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SIMULINK MODELS FOR OPERATIONAL TRANSCONDUCTANCE AMPLIFIERS USING FUZZY SYSTEMS

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Abstract: *High level models for analog modules, as functional models, are invaluable in the modern approach of automatic mixed electronic circuits design. The trade-off between a high accuracy and the computational efficiency of the models can be successfully addressed by means of fuzzy systems. We chose Simulink to develop some fuzzy functional models for operational transconductance amplifiers. These models describe the frequency response of the analog modules, including the temperature effect. The experimental results obtained for a simple and Miller operational transconductance amplifiers prove the validity of the proposed modeling procedure and the accuracy of the resulted models.*

Keywords: *analog module, functional model, frequency behavior, fuzzy system.*

1. INTRODUCTION

The high-level models of input-output behavior of analog modules play a key role in the modern approaches of electronic circuit design, as intellectual property (IP), virtual prototyping and simulation of mixed-signal systems [5]. The current number of analog designers cannot keep up with the demand for analog components. Together with the increasing complexity of the analog blocks, this situation has created an analog-design bottleneck. As the chasm between requirements (analog blocks) and reality (lack of analog designers and increasing complexity) continues to widen, designers are asking analog IP (intellectual property) to fill the gap [9].

A virtual prototype is a software-simulation-based, architectural-level model of an electronic system and includes in its structure high level behavioral models of different constituent block [6].

First, the model should be computationally efficient to construct and evaluate, so that substantial computational savings can be achieved. Second, the model should be as accurate as possible [2]. According to the references [7], [3] fuzzy systems being universal approximators, they are appropriate for modeling any multivariable, non-linear function with any degree of accuracy.

The idea to involve fuzzy systems in analog circuit modeling can be found in some previous works. The paper [12] shows how fuzzy systems are used to model the average dc transconductance and the nonlinearity error of a CMOS transconductance amplifier. The gain, bandwidth, common-mode rejection ratio and slew rate for a basic two stage and a Miller transconductance amplifiers are modeled in [10] using fuzzy systems. A three-layer neural-fuzzy network has been employed in [1] to model the gain-bandwidth and phase margin of a basic two stage operational amplifier and the open circuit bandwidth and short circuit bandwidth for a second-generation current conveyor.

All these works deal with fuzzy modeling of some circuit performance functions of analog modules. To the best of our knowledge, no previous work was reported concerning the fuzzy modeling of input-output behavior of analog modules.

The scope of this paper is to develop and implement in Simulink some models for Simple Operational Transconductance Amplifier (SOTA) and Miller Operational Transconductance Amplifier (MOTA) using fuzzy systems. The models describe the input voltage-output voltage relation in terms of the frequency and phase shift and include the temperature effect in the [-55; +125]^{0}C industrial range.

The implementation on the Simulink platform brings numerous advantages in terms of processing, capability, flexibility and possibility of simulation with other electronic subsystems. The same solution for implementation of different behavioral models was used in [11] and [8].

2. THE MODELING PROCEDURE

The modeling procedure is presented in Fig. 1. The circuit of the analog module has to be created in the frame of analog or mixed signal circuit project in the Orcad environment. We have to run an AC Sweep simulation to capture the frequency response of the circuit, keeping the circuit in its linear region. Each simulation run includes also a Temperature option to reiterate the simulation for different temperature values in the [-55; +125]^{0}C range. It is important to collect data only from the input and output points and to save data in the CSDF format

To build the fuzzy model we need a certain format of data. So it is necessary to extract that data from the .csd files. This is done using some Matlab scripts developed by the authors. These scripts identify the necessary values in the initial .csd format, extract and write them in a array [frequency, temperature, magnitude, phase].

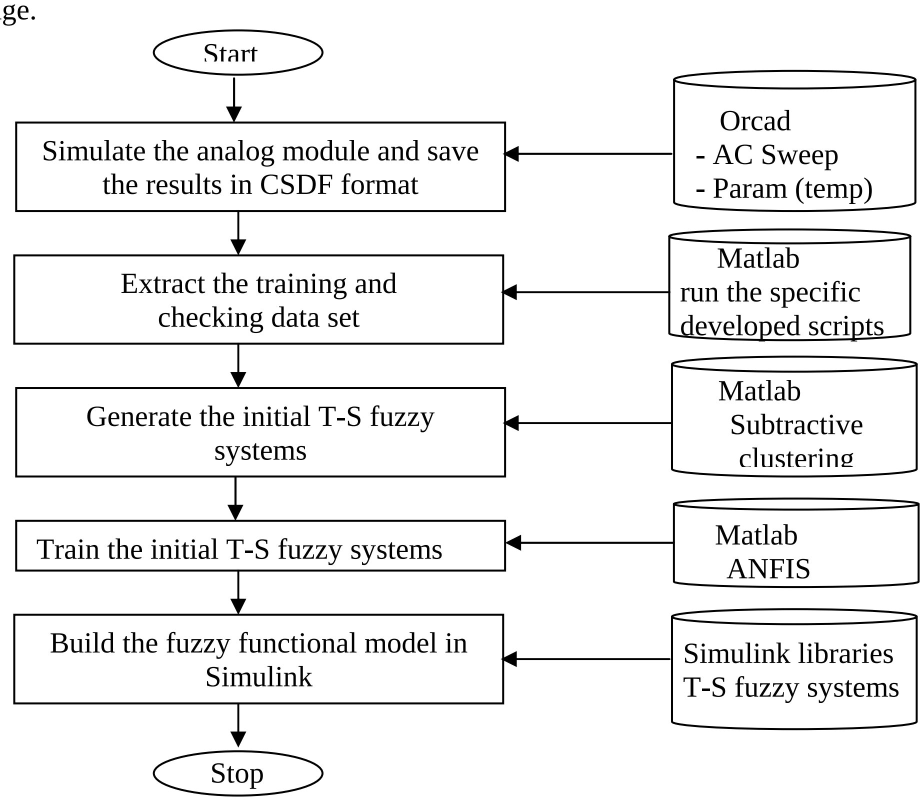

Fig. 1. The modeling procedure

A data conversion takes place here, in order to prepare the data for the first order Tagaki-Sugeno (T-S) fuzzy system that will model the circuit behavior. The temperature will be

translated up with 60oC to have only positive values. For the frequency we will use a logarithmic transformation to dramatically reduce its range. To build the T-S fuzzy systems, we will generate and train a Fuzzy Inference System (FIS) as a model for each of our input-output relation. The generation of initial fuzzy model uses a fuzzy subtractive clustering algorithm.

The initial fuzzy model is then trained with the Adaptive-Network-based Fuzzy Inference Systems (ANFIS), which is the major training routine for Sugeno-type fuzzy inference systems. ANFIS uses a hybrid-learning algorithm to identify parameters of Sugeno-type fuzzy inference systems. It applies a combination of least-squares and backpropagation gradient descent methods for training FIS membership function parameters to emulate a given training data set. ANFIS also performs a model validation using a checking data set, to detect the model overfitting. The fuzzy inference system is trained during a designated number of epochs until overfitting appears or the training error goal is achieved. More details about ANFIS can be found for example in [4], [13].

Finally, once we developed the necessary fuzzy system, all we have to do is to build up the fuzzy functional model in Simulink. The detailed description of this final step is presented in the next paragraph.

3. SIMULINK IMPLEMENTATION

The fuzzy functional model is presented in Fig.2. Applying to the input the vi(t) voltage and the operating temperature, the fuzzy model is capable to generate the vo(t) output voltage.

The internal structure of the model is detailed in Fig.3 and it contains two fuzzy systems.

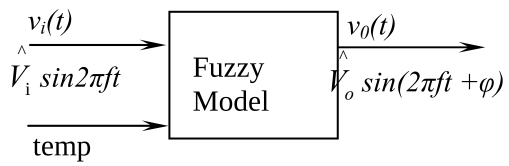

Fig. 2. The fuzzy model

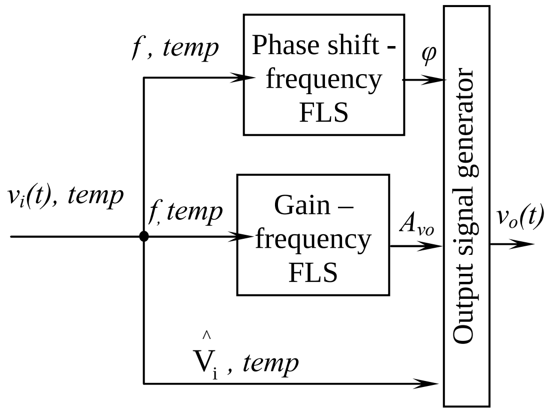

Fig. 3. The structure of the fuzzy model

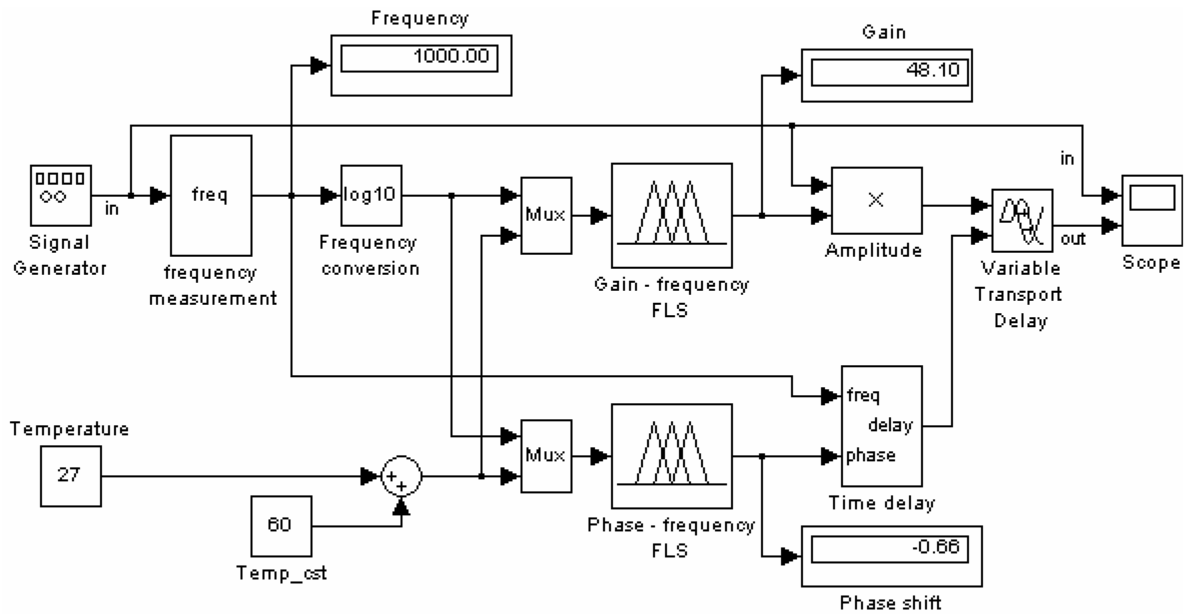

Fig. 4. The Simulink implementation of the fuzzy functional model

The fuzzy systems are:

- The phase shift – frequency FLS that models the nonlinear phase shifting (φ) dependence on the frequency (f) and on the temperature (*temp*);
- The gain – frequency FLS that models the nonlinear gain (A_v) dependence on the frequency (f) and temperature (*temp*).

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

The fuzzy functional model is implemented in Simulink. In this way it can be used as a Simulink block to be included in any complex system. The model is presented in Fig. 4.

The heart of the model consists in the two fuzzy logic systems (FLS). Because they have two inputs, frequency and temperature, it is necessary to use a two-input multiplexer block in front of them. Let us remember that some data conversion was necessary to obtain accurate fuzzy systems. The operating temperature is set in the block called 'Temperature' (270C in the illustration presented in Fig .3). The temperature is translated up with 600 C (set in the 'Temp_cst') using the summing block.

The input sine wave is generated by the 'Signal generator' block, where we have to specify the amplitude and the frequency. To model the frequency behavior of the amplifier we need for the fuzzy logic systems the value of the frequency, so we have to compute the frequency for the time variation of the input signal. For this purpose the 'frequency measurement' block was developed. It provides the frequency after the first half cycle of the input signal. This first half cycle will be treated as a transient time, so the correct output signals will appear to the output after this transient regime.

The decimal logarithmic conversion of the frequency is provided by the 'Frequency conversion' block. We can see the value of the frequency on the 'Frequency' display block (1000Hz in the exemplification presented in Fig.4).

The 'Amplitude' multiplication block receives the input signal at one input and the value of the gain, provided by the 'Gain-frequency FLS' block at the second input; its output signal being the amplified version of the input signal. In order to have the correct output signal, the model has to include the phase-shift corresponding to the operating frequency. This task is carried out by the 'Variable Transport Delay' block, which delays the time-varying signal at its first input with the time value presented to its second input.

The delay time is computed in the specially built 'Time delay' block, starting from the phase shift provided by the 'Phase-frequency FLS' block and the signal frequency.

During the simulation, the values of the gain and phase shift can be read on the 'Gain' and respectively 'Phase shift' display blocks (48.10 for the gain and -0.66 degree for the phase shift, in the exemplification presented in Fig. 4).

The 'Frequency measurement' sub-system is presented in detail in Fig. 5.

The frequency measurement is based on computing the time between two successive zero crossing moments, meaning a half of the signal period. A 'Clock' block generates the time to the inputs of two 'Enabled Subsystems'. The upper block transmits and holds at its output the value of the time corresponding to each negative zero crossing of the input signal, while the bottom block transmits and holds at its output the value of the time corresponding to each positive zero crossing. The 'Frequency computing' block is a user-defined function that compute the frequency from the half period of the signal.

4. EXPERIMENTAL RESULTS

We tested our modeling procedure for a simple operational transconductance amplifier and a Miller operational transconductance amplifier. The SOTA circuit is presented in Fig. 6.

Using the modeling procedure, we generated and trained two fuzzy logic systems for the frequency behavior of the amplifier:

- The phase shift – frequency FLS, 17 rules, 1000 training epochs;
- The gain – frequency FLS, 9 rules, 1500 training epochs.

For each fuzzy system we used 358 data pairs to generate the initial fuzzy system, 35717 data pairs to train the fuzzy system and 497 data pairs to check the fuzzy system.

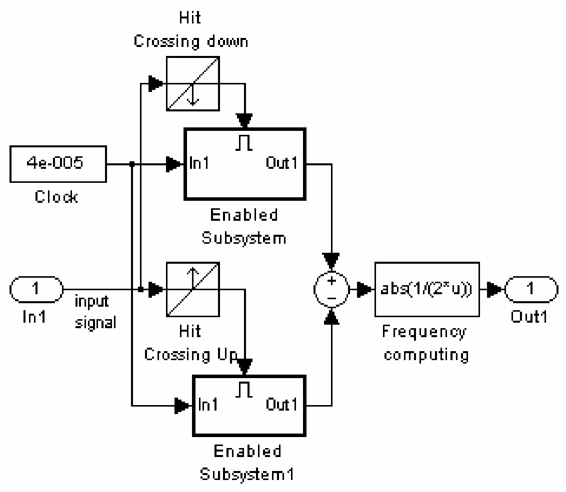

Fig. 5. Frequency measurement sub-system

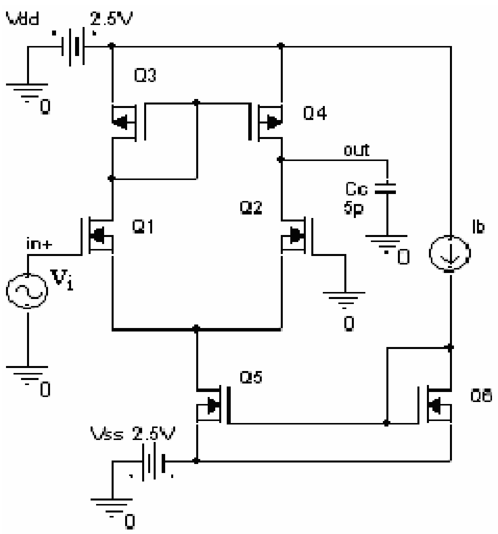

Fig. 6. The simple operational transconductance amplifier.

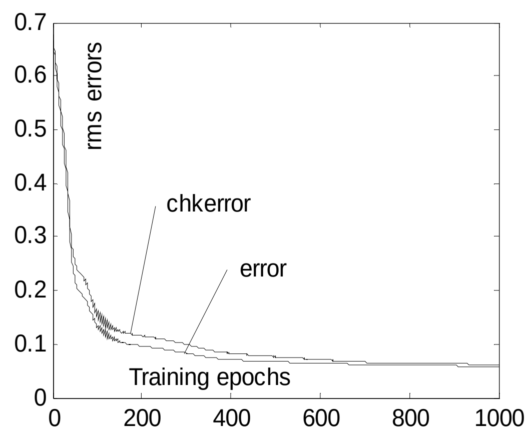

Fig. 7. The evolution of the errors, training the gain-frequency FLS, SOTA

The evolution of the errors (root mean squared error) during the training, performed by ANFIS for the gain – frequency FLS is represented in Fig. 7: error – for the training set, check error - for the checking set. The improvement of the model is very fast on the first 200 training epochs, and then the improvement still happens but no so spectacular.

Fig. 8 presents the 3-dimensional fuzzy model of the gain for SOTA. We can see here both the frequency effect and the temperature effect on the value of the amplifier gain. The fuzzy model for the phase shift results in a similar manner, showing the dependence of the output signal phase on the frequency and on the temperature. Due to the lack of space it is not graphically reproduced here.

We tested our Simulink implementation of the functional model using a sine wave with different frequencies as the input signal, for different operating temperatures. A comparison between the results provided by our Simulink fuzzy model and the ones provided by Spice simulation (in Orcad environment) is presented in Table 1. One can notice the very good match of the values obtained with our fuzzy model and with Spice simulation, for the entire range of the frequency and the entire range of the temperature. As a whole, the fuzzy model is a very accurate one.

As one can see we obtained different values for voltage gain and for phase shift at the same frequency for different values of the temperature. For 1KHz frequency (in the pass-

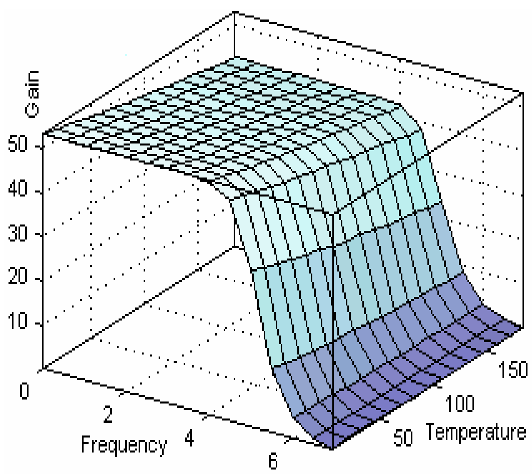

Fig. 8. The fuzzy model of the Gain for SOTA

Table 1: Simulink fuzzy model versus Spice for SOTA

Freq.	Temp.	Gain		Phase shift [degree]	
		Fuzzy model	Spice	Fuzzy model	Spice
1KHz	-40°C	52.22	52.240	-0.81	-0.66
	27°C	48.10	48.104	-0.66	-0.76
	100°C	44.17	44.15	-0.85	-0.86
75KHz	-40°C	39.30	39.47	-41.06	-40.9
	27°C	33.90	34.074	-45.09	-44.92
	100°C	29.47	29.400	-48.65	-48.25
1MHz	-40°C	4.49	4.51	-85.14	-85.07
	27°C	3.61	3.61	-85.68	-85.7
	100°C	2.91	2.95	-86.32	-86.2

band), the voltage gain decreases as temperature increases; the influence of the temperature on the phase shift is insignificant.

For the 75KHz frequency and for the 1MHz frequency (near to the cut off frequency, respectively out of the pass-band) the temperature influences the values of the voltage gain and the phase shift, too. If the temperature increases, the voltage gain decreases and the phase shift increases.

In Fig. 9 the simulation results for the 1KHz frequency at 100°C are presented. Being within the pass-band there is no delay of the output voltage. The voltage gain in this case is 44.17.

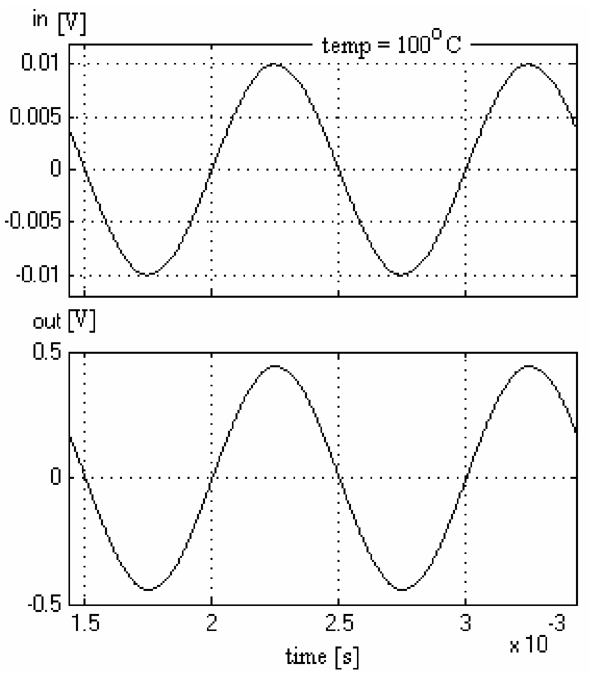

Fig. 9. Input and output waveforms, 1KHz, at 100°C, SOTA

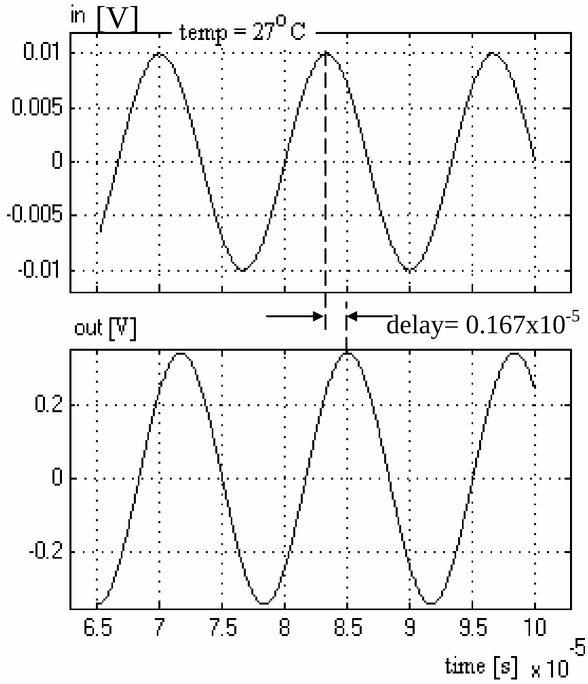

Fig. 10. Input and output waveforms, 75KHz, at 27°C, SOTA

Fig. 10 presents the behavior for the 75KHz frequency (very close to the cut off frequency) at 27°C. We observe a delay of 0.167×10^{-5} seconds for the output voltage. The voltage gain is 33.9, being smaller than the voltage gain in the pass-band.

For the 1MHz frequency (outside of the pass-band) at -40°C (Fig.11), the delay of the output

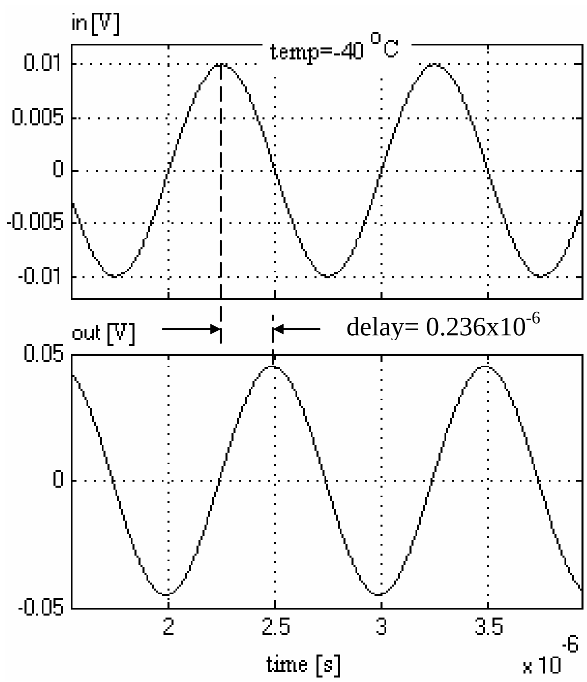

Fig. 11. Input and output waveforms, 1MHz, at -40°C, SOTA

voltage is even greater, 0.236×10^{-6} seconds and the voltage. gain is even smaller (comparing with the results obtained for the 75KHz frequency). The value of the voltage gain is 4.49 in this case.

The second circuit (MOTA) used to test our procedure is presented in Fig. 12.

According to the modelling procedure, we have generated and trained two fuzzy logic systems for the frequency behavior of the amplifier:

- The phase shift – frequency, 9 rules, 400 training epochs;
- The gain – frequency, 11 rules, 350 training epochs.

For each fuzzy system we used 4294 data pairs to generate the initial fuzzy system, 171019 data pairs to train the fuzzy system and 3608 data pairs to check the fuzzy system.

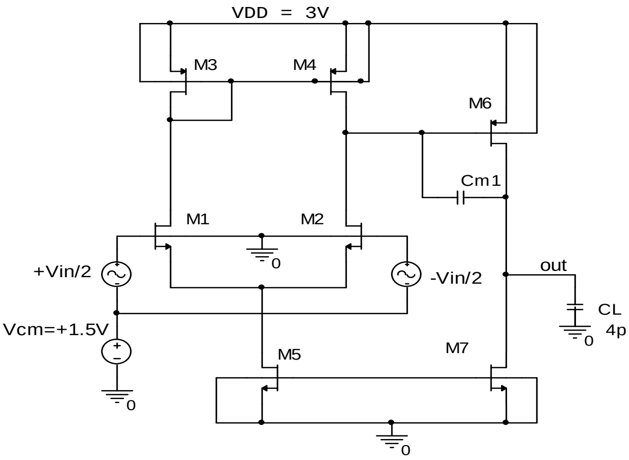

Fig. 12. The Miller operational transconductance amplifier

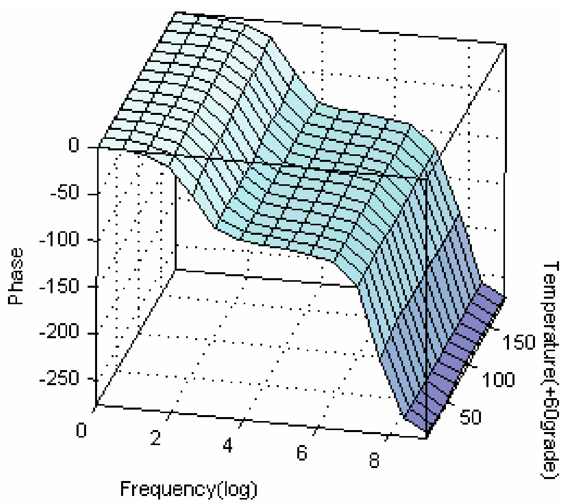

Fig. 13. The fuzzy model of the phase for MOTA

Similar with the SOTA circuit, for the MOTA circuit we have two fuzzy models: a fuzzy model of the gain and a fuzzy model of the phase. Due to the lack of space the fuzzy model of the gain is not graphically reproduced here. Fig. 13 presents the 3-dimensional fuzzy model of the phase for MOTA circuit. We mention here that the frequency is represented using a logarithmic scale, so that on the x-axis appear the values of the decimal logarithm of the frequency. Also, the values that appear on the temperature axis are with 60^0C greater than the real temperature due to the necessary data conversion.

For the MOTA circuit the numerical results that prove the accuracy of the model are presented in Table 2. We tested the model for three different frequencies: 10Hz – in the pass-band, 694Hz – near to the cut off frequency and 5KHz – out of the pass-band. The results are considered for three temperatures in Table 2.

The functional model is a very accurate one, especially in pass-band frequencies. For high frequencies, the relative error of the gain increases up to 6%. This error is acceptable because we are interested into the behavior of the circuit in pass-band frequencies and not out of the pass-band. The values obtained for phase shift are also quite accurate. For frequencies smaller than the cut off frequency the absolute error is smaller than one degree and it goes up to two degrees for frequencies near the cut off frequency.

The simulation results for 10Hz frequency at 27^oC are presented in Fig. 14. Being within the pass-band there is no delay of the output voltage. The voltage gain in this case is 18719.98.

Fig.15 presents the behavior for 694Hz frequency (very close to the cut off frequency) at 27^oC. We observe a delay of 0.19×10^{-3} seconds for the output voltage. The voltage gain is 13170.98 being smaller than the voltage gain in the pass-band.

The delay of the output voltage is even greater, 0.463×10^{-6} seconds, for a 5KHz frequency (outside of the pass-band) at -50^oC (Fig.16).The voltage gain is even smaller (comparing to the results obtained for 694Hz frequency). The value of the voltage gain is, in this case, 2422.72.

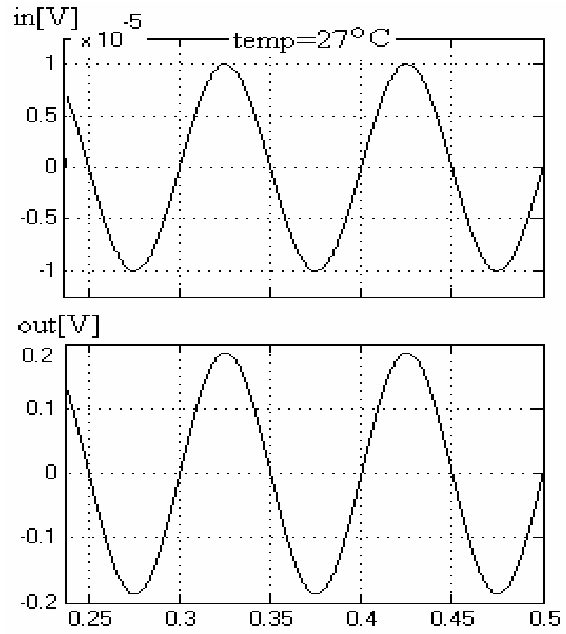

Fig. 14. Input and output waveforms, 10Hz, 27°C

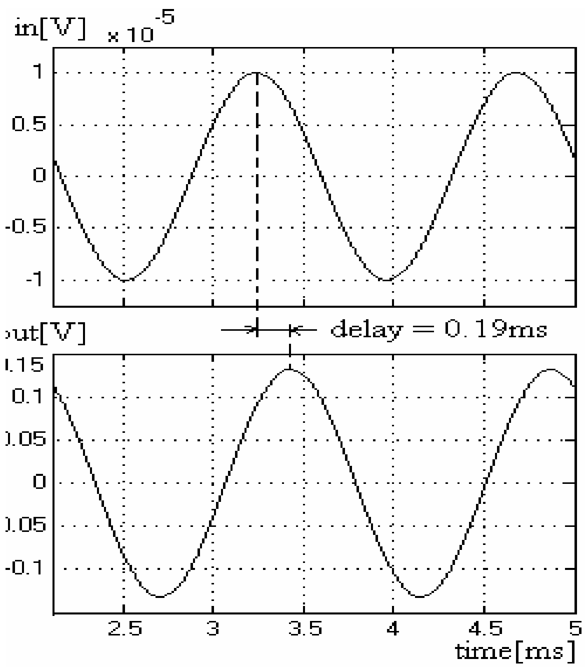

Fig. 15. Input and output waveforms, 694Hz, 27°C

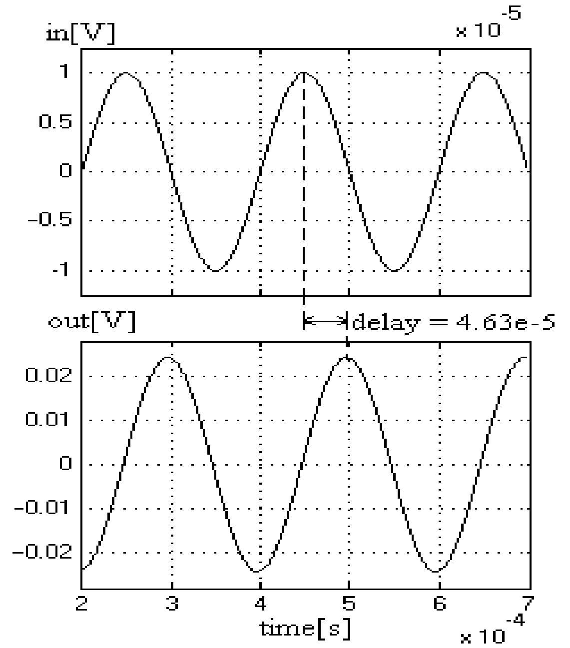

Fig. 16. Input and output waveforms, 5KHz, -50°C

5. CONCLUSIONS

The Simulink models of the simple operational transconductance amplifier and Miller operational transconductance amplifier using fuzzy systems were presented. The Simulink implementation supposes the use of more Simulink blocks. The main blocks are: gain-frequency and phase-frequency fuzzy models.

In our experiments the input signal is supplied by a signal generator block and the input and output waveforms are displayed on a scope. In the simulations of a complex system our Simulink model can be interconnected with other modules.

Table 2: Fuzzy functional model versus Spice for MOTA circuit.

Freq.	Temp.	Gain			Phase shift [degree]		
		Spice	Fuzzy model	Relative error [%]	Spice	Fuzzy model	Absolute error
10Hz	-50°C	25069	24994.38	-0.297	-1.176	-1.04	-0.136
	27°C	18717	18719.98	0.015	-0.824	-0.63	-0.194
	110°C	13029	13074.32	0.347	-0.553	0.42	-0.973
694Hz	-50°C	14413	14414.16	0.008	-54.918	-57.02	2.102
	27°C	13253	13170.98	-0.618	-44.928	-47.31	2.382
	110°C	10829	10776.19	-0.487	-33.795	-34.02	0.225
5KHZ	-50°C	2433	2422.72	-0.422	-84.447	-83.43	-1.017
	27°C	2580	2404.87	-6.787	-82.092	-82.76	0.668
	110°C	2646	2484.73	-6.094	-78.298	-79.46	1.161

The experimental results obtained on both operational transconductance amplifiers prove the validity of our functional model. The model provide very accurate values for the output voltage amplitude and phase shift over a wide range of frequency [1Hz, 1MHz] for SOTA, [1Hz, 10KHz] for MOTA and over the industrial temperature range [-55; +125]^{0}C.

The fuzzy functional models of analog modules can be very useful in verification of complex systems at the system design level; at this level the simulation is done behavioral and tools like Matlab/Simulink are often use.

Our future research will include the integration of the behavior in the nonlinear and saturation regions in the band-pass of the amplifier. In addition, new analog modules as cascode amplifiers will be in our attention.

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