Generation of Analogue Behavioural Models in the Frequency-Domain for Linear Circuits

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Abstract

In this paper, analogue behavioural modelling (ABM) is applied to the synthesis of linear filters within the frequency-domain. The synthesis procedure splits into two main variants that are expound in the paper. In a first part, the modelling techniques are applied to the well-known Sallen & key structures by focussing on the modelling of the active component, i.e. the operational amplifier. In the second part, the ABM focusses directly on the transfer function to be synthesised. Final results of the presented ABM methodology are specified in the form of Verilog-A code and circuit simulations.

1 Introduction

The requirements in modern electronic design and verification impose high standards of accuracy and CPU time-usage specially during the stage of simulating the design after the layout has been compiled. Behavioural modelling constitutes an alternative in order to overcome these problems [1, 2, 3].

In particular, mixed-mode design can profit of the use of behavioural modelling if this is applied to the analogue part of the circuitry which leads us to the so called ABM. Although the use of ABM speeds-up the simulation times, it still has the problems of delivering models that are solid and reliable enough and above all that are valid for several domains of analysis.

In summary, the advantages of ABM lead the designer to the possibility of developing complex analogue models, however they are still non-portable and demand additional manual intervention.

This paper is focussed on generating ABM for a class of linear filters by tackling the problem with two different approaches: on one hand the ABM occurs on the active part of the filter with a hierarchical structure, and on the other hand the ABM is applied to the whole transfer function.

The goal is to produce code in an analogue behavioural language (Verilog-A) and to verify the whole procedure with HSPICE simulations.

The paper is further organised as follows: in Section 2 the general procedure for generating the behavioural models is explained, in Section 3 the circuits under study are expound, in Section 4 the Verilog-A resulting code and simulations are presented, and finally some conclusions are drawn.

2 ABM in the frequency-domain

The use of ABM in the frequency-domain is strictly focussed on aspects regarding the transfer function synthesis or stability parameters that define the behaviour of amplifiers and other classes of linear systems. The transfer function is given as a rate of polynomials:

$$T(s) = \frac{b_m s^m + b_{m-1} s^{m-1} + \ldots b_1 s + b_0}{a_n s^n + a_{n-1} s^{n-1} + \ldots a_1 s + a_0} \quad (1)$$

with $n > m$, where each coefficient is a function of the component values:

$$\begin{aligned} b_i &= f_{b_1}(\boldsymbol{\mathcal{C}}) \\ a_i &= f_{a_1}(\boldsymbol{\mathcal{C}}) \end{aligned} \quad (2)$$

where $\boldsymbol{\mathcal{C}}$ represents the set of component values.

Besides, the component values can be split into the values of the active devices ($\boldsymbol{\mathcal{A}}$) and the values of the passive devices ($\boldsymbol{\mathcal{P}}$), which yields:

$$\begin{aligned} b_i &= f_{b_1}(\boldsymbol{\mathcal{A}}, \boldsymbol{\mathcal{P}}) \\ a_i &= f_{a_1}(\boldsymbol{\mathcal{A}}, \boldsymbol{\mathcal{P}}) \end{aligned} \quad (3)$$

Generally speaking, both, the passive and active components are simulated by a correct set-up of the modified nodal analysis (MNA) representation. For active devices, this involves the task of modelling, which is usually done at circuit-level, i.e. by resorting to an equivalent. This is sketched in Figure 1.

However, when one simulates the circuit after extraction from the layout generation, the parasitics must be included — as shown in Figure 2 — which

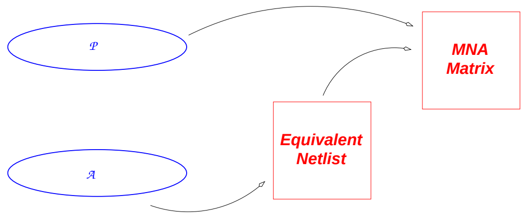


Figure 1: Set-up of the MNA matrix for simulation.

results in the insertion of additional components for both the active and passive parts. This approach may clearly result in a dramatical increase in the size of the MNA matrix.

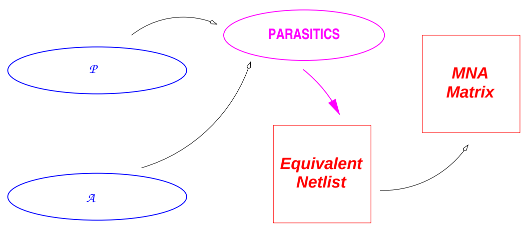


Figure 2: Set-up of the MNA matrix for simulation after circuit extraction.

2.1 ABM of the active part

In order to cope with the problem above, and more specifically for the frequency-domain verification, the use of analogue behavioural models represents a reliable alternative. In our approach, a hierarchy-based analogue behavioural model is devised.

Herein, the hierarchy starts by defining an **ideal behavioural model** of the active part, which is based on the concept of the nullor. In a second level of hierarchy, the idealisation is modified by defining an **opamp-oriented behavioural model** which includes several effects, such as high-gain model, single-pole model, and unit-gain bandwidth model. Finally at the bottom-level, a **transistor-oriented behavioural model** is defined. This hierarchy is depicted in Figure 3.

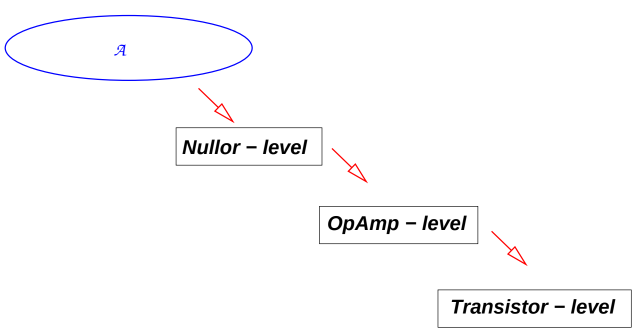


Figure 3: Active devices: hierarchy-based behavioural model.

The nullor model

This model is based on the ideal universal amplifier cell [4, 5], which is a two-port with a nullator at the input, and a norator at the output, as shown in the Figure 4. The nullor is characterised by a transmission matrix given as:

$$\boldsymbol{K} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{4}$$

which means ideal gain factors.

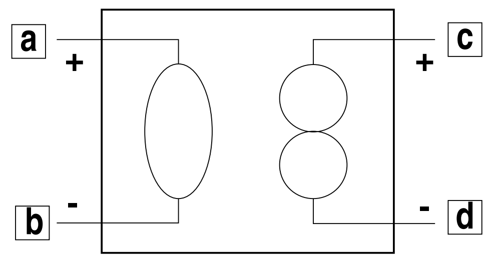


Figure 4: Universal ideal amplifier.

Finite-gain model

This model is based on the combination the ideal universal amplifier and passive components in order to achieve finite-gains of the four types, namely: voltage, current, transconductance and transimpedance gains [5] as shown in the Figure 5.

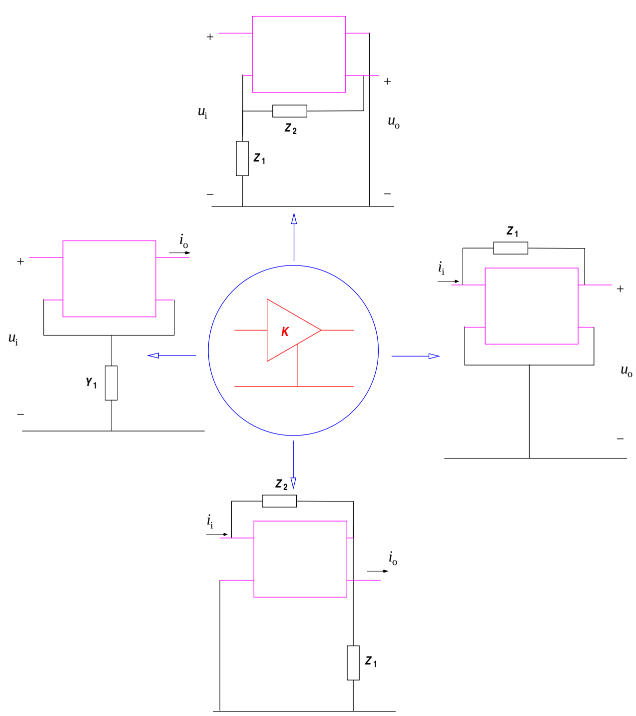


Figure 5: Finite-gain model.

Opamp-based model

This model is based on the use of a generic operational amplifier. Hereafter, the gain of the opamp ($\boldsymbol{A}$) can be expressed by the next variants:

High-gain model

$$\boldsymbol{A} = \boldsymbol{A}_o \tag{5}$$

where $\boldsymbol{A}_o$ represents a high-gain value (typical 2×10^5). It clearly results that no frequency-dependency is included.

Single-pole model

$$\boldsymbol{A} = \frac{\boldsymbol{A}_o}{1 + \frac{s}{\omega_p}} \tag{6}$$

where the pole is located at ω_p.

Unit-gain bandwidth model

$$\boldsymbol{A} = \frac{s}{\omega_t} \tag{7}$$

where ω_t is the unit-gain bandwidth of the opamp.

The models above are currently available in the ABM methodology. However, further ABM schemes can be easily extended in order to model additional op-amp effects, such as: input resistance, output resistance, and second-pole dependency.

3 ABM for Sallen & Key structures

The well-known Sallen and Key filters [6] are used to illustrate the application of the analogue behavioural modelling regarding the active part. These filters are shown in the Figure 6.

The filters above have been designed for a cut-off frequency of 10 kHz and a Q value of unit, and they have been simulated by modelling i) the operational amplifier and ii) the complete filter. Lack of space does not allows us to show results for all types of filters, instead results are depicted only for the bandpass structure.

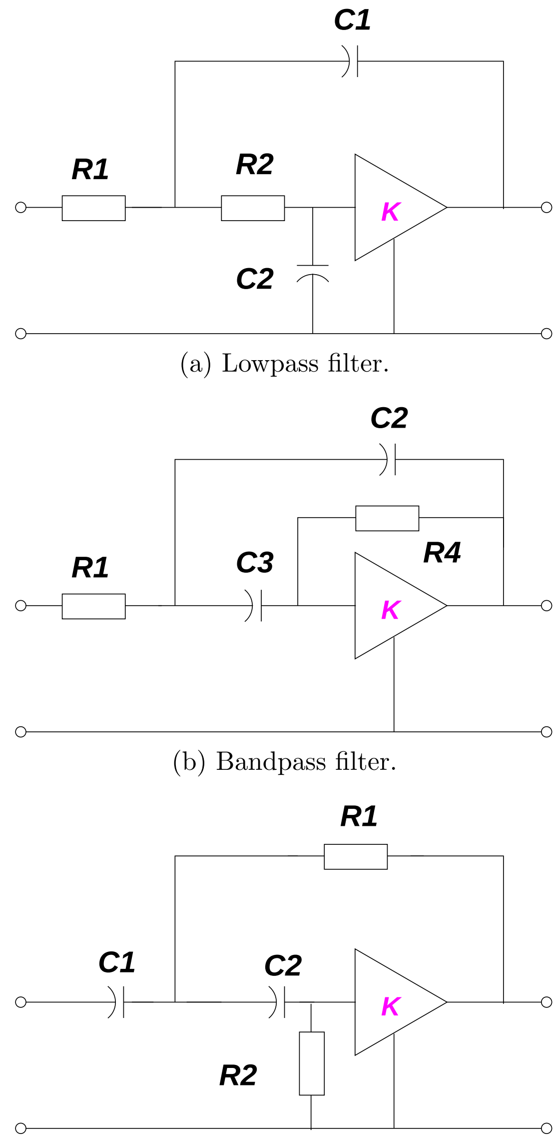
The next is a HSPICE input file which includes an analogue behavioural model for the operational amplifier.

```
.hdl opamp_wt

Vin in 0 ac 1 0 0

X1 2 3 4 opamp_wt

C1 1 3 10n
C2 1 4 10n
R1 in 1 1.59k
```



(a) Lowpass filter.

(b) Bandpass filter.

(c) Highpass filter.

Figure 6: Sallen and Key filters

```
R2 3 4 1.59k

Rb 4 2 1k
Ra 2 0 1k

.op
.options nopage numdgt=4
.ac dec 20 1 1e6
.print ac Vdb(4)
.end
```

Hereafter, the input file for HSPICE that achieves the calling to the complete bandpass ABM is given:

```
.hdl bandpass_filter

Vin in 0 ac 1 0 0

X1 in 2 bandpass_filtro
```

```
.op
.options nopage numdgt=4
.ac dec 20 1 1e6
.print ac Vdb(2)
.end
```

The ABM for the bandpass structure according to the design specifications is given in the next file.

```
'include "std.va"
'include "const.va"

module bandpass_filter(a,b);
input a;
output b;
electrical a,b;

analog begin

V(b) <+ laplace_nd(V(a),
        {0.0,62832},
        {3947860224,62832,1});

end
endmodule
```

Simulation results for the bandpass filter are shown in Figure 7, where the frequency-response are shown for (a) the filter with the op-amp modelled by the unit-gain bandwidth scheme, and (b) by the complete transfer function.

4 Conclusions

Analogue behavioural modelling for the active part of linear circuits has been used to speed-up the simulation process in order to verify the design. It has been shown that it is possible to set up an ABM at circuit level, and at transfer-function level by resorting to Verilog-A. Moreover, it has been confirmed that modeling at behavioral level gives more control to the three basic design parameters of the filters, namely, the cut-off frequency, the quality factor and the gain of the filter.

Acknowledgment

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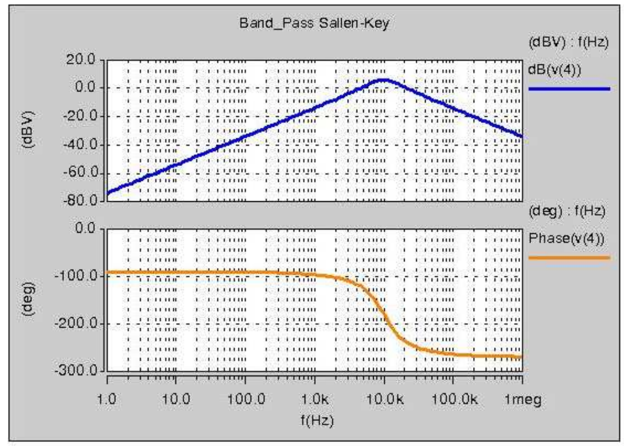
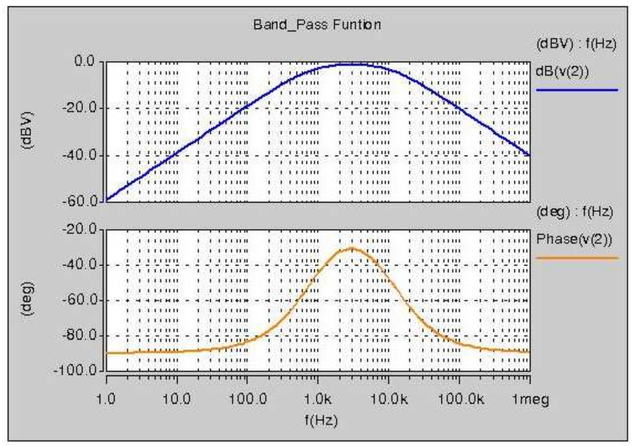


(a)



(b)

Figure 7: Simulation results for the bandpass structure.

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