Understanding EMC Basics series
Webinar #1 of 3, February 27, 2013

EM field theory, and 3 types of EM analysis

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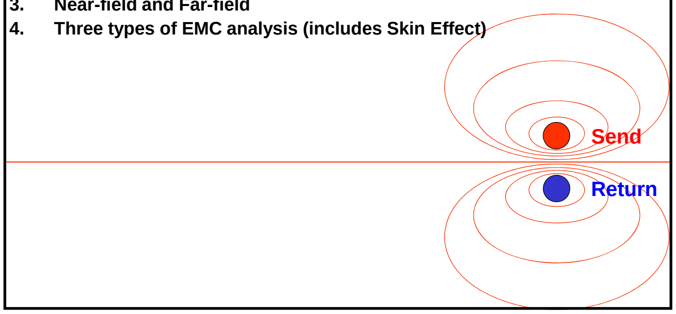

Understanding EMC Basics

1

Electromagnetic fields and waves,
and the importance of the return current path

Electromagnetic (EM) fields

- Every non-DC voltage/current is a wave of propagating EM energy...
  - guided by send and return current paths
    - and the insulators (dielectrics) that surround them (e.g. air)
- EM waves spread out and create EM fields, (like ripples spreading out and making a pattern on a pool)...
    - and we measure fields in terms of field strength
- Design for EMC is mostly about controlling fields
  - so that they are *high* where we *want* power or signals
  - and *low* where we *don't want* emissions or susceptibility

Of course, a wave has different amplitudes along its path

- When a conductor is long enough
  - it *cannot* experience the same voltage or current, at the same time, over its whole length…
    - which is why high frequencies seem to behave so weirdly!
- The ratio between wavelength (λ) and conductor dimension is very important
  - we can usually ignore "wave effects" when the dimension we are concerned with is < 1/100th of the λ...
    - e.g. at 1GHz: < 3mm in air (λ = 300mm); < 1.5mm in FR4 (λ = 150mm)

Importance of the return current path

- Electric and magnetic fields are the *true nature* of electrical and electronic power and signals
  – and they both depend on the physical routes taken by the send and return currents
- A great deal of EMC design depends on *controlling the paths of the return currents*
- All currents always flow in complete loops…
  – taking the path of least impedance – the path with the least area – i.e. the return current flows as close to its send path as it is allowed to

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Field theory, permittivity, permeability, wave impedance and velocity

We don't need field theory – just a few concepts

- Fluctuating voltages create Electric fields (E)
  – which are measured in Volts/metre (V/m)
- Fluctuating currents create Magnetic fields (H)
  – which are measured in Amps/metre (A/m)
- EM waves have power (P)
  – measured in Watts/square metre (W/m^2)
  (i.e. the rate ate which energy passes through an area)

Permeability (μ) and permittivity (ε)

- *All* media or materials have conductivity/resistivity (i.e. loss of EM energy, turned into heat), μ and ε...
  – in vacuum (and air): $\mu_0 = 4\pi \cdot 10^{-7}$ Henries/metre…
    - i.e. the vacuum can contain magnetic field energy
  – And: $\varepsilon_0 = (1/36\pi) \cdot 10^{-9}$ Farads/metre
    - i.e. the vacuum can also contain electric field energy
- Other media and materials are characterised by their *relative* permeability (μ_R) and permittivity (ε_R)
  – so their *absolute* permeability is: $\mu_0\mu_R$
  and their *absolute* permittivity is: $\varepsilon_0\varepsilon_R$

Permeability (μ) and permittivity (ε) continued...

- In conductors (e.g. wires, PCB traces): μ and ε are what causes them to have inductance (L) and capacitance (C)…
  – so *whenever* there is a fluctuating *voltage* (V) there is *always* an associated *current* (I), and vice-versa
- In insulators (e.g. PVC, FR4, air): μ and ε cause effects *similar to* inductance and capacitance…
  – so *whenever* there is a fluctuating *electric field* (E) there is *always* an associated *magnetic field* (H), and vice-versa

μ and ε govern an EM wave's impedance, and it's propagation velocity

- For the wave's 'far field' impedance …
  $Z = E/H$ = V/m ÷ A/m = $\sqrt{(\mu_0\mu_R/\varepsilon_0\varepsilon_R)}$ Ω
  $Z = 377\Omega$ in air or vacuum
  $Z = 377\sqrt{(\mu_R/\varepsilon_R)}$ in a medium or material
- For the velocity of the wave's propagation …
  $v = 1/\sqrt{(\mu_0\mu_R\varepsilon_0\varepsilon_R)}$ metres/second
  $v = 3.10^8$ m/s in air or vacuum (i.e. the speed of light)
  $v = 3.10^8/\sqrt{(\mu_R\varepsilon_R)}$ m/s in a medium or material

And the velocity of wave propagation (v) links frequency (f) to wavelength (λ)

$$v = f\,\lambda$$

- In vacuum or air: $v = c$ = 300 million metres/second
  - $1/\sqrt{(\mu_0\varepsilon_0)}$, equivalent to 3ns/metre, 3ps/millimetre
- But in media or materials with μ_R and/or ε_R >1.0, v is *slower* than c
  - so the wavelength (λ) is shorter (for a given f)
    - e.g. for a printed-circuit board trace, v is approx. 50% of c ....so a λ is approx. 50% of what it would be in air

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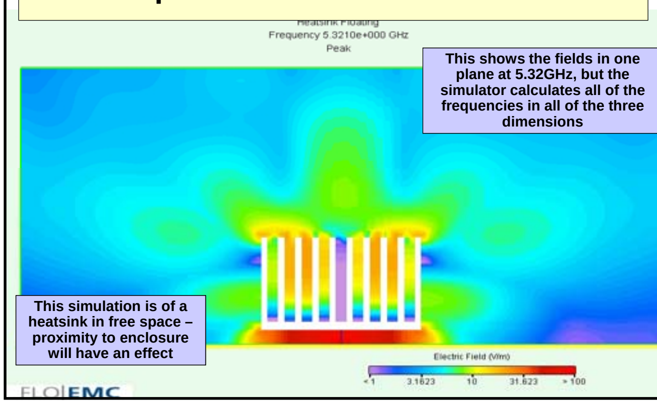
Near Field and Far Field

Near-field and Far-field

- Near fluctuating voltages or currents, E and H fields have complex patterns: field strengths vary as $1/r^3$, $1/r^2$ and $1/r$
  - where r is the radial distance from the source
  - because of stray capacitance and stray mutual inductance effects (i.e. E and H field coupling)
- But, far enough away, the fields become EM waves (E and H fields in the ratio of the wave impedance: Z)…
  - and have simple 'plane wave' spherical distributions with field strengths that vary as 1/r

An example of a near-field field distribution



Near-field and Far-field continued…

- For sources with longest dimensions <<λ, the boundary between the near and far field regions is:

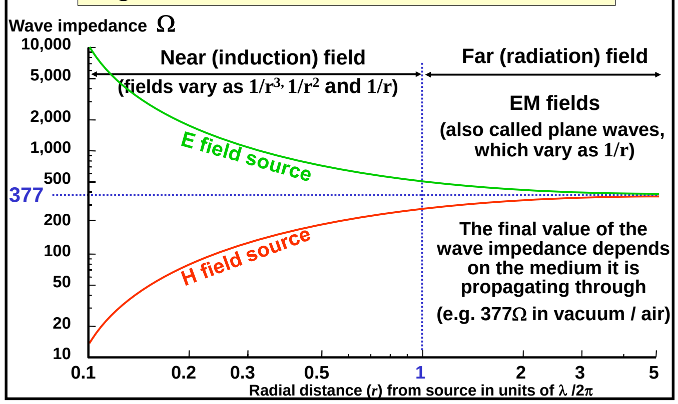
$$r = \lambda/2\pi$$

- But for sources with dimensions >λ, the near/far field boundary is:

$$r = 2D^2/\lambda$$

  - where D is the largest dimension of the source

Near-field and far-field when the source's largest dimension is << λ *(for illustration only)*



Poll Questions

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Three types of EMC analysis (includes Skin Effect)

EMC uses three types of analysis

- For conductor dimensions < λ/6 we can use '*lumped circuit analysis*' methods (based on R, L, C)
- When conductor dimension is > λ/6 along one axis (e.g. a wire) we must use '*transmission line*' analysis
- But when conductors are > λ/6 in two or three dimensions we must use '*full-wave analysis*'
  - based on Maxwell's Equations
    - only practical for very simple situations, or when using computers to do the analysis

Resonances

- *All* circuits have RF resonant modes
  - where their currents or voltages experience resonant gain, called their 'Q factor'...
  - Qs of 100 or more are common (i.e. gains of 40dB or more)
- As the voltage peaks, the current nulls, and vice-versa (to maintain a constant energy as the wave propagates)
- High levels of emissions (and poor immunity) tend to occur at resonances…
  - so we often need to control them to achieve EMC

Lumped analysis… *everything* has resistance (R), inductance (L), and capacitance (C)

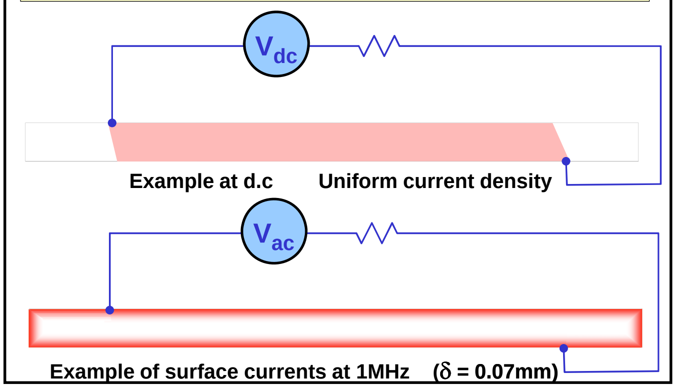
- including <u>all</u> components, wires, cables, PCB tracks, connectors, silicon metallisation, bond wires, etc
- also including their 'stray' or 'parasitic' Rs, Ls, and Cs
  - which can be intrinsic (e.g. the self-inductance of a wire lead)
  - or extrinsic (e.g. stray C or L coupling due to proximity to other objects)

- Resistance increases with f due to Skin Effect

Lumped analysis: Resistance and Skin Effect

- DC currents travel through the *whole* cross-sectional area of a conductor
  - but AC currents are forced to flow close to the surface
- This is known as the "skin effect"
- So, high-frequency currents only penetrate weakly into the *depth* (thickness) of a conductor
  - increasing the resistance in their path

Examples of cross-sectional current density in a copper sheet



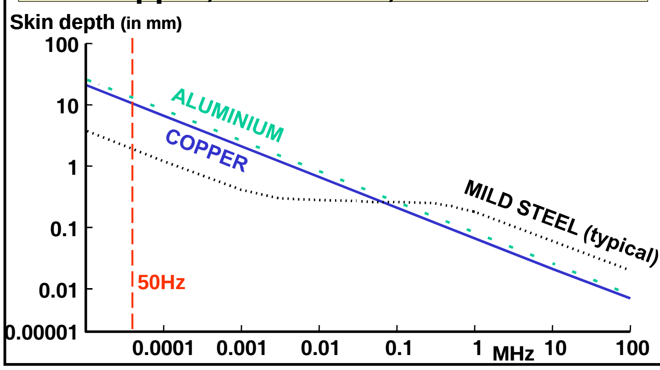
Resistance and Skin effect continued...

- One skin depth (δ) is the depth into the conductor by which the current density has reduced to 1/e

$$\delta = \frac{1}{\sqrt{(\pi f \mu_0 \mu_R \sigma)}} \quad \text{metres}$$

  - where σ = conductivity
- For copper conductors: $\delta = 66/\sqrt{f}$
  (f in Hz gives δ in millimetres)
  – e.g. at 160MHz δ = 0.005mm, so 0.05mm below the surface (10 skin depths) the current density is negligible

Graph of skin depth (δ) for copper, aluminium, and mild steel



Lumped analysis: Stray Inductance

- E.g. a thin wire has self-inductance of about 1µH per metre (1nH per mm)
  - this assumes its return current path is very far away
  - a close return path reduces the overall inductance experienced by the send/return current
- Close proximity to ferromagnetic materials (e.g. steel) with $\mu_r > 1$ will *increase* its self-inductance
- But close proximity to conductors (e.g. cables, metalwork, etc.) will *decrease* self-inductance

Lumped analysis: Stray Capacitance

- E.g. a thin wire on its own in free space has about 40pF per metre length (approx. 0.04pF per mm)....
  – this is its ‘space charge’ capacitance....
  – close proximity to dielectrics ($\varepsilon_r > 1$) will add more stray space charge capacitance
- Proximity of conductors adds stray capacitance...
  – (8.8/d) nF/square metre in air (d is the spacing in mm)
  – ($8.8\ \varepsilon_r$/d) nF/sq. m., when d is the spacing through insulation

Lumped Analysis: Resonances

- L and C store energy in their E and H fields
  – this is true for intentional Ls and Cs (e.g. components) and ‘stray’ or ‘parasitic’ Ls and Cs
- *All* types of circuits have L and C (even if they are only strays) and these cause resonances, at:
  $f_{RES} = 1/(2\pi\sqrt{LC})$
- These resonances are ‘damped’ by the resistances in the circuit

Transmission line analysis…
all send/return conductors have *characteristic impedance* (called Z_0)

- The L and C *associated with a small length* governs the velocity (v) with which EM waves travel *through that length...* $v = 1/\sqrt{(LC)}$
- And the ratio of the L to the C governs the characteristic impedance (Z_0) *of that length...*

$$Z_0 = \sqrt{(L/C)}$$

- Note: the L and C values used in the above expressions are 'per unit length' (e.g. 1μH/metre, 100pF/metre) where the unit lengths used are shorter than $\lambda/6$

The effects of keeping Z_0 constant

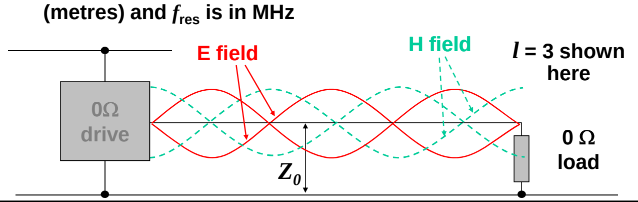
- If Z_0 is kept constant from source to load, almost 100% of the wave (= signal) is communicated
  - which means that there must be low emissions from the wanted signal (because there is very little energy lost)
- This is called *matched transmission line* design
  - and a matched transmission line is a very inefficient antenna
    - which is why all general purpose RF test equipment has 50Ω inputs and outputs, connected with '50Ω cable'

Changes in Z_0 over dimensions greater than $\lambda/6$

- These cause propagating EM waves to be reflected (whether they are signals or power)
  - like the ripples spreading in a pool of water reflecting from a floating stick
- The technique called "EMC filtering" relies upon creating changes in characteristic impedance
  - to reflect unwanted noise away from a protected circuit

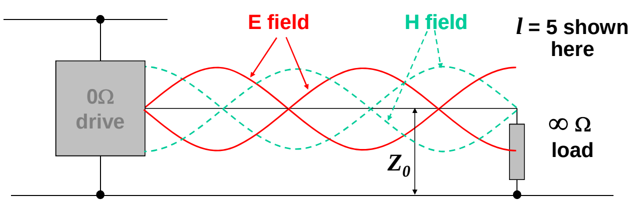
Transmission-line analysis: Resonances

- When a conductor has the *same type* of Z_0 discontinuity at *each* end (whether the source and load impedances are both too high, or too low)…
  - resonances occur when conductor length is a whole number of half-wavelengths... $f_{res} = 150\ l/L$ (air dielectric) where l is an integer (1, 2, 3, etc.), L is conductor length (metres) and f_{res} is in MHz



Transmission-line analysis: Resonances
continued...

- When a conductor has *opposing types* of Z_0 discontinuity at its ends…
  - resonances occur when conductor length is an odd number of quarter-wavelengths... $f_{res} = 75\ l/L$ (air dielectric) where l is an odd-numbered integer (1, 3, 5, etc.), L is conductor length (metres) and f_{res} is in MHz

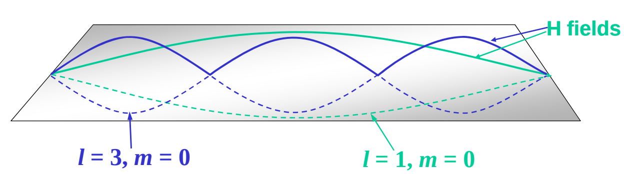


2-dimensional structural resonances: 'standing waves' caused by reflections at the edges of a metal plate

- Resonances can only occur at integer multiples of half-wavelengths, at:

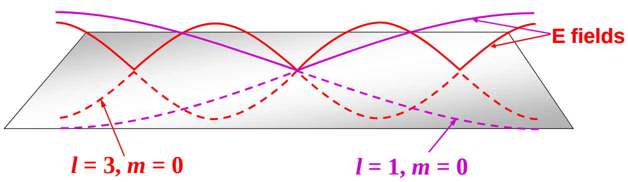
$$f_{res} = 150\ \sqrt{\{(l/L)^2 + (m/W)^2\}} \text{ (in MHz)}$$

  - where: l and m are integers (0, 1, 2, 3, etc.) and L and W are the plate's length and width (in metres)



'Standing waves' caused by reflections at the edges of a metal plate
continued...

- **Magnetic field standing waves must have minima at the edges of the metal plate**
  (air has much higher impedance than metal)...
  - whilst electric fields must be a maximum at the edges

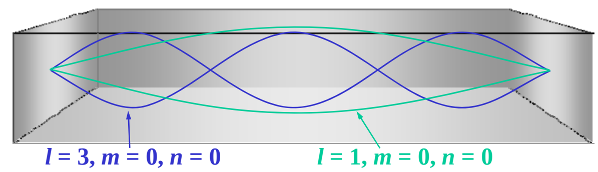


3-dimensional structural resonances: 'standing waves' caused by reflections at the walls inside a metal box

- **Resonances can only occur at integer multiples of half-wavelengths, at:**

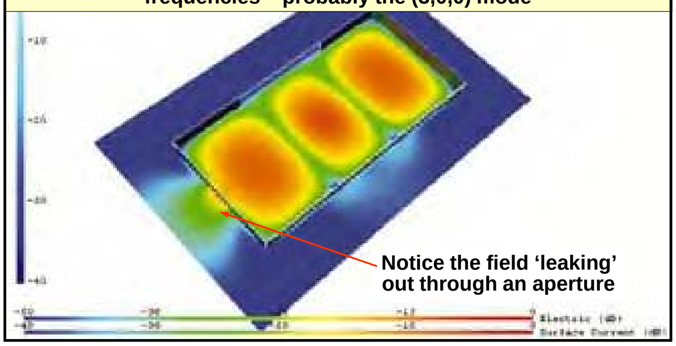
$$f_{res} = 150 \sqrt{(l/L)^2 + (m/W)^2 + (n/H)^2} \quad \text{(in MHz)}$$

  - where: l, m, n are integers (0, 1, 2, 3, etc.)
    and L, W, H are the box's length, width, height (in metres)



A FLO/EMC simulation of the electric field distribution inside a shielded box

The simulator calculates all frequencies, in three dimensions. This figure shows a 'slice' through a box at one of its resonant frequencies – probably the (3,0,0) mode



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