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AUTOMATIC TUNING OF MOSFET-C FILTERS USING DIGITALLY PROGRAMMABLE CURRENT ATTENUATORS

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ABSTRACT

A digital method for the automatic tuning of MOSFET-C filters is proposed.The method has been applied to an active-RC filter where resistors have been replaced by digitally programmable current dividers. The tuning approach uses the traditional master-slave technique and has been applied to a lowpass filter whose specified cutoff frequency is 78 kHz. The cutoff frequency of the slave filter has been kept around ± 5% of its nominal value.

I-INTRODUCTION

Two widely known techniques for the integration of continuous-time filters are the so-called OTA-C and the MOSFET-C [1-8]. Tipically, integrated continuous-time filters have time constants (RC products or C/Gm ratios) that deviate ± 50 % from their nominal values. This deviation is due to factors such as tolerances, temperature variation and aging, and lead to inaccuracies in the frequency response. On the other hand, it has been demonstrated [1, 4, 7-12] that, using techniques of automatic tuning, the time constants can be controlled within a narrow range, leading to high performance continuous-time filters.

MOSFET-C structures are usually derived from classical active-RC filters where the resistors are replaced by MOS transistors operating in the triode region. The tuning of MOSFET-C filters is usually accomplished by controlling the voltage applied to the gates of the transistors. However, this tuning strategy changes the operating point of the MOS transistors. If a wide tuning range is required, filter properties such as linearity and dynamic range are affected [6].

An alternative technique for the tuning of MOSFET-C filters replaces the MOSFETs by digitally programmable MOST-Only Current Dividers (MOCDs) [6, 13]. In this case, tuning does not require adjustments in the transistor gate voltage.

In this paper we propose a technique for digitally programming MOSFET-C filters that overcomes the problems inherent to the use of voltage-controlled MOS resistances. We present a digital method for automatically tuning the center frequency of a Tow-Thomas biquad in which resistors have been replaced by MOCDs. The tuning method employs digitally controlled master and slave filters and is applied to set the cutoff frequency of the lowpass filter to 78 kHz.

II-THE TOW-THOMAS BIQUAD

As an example of a filter we have chosen the Tow-Thomas biquad (Fig. 1), which exhibits low passive and active ω_o sensitivities. Moreover, in this structure all the passive components are connected to low-impedance nodes. The bandpass and lowpass transfer functions are given by:

$$\frac{V_{BP}}{V_I}(s)=\frac{K_1(\omega_0/Q)s}{s^2+(\omega_0/Q)s+\omega_0^2} \tag{1.a}$$

$$\frac{V_{LP}}{V_I}(s)=\frac{K_2\omega_0^2}{s^2+(\omega_0/Q)s+\omega_0^2} \tag{1.b}$$

where

$$\omega_0=\sqrt{\frac{1}{R_2R_3C_1C_2}} \tag{1.c}$$

$$Q=\sqrt{\frac{R_1{}^2C_1}{R_2R_3C_2}} \tag{1.d}$$

$$K_1=-R_1/R_4 \tag{1.e}$$

$$K_2=-R_3/R_4 \tag{1.f}$$

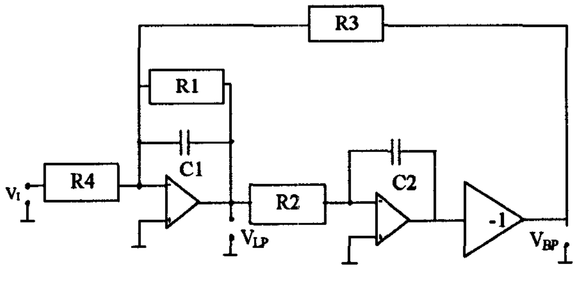

Fig.1 - Tow-Thomas biquad

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Note that the input and the bandpass output signals are 180° out of phase at the center frequency ω_0. This property has been used to tune the center frequency of the filter. In order to tune ω_0 without changing the remaining parameters of the filter, all resistances can be scaled by the same factor.

III-THE MOST-ONLY CURRENT DIVIDER

The basic element for digital programmability of the filters is the MOCD shown in Fig. 2. We propose the use of this digitally controlled current attenuator to replace the resistances in Fig. 1, instead of the conventional (gate) voltage-controlled MOSFET resistance. The output nodes of the MOCD must be at the same potential. Two complementary outputs are available. In the case of a fully balanced structure, both outputs should be used [6].

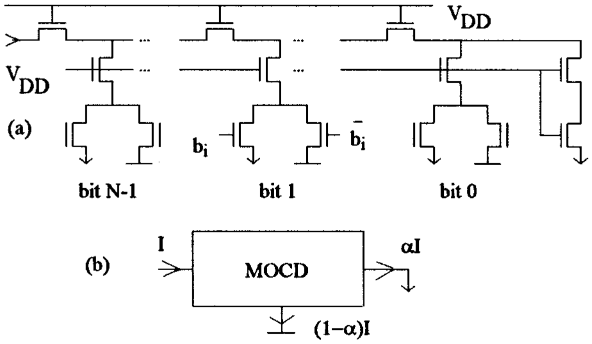

Fig. 2 - (a) MOCD structure (b) Symbol

IV-AUTOMATIC TUNING

Fully integrated continuous-time filters depend on a tuning circuitry for a reduced error in the frequency response. In the master-slave scheme a high performance tuning depends on the capability of the slave circuit to track the master circuit. This capability requires a good matching between them.

Fig. 3(a) shows the block diagram of the automatic tuning circuitry. The master and the slave are bandpass and lowpass DCFs (Digitally Controlled Filters), respectively. Both filters are Tow-Thomas biquads where resistors have been replaced by MOCDs, as shown in Fig. 3(c) α is the attenuation factor, controlled by a digital word, according to

$$\alpha = \sum_{i=0}^{N-1} b_i 2^{(i-N)} \qquad (3)$$

where N is the word length. Assuming all MOCDs identical and having equal input resistances $R_k(k = 1,\ldots,4) = r/\alpha$, ω_0 and Q can be readily calculated from:

$$\omega_0 = \frac{\alpha}{\sqrt{r^2 C_1 C_2}} \qquad (4.a)$$

$$Q = \sqrt{\frac{C_1}{C_2}} \qquad (4.b)$$

In our example, Q = 0.7 has been chosen. All the filter parameters, except ω_0, are invariant if the attenuation factors change equally for all MOCDs.

The input signal $f_{in}(t)$ in Fig. 3(a) is a sine wave at the nominal center frequency of the bandpass filter. Both the input and the output signals of the master filter are converted into square waves by high speed comparators. The outputs of the voltage comparators are applied to a phase comparator (Fig. 3(b)), whose operation is ilustrated in Fig. 4. The CK_1 and CK_2 inputs are shifted by 180°, except for a short delay (< 200ns) introduced by the inverter. The output Q_1 of the phase comparator is high for an increase in the bandpass filter center frequency and low for a reduction in that frequency. When the bandpass filter center frequency is approximately equal to its nominal value, Q_1 and Q_2 are both high and a high signal ($Q_2.Q_1 = 1$) inhibits the counter, indicating that the center frequency of the master filter has been reached. The output of the 6 bits binary counter provides the digital word for the MOCDs. The digital word is initially set to 100000 ($\alpha = 0.5$) and incremented or decremented according to the phase difference between input and output of the master signals, as explained before.

Under normal operation, the tuning is performed continuously by means of an external signal reference. The digital word is automatically set to one of 64 possible values, depending on the deviations of the time constants of the filter. For example, if the nominal value for α is 0.5 and the actual time constants differ from their nominal values by as much as ± 50%, the digital word applied to the MOCD should be varied from 010000 ($\alpha = 16/64$) to 110000 ($\alpha = 48/64$).

A relative error in the time constants occurs because of the finite digital word lenght. The maximum value of this quantization error is, for an N-bit word, given by

$$\Psi = \frac{2^{-(N+1)}}{\alpha - 2^{-(N+1)}} - 1 \qquad (5)$$

The maximum quantization error for a 6 bits MOCD is 3.2%, and occurs when the digital word is 010000 ($\alpha = 16/64$) or 1.05% for 110000 ($\alpha = 48/64$).

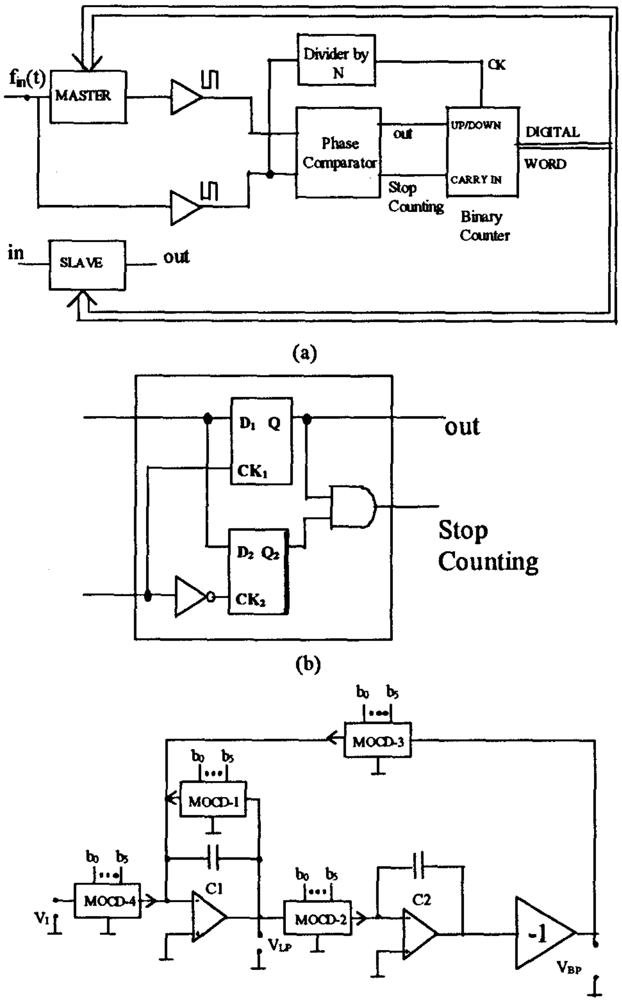

Fig. 3 - (a) Scheme of tuning circuitry
(b) Phase Comparator
(c) Tow-Thomas filter utilized (master and slave)

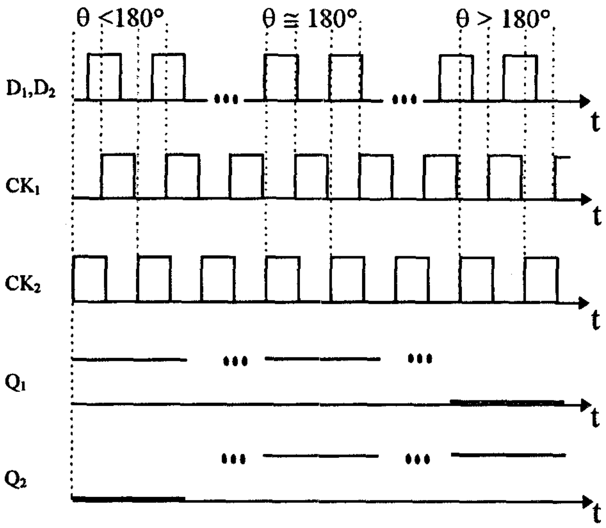

Fig 4 - Operation of the phase comparator for some phase differences between master input (CK_1) and master output (D_1, D_2).

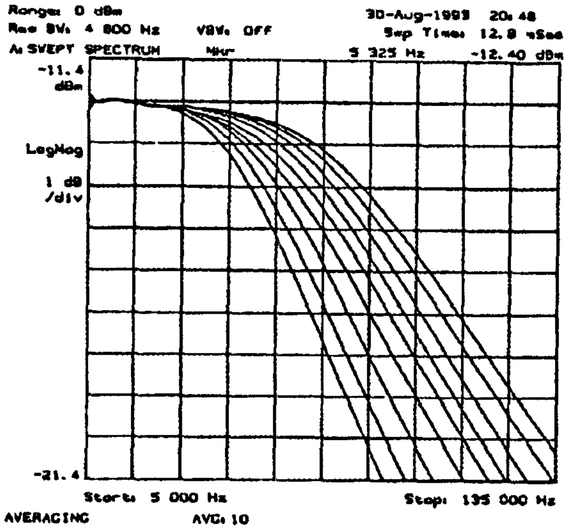

Fig. 5 - Magnitude response of the lowpass filter for attenuation factors in the range $24/64 \leq \alpha \leq 40/64$

V-EXPERIMENTAL RESULTS

The tunable filter has been built with discrete components ($C_1 = 2 \times 270\,pF$, $C_2 = 270\,pF$) and MOCDs integrated in a 1.0 μm CMOS technology (nominal $r = 2.7k\Omega$).

The magnitude response of the lowpass filter is shown in Fig. 5 for different digital words (attenuation factors). The shape of the magnitude response has been preserved regardless of the digital programming word.

Fig. 6 illustrates the magnitude responses of the lowpass filter for 58, 78 and 98 kHz reference input frequencies. The overall tuning error (percentage deviation of cutoff frequency from its nominal value) has been kept around ± 5%. This error results from several factors:

- The mismatches of MOCDs in the same filter and of the master and slave filters, worsened by the discrete prototyping.

- Error caused by the tuning technique.
- Quantization errors.
- Offset voltages of comparators and master filter.

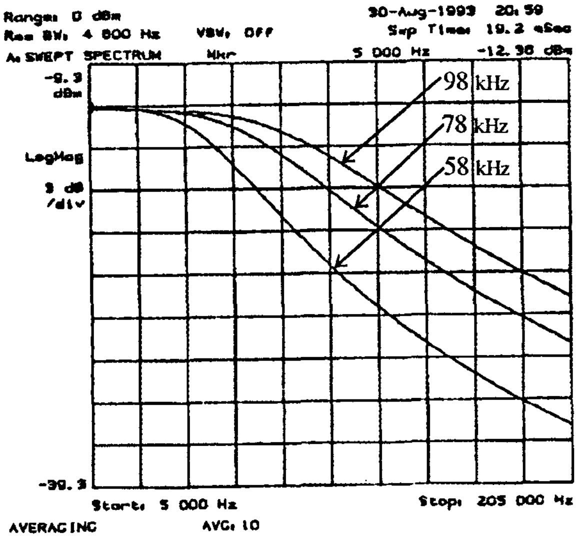

Fig. 6 - Magnitude response of the slave filter obtained with automatic tuning for some reference input frequencies

VI-CONCLUSIONS

A new scheme for a digital automatic tuning circuit for continuous-time filters has been proposed and analyzed. The tuning scheme is based on the digital programmability of MOST-only current dividers. This method has two advantages over the one based on the control of the gate voltage: the simplicity of the control circuitry and a larger dynamic range. Smaller errors in the tuning frequency than those presented here are expected in a fully integrated implementation employing MOCDs with higher resolution, e. g., 8 bits.

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