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MODAL ANALYSIS AND OPTIMIZATION OF RADIATING PLANAR STRUCTURES

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Chapter 1

Current Situation of the Studied Problem

The design of an electrically small antenna (ESA) consists of an analysis and an optimization, or a synthesis. Antenna analysis first specifies the geometry including the material distribution and the boundary conditions, and then evaluates the sources of the field (currents and charges). Finally, it evaluates selected antenna parameters. For this kind of approach, the designer must have previous experience with similar antennas, and it usually takes many attempts to find a structure that is good enough to satisfy all the requirements from the impedance and radiation point of view. While antenna analysis has been satisfactorily resolved, thanks to modern analytical and numerical methods, antenna synthesis involves two challenging tasks. The first task is to find what radiator geometry is the most suitable for a given purpose, and the second is to reveal the best excitation for this shape. These two steps are closely interconnected through the fundamental laws of classical electrodynamics, the Maxwell equations [1, 2]. However, the steps can advantageously be separated, e.g. via modal methods, or – more specifically – via characteristic mode decomposition. Both of these tasks are extremely difficult in all cases when one needs a radiator with parameters reaching out to the fundamental physical limitations. This is often the case for ESA, in which we seek small (subwavelength) dimensions of the radiating device in comparison with its operating frequency. Antenna synthesis presents an as yet unsolved problem, which has been addressed to some extent in antenna arrays. One of the major issues is the principally infinite number of degrees of freedom in possible shapes of the antenna body satisfying particular criteria. Absolutely, any geometry can form the shape of a potential antenna. Thus the antenna synthesis is a seriously difficult problem. The primordial idea of the synthesis lies in determining the best shape from among an infinite number of options.

An ESA is an essential part of present-day wireless communication systems, which are used in everyday life by billions of users around the globe (in mobile cell phones, tablets, GPS receivers, cars, etc.). However, the demand for higher transfer and smaller physical dimensions has made the antenna a serious bottleneck that is hindering further progress. Typically, the antenna fractional bandwidth, the radiation efficiency, and the gain are considered as the key parameters of electrically small antennas, since they are significantly affected by reducing the electrical size. Keeping in mind that these parameters are contradictory, it is not an easy task to designate the optional trade-off. Even worse, all limits and restrictions are analytically known only for a few basic shapes (e.g. the lower bounds of the quality factor of a sphere, the radiation losses of a half-wave dipole) and the explicit relationship between these parameters is a subject of current research.

Many crucial steps towards ESA synthesis have already been taken. The most important breakthrough was the introduction of the source concept, which attempts to represent all antenna characteristics solely by means of the currents flowing on the antenna body. This source concept is one of the core topics of the thesis. It will be demonstrated that this concept can be used for defining the stored energy, various definitions of the Q, radiation efficiencies and radiation patterns, both in modal form and in overall form. The source concept is nowadays a leading approach to antenna analysis. By resolving some principal problems, it also promises to handle ESA synthesis. Some of these crucial problems have been studied and solved in this work.

It is important to have in mind, that the history of antenna analysis and synthesis covers more than one century, and we are still not at the end. In this work, we focus on theoretical difficulties of small antenna synthesis, the relating perspective techniques. We also point out that the present developments have been tending toward a concept referred to called in this thesis as the source concept.

1.1 Organisation of the Thesis

The thesis is intended as a brief abstract that attempts to recapitulate the author's work on ESA analysis and synthesis, and to relate this work to the current state of knowledge. In order to distinguish the author's publications from the work of others, all original works by the author are denoted by a bullet (e.g. as [0•]), and all diploma thesis that were supervised by the author and relate to the topic are denoted by an asterisk (e.g. as [0∗]).

It is important to stress that only published results are explicitly discussed here. Note however, that the author tackled other issues during Ph.D. studies (namely the problem of negative energies, invariance of the energetic functional, a closed form formula for the characteristic mode on a dipole, limits of the quality factor for elliptical obstacles, etc.). These topics are mentioned here for completeness, and will be addressed in future publications.

In order to make the whole text as readable as possible, the author tries to avoid any mathematics in the body of the thesis – the whole mathematical apparatus and the formalism that has been used can be found in the attached papers and in the references. The short text submitted here serves as an accompanying document that summarizes all his publication efforts.

Chapter 2

Aims of Dissertation

The general aim of the thesis is to contribute to the theoretical as well as practical knowledge of electrically small antenna design. The particular goals are specified as:

- revision of the characteristic mode (CM) decomposition, elimination of residual mode, resolution of problems with tracking, implementation of the CM,
- superposition of modal quantities that are important for the ESA design,
- feeding network synthesis, optimization of modal results,
- consistent evaluation of stored electromagnetic energy, source current definition of measurable Q, implementation of the Q calculation during post-processing,
- utilization of fractal geometry, study of its influence on an antenna operation, optimization of radiator's geometry,
- practical verification of obtained results in commercial packages and manufacturing of promising antenna candidates.

Chapter 3

Working Methods and Results

3.1 Revision of CM Theory, Interpretation of Modal Results

This topic is divided into parts covering theory, numerical issues, and implementation.

3.1.1 Theoretical Problems

An important theoretical problem in characteristic decomposition is its completeness and the hypothetical existence of the so-called residual mode. It has been presented [3,4] that a residuum always exists, constituting the difference between the superposition of characteristic modes and the direct solution given by the Method of Moments (MoM). The existence of the residual mode was attributed to the presence of feeding. Based on the completeness of the CM decomposition, proved in [5], which was already mentioned by Harrington [6], no residual mode should however exist. It thus follows that the residuum should be a numerical issue only. After an analysis of several algebraic parameters (modal significance, condition numbers, etc.), the problem was found to reside in a wrong sign of the radiated power of high-order modes (thus typically almost non-radiating modes) [7•]. This also explains why the imaginary part of the residuum was significantly larger than the real part if the real excitation was considered. The same result was obtained by Lagrange multipliers, which were formally used to solve the GEP of the CM decomposition. As a result, a correction formula was proposed [7•]. The numerical verification was performed on an example of a thin-wire dipole [8] fed by a delta gap source [9]. For this purpose, the simple one-dimensional Galerkin formulation of the MoM was implemented [10], and the resultant symmetric impedance matrix was decomposed by the generalized Schur (QZ) decomposition [11] into the CM basis. Using the correction formula, the residual mode was suppressed to a level of numerical noise [7•]. It can be concluded that the issue of the residual mode can mainly be explained the numerically ill-conditioned matrix pencil of CM GEP [11].

An analytical prescription for the dominant CM mode on a half-wavelength dipole was investigated. Unfortunately, no such function is yet known. Determining this function would help to verify the meshing and decomposition techniques. It can be shown via the Fourier transform [12] and the Dirichlet-PoincarĂ© inequality [13] that the CM functional has no solution in 1-dimensional Sobolev $\mathcal{W}^{1,2}$ space [14], when an infinitely thin wire is considered. Some 2-dimensional structures were analytically treated using spectral methods. However, this work remains unpublished, and is therefore not detailed in this thesis.

Finally, an attempt was undertaken to approximate the CM modes by analytical functions. This technique can be used especially in the case of small antennas at their natural resonance (only one mode is excited). Since the CM forms a variational solution, the current shape of the mode is extremely resistant to a change in geometry (the topology has to remain the same). This concept was successfully tested in [15∗] on an example of thin-wire full wavelength loop, which was miniaturized by two U-notches placed at the minima of the current density. The current density was approximated by a sine function, which not only proved to be a very precise approximation but also lead to a tremendous speed-up of the calculation (no need to repeat the CM decomposition). This allowed Q to be optimized with respect to the geometry of the notches. The working frequency was selected exactly at the resonance of the dominant mode, and it was calculated from the (constant) electrical length of the wire. The results for the approximative current shape and the exact current shape were in excellent agreement.

3.1.2 Properties of Radiating and Non-Radiating Modes

Among other classifications, characteristic modes can be divided into two major groups: radiating modes and non-radiating modes [16]. Radiating modes and their properties were studied in [17•] on an example of a rectangular patch and fractal shapes. Non-radiating modes, often called inductive modes, radiate poorly at all frequencies. It has been widely accepted [16] that such modes have strictly inductive behaviour, so that they have no natural resonance. All these reasons let to other notation: static modes.

However, it can be shown that in special cases these modes are able to resonate. For example, consider a static mode on an electrically long cylinder (the current flows uniformly azimuthally along the angular coordinate). Then the eigennumber is positive for reasonably small ka (i.e. the mode is inductive). However, for large enough ka the eigennumber achieves a zero value (the mode resonates), and then the eigennumber starts to be negative. This effect usually occurs for a high values of ka, and only for certain structures. Note here that the value of the eigennumber reflects the amount of reactive power of the mode. As will be shown in Section 3.3, negativeness of the eigennumber is closely related to the problem of stored energy, since the electric energy of these modes is identical to zero (no charge is present), yielding a theoretically negative value for magnetic energy [18, 19]. Exactly the same problem was reported for an example of the dominant TE spherical mode in [20•]. It is important to stress that the inductive characteristic mode cannot, as is widely accepted, be excited alone.

3.1.3 Numerical Issues of the CM

A complete solution of GEP performed by generalized Schur decompostion is extremely time-consuming ($\propto \mathcal{O}(N^3)$, N is the number of unknowns). A further problem is that finer discretization leads to a bigger basis, which contains a lot of high-order (non-radiating) modes which are ill-posed. Both of these modes affect the decomposition [21•]. These problems can be significantly cut short by utilizing the implicitly restarted Arnoldi method [22]. Unfortunately, this method finds only the first few modes, and is therefore not suitable for subsequent modal superposition. No effective preconditioning of the CM decomposition that is valid for the whole basis is known at the present time.

Characteristic modes and numbers are theoretically continuous with respect to frequency. Unfortunately, due to the numerical solution (only a finite number of modes is found at each frequency [23]), both the modes and the numbers are disordered. This means that the resultant characteristic basis should be sorted (tracked) throughout the spectrum. Only simple correlation techniques have been used until now [4], and the sorting algorithm has therefore been significantly improved [21•], making the tracking procedure reliable and robust. Problems with tracking led to the development of the Adaptive Frequency Solver (AFS), which automatically determines what frequency points are calculated in the next iteration [24•].

CM can be calculated only for structures that radiate well at a given frequency. The consequences of violation of this condition are shown in Fig. 3 and Fig. 5 of [20•]. Numerical data is missing around the resonant frequencies of the internal (cavity) modes [25], and even the new tracking routine with AFS fails in these circumstances.

3.1.4 Practical Utilization of CM

Before implementing CM decomposition, it is first necessary to program the MoM. The software that has been developed is inspired by the Makarov code [26], which utilizes the RWG basis functions [27], and currents flowing in a vacuum are considered. Unfortunately, the Galerkin method [28] is affected by asymmetric evaluation of the source and observation regions, since a 9-point barycentric subdivision and centre point integration are used [26]. The points therefore do not coincide, which guarantees that no singularity occurs even for an evaluation of a self-term (all distances between the centre point of a triangle and the centres of 9 small triangles are nonzero). Some features (e.g. PEC mirroring [8]) are present, and the code is properly vectorized in Matlab [29]. The MoM code was verified against FEKO, and the input impedance of a thin-wire dipole is compared in [30•]. The agreement is almost excellent for electrically small and medium size structures ($ka < 10$), but it starts to vary for higher frequencies.

The in-house MeshGen mesh generator written by Jan Eichler can be used to discretize the structure properly [31•]. It is based on the distmesh package [32], which utilizes Delaunay triangulation [33]. All the antenna primitives are meshed subsequently. For further information, e.g. on the role of discretization in CM decomposition, see [31•]. Alternatively, the mesh can be imported from commercial softwares, e.g. Comsol Multiphysics [34] or FEKO.

The TCMapp CM analyser was developed during the author's Ph.D. studies [24•]. To date, the generalized Schur decomposition and the implicitly restarted Arnoldi method are available in TCMapp for impedance matrix factorization. After CM decomposition, a tracking procedure has to be performed. Several tracking methods are available, including the simple correlation method and the adaptive method described above [21•]. The slight asymmetry of the impedance matrix causes serious problems for CM decomposition (the standard symmetrization does not take quantifiable effect). Many pre-processing and post-processing routines are included in the TCMapp package, e.g. the mesh quality analyser, the near-field and far-field calculation, the evaluation of the radiation efficiency and the Q factor, and associated graphical plotting, see [35•] and also [24•]. TCMapp software was extensively used, e.g. for investigating the patch behaviour above the infinite ground plane, L-probe feeding and the design of a circularly polarized patch antenna [36•]. All studies in [17•] were also performed in TCMapp.

3.2 Superposition of Modal Quantities

Instead of simulating the entire antenna system (geometry, materials and feeding), only the PEC motive with no excitation is subjected to CM decomposition. The effect of different feeding scenarios and metallizations can be considered afterwards, during the post-processing step.

This approach is extremely fast, since the full-wave simulation runs only once. The feeding network can then easily be optimized. Thus these methods answer not only the common question "What is the overall value ...", but – more importantly – the question "What might be the overall value ...". Two novel methods are presented below, one for calculating the modal efficiencies, and the other for calculating the modal Q factors.

3.2.1 Modal Radiation Efficiency

If the electrical dimensions are small and a complex geometry is used, the radiation efficiency can be significantly decreased by closely situated out-of-phase currents of high amplitude [9]. This is often due to one specific mode. A proper understanding of modal radiation efficiency therefore makes it possible to optimize the feeding network and, for example, to eliminate a problematic (low-efficiency) mode.

A very simple method [37•] that precluded modal superposition was replaced by an advanced method, which is described in [38•] and [39•]. The key assumption here is that the current density distribution is almost the same for surface currents flowing on a PEC body and for volumetric currents flowing in a lossy body. Only simple model of the skin-effect [25] was utilized, thus the metallization is assumed to be thick enough to suppress the current wave (in practice, this assumption is usually fulfilled).

The approximative method was successfully tested against FEKO (only overall efficiency could be tested, since FEKO does not contain a calculation of modal radiation efficiency). The worst error was less than 1% for good conductors (copper, aluminium) and for standard metallization thickness (10-50 μm).

Since no modification of CM is needed, and since the feeding can be considered in post-processing, the definition of radiation efficiency can be generalized so that the modal efficiencies can be calculated, see [39•] for an exact derivation. The superposition is performed thanks to the so-called beta coupling matrix which concentrates all effects of feeding (various positions, amplitudes and phases). It is interesting that mutual lost powers between different modes occur, and potentially take negative values (the overall lost power is always positive).

3.2.2 Modal Quality Factor

While Harrington's definition of characteristic modal Q [40] is widely known, it is based solely on the behaviour of the associated eigenvalue. It is also known that this definition is correct only near to the natural resonances. A new definition of the modal radiation Q factor was therefore established, utilizing orthogonal and superposition relations of the characteristic modes and expressions derived in [41]. An exact definition, implementation and verification on examples is presented in [42•]. There is also a demonstration of how to obtain lower Q of a given meander dipole by synthesizing the feeding network via the heuristic PSO algorithm [43]. Another example is presented in [44•].

From the practical point of view, the expressions contains a singularity which has to be carefully treated [45], and care must be taken to include a sufficient number of modes since even poorly excited modes may store a considerable amount of energy. As in the case of modal efficiency, the mutual energies are nonzero, and this implies that the CM equivalent network should be extended towards the mutual capacitance and inductance between all resonant RLC blocks.

3.3 Q factor and Stored Electromagnetic Energy

A recent breakthrough in the investigation of stored energy [41] has stimulated new research in this area. The expressions analytically derived in [41] were tested in [46•] on the example of two closely spaced dipoles, see [47•]. It was noticed [48•] that the whole derivation, as presented in [41], can be significantly simplified by an *ad hoc* assumption and by utilizing the dynamic potentials [49]. Thus, all resulting terms are finite, and no extraction technique is needed [46•].

However, it was observed [18] that under certain conditions, e.g. for an electrically long cylinder with dominant TM mode, the stored energy [41] can be negative. Further research will investigate whether the definition is incorrect or the currents are practically unfeasible[1] [19]. Another interesting but as yet unsolved question is whether these energies are invariant under the Lorenz gauge (similarly to the case of Carpenter's relations [50–52]).

3.3.1 Stored Energy in a Non-Stationary Electromagnetic Field

To resolve problems with the definition of stored energy, a new scheme for calculating it is proposed in [53•], yielding the true values for stored energy (at least for the tested structures). By definition, only positive values occur. The method is developed in the time domain, in which the circuit under study is brought to the steady state by a power supply which is switched off after one period. Two simulation runs are in principle necessary in a time domain simulator (e.g. in CST-MWS), and two runs are then needed during a post-processing step in which the currents recorded in the simulator are evaluated. In the first post-processing run, the transient current is used. Then, in the second run, the current is frozen right after the power supply is switched off. The difference between these two runs can extract the radiated energy. For a detailed description and discussion, see [53•]. The universality of this approach reopens the question about the energy stored in dispersive media [54].

3.3.2 Source Concept of the Q_Z Factor

The impedance Q factor, denoted as Q_Z, is based on the assumption that a small antenna can be modelled by a single resonant circuit [55]. Then Q_Z can be expressed from the frequency derivation of an input impedance near the resonance [55]. Q_Z is easy to evaluate, and is indeed widely used in practice. Interestingly, it has been shown that, thanks to the complex power balance theorem and the potential definition of electromagnetic fields [49], the original circuit

[1]The problem of a static mode on a tall cylinder has been treated analytically in the spectral domain, and the results were numerically compared with the eigennumber of the static mode and with spatial integration of energetic expressions [41]. The results were in perfect agreement. Note that none of these approaches take the real excitation into consideration.

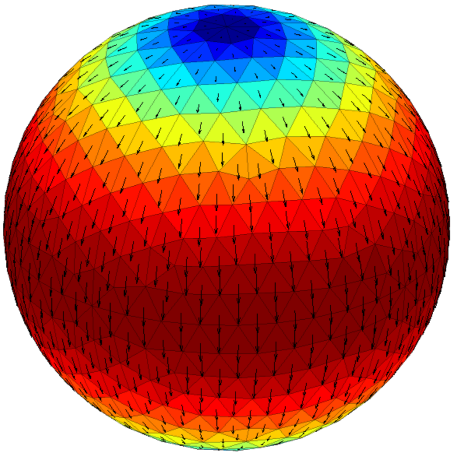

Figure 3.1: Normalized current distribution of the characteristic mode of a sphere PEC shell. The mode has the same shape as the dominant spherical TE mode.

definition of Q_Z can be expressed solely by the currents flowing on an antenna. For a detailed derivation, see [30•] or [56•].

Alternatively, Q_Z can be formulated as a function of several energetic terms, which are discussed in [30•]. Some of them emerge in the definition of the classical Q, compare [41, 57] with [53•]. In other words, classical Q and Q_Z differ, which is explicitly proved in [53•]. The difference is mainly due to the presence (or absence) of explicit derivative terms. This raises the question, whether the quality factor should be defined with or without terms containing the differentiation with respect to the angular frequency.

Since the proportionality between Q (Q_Z) and FBW should be unique, only one of these Q factors can be correct (or none of them). The three different definitions of Q are therefore tested [53•] on two non-trivial RLC circuits, which are analytically worked out by Cauchy's residue theorem and contour integration [58]. Surprisingly, better proportionality of Q_Z to FBW than of Q to FBW is questioned[2].

It is also demonstrated that the Q_Z formulation can be reduced in the vicinity of a resonance to a differentiation of reactance only [59•]. This is in accordance with observations made in [30•].

3.3.3 Fundamental Bounds of the Q_Z Factor

The newly derived source current formulation of Q_Z [30•] allows an analytical solution of Q_Z of any geometry for which the vector wave function is separable [60]. The technique is described in [20•] and [61•] on examples of dominant TM and TE spherical modes, see Fig. 3.1. The whole derivation is analytical, without any approximations. Exactly the same series expansion as for the limits of classical Q in [62] and [63] are found for $ka < 0.5$.

These results are important from both the theoretical and the practical point of view. Since Q_Z is often used in practice for estimating FBW, it is important to know its fundamental lower bounds (which, as has been shown, are in accordance with the lower bounds of Q).

[2]It can be proven on an example of a non-trivial RLC circuit that Q and Q_Z differ, and only Q_Z is proportional to FBW. This observation is yet to be published.

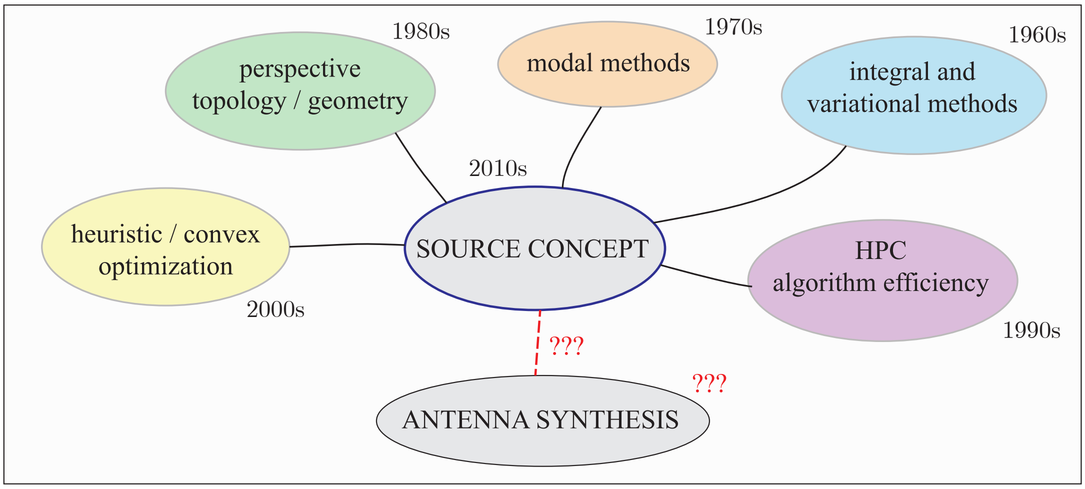

Figure 3.2: The source concept as a summary of a wide range of fields of mathematics, physics and engineering, which have to be properly combined. As depicted, it would also necessarily involve novel advanced techniques such as convex optimization of high performance computing.

3.4 Small Antenna Design

3.4.1 Source Concept Optimization, Utilization of Modal Methods

The expression "source concept" is used throughout this thesis. It labels a contemporary approach to antenna design, which exclusively utilizes source currents as an input or an output for subsequent numerical methods. A wide range of approaches need to be properly combined in order to establish the source concept, see Fig. 3.2. Some undisputed advantages of this approach have already been mentioned, or are clearly explained in the appended publications.

Optimization routines are an important step towards automatized design. For this purpose, the PSOptimizer PSO algorithm [43] was implemented in Matlab, see [64•]. The possible input is not restricted to a particular problem (i.e. any m-file containing a reasonable fitness function can be optimized), and the absorbing, reflecting and invisible boundary condition [65] are included. An invisible wall is greatly preferred since it saves computation time. The PSOptimizer was particularly tested in [66•].

The SOMA algorithm was coded in [67∗], using a set of novel walls. A new updating strategy was proposed, and was successfully tested on examples of some highly degenerate functions.

Note that the practical usage of any optimization routine is strictly limited by the No-free-lunch theorem [68, 69]. Mainly for this reason, some efficient hybrids were developed. A combination of the Nelder-Mead simplex method [70] and PSO was designed in [71∗]. The good global exploring property of a particle swarm is combined with the fast convergence of a simplex method. Formally, the motion equation of the PSO was extended by one additional term, which describes the behaviour of the simplex. Thus, three empirical parameters have to be properly set up before optimization starts.

All the algorithms mentioned above are single-objective optimizations [72]. This means, that the fitness function has to be aggregated into a function of only one scalar variable [72]. However, the complete Pareto-optimal front is often needed. Multi-objective optimization (MOO) was employed for this purpose. MOO is based on a hybrid of PSO [73, 74] and SOMA [75]. Elitism is utilized together with an external archive [76], which is adaptively maintained.

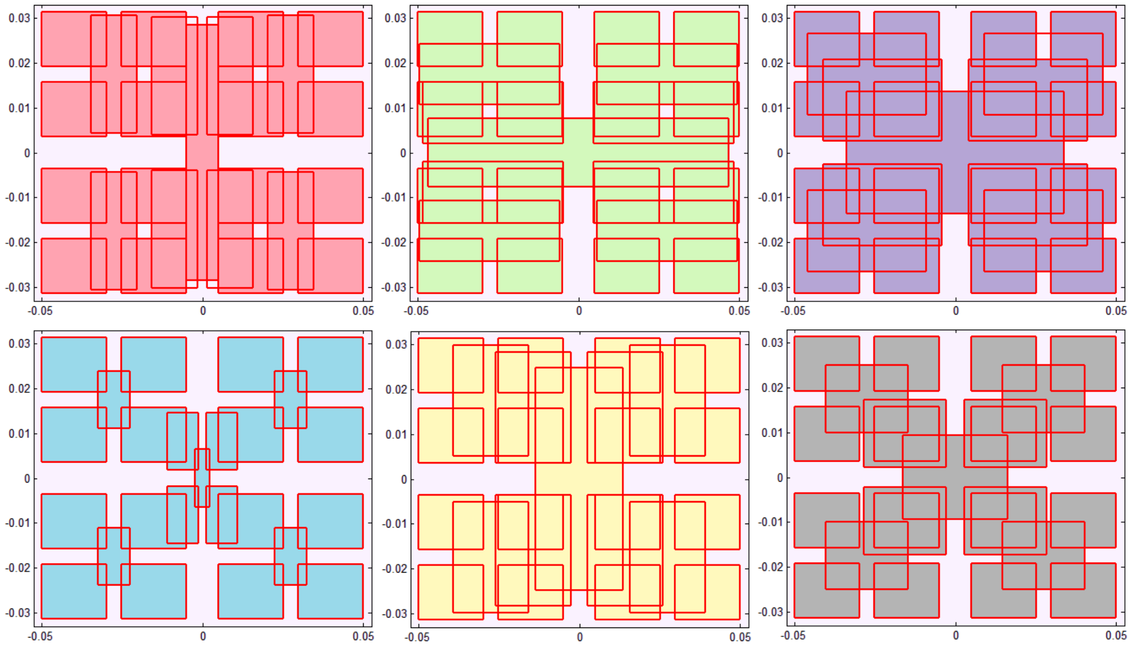

Figure 3.3: Six different particle swarm optimization agents generated by iterated function system radiators. These shapes are candidates for electrically small antenna. The geometry is created in the IFSMaker generator, properly meshed in the MeshGen and then evaluated in the TCMapp characteristic mode analyser. The radiation Q factor and the resonant frequency are then calculated. All steps are performed via in-house tools inside an optimization loop. The full-wave calculation and the post-processing are accelerated on CPU(s) and GPU(s), respectively.

The MOO algorithm is currently being tested on an example of an array of dipoles.

A complete framework consisting of a cavity model in Comsol Multiphysis, the IFS generator and the PSOptimizer is presented in [35•]. Its applicability for antenna design is documented on a example of fractal antenna, which was optimized and then fabricated [35•]. Another example can be found in [67∗], in which the in-house SOMA was used together with CM analysis to find an optimal shape of for a small antenna.

3.4.2 Influence of the Fractal Geometry on Radiation Properties

Dealing with modern small antennas, one quickly note that any geometry with a highly perturbed shape can exhibit resonances at low frequencies with respect to its size [77]. As a special case, fractal geometry [78] was utilized.

It order to study fractal structures, the IFSMaker IFS generator was implemented [79•]. The only inputs are: an initial set of points, generating transformations and required iterations. Fractal patch antennas were then studied in [17•] and [36•] via CM decomposition. The effects of fractal iteration, type of mode and height above the ground plane were investigated. Modal resonant properties of microstrip antennas are studied in [80•]. Note that optimization of the IFS does not produce random segment antennas, which have been criticized. They have still the prescribed topology, and only the geometry is optimized, see Fig. 3.3.

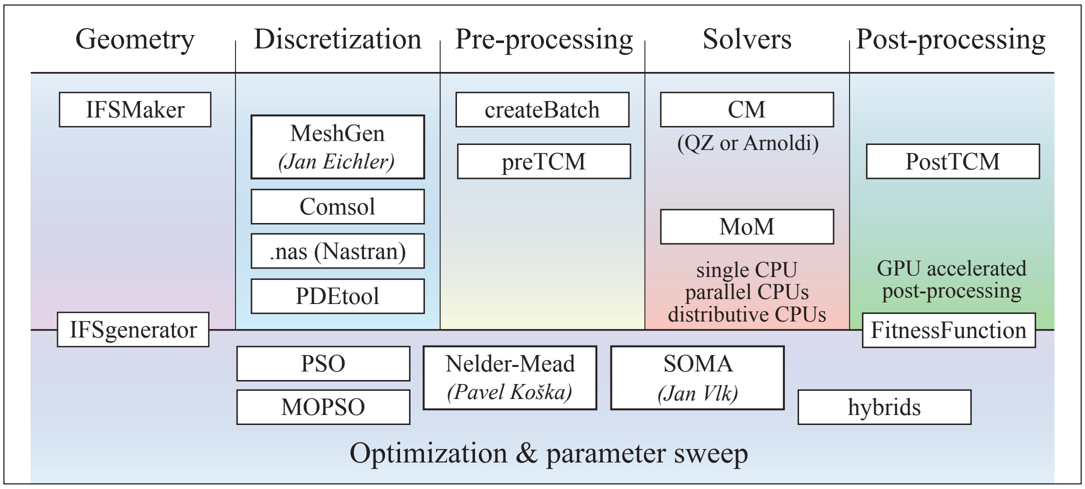

Figure 3.4: Tools already implemented that constitute the AtoM toolbox. Each box represents one functionality. All tools can be used together or separately.

3.4.3 Acceleration Using High Performance Computing

Modal methods like generalized Schur decomposition are typically extremely time-consuming, and a great amount of memory and disk space is required. This is the ultimate price to be paid for the deeper physical insight provided by modal methods. Two ways can be used to reduce the computational effort. The first leads to alternative algorithms (usually iterative algorithms like the Arnoldi method [11]), while the second utilizes High Performance Computing. HPC usually means a simultaneous calculation on more than one CPU thread, more processors, more computers in a cluster, or even – especially in the last decade – calculation on GPU cards [81].

To accelerate the code in Matlab, Parallel Computing Toolbox (PCT, [82]), Distributive Computing Server (DCS, [83]) and the Jacket package [84] were used. PCT allows the use 8 or less cores simultaneously in parallel mode on a single machine[3]. The distributive Computing Server allows the use of significantly more threads (from tens to thousands). However, one has to start the scheduler (the simplest scheduler is the job manager), then prepare a job that contains individual tasks (e.g. decomposition for the selected frequency sample). The network latency should also be considered. The Jacket package enables GPU computing in high-level Matlab code.

Typically, it is better to accelerate complex tasks (matrix inversion, factorization) on CPU, while small atomized tasks are more suitable for GPU acceleration (e.g. massive numerical integrations performed during post-processing). The use of these packages is described in [85•], where the basic theory of HPC and benchmarking are also presented.

Together with other original Matlab functionality described in Sections 3.1-3.4, this completes the AtoM software (Antenna toolbox for Matlab), see Fig. 3.4 and Appendix A.2.

3.4.4 Practical Antenna Design, Manufacturing and Measuring

Finally, the ultimate benchmark for any physical theory must be to confront the predicted results with reality. This is especially true for theories postulated and the tools developed in this thesis.

[3]The limit has been improved to 12 cores from Matlab 2013a.

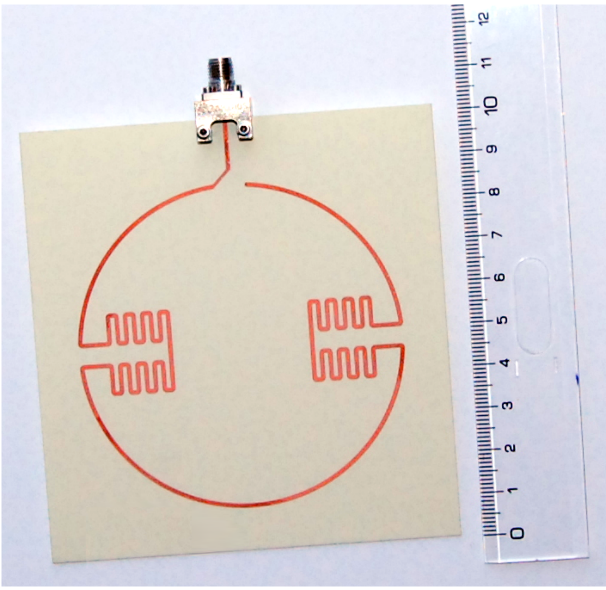

Figure 3.5: A manufactured sample of a dual-band antenna. The original full-wavelength loop was miniaturized using CM analysis and optimization techniques. The simulated values of Q_Z are 14.77 (first band) and 21.48 (second band), the measured values are 15.48 and 24.42, respectively. The antenna operates at $ka = 0.7$ (first band).

The in-house simulations were systematically compared with modern full-wave simulators, e.g. CST-MWS [86], IE3D [87], FEKO [88] and Comsol Multiphysis [34], which are based on various numerical methods, e.g. MoM, FDTD, the Finite Integration Technique (FIT), and the Finite Element Method (FEM), see [28,89,90] for an extensive survey. This diversity minimizes all potential errors and makes it possible to choose the best simulator for a given purpose.

In addition, several antenna candidates were fabricated. A patch antenna with circular polarization [91] is presented in [36•]. The dimensions of the antenna were found by modal analysis.

A dual-band antenna with a fractal motif was simulated both in the AtoM toolbox and in the CST-MWS commercial package [92•]. The fabricated antenna was measured in an anechoic chamber, see [92•] or [93•] for VSWR and radiation patterns.

Other potentialities of CM decomposition are presented in [94•]. The two-element array structure is designed for polarization diversity in UMTS mobile phones.

Finally, a full wavelength loop minimized by modal analysis of U-notches was manufactured and measured [67∗], see Fig. 3.5.

Chapter 4

Conclusion

4.1 What Has Already Been Done

This thesis dealt with an analysis and a synthesis of small antennas, and draw links between each topic and papers that have been published (or submitted). All objectives scheduled at the beginning of Section 3 have been solved, using various techniques involving analytical, algebraic and numerical mathematics, physics and computational methods.

The most important contributions of the thesis are:

- novel tracking method for CM analysis has been introduced,
- the adaptive frequency solver for CM decomposition has been developed,
- the "residual mode" has been explain and compensated,
- the dominant CM has been approximated by an analytic function, and size reduction has been achieved by modal optimization,
- the modal radiation efficiencies and their superposition formula have been derived,
- the modal radiation Q factors and their superposition formula have been derived,
- the source current definition of Q_Z has been derived,
- Q_Z of the dominant spherical TM and TE modes has been determined,
- stored electromagnetic energy has been evaluated in the time domain,
- PSO, SOMA and the Nelder-Mead simplex optimization methods have been implemented, and have been generalized towards a hybrid method with new boundary conditions, and the MOO PSO-SOMA framework with an adaptive external archive,
- a versatile IFS generator (IFSMaker), a CM analyzer (TCMapp) and relating post-processing have been developed, AtoM software have been completed,
- high performance computing in Matlab has been utilized,
- several small antennas of various geometries have been manufactured and measured.

It is essential not only to point out here what has already done, but also to indicate what can be done in the future. This plot is provided in two steps – near-term and long-term goals.

4.2 What Should be Done in the Near Future

Since it has been shown that the characteristic mode can be replaced by an approximative but analytical function, some basic structures may be investigated in details. For example, a loop miniaturized by two U-notches can be closely studied without the need to employ a time-consuming full-wave method. To date, very little is known about characteristic mode decomposition in the time domain, which may bring new applications. Implementing periodic boundary condition into characteristic modes would help with the design of frequency selective surfaces. Since spherical modes are known analytically, it may be useful to calculate a multipole expansion of characteristic radiation patterns into spherical modes. Attention should be paid to the utilization of multi-objective optimization for analysing modal quantities.

Although some progress has been made, the true shape of the dominant characteristic mode on a dipole is still not known. The related mathematics is extremely involved, making this task a true challenge.

The AtoM software needs further improvements. Utilization of Pearson's correlation may perfect the tracking procedure. The method of moments code has to be extended so that dielectrics can be involved. High-order basis functions and the utilization of a magnetic field integral equation together with electric field integral equation may significantly improve the accuracy. An analytical evaluation of potential integrals should be considered to avoid a non-symmetric impedance matrix. Convex optimization needs to be incorporated into the AtoM software, e.g. by using a third-party package. The concept of polarizability promises to solve many problems of small antenna design, and it should therefore be integrated into the source concept. This has only been partially done up to now thanks to the quasi-static calculation of polarizability, which is based on currents obtained from the method of moments.

Structural decomposition, already used in mechanical engineering, has somehow relation to modal methods. It assumes that the radiating structure can be separated into several parts which are connected through the matrix of coupling coefficients. Under certain conditions, these separated parts and their parameters can be evaluated independently. Note that the source concept offers a general principle that can be used in relatively distant fields of electrodynamics, e.g. for seeking new split ring resonator geometries.

The issue of negative energy need to be rigorously handled. The question of the invariance of the Vandenbosch expressions need to be addressed, in order to confirm whether they are correct. The novel technique presented here for calculating the stored energy should be simplified (both formally and numerically) and transformed to the spectral domain.

It is important to resolve what Q is directly proportional to FBW. A single formulation should be used consistently, and various definitions of Q should be unified. The relationship between the modal Q factors and the lower available Q should be closely investigated, and the hypothesis that the lower available Q is an infimum of modal Q factors needs to be proven or refuted.

Implementation of the source definition of the Q_Z factor into the convex optimization may prevent difficulties with the potentially negative stored energy value. The source definition of Q_Z should be generalized for dispersive media. This will significantly simplify the present investigation of high-dispersive structures. It may also be of interest to determine the fundamental lower bounds of the Q_Z factor for an ellipsoid or for any other separable geometry. In comparison with the bounds for a sphere, these limits can be more predicative for common antennas such as dipole.

The true role of the Foster theorem for radiating structures should finally be explained.

4.3 A Long-term Vision

A complete synthesis is nearly impossible, but it is possible to make partially synthesis, with some simplifications. Hypothetically, the source concept, which combines modal and structural decomposition, optimization and other novel methods, e.g. polarizability may solve the problem of synthesis without any restrictions. This may be true at least for certain structures.

Another tedious problem is that antenna characteristics change significantly in the presence of a complex environment. This causes principal difficulties e.g. for analysing on-body wearable antennas or artificial materials. A major issue is how to evaluate the stored electromagnetic energy in this case. This is an as yet unsolved problem in physics. A recently-developed method could be a promising candidate for the evaluation scheme.

Finally, little is analytically known about source current distributions, especially in the case of fractal structures. Today, the wave equation cannot be solved analytically (and, of course, also not numerically) for any fractal structure. Collocation fractal electrodynamics is sometimes used, and it is argued that electromagnetism as a whole should be generalized to noninteger integro-differential calculus. However, only the future will decide whether fractals can be treated effectively in electrodynamics. This ambitious goal is more mathematical than physical. It is therefore necessary to stay prepared for new findings that can be utilized to promote developments in fractal antenna design.

All in all, it is clear that the book of electrically small antennas is still wide open ...

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Summary

This thesis aims to an analysis and a synthesis of electrically small antennas, a focal point in antenna design in recent years due to their massive use in present-day wireless devices. The practical design of electrically small antennas is however encumbered by the intricate and as yet not fully understood trade-off between basic parameters such as a bandwidth, efficiency, directivity, and antenna size. The evaluation of these parameters and the relationships between them is studied in this thesis, including their fundamental limits.

In order to understand the underlying physical mechanism of radiation, an advanced modal decomposition, the so-called theory of characteristic modes is used. Its key property is that just a few modes are usually sufficient to make a good characterization of the behaviour of an electrically small antenna. This thesis resolves some important issues of characteristic decomposition, i.e. direct superposition of the antenna parameters in their modal form, and also an eigennumber sorting, for which a new robust and reliable algorithm has been proposed.

The modal radiation Q factors are derived in this thesis, using a novel superposition formula, orthogonal relations for radiated power and a definition of stored electromagnetic energy in the time-harmonic domain. The modal radiation efficiencies are derived for cases of a strong skin effect in an antenna conductor. This progress facilitates synthesis of the feeding networks.

Nowadays widely exploited Q factor, based on differentiation of the input impedance, is reformulated in this thesis as a function of currents only. Thanks to this new formulation, practical fundamental lower bounds for spherical modes are established. The interrelations between existing definitions of Q are discussed. A new scheme for evaluating the stored electromagnetic energy in the time domain is introduced, and is tested on some canonical circuits.

This thesis also presents a study of fractal antennas. Their specific features are described, including reduction of the resonant frequency and its dependence on fractal iteration, higher radiation losses, multi- but narrow-band behaviour, and ground plane effects.

An original full-wave simulator is implemented, so that all design steps from specification of the geometry to extensive post-processing are presented, including robust heuristic optimization and acceleration of the computation.

The methods proposed in this thesis are finally verified on selected antenna candidates, which are simulated both in an in-house tool and in commercial softwares, and are then fabricated and measured to verify the proposed methods.

Resumé

Cílem disertační práce je systematická analýza a syntéza elektricky malých antén, jež jsou nedílnou součástí všech moderních bezdrátových zařízení. Praktický návrh je zatížen zejména doposud ne zcela známou vzájemnou závislostí všech klíčových parametrů těchto velice specifických zářičů, jimiž jsou zejména pracovní šířka pásma, vyzařovací účinnost, směrovost a jejich elektrická velikost. Právě vzájemné vztahy mezi těmito parametry a hledání jejich principiálních limitů je úkolem této práce.

Za účelem lepšího pochopení samotných fyzikálních principů vyzařování elektromagnetických vln je využita teorie charakteristických modů. Její velkou výhodou je skutečnost, že pro popis elektricky malé antény stačí zpravidla pouze několik málo modů. V této práci jsou vyřešeny některé dlouho přetrvávající problémy základního výzkumu související s modální dekompozicí, například přímý součet vybraných anténních parametrů na základě modálních veličin. Je vyřešen problém tzv. rozdílového modu a navržena nová a robustní metoda třídění vlastních čísel a modů.

Modální činitel jakosti Q je nově odvozen s využitím součtových a ortogonálních relací pro vyzářený výkon a uloženou energii. Ztráty vyzařováním jsou formulovány na základě tepelných ztrát v kovu konečné vodivosti generovaných jednotlivými charakteristickými mody. Tyto formulace umožňují jednoduchou syntézu napájení.

Široce užívaný činitel jakosti Q, charakterizovaný frekvenční změnou vstupní impedance, byl odvozen jako funkce zdrojových proudů. Tato formulace umožňuje nalézt důležité limity Q a nalezne využití v rámci numerických metod jako je konvexní optimalizace. Dále je detailně prozkoumán vztah mezi jednotlivými definicemi Q. Je popsán a prakticky ověřen nový způsob výpočtu energie uložené v blízkém okolí antény.

Práce se rovněž věnuje problematice fraktálních antén. Jsou diskutována jejich specifika, jako je snížení resonanční frekvence vlivem nepravidelností geometrie, menší účinnost nebo vícepásmové a potenciálně širokopásmové chování fraktálních antén.

V rámci práce byl vytvořen nový výpočetní nástroj, který představuje ucelený systém pro návrh antén. Program zahrnuje tvorbu geometrie, tvorbu diskretizační sítě, dekompozici do charakteristických modů, následné zpracování dat a řadu optimalizačních nástrojů.

Metody a teoretické závěry prezentované v této práci jsou ověřeny výpočty v komerčních simulátorech a výrobou vybraných typů antén.