Automatic Optimization of Engineering Designs - Possibilities and Pitfalls

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Computer-Aided Design

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IN THE CONTEXT of computer-aided design, the term optimization has currently taken on a wide range of meanings. On the one hand it can mean the one-at-a-time manual variation of the parameters of the system to be optimized from a remote time-sharing terminal using an analysis program. On the other it can mean the implementation of a more sophisticated automatic optimization strategy to produce the optimal design by batch processing. In terms of both computational effectiveness and ancillary equipment required the latter procedure is felt to be the more efficient. Of course, an automatic optimization program could also be used from a remote terminal.

This paper discusses some possibilities and pitfalls involved in the automatic optimization of engineering designs, whether from a remote terminal or by batch processing. Some of the pitfalls are, however, common to both manual and automatic optimization. Examples will be drawn from the author's own investigations and from those of colleagues at the University of Manitoba attending the author's course on optimization methods for computer-aided design.

Pitfalls

Many pitfalls in automatic optimization have little to do with the optimization strategies themselves – they arise due to the inadequate preparation of the problem. Needless to say, if a reliable model of the system to be optimized is not available, an optimal design would be difficult to achieve. Optimization can, however, be used effectively in the modeling of devices prior to optimization.[1]

An objective function derived from our analysis capability has to be formulated. There are pitfalls inherent in its choice. The author feels there is presently too much emphasis on least squares formulations. If, for example, it is required to approximate a desired circuit response specification in a least squares sense then, of course, a least squares formulation may be used. The designer would then not be surprised if his solution did not turn out to be an equal-ripple solution. Very often it is required to approximate a specified response such that the maximum deviation of the circuit response falls within a specified level or to force a network response between certain upper and lower levels. It is sometimes claimed that an optimum least squares solution provides an acceptable response. If this is so, it may be that the circuit has been overdesigned. It may have more elements than actually required to do the job. Such a design could not be described as optimal if an equally acceptable simpler and less costly design can be found.

Alternatives to least squares formulations are available.[1,2,3,4,5] Least pth approximation,[3] of which least squares is a special case and minimax approximation methods[4,5] can be used to obtain more nearly equal-ripple responses. As Bandler and Macdonald have demonstrated, the pitfalls of discontinuous partial derivatives of the objective function associated with the direct minimax formulation can be overcome.[6,7,8]

Constraints are not always limited to upper and lower bounds on the variable parameters.[2] There may be response constraints, e.g., for stability considerations, relative size constraints, e.g., in microwave networks, etc. Indeed, upper and lower response specifications can also be regarded as constraints.[4] A pitfall in neglecting constraints is an unacceptable "optimum". A pitfall in taking them into account is the possibility of the optimization process terminating at a constraint boundary when a better feasible solution exists.[2]

It does not seem to be widely appreciated among electrical engineers that most direct search methods, i.e. methods which do not rely on estimation of derivatives, are superior to steepest descent in their ability to detect and follow along ridges or narrow valleys in the parameter space.[2] The gradient vector can more profitably be exploited in efficient methods such as the Fletcher-Powell method.[9]

Possibilities

Having discussed some of the pitfalls let us turn to the possibilities.

In common with other techniques in the area of computer-aided design, the use of automatic optimization strategies allows us to remain closer to physical reality during the solution of a problem than classical analytic methods allow us to. There is less reason now for indulging in analytic niceties. Yet one can obtain optimal solutions to design problems for which current synthesis methods are unavailable.[4,8]

McDonald, a colleague at the University of Manitoba, has developed an algorithm which is based on steepest descent but which incorporates a more efficient valley following strategy.[10] The steepest descent strategy and the valley following strategy are invoked at appropriate stages during optimization and a facility for allowing random moves to be made is also incorporated. The net result seems to be a fairly efficient automatic optimization program which compares very favorably with some other published optimization methods including the razor search method of Bandler and Macdonald.[7] As with the razor search method which also allows random moves, McDonald's strategy is capable of getting itself out of trouble and should also perform reliably even in valleys with discontinuous derivatives.

The solution of nonlinear simultaneous equations can be carried out by optimization. S. Sud worked on the solution of

$$a_1\left(\frac{a_1}{4} + \frac{a_2}{5} + \frac{a_3}{7}\right) - \frac{1}{3} = 0$$

$$a_2\left(\frac{a_1}{5} + \frac{a_2}{6} + \frac{a_3}{8}\right) + \frac{3}{2} = 0$$

$$a_3\left(\frac{a_1}{7} + \frac{a_2}{8} + \frac{a_3}{10}\right) - \frac{5}{3} = 0$$

using pattern search.[11] The problem arose in the investigation of the stability of a control system. Any real solution was acceptable. Previously an analog computer was used. Solutions were found in about 1 to 2 seconds each on the IBM 360/65. One solution, for example, is $a_1 = 1.610$, $a_2 = -6.792$, $a_3 = 8.229$.

R. Hazel used pattern search to design an induction coil having a specified resistance and inductance. A long, straight, air induction coil of multi-layer tightly wound windings was chosen. The four variable parameters were those shown in Figure 1. Constraints involved wire gauges, current rating, the fact that certain dimensions had to be integral multiples of the wire diameter, restrictions to maintain the accuracy of the formula for the inductance and, of course, the requirement that all parameters be positive.

C. K. Ma carried out an investigation into an optimization problem previously considered by Temes and Zai.[3] This was the approximation in the least pth sense to a specified G = 5(1 + f)dB over the interval 1 to 2 MHz, where f is in MHz, by the gain of an active equalizer (Figure 2). Instead of the least pth method,[3] Ma applied both razor search[7] and pattern search.[11] Some observations made by Temes and Zai were confirmed.

C. W. Hasselfield and D. J. Richards investigated the design of crossover networks for a high fidelity speaker system (see Figure 3). Pattern search was used to optimize the elements of the network so that the predicted response of the system approximated the desired specifications in a suitably weighted least pth sense. To reduce peaks $p = 10$ was chosen. The complex impedances versus frequency of the speakers were measured and used during optimization. Subsequently, an adjustable attenuation network for the tweeter was also incorporated. The constructed system performed most satisfactorily.

Conclusion

In automatic optimization on the computer it is the time taken to evaluate the objective function that causes the greatest concern, so efforts are (or should be) directed at minimizing the number of evaluations of the objective function as well as making the evaluation process more efficient. In manual optimization, it is probably the delay required in planning and carrying out an inevitably simpler strategy that gives rise to inefficiency. One advantage which on-line designers claim is that they are more able to benefit from their insight into the problem. There seems no reason to the author why some of this insight could not also be exploited in automatic optimization.

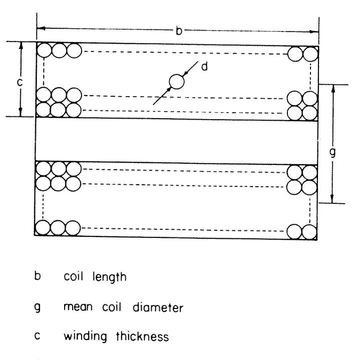

FIGURE 1 — Induction coil.

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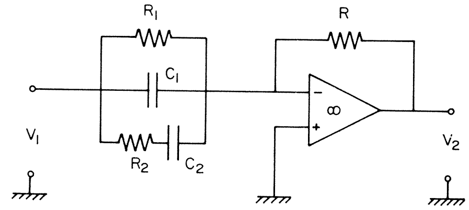

FIGURE 2 — Active equalizer.

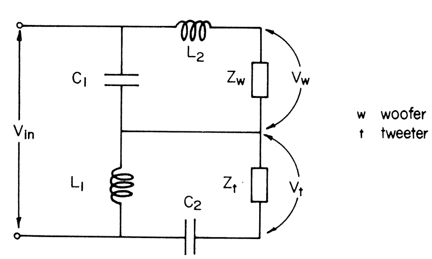

FIGURE 3 — Crossover network.