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The Complementary Roles of Analysis, Synthesis, Numerics, and Experiment in Electromagnetics

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Abstract

The electromagnetic enterprise is now over a century old. In the modern world it has expanded in various directions. This paper summarizes electromagnetics under four headings: analysis, synthesis, numerics, and experiment. Each area is important, as are the relations between the areas.

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1. Introduction.

Electromagnetics has come a long way since its nineteenth century beginnings. Most notably with the discovery of the Maxwell equations (1864) and their experimental verification by Heinrich Hertz (1888), things were off and running, leading to today's state of the art. For more historical details the reader can consult [9, 20, 25].

In a recent paper [7] I discussed the role of the electromagnetic theorist and how it fits in the general scientific/engineering enterprise:

> People often think of dividing the basic and applied sides of the technological enterprise as between science and engineering, but this can lead to confusion. I think that there is a better three-par division, which can shed some light on where electromagnetic (EM) theory fits into the structure. First, there is the basic scientific side which has electromagnetics as part of physics, and the fundamental question concerns the replacement of the Maxwell equations by something more accurate, applying to extreme conditions not normally encountered. This is not of what we think as electromagnetic theory in the usual sense. Second, we have what may be called applied science or basic engineering in which we explore the established physical laws (the Maxwell equations in this case) to see what they imply in the sense of discovering what is possible to analyze, synthesize, optimize, etc. This is distinct from the third category which might be termed applied engineering which concerns itself with the routine implementation of what is known from the second category in terms of technological products ("practicing" engineering), for example, by selection of antenna designs from a product catalog. Of course the reader might prefer some other "diagonalization" but this should suffice for the present.

Here we are not considering the first category, but the second and to some degree the third.

Now take the Maxwell equations . . .

$$\begin{aligned} \nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} - \vec{J}_h^{(s)} \\ \nabla \times \vec{H} &= \frac{\partial \vec{D}}{\partial t} + \vec{J} + \vec{J}^{(s)} \end{aligned} \qquad (1.1)$$

as given and see what useful things we can do with them. Note that we have separated out source terms and that material parameters (e. g. the constitutive parameters including boundary conditions) need to be specified.

There are various aspects of the electromagnetics enterprise undertaken by the scientific/engineering community since the fundamentals were first established. In this paper we divide modern electromagnetics into four categories: analysis, synthesis, numerics, and experiment. Each has its place in the overall subject, contributing its own important role.

2. Analysis.

Initial investigations in electromagnetic theory were in a form which we can call analysis. Initially (for good and/or ill) people did not have the modern computers to directly solve the Maxwell equations in time and/or frequency domains. As such, various mathematical techniques were developed to find exact and approximate results for problems concerning antennas, scattering, and propagation. These are summarized in various classic texts, e. g. , [10, 12, 14, 17, 18].

These results were key to the many advances in communications (radio, television), remote sensing (radar), and electric power.

Let us list some of the important analytic concepts and techniques:

1. Fourier/Laplace transforms
   - relating time and frequency domains
   - consequence of linearity and time-invariance of common electromagnetic problems.
2. Separation of variables (spatial coordinates)
   - applies to certain coordinate systems.
3. Analytic properties in complex-frequency plane

3.1. Low-frequency method
   - expansions in powers of s
   - quasistatic leading term (separation into electrostatic and magnetostatic)
   - multipole expansions

3.2 Singularity expansion method (SEM)
   - expansion in terms of poles in the s-plane (plus other singularities in some cases)
   - factorization of poles in terms of natural frequencies, natural modes and coupling coefficients depending on different parameters of the problem
   - damped sinusoids in time domain

3.3 High-frequency method
   - ray optics
   - diffraction (GTD, UTD, etc.)
   - high frequency asymptotics
   - asymptotic evaluation of integrals

4. Conformal transformation of two-dimensional complex coordinates
   - capacitances, inductances of many shapes
   - TEM modes on appropriate structures
   - combination with stereographic transformation for conical structure.
5. Transmission-line theory
   - exact for TEM structures
   - lumped-element transmission lines
   - approximate application to wire antennas and scatterers
   - multiconductor transmission lines (including nonuniform)

6. Integral equations
   - special techniques, e. g. , Wiener-Hopf
   - approximate solution (variational techniques)
   - operator diagonalization (eigenvalues and eigenmodes)
7. Electromagnetic topology
   - dividing electromagnetic systems into smaller pieces such that the solution for the smaller pieces can be recombined to represent the solution of the whole
   - graph theory
   - BLT equation, scattering matrices
   - hybrid analytical/numerical
   - good shielding approximation

In some cases these give the complete solution where at most one needs to evaluate a few special functions. In others one may have a solution in terms of an infinite series which needs to be numerically computed. In yet other cases the solution is only approximate.

Perhaps the greatest benefit of analytic solutions is the understanding they allow one to have concerning how the solution varies as a function of the various parameters of the problem. These include the various physical dimensions, direction of wave propagation, and frequency/time. This in turn allows one to see the possibilities of electromagnetic performance over the range of these variables — the engineering problem and the beginning of electromagnetic synthesis (or design).

3. Synthesis.

3.1 Background

In contrast to analysis which is concerned with solving Maxwell equations for a specific set of conditions (geometry, constitutive parameters, sources), synthesis begins with some desired performance and asks if an electromagnetic device can be designed to meet this performance. Then one may ask if there is more than one possible design, and which of these is optimal in some sense. This is a kind of inverse problem which may not always have a solution, or the solution may be non unique.

By analogy it is instructive to recall circuit analysis. Circuit analysis based on the Kirchoff laws:

voltage law:

The sum of the voltage drops around a loop in the network is zero.

current law:

The sum of the currents entering a node in the network is zero.

The network is a graph consisting of nodes and branches (a kind of topology or structure of connectedness). For a linear network (typically with branches containing inductances, capacitances, resistances, and voltage/current sources) one forms a matrix relating the response (voltages or currents) to the appropriate sources. Inverting this matrix gives the solution for the response.

Circuit synthesis goes beyond analysis to ask what such networks can be made to do, and to give procedures (algorithms) for synthesizing (designing) networks to meet such performances. This involves positive-real functions and matrices for the impedances and admittances of linear, passive, time-invariant networks. This becomes bounded-real functions and matrices for scattering parameters. Based on these one can decide if certain impedance (admittance) functions and transfer functions are realizable, and for the realizable ones the synthesis procedures. A common text is [11] and a collection of the basic papers is found in [13].

Electromagnetic synthesis is then first the determination of what kinds of electromagnetic devices (systems) with what performance parameters are possible (within specified limitations such as linearity, reciprocity, time invariance, etc.). This is followed by the determination of the specific synthesis (design) procedure for realizing the desired performance.

A classic example of such synthesis is the Dolph-Tchebyscheff amplitude distribution for a uniform spaced array of antenna elements [16]. This finds the minimum achievable beam width for a specified sidelobe level. As this example shows an important aspect of synthesis concerns how one asks the synthesis question. Problem formulation is key to obtaining useful results. Another notable antenna success concerns pattern synthesis for reflector antennas [21]. Note for these examples that they have been considered in a single-frequency (narrow-band) context. We also need to consider time-domain properties (large band ratios) of electromagnetic systems.

In order to extend the possibilities of electromagnetic synthesis, we need to extend the conceptual framework in which to pose the question. In electromagnetics we are dealing with distributed (continuous) systems, giving a more complicated problem than a comparatively simple LRC circuit. On the other hand the very complexity of the electromagnetic synthesis problem suggests that there may be many more possibilities. Not only do we have constitutive parameters and their frequency dependences to consider. We also have spatial distributions and shapes (geometry) to synthesize.

An approach to electromagnetic synthesis that has met with some success begins with a search for analytic concepts used in modern mathematics and physics, but not commonly used in electromagnetics. This is discussed in [3, 7] and summarized here.

3.2 Eigenimpedance synthesis.

Let us first consider a synthesis technique which is an extension of circuit synthesis (discussed above) into the more general electromagnetic domain.

This begins with an integral equation of the form

$$\langle \tilde{\overleftrightarrow{Z}}(\vec{r}, \vec{r}'; s); \tilde{\vec{J}}(\vec{r}, s) \rangle = \tilde{\vec{E}}^{(inc)}(\vec{r}, s) \tag{3.1}$$

(with integration over the common coordinate $\vec{r}\,'$). This could be a surface (S) or volume (V) integral equation over the body of interest (the support). Here, for convenience, we take the symmetric impedance (or E-field) kernel, based on the dyadic Green function of free space. As with matrices we can find eigenvalues and eigenvectors via

$$\begin{aligned} \langle \tilde{\overleftrightarrow{Z}}(\vec{r}, \vec{r}'; s); \tilde{\vec{j}}_\beta(\vec{r}', s) \rangle &= \tilde{Z}_\beta(s)\, \tilde{\vec{j}}_\beta(\vec{r}, s) \\ &= \langle \tilde{\vec{j}}_\beta(\vec{r}', s); \tilde{\overleftrightarrow{Z}}(\vec{r}', \vec{r}; s) \rangle \end{aligned} \tag{3.2}$$

$$\tilde{\vec{j}}_\beta(\vec{r}, s) \equiv \textit{eigenmodes}$$

$$\tilde{Z}_\beta(s) \equiv \textit{eigenimpedances (eigenvalues)}$$

$$\langle \tilde{\vec{j}}_{\beta_1}(\vec{r}, s); \tilde{\vec{j}}_{\beta_2}(\vec{r}, s) \rangle = 1_{\beta_1, \beta_2} = \begin{cases} 1 \text{ for } \beta_1 = \beta_2 \\ 0 \text{ for } \beta_1 \neq \beta_2 \end{cases}$$

With this we have the eigenmode expansion method (EEM) as

$$\tilde{\overleftrightarrow{Z}}^{\nu}(\vec{r}, \vec{r}'; s) = \sum_\beta \tilde{Z}_\beta^{\nu}(s)\, \tilde{\vec{j}}_\beta(\vec{r}, s)\, \tilde{\vec{j}}_\beta(\vec{r}', s) \tag{3.3}$$

(ν an arbitrary power)

Note that the eigenvalues are dimensionally impedances (ohms) for a surface type body, and ohm-meters for a volume type body. For a passive, linear, reciprocal scatterer the $\tilde{Z}_\beta(s)$ are positive real functions like the impedance functions considered in circuit synthesis discussed previously.

As discussed in [3] for a surface type body one can add a sheet impedance $\tilde{Z}_l(s)$ everywhere on S. This gives new eigenvalues

$$\tilde{Z}_\beta(s) \rightarrow \tilde{Z}_\beta(s)+\tilde{Z}_\ell(s) \tag{3.4}$$

with no change in the eigenmodes. A similar result holds for volume type bodies [5]. Now knowing the behavior of some $\tilde{Z}_\beta(s)$ we have a circuit synthesis problem for $\tilde{Z}_l(s)$ to obtain the desired new eigenvalue. An application of this notes that the natural frequencies (SEM, Section 2) satisfy

$$\tilde{Z}_\beta\left(s_{\beta,\beta'}\right) = 0 \tag{3.5}$$

So one can change the natural frequencies of a target (important for identification) to other complex frequencies depending on the choice of $\tilde{Z}_l(s)$. An example of this is the thin wire [3] for which the lowest order natural frequency can be moved to the negative real axis of the s plane and even produce a second order pole (critically damped scatterer or antenna).

3.3 Symmetry and group theory.

A branch of mathematics which has found much use in quantum mechanics is group theory, closely associated with symmetry. Group theory also has much application to symmetries in electromagnetics problems (antennas, scattering, propagation) [21]. Symmetries in antennas and scatterers are associated with symmetries in the electromagnetic waves, and can be used to design antennas and scatterers and identify radar targets.

The simple case of a 3 × 3 dyadic representation of a group has

$$\begin{aligned}
G &= \left\{\overleftrightarrow{G}_\ell \mid \ell = 1, 2, \ldots, \ell_0\right\} \\
\ell_0 &= \textit{group order}\left(\textit{finite or infinite}\right) \\
\overleftrightarrow{G}_\ell^{-1} &\in G \ , \ \overleftrightarrow{1} \equiv \textit{identity} \in G \\
\overleftrightarrow{G}_{\ell_1} \cdot \overleftrightarrow{G}_{\ell_2} &\in G \quad \textit{for all ordered pairs}
\end{aligned} \tag{3.6}$$

This form is particularly suitable for the point symmetry groups (rotations and reflections) for which the dyadics are real and orthogonal. Other types of applicable symmetries include space groups (adding translation) and the linear group (dilation symmetry). Note that in addition to the geometrical symmetries inherent in Maxwell equations (reciprocity, duality, relativistic invariance) need to be incorporated in the group structure. This form is particularly suitable for the point symmetry groups (rotations and reflections) for which the dyadics are real and orthogonal. Other types of applicable symmetries include space groups (adding translation) and the linear group (dilation symmetry). Note that in addition to the geometrical symmetries inherent in Maxwell equations (reciprocity, duality, relativistic invariance) need to be incorporated in the group structure.

An early application of symmetries to electromagnetics was the case of special waveguide junctions (magic T, etc.). Some of the recent symmetry results include [7]:

1. placement and orientation of EM sensors on an aircraft to minimize the influence of aircraft scattering on the measurement (reflection symmetry R)
2. high-frequency capacitors (dihedral symmetry D_N)
3. nondepolarizing axial backscatter (two-dimensional rotation symmetry C_N for $N \geq 3$, e. g. an N-bladed propeller)
4. generalized Babinet principle (for dyadic impedance sheets) and self-complementary structures (C_{Nc} symmetry)
5. vampire signature (zero backscatter cross polarization in h, v radar coordinates) for mine identification (continuous two-dimensional rotation/reflection symmetry $O_2 = C_{\infty a}$) [10]
6. separation of magnetic-polarizability dyadic $\tilde{\overleftrightarrow{M}}(s) = \tilde{M}_z(s)\vec{1}_z\,\vec{1}_z + \tilde{M}_t(s)\vec{1}_z$ into distinct longitudinal and transverse parts, for low-frequency magnetic singularity identification (diffusion dominated natural frequencies) of metallic targets (C_N symmetry for $N \geq 3$)
7. categorization of the scattering dyadic for the various point symmetries, including reciprocity and self dual case.

3.4 Differential geometry for transient lens synthesis.

We begin with some as yet unspecified (u_1, u_2, u_3) orthogonal curvilinear coordinate system with

$$h_n^2 = \left[\frac{\partial x}{\partial u_n}\right]^2 + \left[\frac{\partial y}{\partial u_n}\right]^2 + \left[\frac{\partial z}{\partial u_n}\right]^2$$

$$\left(scale\ factors\ n = 1, 2, 3\right) \tag{3.7}$$

$$[d\ell]^2 = \sum_{n=1}^{3} h_n^2 \left[d u_n\right]^2 = [dx]^2 + [dy]^2 + [dz]^2$$

$$\left(line\ element\right)$$

The electromagnetic field and constitutive parameters are described as real (indicating they can be measured) when expressed in the usual way in Cartesian coordinates. The formal fields and constitutive parameters are primed and denote these parameters expressed in the (u_1, u_2, u_3) system and thought of as though this were a Cartesian system.

The formal and real fields are related by

$$\vec{E}' = (\alpha_{n,m}) \cdot \vec{E} \quad , \quad \vec{H}' = (\alpha_{n,m}) \cdot \vec{H}$$

$$\vec{D}' = (\beta_{n,m}) \cdot \vec{D} \quad , \quad \vec{B}' = (\beta_{n,m}) \cdot \vec{B}$$

$$(\alpha_{n,m}) = (1_{n,m}\, h_n) = \begin{bmatrix} h_1 & 0 & 0 \\ 0 & h_2 & 0 \\ 0 & 0 & h_3 \end{bmatrix}$$

$$(\beta_{n,m}) = \left(1_{n,m} \frac{h_1 h_2 h_3}{h_n}\right) = \begin{bmatrix} h_2 h_3 & 0 & 0 \\ 0 & h_3 h_1 & 0 \\ 0 & 0 & h_1 h_2 \end{bmatrix} \tag{3.8}$$

For the constitutive parameters we have for the special case of diagonal dyadics (in the u_n system)

$$\vec{\vec{\varepsilon}}' = (\gamma_{n,m}) \cdot \vec{\vec{\varepsilon}} \quad , \quad \vec{\vec{\mu}}' = (\gamma_{n,m}) \cdot \vec{\vec{\mu}}$$

$$(\gamma_{n,m}) = (\beta_{n,m}) \cdot (\alpha_{n,m})^{-1} = \begin{bmatrix} \frac{h_2 h_3}{h_1} & 0 & 0 \\ 0 & \frac{h_3 h_1}{h_2} & 0 \\ 0 & 0 & \frac{h_1 h_2}{h_3} \end{bmatrix} \tag{3.9}$$

The synthesis procedure is to:

1. postulate waves (e.g. TEM wave propagating in the u_3 direction) with simple (e.g. uniform) $\vec{\varepsilon}'$ and $\vec{\mu}'$
2. place some constraint on $\vec{\varepsilon}$ and $\vec{\mu}$ (e.g. non uniform but isotropic)
3. ask what coordinate systems (u_n) are able to satisfy the resulting constraint on the h_n
4. use solution to 3 to form the basis of a lens, the solution for the wave being given by the transformation equation.

With postulated frequency-independent constitutive parameters such lenses are dispersionless and are called transient lenses. For TEM waves guided by perfect conductors (as on TEM transmission lines) the conductors follow the curved coordinate lines through the lens.

Various results have been achieved [7, 19]:

1. all six components of $\vec{E}$ and $\vec{H}$ non zero for inhomogeneous but isotropic ε , ε', μ and μ' (only two possible coordinate systems)
2. TEM waves propagating in the u_3 direction, for inhomogeneous but isotropic ε , ε', μ and μ' (coordinate systems constrained by constant u_3 surfaces being planes or spheres, examples including converging, diverging, and bending lenses)
3. two-dimensional lenses for TEM waves (only one component each of $\vec{E}'$ and $\vec{H}'$ nonzero) based on conformal transformations (resulting in only one of ε and μ being inhomogeneous, but both isotropic)
4. lenses with $\mu = \mu_0$ but ε anisotropic and inhomogeneous
5. TEM waves propagating in the ϕ direction in a cylindrical (Ψ, ϕ, z) coordinate system (bending lens) with very general transmission-line cross sections (e.g. bent circular coax) with only ε variation $(\mu = \mu_0)$.

3.5 Electromagnetic topology for electromagnetic system design.

In Section 2 (item 7) electromagnetic topology was considered as an analytic way of dividing a system into smaller parts in a way that the solution for the pieces can be recombined to form a mathematical description of the whole (BLT equation). However, the original conception was to have a way of quantitatively controlling electromagnetic interference, i. e a method of system design [4].

In this design procedure one considers a set of closed surfaces called shields or subshields. (There can be a hierarchy of these). The object is to control all electromagnetic signals passing through such surfaces. By the electromagnetic uniqueness theorem controlling tangential $\vec{E}$ (or $\vec{H}$) on such a surface controls the fields inside (for sources outside). Unwanted signals are stopped at such shields. The realization of such surfaces may include metal sheets, screens, etc. The important parts of the surfaces are the penetrations (apertures, conductors passing through), every one of which must be quantitatively described for purposes of control.

An important concept for such control is *norms* These reduce the associated matrices (including convolution in time domain) to simple scalars which can be used to *bound* the penetrating signals. Not only linear protection devices (such as filters), but other types of simple nonlinear devices can also be included in the formalism.

4. Numerics.

This is not a discussion of how EM numerics are done, but rather where this part of electromagnetics fits into the larger picture.

4.1 Complement to analysis.

One aspect of EM numerics is as a complement to analysis. This has the potential of extending the knowledge of basic electromagnetics processes by definitive calculations of canonical problems, particularly those beyond full analytic treatment. Of even greater significance is the use of a hybrid analytical/numerical treatment. By this is meant that analysis is used to partly solve the problem, including the division of the problem into analytical and numerical parts. For example, the electromagnetic response can be viewed as an analytic function of the complex frequency (in various parts of the complex s-plane). One can use this fact to reduce the number of frequencies used in the computation, the response at other frequencies being implied by analytic continuation. This dovetails with item 3 in Section 2. Note, however, that this type of computation is still limited to structures of not-too-great complexity so that one can trust the accuracy of the numerical part of the solution. By this procedure one can extend the library of canonical solutions of antennas, scatterers, and other electromagnetic structures.

Various other examples of hybrid analytical/numerical solutions are also available. In the case of reflector impulse-radiating antennas (IRAs) [24] the impulsive part of the radiation has been reduced from a surface integral to a contour integral around the aperture. Stereographic transformation reduces the conical feed assembly to an equivalent cylindrical one, making the problem one of conformal transformation in two dimensions. While this has an analytic (closed form) solution for many interesting cases, more complicated feed geometries can be approached by a numerical computation of the potential function from an appropriate integral equation [2]. The low-frequency behavior of reflector IRAs depends on the electric and magnetic dipole moments. Not being analytically calculable the electric-dipole moment has been successfully treated in [1].

4.2 Role in synthesis.

Synthesis (Section 3) defines the optimization conditions and develops realization algorithms. Sometimes there are steps which require numerical computation as part of the problem. See, e. g. , Section 3.2 . Eigenimpedances of the unloaded scatterer are needed to begin the synthesis. These may require numerical computation. The role of EM numerics is then a hybrid one, similar to Section 4.1, in which numerical techniques play an essential role.

4.3 Substitute for experiment in not-too-complicated geometries.

One can think of an experiment as an *analog* computation or *physical* simulation, particularly if some electromagnetic scaling (scale model) is involved. Within the state of the art of numerical techniques, one can think of a numerical computation as a *digital* computation or *mathematical* simulation. One can think of such problems as semisimple: beyond analysis but within numerical capability. The scope of such problems will increase along with the numerical state of the art.

At this point we can also mention the role of numerics in teaching electromagnetics. It would seem that most students of the subject are headed for industry where they are expected to use general numerical EM computer codes to address problems like design of realistic antennas with various real-world compromises included. So professors need to teach this (and write papers on it).

For semisimple problems numerical computation will likely replace much experiment, being even more accurate than experiment in some cases.

4.4 Role in response of large complex systems.

For large, complex systems experiment is essential and both analysis and numerics play but a supporting role. For example, the maze of wiring and conductors in a modern aircraft, communication center, etc. is so large that even describing it is difficult, much less computing its electromagnetic response (especially at high frequencies). These large problems are too complex to reliably calculate. Even if one could accurately calculate the response of such a system, the answer would still normally be incorrect because the system one calculates differs from the actual piece of hardware, the response of which one desires, in important ways. Wires are not always where they are supposed to be, additional wires have been added, seals have corroded, etc.

This is not to say that numerics has no role in modeling the response of such systems. Such computations can be used as an adjunct to EM experiments (system-level tests) to compare to the experimental results and discover what parts of the system are not being adequately modeled. This also gives insight into the important system features controlling important aspects of the system response, and aids in modifying (hardening) the system so as to reduce or remove undesirable responses.

For complex systems electromagnetic topology (Section 2, item 7) can play an important role in such computations. An important example of such a computer code is CRIPTE [23] which has made the largest system computations to date with some success. This and/or similar computer programs need to be further refined and expanded.

5. Experiment.

5.1 Simple structures.

As discussed in comparison with numerics (Section 4) measurements of the EM properties of simple structures is becoming replaced by numerical techniques (for cases that analysis is not sufficiently capable). Even the metal-shear school of antenna design is being replaced by the iterative-number-crunching school of antenna design. Experiment does, however, have some pedagogical benefits and as a demonstration to nonexperts in EM in the case of simple structures.

5.2 Electromagnetic sensors.

In experiments various electromagnetic sensors (special antennas) are needed to measure electric and magnetic fields as well as voltages and currents. Much analysis and synthesis has gone into the design of such sensors [6, 15]. Numerical techniques can be applied here as well. The point is that EM experiments are strongly impacted by other aspect of electromagnetics (Section 2-4).

5.3 Measurement of electromagnetic properties of materials and scatterers.

One measures the constitutive parameters of materials by special kinds of experiments in which the measured voltage, current, etc. are used to infer these parameters. More generally remote sensing techniques (including radar) are used to locate various objects, characterize them, and even identify targets from their scattering properties. Fundamental to this are analytic concepts relating the scattering to the EM properties of a target (inverse scattering in the general case).

Target recognition (identification) is, of course, an experimental discipline. However, this has a strong dependence on analysis. One has some model of the scattering in which certain parameters are used for the discrimination. For example SEM (Section 3.2) uses the aspect-independent natural frequencies as target identifiers [8]. The scattering data needs to be processed, an inherently numerical procedure (hybrid analytical/numerical technique, Section 4.1), so as to be able to use these parameters. Various data-processing algorithms have been developed in this context [8].

5.4 Demonstration of performance of products.

Another common occasion of experiment concerns the final performance characteristics of an EM system, particularly a commercial one. For example, a radar system will be tested for its capability for detecting targets at various ranges. Note that in such tests not only are EM parameters measured but other such mechanical parameters as well. An EM system has to operate in various environments.

5.5 Measurement of response of large, complex systems.

As previously commented, the calculation of the response of large complex electronic systems to arbitrary incident electromagnetic environment is a daunting task. Here we are not concerned with the designed rsponse to some communication or radar signal, but rather the more general out-of-band "back door" response (see Section 4.4).

The response of large complex electronic systems is primarily an experimental problem. It is, however, a difficult problem. How does one go about testing a system to the variety of waveforms and frequencies of interest, including full amplitudes, variation of polarization and angle of incidence, and system configuration as its intended operational environment? One can see that an adequate experiment to determine that a system will successfully operate in some environment (including appropriate variation of the parameters describing the environment) is itself a difficult task.

The primary reason for doing a full system test is that it is in some sense self diagnosing. The fact that we do not have a completely accurate description of the system is mitigated by having a real one in front of us. Of course, we still need to have it in its operational configuration, including especially, all electrical connections.

Even so, real tests are limited and one must deal with various factors (discussed in more detail in a previous paper [6 (Section VI)]:

1. What does it mean for a system to survive a given environment?
2. How does one know that a system will survive a given environment?
3. Complete system test.
4. Extrapolation.
5. Influence of system design (topology) on ease of testing: penetration tests.
6. Low-level testing.
7. Characterization of failure-port response parameters.
8. Probabilistic estimates.

While analytical/numerical techniques cannot hope to make high-confidence predictions for the entire system before the test, they can help guide the experiment. Surprises can point to system features that were unknown or were assumed insignificant before the test. Making the model agree with the data (postdiction) sheds insight into what are important signal paths, and what one may need to do to reduce certain signals to acceptable levels. Theory with experiment in this case is better than either alone.

6. Concluding remarks.

Electromagnetics has expanded into a large intellectual edifice with many practical applications since the beginning of the electromagnetics age in the nineteenth century. Here we have summarized the subjects under four main headings: analysis, synthesis, numerics, and experiments. Each area is important on its own, but the mutual support between each of these and the others is also important.

It would be interesting to know how the subject will advance in the next century. I expect the advancing speed of computers will allow considerably larger computation to be performed. I hope that at least some individuals will come up with whole new fundamental ideas in the analysis and synthesis areas.

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