Pulsed-field ElectroMagnetic immunity in a complex digital environment

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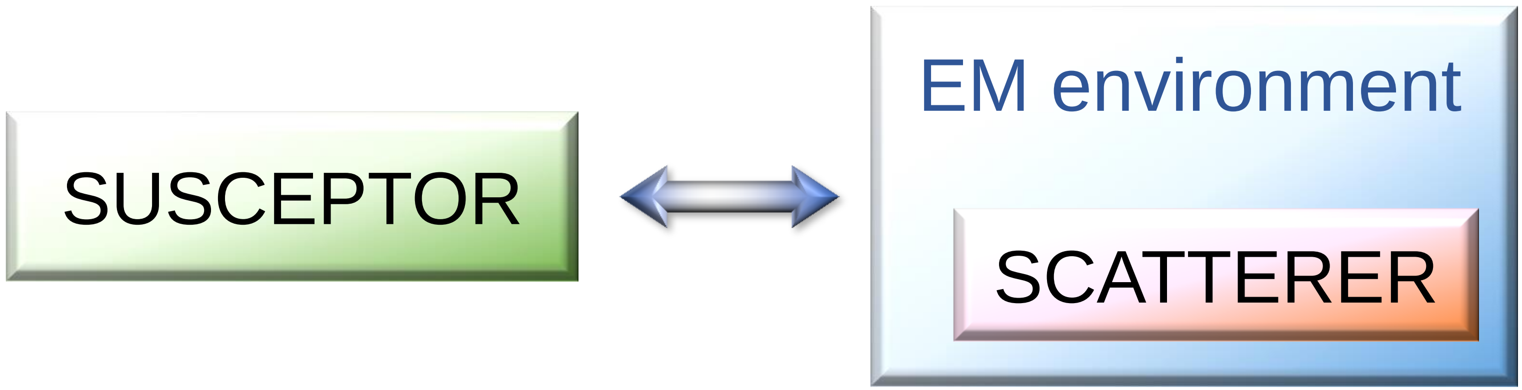
WF1- EMI challenges in future complex multi-functional (digital) systems

Synopsis

- Prerequisites: configuration, notations
- EM field equations + constitutive relations
- Contrast source formulation
- EMI susceptibility analysis
- Wiener-Hopf technique

Prerequisites

- EMI configuration:



$$\mathcal{D} = \text{supp}\{\text{scatterer}\} \subset \text{supp}\{\text{EM environment}\} = \mathbb{R}^3$$

Prerequisites

- Notation:

A.T. de Hoop, "Electromagnetic field theory in (N+1)-space-time: A modern time-domain tensor/array introduction," Proceedings of the IEEE, vol. 101, no. 2, pp. 434-450, Feb. 2013.

$$[\partial_i E_j]^- = (\partial_i E_j - \partial_j E_i)/2$$

Field equations

EM Wavefield and source quantities (arrays, arraylength=3)		
	electric	magnetic
intensive field	E_r	$H^{-}_{m,k} = -H^{-}_{k,m}$
flow of EM energy	$S_m = H^{-}_{m,k} E_k$	
extensive field	D_k	$B^{-}_{i,j} = -B^{-}_{j,i}$
flow of EM momentum	$G_i = B^{-}_{i,j} D_j$	
volume source currents	J_k	$K^{-}_{i,j} = -K^{-}_{j,i}$

$$\partial_{\boldsymbol{x}} \left[\text{intensive field} \right] + \partial_t \left[\text{extensive field} \right] = \left[\text{source currents} \right]$$

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$\boldsymbol{x}$: position

t: time

$$\partial_{\boldsymbol{x}} \left[\text{field} \right] + \partial_t \left[\text{field} \right] = \left[\text{source currents} \right]$$

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$$\partial_m H^{-}_{m,k} + \partial_t D_k = J_k$$

$$[\partial_i E_j]^{-} + \partial_t B^{-}_{i,j} = K^{-}_{i,j}$$

Constitutive relations

$$\begin{bmatrix} \text{intensive} \\ \text{field} \end{bmatrix} \Rightarrow \begin{bmatrix} \text{extensive} \\ \text{field} \end{bmatrix}$$

Constitutive properties (local | passive | linear | time invariant | isotropic)		
	$\mathcal{D}$ (scatterer)	$\mathbb{R}^3$ (free space)
electric	$D_k = \epsilon_0[\delta(t) + \chi^{\mathrm{e}}(\boldsymbol{x}, t)] \overset{(t)}{*} E_k$	$D_k = \epsilon_0 E_k$
magnetic	$B^{-}_{i,j} = \mu_0[\delta(t) + \chi^{\mathrm{m}}(\boldsymbol{x}, t)] \overset{(t)}{*} H^{-}_{i,j}$	$B^{-}_{i,j} = \mu_0 H^{-}_{i,j}$
electric contrast	$\chi^{\mathrm{e}}(\boldsymbol{x}, t)$	
magnetic contrast	$\chi^{\mathrm{m}}(\boldsymbol{x}, t)$	

Constitutive relations

[intensive field] → [extensive field]

$\overset{(t)}{*}$: time convolution

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Contrast-source scattering formulation

- Input:
  - EM environment (free space)
  - Incident field
  - Constitutive parameters of scatterer

Contrast-source scattering formulation

Contrast-source currents ($\boldsymbol{x} \in \mathcal{D}$)	
electric	magnetic
$J_k^{\mathrm{s}} = -\partial_t (D_k - \epsilon_0 E_k)$	$K_{i,j}^{\mathrm{s},-} = -\partial_t (B_{i,j}^{-} - \mu_0 H_{i,j}^{-})$

Total field $[\cdot]$ = Incident field $[\cdot^{\mathrm{i}}]$ + Scattered field $[\cdot^{\mathrm{s}}]$ ($\boldsymbol{x} \in \mathbb{R}^3$)

$$\left[\begin{array}{c}\text{scattered}\\ \text{intensive}\\ \text{field}\end{array}\right] = \left[\begin{array}{c}\text{Green's}\\ \text{function}\\ \text{embedding}\end{array}\right] \overset{(\boldsymbol{x})(t)}{\ast\ \ast} \left[\begin{array}{c}\text{contrast-}\\ \text{source}\\ \text{currents}\end{array}\right] \quad \text{for } \boldsymbol{x} \in \mathbb{R}^3$$

Contrast-source scattering formulation

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Total field $[\cdot]$ = Incident field $\overset{(\boldsymbol{x})}{*}$: spatial convolution ($\boldsymbol{x} \in \mathbb{R}^3$)

$$\begin{bmatrix} \text{scattered} \\ \text{intensive} \\ \text{field} \end{bmatrix} = \begin{bmatrix} \text{Green's} \\ \text{function} \\ \text{embedding} \end{bmatrix} \overset{(\boldsymbol{x})}{*} \overset{(t)}{*} \begin{bmatrix} \text{contrast-} \\ \text{source} \\ \text{currents} \end{bmatrix} \quad \text{for } \boldsymbol{x} \in \mathbb{R}^3$$

Contrast-source integral equation

- Contrast-current integral equation:

for $\boldsymbol{x} \in \mathcal{D}$ **+** constitutive relations in $\mathcal{D}$

- Natural oscillations when incident field = 0

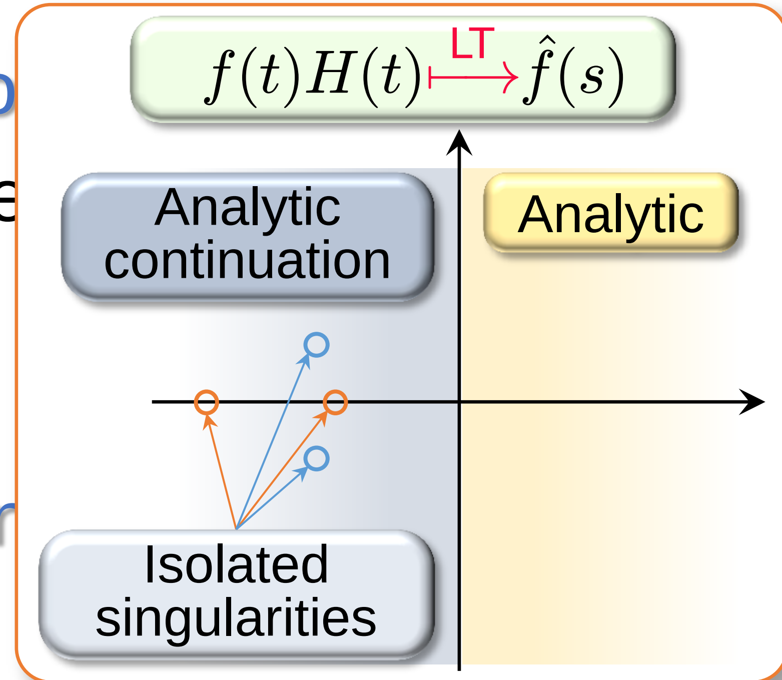
$$\left\{ \begin{array}{c} \text{natural} \\ \text{oscillations} \\ \text{scatterer} \end{array} \right\} = \begin{bmatrix} e_r(\boldsymbol{x}) \\ h^{-}_{i,j}(\boldsymbol{x}) \end{bmatrix}_n \exp(s_n t) H(t), s_n \in \mathbb{C},$$

$$\mathrm{Re}(s_n) < 0, n = 1, 2, 3, \ldots$$

Contrast-source integral equation

- Contrast-current integral equatio

for $\boldsymbol{x} \in \mathcal{D}$ + constitutive



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Open resonator natural modes of oscillation – examples

- Spherical susceptor

  J.A. Stratton, *Electromagnetic Theory*, New York: McGraw-Hill Inc., 1941.

- Fabry–Pérot laser resonator

  H. Blok, *Diffraction Theory of Open Resonators*, (dissertation), Rotterdam, the Netherlands, 1970. http//:www.repository.tudelft.nl.

- Patch antenna element

  G.A.E. Vandenbosch, "Semi-analytical modeling of coaxial feeds," *IEEE Trans. Antennas Propag*., vol. 60, no. 3, pp. 1252–1260, March 2012.

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CONNECTING THE FUTURE

Open resonator natural modes of oscillation – examples

- Dielectric resonator

H.Y. Yee, "Natural resonant frequencies of microwave dielectric resonators," *IEEE Trans. Microw. Theory Techn*., vol. 13, no. 2, p. 256, Mar. 1965.

J. Van Bladel, "On the resonances of a dielectric resonator of very high permittivity," *IEEE Trans. Microw. Theory Techn*., vol. 23, no. 2, pp. 199–208, Feb. 1975.

J. Van Bladel, "The excitation of dielectric resonators of very high permittivity," *IEEE Trans. Microw. Theory Techn*., vol. 23, no. 2, pp. 208–217, Feb. 1975.

EMI susceptibility analysis

- Approach

$$\left\{ \begin{array}{c} \text{natural} \\ \text{oscillations} \\ \text{susceptor} \end{array} \right\} \xleftrightarrow{\text{EM Reciprocity}} \left[\begin{array}{c} \text{incident} \\ \text{field} \end{array} \right]$$

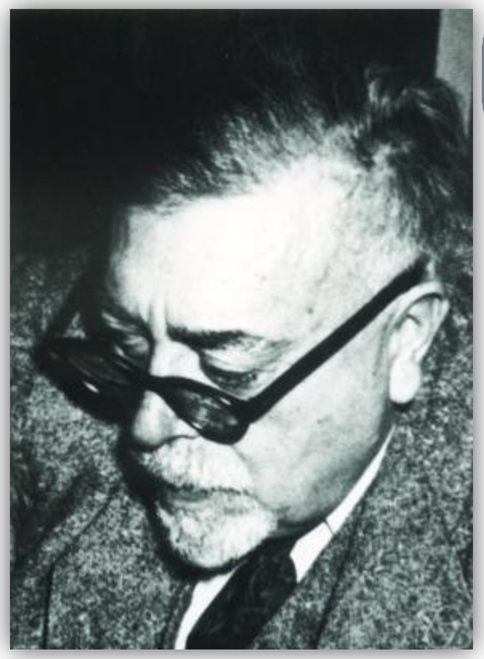
- Incident field

$[\cdot^{\mathrm{i}}]$ = operational field $[\cdot^{\mathrm{op}}]$ + disturbance $[\cdot^{\Delta}]$

- Disturbance mitigation

$[\cdot^{\Delta}]$ → Wiener filter → $[\cdot^{\Delta}]$ (Wiener-Hopf technique)

Wiener-Hopf technique



Norbert Wiener
(1894–1964)

Eberhard Frederich
Ferdinand Hopf
(1894–1964)

J.B. Lawrie and I.D. Abrahams, “A brief historical perspective of the Wiener–Hopf technique,” *J. Eng. Math*, vol. 59, no. 4, pp. 351–358, Dec. 2007.

Single-channel, optimum linear filtering

Definitions

- Time convolution:

$$\mathrm{C}(f_1, f_2; \tau) = \int_{-\infty}^{\infty} f_1(t) f_2(\tau - t) \mathrm{d}t$$

- Time correlation:

$$\mathrm{R}(f_1, f_2; \tau) = \int_{-\infty}^{\infty} f_1(t) f_2(\tau + t) \mathrm{d}t$$

Single-channel, optimum linear filtering

Signals

- Input signal: $f^{\mathrm{in}} = f^{\mathrm{oper}} + f^{\delta}$

  with:
  - $f^{\mathrm{oper}} =$ operational signal
  - $f^{\delta} =$ disturbing signal

- Desired output signal: $f^{\mathrm{out}} = \mathsf{C}(G, f^{\mathrm{in}}; t)$

  with:
  - $G =$ linear, time-invariant, causal filter

Single-channel, optimum linear filtering

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  with:
  - $G =$ linear, tim

Deviation from the desired signal:

$\Delta = \mathsf{R}(f^{\text{out}}, f^{\text{out}}; 0)$ ⇨ Cost function

Single-channel, optimum linear filtering

Assumption: $\mathrm{R}(f^{\mathrm{oper}}, f^{\delta}; \tau) = 0$

- Optimum filter: $G^{\mathrm{opt}} = \min_{G}(\Delta)$

- Solution: Wiener-Hopf integral equation

$$\int_{\sigma=0}^{\infty} \mathrm{R}(f^{\mathrm{in}}, f^{\mathrm{in}}; \tau - \sigma)\, G^{\mathrm{opt}}(\sigma)\mathrm{d}\sigma = \mathrm{R}(f^{\mathrm{in}}, f^{\mathrm{out}}; \tau)$$

for $0 < \tau < \infty$

Single-channel, optimum linear filtering

Example:

$$f^{\mathrm{out}}(t) = f^{\mathrm{oper}}(t-\alpha)$$

- Extrapolation $\alpha<0$
- Instantaneous $\alpha=0$
- Interpolation $\alpha>0$