Adaptive Log Domain Filters Using Floating Gate Transistors

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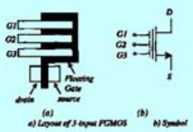
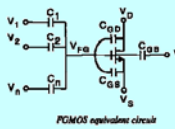
Introduction

- Adaptive log domain filter with integrated learning rules for model reference estimation.
- First order low pass filter with on-line learning of gain and time constant implemented by multiple input floating gate transistors.
- Robust learning rules for both gain and time constant adaptation derived from adaptive dynamical system theory .

Floating Gate Transistors





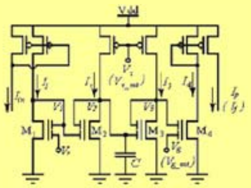
- Floating gate surrounded by an insulator so electrons are prevented from escaping.
- Voltage inputs to a secondary control gate couple capacitively into the floating node to modulate transistor current.

Conservation of charge gives:

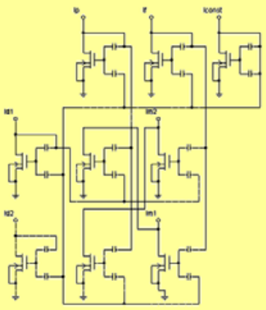
$$V_G = \frac{\sum_{k=1}^{n} C_k V_k + C_{GS}V_S + C_{GD}V_D + C_{GB}V_B}{C_T}$$

$$\approx \frac{\sum_{k=1}^{n} C_k V_k}{C_T} \quad where \quad C_T \approx \sum_{k=1}^{n} C_k$$

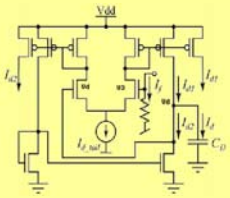
Circuit Implementation



Circuit for both plant and filter



Circuit for computing product of error and derivative



Circuit for computing temporal derivative

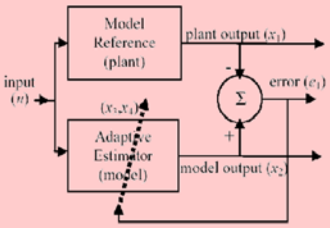
Significance

✓First integrated Adaptive IIR filter

✓Lyapunov method for adaptation

✓ Low power floating gate computation

Derivation of Learning Rules



Model reference adaptation

What we have

Unknown plant output & adaptive estimator output

What we want to do

Minimize the error to ZERO

First order low pass filter:

$\dot{x}_1 = -Ax_1 + ABu$ unknown plant

$\dot{x}_2 = -x_3x_2 + x_3x_4u$ adaptive estimator

Error system:

$e_1 = x_2 - x_1$ output error

$e_2 = x_3 - A$ (1/time constant) error

$e_3 = x_4 - B$ gain error

System dynamics:

$$\dot{e}_1 = \dot{x}_2 - \dot{x}_1 \qquad \dot{e}_2 = \dot{x}_3 \qquad \dot{e}_3 = \dot{x}_4$$

Lyapunov method

Find a Lyapunov function which is:

1. Positive definite
2. Negative definite time derivative
3. Radially unbounded

We choose

$$V(e) = \tfrac{1}{2}\left(e_1^2 + e_2^2 + e_3^2\right)$$

To get a negative time derivative:

$$\dot{V}(e) = -Ae_1^2$$

We choose the control laws:

$$\dot{e}_2 = -e_1\frac{\dot{x}_2}{x_3} \text{ and } \dot{e}_3 = -e_1 Au$$

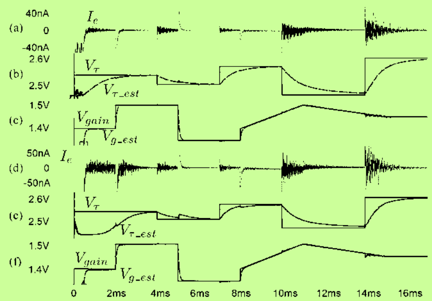
For current mode filters:

$$x_3 > 0$$
$$A > 0$$
$$u > 0$$

If we only consider the direction but not the rate of adaptation:

$$\dot{e}_2 \mu -e_1\dot{x}_2 \text{ and } \dot{e}_3 \mu -e_1$$

Simulation and Testing



HSPICE simulation of successful adaptation

(a) - (c) input:

Mixture of sine waves at 10kHz, 20kHz, 40kHz, and 80kHz

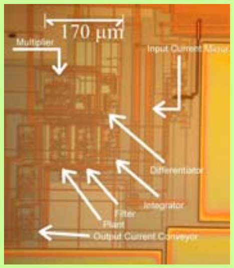
(d) - (f) input:

Summation of 14 sine waves, whose frequency ratio is an irrational number $2^{1/5}$, spanning from 5kHz to 97kHz.

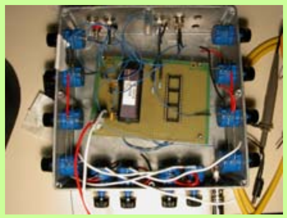
The different values V_τ correspond to I_τ of 40nA from 0-2ms, 80nA from 2-3ms, 20nA from 3-4ms, 160nA from 4-6ms, and 10nA from 6-8ms.

Time constant is inverse proportional to I_τ and gain is proportional to $e^{V_{gain}}$.

In all cases the error converges to zero, and the model closely tracks the plant.



Fabricated chip



Testing setup

Summary

※ Robust learning rules based on Lyapunov stability.

※ Log domain IIR filters have simulated cutoff frequencies above 100kHz with power consumption of 23uW.

※ Fabricated filters have measured cutoff frequencies above 20kHz with power consumption of 170uW.

※ Adaptation is currently being tested.

Acknowledgements

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