electroscope

SEMI - SYMBOLIC METHOD OF AC ANALYSIS AND OPTIMIZATION OF ELECTRONIC INTEGRATED CIRCUITS VIA MULTIPARAMETER LARGE CHANGE SENSITIVITY

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Abstract:
In this paper the theoretical basis and the algorithm of new method of electronic integrated circuit analysis and optimization in the frequency domain based on the multiparameter, large-change sensitivity conception and symbolic description of chosen two-ports have been presented. The method consists in determination increments in value of network functions caused by admittance changes of reactance elements as well as chosen two-ports, resulting from the frequency changes. The admittance two - ports, embedded in the main integrated circuit, have been divided into two groups: one - element two - ports and multi - element two - ports. For faster computer processing, the last ones have been described, symbolically. The main idea of the method proposed relies on it, that in first step the value of the network function is calculated at the first frequency, and then for every consecutive frequencies its increment, caused by admittance vector change of electronic circuit, is determined, only. It was shown, that its effectiveness is greater than traditional methods, especially in the case of circuits, in which the number of nodes of a network exceeds the number of the reactive elements as well as is growing together with the growing of number of frequency points. It was shown that numerical efficiency of this method can be speed up significantly by using special acceleration algorithm. Thanks to the symbolic description of some two-ports the effectiveness of this method has been increased considerably. Basing on this method the optimization task has been formulated and the example of optimization of integrated acoustic corrector with passive subcircuits described symbolically has been also included.

INTRODUCTION

Nowadays arises problem – how to optimally design of integrated circuits with embedded passive modules, especially, in frequency domain. Good final projects in hybrid technology need exact and fast designing methods and tools.
The frequency domain analysis (AC) is one of three basic analyses of electronic integrated circuits. At present, existing methods of the AC analysis differ each from other depending on the way of formulating circuit equations and the way of solving them. One of the most popular methods of formulating the set of equations, on account of its simplicity, is a nodal method (or its alteration so-called modified nodal method) [1, 2]. Also other methods are applied such, as the hybrid method, the state variable method or tableau method and their alterations (taking into consideration the sparseness of the circuit matrices or parallel processing). For solving the sets of circuit equations, the traditional numerical exact or iterative methods of solving linear systems of equations such, as the methods of Gauss, Gauss – Jordan, LU – factorization or Gauss – Seidel are used. Both operations are repeated for every frequency increasing in this way calculation time. The effectiveness of AC analysis becomes particularly important in case of calculations requiring multiple analyses, such as optimization or statistical analysis of large integrated circuits. Another approach to the AC analysis problem is symbolic methods [2], but they generate too long expressions in case of large integrated circuits. Therefore, some mixed numerical - symbolic methods can be a solution of this problem.
In traditional approach to the AC analysis, all circuit elements are treated in the same way, independently on how big influence on frequency characteristics they have, whereas the essential influence have reactance elements such as capacitors and inductors.
In this work, a new method, in which network function increment caused by admittance changes of reactance elements resulting from the change in the frequency has been taken into consideration, is presented. These admittance two-ports, extracted from the main circuit, have been divided into two groups: - one-element two-ports and – multi-element two-ports. For faster computer processing, the last ones have been described, symbolically. This situation occurs very often in RF systems being combination of large integrated circuits and passive circuits [3] embedded inside them. Direct connection separately designed modules can lead towards big errors because of mutual influences of these modules and parasitic [4, 5]. In order to take this effect into account, the definition of large-change, multiparameter sensitivity [6] has been used. The main idea of the method proposed relies on it, that in first step the value of the network function is calculated at the first frequency, and then for every consecutive frequencies its increment, caused by

admittance vector change of electronic circuit, is determined, only.

In Section 2 the theoretical background of the method is delivered. Section 3 details the main algorithm and efficiency of the new method compared to traditional ones. The acceleration algorithm for method proposed is delivered. In section 4 the computer optimization program based on new analysis method is delivered. In section 5 the computer program and three computational tests are described.

THEORETICAL BACKGROUND OF METHOD

Let the considered integrated circuit be represented by two-port shown in Fig. 1. Denote its input terminals as a pair **β** = (i_1, i_2) and its output terminals as **α** = (o_1, o_2).

Suppose that the following two-ports are extracted from this circuit:

a) one-element one-port called further as one-element two-port (because of unification of terms),

b) multi–element one-port called further as multi–element two-port.

In both cases are possible two connections regard of ground node (see Fig. 2. and Fig. 3.).

Let the k – th changed admittance y_k (one-element two-port) be connected to pairs of nodes: $\boldsymbol{\xi}_k = (\xi_{k1}, \xi_{k2})$, $k = 1, 2, \ldots, m$, and the k – th changed admittance Y_k (multi-element two-port) be connected to pairs of nodes: $\boldsymbol{\xi}_k = (\xi_{k1}, \xi_{k2})$, $k = m+1, m+2, \ldots, m+M$; total number of ports is $N = m + M$.

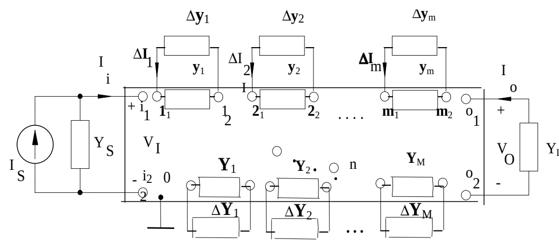


Fig. 1: Integrated circuit with extracted two-ports prepared for large-change sensitivity calculation

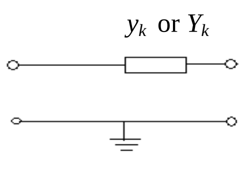


Fig. 2: One-element or multi – element two-port not grounded

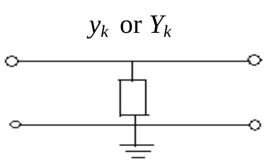


Fig. 3: One-element or multi – element two-port grounded

Let the network function being of our interested is $H(\mathbf{p})$, where: $\mathbf{p} = [p_1, p_2, \ldots, p_N]^T$ – vector of circuit parameters such as admittances of one-element two-ports (capacitors and inductors) and multi-element two-ports. The increment in value of the $H(\mathbf{p})$ function caused by the 'N' circuit parameters simultaneous changes can be written

$$\Delta H = H_N(\mathbf{p} + \Delta\mathbf{p}) - H_0(\mathbf{p}) \qquad (1)$$

where: H_0 – value of the function before any change, H_N - value of the function after the change 'N' parameters caused by frequency increment,

$$\Delta\mathbf{p} = [\Delta p_1, \Delta p_2, \ldots, \Delta p_N]^T \qquad (2)$$

for one-element two-ports the k-th parameter increment is equal to

$$\Delta p_k = \Delta y_k = \begin{cases} j\Delta\omega^* C_k, & \text{capacitor} \\ (j/(\omega_0{}^* L_k))^*\Delta\omega/(\omega_0+\Delta\omega), & \text{inductor} \end{cases} \qquad (2a)$$

where:

$$\omega_0 = 2\pi^* f_0, \qquad \Delta\omega = 2\pi^*(f - f_0)$$
$$k = 1, 2, \ldots, m\,,$$

for multi - element two - ports:

$$\Delta p_k = \Delta Y_k = Y_k(\omega, \mathbf{x}_k) - Y_k(\omega_0, \mathbf{x}_k) \qquad (2b)$$

where: $k = m+1, m+2, \ldots, m+M$,

M – number of multi-element two-ports, and

$$Y_k(\omega, \mathbf{x}_k) = Nom_k(\omega, \mathbf{x}_k)/Den_k(\omega, \mathbf{x}_k) \qquad (2c)$$

is the admittance rational function of k – th two – port, given symbolically. In case of bigger circuit, this admittance can be described by some sequence of expressions (SoE) [5], $\mathbf{x}_k$ – vector of parameters (such as R, C, and L) included in k – th two-port.

The increment of function (1) can be calculated using concept of the two-port transimpedance [7] and its multiparameter large-change sensitivities [6, 8].

Two-port transimpedance and its properties

In this work, the unified, called *the transimpedance method* is proposed for transimpedance determination [7].

Definition 1. Let Z denotes the inverse of the node admittance matrix: $\mathbf{Y}^{-1}$. Let $\alpha = (\alpha_1, \alpha_2)$, $\boldsymbol{\beta} = (\beta_1, \beta_2)$ be pairs of natural numbers, representing circuit nodes of ports **α** and **β.** The transimpedance is defined as

$$Z(\boldsymbol{\alpha},\boldsymbol{\beta}) \;=\; z_{\alpha_1\beta_1} - z_{\alpha_1\beta_2} - z_{\alpha_2\beta_1} + z_{\alpha_2\beta_2} \qquad (3a)$$

where: $z_{\alpha_i\beta_j}$ - is (α_i, β_j) entry of $\mathbf{Y}^{-1}$ matrix.

Its numerical value can be determined by calculating the appropriate elements of the $\mathbf{Y}^{-1}$ matrix; for instance, by the matrix inversion process.

Two-port transimpedance expresses the relation between the voltage responses in the port **α** and the current excitation in the port **β**. It can be explained using some circuit model. Let us consider the two - port shown in Fig. 4, in which the circuit resulted after extracting all passive two-ports, short – circuiting all independent voltage sources and open – circuiting all independent current sources is characterized by the transimpedance matrix *Z*.

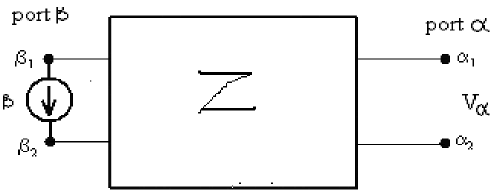


Fig. 4: Explanation of the transimpedance $Z(\boldsymbol{\alpha},\boldsymbol{\beta})$ definition

Port β = (β_1, β_2) is formed by extracting element $\boldsymbol{y_\beta}$ and port α = (α_1, α_2) is formed by extracting element $\boldsymbol{y_\alpha}$. Dividing voltage V_α (measured at port α) by excitation current I_β (at port β) we get the transimpedance from port β to port α:

$$V_\alpha / I_\beta = Z(\boldsymbol{\alpha},\boldsymbol{\beta})\,. \qquad (3b)$$

As it was shown in [6], the transimpedance (3) has the following property - the increment of the two-port transimpedances due to the ξ - th admittance large change Δy_ξ, is

$$\Delta Z(\boldsymbol{\alpha},\boldsymbol{\beta}) = K \;\cdot Z(\boldsymbol{\alpha},\boldsymbol{\xi})Z(\boldsymbol{\xi},\boldsymbol{\beta})\,, \qquad (4a)$$

where: $\boldsymbol{\xi}$ - ξ - th admittance port,

$$K \;= -\frac{1}{1/\Delta y_\xi + Z(\boldsymbol{\xi},\boldsymbol{\xi})}\,. \qquad (4b)$$

As we see, the increment of a two-port transimpedance $\Delta Z(\boldsymbol{\alpha},\boldsymbol{\beta})$ due to ξ - th admittance large - change depends on three new transimpedances nominal and the increment Δy_ξ.

We want to determine the increment $\Delta Z(\boldsymbol{\alpha},\boldsymbol{\beta})$ when number '*N*' admittances are changed, simultaneously. Taking into account the relationships mentioned above, it can be shown that the two-port transimpedances will be changed on each step, in accordance with the recurrent formula [6]:

$$Z_\xi(\boldsymbol{\alpha},\boldsymbol{\beta}) = Z_{\xi-1}(\boldsymbol{\alpha},\boldsymbol{\beta}) + K_{\xi-1} Z_{\xi-1}(\boldsymbol{\alpha},\boldsymbol{\xi}) Z_{\xi-1}(\boldsymbol{\xi},\boldsymbol{\beta}) \qquad (5a)$$

$\xi = 1, 2,\ldots, N$,

where: $Z_0(\boldsymbol{\alpha},\ \boldsymbol{\beta})$ - the transimpedance nominal at $f = f_0$ (parameters are unchanged),

$Z_\xi(\boldsymbol{\alpha},\ \boldsymbol{\beta})$ - the transimpedance after ξ -th - parameter increment caused by frequency change,

$$K_{\xi-1} \;=\; -\frac{1}{1/\Delta y_\xi \;+\; Z_{\xi-1}(\boldsymbol{\xi},\ \boldsymbol{\xi})}\,. \qquad (5b)$$

Network function and its sensitivity calculation

The voltage transmittance in nominal conditions (without any change), as it has been derived in [7, 8], is:

$$T_v = \frac{V_O}{V_I} = \frac{V_{O1} - V_{O2}}{V_{i_1} - V_{i_2}} = \frac{z_{O1i_1} - z_{O1i_2} - z_{O2i_1} + z_{O2i_2}}{z_{i_1i_1} - z_{i_1i_2} - z_{i_2i_1} + z_{i_2i_2}} = \frac{Z(\boldsymbol{\alpha},\boldsymbol{\beta})}{Z(\boldsymbol{\beta},\boldsymbol{\beta})}\,. \qquad (6)$$

In similar way, other network functions like transimpedance, input impedance and output impedance can be also by the appropriate two-port transimpedances expressed:

$$T_{vi} = Z(\boldsymbol{\alpha},\boldsymbol{\beta}),\quad Z_{in} = Z(\boldsymbol{\beta},\boldsymbol{\beta}),\quad Z_{out} = Z(\boldsymbol{\alpha},\boldsymbol{\alpha})\,. \qquad (7)$$

When frequency is changed, then susceptances of reactive elements are also changed in accordance with relationship (2) and in consequence appropriate admittances are changed, too. These increments are marked in Fig.1 as Δy_k or ΔY_k. So, having the increments of appropriate transimpedances, obtained applying the recurrence formula (5), the increment of network functions can be calculated. One should be noticed certain essential fact, that it is possible to calculate demanded transimpedances after the ξ - th admittance large-change on the basis of knowledge about the values of appropriate nominal transimpedances, only. For this purpose we create the nominal transimpedance matrix:

$$Z^{(0)} = \left|\begin{array}{lllll} Z(\xi_1,\xi_1), & Z(\xi_1,\xi_2), & ..Z(\xi_1,\xi_N), & Z(\xi_1,\xi_\alpha), & Z(\xi_1,\xi_\beta) \\ Z(\xi_2,\xi_1), & Z(\xi_2,\xi_2), & ..Z(\xi_2,\xi_N), & Z(\xi_2,\xi_\alpha), & Z(\xi_2,\xi_\beta) \\ & & & & \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ Z(\xi_N,\xi_1), & Z(\xi_N,\xi_2), & ..Z(\xi_N,\ _N), & Z(\xi_N,\xi_\alpha), & Z(\xi_N,\xi_\beta) \\ Z(\xi_\alpha,\xi_1), & Z(\xi_\alpha,\xi_2), & ..Z(\xi_\alpha,\xi_N), & Z(\xi_\alpha,\xi_\alpha), & Z(\xi_\alpha,\xi_\beta) \\ Z(\xi_\beta,\xi_1), & Z(\xi_\beta,\xi_2), & ..Z(\xi_\beta,\xi_N), & Z(\xi_\beta,\xi_\alpha), & Z(\xi_\beta,\xi_\beta) \end{array}\right| \qquad (8a)$$

Direct applying the recursion in the computational process according to the pattern (5) is disadvantageous because of repetition the same calculations while determining the same transimpedances. Creation the initial transimpedance matrix (8a) and its reduction alongside the matrix diagonal using the relations (5a) and (5b) as the suppression formula appears to be more beneficial. As a result of the reducing process a sequence of arrays is obtained: $Z^{(0)} \to Z^{(1)} \to Z^{(2)} \to ... \to Z^{(N)}$. Every next array is smaller than previous one. In the last step an array is obtained with the 2x2 dimension (8b);

$$Z^{(N)} = \begin{vmatrix} Z(\xi_\alpha, \xi_\alpha) & Z(\xi_\alpha, \xi_\beta) \\ Z(\xi_\beta, \xi_\alpha), & Z(\xi_\beta, \xi_\beta) \end{vmatrix}, \qquad (8b)$$

its elements enable us to calculate network functions (6), (7).

ALGORITHMS

The main algorithm

Basing on the theory delivered above the main algorithm called further as LCS algorithm can be formulated in the following way:

Step 1. Obtain the small - signal equivalent circuit and get the information about the network function required and the passive two-ports. Determine the one-element and multi-element ports. Determine the set of the frequencies, at which the ac analysis of the circuit should be carried out. Enter data concerning circuit structure and elements values.

Step 2. Formulate the admittance matrix (NAM) (or modified admittance matrix (MNAM)) of the circuit at $f = f_0$.

Step 3. Accepting f_0 (it is possible often to accept f_0 = 0) calculate the initial transimpedances according to (3) and complete the transimpedance matrix initial $Z^{(0)}$ (8a).

Step 4. for consecutive frequencies determine the admittance increments according to (2) (*frequency loop*) do:

for each one-element two-port, (*elements loop*) successively (for $k = 1, 2, \ldots, m$) - carry out reduction of the Transimpedance matrix (8a) according to the relationships (5).

end

for each multi-element two-port, successively (for $k = m + 1, m + 2, \ldots, m + M$) (*elements loop*) - carry out reduction of the transimpedance matrix (8a) according to the relationships (5).

end

Step 5. Calculate the demanded network functions using elements of reduced matrix (8b).

end (*of frequency loop*).

Basing on the theory outlined above the Matlab scripts have been written, that allowed us many comparison tests to carry out. Comparing operations done in accordance with the LCS algorithm and in accordance with a traditional one, it can be noticed that in the traditional method the frequency loop includes both formulating of '*n*' equations and solving them (Fig. 5), whereas, in the method presented only reduction of the transimpedance matrix of '*N* x *N*' size is needed (Fig. 6). It should be noticed, by the chance, that usually $N << n$ (where: N - is the number of reactive ports, n - is the number of network nodes). Moreover, the transimpedance matrix $Z^{(0)}$ is formed only once at the beginning.

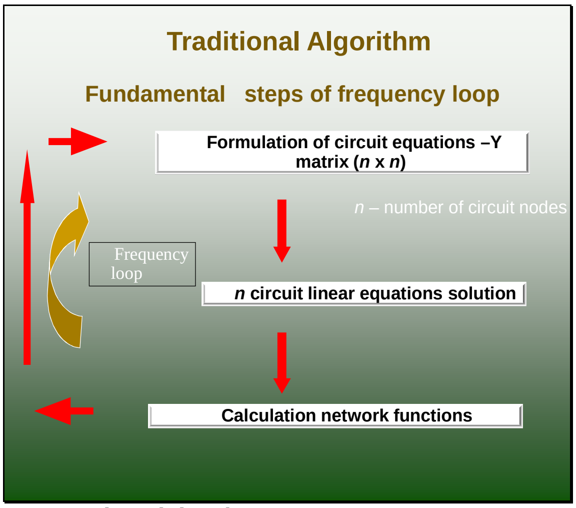


Fig. 5: Traditional algorithm

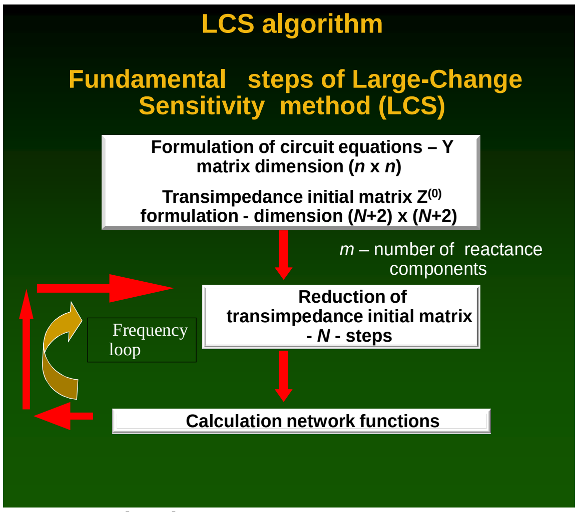


Fig. 6: LCS algorithm

The numerical comparison tests carried out for circuits consisting one–element two-ports, showed (Fig. 7. and Fig. 8.), that the LCS method needs less calculation cost than the Gauss-Jordan or LU–factorization methods, especially in the case of a large number of frequencies and for growing difference between the number of circuit nodes and the number of passive two-ports.

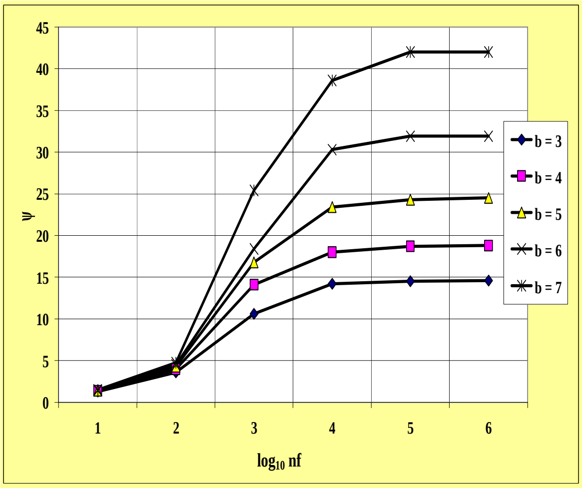


Fig. 7: Comparison of LCS method with Gauss-Jordan: $\psi = t_{GJ} / t_{LCS}$ against number of frequency points, b = n - N as parameter, t – calculation time

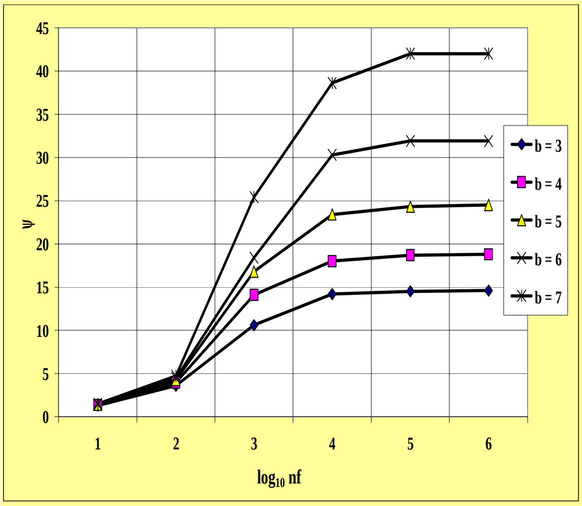


Fig. 8: Comparison of relative efficiency of LCS and LU - factorization ($\psi = t_{LU} / t_{LCS}$) against number of frequency points, b = n - m as parameter

The results of this comparison were depicted in Fig. 4. and Fig. 5. More details concerning this comparison can be found in work [9].
Depending on network functions that have to be calculated, some transimpedances can be omitted, too. In this way, it is possible to reduce the number of arithmetical operations in this method, significantly.

Acceleration method

Because in integrated circuits exist many small capacitances, the computational efficiency of presented AC analysis method can be yet more speeded up. For sufficiently small values of $|\Delta y|$, what in case of hybrid π model capacitors of 'integrated transistors' the following condition is valid for sufficiently low frequencies:

$$\left|\Delta y_{\xi}\right|\left|Z_{\xi-1}(\xi,\xi)\right|\langle\langle 1 \Rightarrow K_{\xi-1} = -\left|\Delta y_{\xi}\right| \to 0 , \qquad (9a)$$

that leads to the approximation (see (5a) and (5b)):

$$Z_{\xi}(\boldsymbol{\alpha},\boldsymbol{\beta}) \approx Z_{\xi-1}(\boldsymbol{\alpha},\boldsymbol{\beta}) . \qquad (9b)$$

Hence, the k - th step in the LCS algorithm, can be omitted, which decreases the number of arithmetical operations by 3. As long as this relation is fulfilled these operations can be omitted many times. In practice, we use sufficiently small number ε_A that fulfils inequality:

$$\left|\Delta y_{\xi}\right|\left|Z_{\xi-1}(\xi,\xi)\right|\langle \varepsilon_A \langle 1 . \qquad (10)$$

Basing on this fact, the following LCS accelerated algorithm has impact in elements loops in step 4 of the main algorithm.

For i = 1:nf % frequency loop
 delta_omega = 2π ($f_i - f_0$);
 %*where:* 'delta_omega' *means* $\Delta\omega$
 Calculate delta_y_k;
 for k = 1:m % *elements loop*
 if (abs(delta_y_k**)*abs(**$Z(\xi_k, \xi_k)$**))** > ε_A
 % *taking*

$$K_{k-1} = -\frac{1}{1/\text{delta\_y}_k + Z_{k-1}(\xi_k,\xi_k)}$$

 carry k–th reducing step out according with (5);
 end
 end
 calculate values of network functions;
end

OPTIMIZATION

Because the LCS analysis method appeared to be very efficient method it should be effective in solving some circuit optimization tasks. Therefore, the following optimization task was formulated.
We want to minimize the difference between calculated and demanded functions on some set of parameters. The optimization task has the following form:

$$\min_{x \in \mathbf{x}} \left(\sum_{i}^{n_f} \left[F_{calc}(f_i, \mathbf{x}) - F_{dem}(f_i)\right]^2 \qquad (11)$$

where: $\mathbf{x} = \left\{x_j : x_{\min_j} \le x_j \le x_{\max_j},\ j = 1,2,\ldots,n_x\right\}$

n_f - number of frequency points,
n_x - number of parameters.

To accomplish this task the optimization computer program was elaborated. The structure of the optimization program is shown in Fig. 9.

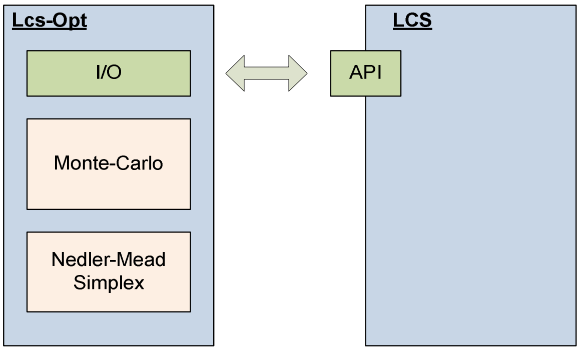


Fig. 9: The structure of optimization program

The optimization program consists of two modules:
a) the LCS analysis module, and
b) the Lcs-Opt optimization module

The LCS analysis module containing the universal computer program performs the AC analysis of integrating circuits with embedded passive two-ports by using semi-symbolic LCS method.

In the optimization module two optimization procedures: Monte Carlo and Nelder -Mead Simplex were applied. The first one is the global search method and its calculation result makes the starting point up for the Nelder -Mead Simplex local search method, which improves the search result.

Whole optimization system has been written in C++ computer language.

COMPUTATIONAL TESTS

Test 1 – Acceleration method

The efficiency of the acceleration algorithm was tested using µA741 OpAmp circuit (Fig. 11), having 25 transistors and working in inverting mode of operation and supplied with +/-15 V. The parameters of small signal equivalent hybrid π transistor models [10] were taken from PSpice computer program [11].

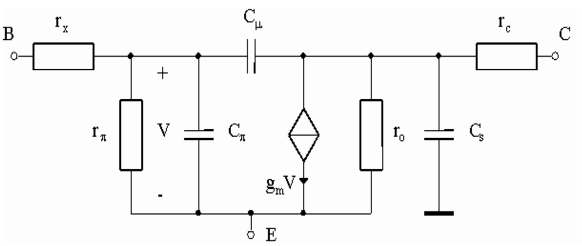


Fig. 10: Hybrid π transistor model

Number of nodes n = 75 (including internal nodes), number of reactance elements N = 51. The following vector of reactance element increments was determined as: $\Delta\mathbf{p} = [\Delta p_1, \Delta p_2, ..., \Delta p_m]^T = \Delta\omega$ $[C_{\pi1}, C_{\mu1}, C_{\pi2}, C_{\mu2}, \dots C_{\pi25}, C_{\mu25}, C_c]^T$; where: C_c – compensation capacitance. As the initial frequency was accepted f_0 = 1 Hz. All analyses were carried out on the set of frequencies $f_i \in F = \{1Hz, 1GHz\}, i = 1,2,...,n_f$ at $n_f = 10^4$ points placed in accordance with logarithmic scale. The calculations were performed according with the main LCS algorithm without acceleration and obtained characteristics showed full accordance with those given by PSPICE (denoted as result A). Next, the calculations were performed according with the LCS accelerated algorithm for different values of ε_A (denoted as B). For each result, for comparison purposes, the following computer processor independent measures were estimated:

a) the coefficient of run time reduction:

$$\Gamma = \tau_A/\tau_B, \qquad (12)$$

where: τ_A – the time of calculations performed in accordance with LCS algorithm without acceleration, τ_B - the time of calculations performed in accordance with LCS accelerated algorithm;

b) the relative error:

$$\delta\,[\%] = 100\,\left|(T_B - T_A)/T_A\right| \qquad (13)$$

where: T_A – the characteristic obtained as result A,
T_B - the characteristic obtained as result B.

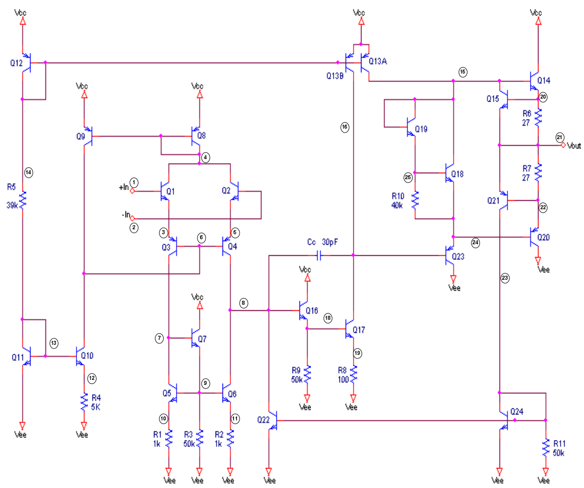


Fig. 11: µA741 OpAmp circuit prepared for analysis

As accuracy of approximation was taken the maximal value of measure (13) over frequency domain. These results were plotted as the functions of ε_A, for magnitude of voltage gain, which is depicted in Fig. 12. As we see, the acceleration method works quite well for $\varepsilon_A \leq 10^{-1}$, where the calculation time is reduced by almost 30 times! It results from this fact, that most of capacitors existing in integrated circuit (µA741) have small capacitance (the biggest one is compensation capacitor C_c = 30 pF).

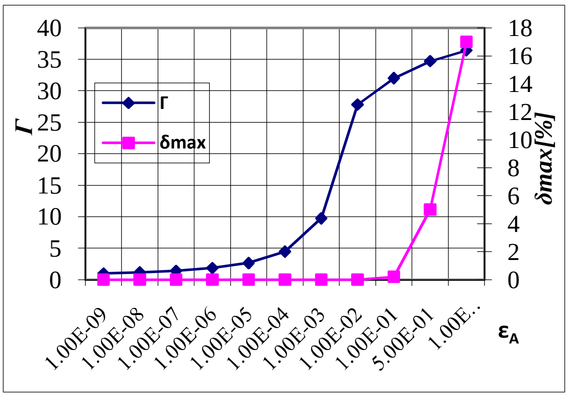


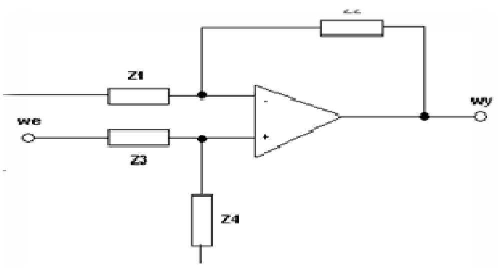
Fig. 12: The coefficient of calculation time reduction and relative error of approximation vs. ε_A for magnitude of voltage gain

Test 2 – Symbolic description

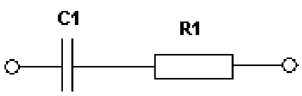
The influence of symbolic description of multi – element two – ports on effectiveness of ac analysis was tested during analysis of the acoustic corrector.

For the acoustic corrector (Fig. 13a) two analyses were performed:

a)



b)



Z1:

c) Z2:

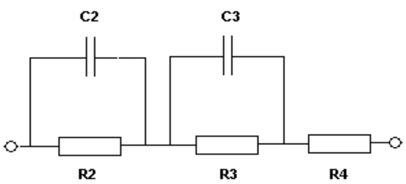


Fig. 13: Schematic diagram of the acoustic corrector used as the test circuit: a) main circuit, b) two-element two-port Z1, c) fife-element two-port Z2

a) Fully numerical analysis using Gauss elimination method, and

b) LCS analysis with two-ports: Z1 and Z2, described symbolically.

The acoustic corrector uses µA741 OpAmp in noninverting mode of operation which has internal structure of the circuit as in test1 (Fig. 3). Full internal circuit with the embedded passive subcircuits was analyzed.

The admittances of the multi-element two-ports are described by the following symbolic expressions: for two-element two-port Z1 and for five-element two-port Z2, respectively:

$$Y1(s) = 1/Z1(s) = sC1/(sC1R1+1) \qquad (14)$$

$$Y2(s) = 1/Z2(s) \qquad (15)$$

where:

$$Z2(s) = R2/((sC2R2+1)) + R3/(sC3R3+1) + R4$$

$s = j\omega$, Z3 = R5 = 50, Z4 = R6 = 10k, R1 = 820, C1 = 3.3 µF, R2 = 2.2 M, C2 = 3.9 nF, R3 = 33 k, C3 = 1.8 nF, R4 = 6.2 k.

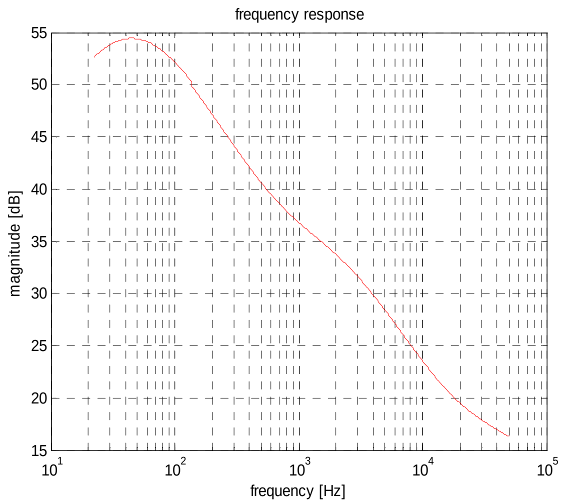


Fig. 14: The RIAA correction characteristics

Both analyses gave the same results – the correction characteristics satisfying the RIAA requirement, which is depicted in Fig. 14. The coefficient of run time reduction achieved value: $\Gamma = \tau_G/\tau_{LCS} = 6.7428$ for 1000 frequency points, and $\Gamma = 8.5725$ for 10000 frequency points, where: τ_G - run time for Gauss method, τ_{LCS} - run time for mixed numeric – symbolic LCS method. It is evident, that the coefficient of run time reduction will be better if number and the models of passive modules are bigger.

Test 2 – Results of optimization

For the integrated circuit shown in Fig. 15 we want to obtain the RIAA correction characteristics shown in Fig. 14. The elements of passive two-ports , described earlier, which have been placed inside the integrated circuit (two-element grounded two-port Z1 (Fig. 13b) and five-element ungrounded two-port Z2 (Fig. 13c)) were used as the optimization parameters.

The vector of optimization parameters is

$$\mathbf{x}=[R1,R2,R3,R4,C1,C2,C3]^T \quad (16)$$

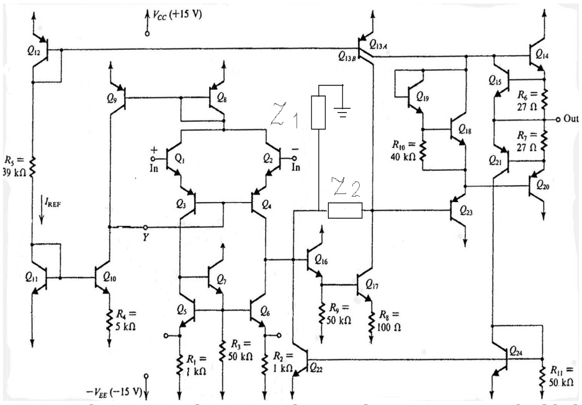


Fig. 15: The integrated circuit with Z1 and Z2 two-ports embedded inside

The optimization parameters have been restricted by lower and upper bounds:

R_min(1) = 500 Ω; R_max(1) = 10e+6 Ω;
R_min(2) = 1e+5 Ω; R_max(2) = 100e+6 Ω;
R_min(3) = 1e+5 Ω; R_max(3) = 100e+6 Ω;
R_min(4) = 1e+1 Ω; R_max(4) = 100e+3 Ω;

```
C_min(1)=1e-10F; C_max(1)=100e-6F;
C_min(2)=1e-12F; C_max(2)=10e-9F;
C_min(3)=1e-12F; C_max(3)=10e-9F;
```

Whole active corrector works in the circuit shown in Fig. 16.

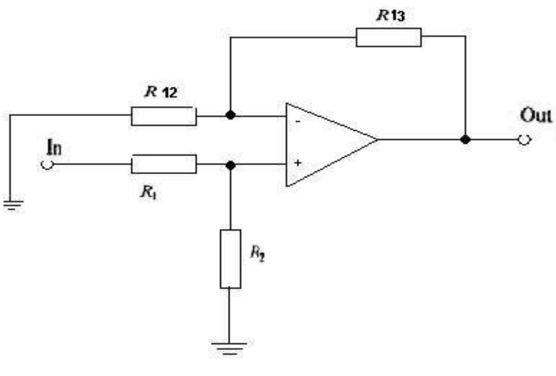


Fig. 16: Simulated circuit

Four additional external resistors R_1, R_2, R_{12}, and R_{13} were attached to reach proper level of amplification. Finally we were taken $R_{13}/R_{12} = 10^3$ that ensures 60 dB of maximal amplification. The criterion function (11) have been calculated at $n_f = 78$ frequency points. The corrector magnitude voltage gain after Monte Carlo procedure of optimization is shown in Fig. 18. (red curve).

The values of parameters obtained after first stage of optimization (Monte Carlo) made up the starting vector for the Nelder -Mead optimization procedure (second stage).

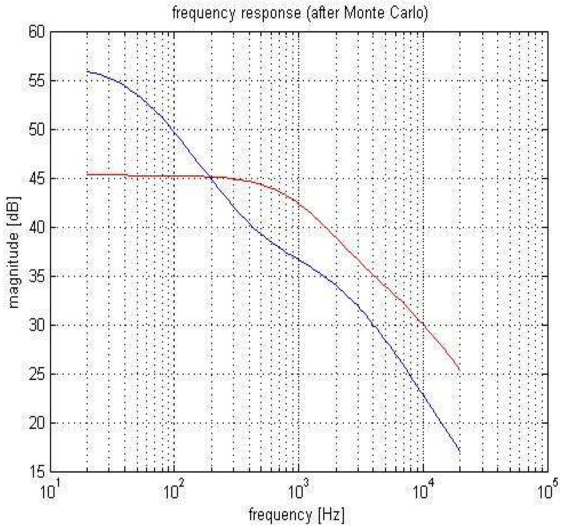


Fig. 17: The corrector magnitude characteristics after Monte Carlo optimization procedure:
- calculated (red)
- demanded (blue)

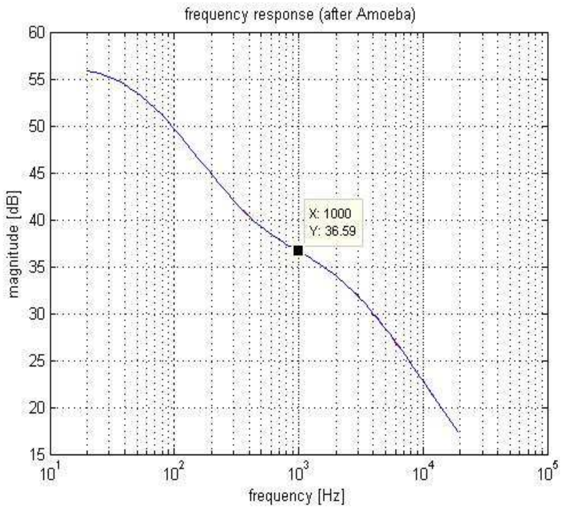


Fig. 18: The final corrector magnitude characteristics after Nelder – Mead optimization procedure:
- calculated (red)
- demanded (blue)

Final optimal parameters are:

r1 = 7.9715e+004 (~80 kΩ),
r2 = 9.9838e+007 (~100 MΩ),
r3 = 4.4987e+005 (~450 kΩ),
r4 = 475.7430 (~470Ω),
c1 = 7.1751e-007 (~720 nF),
c2 = 5.3775e-010 (~540 pF),
c3 = 1.8169e-010 (~180 pF),

Obtained final result is excellent but not unique, what is well known, because impedances Z1 and Z2 have no unique solution in set of parameters **x**. The mean-squared approximation error reached value 0.0416 dB, which is much less than 1 dB demands of RIAA. The nonstandard values can be further reached by laser correction in thick film passive module. It is well known, that the laser trimming increases the noise ratio and decreases the reliability of the hybrid circuit. Some method of minimization of number of trimmed elements as well as the length of trimming traces can be found in work [12]. Each optimization procedure Monte Carlo and Nelder-Mead [13] made about 2000 steps and the overall calculation time was 29.587 seconds, only.
So, the proposed semisymbolic LCS analysis method seems to be very effective tool for integrated RF circuits with embedded passive modules design.

CONCLUSIONS

A new method of AC semi-symbolic analysis of integrated electronic circuits with embedded passive subcircuits, based on the definition of multiparameter large-change frequency sensitivity, has been presented. This method appears to be particularly convenient to analyze integrated circuits with embedded passive subcircuits such as correction circuits, trap circuits, passive filters, and strip lines, matching or decoupling circuits. Thanks to converting the recursive processes into the task of reduction of transimpedance matrix, the repeated calculations were avoided as well as a greater transparency of the method was reached. Computer experiments carried out showed that the elaborated method could be even several dozen times more effective than the method of Gauss – Jordan and several times more effective than the method LU–factorization. The efficiency of the method presented is greater, if the difference between the number of circuit nodes and the number of passive two-ports is larger. Moreover, it should be pointed out that the relative effectiveness is growing together with growing of the number of frequency points. In the method presented it is possible to reduce the number of arithmetical operations, significantly, by omitting unnecessary transimpedance reduction steps. The acceleration method outlined in this work showed significant calculation time decrease (almost 30 times) with good accuracy of approximation. The efficiency of the method was further almost ten times boosted by applying symbolic description of multi-element passive two-ports. These acceleration methods seem to be very useful when analyzing large integrating circuits, having big passive two-ports, over wide range of frequencies. This symbolic description, however, makes the LCS method more flexible, while integrated circuit optimizing.

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