Low-Frequency Magnetic Field Shielding
Physics and Discovery for Fabric Enclosures
Using Numerical Modeling

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2014 IEEE Symposium on Electromagnetic Compatibility
Session ID: MO-PM-5
Outline

- The infinite planar shield as a canonical geometry for the design of magnetic shields
  - Superiority of various materials such as Copper, Steel and Permalloy for different thicknesses
- Comparison of simulated results with the several design approximations for infinite planar shields
- Cylindrical and Spherical magnetic conducting shield
- A simulation tool for LF magnetic field discovery and design
  - Canonical loop problems from the literature
  - MIL-STD 188-125-2 enclosure with loop antenna
Introduction

The infinite planar shield has been studied as a canonical geometry for the design of EM shields. The shield consists of an infinite planar sheet with thickness $\Delta$, large value of the conductivity $\sigma$, and/or of the relative magnetic permeability $\mu_r$. [1] Following figures show geometry of the problem for excitation source current loop placed parallel or perpendicular to the shielding plane.

Benchmark problem 1
Circular current loop parallel to an infinite plane

Benchmark problem 2
Circular current loop perpendicular to an infinite plane
The loop center is at the XYZ origin and the loop is in XY plane.

Magnetic field is monitored at symmetric location behind the shielding plane at: 
\[ Z = 2h = 61 \text{ cm} \]

In simulation model the infinite plate was replaced by a sufficiently large plate with length and width: \[ a = 7h = 3.05 \text{ m}. \]

Modeling is performed in **EMCoS EMC Studio** [4] using Low Frequency Magnetic Field solver [5, 6].
The loop center is at the XYZ origin and the loop is in XY plane.

Magnetic field is monitored at symmetric location behind the shielding plane at: 
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Modeling is performed in EMCoS EMC Studio [4] using Low Frequency Magnetic Field solver [5, 6].
LF Modeling and Measurements: Loop over Al Plate [6]

Number of coil turns: 10
Coil Radius: 51.3 mm
Height of the coil: 53 mm
Wire radius: 3.53 mm

Very good agreement between modeling and measurement for input impedance.
LF Modeling vs. Measurements: Printed Loops over Al [6]

Modeling is performed in **EMCoS EMC Studio**.
Calculation of Shielding Effectiveness

Step 1: Calculation of $\vec{H}_i$ (Incident Magnetic Field) without shield.

Step 2: Calculation of $\vec{H}_t$ (Transmitted Magnetic Field) with shield.

Step 3: Shielding Effectiveness is a ratio of the magnitude of the incident magnetic (electric) field without shield, with the magnitude of the transmitted magnetic (electric) field through the shield [2].

In terms of magnetic field, the shielding effectiveness could be defined as:

$$SE_{dB} = 20\log_{10} \left| \frac{\vec{H}_i}{\vec{H}_t} \right|$$

In terms of electric field, the shielding effectiveness could be defined as:

$$SE_{dB} = 20\log_{10} \left| \frac{\vec{E}_i}{\vec{E}_t} \right|$$
Parallel Loop – Simulation Results Validation

**COPPER**
\[ \mu = 1 \quad \sigma = 54 \times 10^6 \text{ [S/m]} \quad \Delta = 0.5 \text{ mm} \]

**1010 LOW CARBON STEEL**
\[ \mu = 200 \quad \sigma = 9 \times 10^6 \text{ [S/m]} \quad \Delta = 0.5 \text{ mm} \]

Exact and Small Dipole curves are provided from [1], Fig. B.12, pg. 306.
Parallel Loop – Simulation Results Validation

**COPPER**

\[ \mu = 1 \quad \sigma = 54 \times 10^6 \text{ [S/m]} \quad \Delta = 0.5 \text{ mm} \]

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Exact and Small Dipole curves are provided from [1], Fig. B.14, pg. 309
Simulation - Thickness Variation Test

**COPPER**

\[ \mu = 1 \quad \sigma = 54 \times 10^6 \text{ [S/m]} \quad \Delta = 0.5 \text{ mm} \]

At **10 KHz** frequency:

<table>
<thead>
<tr>
<th>Thickness</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 um</td>
<td>~17.1 dB</td>
</tr>
<tr>
<td>50 um</td>
<td>~27.4 dB</td>
</tr>
<tr>
<td>100 um</td>
<td>~33.3 dB</td>
</tr>
</tbody>
</table>

Shielding plate thickness, \( \Delta \) was swept in range from 1 micron to 3 mm.

**1010 LOW CARBON STEEL**

\[ \mu = 200 \quad \sigma = 9 \times 10^6 \text{ [S/m]} \quad \Delta = 0.5 \text{ mm} \]

At **10 KHz** frequency:

<table>
<thead>
<tr>
<th>Thickness</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 um</td>
<td>~5 dB</td>
</tr>
<tr>
<td>50 um</td>
<td>~12.7 dB</td>
</tr>
<tr>
<td>100 um</td>
<td>~18.7 dB</td>
</tr>
</tbody>
</table>

![Graphs showing SE vs Frequency for Copper and Low Carbon Steel](image-url)
Copper and Low Carbon Steel

Comparison of SE for Copper and Low Carbon Steel for different thicknesses:

\[
\begin{align*}
\text{COPPER} & : \mu = 1 \quad \sigma = 54 \times 10^6 \, \text{[S/m]} \\
1010 \text{ LOW CARBON STEEL} & : \mu = 200 \quad \sigma = 9 \times 10^6 \, \text{[S/m]}
\end{align*}
\]
SE vs. Thickness @ 10Hz, 60Hz, 100Hz, 1KHz, 100KHz

COPPER
\( \mu = 1 \quad \sigma = 54 \times 10^6 \text{ [S/m]} \)

1010 LOW CARBON STEEL
\( \mu = 200 \quad \sigma = 9 \times 10^6 \text{ [S/m]} \)

PERMALLOY
\( \mu = 50000 \quad \sigma = 1.7 \times 10^6 \text{ [S/m]} \)

---

Graphs showing SE vs. Thickness for Copper, Steel, and Permalloy at different frequencies: 10Hz, 60Hz, 100Hz, 1KHz, and 100KHz.
SE vs. Thickness @ 10Hz, 60Hz, 100Hz, 1KHz, 100KHz

**COPPER**
\[ \mu = 1 \quad \sigma = 54 \times 10^6 \text{ [S/m]} \]

**1010 LOW CARBON STEEL**
\[ \mu = 200 \quad \sigma = 9 \times 10^6 \text{ [S/m]} \]

<table>
<thead>
<tr>
<th>Thickness [micron]</th>
<th>SE [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
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<tr>
<td>15</td>
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<tr>
<td>30</td>
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<tr>
<td>50</td>
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<tr>
<td>100</td>
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<tr>
<td>250</td>
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<td>500</td>
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<tr>
<td>1000</td>
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<tr>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness [micron]</th>
<th>SE @ 10 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness [micron]</th>
<th>SE @ 60 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness [micron]</th>
<th>SE @ 100 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness [micron]</th>
<th>SE @ 1 KHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness [micron]</th>
<th>SE @ 100 KHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
</tr>
</tbody>
</table>
SE vs. Thickness

SE vs. Thickness @ 1KHz, 100KHz

COPPER
\[ \mu = 1 \quad \sigma = 54 \times 10^6 \ [\text{S/m}] \]

1010 LOW CARBON STEEL
\[ \mu = 200 \quad \sigma = 9 \times 10^6 \ [\text{S/m}] \]

SE vs. Thickness @ 10Hz, 60Hz, 100Hz
With fixed steel conductivity, permeability was tested in the range of values from $\mu = 200$ up to $\mu = 80000$ to find out required value to achieve 20 dB Shielding Effectiveness Spec.

**20 dB SE @ 10 KHz requires:**

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Permeability $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 um</td>
<td>~120,000</td>
</tr>
<tr>
<td>15 um</td>
<td>~70,000</td>
</tr>
<tr>
<td>20 um</td>
<td>~40,000</td>
</tr>
</tbody>
</table>
Skin Depth vs. Frequency

\[ \delta = \sqrt{\frac{2}{2\pi f \mu \sigma}} \]

1010 LOW CARBON STEEL
\[ \mu = 200 \quad \sigma = 9 \times 10^6 \text{ [S/m]} \]

COPPER
\[ \mu = 1 \quad \sigma = 54 \times 10^6 \text{ [S/m]} \]

PERMALLOY
\[ \mu = 50000 \quad \sigma = 1.7 \times 10^6 \text{ [S/m]} \]
Parallel Loop - Bannister Approximation

Two quasi-near approximations are introduced:

1. When the measurement distance is much smaller than the operating wavelength \( L \ll \lambda_0 \), the propagation constant in air can be neglected
2. When the measurement distance is much greater than the skin depth in the shield \( L \gg \delta \) and the shield is thicker than twice the skin depth, the integration variable \( \lambda \) can be neglected

**Bannister Approximation** in the low-frequency case [1]:

\[
S_E \, dB = 8.686 \frac{\Delta}{\delta} + 20 \log_{10} \left[ \frac{L}{8.485 \mu_r \delta (z - \Delta)} \left( \frac{L}{\sqrt{R^2 + z^2}} \right)^3 \right]
\]

With the following assumptions:

- \( L \ll \lambda_0 \)
- \( L \gg \delta \)
- \( \Delta/\delta > 0.5 \)
- \( L/(\delta \mu_r) > 10 \)

\( \Delta = 0.5 \text{mm} \) – Shield Thickness
\( \delta = \sqrt{\frac{2}{2\pi f \mu \sigma}} \) – Skin Depth
\( z = 1 \text{m} \) – Distance from the loop center to field probe
\( R = 2 \text{cm} \) – Loop radius
\( L = \sqrt{R^2 + (z - \Delta)^2} \) – Measurement distance

\( SE_{dB} = A + R \)

**A** – absorption-loss term, a function of shield characteristics.

**R** – reflection-loss term, due to the mismatch between the two impedances at both interfaces.
Bannister Approximation - >100Hz

For Copper restriction $\Delta/\delta > 0.5$ is not fulfilled.
For Permalloy restriction $L/(\delta\mu_r) > 10$ is not fulfilled.

Bannister Approximation is good as long as the quasi-near approximation restrictions are fulfilled, for frequencies >100Hz.

A and R terms according to the eq. (1)

If the shield is thinner compare to the skin depth, multiple reflections occurs between boundaries, because of the small absorption loss [**].

COPPER
$\mu = 1 \quad \sigma = 54 \times 10^6 \text{[S/m]}$

1010 LOW CARBON STEEL
$\mu = 200 \quad \sigma = 9 \times 10^6 \text{[S/m]}$

PERMALLOY
$\mu = 50000 \quad \sigma = 1.7 \times 10^6 \text{[S/m]}$

---


With the additional assumptions: $K > 10$ and $\mu_r \neq 1$

$$SE_{dB} \approx 8.686 \frac{\Delta}{\delta} + 20 \log_{10}[0.354K^{-1} + 0.118K + 0.408]$$

Absorption A term

$$SE_{dB} = A + R$$

Reflection coefficient R term

For materials with $\mu_r \approx 1$, expression (2) is not valid [7].

### COPPER

- $\mu = 1$
- $\sigma = 54 \times 10^6$ [S/m]

### 1010 LOW CARBON STEEL

- $\mu = 200$
- $\sigma = 9 \times 10^6$ [S/m]

### PERMALLOY

- $\mu = 50000$
- $\sigma = 1.7 \times 10^6$ [S/m]

$$K = \frac{z}{\delta \mu_r}$$
TL theory Approximation [7] – Copper, Steel

With the following assumptions: \( L \gg \lambda_0, \ L > 10\delta, \ \Delta > 2\delta, \ z \gg \Delta \)

\[
SE_{dB} \approx 8.686 \frac{\Delta}{\delta} + 20 \log_{10} \left[ \frac{1}{8.485\delta\mu_r} \frac{R^2 + z^2}{z} \right]
\]

(3)

Absorption A term \( SE_{dB} = A + R \) Reflection loss R term

In case of a negative value of reflection loss, \( R=0 \) is manually defined [3].

1010 LOW CARBON STEEL
\( \mu =200 \ \ \sigma = 9 \times 10^6 \ [S/m] \)

COPPER
\( \mu =1 \ \ \sigma = 54 \times 10^6 \ [S/m] \)

PERMALLOY
\( \mu =50000 \ \ \sigma = 1.7 \times 10^6 \ [S/m] \)
Measurement vs. Simulation

Graph represents the measured low-frequency magnetic field shielding effectiveness of various type of metallic sheets [3]. The measurements were made in the near field with the source and receptor 0.1 in apart.

Measured data

Dash lines Simulation results

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative Conductivity $\sigma_r$</th>
<th>Relative permeability $\mu_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Steel</td>
<td>0.02</td>
<td>500</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.61</td>
<td>1</td>
</tr>
<tr>
<td>Mumetal</td>
<td>0.03</td>
<td>25000</td>
</tr>
</tbody>
</table>

With respect to Copper.
Data is acquired from [3]

Absorption Loss Term

Skin depth of copper, [m]:

$$\delta_c = \frac{1}{\sqrt{\pi f \mu_0 \mu_c \sigma_{Cu}}}$$

- $$\mu_0 = 4\pi \cdot 10^{-7}$$ – Permeability of free space
- $$\mu_c = 1$$ – Relative permeability of copper
- $$\sigma_{Cu} = 5.82 \cdot 10^7$$ – Conductivity of copper

Skin depth of arbitrary material, [m]:

$$\delta_m = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \sigma_m \sigma_{Cu}}}$$

- $$\mu_r$$ – Relative permeability of material with respect to copper
- $$\sigma_m = \sigma_{rel,Cu}$$ – Relative conductivity of material with respect to copper

Copper - $$\mu_r = 1$$ \quad $$\sigma_{Cu} = 54 \times 10^6 \text{ [S/m]}$$

1010 LOW CARBON STEEL

- $$\mu_r = 200$$
- $$\sigma_{rel,Cu} = 0.17$$

$$A = \frac{8.686 \Delta}{\delta}$$

Previded figure shows the advantage of steel over copper in providing absorption loss. Also thin sheet of copper has no significant loss below 1KHz.

![Graph showing absorption loss comparison between copper and steel](image-url)
Magnetic Field Reflection Loss

The reflection loss, $R$ term, for magnetic field (according to eq. 3 – copper and steel):

$$ R = 20 \log_{10} \left[ \frac{1}{8.485} \delta \mu_r \frac{R^2 + z^2}{z} \right] $$

$$ R_m = 20 \log_{10} \left[ \frac{\sqrt{\pi f \mu_0 \sigma_{Cu}}}{8.485} \right] + 20 \log_{10} \left[ \frac{\sqrt{f \mu_r \sigma_{rel,Cu} R^2 + z^2}}{\mu_r} \right] = 4.7 + 20 \log_{10} \left[ \sqrt{f} \frac{\sigma_{rel,Cu} R^2 + z^2}{\mu_r} \right] $$

$$ SE = A_m + R_m = 132 \Delta \sqrt{f \mu_r \sigma_{rel,Cu}} + 4.7 + 20 \log_{10} \left[ \sqrt{f} \frac{\sigma_{rel,Cu} R^2 + z^2}{\mu_r} \right] $$

**COPPER**

$\mu_r = 1$  \hspace{1em} $\sigma_{Cu} = 54 \times 10^6$ [S/m]

**1010 LOW CARBON STEEL**

$\mu_r = 200$  \hspace{1em} $\sigma_{rel,Cu} = 0.17$

**PERMALLOY**

$\mu_r = 50000$  \hspace{1em} $\sigma_{rel,Cu} = 0.03$
Magnetic Field Reflection Loss

The reflection loss, R term, for magnetic field (according to eq. 2 – steel, permalloy):

\[
R = 20 \log_{10} \left[ 0.354 \frac{\delta \mu_r}{z} + 0.118 \frac{z}{\delta \mu_r} + 0.408 \right]
\]

\[
R_m = 20 \log_{10} \left[ 0.0242 \frac{1}{z \sqrt{f}} \sqrt{\frac{\mu_r}{\sigma_{rel,Cu}}} + 1.72z \sqrt{f} \sqrt{\frac{\sigma_{rel,Cu}}{\mu_r}} + 0.408 \right]
\]

SE = \( A_m + R_m = 132 \Delta \sqrt{f \mu_r \sigma_{rel,Cu}} + 20 \log_{10} \left[ 0.0242 \frac{1}{z \sqrt{f}} \sqrt{\frac{\mu_r}{\sigma_{rel,Cu}}} + 1.72z \sqrt{f} \sqrt{\frac{\sigma_{rel,Cu}}{\mu_r}} + 0.408 \right] \)
Introduction

Consider an infinitely long cylindrical shell with inner radius $a$, outer radius $b$ and wall thickness $\Delta$ (i.e., $\Delta = b - a$). The shell is placed in uniform ac magnetic field of amplitude $H_0$.

The infinitely long cylindrical magnetic conducting shield has been studied as a canonical geometry for the design of EM shields. The shield consists of an infinitely long cylindrical shell with radius $\rho_0 = 30\text{cm}$ and thickness $\Delta = 0.15\text{mm}$, with large value of the conductivity $\sigma$, and/or of the relative magnetic permeability $\mu_r$ [*].

Following figures show geometry of the problem for cylindrical shell placed in an uniform external “transverse” or “parallel” magnetic field.

Benchmark problem 1
Cylindrical shell placed in an uniform external parallel magnetic field

Benchmark problem 2
Cylindrical shell placed in an uniform external transverse magnetic field

Geometry and Materials

Benchmark problem 1

Cylindrical shell placed in uniform external parallel magnetic field

![Cylindrical shell diagram](image1)

**IRON-NICKEL ALLOY**
- **IN Alloy**
  - \( \mu = 75000 \)  \( \sigma = 2 \times 10^6 \) [S/m]
  - Radius: \( \rho_0 = 30\text{cm} \)
  - Thickness: \( \Delta = 1.5\text{mm} \)

Benchmark problem 2

Cylindrical shell placed in uniform external transverse magnetic field

![Cylindrical shell diagram](image2)

**DURANICKEL STAINLESS STEEL**
- **DS Steel**
  - \( \mu = 10.58 \)  \( \sigma = 2.35 \times 10^6 \) [S/m]
  - Radius: \( \rho_0 = 30\text{cm} \)
  - Thickness: \( \Delta = 2\text{mm} \)

**COPPER CASTING ALLOY**
- **CC Alloy**
  - \( \mu = 1.09 \)  \( \sigma = 1.18 \times 10^7 \) [S/m]
  - Radius: \( \rho_0 = 30\text{cm} \)
  - Thickness: \( \Delta = 2\text{mm} \)
Model of Parallel Magnetic Field

Parameters of cylinder:
Length: $L = 20\rho_0 = 600\text{cm}$
Radius: $\rho_0 = 30\text{cm}$

Parameters of coil:
Length: $L = 20\rho_0 = 600\text{cm}$
Radius: $R = 7\rho_0 = 210\text{cm}$
Number of turns: 20

Number of triangles: $\sim 1400$

Validation of “Coil” Approach

Field probes across the cylinder for monitoring H field.

Observation point in the center at (0,0,0)

Total H Field (Magnitude), [A/m] at 10KHz (Linear Scale)
Parallel Magnetic Field

IRON-NICKEL ALLOY
IN Alloy
μ = 75000  σ = 2 x 10^6 [S/m]

Radius - ρ₀ = 30cm
Thickness - Δ = 1.5mm

![Graph showing SE vs Frequency for Simulation and Exact results.](image-url)

Missouri S&T Electromagnetic Compatibility Laboratory
Parallel Magnetic Field

Benchmark problem 2

Cylindrical shell placed in an uniform external **transverse** magnetic field

**IRON-NICKEL ALLOY**

IN Alloy
μ = 75000  σ = 2 x 10⁶ [S/m]

Radius - ρ₀ = 30cm
Thickness - Δ = 1.5mm

**DURANICKEL STAINLESS STEEL**

DS Steel
μ = 10.58  σ = 2.35 x 10⁶ [S/m]

Radius - ρ₀ = 30cm
Thickness - Δ = 2mm

**COPPER CASTING ALLOY**

CC Alloy
μ = 1.09  σ = 1.18 x 10⁷ [S/m]

Radius - ρ₀ = 30cm
Thickness - Δ = 2mm

Spherical shell placed in an uniform external **transverse** magnetic field
Validation of Spherical and Cylindrical Shells Equally

Data acquired from [*].

According to the graph we can conclude that even as shield geometry changes, the shielding mechanisms remain always the same. So we can place Spherical shell instead of the Cylindrical in an uniform external transverse magnetic field.

**IRON-NICKEL ALLOY**

IN Alloy

$\mu = 75000 \quad \sigma = 2 \times 10^6 \text{ [S/m]}$

Radius - $\rho_0 = 30\text{cm}$
Thickness - $\Delta = 1.5\text{mm}$

Number of triangles: ~ 830

Parameters of sphere:
Radius: $\rho_0 = 30\text{cm}$

Parameters of coil:
Length: $L = 20 \rho_0 = 600\text{cm}$
Radius: $R = 7\rho_0 = 210\text{cm}$
Number of turns: 20

Transverse Magnetic Field

**IRON-NICKEL ALLOY**
IN Alloy
\( \mu = 75000 \quad \sigma = 2 \times 10^6 \text{ [S/m]} \)
Radius - \( \rho_0 = 30\text{cm} \)
Thickness - \( \Delta = 1.5\text{mm} \)

**COPPER CASTING ALLOY**
CC Alloy
\( \mu = 1.09 \quad \sigma = 1.18 \times 10^7 \text{ [S/m]} \)
Radius - \( \rho_0 = 30\text{cm} \)
Thickness - \( \Delta = 2\text{mm} \)

**DURANICKEL STAINLESS STEEL**
DS Steel
\( \mu = 10.58 \quad \sigma = 2.35 \times 10^6 \text{ [S/m]} \)
Radius - \( \rho_0 = 30\text{cm} \)
Thickness - \( \Delta = 2\text{mm} \)
MIL STD 188-125-2 Test Setup

- Antenna diameter is 30 cm (12 inches)
- Antenna position is 1.5 m from the exterior wall, and 1.0 m inside the interior wall
- Antenna locations are shown as #1, 2, …
MIL STD 188-125-2: Model View

Current Loop
Diameter: 30cm
Value: 1A

Field Probe
Step: 1cm

Loop parallel to the wall
Loop perpendicular to the wall

Copper
wall thickness: 20 \( \mu \text{m} \)

Side View

3D View
Shielding Effectiveness at Various Distances to Wall

Parallel Loop

\[ F = 10 \text{ KHz} \]

Perpendicular Loop

COPPER

\[
\begin{align*}
\mu &= 1 \\
\sigma &= 58 \times 10^6 \text{ [S/m]} \\
\Delta &= 20\text{um}
\end{align*}
\]
Simulation – Shielding Effectiveness @ 10 KHz

**CENTER FIELD PROBE**

\[ F = 10 \text{ KHz} \]

**COPPER**

\[ \mu = 1 \quad \sigma = 58 \times 10^6 \text{ [S/m]} \quad \Delta = 20\mu\text{m} \]
Simulation – Magnetic Field @ 10 KHz

- Side View
- Room
- Field Probes
- Excitation Loop
- Top View
- 3D View
Simulation – Magnetic Field @ 10 KHz – Parallel Loop

Field Probes along the loop central axis with 1 cm step

1A Current Loop
30 cm diameter

Parallel Loop :: 10 KHz

Free Space
With the Shielded Room

Distance from the loop [m]
Magnetic Field [dBA/m]

-140 -120 -100 -80 -60 -40 -20 0 20 40
-2 -1 0 1 2 3 4 5

Parallel Loop :: 10 KHz

Free Space
With the Shielded Room
Simulation – Magnetic Field @ 10 KHz – Parallel Loop

Field Probes in plane of the loop with 1 cm step

1A Current Loop 30 cm diameter

Perpendicular Loop :: 10 KHz

Free Space

With the Shielded Room

Magnetic Field [dBA/m]
Distance from the loop [m]
References


