A History of Applied Planar Electromagnetic Analysis

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***Abstract* — Numerical electromagnetics has been applied to main stream high frequency design for over two decades. This paper describes some of the events of those years from the point of view of one who has observed and participated in the entire process.**

***Index Terms* — Electromagnetic analysis, history, Maxwell equations, microstrip, moment methods.**

I. Introduction

The field of electromagnetics began when James Clerk Maxwell [1], Fig. 1, put the known electric and magnetic phenomenon into mathematical form and speculatively added the critical "displacement current" term that meant a changing electric field generates a magnetic field [2]. He then made an absolutely astounding observation [3], [4]:

"The velocity of transverse undulations in our hypothetical medium, calculated from the electro-magnetic experiments…agrees so exactly with the velocity of light calculated from the optical experiments…that we can scarcely avoid the inference that *light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena*." [Italics are original.]

The velocity Maxwell calculated was 193,088 miles per second, the velocity observed was 195,647 miles per second. Very close indeed. Note that somehow the experimental error in both values was about the same magnitude and in the same direction. This is likely due to human nature and is a common situation in experimental work. Today, the speed of light is defined as exactly 2.99792458×10^{8} m/s or 186,282.4 miles per second.

Although now widely viewed as the greatest physicist of the 19th century, Maxwell was modest about his achievements. One unfortunate side effect of his modesty is that it was not until several decades after his death that much attention was given to his "theory of electro-magnetism".

Once the significance of Maxwell's equations was recognized, they were applied to the solution of a large variety of problems. However, most problems involved structures whose boundaries fall on constant coordinate surfaces. The coordinate system might be rectangular, cylindrical, or spherical, etc., but arbitrary structures with arbitrary surfaces were not easily approached.

World War II initiated serious development of electronic computers [5] causing considerable excitement among a few far-sighted researchers. In electromagnetics, Roger

Fig. 1. James Clerk Maxwell founded the field of electromagnetics. This statue was recently installed in Edinburgh, Scotland.

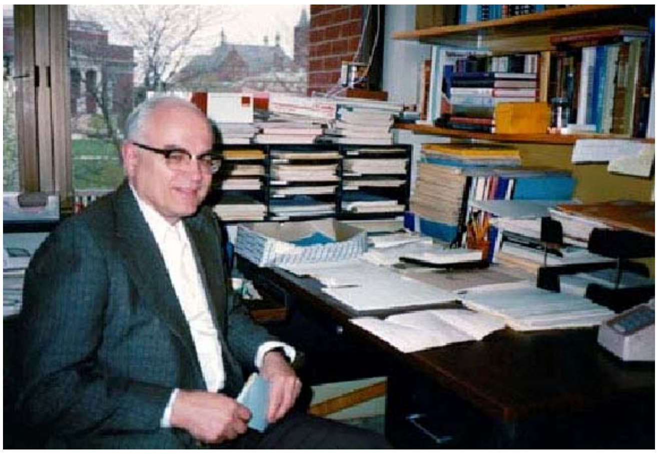

Fig. 2. Prof. Roger Harrington in his office at Syracuse University, 1985.

Harrington, Fig. 2, is one of those researchers, and is today considered the father of the Method of Moments [6]. However, as with Maxwell, his work was not immediately accepted. Prof. Harrington once related to me the comments of a reviewer of one of his first papers; it went something like this, "Your work is useless because it has been proven that it is impossible for a computer to invert even a 100 × 100 matrix because the magnetic tape will wear out going back and forth."

When I started working as a graduate student under Prof. Harrington, the IBM-PC had just been introduced. In my office at Syracuse University was just such a PC, and it had the optional floating point co-processor (8088/8087). In 1984, I hand coded a matrix solve in assembly language and was able to invert a 100 × 100 real matrix in one hour. Prof. Harrington was most pleased, and I was able to complete my dissertation [7], [8].

Acceptance by working microwave designers was slow. In my first presentation on what would become Sonnet, at a June 1986 conference at Blue Mountain Lake organized by Harrington and Sarkar, I was bluntly told by a prominent microwave designer that this was all useless academic ivory tower stuff of no practical use. But sometime around 1989, that same designer made of point of telling me that, because of my work, he had completely changed his mind. At least for me, it is at that moment that the field of *applied* high frequency numerical electromagnetics began, 21 years ago.

This paper is a modified and updated version of [9], with permission.

II. The Method of Moments

The Method of Moments is a general technique of converting a set of linear integro-differential equations into an approximating set of simultaneous algebraic equations suitable for solution on a computer. The method is not limited to planar electromagnetics, or even to electromagnetics. In the field of electromagnetics, special cases of the Method of Moments include Galerkin's Method, Method of Weighted Residuals, Point Matching, and the Rayleigh-Ritz Variational Method.

As applied to frequency domain analysis of planar circuits, a non-mathematical description of the Method of Moments is:

"First we divide a circuit into small subsections. Then we take one subsection at a time and calculate the electric field generated everywhere by the current on that one subsection. We do this for each subsection in turn. Then we place current on all subsections simultaneously and adjust those currents so that the total tangential electric field goes to zero everywhere that there is conductor, because you cannot have voltage across a conductor. The currents that give zero voltage across all conductors form the current distribution. Once we have the current distribution, the S-parameters follow immediately."

There was considerable research in method of moments in the 1980's. Commercialized examples include NEC (Numerical Electromagnetics Code) and (related in name only) MiniNEC, both for analysis of wire antennas. LINMIC, written by Rolf Jansen, included a planar Method of Moments analysis. In fact, it was this work which I used for GaAs MMIC (monolithic microwave integrated circuit) design that inspired my interest in electromagnetics in the early 1980's.

The first planar Method of Moments tool to see widespread promotion was EMSim, developed by Y. L. Chow and distributed by EEsof from 1989 to 1993. My own efforts resulted in Sonnet, which started wide distribution later in 1989. This was quickly followed by HP (now Agilent) HFSS (High Frequency Structure Simulator), a volume meshing finite element code developed by Ansoft. Intended for arbitrary structures, it was also promoted for planar circuits. The final entry in the early days was Compact Explorer, whose distribution was terminated shortly after Ansoft acquired Compact.

A common misunderstanding during this period was that a volume meshing code would be appropriate for planar circuits and would actually be faster than specialized planar codes for large circuits. A more common view today is that no single EM tool can solve all problems; an informed designer must select the appropriate tool for the appropriate problem. Typically, planar tools are both faster and more accurate for planar problems.

III. Present Day Tools

All of today's commercial planar tools can be divided into two groups, shielded and unshielded. Shielded environment tools analyze planar circuits in an enclosing rectangular box. Tools include Sonnet and AWR EMSight. Unshielded environment tools have dielectric substrates going to infinity in all horizontal directions. Tools include Agilent Momentum, Zeland IE3D (now Mentor), and AWR Axiem. Both approaches involve trade-offs. The informed designer selects the appropriate tool for the problem at hand. For "high cost of failure" situations, the skilled designer compares answers from multiple tools.

As described above, Method of Moments requires the precise calculation of voltage induced in one subsection due to current flowing in another subsection. This calculation must be repeated many times, for every possible pair of subsections. The difference between the two techniques is based on how this calculation is done.

Shielded EM analysis uses an exact calculation that is easily implemented using an FFT (Fast Fourier Transform). Because it is so fast, there is no need to pre-calculate, store, and then interpolate results. This yields fast, robust analysis that can achieve the highest accuracy possible even in the most extreme situations, like extremely thin or thick dielectric, many dielectric layers, extreme dimensions, extreme frequencies, large highly resonant structures, etc.

The disadvantage for shielded EM analysis is just like the disadvantage of using digitized audio for music. To be digitized, the audio must be uniformly time sampled. For shielded EM analysis, the circuit layout is snapped to a fine underlying FFT mesh. A mesh 1000 cells on a side, which gives a cell size about equal to the pixel size of an HDTV screen, is very easy and fast. However, it is still a snapped layout.

The unshielded tools calculate the coupling between subsections using a technique that does not require circuits to be snapped to an underlying uniform grid. You can analyze whatever dimensions your circuit actually is. In addition, over the last few years these approaches have seen significant speed enhancements making fast full EM analysis of very large circuits a reality.

Of course, nothing is free. The speed and flexibility come at a price. The informed designer understands the trade-offs and selects the appropriate tools. For example, unshielded EM tools typically pre-calculate look-up tables for the coupling between subsections. The tables are interpolated as needed when performing a Method of Moments analysis. Once the tables are pre-calculated, a shielded Method of Moments is just as fast as unshielded for a given number of subsections.

However, the numbers that come out of the unshielded look-up table are not as accurate as numbers that come out of the shielded FFT approach. This can cause problems in extreme situations. For example, if extremely high accuracy is desired, then large numbers of very tiny subsections must be used. This is difficult for unshielded EM analysis.

On the other hand, when high accuracy is not so important, the unshielded EM analysis can use a few large, arbitrary subsections to analyze a large arbitrary circuit quickly. This speed advantage for so-called "good enough" results is taken even further with the speed-enhanced versions of the unshielded tools. However, keep in mind that speed-enhanced tools have additional approximations for the subsection coupling. Also one must be aware that analysis time is proportional to the number of ports. The biggest advantage for speed-enhanced tools is when there are only a few ports.

Thus, as we mentioned above, multiple EM tools are important for a proper EM based design.

IV. The Early Days of Sonnet

Sonnet started in 1983 as a hobby. I wrote antenna analysis software for the amateur radio market. I started in my home using an Apple][+ computer, Fig. 3, from [10]. I sold some 250 copies in the US and Europe, and my good friend [11] sold a similar number of copies in Japan. The key experience gained in this effort was in seeing firsthand how much effort is required to commercialize highly technical engineering software (see the next section).

At this time, I was also pursuing a Ph. D. under Roger Harrington at Syracuse University, as mentioned above. At that time, our maximum problem size was 100 subsections. That required a 100 × 100 matrix, which took one hour to invert on a 4.77 MHz computer. That is a very very tiny problem. What about future improvement? We would be able to invert a 200 × 200 matrix if computer speeds got up to around 40 MHz. 40 MHz? Crazy! Must be dreaming. That


Fig. 3. Sonnet started in 1983 with amateur radio antenna analysis software on the Apple][+ computer.

could never happen. What did happen next, I describe in [10]:

"Even with the limited problem size, I decided, perhaps foolishly, to pursue commercialization. That would not happen at E-lab [where I was employed], so I accepted a two year visiting professor position at Syracuse University. I also negotiated funding for two years from HP. I then set out to find a tenure track position and a company for commercialization.

"I made serious attempts for a faculty position at both Syracuse and Cornell. Both attempts failed. Prof. Dalman (who had taught me microwaves) was my champion at Cornell. I was most grateful when I last met Prof. Dalman several years ago, he profusely apologized for Cornell not having hired me. He seemed to think if they had hired me, Cornell would still have a strong position in microwaves. Would have been nice to at least have tried.

"I achieved total failure on the second goal as well. Just before Christmas 1987, HP told me they were no longer interested in funding my work. I approached several other companies. Likewise, no interest. So, I either had to drop the issue and get on with life, or do it myself."

It was a major effort to commercialize, but I did meet with success. It is, in fact, an ongoing effort. Let me illustrate with a recent commercialization of a new interpolation technique used in Sonnet, described in the next two sections.

IV. Commercializing Software

I started commercializing software nearly 30 years ago. Now, I would rate the total effort devoted to the underlying theory at about 10%, getting the tool ready for market at about 30%, and marketing and sales at about 60%. I now occasionally receive proposals from researchers to market software that they have developed, sometimes with a comment like, "It's 90% complete, only 10% left to do!" to which I might reply, "I think you have the right numbers, they are just in the wrong order."

The biggest obstacle to commercialization is failing to realize the full magnitude of the task. Getting funding is an important, but clearly secondary issue. After overcoming these first two problems one must put in place a rigorous software development and testing capability. Without development structure, deadlines will never be met and resulting product will be inappropriate for customer needs. Documentation will not be in sync with the product, in addition to delaying introduction. The sales force will be telling customers that the release will be out next month, for 12 to 24 months in a row. Without extensive and automated testing exercised throughout the development process, tools full of bugs will be placed in the customer's hands, destroying a company's reputation and leaving an over-worked support staff unable to respond in a timely manner.

In addition to development and testing, there are business issues like hiring employees, setting up payroll and benefits, dealing with all the government paperwork. And then there is marketing and sales for the final 60% of the total effort. Commercialization is a difficult and time-consuming task.

V. Commercialization Example

No matter what EM analysis you use, a full EM analysis at a given frequency takes time. If you need to analyze 1000 frequencies, it takes 1000 times longer. This is where interpolation becomes useful. Analyze just a few frequencies and interpolate all the rest. A flash of inspiration hit me in December 2000 on a return trip from Japan. I thought of a way to significantly reduce the number of EM analysis frequencies required, and simultaneously substantially increase interpolation accuracy. I was able to execute a simple proof-of-concept right on the airplane. I then did prototype software on Microsoft Excel over the next six months or so.

An initial regression test (a sequence of analyses all automatically performed with results compared to known correct answers) involved 36 circuits. Alternative algorithm implementations were run through the regression test with the best overall approach selected for use. It is important to use a large number of circuits for regression testing. This is because comparing algorithms based on results from just one or two circuits "tunes" the algorithm just for those circuits. The tuned algorithm might then work poorly for a general range of circuits.

About one year was then spent defining the user interface, implementing the algorithm into our core software, testing on about 1,500 circuits and at several beta sites, and documenting the interpolation. In every single one of the 1,500 circuits, the algorithm converges to give results visually identical to an overlaid plot of a complete analysis for all S-parameters above –100 dB, and occasionally down as far as –160 dB.

The software started shipping in August 2002, just over a year and half after the initial flash of inspiration. Fig. 4 shows the result. EM analysis at only four frequencies is needed to exactly interpolate the entire six resonator filter response.

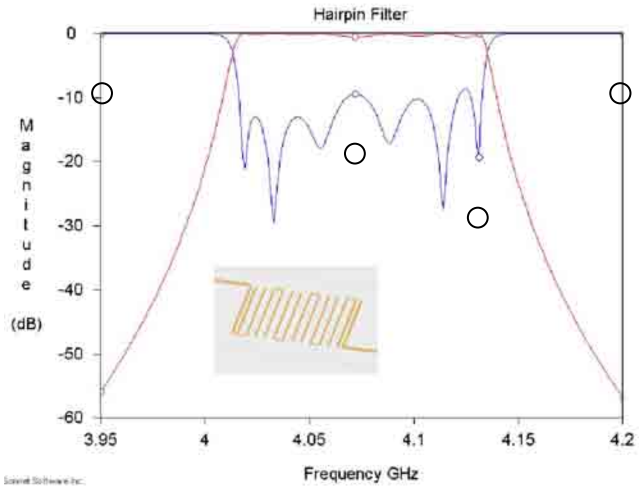

Fig. 4. EM analysis at four frequencies (circled) is interpolated to the entire frequency band using the new interpolation algorithm. EM analysis of the entire filter at every frequency yields exactly the same result.

V. Future predictions

In my previous paper [9], I made a few easy predictions, but I also made one specific, quantitative prediction: That by 2010 we would be able to invert a full matrix using non-iterative techniques at a size of 100 000 × 100 000 in about one hour on a desktop computer costing about US$2 000. We nearly made it. Recently, we inverted a 100 000 × 100 000 matrix in under three hours on a 12 core (dual hexacore) machine costing US$3 000. We expect that by the end of the next decade, this task will become common.

Note that iterative matrix solution can easily achieve this benchmark, however the iterative solution is approximate and must be repeated for every port in the circuit. We are now developing tuning techniques that require hundreds of perfectly calibrated internal ports in a circuit. Iterative matrix solve is not appropriate for this application.

Recall that in 1982, I was able to invert a 100 × 100 matrix in about one hour on the very first IBM PC. Matrix solve is an N^3 process, if you double the size of the matrix, solve time is eight times longer. This means that between 1982 and 2010, with both computer and algorithm improvement, computers are now 300 000 000 times faster.

VI. Interoperability

The "seamless interface" between multiple tools from a single vendor has been available from nearly all framework vendors for quite a while. A recent development has been the increasing importance of interoperability of tools from different vendors. This is especially important from the Sonnet point of view because we provide only one of the many different tools needed by a high frequency designer. Thus, we have developed interfaces to all major vendors.

We have found that some vendors are willing to make it easy to interface. For others, it can be difficult. Since it is clear that no single vendor can provide a total solution, ease of interoperability in a multi-vendor environment, even between competitive vendors, is becoming critically important.

From Sonnet's point of view, we have found Agilent ADS, AWR Microwave Office, and Cadence Virtuoso to be especially open to interoperability, even if there might be some degree of competitive issues involved. These framework vendors are committed to providing the best possible solutions to their customers, and that requires a good degree of interoperability.

VII. Conclusion

The field of electromagnetics started with Maxwell's genius. Wide spread use of numerical solutions to Maxwell's equations waited for the advent of inexpensive and powerful desktop computing. Today, numerical electromagnetics is considered a necessary part of nearly all high frequency design. Multiple EM tools are required in order to efficiently solve a broad spectrum of problems. Even just within the field of planar circuits, two main tools (open and shielded environment) are needed. Since no one vendor can supply all required tools, interoperability is rapidly becoming an overwhelming issue. James Clerk Maxwell would be pleased with our progress over the last 145 years.

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