environmental and systematic reflections and to isolate the sample and support reflections. The horns and path loss are calibrated and removed from the measurement using a direct horn to horn reference. An on-axis, path-loss measurement is made for several distances and is extrapolated to the total measurement distance, \(d = \lambda A + v\). For mono-static measurements, the antennas can be calibrated using a three antenna calibration or the antenna responses can be assumed to be identical in which case we can use the on-axis two antenna measurement. By deconvolving this systematic antenna response, the reflections from the sample and the holder can be isolated.

Data Processing
The data record collected from the background subtraction and antenna calibrations include effects from the sample and its edges, the sample holder and the shadow region and the displaced sample and holder. The desired quantity is the response of the center of the sample to the
A time gate is applied to isolate sample response. The sample reflections are received earlier in time than edge reflections. The direct coupling between the antennas is received prior to the sample, but is reduced by background subtraction and gating.

The incoming pulse produces unwanted reflections that are not indicative of performance of a large area of absorber. For a sample size of 6 ft x 6 ft, we use a 2 GHz span, which generates a 0.5 ns (-6 dB width) equivalent duration pulse, so that the edges can be discriminated from the desired center response.

To identify the relative time positions of the edges and center (fig. 2) and to estimate the effects of the small sample and point sources on the broad-band data, we measured a flat metal plate with the same lateral dimensions of the absorber. The positions of the easily identifiable edges and center are noted as starting points for the search for the edges and sample response in the time record of the entire measurement.

Figure 3 shows the basic processing algorithm for extracting the sample data. Once the background is subtracted, the data are transformed to the time domain to identify the parameters for the gate. The frequency-domain data are windowed and a Chirp-Z [4] transform is applied to give high resolution around the time region of the expected sample response; alternatively, the data can be heavily zero-padded and a conventional FFT may be used. Once the sample response is identified, a frequency domain version of the gate is constructed and convolved with the signal. While the gate may be made in the time domain and multiplied with the signal, the time-domain representation has been truncated by the windowing and full frequency reconstruction is not always possible. By performing the frequency-domain convolution, all the frequency data are maintained.

The gating function is a FIR filter with a Kaiser-Bessel window [5]. The frequency-domain gate is constructed to match the time requirements and to be used with the measured data sets. Its exact form depends on the frequency spacing (Af) and number of data points, N. The gating function, G(\(f\)), is given by,

\[
G(\omega) = \frac{1}{M} \sum_{k=-M}^{M} \delta_{0} \frac{\omega}{f_{\text{max}}} \sin\left(\frac{k\delta_{f} f_{\text{max}}}{2}\right) w(k) e^{-j\frac{k\omega \delta_{f} f_{\text{max}}}{\omega_{\text{max}}}}
\]

where \(\delta_{0}\) is the width of the time window, \(\delta_{f}\) is the center of the window, \(\text{sinc}(x) = \sin(x)/x\), and \(f_{\text{max}} = N \cdot \omega_{\text{max}}\) is the maximum frequency. The number of tap weights, M, determines the falloff and pass-band to stop-band ratio of the time gate. The Kaiser-Bessel windowing function, \(w(k)\), is

\[
w(k) = \frac{1}{I_{0}(\hat{a} M)} I_{0}(\hat{a} k)
\]

In order to obtain a flat passband (<±0.02 dB), 40 dB pass-band to stop-band ratio, and a fast pass-to-stop band transition, we have chosen M to be at least 30 and \(\hat{a}\) to be approximately 5. The gating function, \(G(\omega)\), is circularly convolved with the measured data to isolate the sample’s response to the incident signal.

The antenna response must be removed to accurately characterize the sample. For bi-static sample testing, a direct horn-to-horn calibration is performed. The horns are axially and polarization-aligned to each other.
Figure 5. Setup for normal incidence testing of a small sample of ferrite/urethane hybrid absorber.

other and the path and systematic losses are calculated. A distance scan is done to determine frequency dispersion and near-field effects, and to extrapolate the path losses to the full measurement distance (fig. 4).

Measurement Data

We have measured various ferrite and urethane hybrid absorber combinations. Our tests were conducted in the NIST Free-Field Time-Domain Lab, a 7.3 x 9.1 x 5.5 m high room with no absorber or shielding to reduce reflections or isolate the test environment from external sources. The sample holder is a moveable 2 x 2 x 1.75 m high foam block with a 2 m x 2 m angled surface for placing the absorber under test (fig. 5). The angled plane of the absorber serves two functions. It reduces the reflections from the base and allows the absorber to be placed on the holder without adhesive or permanent alteration to the absorber. The ends of the TEM horns are nominally placed 2 m from the surface of the ferrite sample to minimize wave front curvature and near-field effects, and yet have sufficient differences in path length between \( \delta_s \) and \( \delta_t \) to discriminate the edges from the central sample reflection.

The direct horn-to-horn reference was taken at various distances from 0.25 m to 3 m. It was compared to the mono-static and bi-static metal plate reflections. Properly gated, the direct and reflected signals show that at the 2 m measurement distance, curvature effects are minimal. This shows that the assumption of plane-wave reflection for the gated signal introduces minimal uncertainties.

Normal Incidence

Figures 6 to 9 show the progression from initial measurements to the final reflection data for a 6 ft x 6 ft sample of ferrite tile/urethane-pyramid hybrid absorber. This normal-incidence measurement has the greatest time separation between the edges and the central area of the sample (>2.2 ns).
Proper application of the time gate is essential to obtaining quality data. The metal plate shows the earliest time at which the gate stop can be placed. Since the background subtraction eliminates the systematic reflections, the first substantial signal in the time-domain trace is the sample response itself followed closely by edge scattering. This means that the start of the time gate is relatively unimportant to the final results as long as it is placed well ahead of the start of the signal. The high-frequency results (>100-200 MHz) are stable, but differences can be seen in the low-frequency results when the stop value of the gate is changed. As the stop value of the gate is moved along in time (fig. 8), there are local maxima or minima around the metal plate's edge position that seems to be indicative of the entrance of edge scattering into the data. These maximum or minimum are a good compromise between capturing as much of the sample reflection while rejecting edge effects. A close analysis of the time record (fig. 7) shows the fine structure of the reflection in the absorber system. The differing lengths of cones can be distinguished, as well as the typical ferrite tile unbalanced triplet (fig. 7). We can infer how to improve the different parts of the absorber system when analyzing the time and frequency data together.

**Oblique Measurements**

Oblique, bi-static measurements show the off-normal performance of absorber systems. In small chambers, where the walls are near the central line of propagation, these reflections must be minimized for proper chamber operation.

Measurements of the same mixed ferrite/urethane sample shows the capabilities of the technique to determine forward scattering (fig. 10). Two horns are set in a bi-static configuration to illuminate the sample and receive the forward-scattered energy. In order to preserve polarization purity, the horns must now be rotated and inclined to match the angled surface of the sample holder. As in the normal-incidence case, since the sample is illuminated symmetrically, the leading and trailing edges both appear in the time record concurrently and add in-phase. At 40° incidence, the central time response will come in only 1.1 ns ahead of the start of the edge scattering. Proper time gating is essential to obtain correct values for forward scattering. The oblique-angle scattering is more complicated than the normal-incidence case. However, the edge scattering is reduced by the presence of the urethane in comparison to the metal plate.

Drift is a larger problem for the bi-static measurements. Strong horn-to-horn coupling and multi-path effects may appear 4-6 ns in front of the sample response. The stability requirements for the whole system are much more stringent in order to accurately remove the direct coupling component and avoid data corruption.

The evolution from raw data to calibrated forward scattering is shown in figures 11-14. The choice for the placement of the time gate was not obvious from the gate stop plot (fig. 11), because there were two local maximum within a fairly short time interval. The time-domain record (fig. 12) shows clearly that the choice of the first maxima at 27.7 ns cuts deeply into the last part of the ferrite triplet. The choice of the 28 ns gate stop still allows for the ferrite response to dampen, while minimizing the edge effects (fig. 13).

The raw data for the oblique-incidence case is shown in Figure 14.
Figure 12. Early time gate application can distort the response of the material under test and lead to uncertain results.

Figure 13. Proper positioning of the time gate stop at 28 ns yields good edge reductions while maintaining the fundamental response structure.

Figure 14. Raw data for the oblique measurement of the ferrite/urethane hybrid in vertical polarization.

Figure 15. Ferrite/urethane hybrid calibrated reflection coefficient for 40° incidence and vertical polarization. Final results are relatively invariant to time gate position.

The target and background differ more than in the normal incidence case because of the lack of a strong reflection term from the antenna. The horn-to-horn coupling and the sample are much more apparent when comparing the background and sample measurements. The signal cleans up considerably again when the results of the subtraction are gated. The calibrated response is also not as sensitive to time gate positioning. This may be due to the edge effect being inverted with respect to the response and allowing for less intrusive removal when applying the time gate.

The edges that most severely affect the measurements at large oblique angles are the co-polarized edges (vertical in v-pol and horizontal in h-pol measurements). The co-polarized edges in measurements for horizontal polarization lack the spatial separation of those at vertical polarization and introduce much larger uncertainties into the measurement. The effects of the non-removable sample edges show up as large variations in the final results below 100 MHz (Fig. 16). An oblong (2m x 2.5 to 3m) sample will allow for greater separation with

Figure 16. Sample reflection coefficient for 40° incidence and horizontal polarization. Variance below 100 MHz implies sample geometry is too small to isolate sample and edge reflections.
a minimal amount of added material.

Uncertainty Analysis
A general uncertainty analysis for the oblique vertical polarization measurements presented in this paper is shown following the rough outline of Taylor and Kuyatt[6]. Random and systematic components are combined and assigned maximum values that are approximately equal to a coverage factor, K=2, when comparing to uncertainty values based on standard deviation. Generally, overall uncertainty decreases as frequency increases from 10 MHz to 1 GHz and is roughly equal for the oblique and normal cases with the exception of time gating at large oblique angles. For measurements near a resonant null of the absorber, these values can increase dramatically.

Table 1. Reference Uncertainties (dB values)

<table>
<thead>
<tr>
<th>Reference Horn-to-Horn Measurement</th>
<th>50 MHz</th>
<th>100 MHz</th>
<th>1000 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Repeatability (random effect - 5 measurements)</td>
<td>0.7</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Range Errors / Distance Correction</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Drift</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Time-Gating</td>
<td>0.5</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Polarization Mismatch</td>
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<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>SNR</td>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
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<tr>
<td>I/Q Imbalance</td>
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<td>neg</td>
<td>neg</td>
</tr>
<tr>
<td>Non-linearity</td>
<td>neg</td>
<td>neg</td>
<td>neg</td>
</tr>
<tr>
<td>RSS Uncertainty [dB]</td>
<td>1.0</td>
<td>0.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2. Sample Measurement Uncertainties (dB values)

<table>
<thead>
<tr>
<th>Sample Measurement</th>
<th>50 MHz</th>
<th>100 MHz</th>
<th>1000 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavefront curvature / Plane-wave Assumption / Near-Field</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Measurement Repeatability (random effect - 3 measurements)</td>
<td>1.0</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Range Errors / Distance Correction</td>
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<td>0.2</td>
</tr>
<tr>
<td>Drift</td>
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<tr>
<td>Time-Gating</td>
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<td>Polarization Mismatch</td>
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<td>0.1</td>
</tr>
<tr>
<td>Sample Orientation</td>
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<td>0.2</td>
<td>0.3</td>
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<tr>
<td>SNR</td>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>I/Q Imbalance</td>
<td>neg</td>
<td>neg</td>
<td>neg</td>
</tr>
<tr>
<td>Non-linearity</td>
<td>neg</td>
<td>neg</td>
<td>neg</td>
</tr>
<tr>
<td>Horn-to-Horn Reference</td>
<td>1.0</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Overall RSS Uncertainty [dB]</td>
<td>1.7</td>
<td>1.4</td>
<td>1.1</td>
</tr>
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</table>

Conclusion
Both normal and oblique measurements on absorber can be made with a pair of broad-band, phase-linear horns and a real or synthetic short-impulse transmitter and receiver. The result is a small, compact and inexpensive system that can accurately characterize the plane-wave response of an absorber system using a small sample in an ordinary, uncluttered room. The broadband nature of the measurement can aid in characterization and optimization of the absorber system with minimal expense.

References