PHASE NOISE SIMULATION USING GENERAL-PURPOSE CIRCUIT ANALYSIS PROGRAMS

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Keywords: phase noise simulation, impulse-sensitivity function, general-purpose circuit analysis programs, frequency- and time-domain analyses, Fourier components

In the present paper, parameterized Spice models are developed for the phase noise simulation. It is accomplished by a standard frequency and noise analysis for obtaining the noise factor using the noise sources, incorporated in the library elements. Based on the Leeson model, the single-sideband phase noise is investigated. An approach is developed to phase noise reduction in oscillator circuits. It is realized by a parametric analysis with respect to the feedback element values. A generalized approach to computer-aided phase noise analysis of oscillator circuits is developed with a low-pass filters of first- second- and third order in the feedback circuit. The impulse-sensitivity function is obtained for oscillator circuits, describing the sensitivity to the phase instability due to the noises in the circuit.

1. INTRODUCTION

The development of wireless communications imposes more and more stringent requirements on the phase noise. The adequate phase noise computer modeling and simulation allows the investigation, prediction and minimization of this important characteristic at the design stage [1-3].

In the present paper, parameterized Spice models are developed for the phase noise simulation. It is accomplished by a standard frequency and noise analysis for obtaining the noise factor using the noise sources, incorporated in the library elements. Based on the Leeson model, the single-sideband phase noise is investigated. The spectral density of the phase noise is calculated and visualized in the graphical analyzer Probe using corresponding macro-definitions. A generalized approach to computer-aided phase noise analysis of oscillator circuits is developed with a low-pass filters of first- second- and third order in the feedback circuit. Parameterized *Spice* models are used for this purpose. The incorporated noise sources in the models of the standard *PSpice* libraries are automatically taken into account. The impulse-sensitivity function is obtained for oscillator circuits, describing the sensitivity to the phase instability due to the noises in the circuit. The *PSpice* ISF simulation is reduced to a time-domain and to a Fourier analyses. A number of approaches are proposed for the determination of flicker and white noise conversion factors, participating in the impulse-sensitivity function.

2. PARAMETERIZED SPICE MODELS FOR THE PHASE NOISE SIMULATION

Based on the Leeson model, the single-sideband phase noise can be investigated [1-3]. The phase noise of oscillators with a first-order low-pass filter in the feedback circuit (Fig. 1 – Colpitts oscillator) is in the form [3]:

$$L(\Delta f) = 10\log\left[\frac{1}{2}\left(\left(\frac{F_o}{2Q\Delta f}\right)^2 + 1\right)\left(\frac{F_c}{\Delta f} + 1\right)\left(\frac{FkT}{P_o}\right)\right], \tag{1}$$

$$Q = \frac{\omega_o R_s (C_1 + C_2)}{1 - \omega_o^2 C_1 L} \;;\; C_{eff} = \left(\frac{1}{C_1} + \frac{1}{C_2}\right)^{-1} \;;\; F_o = \frac{1}{2\pi\sqrt{LC_{eff}}}, \tag{2}$$

where F_o is the oscillation frequency; Q is the load quality factor; $f_m = \Delta f$ is the offset from the carrier; F_c is the corner frequency of the flicker noise; F is the noise factor of the transistor amplifier; $k = 1{,}38.10^{-23}$ is Boltzmann constant; T is the temperature in Kelvins; P_o is the output power of the oscillator;

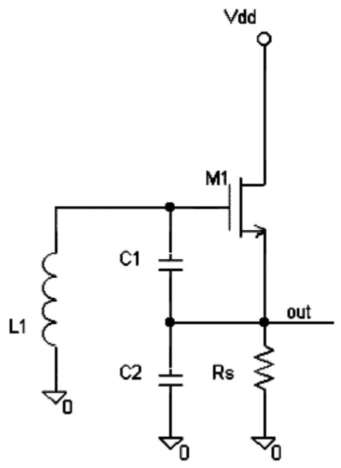

Fig. 1

Based on Equation (1), a PSpice model for the phase noise simulation is constructed (Fig. 2). The parameters F_o and Q , defined by (2) are described using the .PARAM statement. The calculation of the noise factor NF is accomplished by a standard frequency and noise analyses of the transistor amplifier using the noise sources, incorporated in the library elements (Fig. 3):

$$NF = \frac{I(INOISE) * I(INOISE)}{4 * k * T / R} \tag{3}$$

The phase noise is determined using the macro-definition in the Probe analyzer:

```
fm = r(Frequency-V(Fo)*1e9)
J  = V(Fo)*1e9/(2*V(Q)*fm)
L  = 10*log10((1/2)*((J*J)+1)*((Fc/fm)+1)*nf*1.38e-23*300/ Po))
NF = ((I(INOISE)*I(INOISE))/((4*1.38e-23*300)/2.7e3))
nfb =10*log10(NF)
```

The resulting phase noise characteristic is shown in Fig. 4.

The analytical description for the case of low-pass filter of first order in the feedback circuit has the form [3]:

$$L(f_m) = 10\log\left[\frac{1}{2}\left(\left(\frac{F_o}{2Qf_m}\right)^2 + 1\right)\left(\frac{Fc}{f_m} + 1\right)\left(\frac{FkT}{P_o}\right)\right] \tag{4}$$

The behavioral *PSpice* model for the simulation of $L(f_m)$ is constructed and analysed. The basic analysis is *AC Sweep*, and the additional analysis is *Parametric* with parameter f_m.

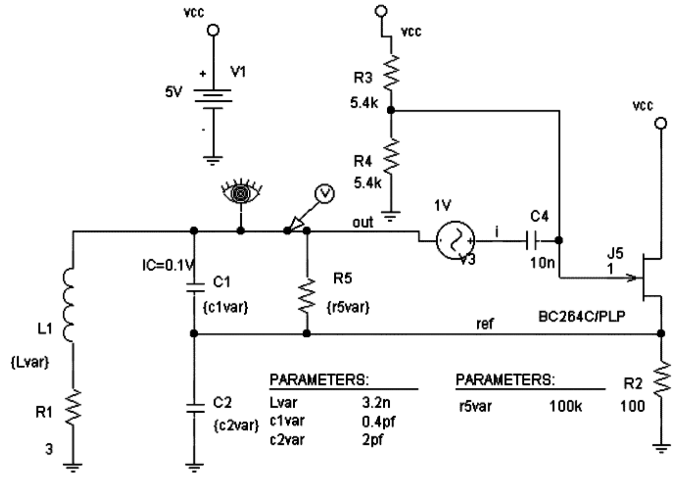

Fig.2

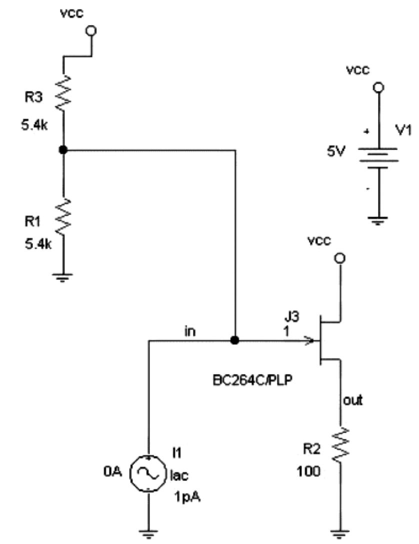

Fig.3

The macro-definitions for the phase noise calculation in *Probe* are in the form:

```
J   = (V(Fo)*1e9)/(2*V(Ql)*V(Fm))
NF  = ((I(INOISE)*I(INOISE))/((4*1.38e-23*300)/2.7e3))
nfb = 10*log10(NF)
L   = ((1/2)*((J*J)+1)*((V(Fc)/V(Fm))+1)*(NF*k*T/V(Pin)))
Ldb = 10*LOG10(L)
```

The simulation results for LdB(f_m) are shown in Fig. 5.

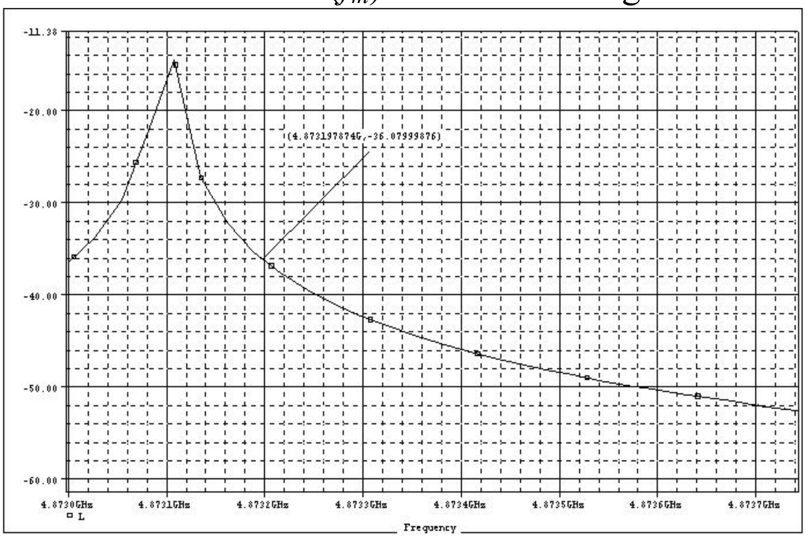

Fig. 4

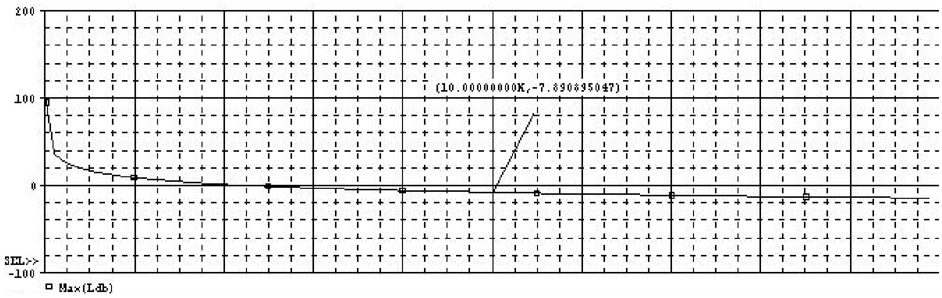

Fig. 5

The analytical description for the case of second-order low-pass filter in the feedback circuit has the form [3]:

$$L(\Delta f)=\frac{1}{2}\left[1+\left(\frac{f_i}{\Delta f}\right)^2\frac{1-2\left(\frac{\Delta f}{f_i}\right)^2}{\left(\frac{\Delta f}{f_i}\right)^2+4\varsigma^2}\right]\frac{FkT}{P_o}\left(1+\frac{f_c}{\Delta f}\right), \qquad (5)$$

where $\alpha_1=\frac{\omega_o}{2Q}=\frac{2\pi f_o}{2Q}$; $\alpha_2=\frac{\alpha_1}{5}$; $\omega_i=\sqrt{\alpha_1\alpha_2}$; $\varsigma=\frac{\alpha_1+\alpha_2}{2\omega_i}$; $f_i=\frac{\omega_i}{2\pi}$

The phase noise is calculated using the following macro-definitions in *Probe*:

```
nfb   = 10*log10(NF)
alfa1= (2*pi*V(Fo)*1e9)/(2*V(Ql))
alfa2= alfa1/5
fi    = wi/(2*pi)
J     = (fi/V(fm))*(fi/V(fm))*(1-2*((V(fm)/fi)*
        (V(fm)/fi)))/(((V(fm)/fi)*(V(fm)/fi))+4*ksi*ksi)
ksi   = (alfa1+alfa2)/(2*sqrt(alfa1*alfa2))
L     = ((1/2)*(J+1)*((V(Fc)/V(Fm))+1)*(NF*k*T/V(Pin)))
wi    = sqrt(alfa1*alfa2)
```

The analytical description for the case of third-order low-pass filter in the feedback circuit

$$L(\Delta f)=\frac{1}{2}\left[1+\frac{1}{\left(\frac{\Delta f}{f_i}\right)^2}\frac{1-2\left(\frac{\Delta f}{f_i}\right)^2\left[1+2\frac{\varsigma}{\mu}\right]}{\left(\frac{\Delta f}{f_i}\right)^2\left[1+2\frac{\varsigma}{\mu}\right]^2+\left[2\varsigma+\frac{1}{\mu}\left\{1-\left(\frac{\Delta f}{f_i}\right)^2\right\}\right]^2}\right]\frac{FkT}{P_o}\left(1+\frac{f_c}{\Delta f}\right) \qquad (6)$$

The corresponding macro-definitions for the phase noise calculation in Probe have the form:

```
alfa1  = (2*pi*V(Fo)*1e9)/(2*V(Ql))
alfa2  = alfa1/5
ch     = 1-(2*(f*f)*(1+2*(ksi/u)))
f      = (V(fm)/fi)
fi     = wi/(2*pi)
J      = (1/(f*f))*(ch/zn)
Ksi    = (alfa1+alfa2)/(2*sqrt(alfa1*alfa2))
L      = ((1/2)*(J+1)*((V(Fc)/V(Fm))+1)*((NF*k*T)/V(Pin)))
Ldb    = 10*LOG10(L)
wi     = sqrt(alfa1*alfa2)
zn     = ((f*f)*(1+(2*(ksi/u)))*(1+(2*(ksi/u))))+(((2*ksi)+((1/u)*
         (1-(f*f))))*((2*ksi)+((1/u)*(1-(f*f)))))
```

3. ISF SIMULATION USING ORCAD PSPICE

The impulse-sensitivity function is obtained for oscillator circuits, describing the sensitivity to the phase instability due to the noises in the circuit. The PSpice ISF simulation is reduced to a *time-domain and to a Fourier analyses*. A number of approaches are proposed for the determination of flicker and white noise conversion factors, participating in the impulse-sensitivity function [3]. The methods can be compared with respect to the computational efficiency (accuracy of the model and simulation speed).

The impulse-sensitivity function has the form:

$$\Gamma(\omega_o \tau) = \frac{c_o}{2} + \sum_{n=1}^{\infty} c_n \cos(n\omega_o \tau), \tag{7}$$

where c_o is the flicker noise conversion factor and c_n is the white noise conversion factor.

The coefficient c_0 can be determined as a mean value of the derivative dVout/dt, It is obtained using the following *Probe* macro-definition (Fig. 6):

```
Co = AVG(D(V(out)))
```

The coefficient c_o can be determined as a conversion factor $\Gamma 1/f$ of the flicker noise. As the parameter co is very sensitive to the accuracy of simulation (number of periods, number of time points), it can be obtained as a conversion factor Γ1/f of the flicker noise;

$$\Gamma_{1/f} \approx \max\left(\frac{dV_{out}}{dt}\right) + \min\left(\frac{dV_{out}}{dt}\right) \tag{8}$$

$\Gamma_{1/f}$ is less sensitive to the accuracy of simulation. It is obtained using the following Probe macro-definition:

```
G1 = MAX(D(V(out)))+ MIN(D(V(out)))
```

An another way for the coefficient co determination is using spectral (Fourier) analysis. The coefficient c_o is the DC component of the derivative $\frac{dV_{out}}{dt}$. The **ABM** block of the **abm.lib** *Pspice* model library is used (Fig. 7). The result for co is saved in the output file (.out) in the form:

```
FOURIER COMPONENTS OF TRANSIENT RESPONSE V(c)
 DC COMPONENT =   2.939491E-02
```

The coefficient c_n is proportional to the total converted white noise. $c_n = \Gamma_{rms}$ can be obtained as a mean-square value of $\Gamma_{1/f}$ in the *Probe* analyzer using the macro-definition:

```
cn=RMS(V(c))
```

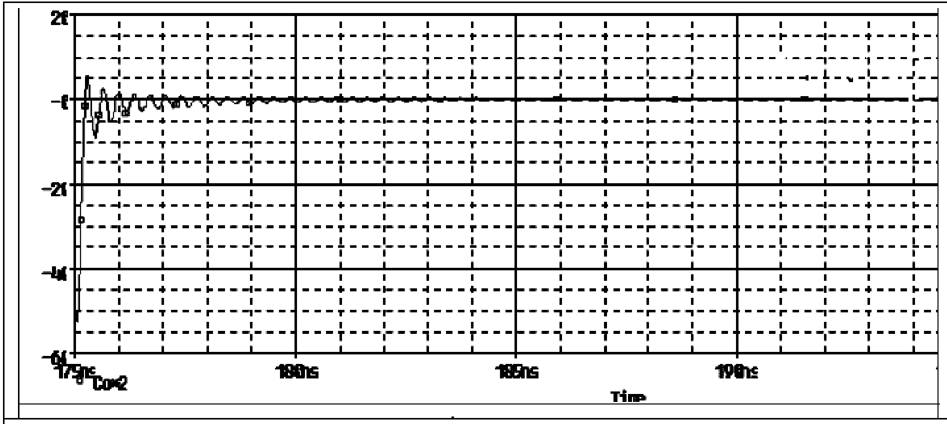

Fig. 6

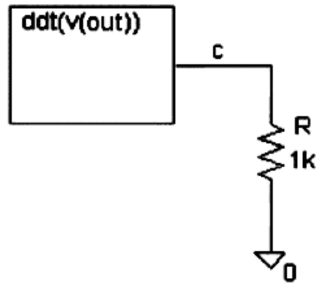

Fig. 7

CONCLUSIONS

An approach has been developed to computer-aided phase noise determination using parameterized Spice models and postprocessing in the graphical analyser Probe. Based on the Leeson model, the single-sideband phase noise is investigated of oscillators with a low-pass filters of first-, second- and third order in the feedback circuit. The incorporated noise sources in the models of the standard *PSpice* libraries are automatically taken into account. The impulse-sensitivity function is obtained for oscillator circuits, describing the sensitivity to the phase instability due to the noises in the circuit. The *PSpice* ISF simulation is reduced to a time-domain and to a Fourier analyses. The flicker and white noise conversion factors, participating in the ISF, are calculated by the simulator.

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