On the Use of Theory of Characteristic Modes to Equalize Two Radiating Structures from Frequency Behavior Point of View

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Abstract— **In this paper, using a specific developed MoM code results in the modal behavior (based on Theory of Characteristic Modes) of two different shape dipole antennas: A simple cylindrical wire dipole antenna and a flat metal plate one, These two simple antennas are instances for our new proposed approach to make two antennas equal from the frequency behavior point of view. By making equal the modal behavior of these two antennas we claim that they became same from frequency behavior point of view and the input impedance of structures is confirmed our claim.**

Keywords-component; Theory of Characteristic Modes (TCMs), Method of Moment (MoM), Dipole antenna, Input Impedance.

I. INTRODUCTION

MODAL analysis has long been used in electromagnetics for the analysis of close structures such as waveguides and cavities, in which it is quite easy to reach close solutions, by applying boundary conditions. Nonetheless, the calculation of modes in open radiating structures, such as antennas or scatterers, is more complicated, and it is usually quite time consuming. However, the information provided from modal analysis of a structure is worth trying for.

There are some limited number of approaches with the goal to achieve modal analysis of electromagnetics structures such as spherical modes, modal expansion methods, and eigenfunctions of conducting bodies [1]. One subdivision of the classical eigenfunction-analysis, termed as Characteristic Modes is introduced by Harrington in early seventies decade [2]. A brief study of TCMs mathematical formulation will be declared in the next part for better understanding. Moreover, modal analysis provides a clear overview of the radiation behavior of open structures which enables the designer to choose an appropriate structure in various conditions which may cause some restrictions for the designer. For instance, some limitations might exist in the manufacturing process, which lead to the need of using a substitute structure. This problem may occur in the design process as well: generally in indoor wireless communication channels which in them, the wind effect is negligible, printed and flat structures as the radiating part of an electrical device are preferred to wire antennas due to their physical characteristics, e.g. robustness and compatibility with other physical parts of the device while attaching to them.

The objective of this paper is to show that if the modal behavior of two different structures equate, they are in practice the same and can be used as substitutes for each other. To show the accuracy of this claim we have chosen two dipole antennas: a cylindrical wire dipole antenna and a flat metal strip one.

The presented approach can be applied for some other antennas as well.

II. BRIEF DISCUSSION ON THEORY OF CHARACTERISTIC MODES

By the method explained in [2], [3] characteristic modes or characteristic currents can be obtained as the eigenfunctions of following particular eigenvalue matrix equation:

$$[X]\overrightarrow{J_n} = \lambda_n [R]\overrightarrow{J_n} \tag{1}$$

where λ_n is eigenvalue, $\overrightarrow{J_n}$ is nth eigenvector or characteristic current, and $[R]$ and $[X]$ are the real and imaginary parts of the generalized impedance matrix $[Z]$, which is produced in traditional MoM analysis of a structure [4]. In fact Eq. (1) is derived from a particular weighted eigenvalue operator equation. One of the most significant things which should be taken into consideration in Eq. (1) is how eigenvalues λ_n respond to alteration of frequency. λ_n's variation range is from $-\infty$ to $+\infty$, and λ_ns of smallest magnitude are more important from radiation problems and scattering problems point of view. As given in Eq. 20 of [2], the modes with positive λ, predominantly store magnetic energy, whereas those with negative λ, mainly store electric energy. The mode having $\lambda = 0$ is called the resonant mode. In other words, at a specific frequency the eigenvalue of a particular mode becomes zero and the mode is at resonance.

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Another representation of λ_n s is α_n s which are called characteristic angles [5]. The formulation is as follows:

$$\alpha_n = 180^\circ - \tan^{-1}(\lambda_n) \tag{2}$$

It is obvious that at resonant frequency, characteristic angle (α_n) becomes 180°. Furthermore, due to [1] the frequencies related to angles between 135° and 225° represent the mode's bandwidth.

III. Proposing the Approach

In the proposed approach, modal analysis using the theory of characteristic modes will be performed on two structures. The discussion is based on the fact that if two "nearly similar" structures ("nearly similar" will be defined later) from the modal behavior point of view, have the same behavior in a particular domain (e.g. frequency), the abovementioned structures are equivalent in that domain. So, we will try to minimize the two structure's differences in modal behavior.

With the assumption of a cylindrical wire dipole (C.W.D) antenna as an original antenna and a flat metal strip dipole (F.S.D) antenna as the target one, the proposed approach can be summarized in three steps as illustrated in Fig. 1.

As the process step.1, using a developed specific MoM code results in calculation of the first four characteristic currents of a 0.5m length C.W.D antenna at the frequency of 300MHz as can be observed in Fig. 2. The diameter of cylinder's cross section is 2mm. Basis functions which have been used in calculation are 81 sub domain triangular ones.

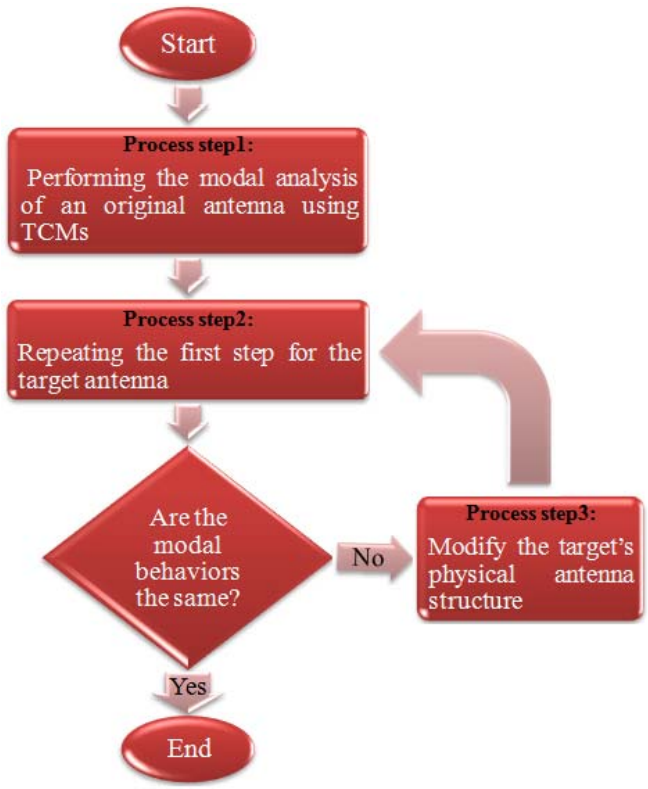

Fig. 1 Algorithm description of the proposed approch.

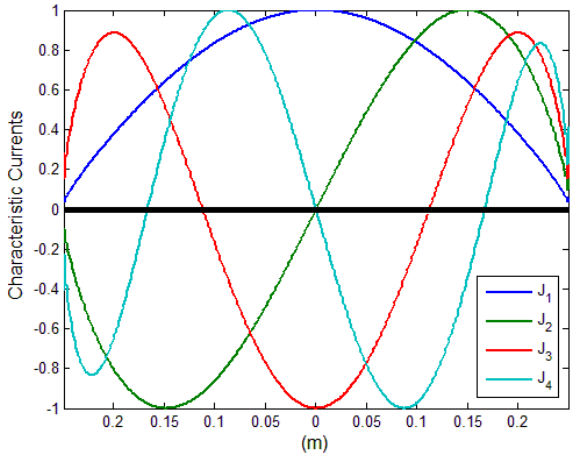

Fig. 2 First four characteristic currents of a 0.5m length cylindrical wire dipole antenna (presented by black line) with diameter of 2mm at frequency of 300MHz.

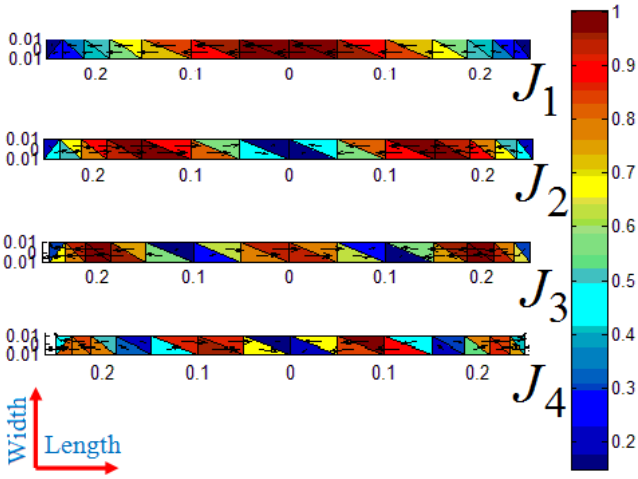

Fig. 3 First four characteristic currents of a flat metal strip dipole antenna at frequency of 300MHz. Dimensions are in meter.

In the next process step, by the use of 27 RWG [6] basis functions, the first four characteristic currents of a 0.5m length F.S.D at the frequency of 300MHz are obtained (shown in Fig. 3). The width of strip is 2cm in order to obtain better visibility of the currents and their directions. Modal analysis of the currents of these two structures shows that the general behavior of the current in different modes is the same. In such circumstance, two structures are called "nearly similar" and therefore can be used interchangeably. Consequently, it is logical to use a F.S.D with 2mm width (equal to the diameter of the C.W.D) as the replacement of the C.W.D. Moreover, to attain a wide-spread overview about the modal behavior of discussed structures, having a study on characteristic angles is significant since it leads to some valuable information about the resonance frequency of each mode.

Fig. 4 represents the variation with frequency of the first four characteristic angles (α_n) associated to the current modes of the C.W.D antenna with 2mm of cross sectional diameter and the abovementioned F.S.D (width is 2mm).

TABLE I COMPARISON BETWEEN RESONANCE FREQUENCY OF MENTIONED STRUCTURES

Mode Number	1	2	3	4
Resonance freq. (MHz) of C.W.D by diameter of 2mm	286	585	886	1188
Resonance freq. (MHz) of F.S.D by width of 2mm	301	593	885	1187
Approximate electrical length	$\lambda/2$	λ	$3\lambda/2$	2λ

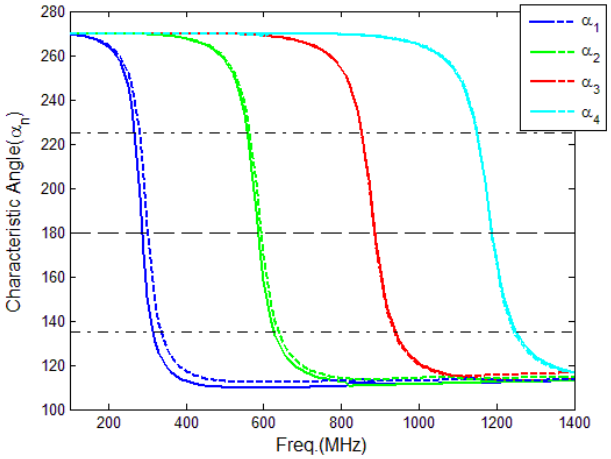

Fig. 4 First four characteristic angles of a 0.5 dipole antenna. Solid lines belong to cylindrical one by diameter of 2mm and dashed lines belong to flat metal plate strip one by width of 2mm.

TABLE II VARIATION OF FIRST RESONANCE FREQUENCY OF FLAT METAL STRIP VERSUS THE WIDTH OF STRIP

Strip's width (mm)	2	3	4	5	6	7	8
Resonance frequency of first mode (MHz)	301	297	294	292	288	286	285

This figure gives information on modal behavior versus frequency of structures. It is observed that characteristic angles start at 270° which lead to store electrical energy, then decline rapidly and reach the angle of 180° results in resonance frequency of the mode and finally, remain steady at the angle of circa 90° (storage of magnetic energy). The resonance frequency of each mode is presented in TABLE I. According to this table, in lower frequencies there is an obvious difference between resonance frequencies so that the first resonance $(l = \lambda/2)$ of the two structures is different by 15MHz and can not be ignored when accuracy is required. Therefore, whenever the working frequency is at about 300MHz (near the first resonance), doing process step3 of Fig. 1 is indispensable.

To do this step, by changing the width of strip we tried to make the first resonance frequency of two structures equal.

In TABLE II first resonance frequency of the F.S.D is a function of strip's width. According to both tables a F.S.D whose width is 7mm is equal to a C.W.D with diameter of 2mm from resonance frequency point of view. Therefore, such structures have the same modal behavior.

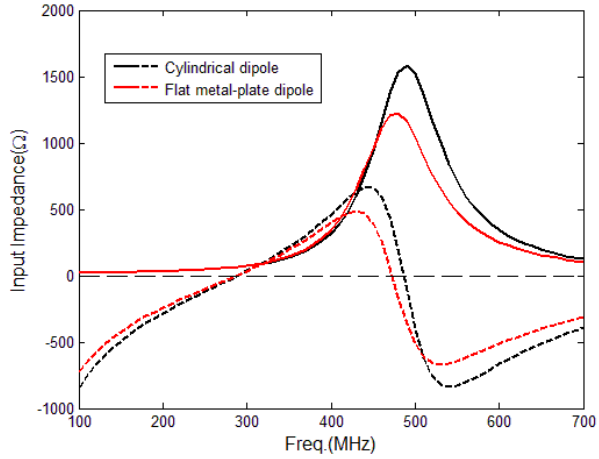

Fig. 5 Input impedance of a cylindrical wire dipole antenna by diameter of 2mm and a flat metal strip one by width of 7mm.

To observe the correctness of calculation, the input impedance of the two structures are compared. According to [1], the first resonance happens when the imaginary part of the input impedance becomes zero for the first time. As it can be observed from Fig. 5, the resonance frequency of the two structures from the input impedance point of view is not almost but completely identical and it proves our claim that a F.S.D of 7mm in width and 0.5m in length is equal to a C.W.D whose diameter is 2mm and the same length as the F.S.D, is true. As a result when dipoles are used at first resonance frequency these can be considered equal. It should be mentioned that the input impedance has been calculated by the use of full wave package Ansoft HFSS.

IV. CONCLUSION

TCMs is used to show how modal analysis of open structures which is not widely used in antenna design nowadays can be beneficial for optimizing the behavior of a structure. The first four characteristic modes of a cylindrical wire dipole antenna have been achieved by developing a suitable MoM code. Afterward a flat metal strip dipole antenna has been analyzed in a same manner. By changing the strip's width the modal behavior of two structures became exactly the same from frequency behavior point of view and the optimum width has been concluded. The advantages of this proposed approach can be summarized as follow:

- Some wide-spread overview about the behavior of structure is achieved using the structure's modal analysis;
- Optimization became directed, we have done that for the intended first resonance frequency of dipole antenna;
- After developing a suitable code, this method is much less time consuming in comparison with using some commercial packages to optimize the results.

To show the correctness of our calculations, simulation of

structures is done using full wave package Ansoft HFSS and the results are quite acceptable.

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