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Yuriy M. Penkin · Victor A. Katrich
Mikhail V. Nesterenko · Sergey L. Berdnik
Victor M. Dakhov

Electromagnetic Fields Excited in Volumes with Spherical Boundaries

Springer

Yuriy M. Penkin
Department of Pharmacoinformatics
National University of Pharmacy
Kharkiv, Ukraine

Victor A. Katrich
V.N. Karazin Kharkiv National University
Kharkiv, Ukraine

Mikhail V. Nesterenko
V.N. Karazin Kharkiv National University
Kharkiv, Ukraine

Sergey L. Berdnik
V.N. Karazin Kharkiv National University
Kharkiv, Ukraine

Victor M. Dakhov
V.N. Karazin Kharkiv National University
Kharkiv, Ukraine

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Theory is when we know everything but nothing works. Praxis is when everything works but we do not know why. We always end up by combining theory with praxis: nothing works and we do not know why.

Albert Einstein

Preface

Development of communication, radar, radio navigation, and radio telemetry systems as well as new approaches in biology, medicine, ecology, and other fields raises new problems for radiophysics. One of the main problems includes excitations of electromagnetic fields in various spatial regions and improvement of mathematical modeling, allowing reduction of temporal and material costs of developing new elements, devices, and systems. Especially, this applies to devices and systems located on mobile objects with complex shape made of new materials, since their experimental development is extremely laborious, time-consuming, and expensive process.

A mathematical modeling of electromagnetic fields in an arbitrary electrodynamic volume is based on problem solution related to a wave excitation in this volume. Therefore, solutions of these problems for any electrodynamic volume are of scientific interest, since they help to construct physically correct mathematical models. Analytic solutions, which can be obtained for volumes with coordinate boundaries by either the eigenfunction or the Green's function method, are known to be the most universal. Since Green's functions can be interpreted as fields excited by a point source at an observation point, they are very effective for solutions of excitation problems and are widely used in mathematical modeling. These methods allow us to derive compact expressions in closed form for wave fields excited by extraneous or induced currents. It is also important that the Green's functions can be used to investigate some general properties of fields in source regions for any sources. The Green's functions can also be applied to derive integral equations for problems related to scattering of electromagnetic waves by inhomogeneities located in the electrodynamic volumes.

The Green's functions for vector potentials and electromagnetic fields are usually used, and their usage has one significant difference. The Green's functions for vector potentials are characterized by integrable singularities in the source region, while the Green's functions for fields are non-integrable. In the latter case, the theory of generalized functions should be involved for regularization of the Green's functions, which considerably complicates the problem solution. Therefore, the Green's tensors for vector potentials are more applicable for numerical simulations.

The tensor Green's functions of Helmholtz equations for vector Hertz potentials both for closed and open domains, whose boundaries are combinations of coordinate surfaces in generalized cylindrical coordinates, were earlier described in the literature. Generally, it was usually assumed that the internal filling of the regions was homogeneous and isotropic, and the boundary surfaces were perfectly conductive. Explicit expressions of the Green's functions for regions with spherical boundaries and spherical regions with inhomogeneous layered dielectric filling, whose boundary surfaces are completely or partially characterized by a distributed impedance, were obtained by the authors of this work.

Due to the huge number of publications devoted to theoretical and experimental studies of electromagnetic fields in spherical volumes, we cannot present here a full overview. The main publication will be analyzed in the following chapters, which contain references with detailed bibliographies. The large number of publications testifies to the great interest of microwave device developers to such studies. Solution of boundary value problems for spherical spatial domains can be applied to the development of various devices. They include shielded and open dielectric resonators used as oscillatory systems of microwave generators and quantum discriminators, integrated circuits of microwave and EHF wavebands, isolated antenna elements in various material media of spherical forms such as homogeneous dielectric spheres or hollow spherical dielectric shells of finite thickness, etc.

Particular attention should be paid to a concept associated with application of spherical surface antennas, which, in general, are systems that combine radiators with the object's body. As known, the object body strongly effects on electrodynamic parameters of low-directional antennas installed near or on the object surface. This influence is determined, first of all, by the object shape and dimensions. External characteristics of such antennas can be evaluated by solving the problems of electromagnetic wave diffraction at complex scatterers, represented by real objects. The solution of these problems in such formulation can meet significant mathematical difficulties, since the object dimensions are often comparable with an operating wavelength, and, consequently, the known asymptotic methods are not applicable for the problem solutions. To overcome these difficulties, the object body or its part, on which the antenna is located, can be replaced by approximating body of regular geometric shape for which rigorous problem solutions are possible. A sphere and a hemispherical projection over an infinite plane, along with others, are often used as such geometric shapes. In a number of cases, finite conductivities of object materials should be taken into account. Electromagnetic fields in arbitrary points of spatial regions and radiation characteristics of the exciting element cannot be studied without effective mathematical models without restrictions on their parameters.

The authors will consider construction of Green's functions for the Hertz potentials in electrodynamic volumes with spherical boundaries, including those with inhomogeneous radial filling. The possible application of the obtained results will be analyzed in the most clear and compact form.

Chapter 1 is of overview character, where basic equations of electrodynamics and boundary conditions for electromagnetic fields are discussed. This allows us to set out the problems in a compact form. The uniqueness theorem and the reciprocity principle for volumes with impedance boundaries are also considered. Excitation problems for regions whose boundaries coincide with coordinate lines in orthogonal curvilinear coordinate systems are solved using the tensor Green's functions of the vector Helmholtz equation for Hertz potentials. General properties of the Green's functions for vector potentials and Green's functions for electromagnetic fields and relationships between them are specified. The components of the tensor Green's functions for vector potentials are a built by the method proposed in Methods Of Theoretical Physics by Philip M. Morse and Herman Feshbach. The components of the Green's functions are presented as series expansions in three types of Hansen vector wave functions: one longitudinal and two transverse. The representations for the Green's functions for spherical coordinates are universal since they depend on the radial coordinates in an implicit form. The explicit dependences are defined as solution the inhomogeneous differential equations with the boundary conditions for these functions based on the boundary value problem geometry specified in a radial direction. The expressions of the integral equations in the system of spherical coordinates in terms of the constructed Green's functions are also analyzed.

Excitation problems of electromagnetic fields in resonators with spherical boundaries are considered in Chap. 2. First, the boundary conditions for the electric and magnetic functions depending on the radial coordinate are define more exactly for three configurations, namely, (1) for spherical perfectly conducting surfaces and arbitrary orientation of sources; (2) for spherical impedance surfaces and sources radially oriented or located on the surfaces; and (3) for the spherical boundary between concentric dielectric layers and radially oriented sources.

Then, self-consistent boundary conditions on the impedance spherical surface are formulated. These conditions are based on the physical effect stating that electromagnetic waves excited in the resonator by radial external currents and reflected from the boundaries conserve their structure, i.e., a mutual transformation of electric and magnetic waves is absent. The field structures are also conserved if the concentric dielectric layers are excited by the radial currents. Relations between magnetic and electric currents on impedance surfaces are determined using Schukin–Leontovich impedance boundary conditions for electromagnetic fields.

The functions of radial coordinates are determined as solution of inhomogeneous Bessel differential equation obtained by the method of variation of arbitrary constants in regions with sources and as solution of homogeneous Bessel equations for layered structures. Field boundedness in the resonator center and radiation conditions at infinity are used, where necessary. Thus, the components of the electric and magnetic Green's tensors are defined for various configurations of spherical regions and excitation sources.

Application of the impedance approach for solving the problem concerning internal excitation of a dielectric sphere with a lower dielectric permeability as compared with that of external medium is studied, and analytic expressions for equivalent surface impedances are obtained. A procedure for modifying the obtained magnetic Green's functions allowing finding the electromagnetic fields excited by radial magnetic currents in semispherical resonators located above a perfectly conducting screen is substantiated. This procedure is based on the well-known principle of incomplete summation in the expressions for Green's functions, in which terms that do not meet the boundary conditions for fields on the screen surface are excluded.

Chapter 3 is devoted to solving excitation problems of spherical scatterers, which are placed in an isotropic infinite medium. A brief description of commonly used methods of mathematical modeling of spherical surface antenna is given. The functions of the radial coordinates for the electric and magnetic Green's tensors are determined for the space outside a perfectly conducting sphere.

In the same way, the electric and magnetic Green's functions are obtained for a space outside a spherical scatterer, whose surface is characterized by a distributed isotropic impedance, radial excitation sources, or extraneous currents specified on the impedance sphere. The impedance approach to the problem of external excitation of dielectric spheres by radial currents is investigated, and analytic expressions for equivalent surface impedances are obtained. Electrical and magnetic Green's functions for a space outside a perfectly conducting or impedance sphere covered by a concentric dielectric layer, excited by radially oriented sources, are constructed. A technique allowing extraction terms of the Green's functions that determine electromagnetic fields as superposition of primary excitation fields in the free space and fields scattered by a sphere is presented.

Two modifications of the Green's functions are made. The first modification allows defining fields excited by radial electric and magnetic currents in a half-space over a perfectly conducting flat screen with a hemispherical projection with a perfectly conducting or impedance surface covered by a concentric dielectric layer. The second modification can be used for axially symmetric excitation by annular surface currents on a perfectly conducting or impedance hemispherical projection above a screen.

The formation of radiation fields by dipoles located on surfaces of spherical scatterers is analyzed in Chap. 4. It is significant that solutions obtained in known works concerning the problem are applicable only for calculating radiation patterns for perfectly conducting spherical surfaces. Expressions for electromagnetic fields radiated by a radially oriented electric dipole on a perfectly conducting sphere, impedance sphere, or spherical scatterer coated by concentric dielectric layers are obtained using the Green's functions for the Hertz vector potentials. These expressions can be used to determine the fields both in the near and far wave zones. Modified expressions for determining radiation fields of radial electric dipoles in the half-space over a perfectly conducting infinite screen are obtained when the dipole is placed on a hemispherical projection.

Expressions for the electromagnetic field components radiated by elementary magnetic vibrators on perfectly conducting or impedance spherical surfaces are obtained. Directional characteristics of electromagnetic fields radiated by electric and magnetic dipoles located on a perfectly conducting sphere in the wave zone are investigated for various diffraction radii of the spherical scatterer.

A synthesis of current distribution on arrays of radial electric dipoles arbitrarily placed on a perfectly conducting sphere is solved by using an RMS approximation of complex radiation patterns of spherical surface antennas. A technique for an array synthesis problem which allows to obtain a maximum directivity for the spherical antenna arrays is generalized. A formula for direct determination of the complex current amplitudes in radiators without a numerical solution of linear algebraic equations is obtained using a discrete Fourier transform for circular equidistant arrays of the radial electric dipoles.

Chapter 5 is aimed at obtaining analytical asymptotics for the electric current in the impedance radial vibrator located on the perfectly conducting sphere excited by a point delta voltage generator placed at a finite distance above the spherical scatterer. The solution of original integral equations is constructed by successive iterations using the natural small parameter of the problem based on the well-known Green's function for the space outside the sphere filled with a homogeneous and isotropic medium. The improved zero approximation is obtained in an analytical form valid for both tuned and untuned vibrators and for arbitrary sphere radii. The analytic expression for the monopole at the sphere of the infinitely large diffraction radius excited at its base coincides with the three-term formula for impedance vibrator currents obtained by R. King and T. Wu.

If vibrator currents and the Green's functions for the vector potential are known, the solutions allowing numerical studies of wave-zone fields radiated by the spherical antenna can be obtained. If the dipole radiator is located directly on the sphere, the expression for the spherical antenna radiation pattern coincides, up to the notation, with the well-known formula obtained earlier by L. A. Weinstein. If the radial monopole is excited at the base, its input impedance at the supply point can be defined as ratio of the voltage to current at this point. As known from literature, the zero approximation for the current does not always ensure required accuracy of the input resistance calculation for vibrator radiators. On the other hand, derivation of analytical formulas for subsequent approximations is difficult to realize. Therefore, the input vibrator resistance was found by the generalized method of induced electro-motive forces (EMF), where the functional dependence for the zero current approximation was used as the basis function. In final expressions for the input resistance of the spherical antenna, the vibrator radiation resistance is determined by complete inversion of differential operators.

In Chap. 6, a circular slot cut in an equatorial plane of a sphere with axially symmetric excitation is considered. Analytical expressions for radiation fields of the slotted spherical antenna with perfectly conducting or impedance spheres are obtained using the Green's functions. These expressions can be used to determine electromagnetic fields of the slotted spherical antennas at any distance between the sphere center and observation point.

The problem of electromagnetic wave radiation into space outside the perfectly conducting sphere through the narrow slot of finite length is also solved by the generalized method of induced magneto-motive forces (MMF). The slot is cut in the impedance end wall of the semi-infinite rectangular waveguide or in-line resonator. The concept of equivalent slot width, which allows the problem solution without defining fields in the internal slot cavity, is applied. A single basis function for the slot magnetic current was obtained as analytical solution of the integral equation current by the asymptotic averaging method. The problem is solved by using the corresponding Green's functions in the two different local coordinate systems related to the coupling electrodynamic volumes. The validity of the solution is confirmed by agreement of the simulation results and experimental data.

In Chap. 7, fields radiated by the combined structure, known as the Clavin vibrator-slot radiator, located on the perfectly conducting sphere, are investigated. The mathematical model of the structure with radially oriented impedance monopoles is constructed using the tensor Green's functions for the space outside the perfectly conducting sphere. The model is based on the solution of the external electrodynamic problem in the rigorous formulation by the generalized method of induced electro-magneto-motive forces (EMMF). Directivity characteristics of the spherical antenna were studied for various vibrator lengths and distances between the vibrators. It is shown that directivities and energy characteristics of the spherical antennas can be varied within wide limits by changing the electric length of the vibrators, the distances between them, and/or the surface reactive impedances of the vibrators. It is shown that optimal characteristics of the Clavin-type radiators with inductive impedance vibrators can be realized with shorter vibrator lengths as compared with perfectly conducting vibrators.

The radiation fields of multielement antenna arrays consisting of radial and arc monopoles located on spherical scatterers are also investigated in this chapter. A simulation of antenna radiation fields in far zone is carried out using expressions obtained for monopoles arbitrary distributed on a spherical surface. Spherical antennas with two-vibrator and four-vibrator arrays intended for use in mobile communication systems are considered. Zonal coverage by the antenna radiation field of the entire surrounding space using different powering modes for two pairs of oppositely located resonant monopoles on a sphere with a quarter-wavelength radius can be achieved.

Appendix A contains expressions for differential operators and Helmholtz equations in orthogonal curvilinear coordinate systems including specific cases of rectangular, cylindrical, and spherical coordinate systems. In Appendix B, a step-by-step procedure for constructing the Green's tensors in spherical coordinate systems is presented. Appendix C provides formulas for determining the surface impedance for various models of practical implementation of thin impedance vibrators. Appendix D is of a reference nature and contains the explicit formulas for the components of the Green's functions in the electrodynamic volumes which will be used in the book. In Appendix E, a relation between the Hertz vectors and pseudovectors in the spherical coordinate system is analytically justified.

This monograph is intended for graduate students, post-graduate students, engineers, and researchers. It is assumed that the reader knows the vector and tensor analysis, and the general theory of electrodynamics. The results presented in the book can be directly used for the development of various spherical antennas.

The authors consider it their pleasant duty to express their gratitude to Anatoliy M. Naboka for editing the English text.

Kharkiv, Ukraine

Yuriy M. Penkin
Victor A. Katrich
Mikhail V. Nesterenko
Sergey L. Berdnik
Victor M. Dakhov

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