URSI AP-RASC 2019, New Delhi, India, 09 - 15 March 2019

Characteristic Mode Analysis of a few Symmetric English Alphabet Shaped Antennas

Sayan Sarkar
Jadavpur University, Kolkata-700032, West Bengal, India

Abstract

This paper presents the Characteristic Mode Analysis (CMA) of antennas resembling some symmetric letters of the English alphabet. The designed structures are analyzed to find out the dominant as well as higher order modes within a selected frequency range (1GHz to 10 GHz). The far-fields of the significant radiating modes are simulated and analyzed for potential use in everyday communication systems. It has been found that apart from possessing acceptable radiation patterns, these structures also cover some IEEE standard wireless communication channels.

1. Introduction

The Characteristic Mode Theory is a great tool for analyzing and designing PEC bodies, N-port networks, antennas, antennas in multilayered medium, dielectric resonators as well as various antenna systems. The most advantageous part of the Characteristic Mode Analysis (CMA) is that it can predict the various modal characteristics of a designed structure without actually modeling any sources. Therefore, the resulting modes of the CMA are modes which are inherent to the structure itself, without any external excitation or influence.

Some symmetric English alphabet shaped antennas have been modeled and analyzed using characteristic mode analysis. It has been found by observing the modal significance and far-fields that the strong radiating modes of each alphabet structure are capable of carrying out communication at their respective resonant frequencies. The English alphabets used in this paper are: - A, H (or flipped I), M (or inverted W) and N (or flipped Z). Each of these structures can be used as a radiating antenna by providing proper feed at the desired frequency.

The location and choice of feed can be decided by observing the simulated electric field distributions of the radiating modes obtained from the CMA of the structures.

2. The Theory of Characteristic Modes

Garbacz and Turpin [1] defined Characteristic Modes as a particular set of surface currents and radiated fields that are the characteristics of the obstacle and are independent of any external source.

The definitions for the characteristic modes show that the characteristic modes constitute a very special orthogonal set in the expansion of any possible induced currents on the surface of the obstacle [2].

The Characteristic Modes give use useful information like resonant frequencies of the inherent modes, far field modal radiation patterns, modal currents on the surface of the analyzed structure and significance of each mode at given frequencies.

The CMA involves solving eigenvalue problem in general. CM can be formulated based on EFIE, MFIE or CFIE. In all the cases, it reduces to solving the generalized eigenvalue equation of the form:-

$$\mathbf{X}\mathbf{J_n} = \lambda_n \mathbf{R}\mathbf{J_n} \quad (1).$$

With

$$\mathbf{X} = \frac{\mathbf{Z} - \mathbf{Z}^*}{2j} \quad (2),$$

$$\mathbf{R} = \frac{\mathbf{Z} + \mathbf{Z}^*}{2} \quad (3),$$

$$\mathbf{Z} = \mathbf{R} + j\mathbf{X} \quad (4).$$

$\mathbf{Z}$ is the Method of Moments impedance matrix which can be represented by its real Hermitian part ($\mathbf{R}$) and its imaginary Hermitian part ($\mathbf{X}$). $\mathbf{J_n}$ and λ_n are the real eigenvectors and eigenvalues while n represents the n^{th} order mode. * represents complex conjugate.

EFIE based CMA can be applied to both open and closed objects. MFIE based CMA is applicable only for closed objects. Most antennas being open structures, EFIE based CMA are used more prevalently.

The CM theory is only applied in electromagnetic problems with electrically small and medium sizes. In electrically large problems, it is usually very difficult to excite a single mode even within a narrow frequency region. Thus CMA is generally used only for electrically medium and small problems [2].

Two of the important parameters involved in CMA include:-

1. Modal significance (MS) is represented as

$$\mathrm{MS} = \left| \frac{1}{1 + j\lambda_n} \right| \qquad (5).$$

It is the intrinsic property of each mode. It states the coupling capability of each CM with external sources. It measures the contribution of each mode in the total electromagnetic response to a given source. Sometimes it is easier to use the MS other than the eigenvalues to investigate resonance of a structure. Regions of the frequency spectrum having MS > 0.6 are considered to be significant modes suitable for radiation. Ideally, the perfect radiating mode should have MS = 1 for $\lambda_n = 0$.

2. Characteristic Angle (α_n) is defined as

$$\alpha_n = 180° - \tan^{-1} \lambda_n \qquad (6).$$

It gives us an understanding of the mode behavior near resonance. For $\alpha_n = 180^0$, the mode associated will be resonant. For α_n within 90^0 and 180^0, the mode associated will be inductive whereas for α_n between 180^0 and 270^0, the mode associated will be capacitive.

For the most effective radiator, we should have $\alpha_n = 180^0$ for $\lambda_n = 0$.

3. Designed Antenna Structures

The following antenna structures were designed using CST STUDIO SUITE®.

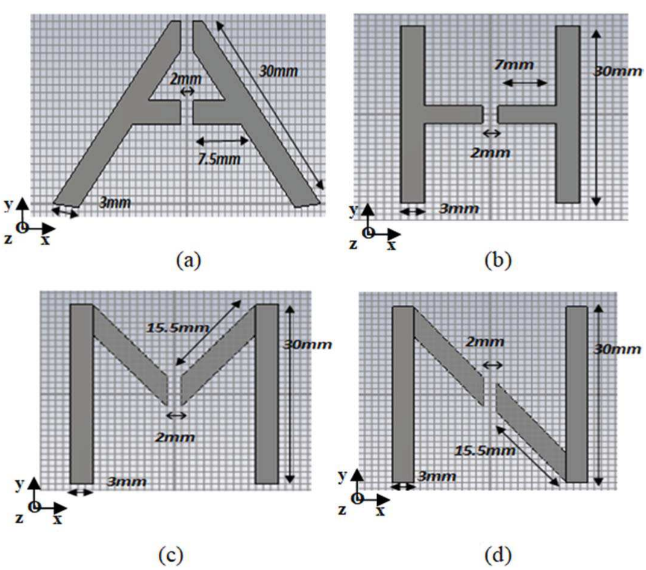


Figure 1. Designed alphabet antennas. (a) A shaped antenna, (b) H / flipped I shaped antenna, (c) M / inverted W antenna, (d) N / flipped Z antenna.

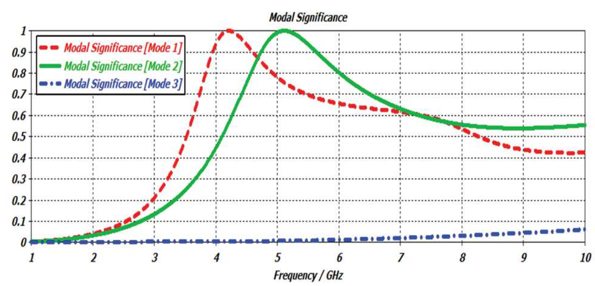
The thickness of each structure was taken to be ~2mm and the design material was considered to be PEC.

4. Modal Significance of the designed antenna structures

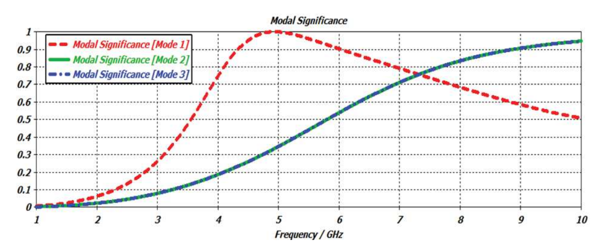
Carrying out the CMA in CST STUDIO SUITE® provides us with three main sets of results:-
1) Modal Significance, 2) Eigenvalue and 3) Characteristic Angle.

Analyzing all the three parameters according to their relations provided in the previous section, only the modal significance results are discussed below. Both the other parameters extracted after the above CM analysis are found to be in good agreement with each other and the modal significance results at the frequencies of interest.

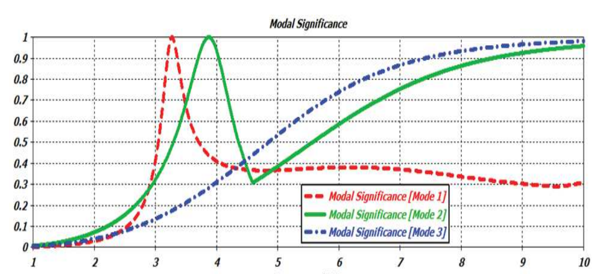
The first three characteristic modes of each structure are studied. The modal significance curves obtained from the CMA analysis are presented below for each of the designed structures. For each modal significance curve, the mode tends to radiate near frequencies where the modal significance ~ 1. This is kept in mind while analyzing the curves presented below.



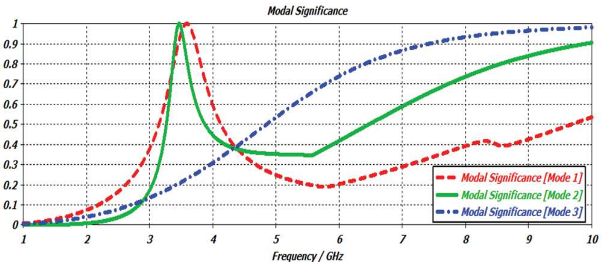
(a)



(b)



(c)



(d)

Figure 2. The modal significance vs frequency curves of the (a) A shaped antenna, (b) H / flipped I shaped antenna, (c) M / inverted W shaped antenna and (d) N / flipped Z shaped antenna within frequency range 1GHz – 10 GHz.

Analyzing the graphs, we can conclude that:-

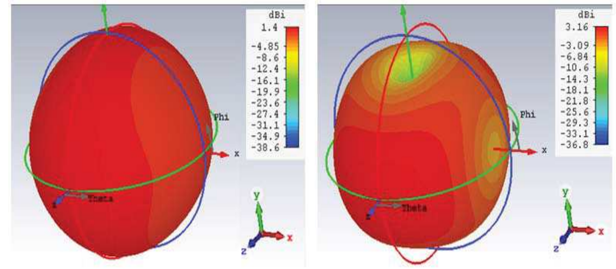
a) The A shaped antenna has a tendency to radiate near two frequencies. Mode 1 ~ 1 near 4.2GHz where the antenna might radiate. Mode 2 ~ 1 near 5GHz where the antenna might radiate as well. The third mode has no significant contributions within the simulated frequency range.
b) The H / flipped I shaped antenna has Mode 1 ~ 1 near 5 GHz. However, both Mode 2 and 3 follow the same curve and it has been found that they are not good radiating modes within the simulated frequency range. Therefore, they have no significant contributions in terms of radiation.
c) The M / inverted W shaped antenna has two probable radiating regions near 3.5 GHz where Mode 1 ~ 1 and near 4 GHz where Mode 2 ~ 1. The third mode has no significant contributions within 1 GHz-10 GHz.
d) The N / flipped Z shaped antenna has a probable radiating region near 3.5 GHz where both Mode 1 and Mode 2 ~ 1. The third mode again plays no significant role in the desired region.

Therefore, it can be stated that in 3 of the 4 designed structures, only Modes 1 and 2 are responsible for proper radiation (except in (b) where it is only Mode 1) while in all the structures, mode 3 is a higher order mode playing no significant role in radiation.

5. Far Field Patterns of the significant radiating modes of the designed structures

Following the analysis of the previous section, the far field directivity patterns of each structure at the potential radiating frequencies is studied and presented using CST STUDIO SUITE®.

5.1 A shaped antenna



(a) (b)

Figure 3. Far field directivity pattern of (a) mode 1 (at 4.2GHz) and (b) mode 2 (at 5GHz).

It can be seen that Mode 1 at 4.2 GHz presents a near omnidirectional radiation pattern which can be used for communication in nearly all directions with a maximum directivity of 1.4 dBi. Mode 2 provides a radiation pattern capable of carrying out communication in the ± z directions at 5GHz with a maximum directivity of 3.16 dBi.

5.2 H / flipped I shaped antenna

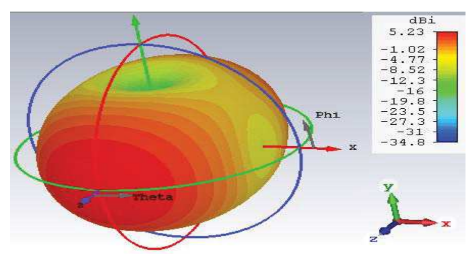
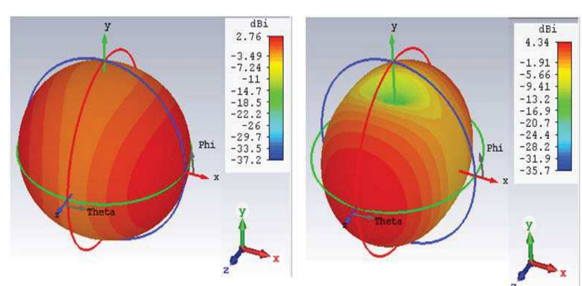


Figure 4. Far Field directivity pattern of mode 1 (at 5GHz)

Mode 1 provides the only acceptable radiation pattern near 5 GHz. The observed radiation pattern can be used to carry out communication in the ± z direction with a maximum directivity of 5.23 dBi.

5.3 M / inverted W shaped antenna

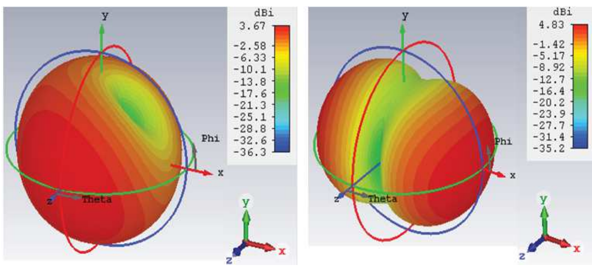


(a) (b)

Figure 5. Far Field directivity pattern of (a) mode 1 (at 3.5 GHz) and (b) mode 2 (at 4 GHz).

The M / inverted W antenna again has two radiating modes which have been shown. Mode 1 is responsible for a radiation pattern capable of carrying out communication in both ± x directions at 3.5 GHz with a maximum directivity of 2.76 dBi. Mode 2 presents a radiation pattern near 4 GHz with communication possible in the ± z directions with a maximum directivity of 4.34 dBi.

5.4 N / flipped Z shaped antenna



(a) (b)

Figure 6. Far Field directivity pattern of (a) mode 1 (at 3.5 GHz) and (b) mode 2 (at 3.5 GHz).

Mode 1 presents a radiation pattern near 3.5 GHz with communication regions lying along the ± z directions with a maximum directivity of 3.67dBi. Mode 2 also presents a radiation pattern near 3.5GHz with communication regions lying along the ± x directions with a maximum directivity of 4.83 dBi.

Therefore, simply by switching the feed positions to excite the different modes, we can get full communication coverage of the x-z plane near 3.5 GHz frequency region.

6. Applications of the designed antenna structures in wireless communication

Apart from the analysis that the designed alphabet shaped antennas can indeed produce acceptable radiation patterns, it can also be shown that some of the frequencies of operation of these structures can cover well known IEEE standards for wireless communication.

Table 1. IEEE wireless standards covered by the designed antennas.

Antenna Shape	Mode 1 Frequency (GHz)	Mode 2 Frequency (GHz)	IEEE Standards covered
A	4.2 GHz	5 GHz	IEEE 802.11n (Wi-Fi 4), 802.11ac (Wi-Fi 5) ,802.11ax (Wi-Fi 6) (all in the 5 GHz region)
H/ flipped I	5 GHz	Non-radiating	IEEE 802.11n (Wi-Fi 4), 802.11ac (Wi-Fi 5) ,802.11ax (Wi-Fi 6) (all in the 5 GHz region)
M/ inverted W	3.5 GHz	4 GHz	IEEE 802.16d, IEEE 802.16e (WiMAX). (both in the 3.5 GHz region)
N/ flipped Z	3.5 GHz	3.5 GHz	IEEE 802.16d, IEEE 802.16e (WiMAX). (both in the 3.5GHz region)

7. Conclusion

Antennas resembling English alphabets have been designed in this paper. Characteristic Mode Analysis is used to find out the inherent modes and radiating nature of each such structure. The modal significance values of the resulting analysis are used to find out near what frequencies the structures can potentially radiate.

The far-fields at these potential frequencies are simulated and presented. It can be seen that the expected radiating modes of the structures do indeed radiate and present acceptable radiation patterns in the far-field region.

The designed antennas can thus be used for wireless communication and they also cover some of the well known IEEE wireless standard communication channels.

The location and positions of the feeds can be determined by analyzing the electric field distributions of each associated mode at each frequency of interest.

8. References

1. R . J. Garbacz and R. H. Turpin, “A generalized expansion for radiated and scattered fields,” *IEEE Trans. Antennas Propag.*, vol. AP - 19, no. 3, pp. 348–358, May 1971.

2. Yikai Chen, Chao-Fu Wang**,** *Characteristic Modes: Theory and Applications in Antenna Engineering*, John Wiley and Sons, 19-May-2015, pp. 6-7, 60-61.