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Antenna Design Using Characteristic Modes for Arbitrary Materials

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***Abstract*—Characteristic mode analysis has traditionally been constrained to problems which utilize only perfect electric conductors (PEC). Through forced symmetry of a method of moments surface integral equation and newly proposed post-processing, characteristic modes can be solved for any material in a computationally efficient manner. As an example, the characteristic modes are solved for a mobile terminal consisting of both PEC and dielectric materials.**

Keywords—Computational electromagnetics, antenna design, Theory of Characteristic Modes

I. Introduction

The majority of computational electromagnetic theory surrounding the Theory of Characteristic Modes (TCM) has been fixated on perfect electric conductors (PEC). This is because the original form of TCM is based on a decomposition of the method of moments (MoM) impedance matrix solved using the electric field integral equation (EFIE) for PEC [1]. The electromagnetic properties of PEC are special, and they allow for a unique solution to be found using the MoM EFIE. The EFIE and magnetic field integral equation (MFIE) solutions to MoM are unique as they produce a symmetric impedance matrix [2]. It was theoretically derived in [1] that a suitably weighted eigenvalue equation can diagonalize a symmetric impedance matrix, thus solving for the complete set of orthogonal currents which an object is capable of producing, i.e. the object's characteristic modes (CMs). Although limited in scope, two papers prior to 2014 focused on developing a CM theory for arbitrary materials. In [3], it is shown that the symmetric form of the MoM volume integral equation (VIE) can solve for the CMs of any object, including those composed of dielectric and magnetic materials. Moreover, a theory was developed in [4] for forcing a MoM surface integral equation (SIE) into symmetry, allowing for a solution to a full set of orthogonal equivalent surface currents for any object. However, neither of these initial papers present any numerical examples of CM computation, and the theories were not further investigated.

In 2014, Alroughani *et al.* [5] stated for the first time that the SIE-based theory in [4] produces some CMs which radiate non-unitary power. However, they did not provide any information on how these modes were calculated, or any explanation to why some modes do not radiate unitary power. This work was followed up and expanded upon in [6], where the theory behind how to calculate both SIE and VIE modes was explained in depth. Moreover, justification was provided into why some modes can be considered "non-real" and how these modes can be identified and removed via post-processing. Herein, this article provides an overview on the problems associated with the VIE and SIE formulations of CMs. Furthermore, multiple methods of removing the non-real CMs from the SIE solution space are outlined, including how these methods can be adapted for lossy materials. Additionally, for the first time, the CMs of a fully equipped mobile terminal with PEC and dielectric materials are solved and presented.

II. Solving For CMs of Arbitrary Materials

Eigenvalue decomposition of a MoM impedance matrix obtained using the VIE formulation provides real CMs for any arbitrary material [3]. However, as is shown in [6], solving for the CMs of a VIE MoM impedance matrix is not practical due to the extremely high computational complexity required for a valid solution. Obtaining acceptable accuracy requires a dense tetrahedral mesh, resulting in small basis functions. If insufficiently sized basis functions are used, the edge element tetrahedral expansion functions give rise to surface singularities on individual tetrahedrons, thus impacting the overall accuracy of the CMs. Furthermore, when mixed (dielectric and magnetic) materials are used the number of basis functions must be doubled; CM solutions require a matrix inversion, and as such the computational complexity increases with $O(n^3)$. Although the VIE CMs provide a real and valid solution, the required computational complexity is not practical for engineering applications, even when addressing electrically compact problems [6]. To increase computational efficiency in obtaining CM solutions, the surface equivalence principle (SEP) for solving electromagnetic structures using the MoM was developed. However, the SIE that has been developed to solve the SEP problem is asymmetric. Hence, a weighted eigenvalue decomposition does not diagonalize the impedance matrix.

The SEP for MoM significantly reduces the computational complexity of any 3D problem when compared to an identical VIE problem. This principle is implemented using different SIE formulations: EFIE, MFIE, and the combined field integral equation (CFIE). The SIE EFIE and MFIE suffer from what is known as the internal resonance problem [2]. The internal resonance problem has been solved through properly

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combining the EFIE, MFIE, electric combined integral equation (ECIE), and magnetic combined integral equation (MCIE), as is shown by (1) and (2) [6]. These two different combined equations have different sets of coefficients. Only specific choices of coefficients lead to an SIE solution free of internal resonances. Any choice of a_i, c_i or b_i, d_i for which $a_i c_i^*$ or $b_i d_i^*$ (where $(\cdot)^*$ is the complex conjugate) is equal to a real and positive number will provide a solution free from the internal resonance problem.

$$\textit{Combined Equation 1: } a_i\, ECIE + b_i\, EFIE \quad (1)$$

$$\textit{Combined Equation 2: } c_i\, MCIE + d_i\, MFIE \quad (2)$$

The Poggio-Miller-Chan-Harrington-Wu-Tsai (PMCHWT) SIE formulation for MoM, whose solution is free from internal resonances, was forced into symmetry in [4]. However, the changes required to force the impedance matrix into symmetry also forced one of the coefficients to become complex, with the resulting SIE equation space no longer satisfying the requirements of [7] (i.e., $b_i d_i^* \neq |\mathbb{R}|$), and as such is no longer free from internal resonances. These internal resonances are a significant problem in traditional MoM solutions, as the resulting induced currents are a mixture of both real and non-real currents. However, TCM is unique as this type of computational electromagnetic problem solves for each of the modal solutions individually, allowing for optional post-processing identification of the non-real modes (internal resonances).

In theory, the far-field radiated power of a non-real mode is zero. The CMs related to internal resonances can thus be identified by calculating the total radiated far-field power of each mode. However, in practice, even for lossless materials, the structure's domain is formed using approximate expansion functions, and thus each internal resonance will radiate a small but unknown amount of power. This problem is further compounded when real materials with losses are added to the solution space, allowing for real modes to radiate powers of less than unity. Distinguishing real modes from non-real modes requires knowledge into the theoretical total radiation efficiency of the subset of currents for each mode. As only the surface currents are known, and not the volumetric currents, the exact loss of the structure cannot be determined. However, the minimum radiation efficiency can be found from the maximum loss of the characteristic currents in the defined material through the use of two equations. First, the quality factor (Q) of each individual mode must be found using (19) in [6]. The Q of a structure (or given mode) determines how much power is stored versus radiated per cycle. When properly applied the Q provides the information required to determine the maximum amount of loss of any given mode if the imaginary component of permittivity and permeability is known (i.e., loss tangent or tan δ). Once the Q of all modes are known, (16) in [6] provides an equation which bounds the theoretical minimum radiation efficiency for the specified CM. If the radiation efficiency associated with any CM is less than the bounded radiation efficiency for that mode, the specific CM at that frequency is related to an internal resonance. This theoretical concept allows for the identification and removal of all modes associated with internal resonances, thus allowing CMs to be efficiently calculated for any arbitrary object.

III. Numerical Example

All previous mobile terminal antennas designed using CMs start from a PEC object, and dielectric materials are only added in conventional full-wave simulations after the antenna feeds have been designed. By applying the theory presented in [6], CM analysis can be performed on a complete mobile terminal for designing terminal antennas. Figure 1 shows a complete mobile phone which includes metallic structures (chassis, battery enclosure, and electromagnetic compatibility backing plate) as well as lossy dielectric structures (chassis support, screen, top/bottom antenna carriers, and bezel). Figure 2 shows both the non-real CMs (i.e., internal resonances) of this structure as well as the real CMs of this structure.

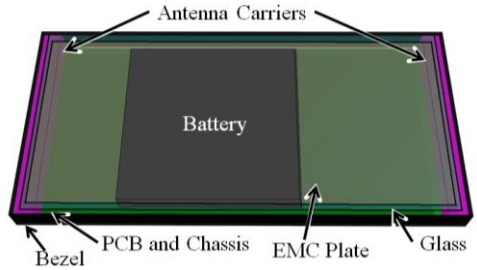

Fig. 1: Mobile terminal consisting of both PEC and dielectric materials.

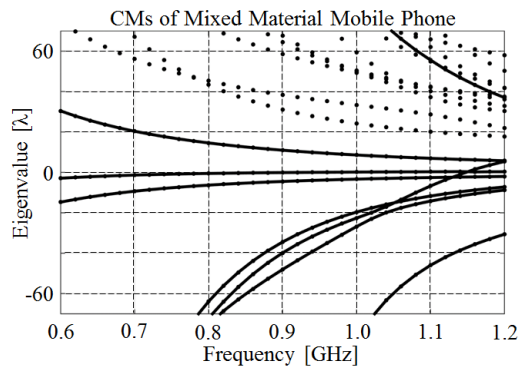

Fig. 2: Real CMs (solid lines) and non-real CMs (dots) of the mobile terminal.

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