Design Principles for Low-Noise Relaxation Oscillators

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Abstract

Phase noise is an important issue in oscillator design. Several classes of different oscillators exist each having their typical noise behavior. Various techniques can be used to optimize the noise behavior, depending on the specific class. Methods vary from optimization of the oscillator itself to coupling of a number of oscillators. Two important classes of oscillators are first-order (relaxation) oscillators and second-order oscillators. One of the most promising optimization strategies for relaxation oscillators seems to be coupling of large number of oscillators, however, technology is not quite ready for this. Optimization of second-order oscillators by coupling is not of great general use. In this case much improvement can be achieved by optimizing the oscillator itself. In this paper, design methodologies are given for the optimization of relaxation oscillators. In a follow-up paper [1], new design methodologies are presented for the optimization of second-order oscillators.

1 First-order oscillator fundamentals

A simple way to generate a time varying signal out of constants is charging a capacitor with a constant current. Mathematically spoken, this comes down to integrating a constant (α).

$$f(t) = \int \alpha \, dt = \alpha \cdot t \tag{1}$$

As this signal ($f(t)$) is not periodical yet, some extra measures are required. Two reference values are defined at which the sign of α is changed. This results in a system in which periodically α and $-\alpha$ are integrated. In principle the integrating capacitor is a time-reference and not a frequency reference. Hence, *there is no frequency of preference*, which explains the easy tunability and therefore also the bad frequency stability. Thus to generate the periodical signal extra functions are necessary apart from the integrator. They are:

- A generator for α.
- A 'sign switcher' for α.
- A binary memory that can hold the actual sign for α.
- A comparator that compares the integrator output with the reference values.

Especially the memory is of interest. A number of implementations for it are known, the most common being the regenerative memory. Other memories are the flip-flop and the Schmitt trigger. There is no fundamental difference between these regenerative circuits. They all show a specific behavior which can cause a lot of noise in the oscillator. Therefore we will focus on the noise of these regenerative circuits in section 2.

First-order oscillators are thus systems that comprise various functions that together determine the output frequency. Not only the various components themselves can cause problems, but also the complete oscillator system may have a serious problem. To reveal this problem, a common system topology for a first-order oscillator is given in figure 1. In this topology the memory is a regenerative circuit (e.g. a Schmitt trigger) which is also able to detect two threshold levels, so it performs the comparator function too.

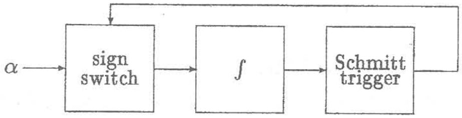

Figure 1: A common topology for first-order oscillators.

When the integrator voltage nearly crosses a reference level, a feedback loop is present from the integrator voltage back to the charging current. In principle this is a *negative*-feedback loop that tries to suppress variations of the capacitor voltage. This loop has a pole in the origin (the capacitor acts as integrator) so it is slow. It is the hysteresis of the binary memory that prevents this loop from stabilizing at a constant capacitor voltage. As this loop makes the tranisition slow, it degrades the noise performance of the system, as it hampers proper switching of the regenerative memory. In section 4 solutions are given for this problem.

2 Basic (noise) behavior of a regenerative circuit.

The memory type that is used mostly in first-order oscillators is the regenerative type. There are other solutions [2], but they will not be discussed in this paper.

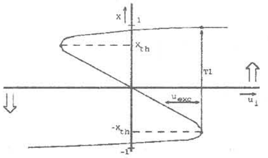

Figure 2: Input signal of a regenerative circuit against its output signal (X).

A regenerative circuit is a positive feedback circuit. Figure 2 depicts a typical plot of the state X of the circuit and its input signal (u_i). The curve connects operating points of the regenerative circuit in which it is in equilibrium, so it *does not change state* when it is in an operating point on the curve. When the the operating point is not on the curve, it does change state. The state changes in the positive direction when the operating point is at the right side of the curve and it changes in the negative direction when the operating point is on the left side of the curve. In figure 2, this is indicated by large arrows.

When the input signal is changed – which causes the operating point to move away horizontally from the curve – the operating point starts moving away vertically from the curve. As in first-order oscillators the input signal of the regenerative circuit changes slowly compared to the speed at which the regenerative circuit changes state, during the vertical motion of the operating point it can be considered constant. In figure 2 we see that the excitation the circuit makes itself (the 'self-excitation') is much larger than the external excitation. Thus, initially the excitation is very small and therefore the circuit is relatively slow. The regenerative circuit is very susceptible to noise at this stage. A small extra external signal can speed up the start very much, which gives a considerable shortening of the first part of the transition, resulting in a large jitter at the output of the circuit. Therefore: *regenerative circuits with small input signals are very susceptible to noise.*

3 Improving the noise behavior of the regenerative memory

In the previous section it has been described and concluded that lacking sufficient input signal (excitation), the regenerative memory is noise sensitive; small variations in the input signal are translated in a considerable jitter in the output signal. When the memory is used in the oscillator system as shown in figure 1, this jitter is directly found as phase jitter in the oscillator output. Several measures exist to improve the inferior noise behavior of a first-order oscillator caused by the memory:

- Increase of the capacitor voltage.
- Use of limiters in front of the memory.
- Exclusion of the memory from the timing path of the oscillator.

In the following subsections these measures are discussed subsequently.

3.1 Increase of the capacitor voltage

For a constant output frequency the slope of the capacitor voltage increases when the amplitude of the capacitor voltage is increased. When the reference levels of the regenerative circuit are crossed with this increased slope, the memory is stronger excited and switches more reliable. This implies that the capacitor voltage should be made as large as possible.

3.2 Use of limiters

Increasing the capacitor voltage, as suggested above can be done to increase the slope of the capacitor voltage. However, when the behavior of the memory is taken into account, this appears to be too harsh a measure. The memory is 'blind' for the capacitor voltage except in the small range around its threshold level. Therefore it is only necessary to increase the slope of the capacitor voltage around these levels. This can be achieved with two limiters, each having their transfers centered around one or the threshold levels. An example of this is depicted in figure 3. This circuit has been proposed in [3, 4]. Due to the (local) enlargement of the slope of the capacitor voltage, the memory is maximally excited. This implies that the extra jitter due to the regenerative character of the memory is reduced to negligible proportions. As the gain of the limiters is large, the only important noise source remaining is now the noise of the limiters. Their noise behavior is not deteriorated by a regenerative loop, so it can be expected to be much better than that of the memory. From this example we clearly see that in a first-order oscillator every building block should

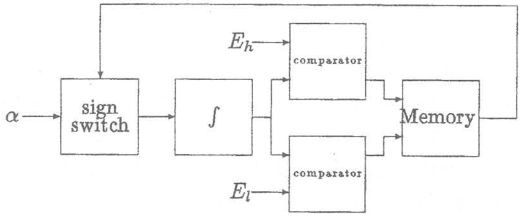

Figure 3: A first-order oscillator with limiters (comparators) to optimize the switching behavior of the regenerative memory.

only do 'what it is good at'. Although a regenerative circuit is able to detect the crossing of threshold levels, in a high-performance oscillator this comparison should be done by real limiters. Stated otherwise: *the basic functions in the oscillator should be orthogonalized.*

3.3 Exclusion of the memory from the timing path of the oscillator

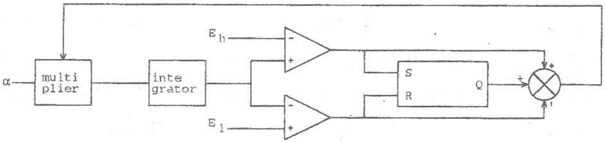

Figure 4: A topology in which the memory and the integration constant are switched in parallel.

From previous sections it can be concluded that it would certainly be the best when the regenerative circuit is not a part of the timing path of the oscillator. In figure 4, a circuit is depicted in which the memory is bypassed by the comparators. In this way the sign switch (multiplier) is directly activated by the output of the comparators. The memory only has to switch before the output of the comparator switches back, in order to memorize the momentary sign of the integration. When the comparator stops generating the necessary output signal, the memory prevents the switch from falling back into its previous position [2, 5, 6].

4 The feedback loop problem; quadrature coupled oscillators

In section 1, the problem of the inherent negative feedback loop was already touched: the oscillator counteracts the cause of its own switching, thereby ruining its noise behavior. Unfortunately, the presence of a negative-feedback loop is essential in the oscillator since it causes the capacitor voltage to 'bounce back' at the two threshold levels, thus establishing the desired periodical signal. Still, the oscillator can be designed such that the negative-feedback action has no effect on the timing of the transitions and thus on the noise performance of the oscillator.

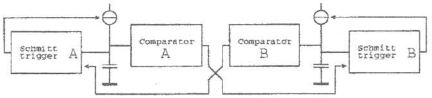

Figure 5: The basic coupled oscillator.

In figure 5 a quadrature coupled first-order oscillator circuit is depicted that effectively breaks the negative-feedback loop. In the coupled oscillator system comparators are used to detect the crossing of some 'virtual' threshold level by the capacitor voltage, a predefined time before the true threshold level is crossed and the transition is due. The required time delay between the crossing of the virtual threshold level and the actual excitation for the transition is derived from a second identical oscillator running on the same frequency but not in phase with the original oscillator. This second oscillator is also equipped with comparators that measure virtual threshold levels, and the required time delay is defined by the first oscillator. In this way a system of two mutually coupled oscillators is created and the negative-feedback loop is effectively broken since the memory is able to complete its transition long before the delay times have expired.

5 In-phase coupled oscillators

As we have seen, quadrature coupled oscillators give us the opportunity to effectively eliminate the degradation of the noise performance introduced by the negative-feedback path in the oscillator. Another way to get a better noise performance is to use in-phase coupling of first-order oscillators. In an in-phase coupled first-order oscillator system, either all oscillators switch when the first of all oscillators switches, or all oscillators wait for the last of all oscillators to switch. In such a system, it can be shown that the probability-density function (figure 6) of the switching time is narrower than the probability density function of the switching time of one oscillator. Therefore, the system is less noisy. For the probability density function of a system of N oscillators, with equal probability functions $p(t)$, the

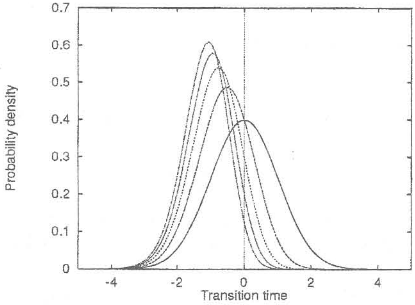

Figure 6: PDF of the transition time of N coupled oscillators, N=1–5 from right to left.

probability density function of the system $p_s(t)$ can be shown to be:

$$p_s(N, t_1) = Np(t_1)\left[\int_{t_1}^{\infty} p(t)dt\right]^{N-1} \tag{2}$$

In figure 6 some of these functions are plotted. It can be seen that in this system, in which the fastest oscillator dominates, the mean of the transition times is narrower (thus the frequency of the coupled system is higher) and the peak is smaller (thus it is less noisy). For a system of two oscillators, the coupled system can be shown to yield an improvement in SNR of about 1.67dB. From this it can be concluded that coupling techniques can result in very stable carriers, but large numbers of oscillators are required.

6 Conclusions

In this paper, the noise behavior of first-order oscillators has been discussed. Two major sources of noise were found: the regenerative memory and the inherent negative-feedback loop in the oscillator. A model was presented for the noise behavior of the regenerative memory. Three methods were presented to improve the noise behavior of the regenerative circuit, of which exclusion of the memory from the timing path of the oscillator was the most advanced.

The second major noise source, the inherent feedback loop, was effectively broken by the use of quadrature coupled oscillators, again improving the noise behavior of the oscillator system.

Finally, in-phase coupling of first-order oscillators was discussed as a measure to further reduce the phase noise of first-order oscillators. The numbers of oscillators required for this technique are too large for nowadays electronic systems.

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