Analog Circuit Design

Structured Mixed-Mode Design, Multi-Bit Sigma-Delta Converters, Short Range RF Circuits

Edited by
Michiel Steyaert
Arthur van Roermund
and Johan H. Huijsing

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Preface

The book contains the contribution of 18 tutorials of the 11th workshop on Advances in Analog Circuit Design. Each part discusses a specific to-date topic on new and valuable design ideas in the area of analog circuit design. Each part is presented by six experts in that field and state of the art information is shared and overviewed. This book is number 11 in this successful series of Analog Circuit Design, providing valuable information and excellent overviews of analog circuit design, CAD and RF systems. These books can be seen as a reference to those people involved in analog and mixed signal design.

This years workshop was held in Spa, Belgium and organized by E. Janssens of Alcatel Microelectronics, Belgium. The program committee consisted of M. Steyaert, KULeuven, Belgium, H. Huijsing, T.U.Delft, The Netherlands and A. van Roermund, T.U.Eindhoven, The Netherlands.

The topics of 2002 Spa (B) are:

Structured Mixed Mode Design
Multi-Bit Sigma Delta Converters
Short Range RF Circuits

The other topics covered before in this series:

1992 Scheveningen (NL):
Opamps, ADC, Analog CAD

1993 Leuven (B):
Mixed-mode A/D design, Sensor interfaces, Communication circuits

1994 Eindhoven (NL)
Low-power low-voltage, Integrated filters, Smart power

1995 Villach (A)
Low-noise/power/voltage, Mixed-mode with CAD tools, Volt., curr. & time references

1996 Lausanne (CH)
RF CMOS circuit design, Bandpass SD & other data conv., Translinear circuits

1997 Como (I)
RF A/D Converters, Sensor & Actuator interfaces, Low-noise osc., PLLs & synth.

1998 Copenhagen (DK)
1-volt electronics, Design mixed-mode systems, LNAs & RF poweramps telecom

1999 Nice (F)
XDSL and other comm. Systems, RF-MOST models and behav. m., Integrated filters and oscillators

2000 Munich (D)
High-speed A/D converters, Mixed signal design, PLLs and Synthesizers

2001 Noordwijk (NL)
Scalable analog circuits, High-speed D/A converters, RF power amplifiers

I sincerely hope that this series provide valuable contributions to our Analog Circuit Design community.

Michiel Steyaert

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Part I: Structured Mixed-Mode Design

Johan H. Huijsing

In order to shorten the design time of integrated circuits, industry has a general need to automate the design flow. Alltough this has been successful for the digital VLSI design flow, automation is still in its infancy for the analog and mixed-mode design flow. The six papers in the first part of this collection of AACD 2002 papers describe approaches towards a more structured and automated design of analog and mixed- mode circuits.

The first three papers cover the structured design of three basic analog building blocks: oscillators, gm-C filters and LNA s.

The fourth paper describes tools for high-level simulation and modeling of mixed-signal front-ends for wireless systems.

The fifth paper discusses a structured simulation-based analog design synthesis.

The sixth paper presents a structured design approach for mixed-mode layout.

Structured Oscillator Design

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Abstract

This paper presents a general design approach applied to the design of oscillators. The design approach is based on classification of oscillator circuits. From this classification rules for designing oscillators can be extracted. These design rules are used as a fast means to get to an overview of the design space and to focus the creativity of the designer to the spot where the real design challenge is. The structured oscillator design approach has led to insight such that new circuits where found. The key ideas in these circuits are also presented.

1. Introduction

A huge amount of papers has been written on oscillators. For a designer it is no problem to find papers on designs similar to his own design. Once a designer has decided to use a certain topology, all available information on that topology is just a few mouse-clicks away on the Internet. This paper is not intended to add yet another paper to this abundance. Structured Oscillator Design does not deal with details of a specific design problem or topology, but with design rules that can help a designer to pick the most appropriate oscillator topology for his application from the known set of topologies or to help him to decide that there is none that is really appropriate. In the latter case, the same rules could help him to "invent" a new topology.

The rules used for Structured Oscillator Design differ from the rules that are needed for CAD. The requirements on a design rule to be used for CAD are much more strict than they are here. The only demand on the rules here is that they can help the designer to find an optimal topology from a known set of topologies and, more

M. Steyaert et al. (eds.), Analog Circuit Design, 3–19.

important, to help him to find really new topologies. So they do not need to be logically correct, mathematically proven, and generally applicable or to form a closed set. As long as they help focusing the designers' creativity on the spot where it is needed, they are "correct".

In this paper, *a* (not *the*) set of design rules will be presented, that has helped the authors to find some new oscillator concepts that will also be discussed in this paper. These new concepts have been designed, tested and patented, so in this respect the usefulness of the rules has been "proven", but it is not the intention of this paper to claim the only, the best or the optimal way to design oscillators. It is just to present *a* structured design approach that may inspire designers and researchers.

2. The first design rule: a proper definition

Everybody knows the definition of an oscillator. So why spend costly design time on producing an exact definition? Two reasons doing so could be:

- Knowing the exact definition, it may be possible that thinking about ways to implement the various "ingredients" of the definition, a designer finds a new circuit.
- Circuits that produce a periodical signal, but do not completely match to the exact definition of an oscillator usually are able to de more than just behave like an oscillator. Pity for the designer when the circuit decides to show this alternative behavior when it is already with the customer. A designer would like to know of this potential danger on beforehand. The Colpitts oscillator is a known example of a circuit that can do more than just oscillate [1,2,3,4,5].

Also, when a designer is aware of the "extra features" of a circuit, he might find a new (non-oscillator) application for the circuit, where a customer could enjoy the formerly undesired behavior.
So let's produce the exact definition:

An oscillator is a tunable circuit that generates a stable periodical signal, which is in the limit independent of the initial conditions.

Note the words *tunable* and *stable* in the definition. For oscillators that are really not tunable there are only some niche-applications (Cesium-standards etc.), for all other oscillators the tunability, either being an intended feature or just a parasitic effect, needs to be evaluated and designed. Stability always is an issue, since stability costs either power or money, or both.

Tunability and stability will be discussed later. Now the focus will be on the phrase *"which is in the limit independent of the initial conditions"*.
Differential equations (DEs) are a very convenient means to describe the behavior of a dynamic circuit. Differential equations that just have one periodic particular solution are of the second order. So the ideal oscillator is described by a second-order differential equation. Higher-order differential equations can have more than one periodical solution, or even a-periodical ones. Practice has proven that higher-order circuits can, and very often will, produce non-periodical (e.g. chaotic) output signals.
A naive choice for a second-order DE would be, for instance,

$$\ddot{x}(t)+\omega^2 x(t)=0 \tag{1.1}$$

For this equation, it is known that the solutions are periodic with frequency ω. However, there is a strong dependence on the initial conditions for the amplitude of the attainable solutions. A solution to this equation is:

$$x(t)=a_1\cos(\omega t) \tag{1.2}$$

in which a_1 (the amplitude) is an arbitrary constant, determined by the initial condition $x(0)=a_1$, which is of course undesirable. The only DE's that can have solutions of which the amplitude is not dependent on the initial condition are *non-linear* DE's like:

$$\ddot{x}(t)+\tilde{f}(x(t))\dot{x}(t)+\omega^2 x(t)=0 \tag{1.3}$$

where the function $\tilde{f}(.)$ is the required amplitude control and defines a *static* non-linearity.

From this it can be concluded that oscillators are *always* non-linear circuits that should be of second order and no more.

3. A classification

Since part-list of an oscillator consists of two time-constants and a non-linearity, it seems a good idea to use the number of dominant time-constants as the basis for a classification. It is not necessary that all time-constants in an oscillator have an equal influence on the output frequency. Based on this the following classification can be made:

Frequency dominated by:	**Class:**
One time-constant	First-order oscillators
Two time-constants	Second-order oscillators
3 time-constants	Third-order oscillators
Etc.	....

Of course classifying in this way, there is an unlimited number of classes, but the higher the order, the less suited a circuit is to be used as a reliable oscillator. Examples of first-order oscillators are a-stable multivibrators, of second-order oscillators Wien-bridge oscillators and of third-order oscillators many RC-oscillators.
Delay-line oscillators seem to form a particular class as they are sometimes called "infinite order oscillators" [6], but actually they show (if working properly) the behavior of a second-order oscillator. They can be described with an infinite set of second order DE's:

$$\begin{cases} \ddot{x} + f_{a1}(x)\dot{x} + f_{b1}(x) = 0 \\ \ddot{x} + f_{a2}(x)\dot{x} + f_{b2}(x) = 0 \\ \ddot{x} + f_{a3}(x)\dot{x} + f_{b3}(x) = 0 \\ ..... \end{cases} \tag{1.4}$$

One of these equations is related to the desired mode in the output signal, the others are related to unwanted modes. Due to the very small interaction between the modes, the behavior of a delay-line oscillator can come very close to that of a true second-order oscillator, but it will take more design effort to obtain the desired oscillator behavior, since there are more parameters to control. The circuit can do more than a true oscillator. Makes one wonder what other applications could be....

3.1. First-order oscillators

In first-order oscillators one time constant is dominant. This means that most of the time, only one time-constant is responsible for the variation of the output signal. Only for a very small part of the period, the *essential* effect of the other time-constant is present. The advantage of this is that the dominant time-constant can be a well-defined integrator. Integrating a constant, the integrator produces a ramp-signal at its output. Two reference levels are chosen at which the sign of the constant that is integrated is changed (see fig.1).
When integrator is around one of the two reference levels, during the switching of the sign, the first-order oscillator really shows "second-order behavior".
Often, the second time-constant comes from a binary memory that switches during (see fig.3a) the transition. Changing the integration constant or the reference levels to tune the oscillator can be done fast and well defined. For this reason first-order oscillators have a high modulation bandwidth, can be *linearly tuned* and have a *wide tuning range*. These properties form the most important reason to select an oscillator from this class.

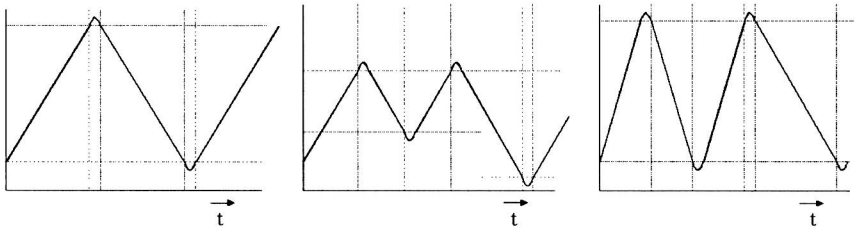

Figure 1: First-order oscillators are easily tuned.

The big "challenge" of first-order oscillators is the frequency stability. Although during the time interval the oscillator is just integrating of which the timing can be very accurate (the Q of a capacitor is generally very high), during the transition many effects play a role that destroys the over-all stability.

One of the most important effects is the poor stability of the switching of the binary memory. The binary memory (Schmitt-

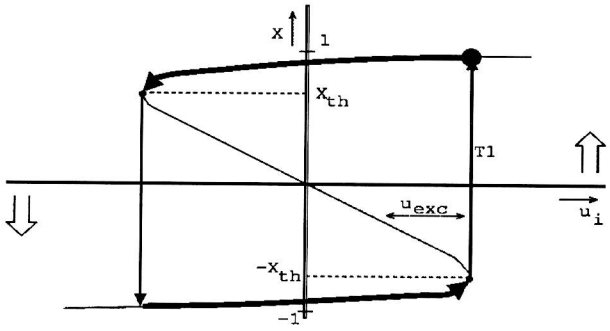

Figure 2: the limit cycle of a first-order oscillator.

trigger, flip-flop) is a regenerative circuit that shows a typical transition behavior. The reason for this poor stability can be explained with the aid of figure 2. It shows the limit cycle of a first-order oscillator (see fig.3). On the horizontal axis is the capacitor voltage and on the vertical axis is the state of the binary memory. Most of the time during a period is spend on the bold part of the limit cycle where the integrator is charged or discharged. At the point where the transition of the memory should occur, the very slowly varying capacitor voltage has to initiate a transition that is usually a few orders of magnitude faster. This means that with respect to the timescale at which the events in the memory occur, it seems as if the capacitor voltage has come to a near "stand-still", just before it could initiate the transition. Any signal from outside that falls within the bandwidth of the memory, (noise, a spike etc.) can initiate a transition well before it is due or delay it after the capacitor voltage just crossed the reference level. This can result in an enormous jitter [6,7]. Two methods that can be used to counteract the problem are:

- **Removing the binary memory from the essential timing path.** Observing the generally used block diagram in fig.3a, it can be seen that the memory is in the timing path. The only essential function of the memory is to keep the sign of the integrated constant in the right position during the charging and discharging of the capacitor. There is no rule that states that this memory has to "deliver" the second time-constant that is needed according to the oscillator definition. The circuit shown in fig.3b shows a block diagram in which a comparator delivers this second time-constant and the memory is bypassed [9].

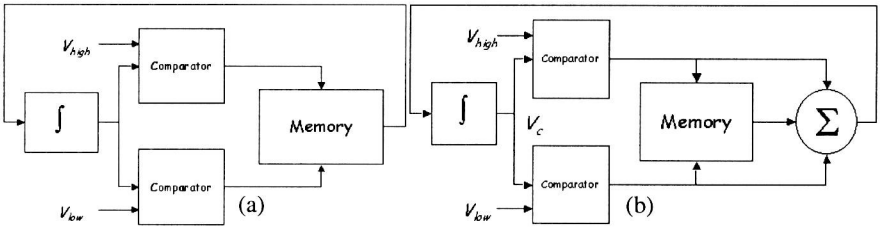

Figure 3: The commonly used block diagram of a first-order (a) and a block diagram showing the memory bypass (b).

- **Introducing an intentional well-timed external transition pulse.** Injection-lock can cause big problems in an oscillator, and first-order oscillators are very susceptible to this problem. But when the mechanism is there anyway, why not use it beneficially? The only problem is to obtain this well-timed external pulse in such a way that there is no additional high-quality oscillator is necessary to derive it. Then it would be better to use that oscillator in the first place. So if no other type

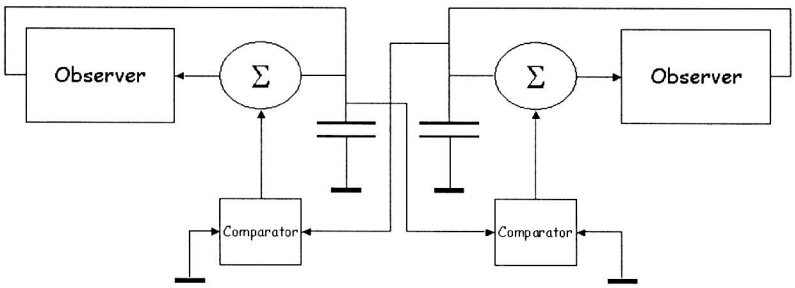

Figure 4: Two first-order oscillators coupled in quadrature.