Fast and Accurate Simulation of the Steady-State of Voltage Controlled Oscillators with SmartSpice-RF

1. Abstract
A novel simulation method of the steady-state of oscillators, based on Harmonic Balance (HB), is presented. A comparison with regular transient simulations demonstrates its advantages on a feedback voltage-controlled oscillator (VCO).

2. Introduction
Oscillators are the key components of many radio frequency (RF) circuits. Simulating their steady-state and extracting their characteristics (oscillation frequency, power spectra, phase noise...) has become one of the most critical challenge in the design flow. Regular SPICE transient simulations suffer from severe drawbacks on these circuits. First, simulation run times are often prohibitive to reach the steady-state, particularly for high-Q circuits, which are the major part of today’s RF applications. Second, it is necessary to manually start the oscillator, which is not an easy task and can lead to false steady-states. Third, phase noise characteristics cannot be extracted directly from transient results. And sweeping a parameter (for example, to study the oscillation frequency dependance of a VCO) is very costful, since the simulation time is simply multiplied by the number of sweeping points.

SmartSpice-RF proposes a new method which remains fast and accurate in all these situations where transient simulation fails or shows poor performance. Based on Harmonic Balance, the oscillator steady-state is computed directly in the frequency-domain thanks to a two-stages method. In the following, we first describe briefly the method, then shows its application on a feedback VCO and compares its performance to transient simulations.

3. Basics of the Method
A two-stages approach [1] is used to compute the steady-state of autonomous circuits. It uses the concept of a probe. A probe is a special-purpose voltage source which behaves as a pure sinusoidal generator at the oscillation fundamental frequency, and an open circuit at all other frequencies. This component must be inserted in the circuit to compute the frequency and oscillation level at insertion point.

First, SmartSpice RF uses an initialization procedure to find the probe voltage corresponding to the probe admittance minimum at the oscillation frequency estimated by the user. Then it operates an optimization procedure to compute the oscillation frequency and magnitude of the probe. This stage ends when the current across the probe is considered as null (the probe is then like disconnected) or when the accuracy on oscillation frequency is reached. At this frequency, the circuit must be an oscillator. The method requires a good starting point for the oscillation frequency to have good convergence properties. If the user doesn’t know accurately enough the expected oscillation frequency, a linear AC simulation, a S-parameter simulation can be run to determine a satisfying initial guess.

Success and efficiency of analysis depends also on where the probe is connected. Typically, it should be inserted in parallel with the resonator or in parallel with the load. Since the probe must have some effect on the oscillation, it should not be placed after the buffer nor in the biasing circuitry. SmartSpice-RF can handle 1-tone autonomous circuits, as well as efficient parametric sweep, allowing

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applications like VCO frequency tuning. Additionally, a small-signal noise analysis can be performed around the steady-state operating point to compute phase noise (as well as total output noise). Phase noise is usually characterized in terms of the single-sideband noise spectral density. The phase noise is defined as mean-square noise voltage density to the mean-square carrier voltage, and reports the ratio in decibels [2]:

\[
L(\Delta \omega) = 10 \log \left( \frac{v_n^2}{(\Delta f)} \right)
\]

The most commonly used unit for phase noise is power below the carrier per Hertz, expressed in dB, or dBc/Hz, at some offset frequency \(\Delta \omega\) from the carrier frequency \(\omega_0\).

One of the possible ways to model phase noise in oscillators is a noise mixing analysis. The noise at the sidebands on either side of the carrier \((\omega_0 \pm \Delta \omega)\) is obtained from small-signal mixer analysis where noise sources \((\Delta \omega + k\omega_0)\) mix with the oscillator large signals \((k\omega_0)\) to produce noise sidebands. These noise simulation results are then used to compute the phase noise.

4. Example

We consider a regular Wien-Bridge oscillator circuit, which contains two basic sections: an RC tuning network and an amplifier. In the RC tuning network, the capacitance value \(C_{tune}\) can be swept to control the oscillator frequency. A UA741 amplifier is used, containing 16 BJT transistors. The corresponding SPICE netlist is given below:

```plaintext
; Sources
Vcc vcc gnd dc=15
Vee vee gnd dc=-15
; Op Amp
XAmpl 1 2 3 ua741
; Resistors
R1 2 gnd r=10k
R3 2 3 r=21k
R4 2 4 r=200k
D1 4 3 DioN
D2 3 4 DioN
.model DioN D is=.1fA
.param Ctune=1nF
.subckt FeedbackNet pIn pOut pGnd
.Resistors
RA pIn 1 15.8k
RB pOut pGnd 15.8k
.Capacitors
UA 1 pOut ‘Ctune’
pOut pGnd ‘Ctune’
.ends
XRes1 3 1 gnd FeedbackNet
```

The analysis statement looks like the following:

```plaintext
;.HOSCIL probe(3,1)
+ fundosc=12.591kHz nharm=7
+ fundoscreltol=0.1
+ sweep Ctune 0.8n 1.2nF 0.05nF
```

A logical choice is to connect the probe in parallel with the RC feedback network (probe(3,1)). The theoretical center pulsation characterizing the feedback network is equal to \(1/(RC)\). Let \(R\) and \(C\) be the resistance and capacitance values of the first sweeping point. It is a good choice for the initial oscillation frequency (\(fundosc=12.591kHz\)).

The specified number of harmonics (\(nharm=7\)) is chosen so that aliasing, which is a common phenomenon to all HB-based methods, is negligible. The required accuracy on the computed oscillation frequency is set to 0.1 Hz (\(fundosc=12.591kHz\)). The HOSCIL statement propose a lot of other tunable parameters allowing a fine control of both the accuracy and the convergence quality, which are beyond the scope of this paper. The last line specifies that the capacitance of the RC tuning network \((C_{tune})\) is swept from 0.8 nF to 1.2 nF, with steps of 0.05 nF, which will induce a sweep of the oscillator frequency.
After a few seconds, the steady-state results are available. The figures 1 and 2 show examples of waveforms and spectra obtained at the point \( C_{\text{tune}} = 1 \, \text{nF} \).

With a regular transient simulation (TRAN statement), the VCO must be started (for example using an initial condition \([3]\)) and the steady-state is only reached after a lot of simulation time points, when all transients have sufficiently vanished. It is completely prohibitive for circuits with a high-Q factor or for circuits containing elements like transmission lines which are better described directly in the frequency domain by HOSCIL (whereas TRAN uses costful convolution techniques).

With HOSCIL analysis, each point in the parametric analysis will use the result from a previous run as an initial guess. The convergence of the subsequent points is then much faster. The fundamental oscillation frequency can be easily extracted for each run, through a \texttt{measure} command.

\texttt{.measure hop_sp fosc AMAX vdb(3)}

Figure 4 shows the oscillation frequency as a function of the control capacitance.

With TRAN analysis, the parametric analysis is equivalent to as many independent runs as swept points. Besides, the oscillation frequency has to be extracted carefully with a subsequent measurement (when have we really reached the true steady-state?).

Table 1 gives a comparison of the CPU time between HOSCIL and TRAN depending on the number of sweeping points.

The speedup is significant even for a single run since HOSCIL computes directly the steady-state in the frequency domain. For parametric simulations with a high number of sweeping points, the performance improvement is even more important.

Furthermore, HOSCIL analysis proposes an efficient small-signal noise analysis around the oscillator steady-state, allowing the extraction of phase noise, which is a critical figure-of-merit of modern oscillator designs.

5. Conclusion

In this paper, the advantages of the new harmonic balance-based method (HOSCIL) for the simulation of oscillators, included in \textit{SmartSpice-RF}, have been demonstrated. It is definitely more reliable and much faster than regular transient approaches for applications like VCO frequency tuning, and it allows easy and accurate phase noise extraction.

6. References

