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Design of Wide-Tunable Translinear Second-Order Oscillators

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ABSTRACT

This paper introduces a translinear second-order oscillator that is a direct implementation of a non-linear second-order differential equation. It comprises only two capacitors and a handful of transistors and can be controlled over a very wide frequency range by only one control current. A breadboard version, using transistor arrays, proves the correct operation of the proposed circuit. The oscillator frequency equals 25 kHz, while the total harmonic distortion equals 2.4 %.

1 Introduction

Recently, both an analysis method and a synthesis method for dynamic translinear circuits were proposed by the Authors [1, 2]. The dynamic translinear principle can be regarded as a generalization of the well-known 'static' translinear principle, formulated by Gilbert in 1975 [3].

An important subclass of dynamic translinear circuits is the class of 'translinear filters,' also called 'log-domain' or 'exponential state-space' filters, which were originally introduced by Adams in 1979 [4]. Although not recognized then, this was actually the first time a first-order linear differential equation was implemented using translinear circuit techniques. In 1990, Seevinck introduced a 'companding current-mode integrator' [5] and since then the principle of translinear filtering has been extensively studied by Frey, see, e.g., [6], Punzenberger and Enz [7], Toumazou and Lande [8], Perry and Roberts [9] and Mulder et al. [10].

However, the dynamic translinear principle is not limited to filters, i.e. linear differential equations. Using the dynamic translinear principle, it is possible to implement every linear or non-linear differential equation, using transistors and capacitors only. See, e.g., [14]. Hence, a high functional density can be obtained, whereas the absence of large resistors makes them especially interesting for ultra-low-power applications [15].

Apart from this, dynamic translinear circuits also exhibit other interesting properties.

1. Owing to the exponential behavior of a bipolar transistor or a MOS transistor in its subthreshold region, the voltages in dynamic translinear circuits are logarithmically related to the currents. As a result, the voltage excursions are small, typically only a few tens of millivolts. This is beneficial in a low-voltage environment.
2. Due to these small voltage swings, the effects of parasitic capacitances are reduced. This facilitates relatively wide bandwidth operation [11, 12].
3. Dynamic translinear circuits are easily controlled over a wide range of several parameters, such as gain, frequency or threshold. This increases their designability and makes them attractive to be implemented as standard cells or programmable building blocks.
4. Dynamic translinear circuits are easily implemented in class AB, which enables the signal currents to be much larger than the quiescent currents. This, in turn, entails a larger dynamic range and a reduced average current consumption [13].
5. In dynamic translinear circuits, transistors are used either as elements of the translinear loops or as nullors, to provide additional loop gain. Hence, in an IC process only three types of components are required:
   - transistors that are well matched and have an accurate exponential transfer over a wide range of transistor current,
   - transistors with a large gain, also at higher frequencies, and
   - capacitors.

Second-order oscillators are important building blocks in electronic systems to generate a periodic signal from DC power. They implement a second-order differential equation, which ideally equals

$$\ddot{x}(t) + \omega^2 x(t) = 0 \tag{1}$$

$x(t)$ and ω being the oscillator signal and the angular frequency, respectively. The dot represents differentiation with respect to time.

In order to compensate for the effects of non-idealities, such as noise and drift, in the oscillator circuitry, which

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cause the oscillator amplitude to be unstable, all practical second-order oscillators somehow implement the (non-linear) second-order differential equation

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

where $f(x)$ is an arbitrary (non-linear) even-symmetry function of x. When $f(x) > 0$, the oscillator is damped and the amplitude decreases. When $f(x) < 0$, the oscillator is undamped and the amplitude increases.

One way to implement (2) is to use a (passive) resonator and a non-linear time-invariant circuit or component to undamp the resonator. Usually, this type of oscillator is used to achieve a low phase noise. Another approach is the use of two active integrators in a two-integrator oscillator. This paves the way to a good (frequency) tunability.

The first translinear oscillator was proposed not earlier than in 1995, by Pookaiyaudom and Mahattanakul [16]. The circuit, basically, comprises a cascade of an inverter (a current mirror) and two first-order all-pass filters that each have a transfer function

$$y(t) + \omega\dot{y}(t) = x(t) - \omega\dot{x}(t) \qquad (3)$$

$x(t)$ and $y(t)$ being the filter input and output signal, respectively. The undamping circuit, an AGC, was not discussed in the paper.

Although not (yet) verified experimentally, simulations predicted a wide tuning range and the ability to operate from low supply voltages. These attractive properties are characteristic of translinear circuits [1].

Here we present the design and experimental results of a wide-tunable translinear second-order oscillator. The circuit, which comprises only two capacitors and a handful of transistors, is a direct implementation of a non-linear second-order differential equation and is tuned by only one control current.

2 Operation principle

The block diagram of the proposed circuit is depicted in Figure 1. It contains two integrators in a feedback configuration and a non-linear time-invariant block F. This circuit implements the (non-linear) second-order differential equation

$$\ddot{x}(t) + 2\omega\dot{x}(t) + \omega^2 x(t) = \dot{F}(x(t)) \qquad (4)$$

Comparing (2) and (4), it follows that, in order to implement an oscillator, F must be an odd-symmetry function of x, whose derivative with respect to x is larger than two for small values of x and smaller than two for large values of x. A suitable choice is

$$F(x) = \frac{2Gx}{x^2+1} \qquad (5)$$

G being a constant, which is larger than one. This function is easily implemented in a translinear circuit [12]. Using (5), the equation describing the complete oscillator becomes

$$\ddot{x}(t) + \omega\left(2 - 2G\frac{1-x^2(t)}{(1+x^2(t))^2}\right)\dot{x}(t) + \omega^2 x(t) = 0 \qquad (6)$$

Note that the signal amplitude, the signal wave form and to some extent the signal frequency, all depend on the value of G.

3 Circuit description

A possible, very compact embodiment of a translinear integrator was presented in [5]. See Figure 2. Its output current equals

$$I_{\text{out}} = \frac{I_O}{V_T C}\int I_{\text{in}}dt \qquad (7)$$

V_T being the thermal voltage kT/q.

From this expression, it can be deduced that the time constant of the integrator, and thus the oscillator frequency f_c, can be electronically controlled by means of a current I_O.

$$f_c = \frac{I_O}{2\pi C V_T}\ (\text{Hz}) \qquad (8)$$

As in all translinear circuits, the voltages are non-linearly, in this case logarithmically, related to the input and output currents, while the transfer function is linear as a whole. This companding action is beneficial in a low-voltage environment.

The complete circuit diagram of the translinear oscillator is depicted in Figure 3. The heart of the two integrators is formed by transistors QN1 through QN6 and QN11 through QN16, respectively. QN7 and QN17 provide a current sink for the emitter currents of QN2 and QN12. QN8, QN9 and QN18 are connected as current followers and reduce the influence of the Early effect. The current mirror with two outputs, formed by QP1, QP2 and QP3, implements the feedback loop around the left integrator and delivers its output current to the input of the right integrator. The feedback loop around the right integrator would lead to two paths from capacitor C_2 back to the integrator input, having opposite transfers that cancel each other. These paths are thus redundant. This explains why QN15 is missing.

The embodiment of the odd-symmetry function F was inspired by the generic principle described in [12] and adapted for our purposes. The heart is formed by transistors QN21 through QN26. QN27 takes care of the symmetrical driving. Current mirror QP21,QP22 doubles the output current and eliminates its common-mode component. The constant G in (5) equals I_O/I_G. Finally, QN28 provides the oscillator output current.

4 Experimental results

The circuit shown in Figure 3 was simulated using SPICE and realistic (IC) capacitor and (minimum-size) transistor models. The results indicate the correct operation of the translinear oscillator for various temperatures and values of I_O, I_G ($> I_O$) and C_1 ($= C_2$), yielding oscillations from 70 mHz ($C_1 = C_2 = 1$ nF, $I_O = 10$ pA) up to 250 MHz ($C_1 = C_2 = 1$ pF, $I_O = 1$ mA). The supply voltage equaled 3.3 V. For $I_G/I_O = 1.1$, the total harmonic distortion was below 2 %.

To verify the circuit operation in practice, the oscillator was "breadboarded," using transistor arrays of a standard 2 μm, 5 GHz IC process. Current sources I_O were implemented by 10 MΩ resistors; current sink I_G by a 2.7 MΩ resistor. Current sink I_O was embodied by connecting an additional transistor in parallel with QN11. C_1 and C_2 equaled 47 pF. The supply voltage again equaled 3.3 V. Figure 4 shows the measured output spectrum of the translinear oscillator (upper curve). The oscillator frequency equals 25 kHz, which is in accordance with (8). The total harmonic distortion equals 2.4 % and mainly results from the second harmonic at 50 kHz. This suggests that for a fully integrated version of the circuit, due to a better matching between the devices, a lower distortion is feasible. The frequency component at 36 kHz originates from the measurement setup. This can be deduced from the lower curve, which depicts the output spectrum when the oscillator is disconnected from its power supply.

5 Conclusions

A translinear second-order oscillator has been introduced. The circuit is a direct implementation of a non-linear second-order differential equation. It comprises only two capacitors and handful of transistors and can be controlled over a very wide frequency range by only one control current (I_O). A breadboard version, using transistor arrays, has proved the correct operation of the proposed circuit.

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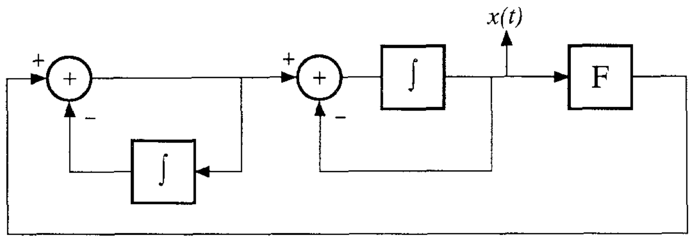

Figure 1: Block diagram of the translinear oscillator

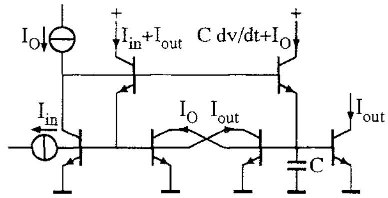

Figure 2: Compact translinear integrator by Seevinck

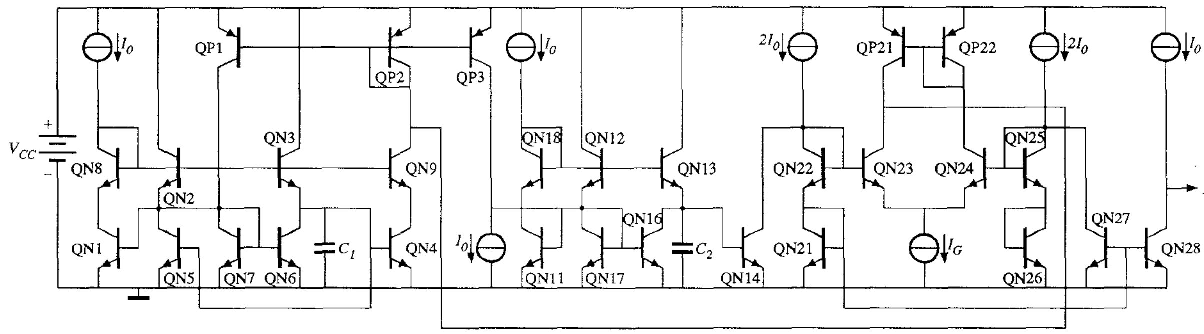

Figure 3: Circuit diagram of the translinear oscillator

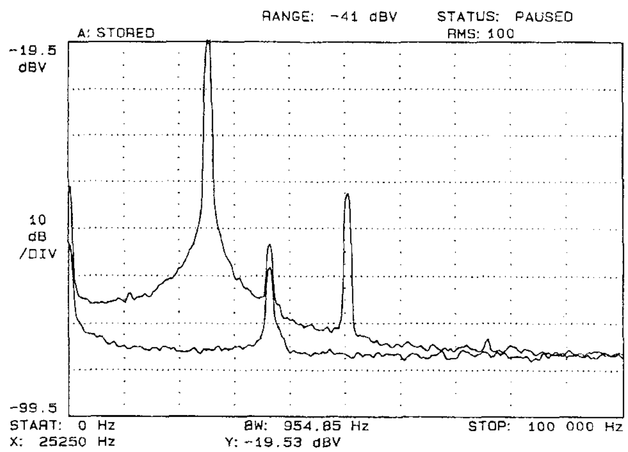

Figure 4: Measured output spectrum of the translinear oscillator (upper curve). The oscillator frequency equals 25 kHz. The total harmonic distortion equals 2.4 %. The 36 kHz frequency component originates from the measurement setup and is also visible when the oscillator is switched off (lower curve).