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Frequency Analysis of Rounded Shaped Inductive Metallic Objects in Waveguides via some PEC Approximations and GSM Method

Ahmet AYDOĞAN*[1]

Abstract

A hybrid method is proposed for the frequency analysis of rounded metallic objects inductively loaded in rectangular waveguides. The proposed method combines the efficiency of the generalized scattering matrix method (GSM) and the flexibility of the method of moments (MoM) and the fact that fields cannot exist inside perfect electric conductors. Metallic discontinuities are modelled as a dielectric medium with extreme conductivity and the volume is emptied except the surrounding area. The proposed method is tested against several structures including a band-pass filter composed of metallic rods and an arbitrarily shaped discontinuity. The accuracy of the method is compared to commercial software based on the finite element method. The proposed method is exclusively competent for the frequency analysis of rounded or arbitrarily shaped metallic discontinuities.

Keywords: Arbitrarily shaped discontinuities, computational efficiency, generalized scattering matrix method, microwave devices, waveguide discontinuities.

1. INTRODUCTION

Due to their high-power handling, high-quality factor, and low insertion loss, waveguides are essential for military, space, and terrestrial communication systems [1]. Scattering analysis of the modes supported by rectangular waveguides loaded with inductive discontinuities is simpler than that of waveguides loaded with capacitive or inductive and capacitive discontinuities. Furthermore, due to their ease of fabrication, inductive waveguides are popular microwave device elements. As a result, there is a large body of literature devoted to the fast and reliable analysis of inductively loaded waveguide structures.

A variational method was proposed for inductive metallic and low-valued dielectric posts with a small radius positioned in a waveguide [2]. In the following decades, physical property limitations are eliminated by analyzing higher-order modes and employing computational methods such as the method of moments (MoM) for the analysis of various

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and arbitrarily cross-sectioned dielectric posts [3], or the numerically cost-effective mode-matching (MM) method for the analysis of inductive parts [4]. The demand for high numerical flexibility and efficiency on problem configuration resulted in the development of hybrid methods that integrate the effectiveness of MM method with the flexibility of spatial techniques such as the finite element method (FEM), MoM, or finite difference (FD), for which an extensive study was published [5]. To investigate the scattering of dielectric posts, a circular boundary technique is utilized [6], however, this approach becomes inefficient once the discontinuities are close to the step discontinuities since the method regards only the dominant mode and higher-order mode interaction should be regarded in mentioned cases. Higher-order modes overcome this barrier [7], allowing inductive step frequency responses to be analyzed independently using the well-known mode matching method [8]. A more generic solution in terms of the shape and type of discontinuities (metallic and/or homogeneous dielectric bodies) for inductively loaded waveguides was introduced by solving the surface integral equation with MoM [9] and the same procedure is applied to a similar waveguide problem with a step offset combining two waveguides [10]. Although having no capability for metallic discontinuities, a hybrid technique for an effective analysis of dielectric discontinuities using a volumetric MoM procedure removes the restrictions on the homogeneity of dielectric discontinuities [11]. A method for the efficient analysis of metallic discontinuities is proposed in [12] where the basic strategy is inspired by [11]. In [12] the metallic discontinuities are modeled with extremely lossy dielectric values [13] and the analyzed shapes are competitive with cuboid shapes since the analysis of non-cuboid obstacles has a high computational cost due to the volumetric analysis of discretized cells in MoM procedure. The recent interest in the fast and efficient analysis of waveguide structures is not limited to only inductive structures but also directed to those of capacitive structures and axially symmetric waveguides or discontinuities. In [14], the integral equation method introduced in [9] is adapted for capacitive obstacles, and in [15] capacitive obstacles in waveguides with step offsets are analyzed. The fast analysis of discontinuities in axially symmetric waveguides [16] and axially symmetric discontinuities in waveguides [17] via hybrid techniques are introduced to the community. Besides, the GSM method is still a powerful, efficient, and reliable tool for actual guided wave problems [18, 19].

In this study, the high computational cost is reduced for non-cuboid shapes by utilizing the boundary conditions of electric fields for PEC objects. Therefore, the electric fields inside the objects are null and no computational analysis is needed inside the objects. This new efficient analysis tool also has the potential to propose new design possibilities for microwave devices built by waveguides loaded with inductively and arbitrarily shaped PEC obstacles. The time dependency is chosen as $e^{-i\omega t}$ during numerical analysis.

2. PROBLEM DESCRIPTION

Fig. 1 depicts the problem to be considered. Arbitrarily shaped metallic discontinuities are located in a rectangular waveguide. Obstacles fill the waveguide in the height (i.e., y direction) so only TE^{m0} type modes can exist in the waveguide in the dominant mode region and the case of dominant mode excitation.

Note that several metallic discontinuities aligned horizontally (by discretizing the whole system in the widthwise direction) and/or longitudinally (by cascading the GSMs of longitudinal elements) can be analyzed with the proposed method in the most general sense. The scattering parameters for the two-port network are aimed to be calculated at $Port\ 1$ and $Port\ 2$.

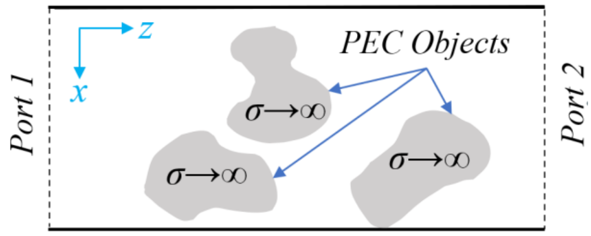


Figure 1 Problem description – longitudinal and top view of the waveguide loaded with arbitrarily shaped and oriented PEC objects (σ is the electrical conductivity)

3. METHOD

The cascading capabilities of the GSM approach are used to perform the scattering analysis of the discontinuities, while the elements of GSM for the cascaded structures are built using an MoM-based procedure [12]. The obstacles are divided into individual blocks in the longitudinal direction (z-direction in Fig. 1) and the GSM of each individual block is constructed separately. Finally, the GSM of the obstacles and the whole system is obtained by cascading the GSMs of individual blocks and GSMs of longitudinally separated obstacles, respectively. In terms of electrical response, all metallic discontinuities are considered to have an extremely high loss dielectric characteristic model as applied in [12] by a complex relative permittivity of $\varepsilon_r\ = 1 + j\,{}^{\sigma}/_{\omega\mu_0}$, where ω, μ_0, and σ are the angular frequency, magnetic constant of free space, and the conductivity of the dielectric model under investigation, respectively. Modal interactions are examined utilizing the orthogonality of the modes and some powerful acceleration steps are applied. To avoid repetition, the interested readers are referred to [11], [12]. Due to the high change in the value of the Dyadic Green's Function (DGF) as the kernel in the integral equation of the interested scattering problem for an extremely lossy model (e.g., extremely high conductivity), one should discretize the obstacles with tiny cells. Hence, the number of cells increases tremendously and the proposed method in [12] becomes competitive for repeating individual blocks such as longitudinally oriented cubes, and inductive discontinuities but not for rounded or arbitrary shapes due to a high amount of individual blocks with too many cells to be examined. In this study, this challenge is tackled, and to reduce the numerical cost, the number of cells to be analyzed is decreased by utilizing the fact that the electric fields are null inside the PEC. A narrative illustration of the mentioned steps is given in Fig. 2. In Fig. 2a, two representative PEC obstacles are separated by a distance d in the longitudinal direction as the original problem. The GSM of separated parts, if exist, can be obtained by using the transmission line approach. In Fig. 2, the GSM of the gap with the length of d for an $M \times M$ modal analysis is a diagonal matrix for which the diagonal elements $D_{mm} = e^{j\beta_m d}$, m $=$ 1,2, … , M and β_m is the propagation constant for related TE^{m0} mode. Note that since the obstacles are invariant in y direction, only TE^{m0} type modes can be excited. Then, obstacles are discretized with tiny cells as in Fig. 2b where cells are not scaled as in the practical case but depicted comparatively large for the sake of narration. Also, discretized cells are modeled with extremely high lossy dielectric material instead of PEC behavior. The considered problem can be solved with such discretization (as in Fig. 2b) at the cost of immensely high computational effort with the method given in [12]. In this study, Fig. 2c and Fig. 2d strategies are proposed to solve the original problem. In Fig. 2c, it is illustrated that the discretized cells are removed except those at the boundary applying the theoretical fact that fields are null inside. Then the computation domain is reduced by removing the repeating individual blocks as in Fig. 2d if any exist. The reduced discretized cells are arranged as individual blocks containing lateral cells and the GSMs of individual blocks are calculated via the proposed method in [11] and the calculations are also accelerated by applying the proposed strategies in [12]. A considerable amount of the computational cost for each individual block arises due to the number of cells in the width-wise direction (i.e., x direction).

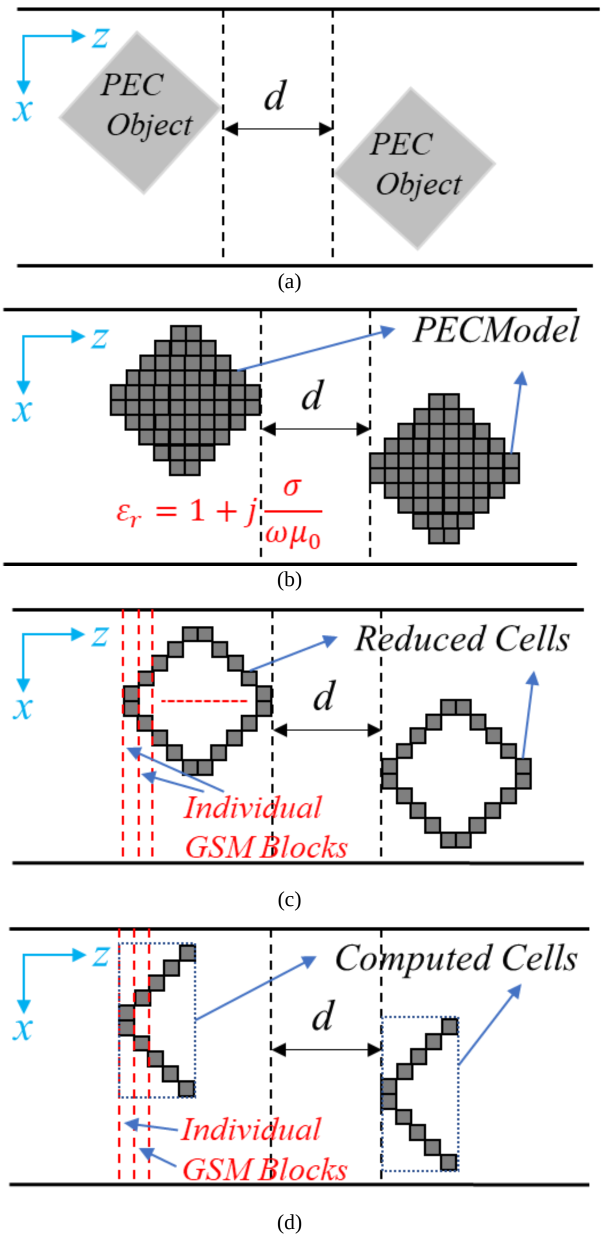


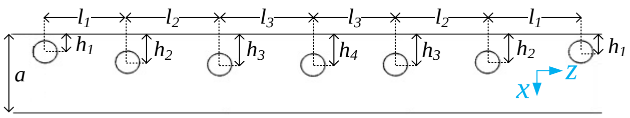
Figure 2 Example problem (a) original case (b) discretized PEC model (c) proposed approach with reduced cells (d) final computation case

A new computational strategy is also applied in this study alongside the previous strategies mentioned. One should discretize the cells so that the integral of the DGF becomes stable as much as possible for the applied point-matching MoM. The DGF to be integrated inside each cell varies as a function of the medium parameters only in the z direction ($e^{j\beta_m|z-z'|}$ term in (Equation (1), [11]). On the other hand, the roundedness of an arbitrarily shaped object decreases as the cubicity of the discretized cells increases. Regarding these points, the cells are discretized tinier in the direction of the propagation (i.e., z direction in the given geometry) and larger in the height (y direction) and width (x direction). Finally, all GSMs (those of the PEC bodies, the gap between bodies, etc.) are cascaded to obtain the general scattering matrix of the whole system [20].

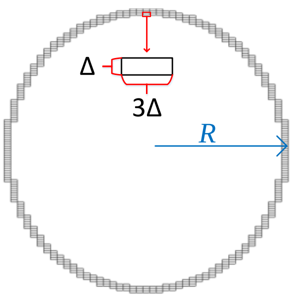
4. NUMERICAL CONSIDERATIONS & EXAMPLES

A band-stop filter [13] and an arbitrarily shaped PEC obstacle are analyzed to test the proposed method and obtained results are compared with FEM-based commercially available software high-frequency structure simulator ($HFSS$). PEC obstacles are modeled with a relative complex permittivity of $\varepsilon_r = 1 + j\,{}^{\sigma}/_{\omega\mu_0}$ where conductivity value is assigned as $\sigma = 10^{30}\ S/m$. The analyses are carried out on a standard PC. The heights of the waveguides are reduced to that of the cell size in the vertical direction (i.e., y direction in the given problem geometry) which gives one discretized cell in the height as proposed in [11], [12]. Besides, each individual block has one discretized cell in the direction of propagation (i.e., in the z direction). The obstacles are discretized with $(3\Delta, 3\Delta, \Delta)$ in (x, y, z) directions, respectively to reduce the computational cost and provide computational stability where $\Delta = \lambda_{min}/600$ is the cell dimension and λ_{min} is the smallest wavelength in the analyzed frequency band. The frequency band is divided into S equispaced points for both examples.

In the first example, the analysis of a band-pass filter composed of constant diameter and off-centered circular metallic cylinders is performed [7]. The analysis is conducted for *S=91* equispaced frequency points in the given band. The geometry and dimensions of the system and the discretized mesh distribution are given in Fig. 3. As mentioned previously, the inner cells are removed and the GSMs of each separate cylinder and those of the empty parts between cylinders are calculated. Then, the GSMs of the cylinders and the empty regions are cascaded to obtain the GSM of the whole structure. The desired S- parameters are extracted from the GSM of the whole structure, and these are the dominant mode (TE^{10}) to dominant mode (TE^{10}) interaction between ports. The frequency response of the metallic-cylinder filter is compared in Fig. 4 between the proposed method and *HFSS* both for phase and magnitude. A close agreement can be observed and the average computation times per frequency are recorded as 1.31 s and 4.46 s for the proposed method and *HFSS*, respectively. The comparison of computational time for the commercial software and this method is given in Table 1.



(a)



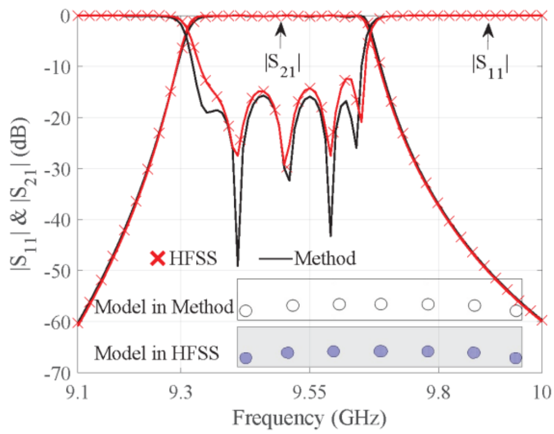
(b)

Figure 3 (a) Geometry of the metallic post filter with $a = 22.86\, mm, r = 3.21\, mm, h_1 = 5.215\, mm, h_2 = 8.172\, mm, h_3 = 8.863\, mm, h_4 = 8.971\, mm, l_1 = 21.895\, mm, l_2 = 24.461\, mm, l_4 = 24.797\, mm$, (b) mesh distribution of an equal cylinder in the system

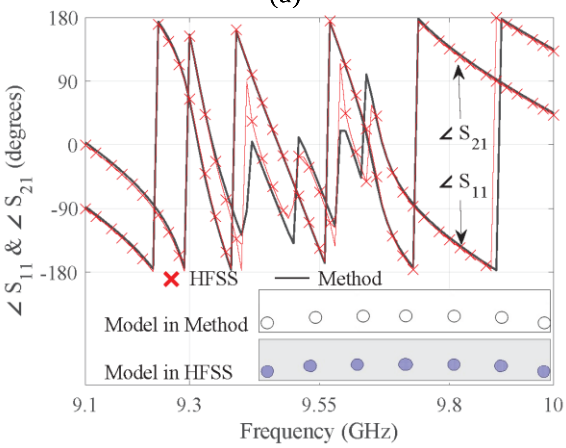
Table 1 Comparison of computational times

Time per frequency	Method	HFSS
Example 1	1.31 s/f	4.46 s/f
Example 2	0.82 s/f	2.27 s/f

In the second example, an arbitrarily shaped PEC obstacle is investigated in the $8 - 12\ GHz$ band which is depicted with geometrical properties in Fig. 5a. The commercial software model of the object is also shown as an inset in Fig. 6. Also, the discretized cell distribution analyzed via proposed method is given in Fig. 5b. As in the previous example, the inner cells are removed and the object is divided into individual blocks in the direction of propagation (i.e., z direction).



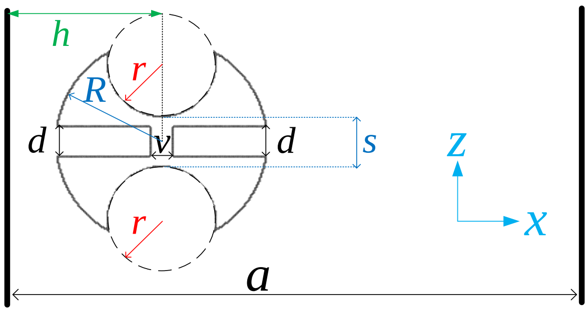
(a)



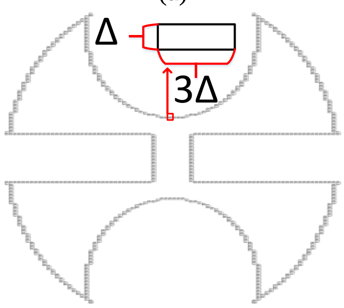
(b)

Figure 4 Comparison between the proposed method and HFSS for the frequency response of the band-pass filter (a) magnitude (b) phase

Following the calculation of the GSM of each individual block, these GSMs are cascaded to obtain the GSM of the whole structure (the arbitrarily shaped PEC object). Then, the desired modal interaction is obtained from the whole GSM. In this problem, it is the dominant mode (TE^{10}) to dominant mode (TE^{10}) interaction between ports. The frequency band is divided into $S = 41$ equispaced frequency points in the given band. An excellent agreement can be observed both for magnitude and phase of the scattering parameters observed at $Port$ 1 and $Port$ 2 as shown in Fig. 6. The average computation times per frequency is recorded as 0.82 s/f and 2.27 s/f for the proposed method and $HFSS$, respectively. The comparison of computational time for the commercial software and this method is listed in the second row of Table 1.

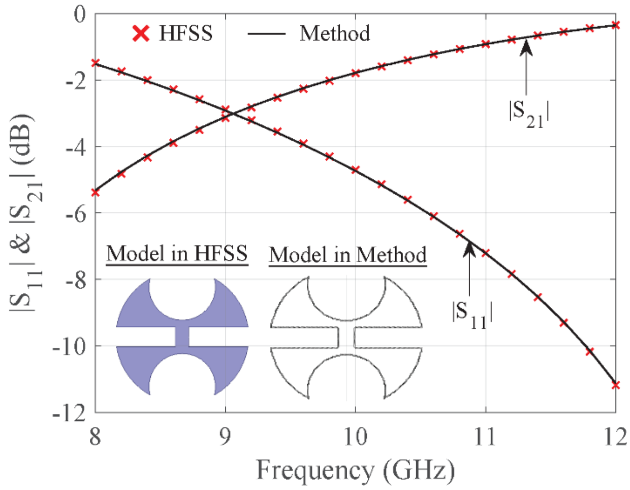


(a)

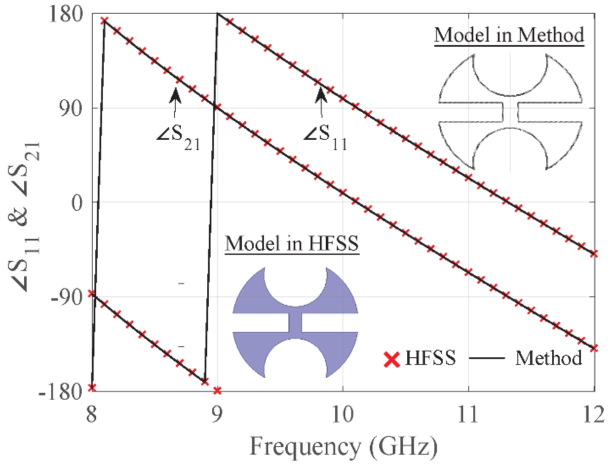


(b)

Figure 5 Arbitrarily shaped rounded PEC object a) the geometry with $R = 2\,mm$, $h = 3.715\,mm$, $r = 1\,mm$, $v = 0.8\,mm$, $s = 0.6$, $d = 0.6\,mm$ b) constructed model in the method



(a)



(b)

Figure 6 Comparison between the proposed method and HFSS for the frequency response of the arbitrarily shaped PEC object (a) magnitude (b) phase

5. CONCLUSIONS

The previous inefficiency in the computational competency of volumetric analysis for metallic obstacles inductively located in a rectangular waveguide is addressed. The metallic obstacle is modeled by an extremely lossy dielectric material and discretized for an MoM procedure. PEC boundary conditions are utilized and the inner cells are removed which immensely reduces the computational cost. The scattering analysis of the whole structure is carried out via the GSM method. The proposed method is tested with numerical examples involving rounded or arbitrarily shaped metallic obstacles and compared with $HFSS$. The results show that the proposed method provides a fast and reliable analysis tool for the frequency analysis of arbitrarily shaped metallic objects inductively loaded in rectangular waveguides. This method may provide new possibilities with analysis capabilities for the design of microwave devices via iterative optimization techniques where a fast and reliable analysis of the system is vital. Besides, the considered problem can be extended to the analysis of systems composed of both dielectric and rounded metallic obstacles.

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the author.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The author of the paper declares that they comply with the scientific, ethical, and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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