Guest Editorial
Theory and Applications of Characteristic Modes

THE theory of characteristic modes (TCM) is a versatile design and analysis tool that gives the unique possibility to determine the electromagnetic properties of a structure based only on its geometry and material properties. In antenna applications, this ability provides valuable insights into an antenna's behavior independent of the feeding arrangement, as well as providing information about how desirable radiation modes can be excited. TCM had its humble beginnings in the early 1970s, largely through the pioneering works of Garbacz [1] and Harrington [2], together with their co-workers.

"But why now?" is a fair question to ask about the publication of a special issue on this topic in the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION (TAP), the flagship journal of our field. After all, this special issue coincides with the 45th anniversary of the first TAP papers on the subject [1], [2]. Moreover, TCM is neither an established antenna discipline nor a single-application driven hot topic.

To help answer this question, the number of papers on characteristic modes (CMs) in TAP since 1971 is summarized in Fig. 1(a). Only 21 papers were published during 1971-1994, or slightly less than a paper per year, indicating the topic was a specialist field rather than one of general interest. This was followed by a period of complete silence between 1995 and 2009. However, a turning point came in 2010, as a critical mass of researchers discovered wide-ranging applications of TCM, and since then a trend of fast-growing interest in the field can be observed. A similar story is told from Fig. 1(b), where 137 of the 218 CM papers found in the IEEEXplore database (63%) were published during 2010-2015. In this context, we are convinced that the timing of this Special Issue is ideal in stimulating and capturing a representative collection of the high-quality research results in the topic during its rapid growth phase.

Moreover, careful planning that preceded the special issue proposal provided very strong indication of increasing interest and active participation in CM research from both new and established researchers. In particular, this Special Issue is a major initiative of the Special Interest Group (SIG) on TCM that was established in 2014 to serve the growing TCM community (characteristicmodes.org). More than 60 research groups or companies have since joined this dedicated effort to improve coordination among members as well as to promote activities in the field.

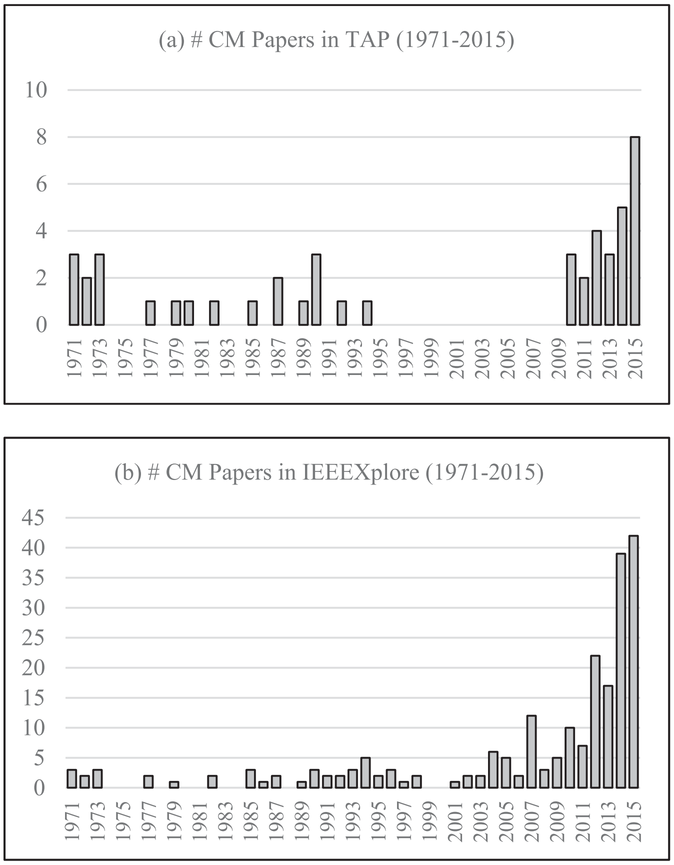

Fig. 1. Trend of CM research according to published papers in (a) TAP and (b) IEEEXplore database.

It is also noteworthy that one barrier to the adoption of CM as a design and analysis tool was the limited availability of such a software tool, previously only available in Altair Engineering's FEKO or through in-house implementations. However, due to solid industrial interests in applying TCM to commercial work, major electromagnetic simulation software vendors including CST and WIPL-D have now joined Altair Engineering in incorporating CM analysis features into their full-wave method-of-moments (MoM) solvers. Therefore, we are excited and optimistic about the opportunity for many more researchers to discover for themselves the vast potential of TCM.

Among the 37 papers considered for the special issue, 16 papers were finally included, partly to meet the publication deadline (i.e., 11 months from the submission deadline of July 31, 2015). The authors of these papers are affiliated with 16 different groups/institutions from eight countries.

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Consistent with the focus of the Special Issue, the included papers present some of the latest advances in both theoretical and application aspects of TCM. Accordingly, they are introduced in the following sections under these two broad categories.

I. THEORETICAL ASPECTS OF CHARACTERISTIC MODES

Readers may find it surprising that interesting theoretical research issues still remain in TCM. It is true that the theory behind the computation of CMs for conducting bodies is complete [2]. In addition, subsequent works of Harrington *et al.* have proposed generalization of TCM to structures with dielectric and magnetic materials [3], [4]. However, there remain significant scientific challenges in applying the achieved results to solve a number of practical problems. Several of these challenges are carefully addressed in this first category of papers.

A. Computation of Characteristic Modes

One important theoretical aspect in computing the CMs of dielectric and magnetic structures is that the CMs, as obtained from the original volume- and surface-based formulations of Harrington *et al.* [3], [4], do not fully conform to the definition of TCM for conducting bodies [2]. This is because the characteristic eigenvalues from these formulations are not related to the difference in the stored magnetic and electric energies, unlike the case for conducting bodies. Moreover, the existing use of surface formulations has resulted in the existence of internal resonances in the CM solution.

Miers and Lau take a pragmatic approach to remove internal resonances in the general case of lossy dielectric and magnetic materials. In particular, the CM solution as obtained from the MoM impedance matrix of the symmetric PMCHWT surface formulation is post-processed to identify and remove the internal resonances. For this purpose, a physical lower bound of the modal radiation efficiency is derived from the quality factor associated with each CM.

Until now, the application of CMs is largely confined to medium-scale problems, where the largest dimension of the structure to be analyzed is typically smaller than one wavelength (but at the same time not so electrically small that CMs cannot be efficiently excited). Therefore, the work of Dai *et al.* challenges conventional theory by applying fast multipole algorithms (FMAs) to appropriate electric and combined field integral equations to extend the capabilities of TCM to solve electrically larger problems as well as problems with fine, subwavelength features.

B. Techniques for Characteristic Mode Analysis

When utilizing CMs to interpret the physics of a particular antenna, the frequency dependence of the characteristic eigenvalues CMs are of interest. While the set of CMs is unique throughout the frequency band of interest, the eigenmode decomposition from the impedance matrix is performed separately for all calculated frequencies. Therefore, in order to obtain a smooth eigenvalue curve of a particular mode, it has to be labeled accordingly for all frequencies. There are different aspects which make this a difficult task. First of all, only a limited set of CMs is calculated numerically whereas in theory an infinite set of CMs exists. Consequently, a certain mode that has been labeled at a certain frequency may not be part of the set of modes calculated at another frequency. Moreover, the modal current distribution itself is frequency dependent. Therefore, it may be difficult to recognize a particular mode at different frequencies and track it correctly. Different mode tracking techniques based on the correlation of the modal current distributions, the modal radiation patterns, or simply the continuity of the eigenvalue curves, are known and implemented in commercial software. Unfortunately, these methods still fail quite frequently especially when two modes have similar eigenvalues. This problem is addressed by Schab *et al.* Advanced algorithms to improve the tracking of modes over frequency are presented by Safin and Manteuffel.

Apart from characteristic eigenvalue, several other parameters are of interest to better understand the physics of an antenna. A specific one is the quality factor (Q). In recent years, Q has been studied by different researchers as it can be used to predict the bandwidth potential of an antenna. Chalas *et al.* demonstrate how TCM can be used to calculate Q limits for arbitrary-shaped antennas.

II. APPLICATIONS OF CHARACTERISTIC MODES

The overarching challenge in the design and analysis of the radiation and scattering properties for a given structure is the lack of a convenient tool that can give critical and intuitive insights of these properties. In fact, the realm of compact antenna design such as that of mobile terminal antennas is often compared to "black magic," in that a skilled designer has the ability to tune the antennas according to different requirements (wideband or multi-band operation, gain, space restrictions, etc.) according to intuition and smart guesses based on experience. For this reason, TCM is ideally suited for providing a systematic approach to understanding the possible resonant modes on a structure and applying them to achieve the desired outcomes. Apart from presenting further results on some established uses of TCM, for example the broadening of bandwidth by combining multiple CMs, this section also showcases new and emerging applications.

A. Antenna and Antenna Array Designs

TCM provides antenna designers with physical insights based on eigenmode analysis to fulfill a given set of requirements. Shih and Behdad extend the bandwidth of HF (high frequency) electrically small antennas by optimizing the feeding structure of platform modes. Examining how a platform-mounted antenna can be used to excite CMs, the bandwidth is enhanced by a factor of 2, 7, or 10 compared to one standalone full-loop antenna. Deng *et al.* present a design of merging multiple CMs to improve bandwidth in MIMO handset antennas based on chassis and bezel modes. A half-wavelength dipole mode of the chassis and a one-wavelength mode of the bezel are used to achieve MIMO performance requirements in a mobile handset.

Yang and Adams describe a systematic design method for a class of symmetric MIMO antennas by combining their decoupling property with CM analysis. Based on this result, the Q of each CM is obtained and used to optimize the antenna shape and feed locations of the desired modes. Bouezzeddine and Schroeder develop a systematic procedure for the design of a tunable multi-port antenna with high isolation, involving the chassis currents given by CM analysis. A tunable 4-port MIMO antenna is demonstrated for a cognitive femto-cell covering the frequency range from 470 MHz to 790 MHz. Manteuffel and Martens present a concept for a compact ultra-wideband multi-element antenna for massive MIMO indoor base stations by finding uncorrelated ports through CM analysis. Based on the general concept, a four-port array element is developed and used to generate an 11×11 element array containing 484 antenna ports. Dicandia *et al.* present the design of null-scanning antennas, based on asymmetric excitation of two CMs that contribute to null shifting in the array pattern. A prototype of the antenna is realized by applying a discrete phase shifter based on PIN diodes to scan the null.

B. Antenna and Scattering Analysis

TCM has been used to guide the design of multi-port antennas, particularly in MIMO applications. However, the design of such antennas has largely been *ad-hoc* once the CMs of the antennas have been identified. Furthermore, the introduction of physical feeds often requires the CMs of an antenna to be recomputed in the case of complex antenna shapes. Yang and Adams devise and present a technique for analyzing the CMs of such antennas but requiring only one eigenmode decomposition. They further show that the method can be used to generate useful heat maps for optimizing feed locations in multi-port antenna designs.

Rabah *et al.* explore the important relationship between the CMs of the antenna and the fundamental Q of the antenna. They show that the Q of the antenna can be expressed solely in terms of the characteristic eigenvalues of the antenna, eliminating the need to compute reactive energies for specific excitations. Such formulations can be useful in evaluating the performance of electrically small antennas, including those placed on magneto-dielectric substrates and metamaterials, which the authors explore.

Additionally, TCM can be used to decouple antenna ports in a multiport design, even when the ports do not operate at the same frequency. Wu *et al.* observe that modes that do not contribute much to a port's self-admittance at one frequency may contribute significantly to the mutual admittance between two ports operating at different frequencies. They demonstrate that it is possible to introduce loading at discrete points in the antenna to reduce this out-of-band coupling considerably.

TCM can offer insights into the design and analysis of antennas and scatterers as well. Hassan *et al.* explore the application of TCM to the analysis of electromagnetic scatterers realized from carbon nanotubes (CNTs). As the shape of realistic CNT scatterers can be non-canonical and quite complex, TCM offers insights on the impact of CNT shapes on the scattering response and resonance of these structures, which will aid the design of novel CNT devices in the future. Finally, Khan and Chatterjee utilize TCM to better understand the impact of design parameters in U-slot microstrip patch antennas. Understanding the eigenmodes of this antenna type allows performance in terms of bandwidth and polarization purity to be better optimized.

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