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EDITORIAL

Guest Editorial: Method of analytical regularisation for new frontiers of applied electromagnetics

1 | INTRODUCTION

The recent advances in nano-optics and photonics, the introduction of novel materials, such as graphene, and the interest in the development of wireless communications at millimetre-wave and THz-wave frequencies have led to the development of powerful, full-wave general-purpose electromagnetic solvers. Amongst them, a special place is occupied by the integral equation formulations and associated discretisation techniques. This is due to the radiation condition being automatically satisfied and the unknown functions usually being defined on finite supports. However, the results obtained with commercial software need to be validated ex-post by comparing them with closed form expressions, measurements, or asymptotic solutions because, in general, neither the existence of a solution of an arbitrary integral equation, nor the convergence of an arbitrary discretisation scheme can be established a priori.

An exception is represented by the Fredholm second-kind integral equation, for which the convergence of a discretisation scheme, preserving the nature of the integral equation at hand, to the exact solution of the problem, can be stated and the truncation error be controlled. For example, the Magnetic Field Integral Equation is appropriate when dealing with closed, perfectly electrically conducting smooth surfaces and the Muller Boundary Integral Equation is adopted for studying the propagation and scattering problems involving dielectric objects with smooth boundaries.

It should be remembered that a wide class of the wave propagation, radiation and scattering problems, involving open scatterers, objects with wedges, planar surfaces, etc., can be equivalently formulated as singular integral equations, for which the Fredholm theory cannot be applied. This problem can be completely overcome, however, by the use of the Method of Analytical Regularisation (MAR). MAR is a family of methods based on the conversion of the first-kind weakly singular and various strongly singular integral equations to the second-kind integral or matrix equations, for which the Fredholm theory, generalised for operators by Steinberg, is valid. This terminology appeared, apparently for the first time, in the book 'Singular Integral Equations' by Muskhelishvili in 1953 and, sometimes, it is equivalently defined as the semi-inversion method. The basic idea is, in principle, simple but, at the same time, intriguing: individuate a suitable operator containing the most singular part of the integral operator at hand and perform its analytical inversion. Such an operator can be conveniently selected in many ways depending on the problem at hand, for example, as the static part, the high-frequency part, a frequency dependent canonical-shape part of the integral operator itself, and so on. Moreover, functional techniques, such as Titchmarsh, Wiener-Hopf, Cauchy, Abel and Riemann-Hilbert Problem techniques can be applied to obtain the analytical inversion of the static/high-frequency part of the integral operator, while the canonical-shape problems can be solved by means of the separation of variables.

In some problems, the analytical regularisation and the discretisation of the integral equation are performed simultaneously. These methods are appropriately called analytical preconditioning. Indeed, by selecting the eigenfunctions of a suitable singular part of the integral operator, containing the most singular part of the operator itself, as expansion functions, Galerkin projection acts as a perfect preconditioner and the obtained matrix operator is of the Fredholm second kind. More generally, Fredholm theory can be applied if the obtained discretised operator can be written as the sum of an invertible operator, with a double-side continuous inverse operator, and a completely continuous operator. If the convergence is provided, then the accuracy of computations can be easily controlled by the matrix truncation order. In principle, the error can be brought to the machine precision that is unthinkable for the popular commercial codes available today.

Although the convergence of the MAR-based algorithms is guaranteed from the general theory, a practical necessity of the results validation remains. Making such a validation via comparison with commercial codes, as frequently requested by the reviewers in engineering journals, is possible. However, it is impractical because of the mentioned superiority of MAR-based codes in terms of accuracy. Therefore, adequate validation must use the results obtained by some other, however a equally accurate technique. Such techniques are not numerous; in fact, there are only two.

One is the method of separation of variables, which is applicable to simple-shape scatterers such as circular cylinders and spheres, including the layered ones, and ends up with convergent series in terms of the explicitly given functions.

The second is a different, but a fully grounded approach of solving numerically the singular integral equations–the Nystrom-type discretisation. In this case, the convergence of the method does not descend from the Fredholm theorems but is guaranteed by the interpolation-type quadrature formulas used, taking into account both the integral equation singularities and the edge behaviour of the unknowns.

Much effort has been devoted in the last decades to devise suitable strategies 'to put MAR into practice'. Moreover, recently MAR is attracting a growing interest in the electromagnetic community due to the paramount number of applications in novel fields of interest. For all these reasons, we all are firmly convinced of the importance of a Special Issue focussed on both the fundamental issues of the state of art of the novel techniques of analytical regularisation and their modern applications.

2 | ARTICLES′ OVERVIEW

In the following, we introduce the papers published in this Special Issue on MAR.

The paper ***'Trade-off between threshold gain and directionality of emission for modes of two-dimensional eccentric microring lasers analysed using lasing eigenvalue problem'*** by Repina et al. [1] shows an efficient engineering tool for the design and optimisation of promising microring lasers. It is based on the Muller Boundary Integral Equation and the entire-domain Galerkin discretisation method, adapted to the study of on-threshold modes of the open cavities with active regions.

In the paper ***'Magnetic field penetration through a circular aperture in a perfectly conducting plate excited by a coaxial loop'*** by Lovat et al. [2], the first-kind singular integral equation in the Hankel transform domain is analytically regularised by means of the application of the Abel integral-transform technique. Moreover, fast convergence is achieved by expanding the unknown in terms of the orthogonal basis functions reconstructing the edge behaviour of the fields at the aperture rim. The results are directly applicable to certain aspects of electromagnetic compatibility.

The analysis of a dielectric open resonator, frequently met in the millimetre-wave and terahertz antenna, filter and sensor applications, is presented in the paper **'Plane wave scattering from thin dielectric disk in free space: Generalised boundary conditions, regularising Galerkin technique and whispering gallery mode resonances'** by Lucido et al. [3]. The regularisation is carried out by means of the fast-converging Helmholtz-Galerkin technique applied to singular integral equations in the Hankel transform domain obtained by imposing the generalised boundary conditions on the disk median section surface.

The paper ***'Excitation of guided waves of grounded dielectric slab by a THz plane wave scattered from finite number of embedded graphene strips: singular integral equation analysis'*** by Kaliberda et al. [4], is of interest in the area of tuneable guided-wave launchers. Here, the problem, formulated in the spatial domain in terms of a singular integral equation of the Cauchy type for the derivative of the transverse currents on the graphene strips, is discretised by means of the Nystrom-type algorithm.

A subject of relevance to radioscience, near-field optics and nanotechnologies is considered in the paper ***'The rigorous solution of the scattering problem for the finite cone embedded in the dielectric sphere surrounded by the dielectric medium'*** by Kuryliak [5]. Here, a first-kind matrix equation, obtained by means of the mode-matching technique and the orthogonality properties of the Legendre functions, is analytically regularised by a pair of operators consisting of the convolution type operator and the corresponding inverse one expressed in closed form.

The electromagnetic scattering from two different (but of the same-period) all-dielectric rectangular bar gratings on substrates, with applications in the realisation of metasurfaces for the control and manipulation of electromagnetic waves, is the subject of the paper ***'Second-kind Fredholm integral-equation analysis of scattering by layered dielectric gratings'*** by Tsitsas [6]. The analysis is carried out by means of a Fredholm second-kind volume integral equation formulation discretised by applying an entire-domain Galerkin technique.

In the paper ***"Complex WGM frequencies of gyroelectric cylindrical resonators"*** by Katsinos et al. [7], the problem is formulated as an hypersingular volume integral equation and regularised by means of Dini series expansion of the electric field. This enables fine analysis of complex natural frequencies of this open resonator including the removal of the mode degeneration.

In the paper ***'The Carleman regularisation technique in the modelling of the plane E-polarised electromagnetic wave scattering by a flat system of impedance strips'*** by Koshovy et al. [8], the authors perform the analytical regularisation of a first-kind integral equation with a logarithmic kernel by means of the Carleman inversion formula.

In the paper ***'Electromagnetic characterisation of tuneable graphene-strips-on-substrate metasurface over entire THz range: Analytical regularisation and natural-mode resonance interplay'*** by Yevtushenko et al. [9], the fine analysis of the scattering and absorption resonances on the H-polarised substrate modes, graphene-strip plasmon modes and lattice modes is performed by means of a dual-series formulation regularised using the Riemann-Hilbert Problem solution.

The property of graphene tunability is further exploited in the paper ***'Evaluation of the E-polarisation focussing ability in THz range for microsize cylindrical parabolic reflector made of thin dielectric layer sandwiched between graphene'*** by Oğuzer et al. [10]. The boundary value problem is formulated as a set of two coupled singular integral equations, regularised by means of a procedure based on the Riemann-Hilbert Problem solution.

In the paper ***'Radiation characteristics of a double-layer spherical dielectric lens antenna with a conformal PEC disk fed by on-axis dipoles'*** by Tikhenko et al. [11], the dual-series equations obtained by imposing the boundary conditions are transformed to new dual-series equations by means of the Abel integral transform and regularised by inverting the static part of the operator by means of inverse Fourier transform. This enables a fine analysis of the interplay of the geometrical-optics effects and the whispering-gallery mode resonances.

Dirichlet's boundary value problem for the Helmholtz equation in 2D open domain, which hosts arbitrarily shaped zero-thickness PEC scatterers, generates dual integral equations with a weakly singular (logarithmic) kernel. They can be analytically regularised via Abel's integral transform to yield coupled systems of linear algebraic equations with the Fredholm second-kind operators, giving rise to fast-converging algorithms that are successfully applied to the accurate analysis of isolated and coupled PEC open resonators in the papers ***'Scattering of an obliquely incident E-polarised plane wave from ensembles of slotted cylindrical cavities: A rigorous approach'* and *'Complex eigenvalues of natural TM-oscillations in an open resonator formed by two sinusoidally corrugated metallic strips'*** by Vinogradova et al. [12, 13].

An efficient numerical tool for the analysis of the radar cross sections of small to resonant size drones is presented in the paper ***'Integral equation modelling of unmanned aerial vehicle radar scattering characteristics in VHF to S frequency bands'*** by Zalevsky et al. [14]. The problem is formulated in terms of the Fredholm second-kind Magnetic Field Integral Equation and Muller Integral Equation and discretised with the aid of interpolation method.

In the paper ***'The Cauchy method of analytical regularisation in the modelling of plane wave scattering by a flat pre-fractal system of impedance strips'*** **by Koshovy** [15], which can be a useful tool for the modern microwave devices design, a first-kind integral equation with a logarithmic kernel is transformed into an integral equation of the Cauchy type. Moreover, the most singular part of the integral operator is analytically inverted after imposing the prescribed edge behaviour of the surface currents.

The analysis provided in the paper ***'Longitudinal coupling impedance of a particle travelling in PEC rings: A regularised analysis'*** by Assante et al. [16], of relevance in the accelerator and collider physics, is carried out in the Hankel transform domain. The obtained first-kind singular integral equation is discretised by means of the method of analytical preconditioning with expansion functions reconstructing the behaviour of the unknowns at the edges.

In the paper ***'Asymptotic regularisation of the solution to the problem of electromagnetic field scattering from a set of small impedance particles'*** by Andriychuk [17], the regularisation consists in the derivation of the explicit form of the solution by means of an asymptotic approach. Explicit expressions of the effective permeability and refractive index are provided for an artificial medium consisting of a distribution of a large number of electrically small particles of arbitrary shapes, which are characterised by a prescribed surface impedance.

The paper ***'Coupling impedance of a PEC angular strip in a vacuum pipe'*** by Assante et al. [18], presents a general methodology which can be applied in the case of the angular discontinuities in particle accelerators. The evaluation of the longitudinal and transverse coupling impedance of a charge travelling in a drift tube with an angular strip is formulated in terms of the dual series equation solved by means of the method of analytical preconditioning selecting the expansion functions reconstructing the behaviour of the unknown at the edges.

The paper ***'Integral transforms and regularisation method in time domain excitation of open pec slotted cone scatterers'*** by Doroshenko et al. [19], is of interest in the context of wideband and ultra-wideband antennas. The formulation is based on the use of the Mehler-Fock integral transform, and the regularisation is provided by the analytical inversion of the static part of the operator with aid of the Riemann-Hilbert Problem solution.

In the paper ***'Regularised discretisations obtained from first-kind Fredholm operator equations'*** by Fikioris [20], the general conditions under which the discretisation of certain first-kind integral equations lead to matrix equations with the properties of a Fredholm second-kind matrix operator equation are carefully examined.

In the paper ***'A parallel-plate waveguide antenna radiating through a perfectly conducting wedge'*** by Tsalamengas et al. [21], the discretisation of a first-kind singular integral equation is performed in the framework of the Nystrom method, by means of the selection of the fast converging quadrature rules taking into account both the singularities of the kernel and of the fields' behaviour on the wedges.

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