Analysis and design of microwave structures using broad frequency band and shape driven edge finite element models

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Abstract—The use of high order derivatives is applied to obtain parametrized solutions in terms of frequency and shape for the analysis of microwave structures using 3D edge finite elements. These solutions are derived from the derivatives with respect to the frequency and/or geometric parameters of single frequency and/or geometric finite element solutions. These techniques allows the broad frequency band extrapolation as well as the shape optimization.

I. Introduction

Electromagnetic simulations can now be directly used to analyze microwave structures such as waveguide discontinuities, planar circuits, filters, beam forming networks, antenna feed networks. However, many computations have to be performed to get solutions in the whole frequency band when using harmonic simulators, and specially when optimization is further needed in terms of certain critical structure shape parameters. Some techniques such as the Asymptotic-Wave-Expansion (AWE)[1] or Model-Based Parameter Estimation (MBPE)[2] have been proposed to extrapolate the frequency response of a structure from information computed at one or several points. For the geometry optimization, the Space Mapping (SM) technique [3] can be judged as an interesting way to efficiently consider repeated geometry changing configurations.

In this paper, high order derivatives techniques are used to generate frequency and geometry parametrized solutions of microwave structure problems based on 3D edge finite elements techniques. Derivatives with respect to these parameters are then calculated from finite element solutions [4]. The proposed method is very similar to MBPE when considering only a frequency parameter. But our approach extends to include a whole set of parameters including geometric ones. To our knowledge, the extrapolation of solutions for geometric parameters has not ever been presented. The basic principles are given. Three examples are provided to demonstrate the efficiency of the method.

II. Theory

A. Edge finite element formulation

The 3D finite element method is based on the use of edge elements. The formulation is recalled briefly for the presentation of the parametrization method as it has already been presented elsewhere [4]. A microwave structure can be modeled as an inhomogeneous domain bounded by walls and ports, P_i, $i = 1..N$, defining an N-port. The variational form for the electric field (1):

$$\int_V \frac{1}{\mu_r} \operatorname{rot} \mathbf{E}. \operatorname{rot} \mathbf{E}' - k^2 \varepsilon_r \mathbf{E}.\mathbf{E}' = \int_{\partial V} (\mathbf{H} \times \mathbf{n}).\mathbf{E}' \quad (1)$$

is discretized with edge elements basis functions giving N linear systems to be solved (2):

$$\overline{G}\overline{e_i} = \overline{J_i}, \qquad i = 1..N. \quad (2)$$

The vector $\overline{e_i}$ contains the degrees of freedom (circulations of the electric field along the edges) related to the excitation vector $\overline{J_i}$. The S-parameters are then obtained from these independent solutions. The terms of the S matrix are given by (3):

$$S_{ij} = j\omega\mu_o \overline{J_i}^t \overline{e_j} - \delta_{ij}. \quad (3)$$

B. Parametrization method

Let's state some definitions on the parametrization problem :

- the vector p of the parameters : shape and/or frequency
- the solution matrix $E = [\overline{e_1}, ..., \overline{e_N}]$
- the excitation matrix $J = [\overline{J_1}, ..., \overline{J_N}]$
- the solution E is given by the solution of the linear system :
$$G(p)E(p) = J(p) \quad (4)$$

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The aim of this method [5] is to build a Taylor expansion or a Pade approximation of the solution, by computing high order derivatives of $E(p)$. Taking the derivative of (4) subsequently, these quantities are computed by solving linear systems :

$$G(p)E'(p) = J'(p) - G'(p)E(p)$$

$$G(p).E^{(m)}(p) = J^{(m)}(p) - \sum_{i=1}^{m} C_m^i G^{(i)} E^{(m-i)}(p) \quad (5)$$

All the derivatives $E^m(p)$ are computed using the same factorized matrix $G(p)$. Compared to a standard analysis which needs factorizing and solving a new linear system at each frequency and geometric configuration, the overcost due to the computation of derivatives is low.

However, the Taylor expansion can meet some singular points, which reduces its radius of convergence. The singular points are explained by the presence of cut-off frequencies of the waveguide and complex resonances of the structure. Therefore, to cope with these poles, we use Pade approximation, which is a rational function of two polynomials :

$$\frac{P(p)}{Q(p)} \quad (6)$$

III. Applications

A. Mitered bend

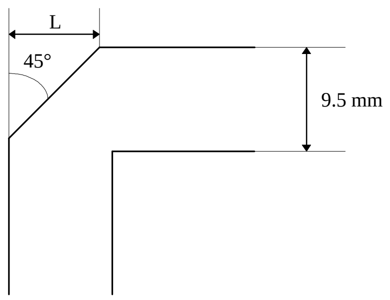

Fig. 1. E-plane mitered bend configuration

A first case study concerns an E-plane mitered bend shown in Fig.1. The S-parameters are computed for a frequency $f = 12.5GHz$ and a length $L = 7.4mm$. Then the parametrized solution with respect to frequency f and length L is obtained. Fig.2 shows the return loss as a function of both f and L. The whole frequency band of interest is obtained for various values of the parameter L. For example, Fig.3 gives the return loss extracted from the surface solution shown in Fig.2 for three values of L. In the same figure are also plotted results given by a direct calculation for $L = 7.4mm$.The comparison shows the excellent agreement between the extrapolated solution and the direct ones. For a given frequency, the optimal of return loss can be directly determined by considering its variation as a function of the length L (Fig.4). The optimal length L at this frequency is about $7.5mm$. In Fig.4, the direct F.E. solutions are also plotted for comparisons.

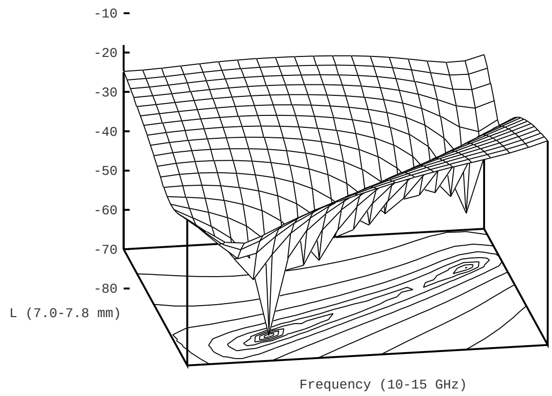

Fig. 2. Return loss of the mitered bend versus the frequency and the length L

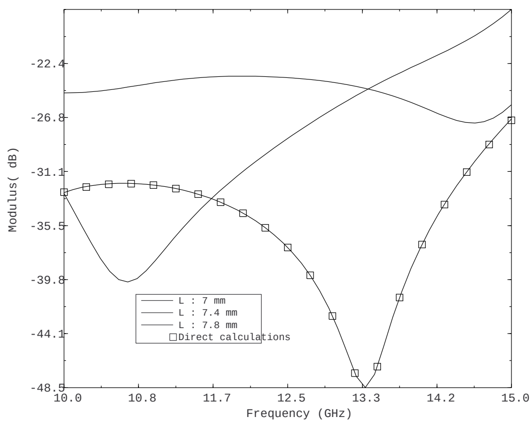

Fig. 3. Return loss of the mitered bend versus frequency for three values of parameter L

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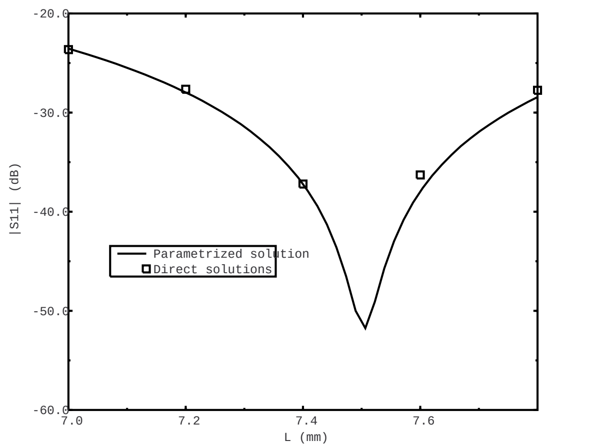

Fig. 4. Return loss of the mitered bend versus the length L : parametrized solution and direct solutions

B. Stub filter

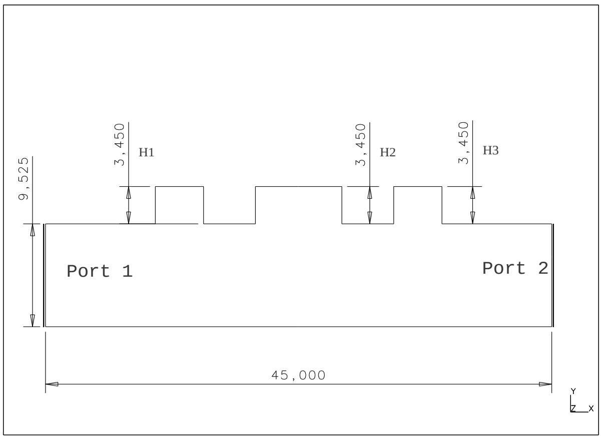

Fig. 5. Stub filter

As discussed previously, a Taylor series expansion may be insufficient to extrapolate over the whole frequency band. On the contrary, Pade expansion is able to catch the poles of the S-parameters giving a broad band parametrization. This is particularly pointed out with structures like filters which exhibit more complex responses. A stub filter is here considered (Fig.5). Fig.6 shows the return loss of the stub filter over the whole frequency band obtained from the F.E. solution calculated at a single frequency $f = 12GHz$. For this

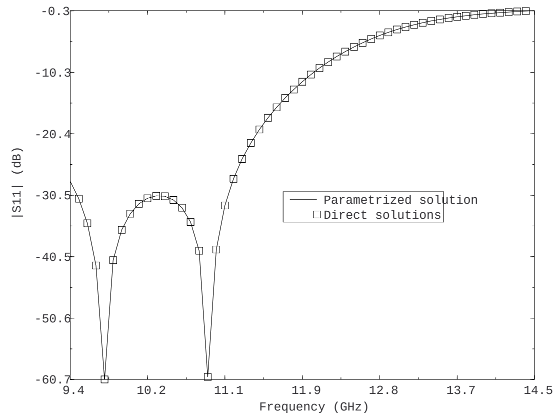

Fig. 6. Return loss of the stub filter

example, we use a Pade approximation, with orders 11 for $P(p)$ and 9 for $Q(p)$. Very good agreement, less than 1%, is achieved between the parametrized solution and a frequency swept solution. For this example, CPU times are :

- For the standard analysis : 123 seconds per frequency
- For the parametric analysis (order 20) : 383 seconds

C. Orthomode Transducer

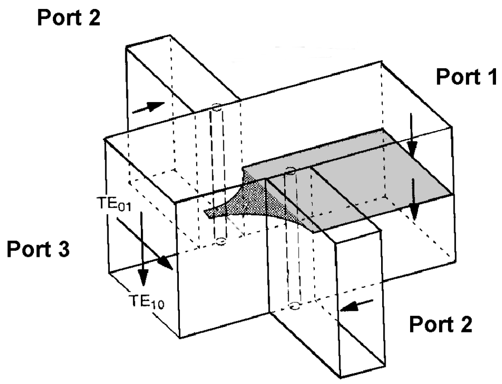

Fig. 7. Orthomode Transducer

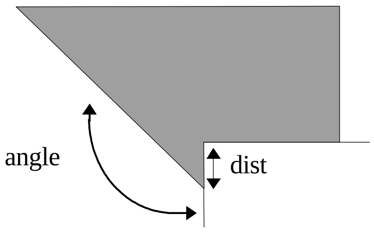

Fig. 8. Geometric parameters for the septum (symmetric part shown)

The design of an orthomode transducer like the one shown in Fig.7 is considered. The most critical requirement in this structure is that the return loss S_{22} for the horizontal polarization must be better than 20dB over a large frequency band (40% bandwidth). This value depends on the septum shape. The geometric parameters of the septum are shown in Fig.8.The return loss as a function of the geometry parameters is then calculated giving a geometry parametrized solution. The optimal values of the geometric parameter is obtained by exploring the parametrized solution. Fig.9 shows an example of the S_{22} surface as a function of the geometric parameters at a frequency $f = 17.5GHz$. The frequency response near an optimal solution is shown in Fig.10 using a Pade expansion of order 11 and 9.

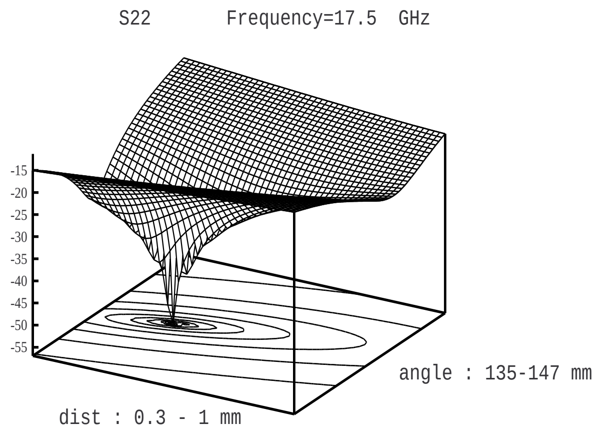

Fig. 9. Return loss for the OMT versus the geometric parameters at a frequency of 17.5 GHz

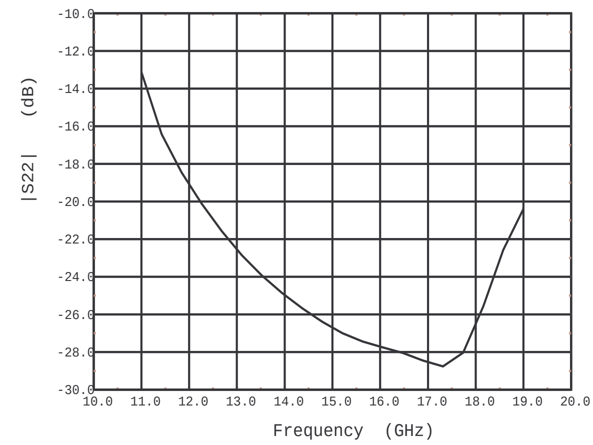

Fig. 10. Return loss for the OMT versus frequency

IV. Conclusion

A 3D microwave structure can be characterized in terms of frequency and geometry shape parameters by extrapolating from the solutions at single frequency and geometry solutions. The method avoids the closely sampling of the parametric space both in frequency and geometry configuration and thus reduces significantly the computation times. It could also enable the easy derivation of analytical models from the parametrized finite element solutions. The 3D edge element method enhanced with high order derivatives paves the way to shape optimization in a broad frequency band.

References

[1] X. Huang, V. Raghavan and R.A. Roher, "AWEsim : A program for the efficient analysis of linear(ized) circuits", Technical digest of the IEEE Int. Conf. on Computer-Aided Design", 1990, pp.534-537.

[2] J. Pekarek and T. Itoh, "Use of frequency derivatives in the 3-D full-wave spectral domain technique", 1996 IEEE MTT-S Digest, pp.343-346.

[3] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Fully automated space mapping optimization of 3D structures", 1996 IEEE MTT-S Digest, pp.753-756.

[4] M.F. Wong, O. Picon and V. Fouad Hanna, "Three dimensional finite element analysis of N-port waveguide junctions using edge elements", 1992 IEEE MTT-S Digest, pp. 417-420.

[5] Ph. Guillaume, "Computation of high order derivatives in optimal shape design", 1994 Numerische Mathematik, 67 (1994), pp. 231-250.