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Parameterized Macromodels for EMC/EMI Simulation of Electrical Interconnects

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Abstract — **This paper proposes a reduced-order behavioral modeling workflow for transient simulation of electrical interconnects, excited by a suitably parameterized incident electromagnetic field. The procedure leads to a low-order equivalent netlist, compatible with legacy circuit solvers of the SPICE class, that can be used in system-level transient simulations aimed at the quantification of noise at the interconnect ports induced by the incident field.**

1 INTRODUCTION

The accurate characterization of all parasitics effects of electrical interconnects is a necessary step during the design and verification of electronic systems and products. The Signal Integrity of a given system is strongly dependent on non ideal effects of conductor and dielectric materials causing dispersion and losses, on near and far field coupling with neighboring conductors, on discontinuities in current return paths, to name a few. All these phenomena may lead to signal deterioration and corrupt the transfer of information between subsystems. Moreover, the presence of incidents fields may cause ElectroMagnetic Interference (EMI), adding field-induced noise.

The above phenomena are best captured through a full-wave characterization of the signal transmission system, defined at suitable electrical ports where transmitters and receivers are located. In addition, some electromagnetic ports are needed to account for the possible presence of incident fields [1, 2]. The objective of this work is to construct behavioral, reduced-order interconnect models that can account for external field excitation, and that can be simulated in time-domain for Signal Integrity analyses using standard ODE or circuit (SPICE) solvers. We include in the models also external parameters, such as geometrical or material characteristics or incident field direction, so that the effects of such parameters can be properly estimated through parametric numerical simulations.

We approach the above problem by fitting a parameterized macromodel with rational transfer function and parameter-dependent coefficients to a set frequency (scattering) responses obtained by

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a field solver [4, 5], suitably generalized to account for the electromagnetic ports [2]. The model is identified through a parameterized Generalized Sanathanan-Koerner iteration [2,5], and model stability and passivity are checked and enforced based on structured perturbation [6, 7]. Several examples are provided to demonstrate and validate the approach.

2 FORMULATION

Let us consider a P-port electrical interconnect structure, whose input-output representation can be expressed as

$$\mathbf{b} = \mathbf{H}_o \mathbf{a} + \mathbf{H}_i \mathbf{q} \qquad (1)$$

where $\mathbf{a}, \mathbf{b} \in \mathbb{C}^P$ collect the incident and reflected scattering waves at the P electrical ports, with $\mathbf{H}_o \in \mathbb{C}^{P \times P}$ denoting the scattering matrix. In (1), we introduce also the contribution due to an incident field, characterized by the components of vector $\mathbf{q} \in \mathbb{C}^Q$ and by the corresponding transfer functions collected in matrix $\mathbf{H}_i \in \mathbb{C}^{P \times Q}$. Various representations of the incident field are possible. For instance, $\mathbf{q}$ becomes a scalar in case of a single plane wave. More general representations are possible, however, as in the case of a finite set of plane waves or an expansion into spherical waves, in which case $\mathbf{q}$ collects the corresponding coefficients [1]. In this work, we will define the incident field to be a single plane wave with incidence and polarization angles (ϕ, θ, η), whereas q will be defined as the associated incident electric field E_i. The two transfer matrix blocks are collected into a single $P \times (P+Q)$ matrix $\mathbf{H} = [\mathbf{H}_o, \mathbf{H}_i]$. Note that we are not interested here in radiated fields excited either by electric signals or by scattering from the incident field.

The transfer matrix $\mathbf{H}(s; \vartheta)$ is considered as a function of the Laplace variable s in order to enable later conversion to time-domain, and as a function of some additional parameters collected in vector $\vartheta \in \mathbb{R}^\rho$, which represent the incidence/polarization angles of the field, and/or geometrical/material parameters defining the structure. The main objective of this work is the representation of this transfer matrix as a rational function of s, so that a SPICE netlist extraction via state-space realization can be performed [5]. Dependence on the ex-

ternal parameters ϑ is here approximated through a low-order expansion into suitable basis functions such as the Fourier basis (for periodic variations) or orthogonal polynomials (e.g., Chebychev). The following standard model structure is therefore adopted

$$\mathbf{H}(s;\vartheta) = \frac{\mathbf{N}(s,\vartheta)}{\mathsf{D}(s,\vartheta)} = \frac{\sum_{n=0}^{\bar{n}}\sum_{\ell=1}^{\bar{\ell}}\mathbf{R}_{n,\ell}\,\xi_\ell(\vartheta)\,\varphi_n(s)}{\sum_{n=0}^{\bar{n}}\sum_{\ell=1}^{\bar{\ell}}r_{n,\ell}\,\xi_\ell(\vartheta)\,\varphi_n(s)},$$

where $\varphi_n(s)$ are partial fraction basis functions [4,5] and $\xi_\ell(\vartheta)$ are multivariate basis functions parameterizing the macromodel.

The coefficients $r_{n,\ell} \in \mathbb{R}$ are scalar quantities, whereas $\mathbf{R}_{n,\ell} \in \mathbb{R}^{P\times(P+Q)}$. Such coefficients are computed starting from scattering responses $\breve{\mathbf{H}}_{k,m} = \breve{\mathbf{H}}(\mathrm{j}2\pi f_k;\vartheta_m)$ available from a combined parameter and frequency sweep of some electromagnetic field solver, using a linear relaxation of the associated least squares fitting problem known as Generalized Sanathanan-Koerner iteration [3], which can be expressed as

$$\min \left\| \frac{\mathbf{N}^\mu(\mathrm{j}2\pi f_k,\vartheta_m) - \mathsf{D}^\mu(\mathrm{j}2\pi f_k,\vartheta_m)\,\breve{\mathbf{H}}_{k,m}}{\mathsf{D}^{\mu-1}(\mathrm{j}2\pi f_k,\vartheta_m)} \right\|$$

for $\mu = 1,2,\dots$, starting with $\mathsf{D}^0 = 1$.

The above procedure is known to provide excellent accuracy in matching the optimized model responses and the original field solver data [2]. However, it is not guaranteed that the model will be uniformly stable $\forall\vartheta$, nor that the homogeneous part $\mathbf{H}_o$ will be passive, a fundamental requirement for running stable transient simulations independently on the termination networks that are to be connected to the electrical ports. More precisely, the constraints that are required for passivity are

1. $\mathbf{H}_o(s;\vartheta)$ regular for $\mathrm{Re}\{s\} > 0$,

2. $\mathbf{H}_o^*(s;\vartheta) = \mathbf{H}_o(s^*;\vartheta)$,

3. $\mathbf{I}_P - \mathbf{H}_o^\mathsf{H}(s;\vartheta)\mathbf{H}_o(s;\vartheta) \geq 0$ for $\mathrm{Re}\{s\} > 0$,

expressing the Bounded Realness of the scattering matrix $\mathbf{H}_o$ of the model [3], whereas a set of constraints that guarantee uniform stability of the model are

1. $\mathsf{D}(s;\vartheta)$ regular for $\mathrm{Re}\{s\} > 0$,

2. $\mathsf{D}^*(s;\vartheta) = \mathsf{D}(s^*;\vartheta)$,

3. $\mathsf{D}(s;\vartheta) + \mathsf{D}^\mathsf{H}(s;\vartheta) \geq 0$ for $\mathrm{Re}\{s\} > 0$,

expressing the Positive Realness of the denominator function $\mathsf{D}(s;\vartheta)$. Both these constraints are here checked and enforced through a perturbation process, as described in [6,7]. Synthesis of a parameterized SPICE netlist for system-level transient simulation is discussed in [7].
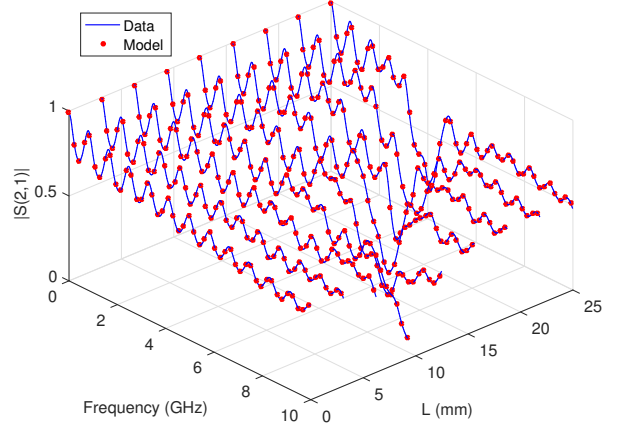

Figure 1: Validation of the PCB link passive model for varying L.

3 EXAMPLES

3.1 A PCB link with slotted reference plane

As a validation of the parameterized model extraction with stability and passivity constraints, we consider a PCB microstrip running on a reference plane, where a rectangular slot breaks the current return path. The parameter describing the discontinuity is the slot length L (see [7] for a detailed geometry description).

Figure 1 provides a validation of the final passive model vs raw data, for selected values of the slot length L. The model has dynamic order $\bar{n} = 29$ and uses $\bar{l} = 4$ Chebychev polynomial basis functions for the parameterization. The model is uniformly stable and passive as demonstrated by Fig. 2, where model poles are depicted for varying L in the top panel, and where the distance of the Hamiltonian eigenvalues from the imaginary axis is plotted in the bottom panel (this distance must be strictly positive in order to guarantee uniform passivity, see [6]). The worst-case accuracy in terms of relative RMS error among all frequency/parameter values and scattering responses is below 1%.

3.2 EMI on a high-speed transmission link

As a seond example, we consider a transmission line structure ($\mathcal{L} = 10$ cm, wire radius $r_w = 0.1$ mm, height $h = 1$ cm over an ideal ground plane), which is modeled as a two-port structure [2]. The geometry is fixed, whereas an impinging plane wave is parameterized by its azimuth and polarization angles $\vartheta = (\psi,\eta)$, with fixed inclination angle $\theta = 45^o$. Both the homogeneous part $\mathbf{H}_o(\mathrm{j}\omega)$ and the field excitation coefficients $\mathbf{H}_i(\mathrm{j}\omega;\vartheta)$ induced by an incident plane wave were computed by NEC. Then, a

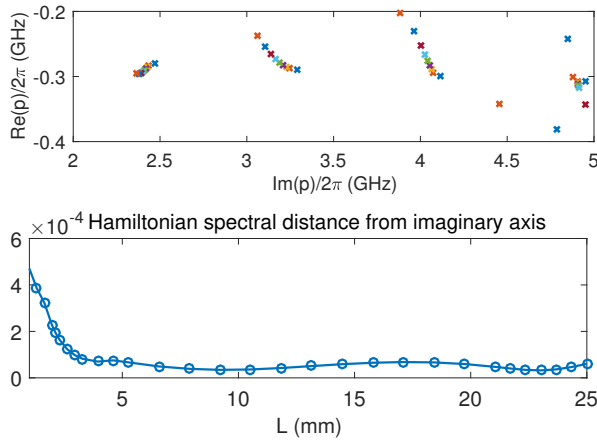Figure 2: PCB link passive model for varying L. Top panel: model poles computed over a sweep on L; bottom panel: Hamiltonian spectral distance from imaginary axis.
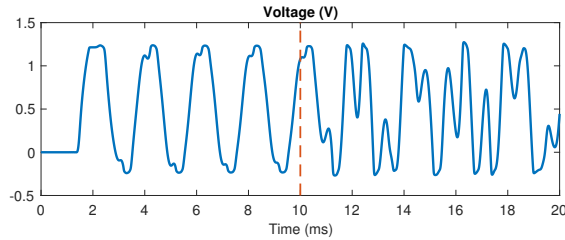

Figure 3: Transient response of a clock-driven transmission line disturbed by an incident field triggered at $T_* = 10$ ns.

parameterized two-port macromodel was computed using the proposed fitting procedure up to 10 GHz and synthesized as a SPICE equivalent.

A typical applicaton that is enabled by the macromodel is demonstrated in Figure 3. The line is driven on one end by a clock signal (voltage swing: 1 V, internal source resistance $R_S = 50\,\Omega$, bit time: 1 ns, rise and fall times: 100 ps) and terminated into a parallel RC load ($R_L = 10\,k\Omega$, $C_L = 1$ pF) protected by a diode-based circuit clipping the voltage within the range $[-0.2, 1.2]$ V. A continuous-wave (50 V/m, 1.3 GHz) incident field from a direction $(\theta, \psi, \eta) = (45^o, 0^o, 55^o)$ is then switched on at $T_* = 10$ ns (red dashed line in the figure). The received voltage at the far end of the line is significantly distorted by the disturbing field, as Figure 3 confirms. The SPICE runtime for this simulation took only 0.19 seconds on a standard laptop. This very short runtime confirms the suitability of proposed approach for fast SPICE-based assessment of EMI disturbances, including parametric sweeps, what-if analyses, and optimization.

4 CONCLUSION

This paper demonstrated the feasibility of a parameterized macromodeling flow that converts a set of sampled scattering responses obtained by an electromagnetic field solver into a closed-form parameterized and reduced-order rational macromodel, whose synthesis as a SPICE netlist is straightforward. This flow, combined with a stability and passivity-preserving perturbation scheme, is used to derive behavioral compact time-domain macromodels of electrical interconnects, possibly excited by external fields as EMI sources. The resulting model can be safely used in standard circuit solvers to perform Signal Integrity and EMI simulations, as required in automated CAD-based design flows.

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