

COMPUTER AIDED DISTORTION ANALYSIS OF SWITCHED CAPACITOR FILTERS IN THE
FREQUENCY DOMAIN

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Abstract

A Volterra series based distortion analysis of nonlinearities of op amps and parasitic capacitances ... has been developed and implemented in the DIANA-SC program. Examples and tests demonstrate the use and the efficiency.

Summary

1. Introduction

In recent years switched capacitor (s.c.) techniques have allowed to integrate a variety of signal processing circuits such as audio and PCM filters, speech synthesizers. In all these applications the signal to noise ratio (S/N) of the circuit can be ruined by the inherent nonlinearities of the circuit (op amps, parasitic capacitances ...). Accurate computations of linear effects such as frequency, aliasing, noise and sensitivity characteristics require already CAD tools [1] for small sized networks. Even more so the analysis of the second and third order harmonic distortion cannot be done by pen and paper techniques.

In this paper we first describe briefly a frequency domain method for the distortion analysis of weakly nonlinear switched capacitor circuits using the Volterra series [2]. Much efficiency can be obtained by combining it with the fast frequency domain analysis of linear switched capacitor circuits [3-5] (extended modified nodal analysis (MNA) matrix, sparse matrix methods, adjoint switched capacitor network and compaction techniques). This distortion analysis of second and third order harmonics of arbitrary circuits has been implemented and tested in the DIANA program, on a VAX 11/780. Plots are given for the well-known fifth order elliptic lowpass PCM filter, which illustrate the use as a CAD tool. The technique proves to be a fast and accurate tool which can be easily used by the designer. The circuit is assumed to be ideal in the sense that there are no parasitic resistances and that there is no continuous input output coupling.

2. Frequency domain harmonic distortion analysis of nonlinear s.c. circuits

The method starts from the nonlinear characteristic of certain components. In Fig. 1 we have plotted the nonlinear characteristics for the parasitic capacitors (for a built in bulk voltage of -7V) and for the op amps which are used for the example in Section 3. Since the nonlinearity is assumed to be weak over the range where the variables change, it makes sense to represent the characteristic by a polynomial. This is also the way it is finally represented by a model in the computer program. If one considers the steady state in the output (or in any internal variable) due to an input cosine of 1V, then this output contains contributions at several frequencies. Some contributions vary linearly in terms of the size of the input, others as a second order, a third order and so on (Fig. 2). The linear part contains contribution A_{11} (cosine amplitude) at the same frequency f as the input and at the

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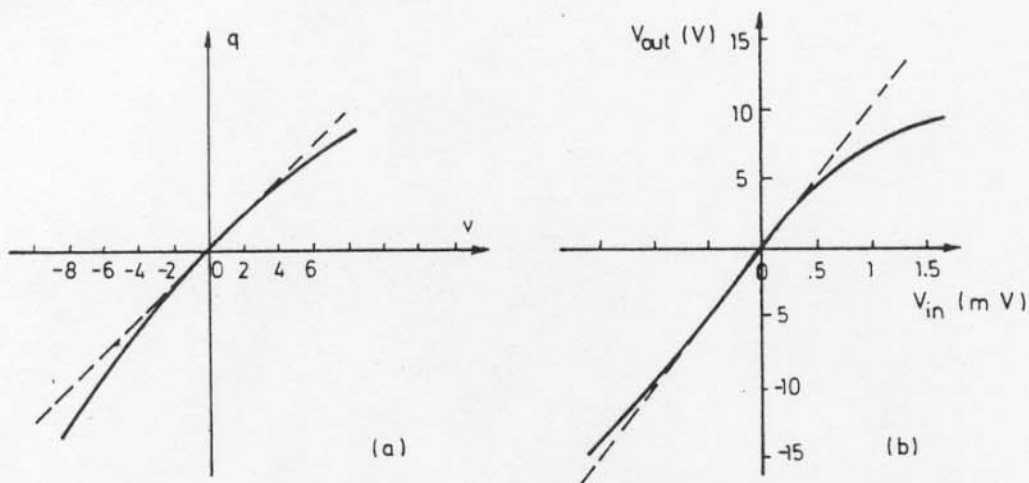


Fig. 1. Examples of nonlinear characteristics (a) for the parasitic capacitors and (b) for the op amps.

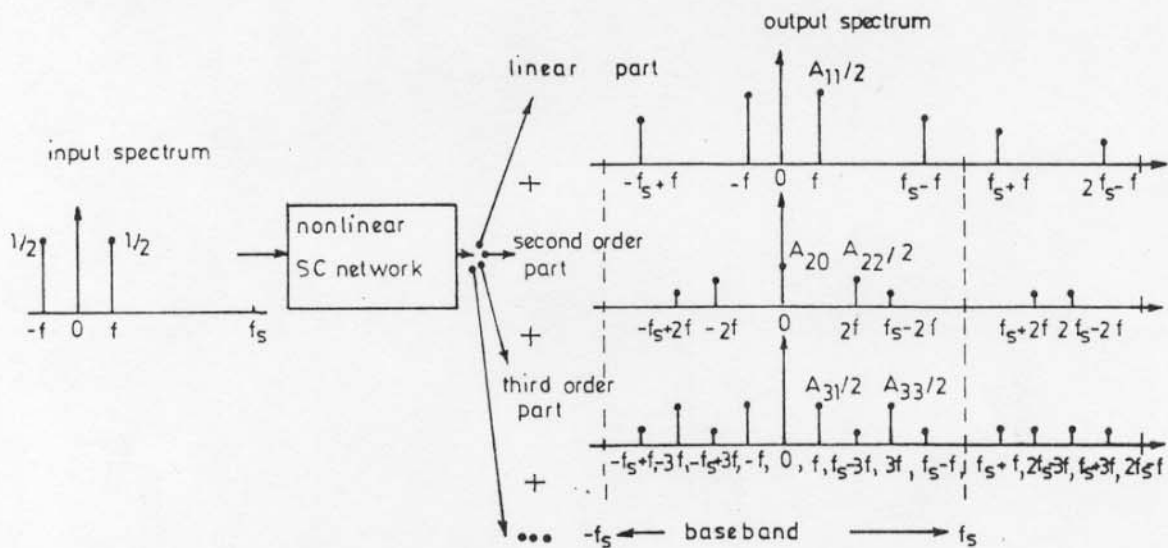


Fig. 2. The decomposition of the output spectrum in a part which varies linearly with the cosine input, a part which varies as a second order of the cosine input, a third order and so on.

frequencies $kf_s \pm f$ (aliasing terms) where $f_s = 1/T$ with T the clock period. The aliasing is usually negligible and is due to the periodic switching. The second order part contains a contribution A_{22} (cosine amplitude) at $2f$ and a constant term A_{20} and aliasing terms which are usually negligible. The third order part contains a contribution A_{33} (cosine amplitude) at $3f$ and a contribution A_{31} (cosine amplitude) at f and aliasing terms. Observe that these are the contributions which can be measured in the output with a (tracking) spectrum analyzer. The Volterra series give representations via contributions with impulse responses or transfer functions for the different parts [6]. For time invariant circuits these parts can be computed [7] one after another. This algorithm has been adapted to the discrete time and periodic character of nonlinear s.c. circuits, and combines rather well with the frequency domain MNA of linear s.c. circuits [3].

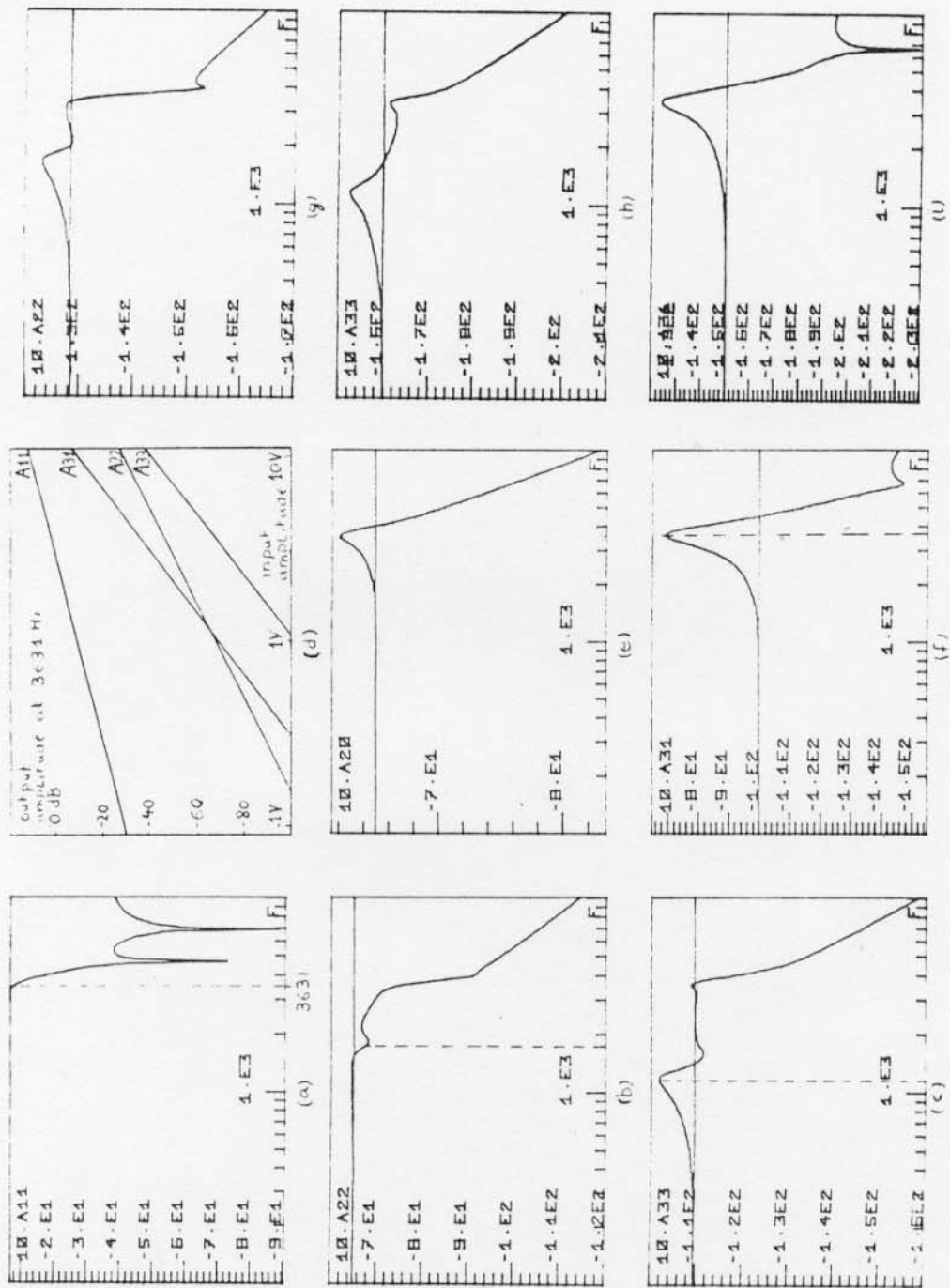


Fig. 3. Major distortion contributions in the fifth order elliptic low pass PCM filter due to parasitic capacitances at all nodes (a-f) or due to nonlinear op amps (g-i). Observe that the plots (a-c) and (e-i) describe for an input of 1V and frequency f the amplitude in dB of the output cosine contributions in terms of the input frequency f .

Two key observations are first that for any nonlinear characteristic any higher order term of the controlled variable is only a function of the lower order terms of the controlling variable and second that the MNA matrix relates the n -th order parts of the network variables to the input variables and lower order parts of these variables. Thus one computes first a source vector which represents the lower order parts of the nonlinearities and the external sources. This can be easily done with the polynomial representation of the characteristic. The second and most involved step is the solution of the linear network equations with this source. This can be done efficiently with the techniques of [3,5].

3. Computer implementation in DIANA-SC and examples

The nonlinear characteristics have to be supplied by the user in the form of a polynomial. Nonlinearities are allowed in op amps (voltage controlled voltage sources VCVS) VCQS, QCQS, QCVS as well as in capacitors as switched capacitors SW3 and SW4. Let us consider the example of the fifth order elliptic low pass PCM filter also used in [1]. First a parasitic capacitor with characteristic given in Fig. 1.(a) is added to all the nodes. The plot $A_{11}(f)$ is the desired low pass characteristic (Fig. 3.(a)). The plot of $A_{22}(f)$ (resp., $A_{33}(f)$) gives in Fig. 3(b)(c) in dB the attenuation between a cosine of 1V and frequency f at the input and the cosine of the second (resp., third) order part and frequency $2f$ (resp., $3f$) at the output. Fig. 3.(e) and (f) give second and third order effects at dc and frequency f . Though these plots tell that the nonlinear effect for an input amplitude of 1V is in general negligible, the effect of the nonlinear terms is most critical around the corner frequency. Therefore at this output frequency one can plot the contributions in terms of the size of the input (Fig. 3(d)). The whole set of plots over 200 frequency points required 210 s on a VAX 11/780. Next we plotted in Fig. 3.(g)(h)(i) the effect of opamps with nonlinear characteristics of Fig. 1.(b). The nonlinear effects are even smaller. This computation only required 30 s.

The Volterra series analysis as well as its implementation in DIANA also allow to analyse any baseband contributions in the output spectrum which are due to several frequency contributions in the input (cross modulation).

4. Conclusion

We have shown with an analysis, a computer implementation and realistic applications that the distortion analysis with Volterra series is feasible, attractive and easy to use in order to check the specified S/N ratio .

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