Auto Correlation in Micropower Analog CMOS

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Abstract. A fully working analog computational system for time-domain signal analysis is implemented in micropower CMOS. Based on a simple four-transistor correlator circuit, an auto correlation system is designed in combination with a delay-line. A high level of feedback adjusts the unit delay such that the time-span of the delay-line is one period, independent of the input frequency.

1. Introduction

The computational power of analog systems implemented in silicon is gaining interest. Several successful systems with on-chip photo sensors have been implemented [1-3]. The two-dimensional nature of picture processing is elegantly utilized with photo sensors distributed on the silicon surface together with analog processing elements. If the computational power is scaled by the power consumption, these analog systems are beating similar digital implementations with orders of magnitude [4].

In processing systems with lower fundamental dimensionality like systems for audio sound processing, there are successful digital approaches (DSP systems). Although there is only one basic dimension (i.e., sound intensity), these systems do temporal processing where time is the second dimension. Digital representation of sound is being used in ever new applications. Just think of CD-players, digital telephone systems and even digital television.

In spite of the constant growth of digital systems, there are several untractable tasks. Good systems for speech analysis and speech synthesis are hard to build based on a digital paradigm. Fuzzy perception problems where the signal is ill-conditioned and the method not very well understood are hard to handle digitally.

Recently, micropower analog computational systems (MACS) have been built in silicon with surprising results. One good example is the detection of the pitch in an audio signal with good match compared to the pitch detection found in the auditory system [5-7]. A notable fact about these systems is that they all work in real time with processing paradigms found in biology.

Believing that analog computational systems may handle untractable problems, we will show how auto correlation is implemented using silicon and very simple circuits. These circuits are used to build a large computational system with a high level of feedback maintaining a frequency-independent representation of a periodic analog signal.

2. Analog Correlators

The statistical understanding of correlation is a unitless number between one and zero where one indicates perfect correlation and zero no correlation or anti correlation regardless of the magnitude of the two signals correlated. We might struggle to be faithful to this invariant and try to build a perfect analog correlator.

This perfect correlator is possible to realize, but would require a significant number of transistors. With really large computational systems in mind, we will instead explore simple, non-ideal circuits with correlation-like behavior.

The heart of the processing system is a current-mode circuit shown in Figure 1(a) [11, 7]. Only four transistors are required to implement a correlation-like function.

2.1. Translinear Analysis of Non-Saturated MOS-Devices

Although the transfer-function of the simple correlator circuit may be derived by conventional analysis, we
will use this simple circuit to show how the translinear principle created by Berrie Gilbert [8] may be applied to non-saturated MOS-transistors in weak inversion.

Although Berrie Gilbert disregards the feasibility of translinear analysis of saturated MOS-transistors in weak inversion due to poor matching, we believe that translinear analysis is very useful for analysis of large analog circuits (MACS) such as the one presented in this paper. Designing MACS demands a different design approach. The building blocks should be simple in order to achieve high computational density. Instead of fine tuning of each computational element, we use quite inaccurate circuits where only first-order approximation is needed.

Another important strategy in MACS is localized or distributed computation. In this way, we may cope with random variations such as transistor mismatch. Systematic errors, on the other hand, must be avoided in order to keep the operating point away from the rails. In order to make the system scalable we have to handle systematic errors.

In this context, the translinear analysis is a very powerful tool. Andreou [9] showed how the translinear principle may even be used for non-saturated MOS-devices. We would therefore expect the translinear principle to be applicable to a large class of weak inversion circuits.

In the following, we will use translinear analysis to find the transfer function of the simple correlator. Not only is the beauty of translinear analysis shown, but the genuine symmetrical property of the MOS-transistor is illustrated.

In [10], p. 59, Vittoz points out the fact that the source-drain current of a MOS-transistor may be decomposed:

\[ I_{ds} = I_F - I_R = I_{gs} - I_{gd} \]

For MOS-transistors in weak-inversion both the \( I_{gs} \) and the \( I_{gd} \) are exponential functions in terms of the voltages involved:

\[ I_{ds} = I_0 e^{\frac{V_g - V_d}{V_T}} - I_0 e^{\frac{V_g - V_D}{V_T}} \]

A translinear analysis requires an exponential dependence. For this reason, translinear circuits are usually biased in saturation, and the \( I_{gd} \)-term approaches zero leaving us with a single exponential relation just as required.

The saturation requirement excludes any circuit with non-saturated transistors such as the correlator we are using. In [9], Andreou points out the surprising fact that translinear analysis may be carried out even on non-saturated MOS-transistors by utilizing the fact that the current is a \textit{difference} between two exponentials, as suggested by equation (1). The drain-source current is decomposed, as Vittoz suggested, into two “independent” currents with opposite signs.

In Figure 2, arrows indicate exponential relations. The \( T_2 \) transistor will not be saturated, so we have to account for two exponential relations as indicated. By inspection, the following equations may be derived:

\[ I_1 = I_{gs} \]
\[ I_{out} = I_{gs} - I_{gd} \]
\[ I_2I_{gd} = I_{out}I_{gs} \]