AN INTERACTIVE OPTIMAL POSTPRODUCTION TUNING TECHNIQUE UTILIZING SIMULATED SENSITIVITIES AND RESPONSE MEASUREMENTS

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ABSTRACT

An interactive postproduction tuning technique is presented. The technique uses linear programming iteratively for estimating necessary tuning amounts. It is completely general and is applicable to reversible and irreversible tuning processes. By eliminating completely the common trial and error approach it optimally exploits network response measurements.

Introduction

This paper addresses itself to the automation of postproduction tuning processes in microwave networks. Postproduction tuning is often essential in the manufacturing of electrical circuits. Bandler et al. [1] have already considered tuning as an integral part of the design process. Their results verified the importance of tuning in increasing the tolerances on the design parameters and in compensating for the uncertainties in the model parameters.

Here, we propose an interactive postproduction tuning technique which is based mainly on the formulation of tuning as a minimax optimization problem. By measuring the actual response and exploiting the availability of a good approximate model simulating the actual network under consideration, tuning can be carried out in a highly efficient iterative procedure. Each step requires one set of response measurements. A linear approximation of the minimax optimization problem is solved providing the amounts of tuning to be implemented experimentally. The tunable parameters are adjusted to the extent possible and the process is repeated until an optimum is achieved.

In what follows we present the mathematical formulation, the tuning algorithm and a microwave example which demonstrates how few adjustments appear to be necessary in practice.

Mathematical Formulation

A network design problem can be formulated as a minimax optimization problem as follows.

$$\text{Minimize } \phi_{n+1} \tag{1a}$$

subject to

$$f_i(\underset{\sim}{\phi}) \le \phi_{n+1}, \quad i = 1, \ldots, m, \tag{1b}$$

where f_i is a designer defined function, m is the number of these functions, $\underset{\sim}{\phi}$ is the n-vector of design components and ϕ_{n+1} is an additional independent variable.

Taking the tuning process into account we separate the design components into tunable elements and nontunable elements [2]. Let

$$\underset{\sim}{\phi}_t \triangleq \begin{bmatrix} \phi_1 \\ \phi_2 \\ \cdot \\ \cdot \\ \cdot \\ \phi_k \end{bmatrix} \tag{2a}$$

define the tunable design elements and

$$\underset{\sim}{\phi}_r \triangleq \begin{bmatrix} \phi_{k+1} \\ \phi_{k+2} \\ \cdot \\ \cdot \\ \cdot \\ \phi_n \end{bmatrix} \tag{2b}$$

define the nontunable elements. Manufacturing tolerances are associated with all elements. The deviations of the design parameters from their nominal values, the effect of parasitics and other uncertainties may cause violation of the design specifications. Tuning is carried out to force the response within its specified values. Mathematically the tuning problem can be formulated as a minimax optimization problem as follows.

$$\text{Minimize } z \tag{3a}$$

subject to

$$f_i(\underset{\sim}{\phi}_t^a + \Delta\underset{\sim}{\phi}_t, \underset{\sim}{\phi}_r^a) \le z, \quad i = 1, \ldots, m, \tag{3b}$$

$$\underset{\sim}{a} \le \Delta\underset{\sim}{\phi}_t \le \underset{\sim}{b}, \tag{3c}$$

where the superscript a denotes the actual manufactured values (not known exactly in practice) and the minimization is carried out by varying $\Delta\underset{\sim}{\phi}_t$. The linear constraints (3c) represent limits on the tuning amounts. For irreversible tuning where, for example, the elements are only permitted to increase, the limits are nonnegative.

Since we restrict the tuning amounts by equation (3c) a differentiable approximation can be used to estimate the change in the functions and the minimax optimization problem, namely (3), can be approximated as follows.

$$\text{Minimize } x_{k+1} \tag{4a}$$

subject to

$$f_i(\underset{\sim}{\phi}_t^a, \underset{\sim}{\phi}_r^a) + \sum_{j=1}^{k} \phi_j^x \frac{\partial f_i}{\partial \phi_j} x_j \le x_{k+1}, \quad i = 1, \ldots, m, \tag{4b}$$

$$\bar{a}_j \le x_j \le \bar{b}_j, \quad j = 1, \ldots, k, \tag{4c}$$

where

$$x_j \triangleq \frac{\Delta\phi_j}{\phi_j^x} \tag{4d}$$

and x_{k+1} is an additional independent variable. The sensitivities should be evaluated at the actual manufactured values $\underset{\sim}{\phi}^a$. In our implementation we

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utilize a suitable approximate network model ϕ^x for simulating these sensitivities, since the actual manufactured values are usually unknown. The functions f_i are evaluated by directly measuring the response.

Linear minimax optimization has been considered by Madsen et al. [3], and by Hachtel et al. [4]. Their reported success in solving different circuit design problems motivated us to employ similar concepts in the tuning problem.

The Tuning Process

The tuning procedure can be summarized by the following steps.

Step 1 Measure the network response. Check whether the design specifications are satisfied. If they are satisfied stop.

Step 2 Construct the linear program defined in (4). Use sensitivities which are derived from a suitable network model with the design parameters assumed at certain reasonable values ϕ^x (e.g., their nominal values). The upper and lower limits $\bar{a}_i$, $\bar{b}_i$, i=1,2,...,k are defined to ensure the validity of linear approximation and the type of tuning (reversible or irreversible).

Step 3 Check the output of the linear program. If the absolute value of the tunable amount of any tunable element is less than the minimum amount of tuning which can be carried out in practice we assume that it is zero. If all the absolute values of the tunable amounts are less than their corresponding minimum allowable values stop.

Step 4 Adjust the parameters to the extent possible by the amounts obtained from the linear program. If the maximum number of iterations specified has not been exceeded return to Step 1.

The network sensitivities can be updated using the Broyden rank one updating formula [5]. This will utilize the measurements in improving the assumed initial network model, and a better approximation of the actual sensitivities is obtained after each iteration.

Example

As an example we consider a broadband amplifier with a complex antenna load as shown in Fig. 1. The object is to match the antenna load over the frequency band 150 MHz to 300 MHz.

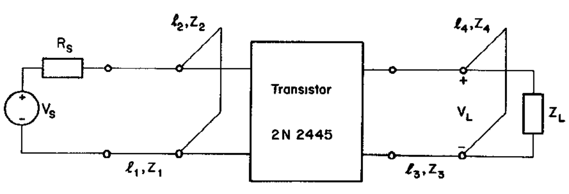

Fig. 1 The broad-band amplifier.

We considered the design given by Sanchez-Sinencio [6] as the nominal design for simulation purposes. The power gain at a certain frequency is given by $4R_S G_L |V_L|^2/|V_S|^2$, where R_S is the source resistance, G_L is the real part of the admittance of the load, $|V_L|$ is the absolute value of the voltage across the load and $|V_S|$ is the absolute value of the input voltage which we assumed to be unity. The response was assumed to be measured at sixteen uniformly distributed frequencies over the given frequency band. At each frequency an error function was defined as the absolute difference between the measured response and the 10 dB specified power gain value. The source resistance was assumed to be 50 ohms. The transistor scattering parameter values and the antenna impedances at the sixteen frequencies were obtained from Sanchez-Sinencio [6].

A number of different cases are considered here. In all of them, the tuning process is stopped when the response is within $\pm$ 0.7 dB of the specification. Also, we have assumed that the minimum tuning amount to be implemented is $\pm$ 0.1 percent of the nominal element value for all tunable elements. Any amount less than that is neglected. For Case 1 and Case 2 the four characteristic impedances are considered as the tunable elements. In Case 1 we have taken $\bar{b}_i = -\bar{a}_i = 0.1$, i=1,...,4. In Case 2 we have taken $\bar{b}_i = -\bar{a}_i = 0.05$, i=1,...,4. The four transmission-line lengths are considered to be the tunable elements in Case 3 with $\bar{b}_i = -\bar{a}_i = 0.1$, i=1,...,4.

The network sensitivities have been calculated using the network model with the components assumed at their nominal values. Tables 1 and 2 summarize the results for the three cases. A plot of the response before and after tuning for the three cases is given in Figs. 2, 3 and 4, respectively. It should be noted that the elements used in Case 3 are closer to nominal than in the first two cases, manifesting itself by tuning converging in one step. The Broyden updating formula has also been used. Quite similar results were obtained.

Table 1
Element Values

Element	Nominal Value	Actual Value Case 1&2	Actual Value Case 3	Percentage Deviation Case 1&2	Percentage Deviation Case 3
ℓ_1	2.012	2.25	1.9	11.82	-5.56
Z_1	86.76	74.07	93.4	-14.62	7.65
ℓ_2	0.976	0.85	0.982	-12.90	0.60
Z_2	97.57	83.33	93.45	-14.59	-4.25
ℓ_3	0.833	0.72	0.85	-13.56	2.04
Z_3	125.	111.11	129.87	-11.11	3.89
ℓ_4	0.927	1.07	0.91	15.42	-1.83
Z_4	132.	113.63	128.2	-13.91	-2.87

ℓ is the normalized length. The actual length equals $\ell\ \lambda_n/2\pi$, where λ_n is the wavelength at 230 MHz.
Z is the characteristic impedance in ohms.

Table 2
Results of Tuning

	Case 1	Case 2	Case 3
No. of Iterations	6	8	1
Tuned Element Values	Z_1 = 112.35	Z_1 = 109.89	ℓ_1 = 2.090
	Z_2 = 102.04	Z_2 = 106.38	ℓ_2 = 0.976
	Z_3 = 121.21	Z_3 = 117.64	ℓ_3 = 0.788
	Z_4 = 169.49	Z_4 = 147.70	ℓ_4 = 1.001

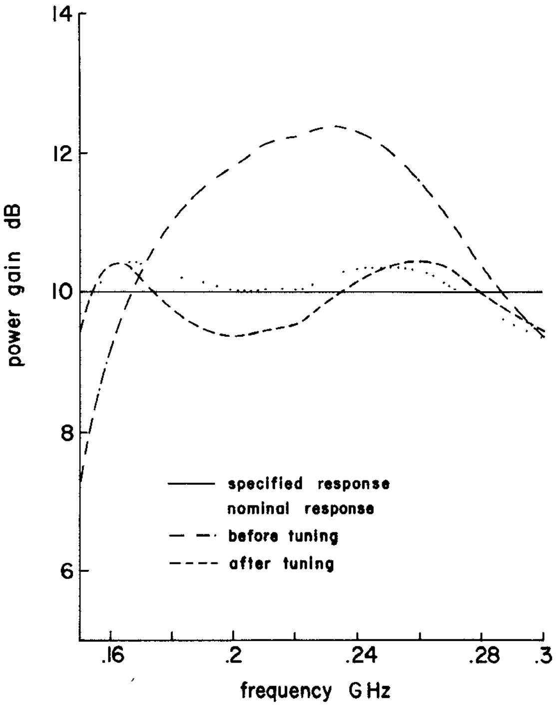

Fig. 2 The responses for Case 1.

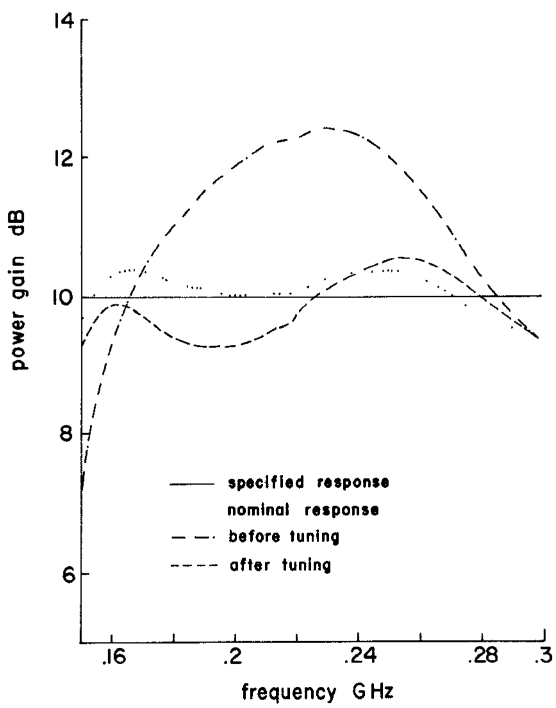

Fig. 3 The responses for Case 2.

Conclusions

In this paper we have presented an optimal postproduction tuning technique. The formulation of the tuning problem as a minimax problem allowed us to use the fast and efficient linear programming optimization technique for estimating the tuning amounts. In each step the tunable parameters are simultaneously allowed to change. The technique optimally uses available response measurements and eliminates completely the experimental trial and error and one-at-a-time approaches. The technique is quite

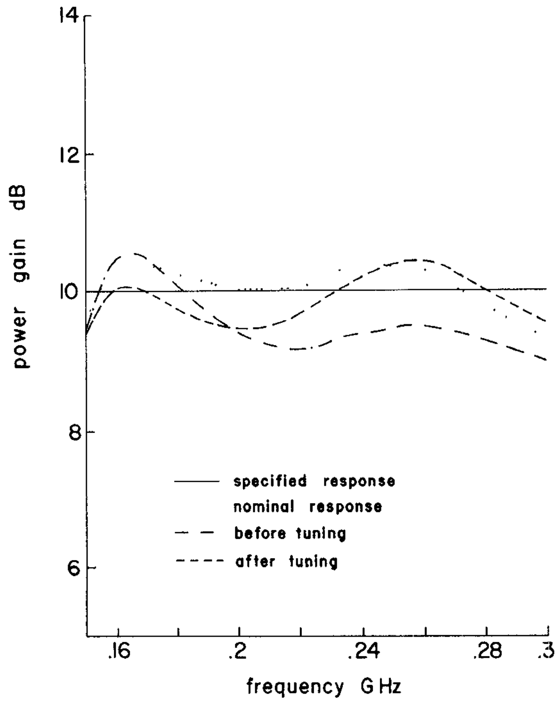

Fig. 4 The responses for Case 3.

general and can be applied to any microwave network for both reversible and irreversible tuning.

The formulation of the postproduction tuning problem as a linear programming problem facilitates the inclusion of many physical constraints such as the direction of tuning, the tuning amounts and the constraints on other functions obtained by simulation.

A good approximate model for the network for evaluating the sensitivities usually exists and these sensitivies can be updated using the measured data during the tuning process.

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