Reverberation Chamber
“Statistically deterministic Chaos”

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Overview

- History
- Theory
- Electromagnetic Environment
- Statistical Distributions
- Calibration/Working Volume
- Correlation
- Applications
- Limitations
History

- 1947 Patent
- 1968+ Early papers
- 1976+ Instituto Universitatio Navale (Paolo Carona)
- 1977+ Naval Surface Warfare Center, Dahlgren Division (Mike Hatfield, Mike Slocum, …)
- 1983+ National Institute of Standards and Technology (Crawford)
- 1991+ Ted Lehman Theory
- 1996+ Standards (GM, SAE, IEC, RTCA DO 160E, MIL STD)
- 1999+ NIST (Hill, Koepke, Ladbury, …)
- 2001+ Arnaut
Anechoic / Reverb Chamber

**Pros**
- Plane waves from one specific angle and polarization – great for antenna pattern measurements
- Susceptibility – Large impact can be made if the characteristics of the device being tested are known
- Emissions – Measures the radiated power in a specific direction

**Cons**
- Test time will be large if a complete test is done
- Uncertainty levels are huge

**Pros**
- Plane waves from all angles and polarizations – great model for complex environments
- Susceptibility - Uncertainty levels are much smaller and predictable (statistically)
- Emissions – Directly measures max. radiated power

**Cons**
- Test time is large (especially for susceptibility)
- No directivity information
Theory

- **Modal Structure**
  - Sum of set of basis functions, useful for visualizing variations in fields as a function of location
  - Hard to include complex tuner boundary conditions (BC)

- **Ray tracing**
  - For simple geometries can evaluate amplitude and phase
  - Convergence is a problem for complex configurations

- **Plane wave integral**
  - Electromagnetic Environment (EME) inside a (Reverb Chamber) RC can be expressed as a sum of plane waves (Hill)
  - Applies only to source free region

- **Chaos model**
  - Can predict the large change in EME for small changes in BC
  - Limited work and relevance to RC not demonstrated; (Arnaut work might change things here!)
Modal structure

- Avoid cubical cavity or cavities that have dimensions as multiples of one side
- The more complex the structure, the better the reverberation but also think about structural rigidity and repeatability

1. http://aemes.mae.ufl.edu/~uhk/mem2.jpg
Simulation of the EME inside RC

Ack: Charles F. Bunting
Vignesh Rajamani

Reverb chamber operational frequency

10.92’ x 10.58’ x 8.88’

- Avoid cubical chamber!
- Theoretical modes are calculated for the chamber size (eliminating the small regions at 2 corners)
- Higher the conductivity of the material used to construct the chamber, higher the Q
- **Rule of thumb**
  - The chamber can operate from 3x or 6x frequency with ‘x’ being the cutoff frequency of the cavity
  - At least 160 modes to start reverberation
- **IBM chamber can go from 350MHz and above**
  \( f_0 = 64.76 \text{ MHz} \)
- The energy has to be distributed among several modes
- A statistical uniform field is experienced by the use of a complex tuner
Computational model

Simulation of the Electromagnetic Environment (EME) inside Reverb Chamber (RC)

Ack: Charles F. Bunting
Chambers
Chambers – cont’d
The tuner is used to stir the field inside the chamber thereby creating a statistically uniform field over a specified volume of the chamber.

Tuner usually occupies considerable (25-30%) volume of the chamber.

Though reverb chamber testing asks for randomness, for repeatability the effects must be deterministic.

Measurement time is also proportional to the tuner settling time.
Tuners

Ack: Cessna, Christian Bruns
A well stirred RC provides a test EME that is statistically isotropic, randomly polarized and uniform within an acceptable uncertainty and confidence limit.

- **Isotropic** implies RC EME is the same in any direction (inside the usable volume).
- **Random polarization** implies that the phase relationship between polarized components is random.
- **Uniform** implies all spatial locations within the usable volume of the RC are equivalent.
Reminder

- A tuner is used to change/alter the mechanical boundary conditions associated with the chamber.

- A statistically uniform field over a specified volume of the chamber is created by rotating the complex tuner.

- Rotating the tuner once is sufficient.
Mode tuning

- Repeated fixed tuner positions, consistent with the standards requirements
- Dwell time (amount of time an EUT is exposed to a certain field level, as given by the standard) is controllable
- Provides enough setting/response time for the devices that operate with the chamber (ex: Field probes, antennas, etc…)
- Mathematically less difficult to derive boundary conditions and predict field levels
- Problem: test time is large
Mode Stirring

- The tuner is rotated continuously
- Can utilize all available independent samples
- Highest EME and lowest uncertainty available for the chamber
- Multiple tuners reduce uncertainty even further
- Problems: Mathematically very intense, Response/Settling time of devices have to be considered
Frequency Sampling (Stepped/Scan)

- Excites modal structure as a function of frequency bandwidth for fixed boundary conditions (tuner is not moved!)
- Can provide enough number of independent samples with the excitation bandwidth is large
- Problem: The sensitivity depends on the excitation bandwidth, i.e.…. statistics gets better with bigger bandwidths
Combined Stirring

- Combined stirring utilizes both the mechanical movement of the tuner along with the scan in the operating frequency.
- A well stirred field (or uniform EME) can be established.
- The number of independent samples is the product both methods operated individually.
- Problem: Very complex procedure.
Why statistics for RC?

- **In principle**, an EMC test is deterministic
  - EME determined by EM source and boundary conditions
  - Specific operating state of specific EUT in a specific configuration (e.g. cable and component arrangement)
  - Specific instrumentation configuration and procedures

- **In practice**, an EMC test has many statistical variables
  - Facility dependent
    - EME
    - Instrumentation
    - Calibration and test procedures
    - Operator and software
  - EUT dependent
    - Unit to unit variations
    - Test configuration
    - Software system (version, cycle time, etc)
    - Operational state
Importance of statistics

- It is possible to construct and operate a reverberation chamber (RC) without understanding statistical basis to implement a few relatively simple tasks based on performance rules and a robust software support system.

- However, without statistics it is not possible to understand,
  - theoretical basis for operation
  - techniques for evaluating RC performance
  - RC test procedures
  - directivity / polarization effects
  - predict expected values for EME and associated uncertainty and confidence limits

- Without statistics you cannot OPTIMIZE test time versus desired results.
Distributions of interest to RC

- Uniform
- Normal
- chi with 2 dof (component of electric field)
- chi with 6 dof (total electric field)
- chi square with 2 dof (received power)
- maximum to mean ratios (chi with 2 dof, chi square with 2 dof) including linear and logarithmic formulations of above
Characterization

- Statistical characteristics
  - Stirring ratio
  - Independent samples
  - Q factor
  - Insertion loss
  - Chamber time constant, etc…

- Introducing a known signal into the RC and mostly looking at the received power as a function of tuner position, the above mentioned parameters can be measured/calculated

Note: Frequency dependent
Good data!

Received power as a function of tuner position

- $<P_{\text{rec}}>$ gives a sense of the Q of the chamber
- Everything is valid for one complete rotation of the tuner
  - No measurement or calculation is valid at only one tuner position

Note: $<>$ means ensemble or average taken over all tuner positions
E field

- Can be measured using a set of three electrically short orthogonal dipoles

- Ideally the centers of these dipoles should be located at a single point in space (differences will be negligible if separated by a electrically short distance)

- In a well stirred chamber, the average electric field is assumed to be independent of orientation

\[ <|E_{R1}|> = <|E_{R2}|> = <|E_{R3}|> \]

- The magnitude of the total electric field is

\[ |E_T| = \sqrt{|E_{R1}|^2 + |E_{R2}|^2 + |E_{R3}|^2} \]
E field and power transitions

\[ \langle |E_i(f)| \rangle = 0.166 f(MHz) \sqrt{\frac{\langle P_{\text{rec}}(f) \rangle}{\eta_{Rx}}} \]

\[ |E_{i_{\text{max}}}(f)| = 0.187 f(MHz) \sqrt{\frac{P_{\text{rec,max}}(f)}{\eta_{Rx}}} \]

- An estimate of the mean V/m of a single field component and by using the maximum to mean ratio for N independent samples based on a 2 dof chi distribution to estimate the max
- From mean \( P_{\text{rec}} \), \( P_{\text{max}} \) can be found using the maximum to mean ratio for N independent samples based on a 2 dof chi square distribution to estimate the max power
Independent Samples

- The number of independent samples can be defined as the number of statistically independent field configurations that can exist inside the chamber (frequency dependent).
- The number of independent samples can be found by autocorrelation which measures the relative correlation between a sequence of N samples and an offset of the same sequence.
- Tuner complexity can contribute to the number of independent samples.
- Correlation analysis is usually used to indicate the sample independence.
Correlation analysis

\[ N_{\text{ind}} = \frac{N_{\text{meas}}}{\Delta} \]

- \( N_{\text{meas}} \) is the total number of measured samples and \( \Delta \) is the lag (in samples) in which the correlation coefficient reduces to 1/e (0.367)
Scatter plot

- Scatter plot represents the association between the two variables
- For a reverb chamber, the real and img. components of $S_{21}$ must be independent of each other
- Scatter plot does not specify dependent or independent variables
- Correlation can be seen because of a poor (non complex) tuner
- Strong correlation can also be seen if there is path of direct coupling between the Tx and the Rx (not desirable for a reverb chamber)
Quality factor (Q) of the chamber

- Q can be defined as the ratio of energy stored in cavity to power dissipated per cycle

**Theoretical**

\[
Q_{\text{wall}} = \frac{3}{2} \frac{V}{S\delta_w} \quad \delta_w = \frac{1}{\sqrt{\pi f \sigma \mu}}
\]

\[
Q_{\text{One-Ant}} = \left(5.85 \times 10^{-6} \times \text{freq(MHz)}^3 \times \text{Vol(m}^3\text{)}\right) / m_i
\]

\[
Q_{\text{Two-Ant}} = \left(\frac{Q_{\text{one-Ant}}}{2}\right)
\]

\[
Q_{\text{Total}} = \left(\frac{Q_{\text{Wall}} \times Q_{\text{Ant}}}{Q_{\text{Wall}} + Q_{\text{Ant}}}\right)
\]

**Measured**

\[
Q = 16\pi^2 \frac{V}{\lambda^3} \frac{<P_r>}{P_t}
\]

V- Volume
S- Surface area
\(\delta_w\) - Skin depth
\(\lambda\) - Lambda (c/f)
P_r - Power received
P_t - Power transmitted
Received power as a function of tuner position

For good stirring the max to min variation must be at least 20dB

- Complexity increases with frequency
- $\langle P_{\text{rec}} \rangle$ gives a sense of the Q of the chamber

Note: $\langle \rangle$ means ensemble or average taken over all tuner positions
The antenna losses dominate at the low frequencies
Q measured & K factor

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Q measured</th>
<th>No. of independent samples</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>3507</td>
<td>178</td>
</tr>
<tr>
<td>1.25</td>
<td>7278</td>
<td>178</td>
</tr>
<tr>
<td>1.5</td>
<td>6604</td>
<td>229</td>
</tr>
<tr>
<td>1.6</td>
<td>8026</td>
<td>320</td>
</tr>
<tr>
<td>2.5</td>
<td>12072</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>17059</td>
<td>534</td>
</tr>
</tbody>
</table>

Note: No. of measured samples = 1601 (all cases)

- **K factor (must be less than 5)**

  \[
  K = \left( \frac{Q_{\text{theory}}}{Q_{\text{measured}}} \right) = \frac{12893}{3506} = 3.67
  \]

- **K < 5**
Calibration

- The receiver antenna is placed in the working volume
- The E field probe is placed at the corners of the cube forming the usable volume
- The tuner is stepped in discrete steps over one complete rotation of the tuner
- Record maximum and average power, maximum field strength for each axis
- The antenna position or orientation or polarization is changed inside the working volume for every probe position
- This is started at the LUF of the chamber and repeated at all frequencies
- 18 steps for 3fs to 6fs and 12 steps above that
- Standard deviation will show you the uncertainty and standard calls for ±3dB
Working Volume

- Volume defined at the lowest usable frequency, \(\sim \lambda/4\) to \(\lambda/2\) away from any metals
- If the EUT has to be tested on a ground plane, chamber floor can be used
- For a well-stirred chamber there must be no shadowing
- When EUT is placed inside the working volume, before the test, it must be ensured that the EUT did not load the chamber badly
- In some cases if the Q is too high, the chamber can be intentionally loaded to increase the time constant associated with the chamber
- Some do multiple unit testing at one run - as far as all the units are placed inside the usable volume, this is possible
The directivity of the device is not changed when placed inside the reverberation chamber.

Direct illumination (both Tx and Rx) to the EUT is avoided.

The directivity and polarization effects are washed out as the EUT is illuminated equally from all directions.

Better test environment than a plane wave environment.
Correlation

- Every test technique produces or measures a different EME
- Open Area Test Site (OATS) requires a 2D scan (1 to 4m vertically and 360° horizontally) for horizontal and vertical polarizations and every test frequency
- Fully anechoic chamber requires a four aspect angle illumination at EUT face normals
- RC has an all aspect angle, randomly polarized, isotropic EME
- True directivity of the device is not known (most cases)
- Any correlatibility between test techniques will be fortuitous
- Based on an extensive test uncertainty associated with AC has been found to be 12dB
An EM engineers nightmare, is to test something like this for susceptibility and emissions!

Consistent results possible with reverberation chamber
The use of reverberation chambers for determining the shielding effectiveness has the advantage over other techniques in that the reverberation chamber exposes the material to a more realistic environment.

In a reverberation chamber, the fields are incident on the material with various polarizations and angles of incidence.
Applications – Simulation of a Radio Environment

- Reverberation chamber can be used to simulate a controllable Rician radio environment for the testing of a wireless device
- by varying the characteristics of the reverberation chamber and/or the antenna configurations in the chamber, any desired Rician-factor can be obtained

Ref: On the Use of Reverberation Chambers to Simulate a Rician Radio Environment for the Testing of Wireless Devices; Christopher L. Holloway, David A. Hill, John M. Ladbury, Perry F. Wilson, Galen Koepke and Jason Coder
For antenna efficiency measurement, the scattering parameters for transmission and reflection coefficient at the excitation antenna with respect to antenna under test is needed.

The scattering parameters are measured at two antenna ports between one port of the fixed transmitting antenna (Port 1) and the port of AUT (Port 2) from the network analyzer.

Ex: 3rd generation cell phones

Ref: A Comparative Study of Small Antenna Efficiency Measurements; A.A.H. Azremi, H. Ghafouri Shiraz and Peter S. Hall
Advantages

- Repeatability and reproducibility
- Robust test
- Replicates the EME close to real world
- More field strength for less input power
- Facility cost is significantly less
- Lower uncertainties
- Results are correlatable under certain conditions
Limitations

- Directivity of the device cannot be measured in RC.
- For emissions, RC measures the maximum radiated power and AC measures the field strength at a distance.
- With the current method specified by the standard, the test time associated with susceptibility is large.
- RC is gaining wide popularity in the EMC community but some gray areas have to be addressed.
- Statistical procedure.
On the whole RC is not an EMC test *panacea* but a better test method
Acknowledgements

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- Ted Lehman
- John Ladbury, Galen Koepke (NIST)
- Mike Hatfield, Mike Slocum (NSWCDD)
References

- IEC 61000-4-21
- MIL-STD 461E
- RTCA DO 160E
- SAE J551/J113
- Tech note 1508
- Lehman, Interaction notes 494
- Papers from NIST, Corona, Freyer, Hill, Arnaut, Lehman, Bunting, Bruns, Moglie…