FUNCTIONAL MODELING OF A TRANSCONDUCTANCE AMPLIFIER USING FUZZY SYSTEMS

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Abstract: The co-designing of SoC analogue and digital modules asks for the usage of high-level of abstraction in the modeling of analogue modules for efficient simulation. Fuzzy systems, considered as universal approximators, are appropriate to build functional model of the analogue modules. We tackled here a very common analogue module, a CMOS operational transconductance amplifier. Using Matlab we developed a fuzzy functional model of the input-output relation of the amplifier. The model takes into consideration the gain-frequency dependence and the phase-frequency dependence. The numerical results obtained with our fuzzy model, at different frequencies prove a high modeling accuracy.

Keywords: functional model, input-output relation, fuzzy system, simulation.

1. INTRODUCTION

Analogue design has been traditionally a difficult discipline of IC design. While in digital design functionality depends on discrete sequences of discrete signals, continuous sequences (waveforms) of continuous values encode the information we need to manipulate and use in the analogue case. For this reason, any second-order physical effect may have a significant impact on function and performance of an analogue circuit (Bernardis, *et al.*, 2004).
Consequently, the development of CAD tools that automate and speed up the design process of analogue portions of circuits and systems remains as an active research area in both industry and academia (Balkir, *et al.*, 2004). Gielen and Rutenbar (Gielen and Rutenbar, 2000) take into consideration three reasons to develop high level models to describe the electronic circuit behaviors. In a top-down design methodology at higher levels of the design hierarchy, where the detailed lower-level circuit implementations are yet unknown, there is a need for higher-levels models describing the pin-to-pin behavior of the circuits rather than the (yet unknown) internal structural implementation. Second, the verification of integrated mixed-signal systems also requires higher description levels for the analog sections, since such integrated systems are computationally to complex to allow a full simulation of the entire mixed-signal design in practical terms. Third, when providing or using analog IP macrocells in a SoC context, the virtual component has to be accompanied by an executable model that efficiently models pin-to-pin behavior of the virtual component. This model can then be used in system-level design and verification, even without knowing the detailed circuit implementation of the macrocell.
Two factors determine the utility of the functional model. First, the model should be computationally efficient to construct and evaluate so that substantial computational savings can be achieved. Second the model should be accurate (Chen, 1995).
The fuzzy systems are appropriate for modeling because they are universal aproximators (Mendel, 1995; Godjevac, 1997; Koh, *et al.*, 1990) and can model any nonlinear, multivariable function.
The objective of this paper is to develop a fuzzy functional model for a simple operational transconductance amplifier. The model describes the input-output relation for the amplifier in terms of the amplitude, frequency and phase shift of the voltage signals.

2. THE MODELING STRATEGY

Due to the fact that Takagi-Sugeno fuzzy systems can accurately approximate any nonlinear functions, we have selected this class of models to construct the fuzzy model for our circuit. The general structure of the fuzzy model is presented in Fig.1. Applying to the input the $v_i(t)$ voltage our fuzzy functional model is capable to generate the $v_0(t)$ output voltage.

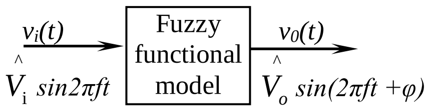

Fig. 1. The Fuzzy functional model

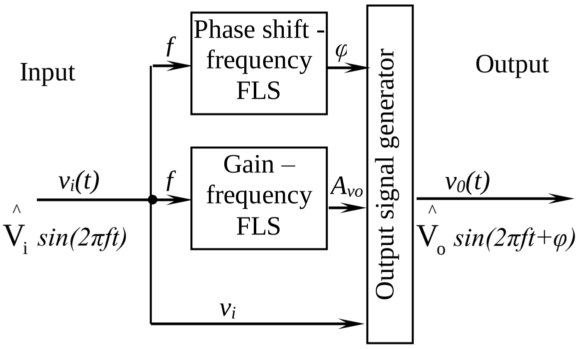

Fig. 2. The structure of the fuzzy functional model

The internal structure of the model is detailed in Fig.2.

The fuzzy functional model comprises two SISO fuzzy systems:

- Phase shift – frequency FLS that model the nonlinear phase shifting (φ) dependence on the frequency (f).
- Gain – frequency FLS that model the nonlinear gain (A_{vo}) dependence on the frequency (f).

The Output signal generator block provides the time variation of the actual output voltage.

According to (Godjevac, 1997; Jang, 1993; Torralba, et al., 1996) for building the fuzzy systems we need sets of numerical data. To obtain accurate models, a large number of data pairs is requested, that should uniformly cover the function domain and include, as much as possible, all his features**.**

The algorithm used to build the fuzzy functional model consists in the following steps:

- run Spice simulations (.AC analysis) and save the data points in .csd output files
- extract the training data set and the checking data set from the .csd files (in Matlab)
- generate the initial T-S fuzzy system using a fuzzy subtractive clustering (in Matlab)
- train the initial T-S fuzzy system using ANFIS, Adaptive-Network-based Fuzzy Inference Systems (in Matlab)
- write the necessary functions and scripts to implement the fuzzy functional model (in Matlab).

3. THE SIMPLE OPERATIONAL TRANSCONDUCTANCE AMPLIFIER

The schematic of the simple operational transconductance amplifier is presented in Fig.3. The input transistors Q_1 and Q_2 are identical, therefore $(W/L)_1 = (W/L)_2$. The transistors Q_3 and Q_4 which form the active load must be paired, resulting $(W/L)_3=(W/L)_4$.. For the current mirror formed by Q_5 and Q_6 we consider the current (I_b) equal trough both transistors so $(W/L)_5 = (W/L)_6$. In order to keep an minimal area, we have taken W = L for these

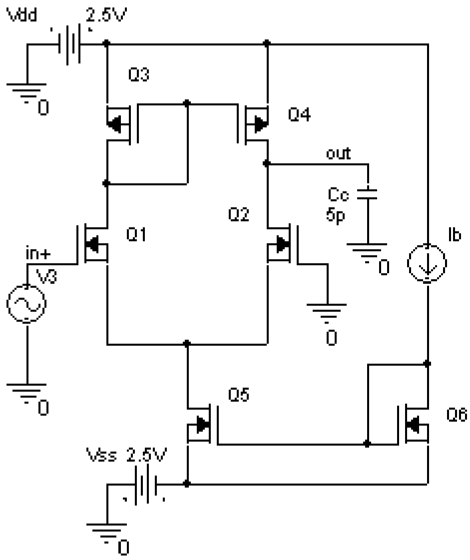

Fig. 3. The simple operational transconductance amplifier

amplifier. Ib is the biasing current source.

In order to assure a high value for the voltage gain, the transistors Q_1 and Q_2 should be biased with a small overdrive voltage $V_{GS12} - V_{Pn} \approx 0.2V$ (Laker and Sansen, 1993). To stay in the active region $V_{DS12} > V_{GS12} - V_{Pn} = V_{DS12\ sat}$ and $V_{DS12} > 0,2$ V must be fulfilled. For Q_5 and Q_6 we have $V_{DS56} > V_{GS56} - V_{Pn} = V_{DS56\ sat}$ and taking into consideration their connection $V_{DS56} = V_{GS56} > V_{DS56\ sat}$. For the same reason Q_3 and Q_4 will always stay in the active region. If the transistors work at higher overdrive voltages the matching is better.

The modeling parameters used in Spice simulation are for the 0.25μm technology.

We take into consideration the single end gain A_{vo}: differential input with full input voltage applied to the non-inverting input (in+) while the inverting input is ground connected, and the output in the drain of the Q_2 transistor (out). Our amplifier works on a capacitive load (*Cc*=5pF).

4. EXPERIMENTAL RESULTS

The data necessary for training set and checking set are obtained by Spice simulation. We run two .AC analyses in the [0.1Hz, 100MHz] frequency range: one for the training data set (with 200point/decade) and another one with 20 points/decade. The plots provided by Spice for the first simulation are presented in Fig. 4.

On the first plot we have the phase shift of the amplifier and on second one we have the magnitude of the output voltage. Because the magnitude of the input voltage was set to 1mV, we directly have the value of the gain, A_{vo} (48,11 in the passband)

Following the modeling strategy, presented in section 2, we generate and train the two fuzzy logic systems:

- Phase shift – frequency FLS, 2 rules, 2000 training epochs
- Gain – frequency FLS, 2 rules, 840 training epochs

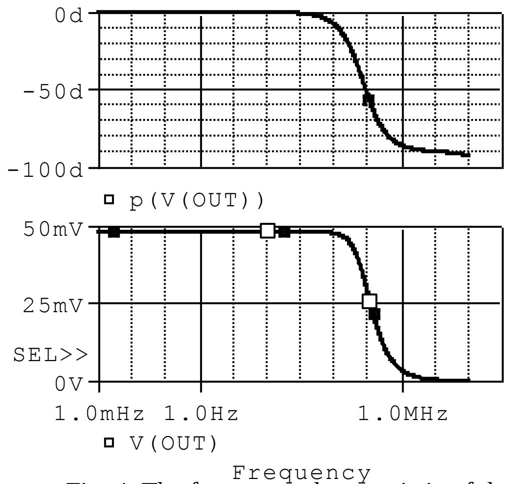

Fig. 4. The frequency characteristic of the amplifier by Spice simulation

The evolutions of the errors (root mean squared error) during the training perform by ANFIS for the Gain – frequency FLS is represented in Fig. 5: error – for the training set, chkerror – for the checking set.
We mention here that we will consider the valid input domain of our fuzzy models as the [1Hz, 10MHz] range, even if the range of training data set was wider. This is necessary to reduce the modeling errors on the ends of the input domain.
The phase shift – frequency fuzzy model versus

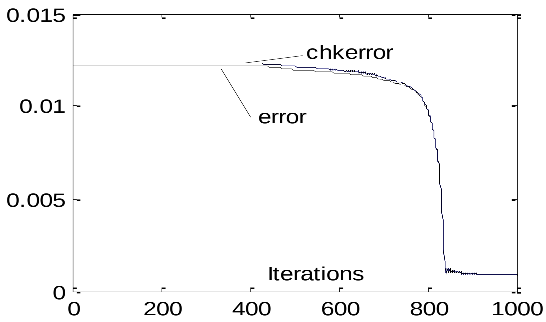

Fig. 5. The evolution of the errors training the Gain – frequency FLS

Spice model is presented in Fig. 6. As one can see our model presents a very high accuracy, the two

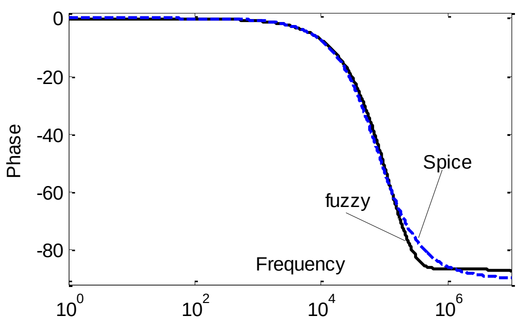

Fig. 6. Phase shift – frequency. Fuzzy model vs. Spice model

curves being almost identical. A certain difference appears at high frequency (over 10^5 KHz), but it is acceptable. In order to better appreciate the

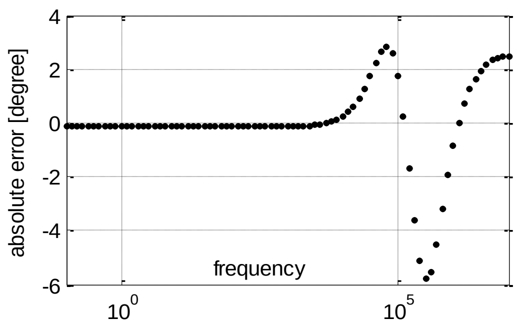

Fig. 7. Absolute errors for phase shift - frequency fuzzy model

modelling accuracy we computed the absolute errors in 5 frequency point/decade. The results are graphically presented in Fig. 7.
The extreme values of absolute errors are 2.8493

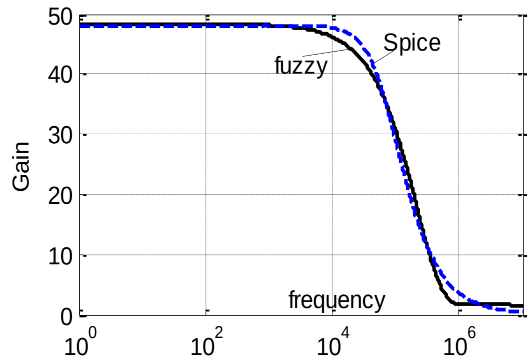

Fig. 8. Gain – frequency. Fuzzy model vs. Spice

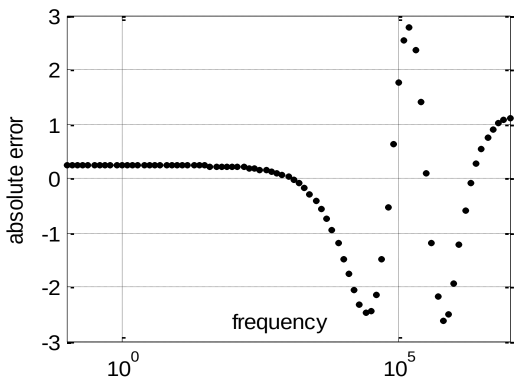

Fig. 9. Absolute errors for gain - frequency fuzzy model

degrees at 63.095KHz and -5.8049 at 316.227KHz. Due to the actual values of the phase, the relative errors are rather small: -7.15% and respectively 7.57%.
The gain – frequency fuzzy model versus Spice model is presented in Fig. 8. As one can see our model presents a very high accuracy, the two curves being similar. Certain differences appear around the cutoff frequency and at high frequency (over 10^5 KHz), but they are acceptable.
The absolute errors in 5 frequency point/decade for the fuzzy model are highlighted in Fig. 9.
The extreme values of absolute errors are 2.7736

degrees at 158.489KHz and -2.635 at 630.957KHz. The relative errors in these points are irrelevant due to the low values of the gain.

Now let's focus our attention on the full fuzzy functional model of the simple transconductance amplifier. We consider as input a sine wave with a specific amplitude and frequency. Fig. 10 presents the waveforms of the input voltages and of the output voltages generated with our fuzzy functional model. The frequency of the signal is 1KHz, in the passband of the amplifier.

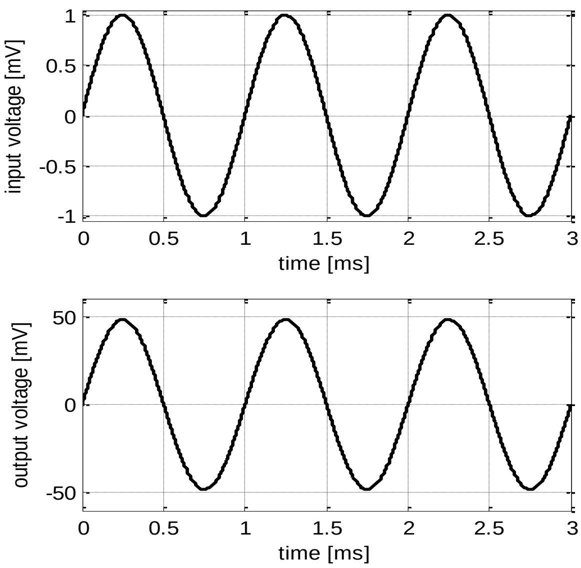

Fig. 10. Input and output waveforms, 1KHz

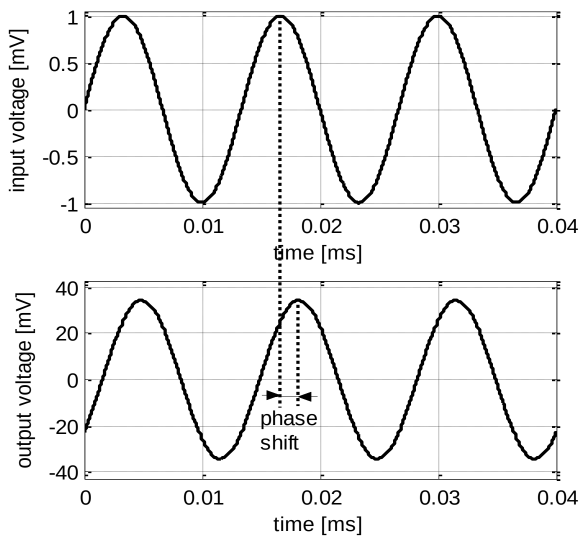

Fig. 11. Input and output waveforms, 75KHz

For the output voltage the phase shift is -0.895 degree (-0.761 degree provided by Spice) and the amplitude is 48.124mV (48,104mV provided by Spice) for 1mV input amplitude.

Fig. 11 presents the waveforms of the input voltages and of the output voltages for 75KHz signal frequency, the cutoff frequency of the amplifier.

The resulted phase shift is -42.209 degree (-44,92 degree provided by Spice) and the resulted output amplitude is 34.39mV (34.073mV in Spice).

As a whole our model proves very high accuracy on the entire range of frequency under consideration.

5. CONCLUSION

A new strategy to build a fuzzy functional model and a fuzzy functional model for a simple operational transconductance amplifier are presented in this paper. The model describes the input-output relation for the amplifier in terms of the amplitude, frequency and phase shift of the voltage signals. Applying to the input a sinusoidal voltage the model can accurately provide the output waveform, with correct amplitude and correct phase shift. Up to this point our model is able to work well in the linear region of the transfer characteristic. A future research direction is to improve the model to extend its validity on the full transfer characteristic including the saturation of the amplifier.

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