An Integrated System for the Synthesis of Coated Waveguides from Specified Attenuation

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Abstract—**The problem of describing the thickness and material properties of inner coatings of waveguides so as to produce a specified rate of attenuation is an increasingly important one. However, the technology for solving such problems is not yet suitable for routine use because (i) The solution procedure requires the solution of two finite element eigenvalue problems to compute the gradient of the object function with respect to every parameter of description and as a result, convergence to the optimum is very slow, and (ii) There is no integrated system for the implementation of these methods that would allow easy use. This paper presents the modules for an integrated synthesis system that incorporates (i) A new, algorithm for the quick computation of the gradients of the object function, and (ii) Integrates drafting and word-processing packages into the finite element field computations so as to allow easy implementation of the synthesis algorithms and their comfortable incorporation into an engineer's other duties, such as writing reports and proposals.**

I. Stealth Technology and Coated Waveguides

Stealth technology involves the construction of aeroplanes with minimal signature in the presence of radar. The principal methods, just as with the coating of camera lenses, is to use several layers of different materials on the surface of the aircraft so that no reflections occur. The materials are designed so that their characteristic impedance $[\mu/\epsilon]^{0.5}$ is the same as that of free space; but because this impedance is frequency dependent, the several layers take care of the range of frequencies that might be in use, for purposes of design, matrix algorithms are used to compute the reflection coefficient from the layers [1]. Through these methods fairly optimal values for both coating materials and coating thickness are now known [2].

However, it has been found that while waves reflected off the aircraft surface are killed, those that enter the engine ducts travel as though the ducts were waveguides and are transmitted back, thereby making the aircraft identifiable [3]. In an attempt to make the aircraft less visible, the insides of the engine ducts too are now coated with special materials so as to absorb the energy of the waves that might enter them. The direct problem of computing the attenuation for given materials and thicknesses, while useful, is inadequate as far as the answers we seek are concerned. We may guess at the combination of parameters that would give us our desired performance and analyze the system for that combination. And if the result were not desirable and we were inexperienced in the field, we would not know how to change the values of the assumed parameters so as to attain the desired performance. What is required then, is a formal methodology for the solution of the inverse problem [4] of determining the required thicknesses and material values ϵ and μ of coatings that would yield a desired attenuation.

Although optimization and adjoint network gradient calculation has been well known to microwave circuit designers for some time [5]–[7], it is only recently that the mathematics for optimizing electromagnetic devices using finite elements has emerged [8]–[24]. Finite element optimization for high frequency systems has been even more recent [8], [19]. In [8], the methodology for optimizing a ridged waveguide so as to yield either a specific field distribution or a specific cut-off frequency is established. In that paper, an object function based on a performance measure m and its desired value m_o,

$$F = \tfrac{1}{2}[m - m_o]^2 \quad (1)$$

is defined. Here m can be a scalar such as the eigenvalue or a vector such as the eigenvector [8]; where it is a vector, the square represents taking the scalar product with itself. Thereafter, taking estimates of the parameters of description—the dimensions in the case of the ridged waveguide—the guide is analyzed by finite elements, the derivative of the object function with respect to every parameter computed by a finite difference scheme, and finally, the parameters adjusted against the gradient until the object function is minimized. The clear application of the scheme to the aircraft problem has been pointed out.

However, there are practical impediments to the routine industrial implementation of the scheme and it is these that are addressed in this paper so as to result in an integrated system that would return the synthesized device corresponding to specified performance requirements:

i. The finite difference differentiation requires a different field solution—an eigenvalue problem—for every parameter and is therefore very costly. This is addressed by a new means of computing the gradient without having to solve a second eigenvalue problem.

ii. When dealing with the ridged waveguide, the essentially rectangular parts of the guide allow a uniform

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mesh generating capability with a specified number of subdivisions of the boundary. As such, when a parameter is adjusted, the mesh changes uniformly, thereby avoiding the jumps in the object function pointed out in [9]. But the cross-sections of the B-2 bomber's engine inlets, although of almost rectangular cross-section, are not exactly so [3] and, as such general-purpose mesh-generators need to be employed. In integrated systems, such mesh generation is accomplished by drawing the outline of the device and then employing algorithms that identify the boundaries automatically and create the mesh. But it is such free-meshing algorithms, it has been shown [9], that result in fictitious minima in object functions based on mesh error that then require elaborate (and therefore slow) algorithms such as tunneling [10], simulated annealing [11], [12] and search methods [13] to by-pass these fictitious minima. In fact, in the optimization of planar microwave devices in [19], free meshing has been used along with gradient methods. In view of the findings in [9], the accuracy of the gradient computations would have suffered and, as a result, convergence would have taken more iterations than required. In this paper therefore, a special purpose mesh generator is used to get around this problem.

iii. For easy routine use in industry, a synthesis system ought to be integrated into the daily work routine of an engineer and be black-boxed. The synthesis system under discussion therefore integrates drafting and word-processing packages with the larger numerical computation packages as described below.

II. The Coated Waveguide and Parameters of Description

While the physical problem under discussion is the stealth aircraft, mathematically, it may be cast in terms of a translationally symmetric (i.e., a two-dimensional system with $\partial / \partial z = 0$) guide with multiple coatings, each described by the complex permittivity ϵ and permeability μ, of different uniform thicknesses. A fortunate simplification in the parametric description, however, is the fact that the materials in use are of restricted characteristics. In industrial use, only certain classes of materials are used, all parametrized by a constant α [2], [3]. These are the E-type carbon-based electric materials, the C-type lossless electrical materials that are often used between the layers, and the M-type iron-based magnetic materials, characterized by

$$\begin{aligned}
\text{E-type: } \epsilon_r &= (1 + 0.04\alpha) + j\,\frac{0.3\alpha}{\omega} \\
\mu_r &= 1 \\
\text{C-type: } \epsilon_r &= \alpha \\
\mu_r &= 1 \\
\text{M-type: } \epsilon_r &= 8\alpha \\
\mu_r &= \alpha + j\,0.75\alpha.
\end{aligned} \tag{1}$$

Thus the parametrization of the material is reduced to just one constant α, greatly simplifying our computations. This parameter α can take any value from 0.0 to 20.0. The number of coatings typically varies from 0 to 20 and the thickness t of each layer from 0 to 5 inches. Thus for each layer of coating, there are only two parameters to be determined: the material characteristic α and the thickness t.

III. Optimization of the Guide and Desired Modules

The finite element analysis of wave guides with inhomogeneities is now a well known art [25]–[27]. The optimization of the shape of a guide so as to yield a certain cut-off frequency or field distribution is also established [8], although it is a little slow because of the need to compute many gradients through finite difference schemes. Thus, as shown in Fig. 1, using a classical wave-guide analysis program as a module and building around it the optimization package, a system has been built to determine the necessary material values and thicknesses of a given number of coatings. Since the number of coatings is discrete, starting with a small integer, the optimization process attempts to synthesize the device that would give us the desired attenuation; in the event of failure—as measured by how much the object function has been minimized—the number of layers is increased and the run repeated.

In solving the wave equation for the guide (with TE or TM propagation) by the finite element method, the solution is assumed to vary as exp $(-jkz)$ where z is the direction of unchanging geometry and k is the wave-number. It is the imaginary part of k, k_{im}, that determines the rate of attenuation so that we define the object function on the basis of (1) as

$$F_o = \tfrac{1}{2}\,[k_{im}^{des} - k_{im}]^2 \tag{2}$$

where k_{im}^{des} is the desired rate of attenuation. For optimizing the system so as to make it yield the desired performance, from iteration k to $k + 1$, we need to change the parameters in a direction $\{s\}$ so as to move towards the minimum of the object function:

$$\{p\}_{k+1} \leftarrow \{p\}_k + \alpha\{s\}_k \tag{3}$$

where $\{p\}$ is a vector of all the parameters of description. How $\{s\}$ is chosen determines the method of optimization employed [28]. Two algorithms are best known for this, the steepest descent algorithm and the conjugate gradients algorithm. In the steepest descent algorithm, to effect the change in (3), we take $\{s\}$ to be the vector containing the derivatives of F with respect to every parameter:

$$\{s\} = -\left\{\frac{\partial F}{\partial p}\right\} \tag{4}$$

Intrinsically, this is seen to be right since we must move against the direction of the slope to go to the minimum. In the conjugate gradients algorithm [28], on the other

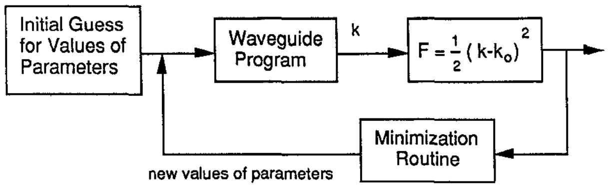

Fig. 1. Extension of waveguide program for optimization.

hand, $\{s\}$ is as in (4) only for the first iteration. Thereafter,

$$\{s\}_k = -\left\{\frac{\partial F}{\partial p}\right\}_k + \beta_k\{s\}_{k-1}; \qquad \beta_k = \left|\frac{\left\{\frac{\partial F}{\partial p_k}\right\}}{\left\{\frac{\partial F}{\partial p_{k-1}}\right\}}\right|^2. \tag{5}$$

It is noted that with $\beta = 0$, the conjugate gradients scheme would amount to the steepest descent algorithm. Thus now, with the direction of change established, the problem is reduced to finding just one constant α and for this a so-called line search is required; starting with a low value of α, we solve the field problem posed by the new set $\{p\}$ given by (3), evaluate the object function F, increase α by a factor of 1.6 or thereabouts, repeat the solution and so on, until the decreasing F begins to increase, thereby indicating that the trough has been passed. Usually because of the geometric progression by which α is increased, the trough in the F versus α function is passed within 6 or 7 field solutions at most. When this occurs, the last 4 values of α and F are used to construct a third order polynomial of F in α, and then we find that α that would make F a minimum [Higher order fits are not advised since they result in many local minima in $F(\alpha)$]. Now, knowing α, we know $\{p\}$ from (3) to begin the next iteration. Be it noted that, of the many field solutions within an iteration, the gradients computation accompanies only the first field solution to evaluate the search direction $\{s\}$. The other field solutions are only to find α and need no evaluation of gradients. Now for the next iteration with the updated $\{p\}$, the gradients are computed again and many solutions of slightly changed configurations are gone through as before to get α for the new gradients, and so on.

Just to ensure that there are no real physics-based local minima in the object function—if there are then more sophisticated techniques such as tunneling, simulated annealing and search methods would be required [10]–[13]—the object functions were tested allowing only one parameter in a multi-parameter description to vary at a time. It was always found, as shown in Fig. 2 for α of one layer varying, that there was only one minimum for the object function.

IV. Differentiation of the Object Function

We have seen from the above section that one of the keys to successful optimization is the determination of the search direction as determined by the gradients. In solving the finite element problem for the wave equation, the linearized eigenvalue problem that results is of the form [25]–[27]

$$[P^g]\{x\} = \lambda[T^g]\{x\} \tag{6}$$

where $[P^g]$ and $[T^g]$ are the globally assembled matrices and the vector $\{x\}$ contains the z-component of the E or H field vector depending on whether it is the TM or TE mode of propagation that is under consideration, or the vector potential A. The derivative of the object function as we have defined it, in turn requires the derivative of the wave number k. To determine this, what we need is the gradient of the eigenvalue λ. In [8] this is done by changing the parameter p slightly and then solving a second eigenvalue problem. However, this is very costly.

On the other hand, with direct finite element problems involving the Poisson equation that yields matrix equations of the form:

$$[P^g]\{x\} = \{Q^g\} \tag{7}$$

following differentiation and rearrangement of (7), we arrive at

$$[P^g]\left\{\frac{\partial x}{\partial p}\right\} = \left\{\frac{\partial Q^g}{\partial p}\right\} - \left[\frac{\partial P^g}{\partial p}\right]\{x\}. \tag{8}$$

Obviously since the same coefficient matrix is involved as in (7), using Cholesky's factorization for solving (7), the gradients of (8) may be computed directly and quickly without a second finite element solution [20]–[24]. The issue then is, can the same advantage that finite element solutions have in computing gradients from direct problems, be also reaped with the eigenvalue problem ? Statistical methods have been attempted before to this end, but are slow [29]. In this section we will develop a technique similar to that used with direct problems as in (8). The technique is highly efficient in that the matrix of coefficients is the same regardless of the parameter (which affects only the right hand side of the equation), so that with one Gaussian triangulation of the coefficient matrix, the gradients with respect to all the parameters may be

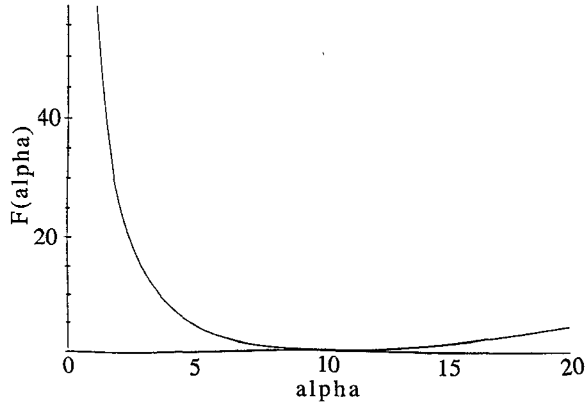

Fig. 2. F Against α showing smoothness and single minimum.

quickly computed. To this end, differentiating (6),

$$[P^g]\left\{\frac{\partial x}{\partial p}\right\} + \left[\frac{\partial P^g}{\partial p}\right]\{x\} = \lambda[T^g]\left\{\frac{\partial x}{\partial p}\right\} + \frac{\partial \lambda}{\partial p}[T^g]\{x\} + \lambda\left[\frac{\partial T^g}{\partial p}\right]\{x\}. \tag{9}$$

Now, because we have already solved (6) for λ and $\{x\}$, many of the terms of (9) are known. It is to be noted that the derivatives of $[P^g]$ are exactly as given in [22], [23]. The only new matrix, $[T^g]$ for first order triangular elements [25] is given by the local matrix

$$[T^1] = \frac{A^e}{12}\begin{bmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{bmatrix} \tag{10}$$

where A^e is the triangle area. Thus the derivative of T^e may be trivially evaluated from the derivative of the triangle area given in [22] and [23]. Further, it is important to note that since if $\{x\}$ is a solution any $c\{x\}$ is also a solution, the vector $\{x\}$ is always scaled so that its largest component is 1. And because of the way we have defined the vector $\{x\}$, where the component of $\{x\}$ is 1.0, there the component of $\{\partial x/\partial p\}$ will be zero. Thus for an nxn matrix (6), (9) represents only n unknowns: the unknown $n - 1$ components of $\{\partial x/\partial p\}$ and $\partial\lambda/\partial p$. Thus, manipulating (9), and denoting by $\{u_i\}$ the ith column of the known matrix $[P^g] - \lambda[T^g]$ and by $\{v\}$ the known column vector $[T^g]\{x\}$, we have the nxn matrix equation

$$[\{u_1\}, \{u_2\}, \cdots, \{u_{j-1}\}, -\{v\}, \{u_{j+1}\}, \{u_{j+2}\}, \cdots, \{u_n\}]\begin{Bmatrix} \frac{\partial x_1}{\partial p} \\ \frac{\partial x_2}{\partial p} \\ \cdots \\ \frac{\partial x_{j-1}}{\partial p} \\ \frac{\partial \lambda}{\partial p} \\ \frac{\partial x_{j+1}}{\partial p} \\ \cdots \\ \frac{\partial x_n}{\partial p} \end{Bmatrix} = \lambda\left[\frac{\partial T^g}{\partial p}\right]\{x\} - \left[\frac{\partial P^g}{\partial p}\right]\{x\} \tag{11}$$

which may be solved for all the unknown gradients. In the foregoing, j is the location of the largest element of the eigenvector. The coefficient matrix is not symmetric nor does it bear any semblance to (6) as with (7) and (8) associated with the direct problem. However, the u's and v are the same regardless of the parameter so that with one Gaussian upper triangulation of the matrix, any number of parameters may be handled very quickly. Thus, although not as elegant as the direct problem, requiring only one matrix triangulation, it is a significant improvement over having to solve a second eigenvalue problem.

V. Mesh Generation and Integrated Package

We have already noted that for easy acceptance in routine design use, the computer-synthesis system ought to be an integrated one—integrated not only as a hardware system, but into the every day work environment. In this section, the mesh generation and postprocessing schemes as an integrated whole on a Macintosh IIx™ platform, linked by ETHERNET™ to a VAX 8600™ for the matrix solution and running terminal emulation, drafting and word-processing packages used by an engineer are described. This scheme is depicted in Fig. 3. Although a Macintosh IIx™ is depicted because it is the one in use, any smaller Macintosh computer would do since no heavy computing is done on it; the only requirement is 4 MBytes of internal memory to run a multi-window environment called the multi-finder.

For purposes of mesh generation, a drafting program such as MacDrawII™ is run using the Macintosh computer. Fig. 4 shows an actuator configuration being drawn by the drafting program MacDrawII™. This can now be saved as a PICT file [30], in a format that is becoming increasingly standard for graphics. Thereafter, two options are allowed. First, in the simpler approach, the PICT file is imported into a Macintosh-based finite element program meant for solving the Poisson equation, and, as shown in Fig. 5, using this as background, the mesh generator of the finite element program is used to construct the mesh. This mesh may then be used for the waveguide synthesis program. In the alternative, the elements of the PICT file are considered as hierarchical sets—points, lines, polygons and so on as described in [31]—and we search through the objects for closed regions and mesh them into first order triangles using the Delaunay optimization technique [25]. However, we have noted that unless the nodal connections in a mesh are held fixed, there will be fictitious minima in the object function making the reaching of the global minimum difficult [9]. As such, as shown simplistically for clarity in Fig. 6 for engine-inlets assumed to be of rectangular cross-section and with one coating, as the thickness of the coating is increased in the optimization iterations, the same mesh is used with the coordinates changed in such a way that the coating region is merely scaled up or down. This ensures that the object function is smooth. However, at some point, the mesh could be distorted so much as to be useless. Should this happen, a new mesh is constructed with the latest combination of parameters and the iterations are

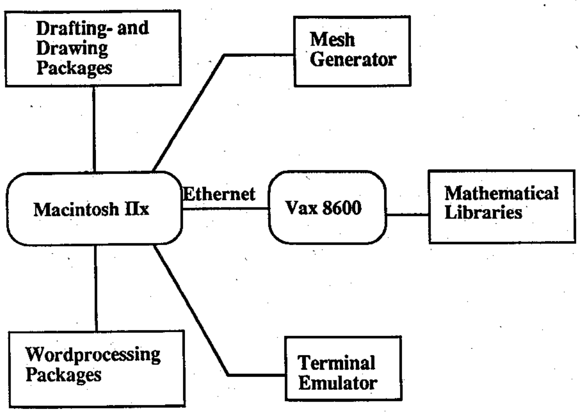

Fig. 3. The Macintosh platform for synthesis.

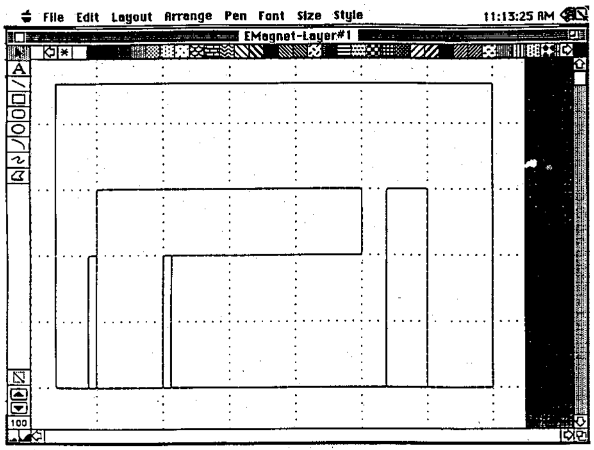

Fig. 4. Drafting program MacDrawII being used to sketch a device.

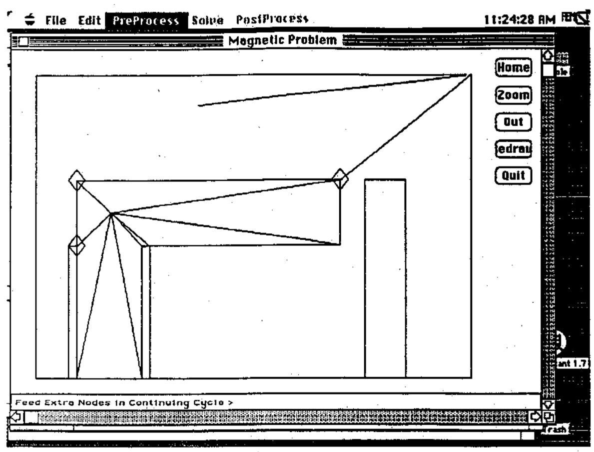

Fig. 5. A finite element program using Fig. 4 as background for mesh generation.

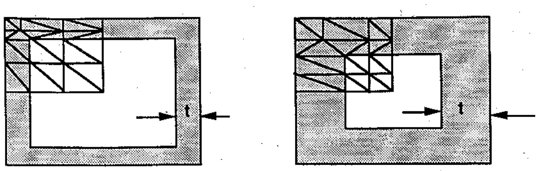

Fig. 6. Scheme for mesh generation in an engine-inlet.

begun anew with this as the starting point. Although this method of ensuring smooth object functions has been well known in the civil engineering and mechanics literature for long [32], it is an unfortunate fact that research in electromagnetics has proceeded apace without regard to this well established and widely reported literature on optimization outside the community [32]–[35]. Thus, optimization in electromagnetics has generally been by working with these easily avoided discontinuities and then using sophisticated mathematical routines that work around these mesh-induced artificial minima at great cost [11]–[13][1]. In fact, despite all the contravening evidence [28], it has been claimed that the steepest descent method is faster than the conjugate gradients method [36]—presumably an erroneous conclusion arrived at by differentiating object functions with artificial jumps in them[2].

We have so far described the integration of hardware as well as different codes into a unified whole, working towards the same end. However, in a real design environment, engineering not only involves clever and sophisticated numerical analysis, but the selling of ideas through proposals and the presentation of results through reports, among others. Therefore it is essential to have commonly used wordprocessing, drawing and analysis tools integrated. This is easily permitted by the Macintosh environment which was chosen for this project because of its low cost and ubiquitousness. Under this environment, when a mesh is ready and needs to be transferred into a report, it may be copied into internal memory by writing the program to permit that [30] and then pasted into the wordprocessing program in use such as Microsoft Word™. Alternatively by pressing that combination of keys on the board specified by the Macintosh operating system, a picture of the screen is formed in a file. Now, running a drawing program like SuperPaint™, as the case may be, the copied picture is pasted in or the snap-shot of the screen in a file is read in. Fig. 7 shows the program SuperPaint being used to work on a snapshot of the screen during mesh-generation. At this stage captions may be inserted as required by the report. Now, using the intrinsic features of the Macintosh, the modified diagram with captions, is copied and pasted into the wordprocessing program.

At this stage the initial mesh is ready and, assuming that all the other data also is, we may wish to solve the

[1]A whole session at the COMPUMAG Conference in Sorrento, Italy, July, 1991 was devoted to these methods. It is noteworthy that the correct and computationally fast way of optimization requires much code development involving the derivatives of the coefficient matrices and the preservation of the mesh connections, whereas the computationally intensive way of dealing with fictitious local minima, can be implemented quickly by appending separate optimization routines to existing finite element packages. One cannot help wondering how much of this unfortunate trend is on account of the attempts by the different code vendors to be the first on the market with optimization code.

[2]As this paper goes to press, selected papers from the *Fourth Biennial IEEE Conference on Electromagnetic Conference* have appeared in the IEEE TRANSACTIONS ON MAGNETICS. Here Preis, Friedrich, Gottvald and Magele [37], in expanding on their conference paper [36], without explicitly saying they are doing so, have reversed their position and report conjugate gradients to be superior to steepest descent.

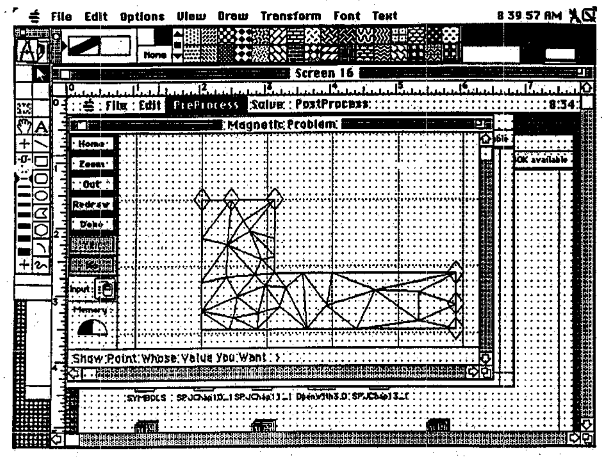

Fig. 7. Drawing program SuperPaint being used to process figures for reports.

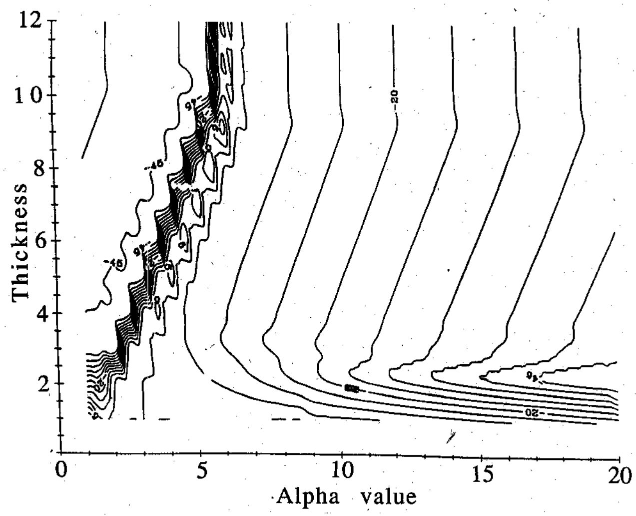

Fig. 8. Constant k_{im} lines with E-type material.

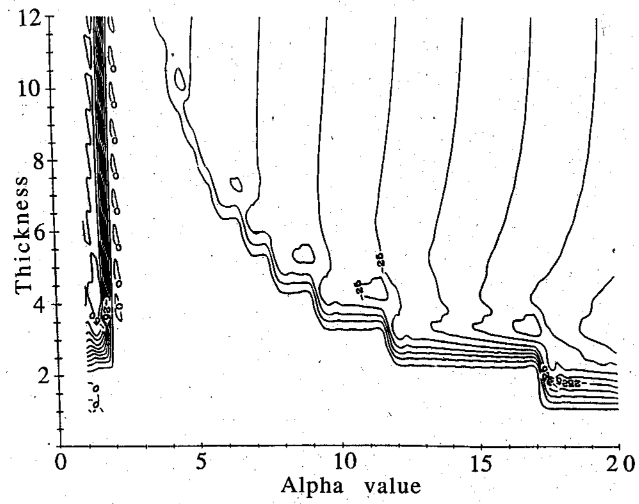

Fig. 9. Constant k_{im} lines with M-type material.

program as depicted in Fig. 1. But because of the heavy matrix computation involved, the solution has to be done on a larger machine, such as the VAX8600™ that is linked to the Macintosh via ETHERNET™. Running a terminal emulation program that creates an additional window under the Macintosh environment, the user logs into the VAX™ and runs the program. The results may be brought back to the Macintosh by file-transfer for post-processing, or, alternatively, as we have chosen to do, equipotential plots are plotted on the VAX™ on the emulated screen; then, using the Macintosh environment, whatever is on the emulated screen is copied as graphics into the internal memory of the Macintosh and, reverting to a Macintosh window, such as under the wordprocessing program Microsoft Word™, the equipotential plots may be pasted.

VI. Results and Constraints Based on Them

The user-interface of the synthesis program on the VAX requires as input

i. The radar frequency, the range of interest being from 0 to 30 GHz.

ii. The targeted rate of attenuation, usually from 0 to −200 decibels. The corresponding value of k_{im} is immediately computed by the program and displayed.

iii. The number of layers of coating, usually from 0 to 20. The program has been rigorously tested for up to 3 layers, that is 6 parameters of description, these being the α describing the material and the thickness t of each layer.

iv. The material-type of each layer, that is whether E-, C- or M-type as described earlier.

v. Starting values of α and t for each layer.

vi. The name of the output data file.

Additional insights into the problem were gained when running the program. First, it was found that there are many values of the parameters that gave us the desired attenuation. For example, Fig. 8 for an E-type material at 15 GHz and Fig. 9 for an M-type material at 0.1 GHz show contours of equal values of k_{im}, indicating that any point on a given contour would give us the same rate of attenuation. Which of these multiplicity of values then do we choose? This we do on the basis of engineering constraints. The aircraft industry, for reasons of airflow, weight and cost, prefers low values of thickness t and material parameter α. With this in mind, therefore, the object function of (2) was modified to read thus:

$$F_o = \frac{1}{2}\left[k_{im}^{des} - k_{im}\right]^2 + \sum_{i=1}^{n}\left[\frac{1}{12.7 - t_i} + \frac{1}{20 - \alpha_i}\right] \tag{12}$$

where n is the number of layers. Now, as the thickness approaches 0.127 m, or $\alpha = 20$, the object function grows large so as to make us avoid these values.

Figs. 10 and 11 show convergence by the steepest descent and conjugate gradients algorithms, the iterations being summarized in Fig. 12. Clearly, contrary to [36] and as stated in [28][3], the conjugate gradients approach is superior and, as the preferred method, is what we now use in all optimization studies. While up to 6 parameters

[3]See footnote 2.

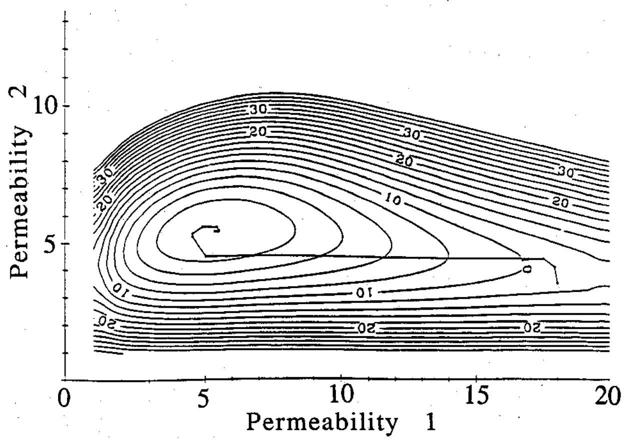

Fig. 10. Convergence with steepest descent.

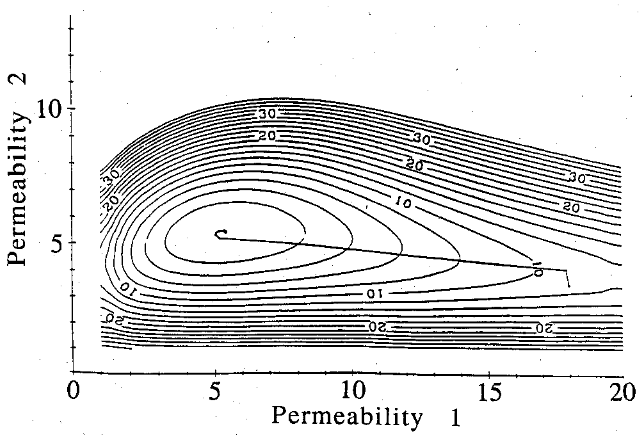

Fig. 11. Convergence with conjugate gradients.

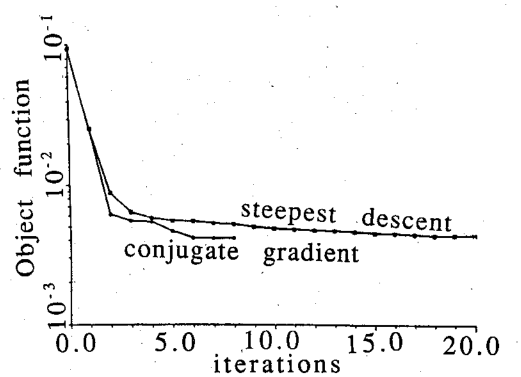

Fig. 12. Comparison of steepest descent and conjugate gradients for optimizations.

TABLE I
CONVERGENCE HISTORY FOR A DESIRED k_{im} OF −20 WITH AN E-TYPE MATERIAL AT 20 GHz

k	α	t	F	$\frac{dF}{d\alpha}$	$\frac{dF}{dt}$
−1.0250	1.000	0.0254	180.0254	−39.8023	−1393.1779
−14.2590	4.980	0.0304	26.8981	0.3228	−102.1268
−14.1025	4.948	0.0314	27.9194	−21.8651	−61.7321
−19.9875	7.134	0.0320	10.6084	0.2659	111.1537
−19.9948	7.108	0.0309	10.4863	0.0089	108.5676
−19.9930	7.107	0.0298	10.3700	0.0092	106.1329
−19.9874	7.106	0.0288	10.2589	0.0102	103.7865
−19.9770	7.105	0.0277	10.1526	0.0120	101.4358
−19.9600	7.104	0.0267	10.0512	0.0146	98.8995

of description (3 layers) have been tested, for the sake of meaningful readability, the convergence characteristics for a single-layer, two-parameter problem are shown in Table I.

VII. Conclusion

A robust program for synthesizing coated waveguides from specified attenuation is described. It is based on gradient methods, and the means of computing the gradient of the object function without resorting to a second finite element solution of the wave equation is also described. With one triangulation of the coefficient matrix, the gradients with respect to all the parameters can be quickly computed. As a result, optimization times are cut down by as much as 75%.

The need to integrate such sophisticated computational tools with word-processing and drafting facilities of an engineer is recognized and the integrated system has been built on a Macintosh platform.

Acknowledgment

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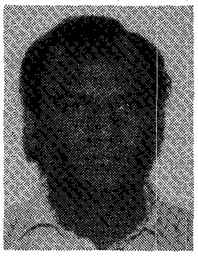

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