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Preliminary Study on Differences between Full- and Sub-Structure Characteristic Modes

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***Abstract*—In this paper, full- and sub-structure characteristic modes (CMs) are explored through the effect of coupling between the target and background structures. The eigenvalues and eigen-current distributions of the first few modes are compared for different coupling levels in the numerical example. Similarities and differences between the two types of CMs in specific conditions are revealed, paving the way for further feasibility studies of the sub- structure method for antenna design.**

***Index Terms*—characteristic modes, electrically large structure, electric field integral equation**

I. INTRODUCTION

Characteristic mode (CM) analysis is a popular topic in the antenna community as it provides useful physical insights for understanding the radiation mechanism of various antennas [1], [2]. A suitable choice of significant CMs and their excitation method can yield antenna designs that meet tough requirements, e.g., [3]. However, electrically large structures lead to large mesh sizes and large increases in the number of significant modes [4]. Thus, CM analysis (CMA) of the full structure is not only computationally demanding, but more importantly the cost is high for finding a subset of modes that are relevant for the antenna design problem at hand. For example, an electrically large structure can consist of an electrically small structure (used for antenna design) and a larger background structure, e.g., a ground plane. Therefore, only modes that can be excited on the small (or sub) structure are of interest in CMA.

To address this problem, substructure CMs were proposed to reduce the dimension of the structure for analysis [5]. The properties of substructure CMs were studied in the literature, e.g., [6], [7]. Nonetheless, whether substructure CMs can be effectively applied as conventional (full-structure) CMs to guide antenna design is still an open issue. One interesting aspect is to compare the modes obtained from full- and sub-structure CMA. This comparison can be performed with respect to different parameters or perspectives. As a preliminary study, this work focuses on the coupling effect between the substructure (antenna) and the background structure.

II. THEORY AND FORMULATION

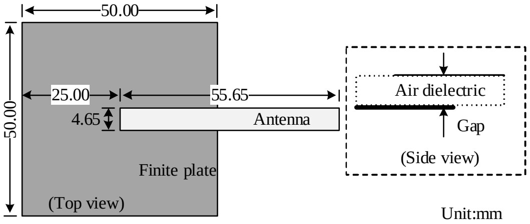

Fig. 1. Simplified strip antenna structure with a finite background plate.

A full structure consisting of a strip structure (“antenna”) and a finite background plate is illustrated in Fig. 1. In the numerical procedure, the antenna and the plate are meshed into N_A and N_P triangles respectively, and N_P is nearly ten times larger than N_A, based on the sizes of the structures. Expanded by the conventional RWG basis function and tested with the aid of the Galerkin method, the electric field integral equation of the full-structure can be constructed as

$$\begin{bmatrix} \boldsymbol{Z}_{AA} & \boldsymbol{Z}_{AP} \\ \boldsymbol{Z}_{PA} & \boldsymbol{Z}_{PP} \end{bmatrix} \begin{bmatrix} \boldsymbol{J}_A \\ \boldsymbol{J}_P \end{bmatrix} = \begin{bmatrix} \boldsymbol{V}_A \\ \boldsymbol{V}_P \end{bmatrix}, \tag{1}$$

where $\boldsymbol{Z}_{AA}$ and $\boldsymbol{Z}_{PP}$ are the self-impedance matrices of the antenna and plate in the free space, respectively. The remaining matrices $\boldsymbol{Z}_{AP}$ and $\boldsymbol{Z}_{PP}$ represent the mutual coupling between the two parts. $\boldsymbol{J}$ and $\boldsymbol{V}$ with suffixes are the inductive current and external excitation voltage on the two metal structures. Performing algebraic transformation on (1), we get

$$\left(\boldsymbol{Z}_{AA} - \boldsymbol{Z}_{AP}\boldsymbol{Z}_{PP}^{-1}\boldsymbol{Z}_{PA}\right)\boldsymbol{J}_A = \boldsymbol{Z}_{sub}\boldsymbol{J}_A = \boldsymbol{U}_A - \boldsymbol{Z}_{AP}\boldsymbol{Z}_{PP}^{-1}\boldsymbol{U}_P, \tag{2}$$

where $\boldsymbol{Z}_{sub}$ is the matrix of the substructure (antenna) with its dimension determined only by the relatively smaller number of the basis functions on the antenna. According to the definition of CMs, $\boldsymbol{Z}_{sub}$ is split into a real part $\boldsymbol{R}_{sub}$ and an imaginary part $\boldsymbol{X}_{sub}$. By solving the matrix eigenvalue equation

$$\boldsymbol{X}_{sub}\boldsymbol{J}_{sub}^{n} = \lambda_{sub}^{n}\boldsymbol{R}_{sub}\boldsymbol{J}_{sub}^{n}, \tag{3}$$

where $\boldsymbol{J}_{sub}^{n}$ and λ_{sub}^{n} are the *n*th order eigencurrent and eigenvalue of the target antenna in the presence of the background plate. The contribution of the relatively large plate has been included in $\boldsymbol{Z}_{sub}$ and the orthogonality of the far-fields over the sphere at infinity is guaranteed [6], identical to the far-field orthogonality property of full-structure CMs.

III. RESULTS AND ANALYSIS

To explore the differences between the two types of CMs under different intra-structure coupling effects, the eigenvalues

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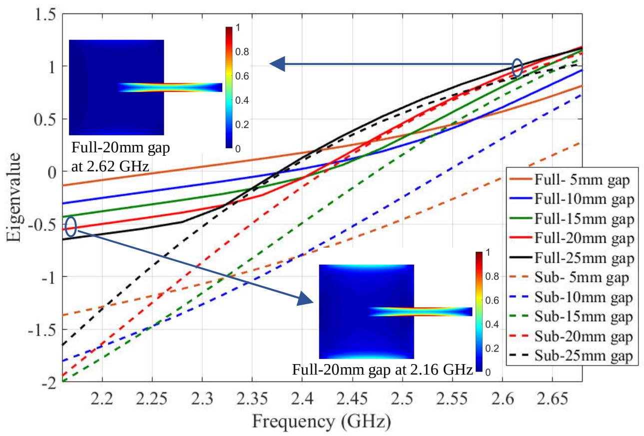


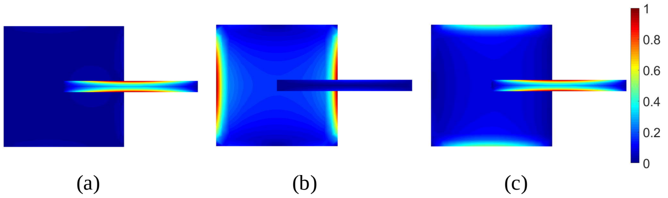
Fig. 2. Eigenvalues of full- and sub-structures with different gaps (5-25 mm) between the strip and the plate.

TABLE I

ERROR COMPARISON FOR DIFFERENT COUPLING STRENGTHS (AT 2.4 GHZ)

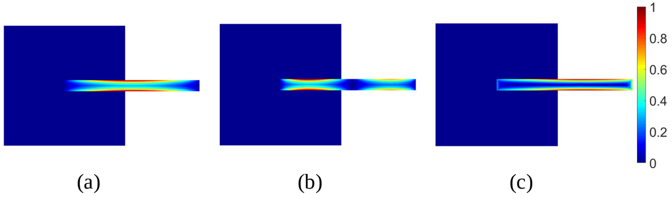
Gap	Average error	Standard deviation	Maximum error
0.04λ	1.655%	4.969%	104.633%
0.08λ	1.467%	4.817%	101.058%
0.12λ	1.094%	2.575%	41.53%
0.16λ	0.387%	1.174%	10.16%
0.20λ	0.101%	0.134%	2.401%

$$Error = \left|([J^i]_{sub} - [J^i]_{full}) / [J^i]_{full}\right| \times 100\%,\ \ i: 1, 2, \ldots, N(number\,of\,basis\,functions)\ .$$



(a) (b) (c)

Fig. 3. Normalized (a) mode 1 (b) mode 2 (c) mode 3 current distribution of full-structure at 2.4 GHz with 0.16λ gap.



(a) (b) (c)

Fig. 4. Normalized (a) mode 1 (b) mode 2 (c) mode 3 current distribution of substructure CMs at 2.4 GHz with 0.16λ gap.

of mode 1 are plotted in Fig. 2 for the full- and sub-structures in Fig. 1, for 2.15-2.65 GHz. Although the overall trends of the two sets of curves are similar to some extent, it can be seen that in general a smaller gap results in a larger deviation of the eigenvalues across the frequency range. In particular, for the gaps of 20 mm and 25 mm, the eigenvalues obtained by the two methods are relatively consistent above 2.4 GHz. This can be due to the plate not contributing to this mode above 2.4 GHz. Specifically, for the structure with 20 mm gap, the current distribution at 2.16 GHz shows both the plate and strip being excited, whereas only the strip is excited at 2.62 GHz (see Fig. 2). The latter case is similar to the current distribution of mode 1 from substructure CMA at 2.4 GHz, as shown in Fig. 4(a).

To further assess the impact of the coupling strength, an error comparison of the characteristic current coefficient is made in Table 1, based on the first mode at 2.4 GHz. Compared to the full-structure CMs which are set as the benchmark, the smaller gap (stronger coupling) results in larger error fluctuations and average error in the substructure eigencurrents. According to this data, the differences in mode 1 between the two methods are more obvious as the coupling between the target structure and the background structure becomes stronger at a fixed frequency.

To further compare the two methods, the eigencurrent distributions of the first three significant modes from the full- and sub-structure CMA are shown in Figs. 3 and 4, for a fixed frequency and gap. Considering only the currents on the target antenna, the obtained substructure modes 2 and 3 differ greatly from the corresponding full-structure modes. Due to the obvious difference in eigencurrents, the obtained physical insights will be different when they are utilized to guide antenna geomtry or feeding design. As opposed to modes 2 and 3, the two methods produce nearly identical current distributions for the more significant mode 1, having the feature of a fundamental dipole mode. Thus, this substructure mode can be applied in the same manner as mode 1 of the full-structure method.

IV. CONCLUSION

In this paper, the coupling effect between the target strip and the background plate is used to explore differences between full- and sub-structure CMs. From the results, it can be concluded that the full- and substructure CM methods can have modes with similar modal properties, but only for special cases (i.e., weakly coupled case over some specific frequencies). For strong intra-structure coupling, the differences in the parameters obtained by the two methods are significant. However, due to fundamentally different impedance matrices used by the two methods, different CMs are not unexpected. Further studies are needed to verify if substructure CMA can be used for the design and analysis of antennas.

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