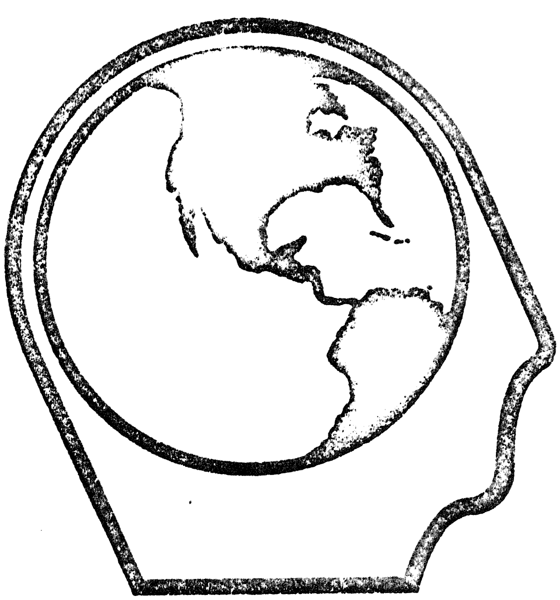
Cat. No. 71C28–COM

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

INTERNATIONAL CONFERENCE ON COMMUNICATIONS

LA CONFERENCE INTERNATIONALE SUR LES COMMUNICATIONS



ICC 71 CIC

JUNE 14, 15, 16, 1971 MONTREAL, CANADA

A REVIEW OF COMPUTER-ORIENTED CIRCUIT OPTIMIZATION

John W. Bandler
Communications Research Laboratory and
Department of Electrical Engineering
McMaster University, Hamilton, Ontario, Canada

Invited Paper

ABSTRACT

Computer-oriented circuit optimization techniques are reviewed. The preparation of the circuit design problem for computer optimization is discussed in some detail. Approximation methods, including least pth and minimax, are also discussed in detail. In particular, generalized least pth and minimax objectives are proposed as the most meaningful for circuit optimization. The adjoint network method of evaluating derivatives of circuit responses with respect to circuit parameters both in terms of voltages and currents and also in terms of wave variables is reviewed. A bibliography of relevant papers, including state-of-the-art reviews, is appended.

INTRODUCTION

The prospect of fully automated optimal design of electrical circuits is an exciting one. Many research workers are currently developing techniques which should ultimately lead in this direction. Problem areas of relevance include development of efficient circuit analysis methods, development of efficient methods of generating circuit sensitivities and development of efficient methods of optimization.

The purpose of this paper is to review computer-oriented circuit optimization techniques. Good preparation of the circuit design problem as an optimization problem is essential if meaningful results are to be obtained. One section is devoted to this topic. Another section concerns least pth and minimax approximation. In particular, it is recommended that generalized objectives be used more often than is currently done. A section on the adjoint network method of evaluating the required derivatives for use in the optimization process is included. Finally, a bibliography of selected relevant papers is appended. Included are state-of-the-art reviews which the computer-oriented circuit designer should find useful as an introduction to the subject.

STEPS IN CIRCUIT DESIGN

We may outline ten fairly distinct steps involved in the computer-aided design of circuits using numerical optimization methods as follows.

1) Possible design goals must be considered in general terms. The designer should then clearly understand what his problem is and what the circuit to be designed is to achieve.

2) Suitable components have to be decided upon. They may be lumped, distributed, active, and so on, depending on the application. A suitable circuit configuration has to be chosen.

3) An objective function for minimization has to be formulated. It must adequately reflect the design goal and should preferably not contain scale factors or constants which can not be easily fixed in advance. In circuit design the objective is usually to realize a least pth or minimax approximation.

4) Constraints should be formulated at this stage accounting, for example, for cost, size, stability, parasitic effects, parameter bounds, and so on. Too many designers appear to ignore this problem and then complain that optimization does not yield a realizable design.

5) A circuit analysis scheme for the chosen configuration has to be selected. Its choice will depend, for example, on whether the circuit is linear or nonlinear, lumped or distributed, and whether frequency- or time-domain responses are to be computed.

6) An important factor in choosing the analysis scheme is the availability or otherwise of partial derivatives of the response functions with respect to those parameters which are to be optimized. The use of the adjoint network method, for example, should be contemplated at this stage.

7) An optimization method has to be chosen. It may be a direct search method if derivatives are not readily available. If derivatives are readily available an efficient gradient method is to be preferred. The optimization method may itself involve iterative use of another optimization method, for example, linear programming.

8) The design problem should now be ready for programming. Available computer programs should be used when possible. Programs should, if necessary, be adapted to the problem rather than the other way round.

9) An initial design, preferably feasible, has to be found to serve as a starting point in the optimization process. Generally speaking, the better this initial guess the faster the process will be.

10) If all the foregoing steps have been carefully implemented the optimal design should now be obtained by running the program. Unfortunately, however, snags may occur. False (as distinct from local) minima are often obtained due to poor scaling. Nonconvexity of the objective function may also result in the failure of the process to converge to the proper solution. As a rule of thumb, the program should be run starting from as many different feasible starting points as there are variable parameters, for a modest number of parameters. If at least a few terminating points are found to be the same it is reasonable to assume that a local minimum has been found. In the

---

This work was supported by the Communications Research Laboratory of McMaster University and by the National Research Council of Canada under grant A7239.

author's experience, the widely-held conviction that every point at which an optimization process terminates in a circuit design problem is a local minimum is usually unfounded. The corresponding design may be acceptable, but it need not even correspond to a local minimum.

APPROXIMATION METHODS

The approximation of desired frequency- or time-domain responses is probably the most common type of problem a circuit designer has to solve. Both least pth (a generalization of least squares) and minimax (or Chebyshev) approximation techniques are employed. In this section the two types of approximation will be discussed.

Least pth Approximation

Minimization of an objective function of the form

$$U = \sum_{i \in I} |e_i(\phi)|^p \tag{1}$$

where $e_i(\phi)$ is (in general) a complex nonlinear error function of the variable parameters ϕ, I is a set of indices i and p is usually greater than or equal to 1, is called discrete least pth approximation. A sufficient number of sample points is chosen so that the discrete problem adequately represents the continuous problem.

Temes and Zai[1] have presented a method of solving least pth approximation problems and applied it to the design of an active equalizer[1,2]. Assuming that partial derivatives of the objective function are available, any suitable efficient gradient method of minimization can be used to solve the problem[3-6]. A necessary condition for optimality is that the gradient vector of the objective function is zero. Sufficiency results if the function is also convex.

Bandler and Charalambous have recently presented generalized least pth objectives[7]. Design problems in which it is desired to meet or exceed certain upper and lower response specifications should be capable of solution using these objectives.

If the specification is violated it is recommended that

$$U = \sum_{i \in J_u} [e_{ui}(\phi)]^p + \sum_{i \in J_\ell} [-e_{\ell i}(\phi)]^p \tag{2}$$

where

$$J_u \triangleq \{i \mid e_{ui}(\phi) \geq 0, \;\; i \in I_u\}$$
$$J_\ell \triangleq \{i \mid -e_{\ell i}(\phi) \geq 0, \;\; i \in I_\ell\} \tag{3}$$

where subscript u denotes quantities related to an upper specification, i.e., one for which it is desired to force the circuit response below, and subscript ℓ denotes quantities related to a lower specification, i.e., one for which it is desired to force the circuit response above. The error functions in this case are assumed to be real. Briefly, only those parts of the response which violate the specification are included in the objective function. For p>1 and under some mild restrictions the objective function and its first derivatives are continuous and the matrix of second partial derivatives is positive-semi-definite. Good results are, therefore, to be expected using gradient methods.

If the specification is satisfied it is recommended that

$$U = \sum_{i \in I_u} [-e_{ui}(\phi)]^{-p} + \sum_{i \in I_\ell} [e_{\ell i}(\phi)]^{-p} \tag{4}$$

where

$$-e_{ui}(\phi) > 0 \qquad i \in I_u$$
$$e_{\ell i}(\phi) > 0 \qquad i \in I_\ell \tag{5}$$

Thus, all parts of the response satisfy the specification. For $p \geq 1$ and under some mild restrictions the objective function and its first derivatives are continuous and the matrix of second partial derivatives is positive-semi-definite.

Minimax Approximation

Minimization of an objective function of the form

$$U = \max_{i \in I} |e_i(\phi)| \tag{6}$$

where the error functions may again be complex, is called discrete minimax approximation. It is easily shown that minimizing the objective function of (1) for a sufficiently large value of p results in a solution very close to the minimax solution. p=10 is often sufficiently large for practical purposes.

More general minimax objectives suitable for solving circuit design problems involving upper and lower specifications have been discussed[8]. Consider the objective function

$$U = \max_i [e_{ui}(\phi), \; -e_{\ell i}(\phi)] \tag{7}$$

to be minimized, where, as previously, the error functions are assumed to be real. Letting $\breve{U}$=minU, if $\breve{U}$>0 the maximum (weighted) amount by which the response fails to meet the specification has been minimized, and if $\breve{U}$<0 then the minimum (weighted) amount by which the response exceeds the specification has been maximized.

Lasdon and Waren[9] have presented a method for minimax approximation and have applied it to the design of crystal filters and other problems[9,10]. Their approach requires the reformulation of the problem in terms of inequality constraints[8] and solution via the sequential unconstrained minimization technique[11,12].

Ishizaki and Watanabe[13] have developed a method employing linear programming iteratively and have applied it to the design of attenuation and group delay equalizers. Their method at a particular stage involves linearization of the nonlinear error functions and the solution of an appropriate linear programming problem by the simplex method[14]. The Osborne and Watson method of minimax approximation appears to be basically the same[15]. A method based on it has been tested on transmission-line impedance matching circuits [16].

Bandler and Macdonald developed the

razor search method[17] for direct minimax approximation for situations when partial derivative information is not readily available. Their method is based on pattern search[18] and involves a few random moves to negotiate paths of discontinuous derivatives created by using an objective function of the form of (6). More recently, a gradient razor search method has been presented by Bandler and Lee-Chan[19] exploiting the adjoint network method of evaluating derivatives. Downhill paths of discontinuous derivatives are sought by solving an appropriate set of linear simultaneous equations. A generalization of the gradient razor search method is the method due to Bandler and Srinivasan[16], involving the solution of linear programming problems at various stages during the optimization process. Transmission-line impedance matching circuits and filters have been optimized to test these algorithms[16,17,19].

Conditions for optimal approximations in the minimax sense have been formulated[20]. Their use in tests for optimality of proposed circuit designs has been demonstrated.

Discussion

An ideal response is usually impossible to achieve in practice. The most logical design specifications, in this author's opinion, are those which indicate acceptable deviations from the ideal. The optimization procedure would then be used to force the circuit response to meet or exceed these specifications. The most meaningful objective functions, in general, from the point of view of practical circuit design are, therefore, of the form of (2), (4) and (7). Unfortunately, however, least squares approximation of ideal responses by circuit responses are still widely employed. This practice is not usually consistent with step 3) of the previous section. Designs obtained by least squares approximation may sometimes be acceptable, but they may not be the best that the corresponding configurations can realize.

THE ADJOINT NETWORK METHOD

The adjoint network method of evaluating partial derivatives of circuit responses with respect to circuit parameters has undoubtedly stimulated renewed interest in the possibility of fully automating circuit design as well as the application of efficient gradient methods of minimization.

Originally proposed by Director and Rohrer as a useful tool for computer-aided circuit design[21,22], the method has since received considerable attention and further developments and applications have become widespread[23-35].

The main result of using the adjoint network method is that all required first-order partial derivatives of the objective function can be obtained using at most the results of two complete analyses of the circuit regardless of the number of parameters involved and without actually perturbing them. At best, one can obtain the first partial derivatives using the results of only the analysis of the given circuit. This is true, for example, in the one-port design of reciprocal circuits using the reflection coefficient. Second-order derivatives may also be obtained efficiently using the adjoint network method.

Director and Rohrer presented their fundamental paper on the generalized adjoint network and network sensitivities[21]. They applied it to design in the frequency domain of lumped linear time-invariant circuits, employing a least squares type of objective function[22]. It has also been shown how least pth and minimax types of objective functions can be used[23,24,25]. An extension of the adjoint network method to second-order sensitivities has been published[26]. Recent applications of the adjoint network concept include the simultaneous automated a.c. and d.c. design of linear integrated circuit amplifiers[27]. Of interest in that paper are the ideas on "growing" transistors.

Bandler and Seviora have extended the usefulness of the adjoint network method to gradient computations for circuits containing a variety of uniformly distributed elements[24,25]. Mokari-Bolhassan and Trick[28] have also considered distributed elements and have applied these ideas to the design of a lumped-distributed-active RC filter.

Seviora and Sablatash[29] have considered the adjoint network approach from the point of view of discrete networks, in particular, the adjoint digital filter.

Monaco and Tiberio have considered adjoint networks using wave variables[30]. Bandler and Seviora have also dealt with wave variables, showing how first- and second-order sensitivities can be efficiently computed for linear time-invariant (lumped and distributed) circuits[31,32]. Tables of useful sensitivity formulas have also been presented.

Group delay computations using the concept of the adjoint network have been considered[33,34].

CONCLUSIONS

Out of the profusion of literature that now exists on subjects relevant to computer-aided circuit design, which papers might a circuit designer interested in applying computer-oriented optimization techniques benefit from?

Introductions to optimization techniques have been published by Temes[2] and Bandler[8]. Another useful article, dealing specially with minimax approximation, has been published by Waren et. al.[10]. More recently, Bandler and Seviora have reviewed the application of the adjoint network method for design in the frequency domain[24].

Rather up-to-date survey papers on optimization methods have been published by Powell[36] and Fletcher[37].

REFERENCES

[1]G.C. Temes and D.Y.F. Zai, "Least pth approximation", IEEE Trans. Circuit Theory, vol. CT-16, pp. 235-237, May 1969.

[2]G.C. Temes, "Optimization methods in circuit design", in Computer Oriented Circuit Design, F.F. Kuo and W.G. Magnuson, Jr., Eds. Englewood Cliffs, N.J.: Prentice-Hall, 1969.

[3]R. Fletcher and M.J.D. Powell, "A rapidly convergent descent method for minimization", Computer J., vol. 6, pp. 163-168, June 1963.

[4]R. Fletcher and C.M. Reeves, "Function minimization by conjugate gradients", Computer J., vol. 7, pp. 149-154, July 1964.

[5]R. Fletcher, "A new approach to variable metric algorithms", Computer J., vol. 13, pp. 317-322, August 1970.

[6]D.H. Jacobson and W. Oksman, "An algorithm that minimizes homogeneous functions of n variables in n+2 iterations and rapidly minimizes general functions", Division of Engineering and Applied Physics, Harvard University, Cambridge, Mass., Technical Report No. 618, October 1970.

[7]J.W. Bandler and C. Charalambous, "Generalized least pth objectives for networks and systems", presented at the 14th Midwest Symposium on Circuit Theory, Denver, Colo., May 1971.

[8]J.W. Bandler, "Optimization methods for computer-aided design", IEEE Trans. Microwave Theory and Techniques, vol. MTT-17, pp. 533-552, August 1969.

[9]L.S. Lasdon and A.D. Waren, "Optimal design of filters with bounded, lossy elements", IEEE Trans. Circuit Theory, vol. CT-13, pp. 175-187, June 1966.

[10]A.D. Waren, L.S. Lasdon and D.F. Suchman, "Optimization in engineering design", Proc. IEEE, vol. 55, pp. 1885-1897, November 1967.

[11]A.V. Fiacco and G.P. McCormick, "The sequential unconstrained minimization technique for nonlinear programming, a primal-dual method", Management Science, vol. 10, pp. 360-366, January 1964.

[12]A.V. Fiacco and G.P. McCormick, "Computational algorithm for the sequential unconstrained minimization technique for nonlinear programming", Management Science, vol. 10, pp. 601-617, July 1964.

[13]Y. Ishizaki and H. Watanabe, "An iterative Chebyshev approximation method for network design", IEEE Trans. Circuit Theory, vol. CT-15, pp. 326-336, December 1968.

[14]S.I. Gass, Linear Programming. (3rd. Ed.). New York: McGraw-Hill, 1969.

[15]M.R. Osborne and G.A. Watson, "An algorithm for minimax approximation in the nonlinear case", Computer J., vol. 12, pp. 63-68, February 1969.

[16]J.W. Bandler and T.V. Srinivasan, "A new gradient algorithm for minimax optimization of networks and systems", presented at the 14th Midwest Symposium on Circuit Theory, Denver, Colo., May 1971.

[17]J.W. Bandler and P.A. Macdonald, "Optimization of microwave networks by razor search", IEEE Trans. Microwave Theory and Techniques, vol. MTT-17, pp. 552-562, August 1969.

[18]R. Hooke and T.A. Jeeves, "'Direct search' solution of numerical and statistical problems", J. ACM, vol. 8, pp. 212-229, April 1961.

[19]J.W. Bandler and A.G. Lee-Chan, "Gradient razor search method for optimization", presented at the 1971 IEEE G-MTT International Microwave Symposium, Washington, D.C., May 1971.

[20]J.W. Bandler, "Conditions for a minimax optimum", IEEE Trans. Circuit Theory, vol. CT-18, July 1971.

[21]S.W. Director and R.A. Rohrer, "The generalized adjoint network and network sensitivities", IEEE Trans. Circuit Theory, vol. CT-16, pp. 318-323, August 1969.

[22]S.W. Director and R.A. Rohrer, "Automated network design - the frequency-domain case", IEEE Trans. Circuit Theory, vol. CT-16, pp. 330-337, August 1969.

[23]R. Seviora, M. Sablatash and J.W. Bandler, "Least pth and minimax objectives for automated network design", Electronics Letters, vol. 6, pp. 14-15, January 1970.

[24]J.W. Bandler and R.E. Seviora, "Current trends in network optimization", IEEE Trans. Microwave Theory and Techniques, vol. MTT-18, pp. 1159-1170, December 1970.

[25]J.W. Bandler and R.E. Seviora, "Computation of sensitivities for noncommensurate networks", IEEE Trans. Circuit Theory, vol. CT-18, pp. 174-178, January 1971.

[26]G.A. Richards, "Second-derivative sensitivity using the concept of the adjoint network", Electronics Letters, vol. 5, pp. 398-399, August 1969.

[27]A.J. Brodersen, S.W. Director and W.A. Bristol, "Simultaneous automated a.c. and d.c. design of linear integrated circuit amplifiers", IEEE Trans. Circuit Theory, vol. CT-18, pp. 50-58, January 1971.

[28]M.E. Mokari-Bolhassan and T.N. Trick, "Computer-aided design of distributed-lumped-active networks", IEEE Trans. Circuit Theory, vol. CT-18, pp. 187-190, January 1971.

[29]R.E. Seviora and M. Sablatash, "A Tellegen's theorem for digital filters", IEEE Trans. Circuit Theory, vol. CT-18, pp. 201-203, January 1971.

[30]V.A. Monaco and P. Tiberio, "On linear network scattering matrix sensitivity", Alta Frequenza, vol. 39, pp. 193-195, February 1970.

[31]J.W. Bandler and R.E. Seviora, "Sensitivities in terms of wave variables", Proc. 8th Annual Allerton Conf. on Circuit and System Theory, Urbana, Ill., pp. 379-387, October 1970.

[32]J.W. Bandler and R.E. Seviora, "Wave sensitivities of networks", to be published in IEEE Transactions on Microwave Theory and Techniques.

[33]G.C. Temes, "Exact computation of group delay and its sensitivities using adjoint-network

concept", Electronics Letters, vol. 6, pp. 483-485, July 1970.

[34]G. Iuculano, V.A. Monaco and P. Tiberio, "Network sensitivities in terms of scattering parameters", Electronics Letters, vol. 7, pp. 53-55, January 1971.

[35]S.W. Director, "LU factorization in network sensitivity computations", IEEE Trans. Circuit Theory, vol. CT-18, pp. 184-185, January 1971.

[36]M.J.D. Powell, "Recent advances in unconstrained optimization", presented at the 7th Mathematical Programming Symposium 1970, The Hague, The Netherlands, September 1970.

[37]R. Fletcher, "Methods for the solution of optimization problems", presented at the Symposium on Computer-aided Engineering, Waterloo, Canada, May 1971.