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Low-Frequency Modal Extrapolation and Regularization for Full-Bandwidth Macromodeling of Electromagnetic Structures

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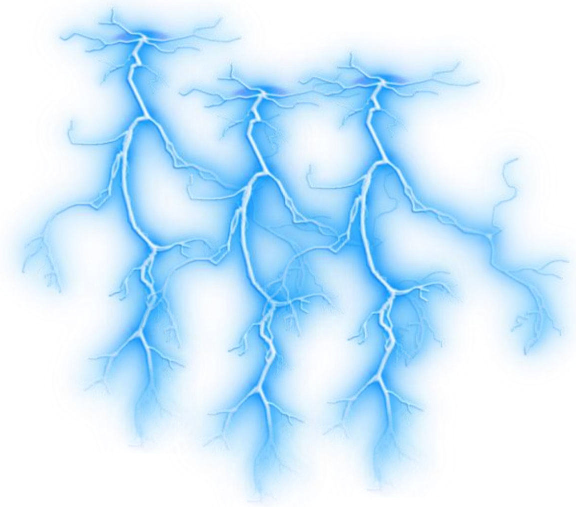
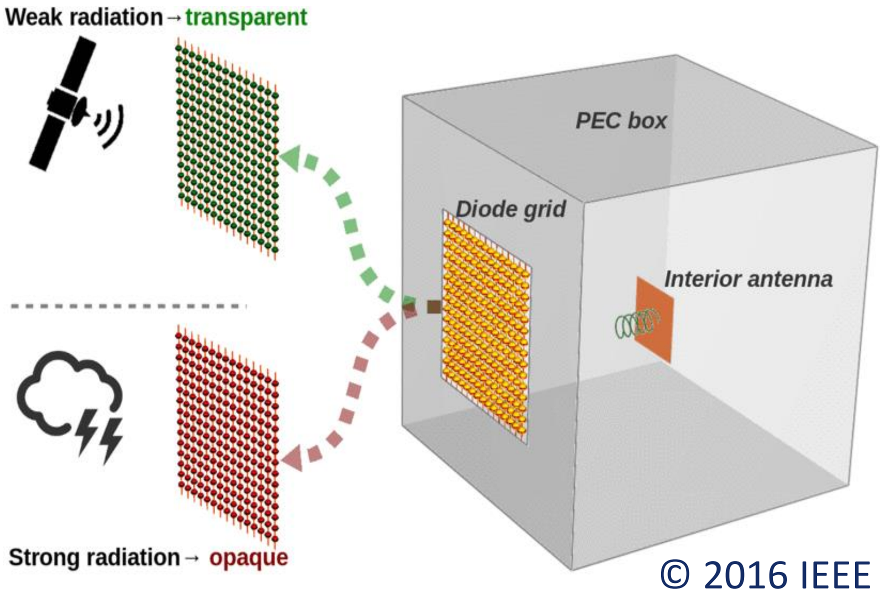
Research Context and Motivations

High-intensity radiation fields (HIRFs) and **Electromagnetic Interference (EMI)** can result in software or even hardware failure for many electronics devices

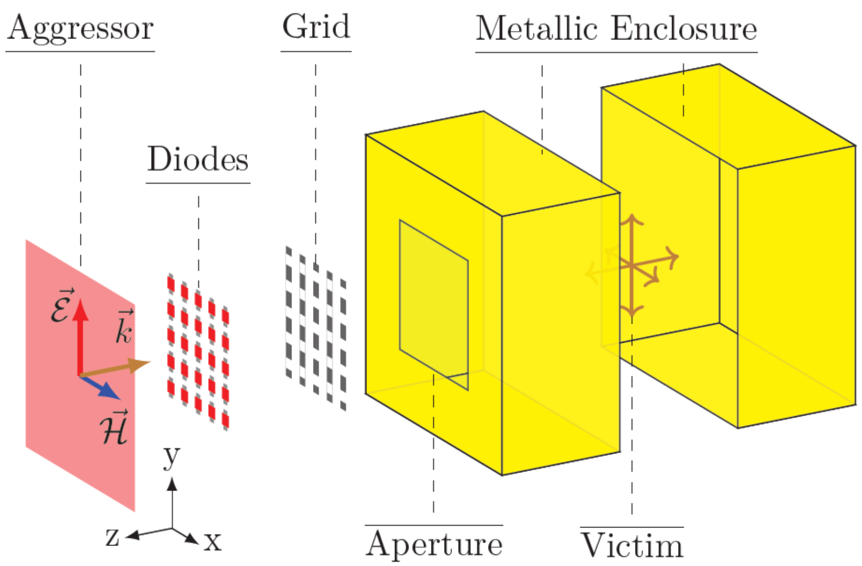


Protect *from interferences*
Allow *communications*

Energy selective (shielding) structures



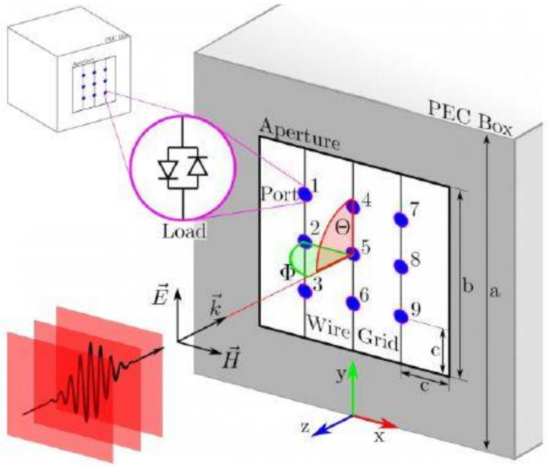
Research Context and Motivations



Design through **simulation**

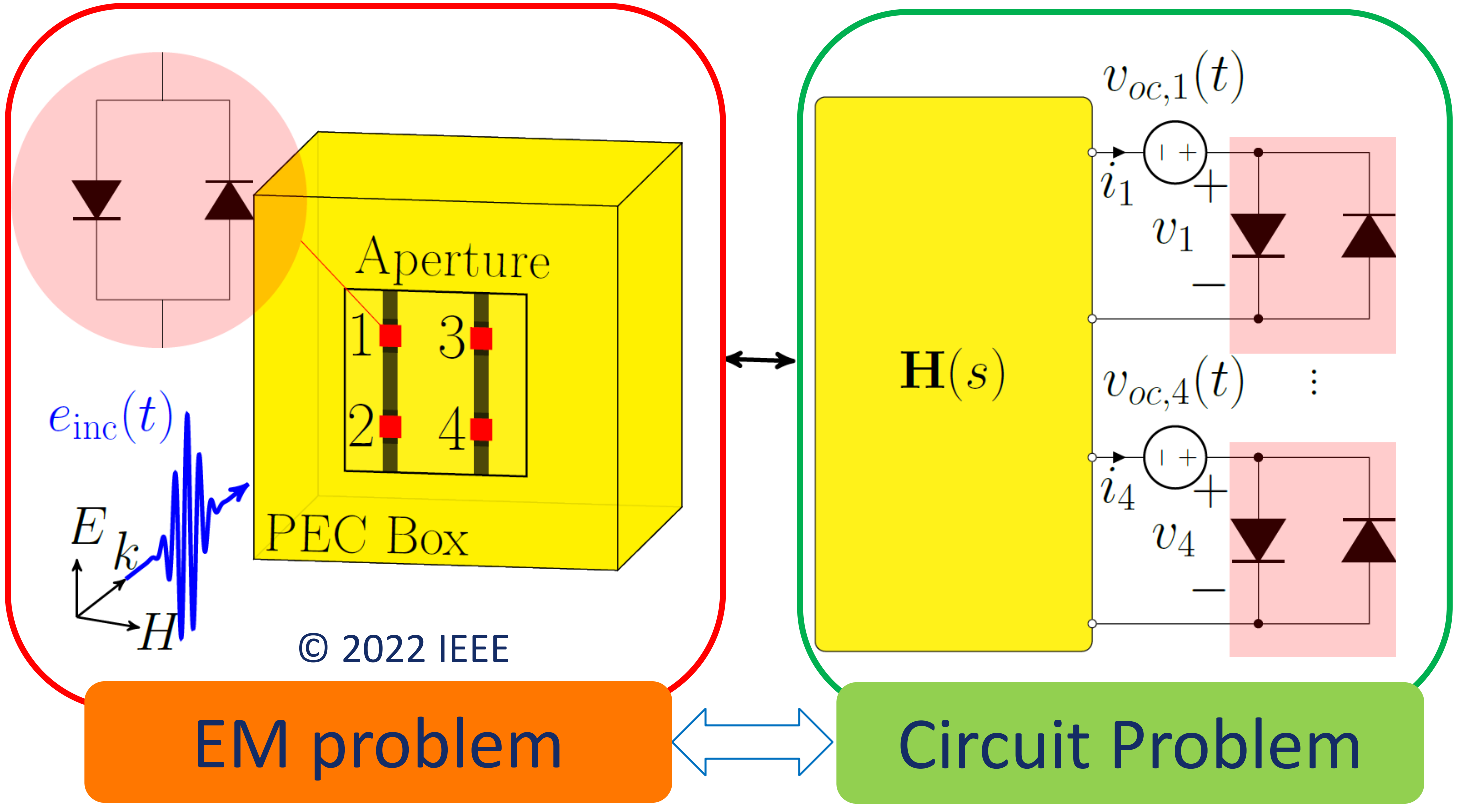
1. Full time-domain solvers
2. **Hybrid techniques**: decouple
   - **linear part**
   - **nonlinear terminations**

Frequency-domain solver based on Method of Moments (**MoM**)



Source: www.tet.tuhh.de

Research Context: Hybrid Solver



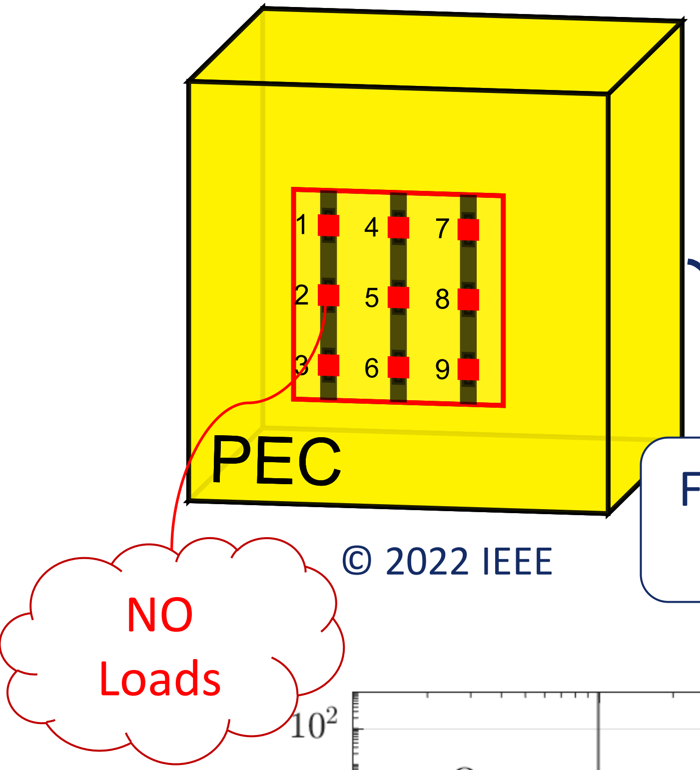
Large-scale LTI system terminated with many **nonlinear loads**

Main ingredients

1. Characterization of the shielding enclosure → $\mathbf{H}(s)$
2. Characterization of nonlinear terminations
3. Incident field $e_{inc}(t)$ → eqv sources $\boldsymbol{v}_{oc}(t)$

*T. Wendt, C. Yang, H. D. Bruns, S. Grivet-Talocia, and C. Schuster, "A Macromodeling-Based Hybrid Method for the Computation of Transient Electromagnetic Fields Scattered by Nonlinearly Loaded Metal Structures," *IEEE Trans. Electromagn. Compat.*, vol. 62, no. 4, pp. 1098–1110, Aug. 2020, doi: 10.1109/TEMC.2020.2991455.

Box Characterization: Lossless LTI System

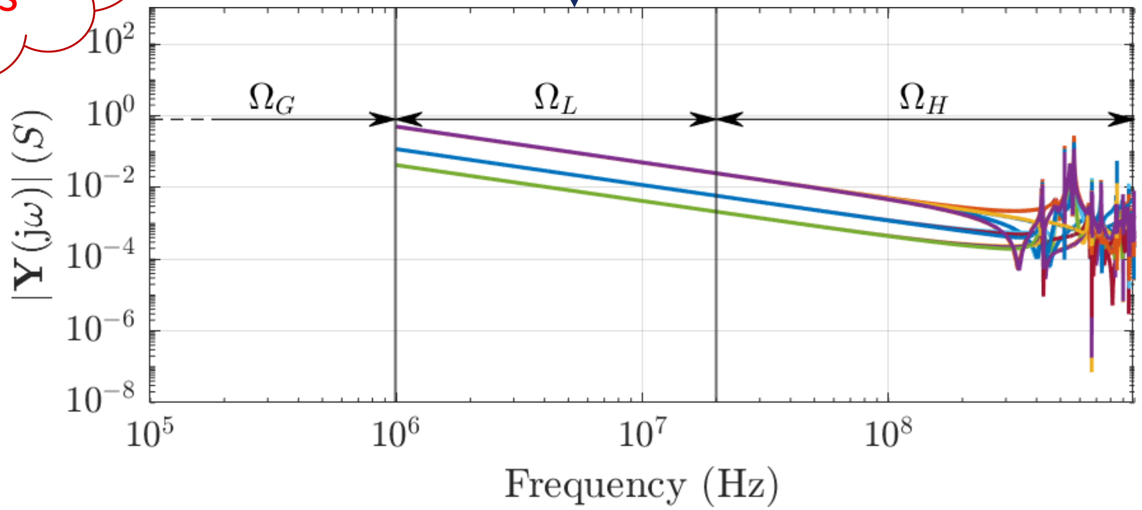


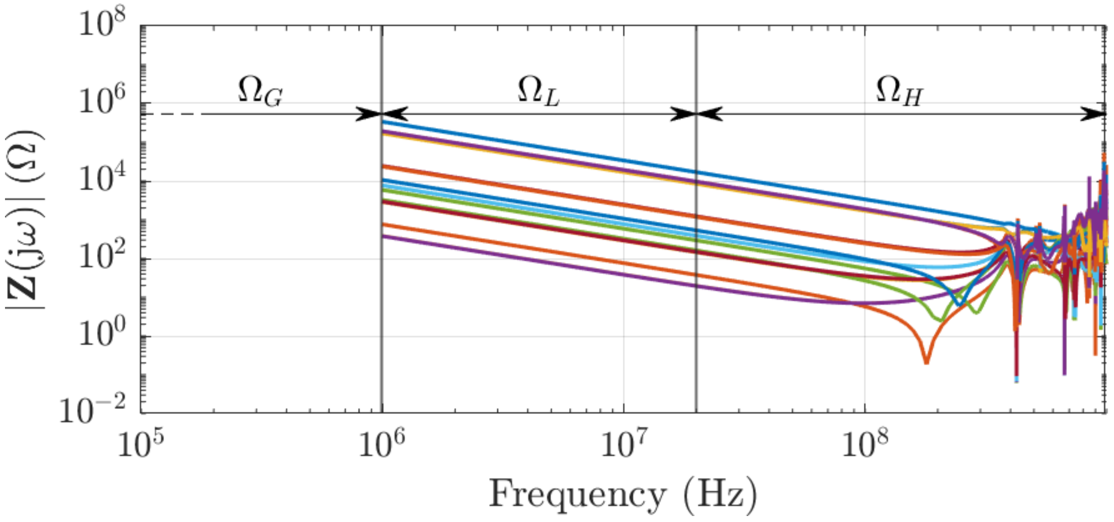
Field Solver (MoM)

Remove loads → Field Solver → Data $\mathbf{H}(s)$ → Model

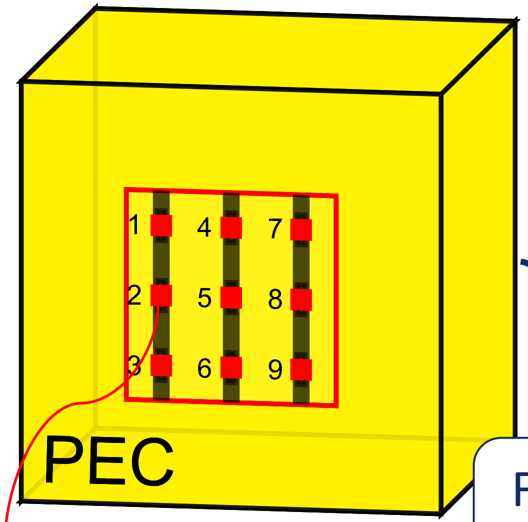
3 frequency regions

1. Ω_H high-frequency, rich of resonances
2. Ω_L mid-frequency, **asymptotic** behavior
3. Ω_G gap region, **unknown** with solver MoM





Why a Shielding Enclosure?



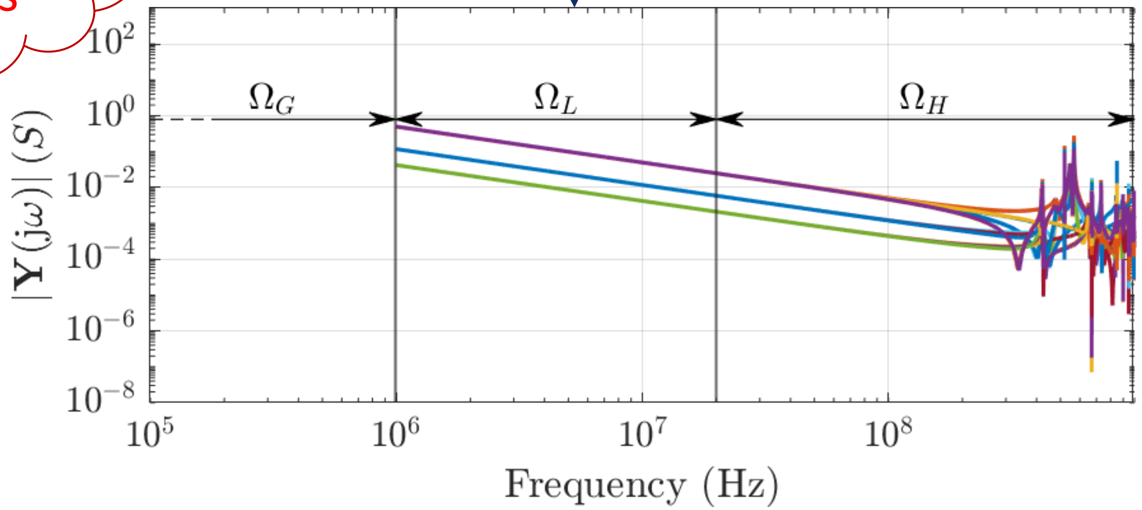
NO Loads

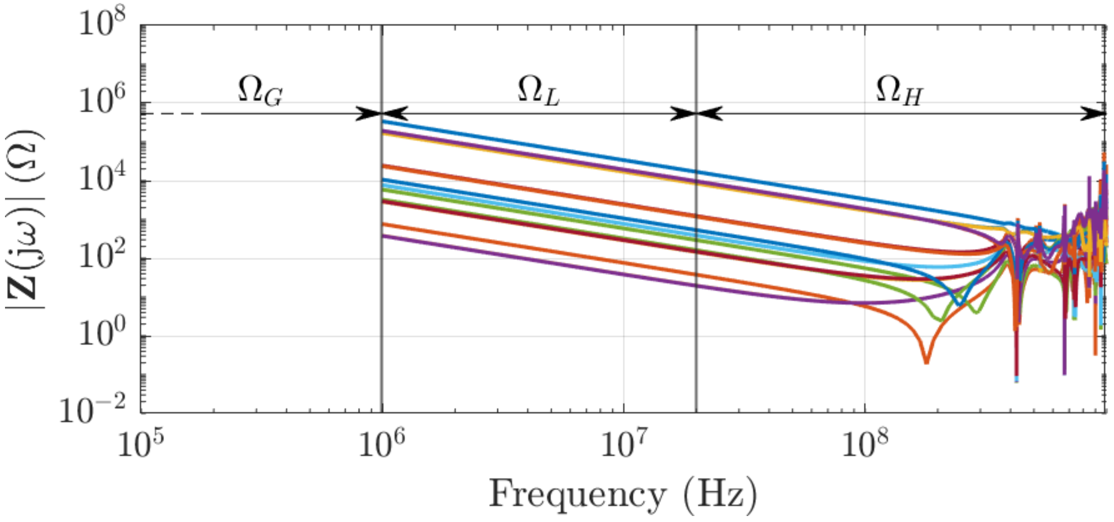
Field Solver (MoM)

Most general case

Both $\mathbf{Y}(j\omega)$ and $\mathbf{Z}(j\omega)$ show a **pole at DC**!!!

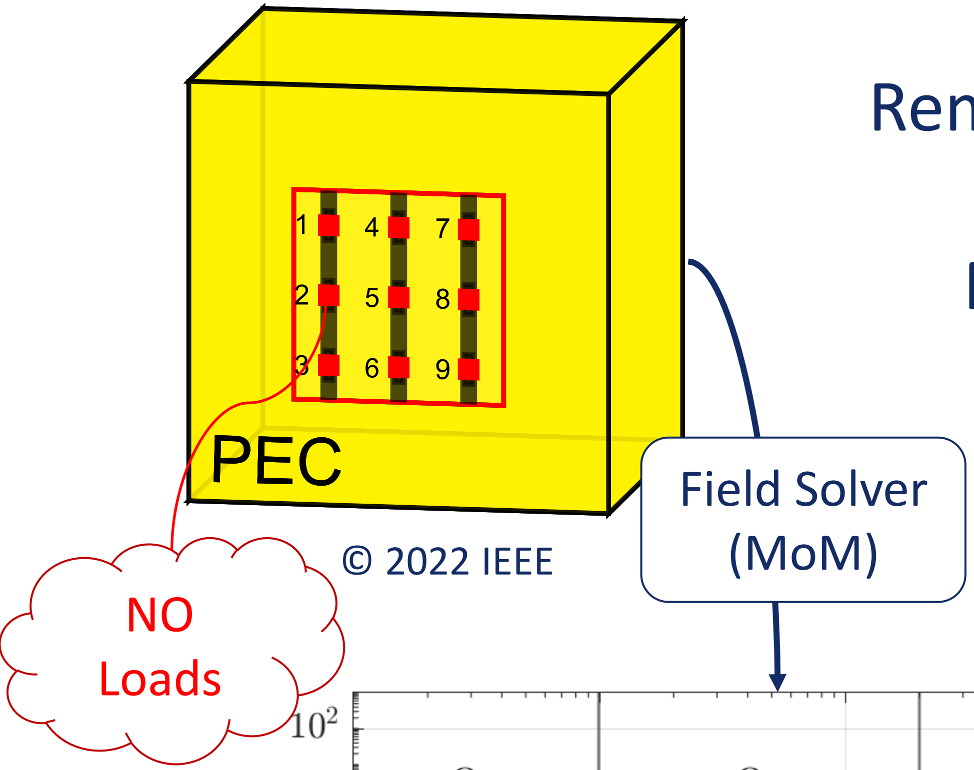
- $\omega \to 0 \ \to \mathbf{Y}(j\omega) \to \infty$
- $\omega \to 0 \ \to \mathbf{Z}(j\omega) \to \infty$





Macromodeling Challenges (1/3)

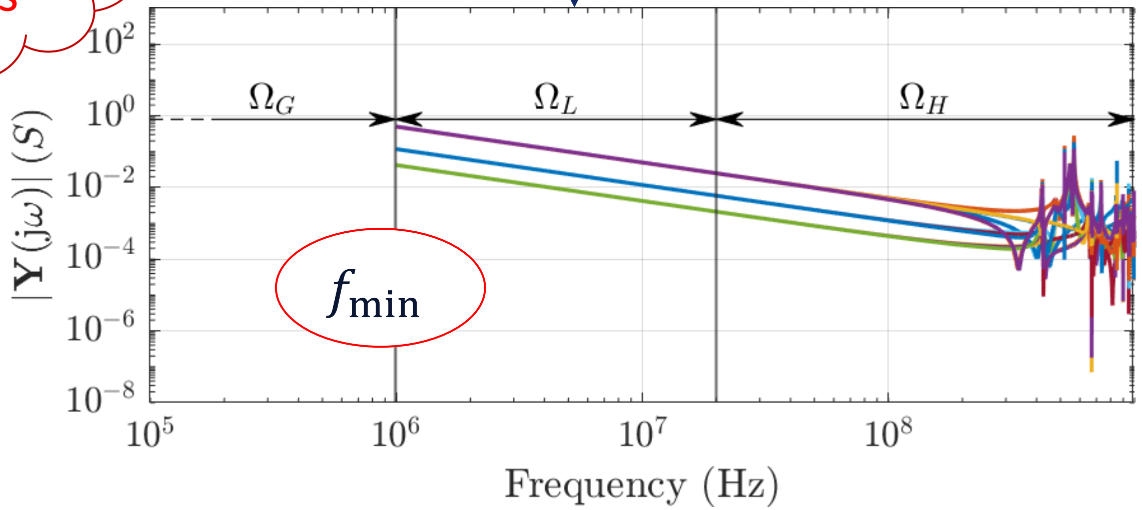
Remove loads → Field Solver → Data $\mathbf{H}(s)$ → Model

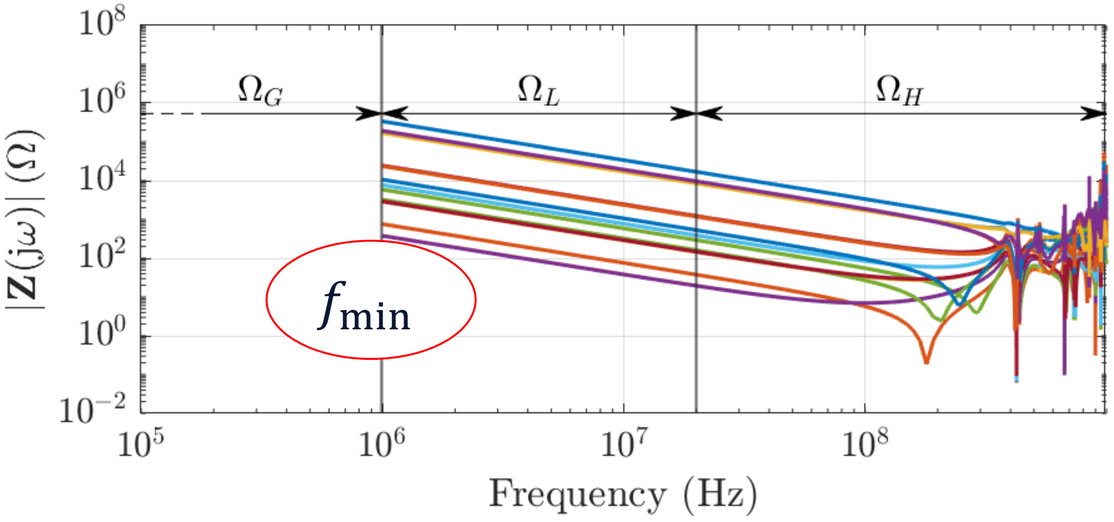


Macromodeling challenges

a) DC point is **missing**

b) Wide **low-frequency gap** Ω_G





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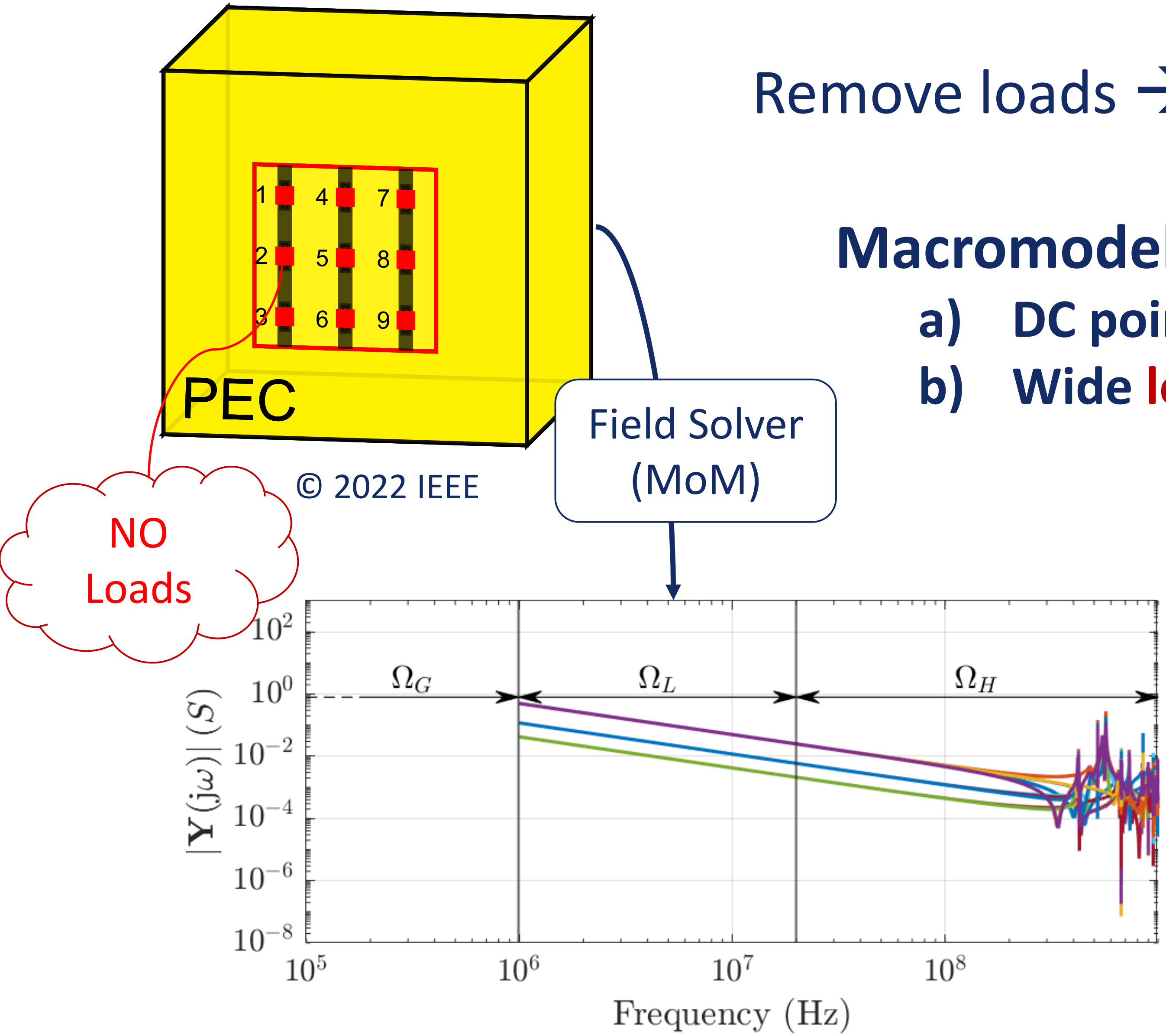
Macromodeling Challenges (2/3)

Remove loads → Field Solver → Data $\mathbf{H}(s)$ → Model



Macromodeling challenges

a) **DC point is missing**

b) **Wide low-frequency gap Ω_G**

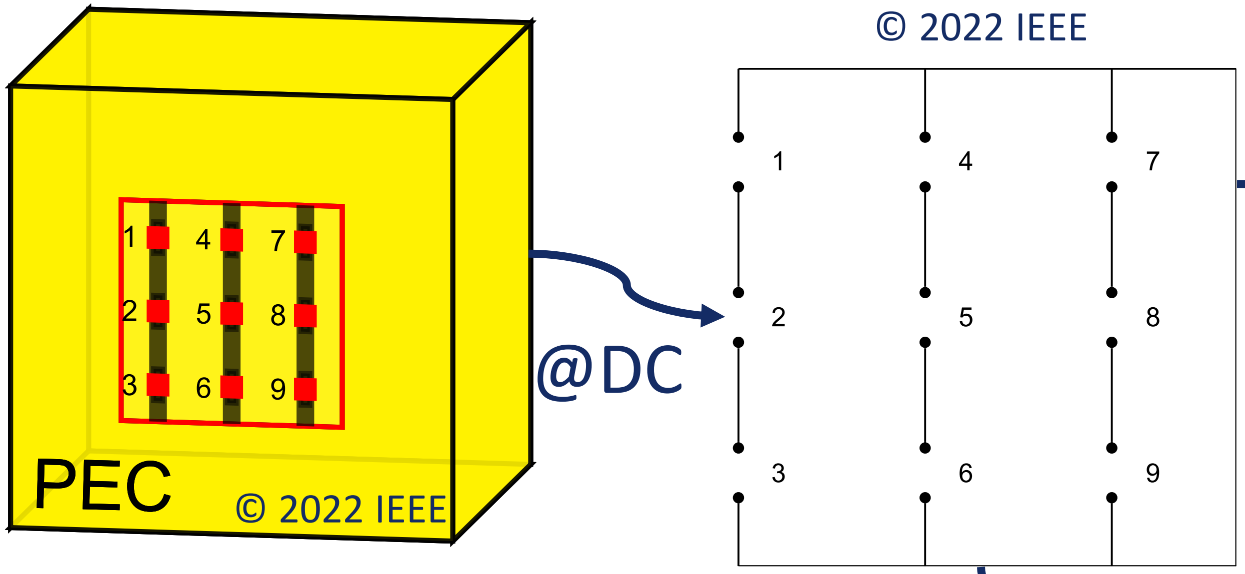
Proposed solution

Data preprocessing

a) Full-band **regularization**

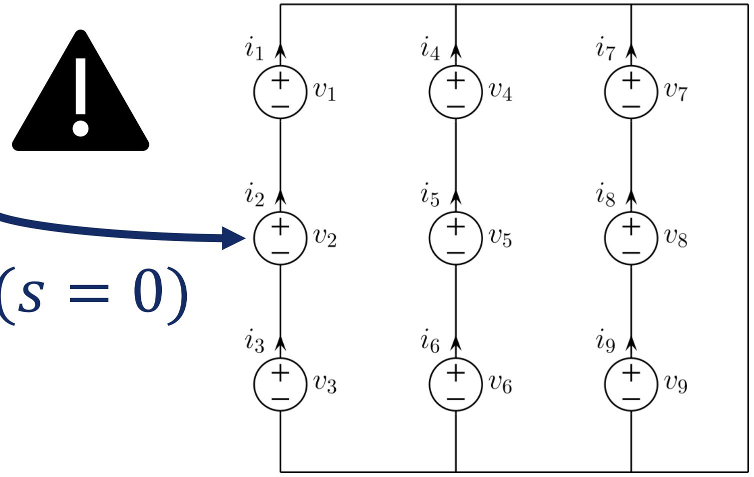
b) LF **modal extrapolation**

Box Characterization: DC Matrix

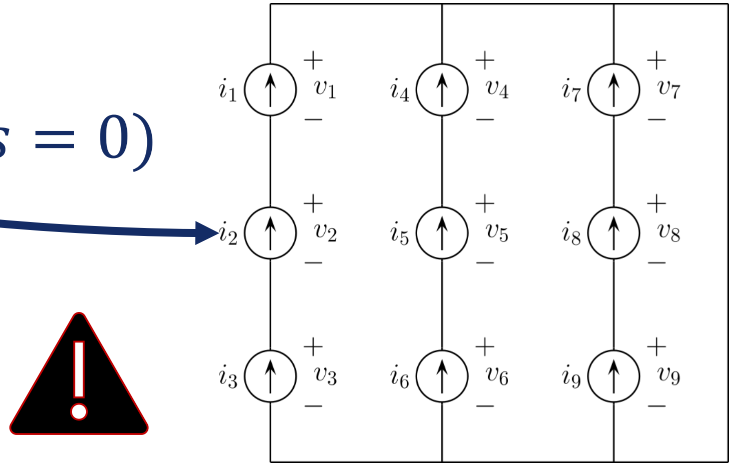


Perfect Electric Conductor

$\mathbf{Y}_0 = \mathbf{Y}(s = 0)$



$\mathbf{Z}_0 = \mathbf{Z}(s = 0)$



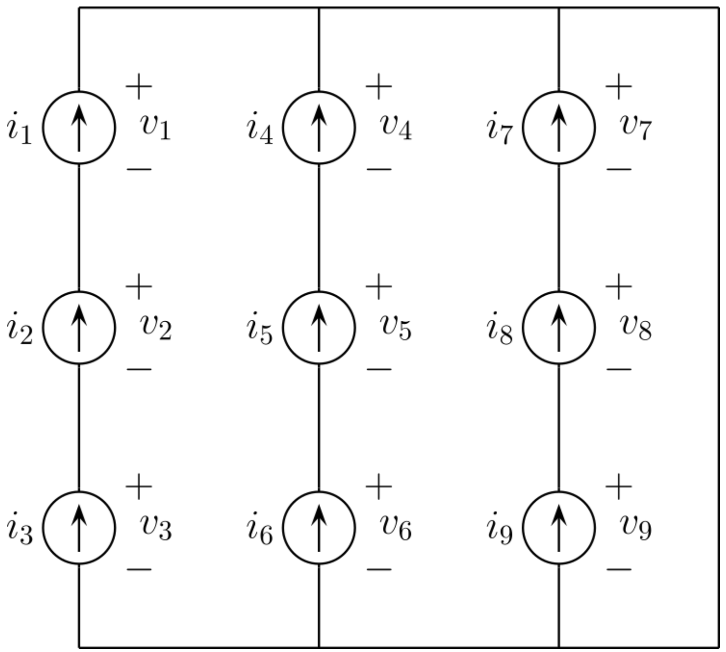
Both
ill-defined
at DC

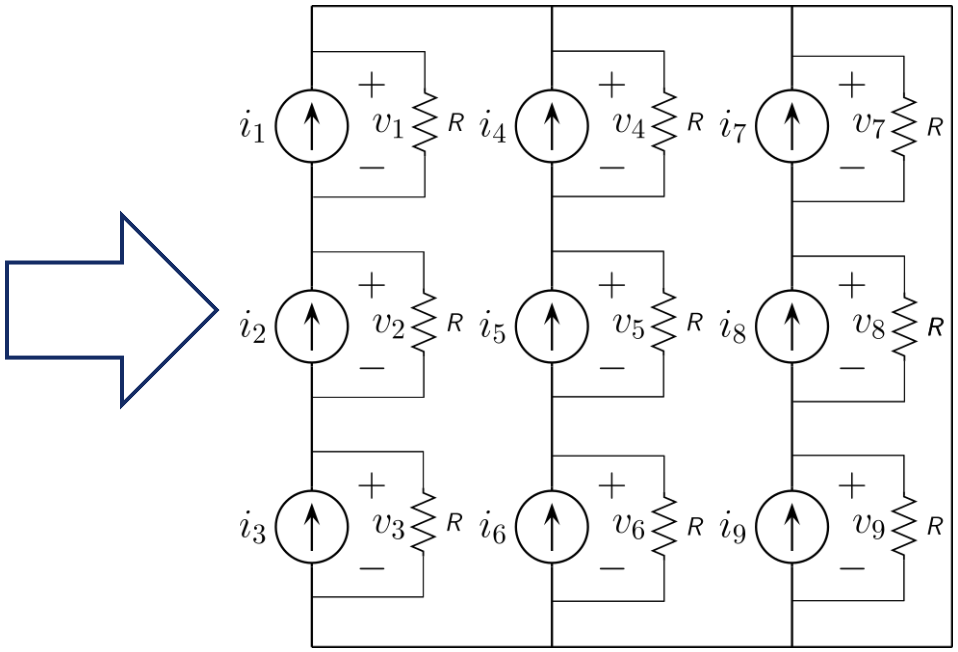
Data Regularization (1/3)

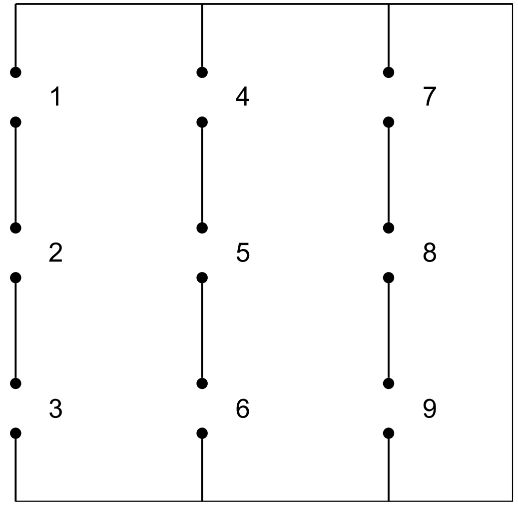
1. How to regularize $\mathbf{Z}(s)$?
   → add shunt resistor R

How to regularize MoM data ?

1. $\mathbf{Y}(s) \longleftarrow \mathbf{Y}(s) + \frac{1}{R}\mathbb{I}$







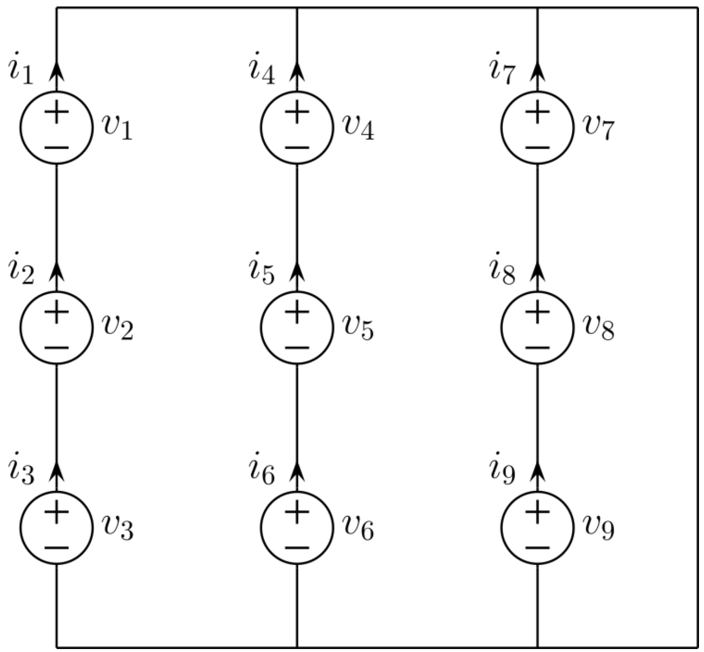
$\mathbf{Z}_0$ is well defined

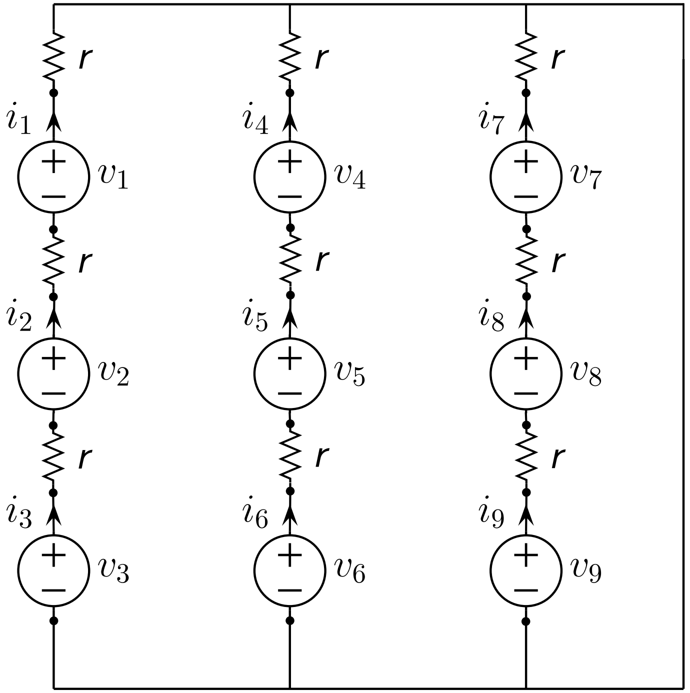
Data Regularization (2/3)

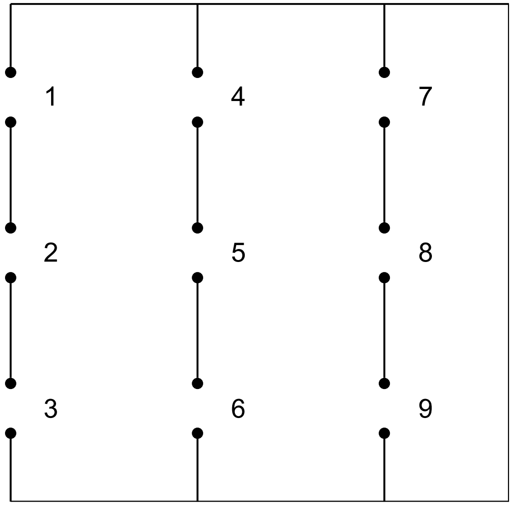
1. How to regularize $\mathbf{Z}(s)$?
   → add shunt resistor R
2. How to regularize $\mathbf{Y}(s)$?
   → add series resistor r

How to regularize MoM data ?

1. $\mathbf{Y}(s) \longleftarrow \mathbf{Y}(s) + \frac{1}{R}\mathbb{I}$
2. $\mathbf{Z}(s) \longleftarrow \mathbf{Z}(s) + r\mathbb{I}$







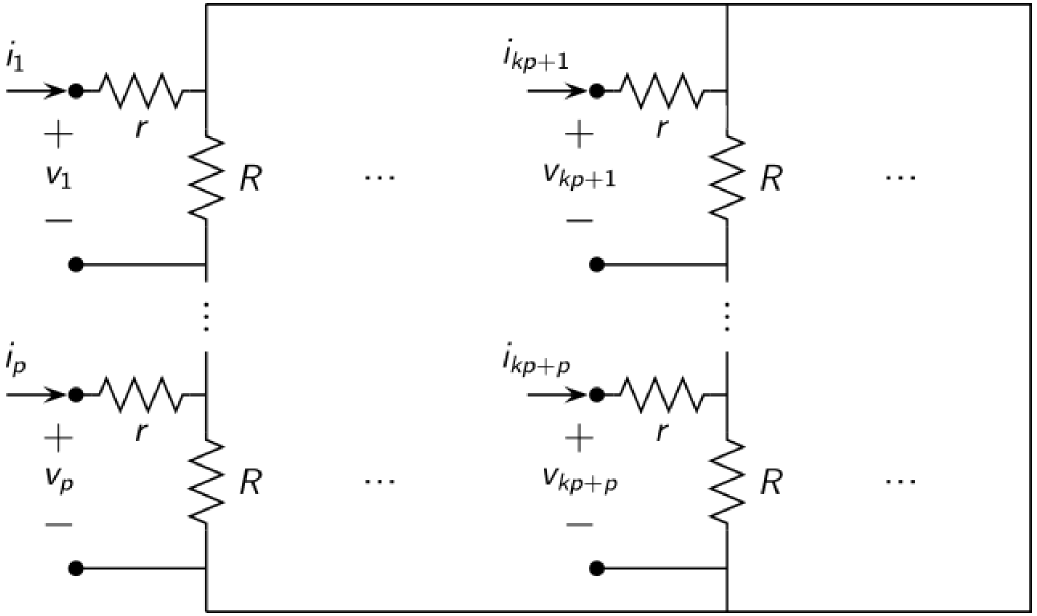
$\mathbf{Y}_0$ is well defined

Data Regularization (3/3)

1. How to regularize $\mathbf{Z}(s)$?
   →add shunt resistor R
2. How to regularize $\mathbf{Y}(s)$?
   → add series resistor r

How to regularize MoM data ?

1. $\mathbf{Y}(s) \longleftarrow \mathbf{Y}(s) + \frac{1}{R}\mathbb{I}$
2. Convert to $\mathbf{Z}(s) = \left(\mathbf{Y}(s)\right)^{-1}$
3. $\mathbf{Z}(s) \longleftarrow \mathbf{Z}(s) + r\mathbb{I}$

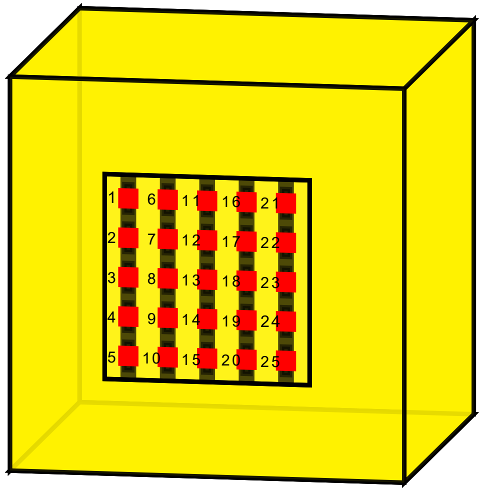


DC matrices can be **analytically computed** for all system representations

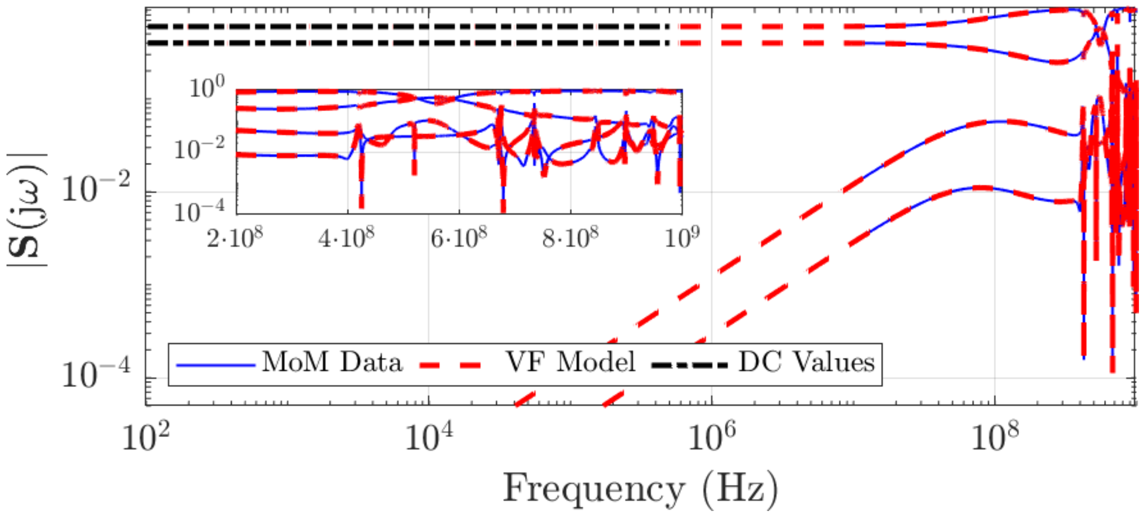
$$\mathbf{Y}_0 = \mathbb{I}_p \otimes \mathbf{Y}_p \qquad \mathbf{Y}_p = \frac{(p\,r\,\mathbb{I}_p + R\boldsymbol{u}\boldsymbol{u}^{\mathsf{T}})}{p\,r\,R'}$$

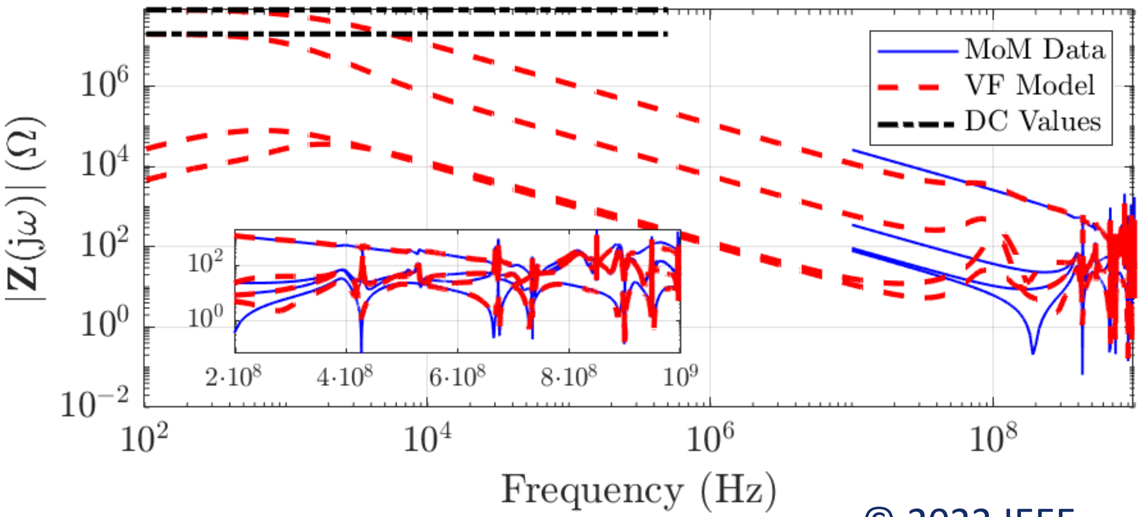
$$R' = R + r \qquad \boldsymbol{u}^{\mathsf{T}} = [1, \cdots, 1]$$

Macromodeling Challenges: a 25-port Box(3/3)



What if we built a model?





Macromodeling challenges

a) ~~DC point is missing~~
- ✓ Physics-based DC point added for model generation

b) **Wide low-frequency gap Ω_G**
- ➢ LF extrapolation is needed

Low Frequency Extrapolation (1/4)

Start with original data

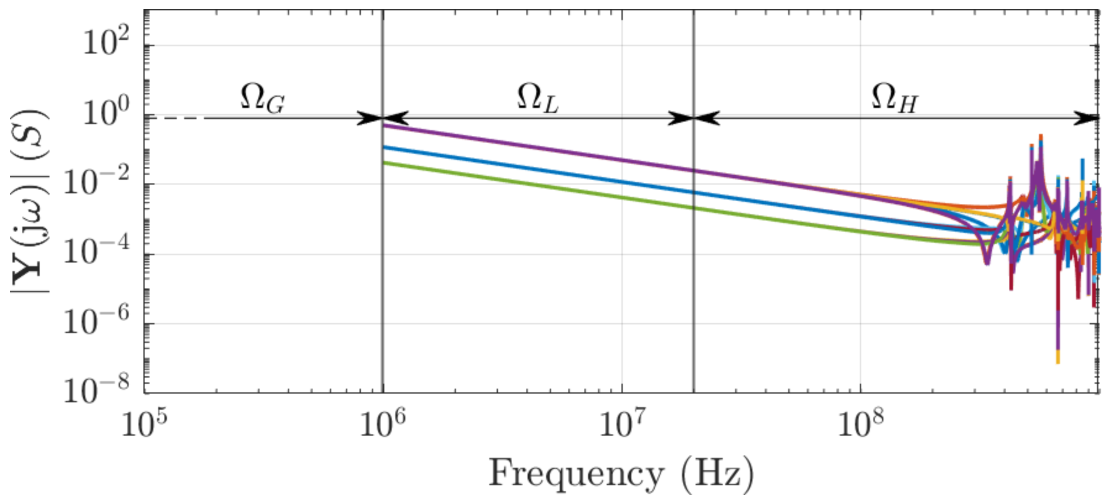
1. Eigenvalue decomposition at DC

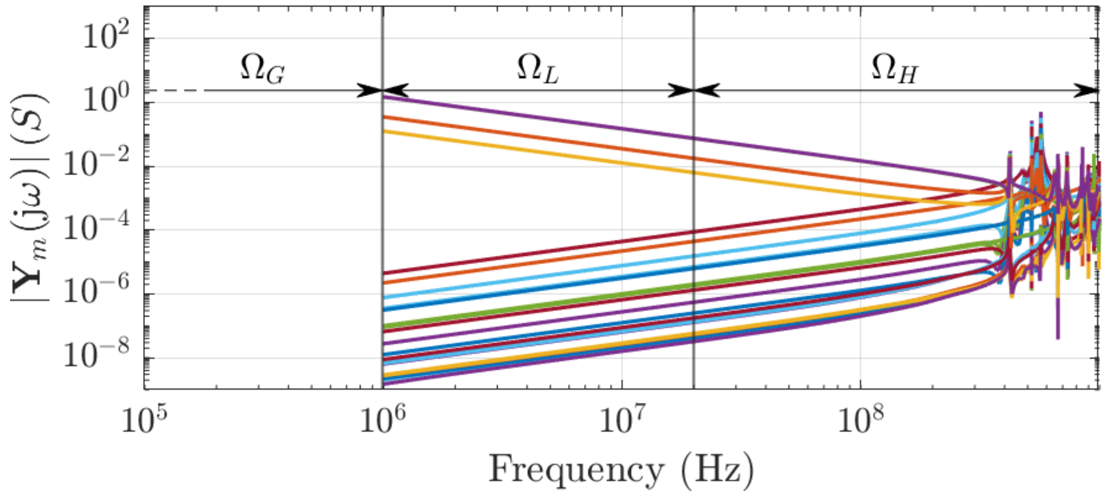
$$\mathbf{Y}_0 = \mathbf{Q}\boldsymbol{\Lambda}_0\mathbf{Q}^{\mathsf{T}}, \quad \boldsymbol{\Lambda}_0 = \mathbf{Q}^{\mathsf{T}}\mathbf{Y}_0\mathbf{Q} = \begin{bmatrix} \frac{1}{R'}\mathbb{I}_c & \mathbf{0} \\ \mathbf{0} & \frac{1}{r}\mathbb{I}_\ell \end{bmatrix} \qquad (2)$$

2. Projection to DC modal domain

$$\mathbf{Y}_m(\mathrm{j}\omega_k) = \mathbf{Q}^{\mathsf{T}}\mathbf{Y}(\mathrm{j}\omega_k)\mathbf{Q}\,, \quad k = 1, \cdots, K. \qquad (4)$$

Causality and passivity are preserved by the constant (real) and orthogonal $\mathbf{Q}$





Low Frequency Extrapolation (2/4)

Start with original data

1. Eigenvalue decomposition at DC

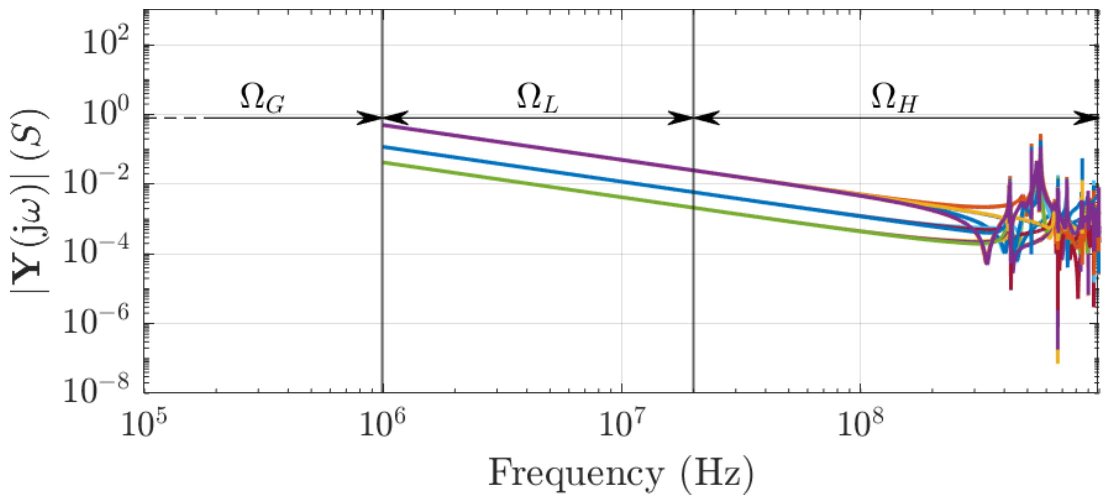
$$\mathbf{Y}_0 = \mathbf{Q}\mathbf{\Lambda}_0\mathbf{Q}^\mathsf{T}, \quad \mathbf{\Lambda}_0 = \mathbf{Q}^\mathsf{T}\mathbf{Y}_0\mathbf{Q} = \begin{bmatrix} \frac{1}{R'}\mathbb{I}_c & \mathbf{0} \\ \mathbf{0} & \frac{1}{r}\mathbb{I}_\ell \end{bmatrix} \qquad (2)$$

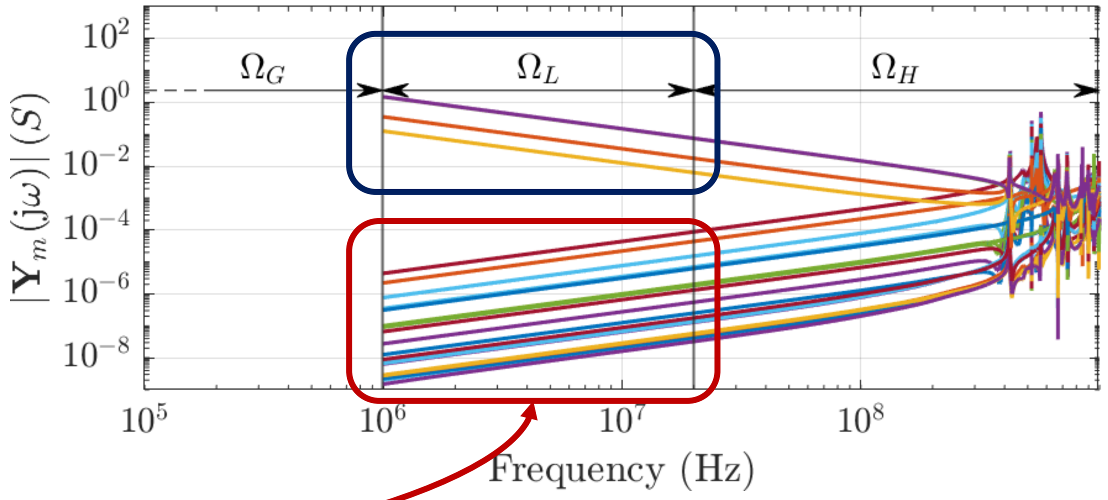
2. Projection to DC modal domain

$$\mathbf{Y}_m(\mathrm{j}\omega_k) = \mathbf{Q}^\mathsf{T}\mathbf{Y}(\mathrm{j}\omega_k)\mathbf{Q}\,, \quad k = 1, \cdots, K. \qquad (4)$$

Low-frequency (asymptotic) behaviors are well separated in the modal domain!

$$\mathbf{Y}_m(\mathrm{j}\omega) \approx \frac{1}{\mathrm{j}\omega}\mathbf{\Gamma}_m + \mathrm{j}\omega\mathbf{C}_m = \begin{bmatrix} \mathrm{j}\omega\widetilde{\mathbf{C}} & \mathrm{j}\omega\mathbf{X} \\ \mathrm{j}\omega\mathbf{X}^\mathsf{T} & \frac{1}{\mathrm{j}\omega}\widetilde{\mathbf{\Gamma}} \end{bmatrix} \qquad (5)$$





Low Frequency Extrapolation (3/4)

Start with original data

1. Eigenvalue decomposition at DC

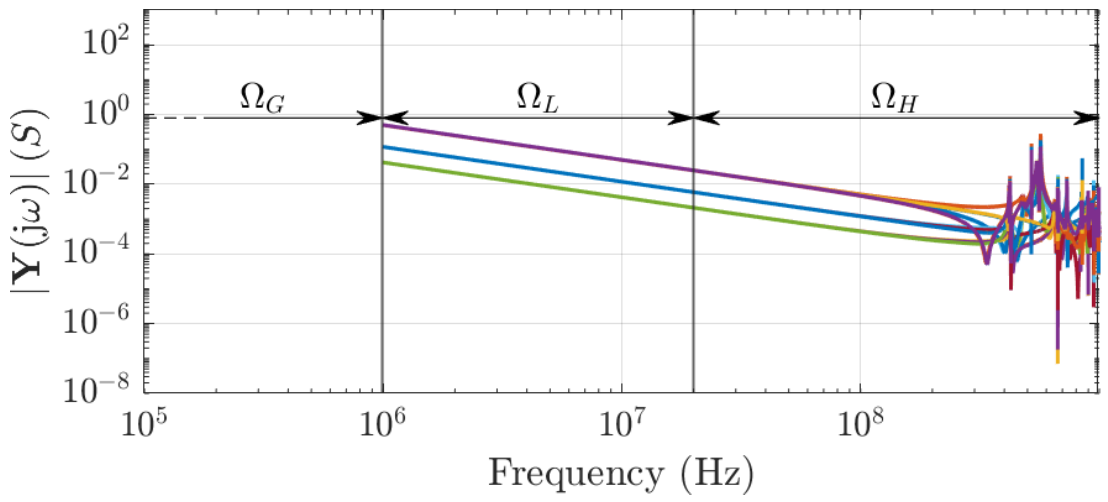
$$\mathbf{Y}_0 = \mathbf{Q}\mathbf{\Lambda}_0\mathbf{Q}^\mathsf{T}, \quad \mathbf{\Lambda}_0 = \mathbf{Q}^\mathsf{T}\mathbf{Y}_0\mathbf{Q} = \begin{bmatrix} \frac{1}{R'}\mathbb{I}_c & \mathbf{0} \\ \mathbf{0} & \frac{1}{r}\mathbb{I}_\ell \end{bmatrix} \quad (2)$$

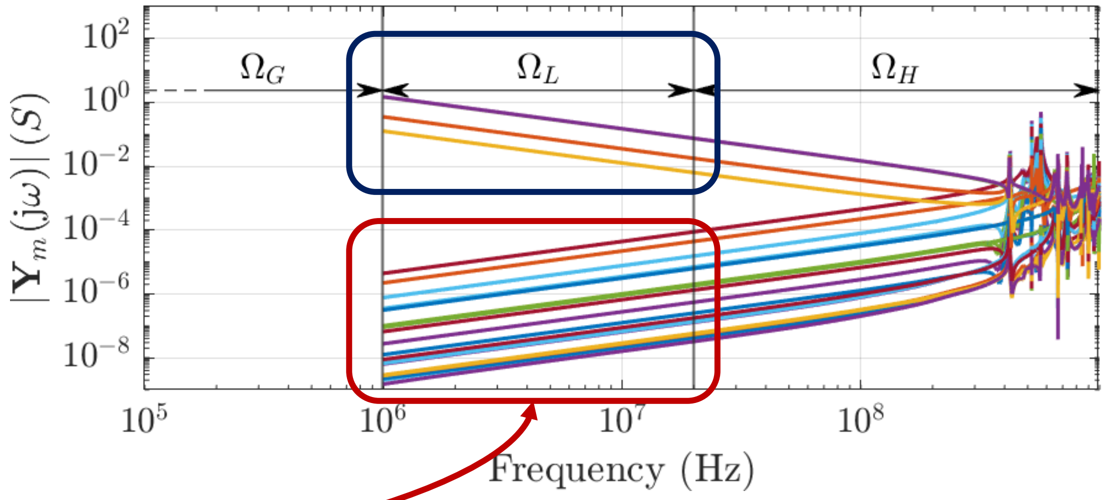
2. Projection to DC modal domain

$$\mathbf{Y}_m(j\omega_k) = \mathbf{Q}^\mathsf{T}\mathbf{Y}(j\omega_k)\mathbf{Q}\,, \quad k = 1, \cdots, K. \quad (4)$$

3. Fit (5) with element-wise regression in Ω_L

$$\mathbf{Y}_m(j\omega) \approx \frac{1}{j\omega}\mathbf{\Gamma}_m + j\omega\mathbf{C}_m = \begin{bmatrix} j\omega\widetilde{\mathbf{C}} & j\omega\mathbf{X} \\ j\omega\mathbf{X}^\mathsf{T} & \frac{1}{j\omega}\widetilde{\mathbf{\Gamma}} \end{bmatrix} \quad (5)$$





Low Frequency Extrapolation (4/4)

Start with original data

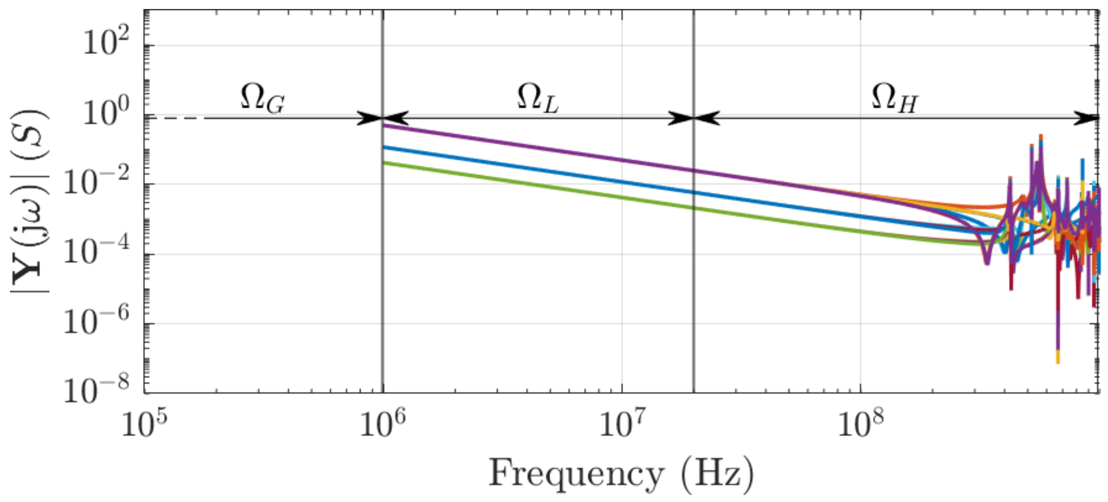
1. Eigenvalue decomposition at DC

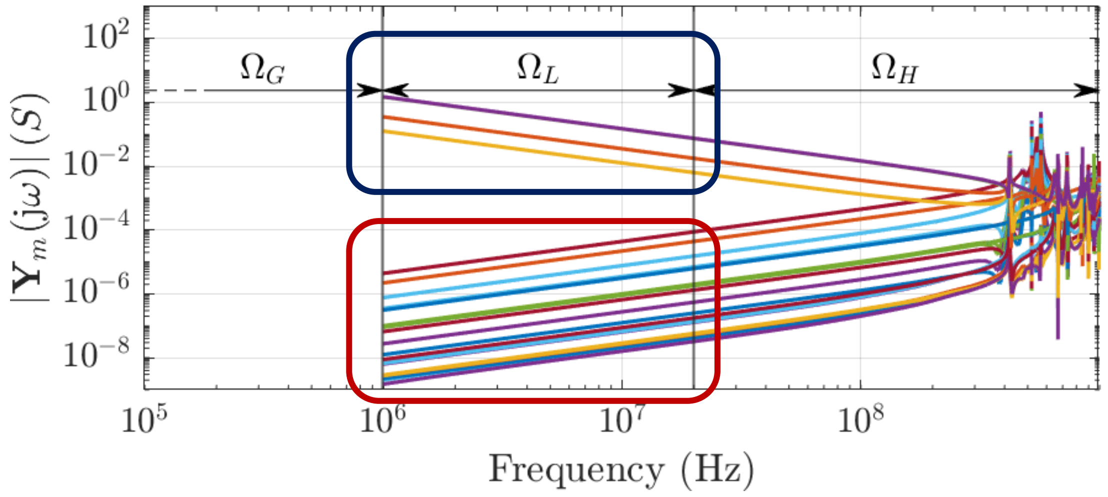
$$\mathbf{Y}_0 = \mathbf{Q}\boldsymbol{\Lambda}_0\mathbf{Q}^\mathsf{T}, \quad \boldsymbol{\Lambda}_0 = \mathbf{Q}^\mathsf{T}\mathbf{Y}_0\mathbf{Q} = \begin{bmatrix} \frac{1}{R'}\mathbb{I}_c & \mathbf{0} \\ \mathbf{0} & \frac{1}{r}\mathbb{I}_\ell \end{bmatrix} \qquad (2)$$

2. Projection to DC modal domain

$$\mathbf{Y}_m(\mathrm{j}\omega_k) = \mathbf{Q}^\mathsf{T}\mathbf{Y}(\mathrm{j}\omega_k)\mathbf{Q}, \quad k = 1, \cdots, K. \qquad (4)$$

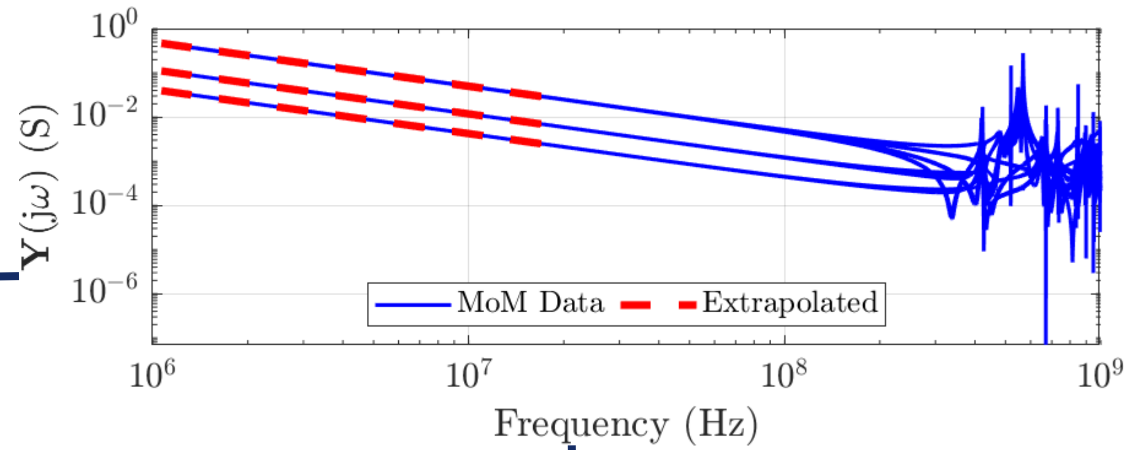
3. Fit (5) with element-wise regression in Ω_L
4. **Extrapolate in the gap band Ω_G**

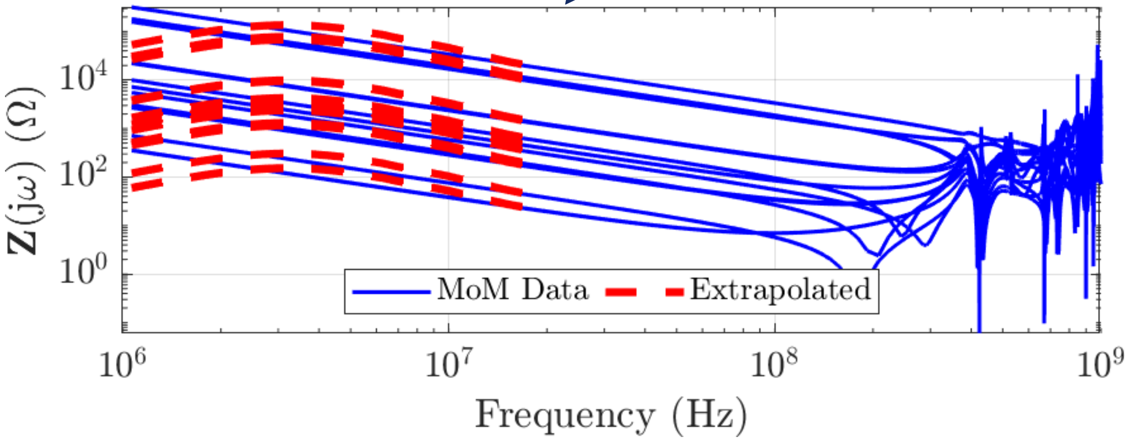


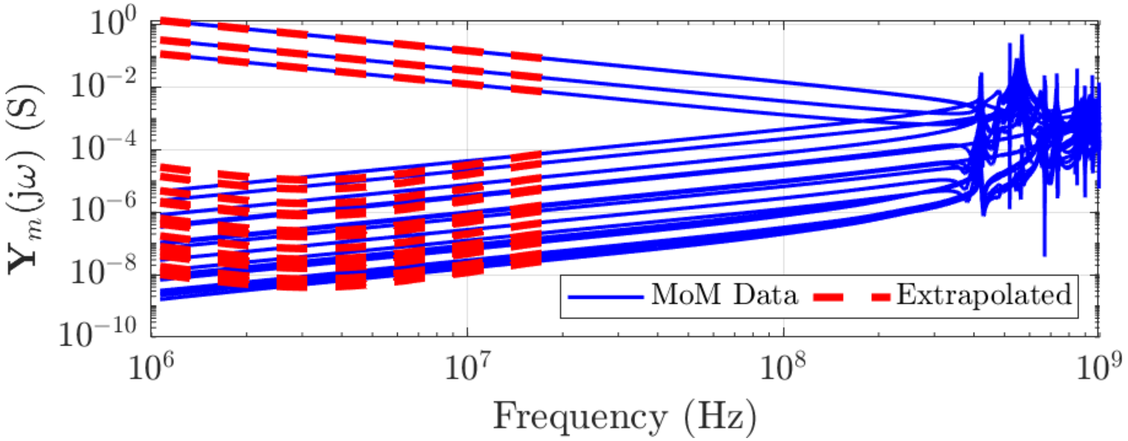


Why not a Direct Extrapolation?

Direct fit at low-frequency
→ **inaccurate results**
(changing representation)







Capacitive modes are not well visible in the admittance representation!

Low Frequency Extrapolation and Regularization

Start with original data

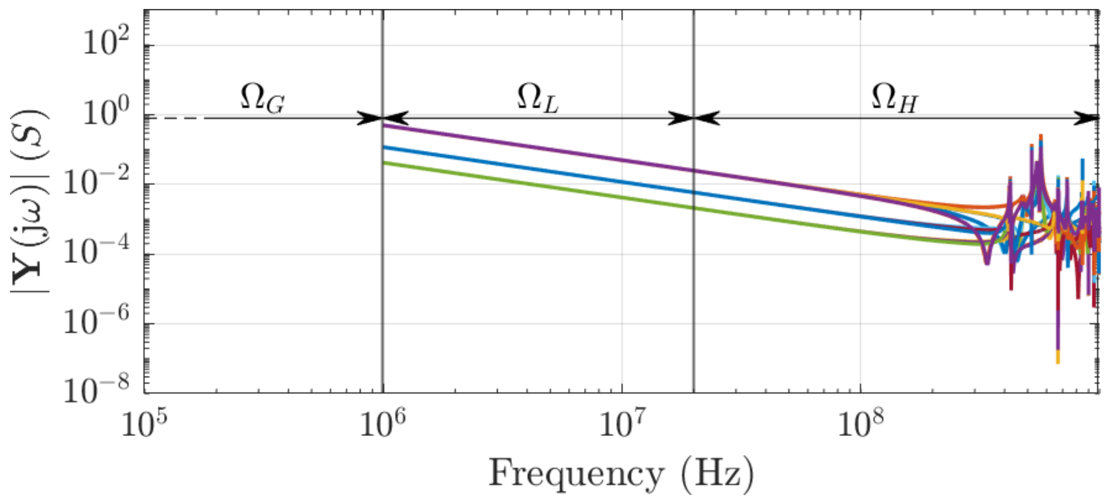
1. Eigenvalue decomposition at DC

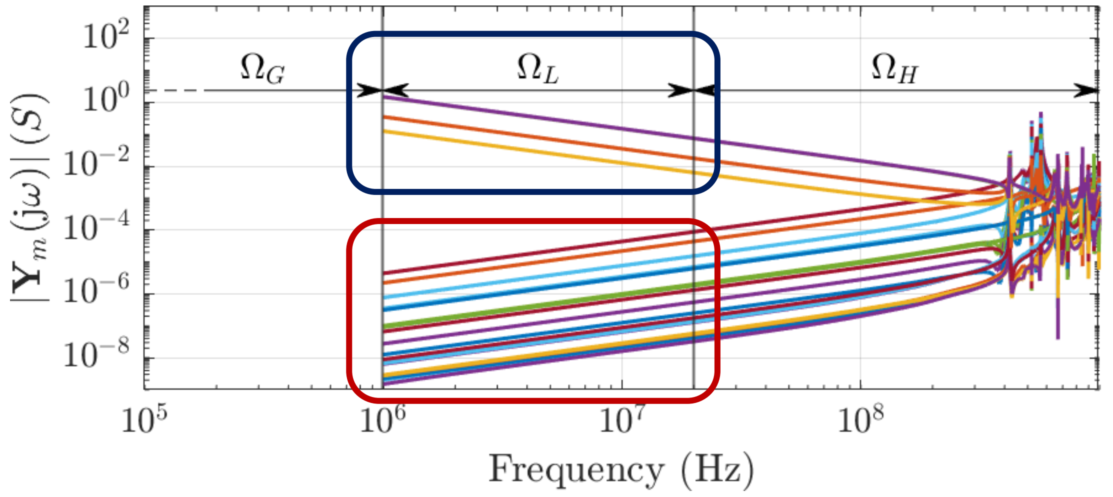
$$\mathbf{Y}_0 = \mathbf{Q}\boldsymbol{\Lambda}_0\mathbf{Q}^\mathsf{T}, \quad \boldsymbol{\Lambda}_0 = \mathbf{Q}^\mathsf{T}\mathbf{Y}_0\mathbf{Q} = \begin{bmatrix} \frac{1}{R'}\mathbb{I}_c & \mathbf{0} \\ \mathbf{0} & \frac{1}{r}\mathbb{I}_\ell \end{bmatrix} \qquad (2)$$

2. Projection to DC modal domain

$$\mathbf{Y}_m(\mathrm{j}\omega_k) = \mathbf{Q}^\mathsf{T}\mathbf{Y}(\mathrm{j}\omega_k)\mathbf{Q}\,, \quad k = 1, \cdots, K. \qquad (4)$$

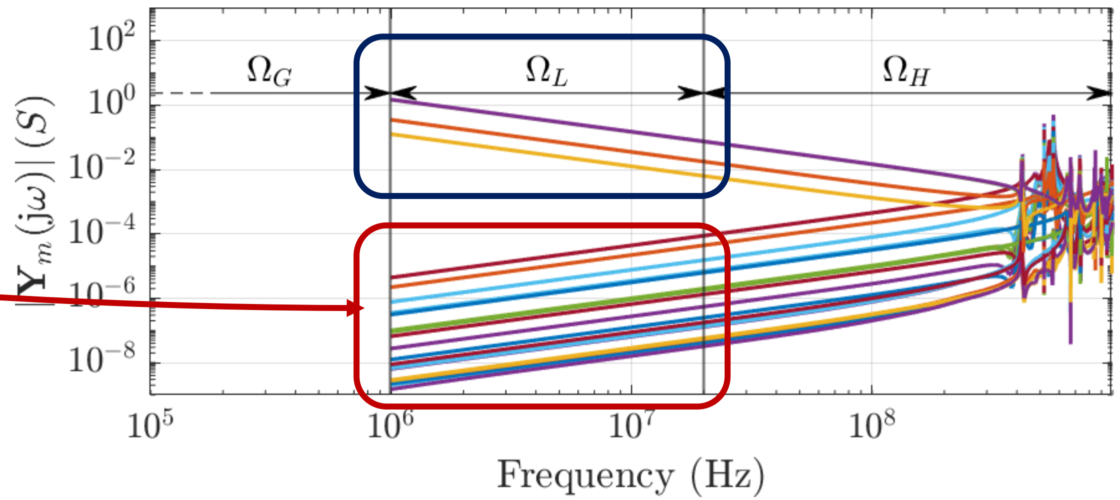
3. Fit (5) with element-wise regression in Ω_L
4. Extrapolate in the gap band Ω_G
5. Regularize data in the modal domain





Regularization in the Modal Domain

$$\mathbf{Y}_m(\mathrm{j}\omega) \approx \frac{1}{\mathrm{j}\omega}\mathbf{\Gamma}_m + \mathrm{j}\omega\mathbf{C}_m = \begin{bmatrix} \mathrm{j}\omega\widetilde{\mathbf{C}} & \mathrm{j}\omega\mathbf{X} \\ \mathrm{j}\omega\mathbf{X}^\mathsf{T} & \frac{1}{\mathrm{j}\omega}\widetilde{\mathbf{\Gamma}} \end{bmatrix} \qquad (5)$$



Capacitive blocks are responsible for the singularity of (modal) admittance in **DC**

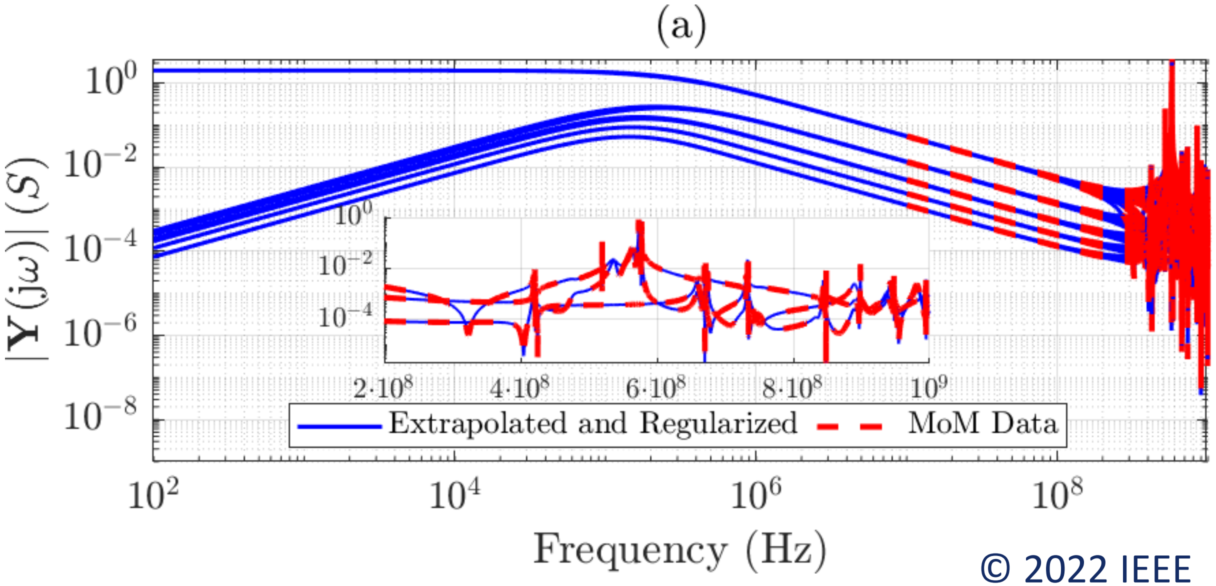
Minimize the perturbation: modify only the **eigenvalues** associate to **capacitive blocks**

5. Regularize data in the modal domain
   a) **Regularize** (modal) **admittance** $\widehat{\mathbf{Y}}_m(\mathrm{j}\omega) = \mathbf{Y}_m(\mathrm{j}\omega) + \begin{bmatrix} \frac{1}{R'}\mathbb{I}_c & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}$
   b) **Regularize** (modal) **impedance** $\check{\mathbf{Z}}_m(\mathrm{j}\omega) = \widehat{\mathbf{Y}}_m(\mathrm{j}\omega)^{-1} + \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & r\mathbb{I}_\ell \end{bmatrix} = \begin{bmatrix} R'\,\mathbb{I}_c + \star_1 & \star_2 \\ \star_2 & r\,\mathbb{I}_\ell + \star_1 \end{bmatrix}$
6. Convert back to the **physical domain** $\check{\mathbf{Z}}(\mathrm{j}\omega) = \mathbf{Q}\,\check{\mathbf{Z}}_m(\mathrm{j}\omega)\,\mathbf{Q}^\mathsf{T}$

Low Frequency Extrapolation and Regularization

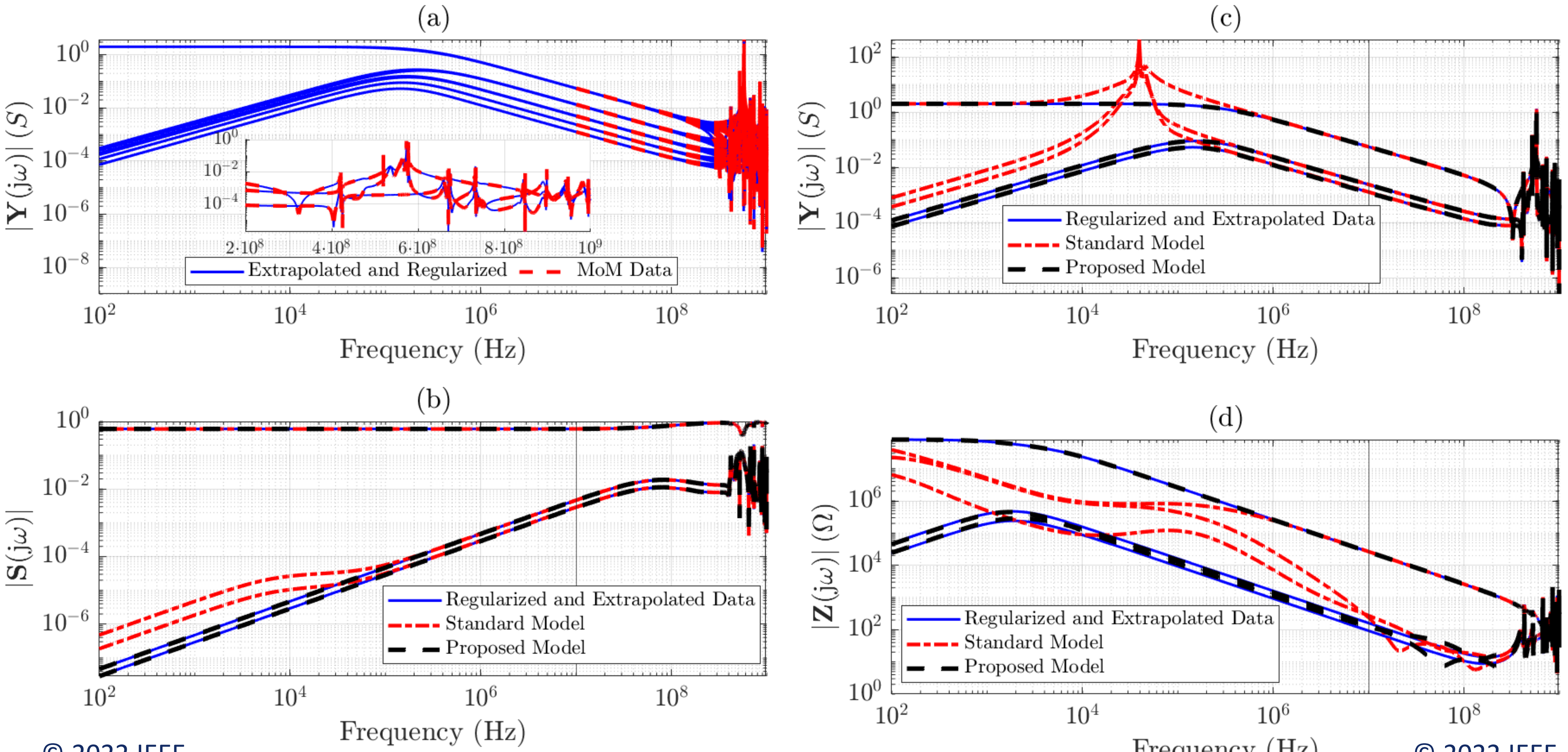
Start with original data

1. Eigenvalue decomposition at DC
2. Projection to DC modal domain
3. Fit (5) with element-wise regression in the low-frequency range Ω_L
4. Extrapolate in the gap band Ω_G
5. Regularize data in the modal domain
   a) Regularize (modal) admittance
   b) Regularize (modal) impedance
6. Convert back to the physical domain



Well-defined full-bandwidth data
→ now we can build a model

A 25-ports Shielding Enclosures



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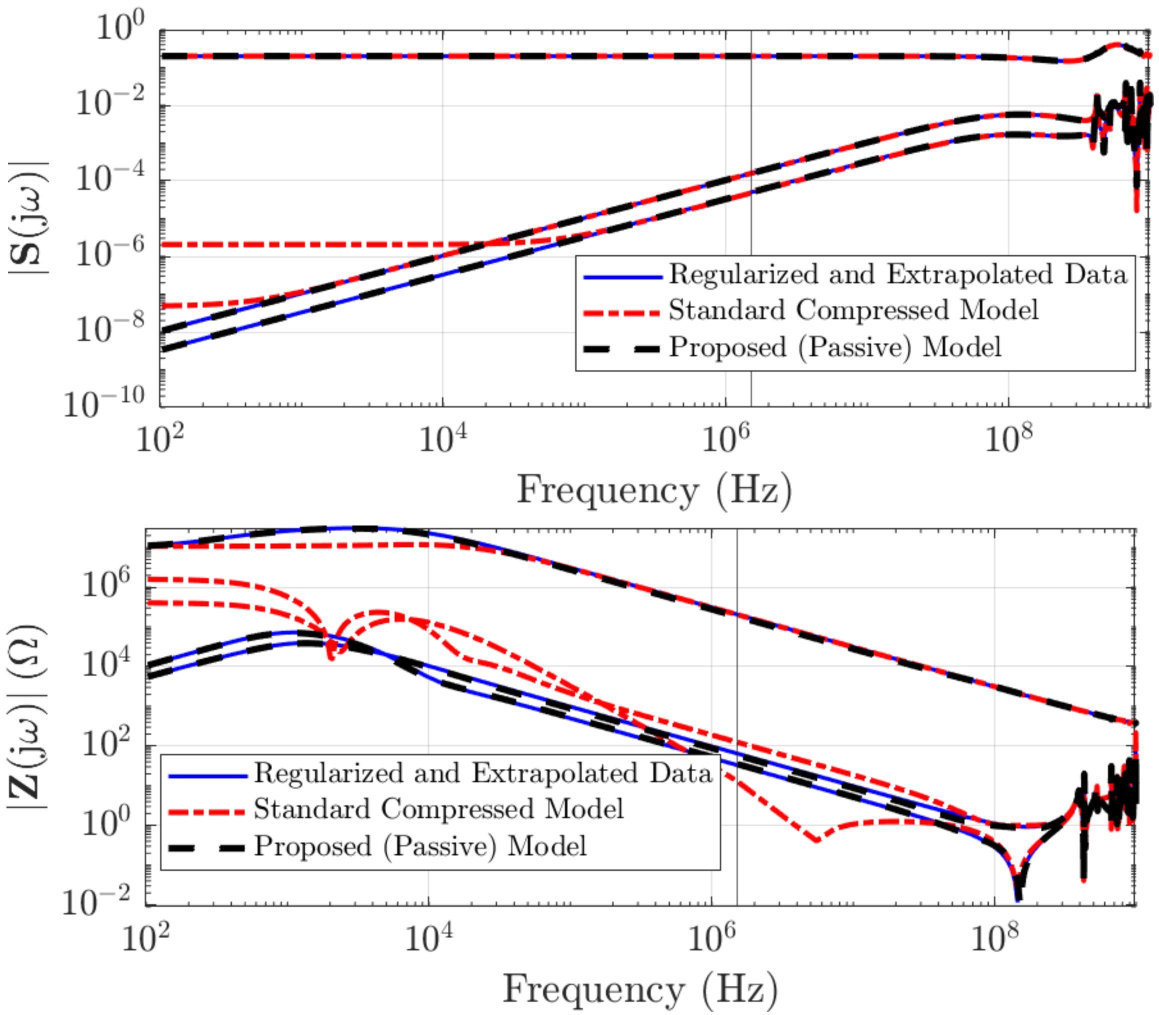
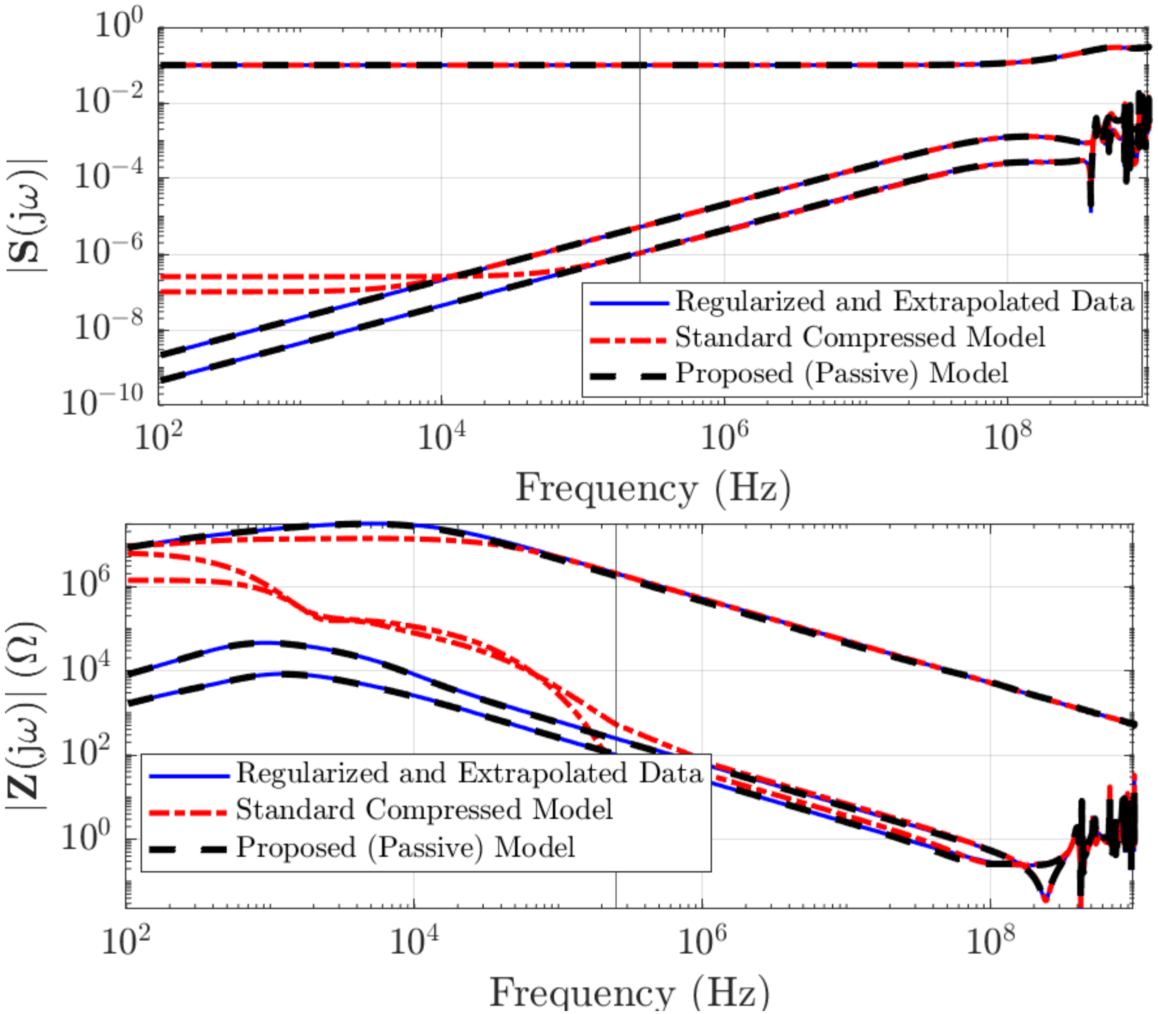
Shielding Enclosures of Increasing Complexity

100 ports

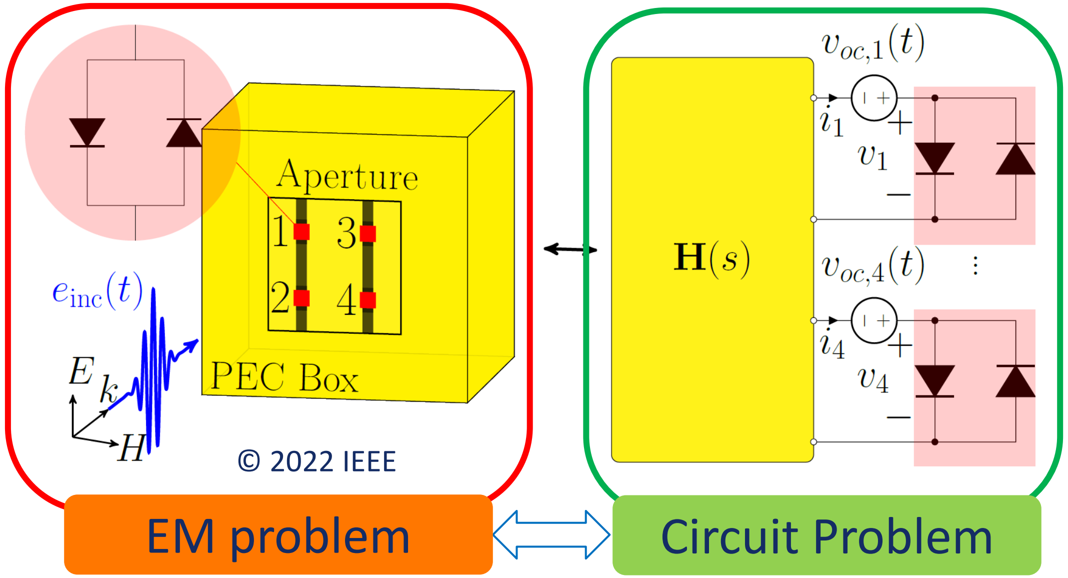


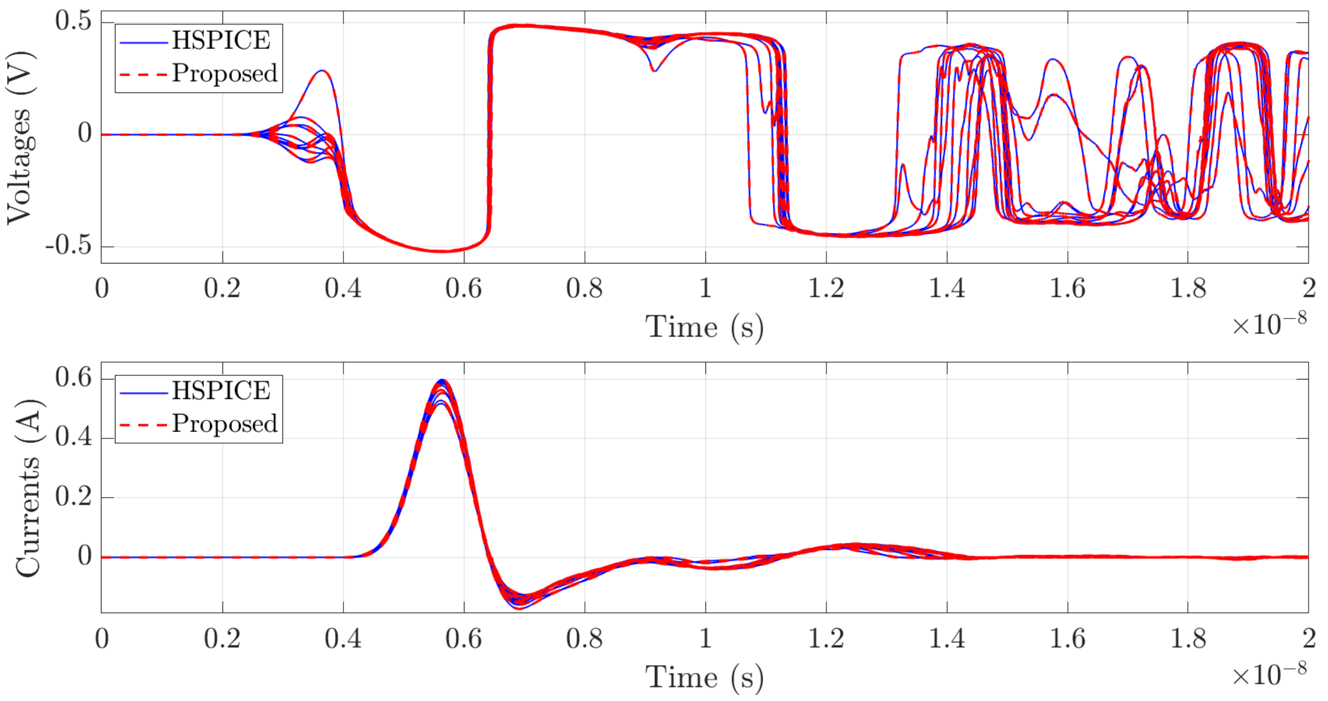
400 ports



From: M. De Stefano, T. Wendt, C. Yang, S. Grivet-Talocia, and C. Schuster, "Regularized and Compressed Large-Scale Rational Macromodeling: Theory and Application to Energy-Selective Shielding Enclosures," *IEEE Trans. Electromagn. Compat., accepted*

A Simulation Example with 400 Ports

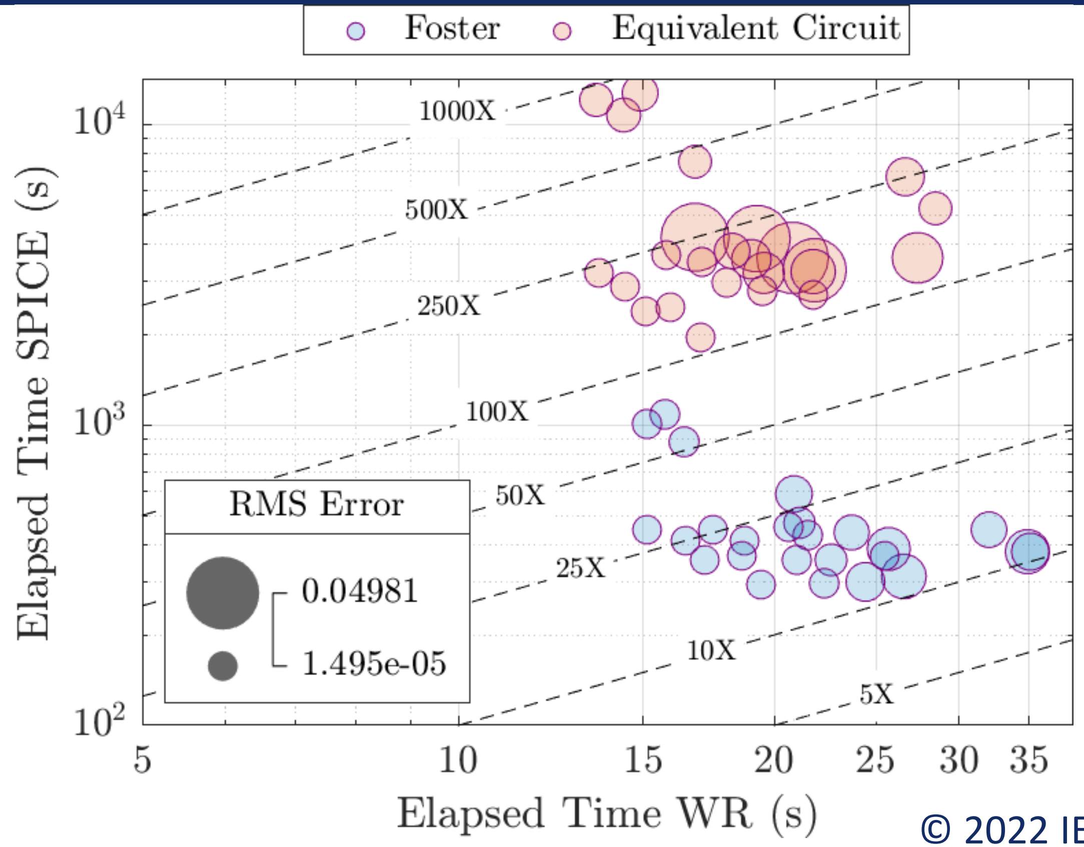


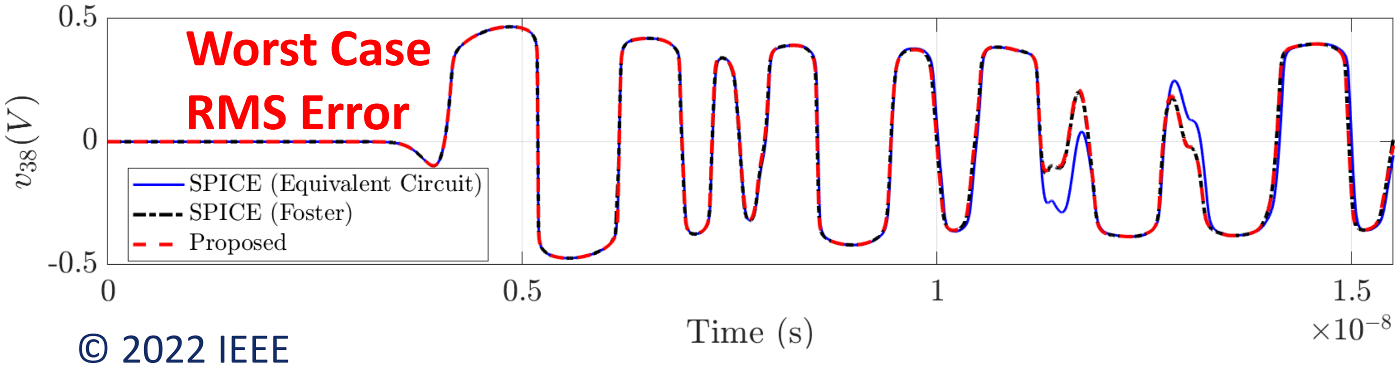


- $\mathbf{H}(s)$ is a **400-ports** box (**85 poles**)
- Incident wave $e_{inc}(t)$ is a Gaussian Modulated Pulse centered at 400MHz
- The resulting $v_{oc}(t)$ has a maximum amplitude of 473 V
- HSPICE Elapsed time: ≈ 1.27 hours
- Hybrid solver (Proposed) time: ≈ 203 seconds → **SPEED UP ≈ 22X**

Systematic Performance Comparisons

- 100-port Box + Gaussian Modulated Pulse
- **25 different simulations**
  - Sweep on center frequency and amplitude
- **2 SPICE representations**
  (Foster and Equivalent Circuit)
- Total of **50 simulations**





Now we can run **systematic analyses safely!**

Conclusions

- A **full-bandwidth regularization and extrapolation procedure**
- Reliable data **pre-processing phase** for later **macromodeling**
  - **Full control** of **DC** → nonlinear simulations
  - **Data driven** → no need of a specific solver for the **low-frequency extrapolation**

- **Applicable to multiport** structures with **similar asymptotic behavior**
  → **DC regularization circuit** is needed
- If a **DC** characterization is **already available** → **minor modifications**

Thank you! Questions?