

SpectreRF Periodic Analysis Switched capacitor Circuit Simulation

Agenda

- Sampled data systems
- Brief explanation and usage of PAC/PXF analyses in SpectreRF
- PNOISE Analysis
- Simulation Examples
 - Simple S/H
 - Switch capacitor buffer
 - T/R

SpectreRF Analyses

- PSS Periodic Steady State Analysis
- □ PAC Periodic AC Analysis
- PSTB Periodic Stability Analysis
- PXF Periodic Transfer Function
- PNoise Periodic Noise Analysis
- Dist Periodic Harmonic Distortion Analysis
- QPSS?

PSS Analysis

- Periodic Steady-State Analysis
- PSS calculates the period operating point
 - Required for other small-signal analyses (PAC, PXF, PNoise)
 - Only clock is applied, transient input disabled
- PSS Cadence parameters
 - harmonics specifies requested output harmonics to be viewed
 - maxacfreq is an accuracy parameter that specifies the maximum frequency that will be used in any subsequent small-signal analyses (4xharmonics by default)
 - Recommended formula:
 - fstop is maximum frequency of PAC/PXF/etc. sweep range
 - maxsideband specified in PAC/PXF/etc.
 - fs is clock frequency

SpectreRF Analysis Forms

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PAC Analysis

- Periodic AC Analysis
- PAC "computes the output signal at every node and every sideband given a single input"1
 - Creates a mapping between an input freq range and each resulting output freq range due to modulation
 - Use PAC to find how an interesting input frequency is modulated and attenuated to resulting frequencies at the output

PAC Cadence parameters

- Specified sweep frequency is the INPUT frequency range
- maxsideband determines the number of output frequency bands calculated by Cadence to which the input range is modulated
- Set pacmagnitude in source to 1V
- Can choose any circuit node as PAC output

PAC Analysis





- □ Sweeping PAC input frequency from 0 → fs/2 shows the modulation of the input signal baseband into all of the specified output bands ...perfect for nyquist band limited input signals
- Sweeping past fs/2 shows the modulation of higher input signal bands into all of the specified output bands

PXF Analysis

- Periodic Transfer Function Analysis
- PXF "computes the transfer function from every input source at every sideband to a single output"1
 - Creates mapping between a particular output frequency and the combination of modulated input frequencies that compose it
 - Use PXF to find the input frequency composition of an interesting output frequency
 - PXF Cadence parameters
 - Specified sweep frequency is the OUTPUT frequency range
 - maxsideband specifies the number of input frequency bands calculated by Cadence that are modulated into the output frequency range
 - Set specific output node in analysis form
 - Can choose any source in the circuit to view XF to the output

PXF Analysis





- □ Sweeping PXF from $0 \rightarrow fs/2$ shows how all of the chosen input frequency bands modulate into the output baseband
- Each color curve segment represents the output baseband where the starting harmonic is DC

PXF Analysis



Sweeping PXF past fs/2 shows how the specified input frequency bands modulate into higher output bands

Comment About PAC/PXF Sweep Type

- Previous results have been plotted for linear sweeps
- Logarithmic sweeps refer all waveforms into frequency sweep range:
 - PAC all output sidebands are shown as folded into the input frequency sweep range. Output signal frequency information not shown.
 - PXF input sideband contributions are folded into output frequency sweep range. Information relating contributions to input frequencies not shown.
- Example: PAC linear sweep (left), log sweep (right, changed to lin axis)



PXF vs PAC

PAC

I know my input signal, how does this become my output signal?

PXF

I know my output signal, how does this come from my input signal?

SpectreRF PAC/PXF Analysis Forms

Periodic AC Analysis	
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Sweeptype Sweep is Curr	rently Absolute
Frequency Sweep Range (Hz)	
Start-Stop = Start 100	Stop 50e6
Sweep Type Step Size Linear Number of Step	s
Add Specific Points 🗌	
Sidebands	
Maximum sideband 🖃 🍕	
Specialized Analyses	
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Periodic XF Analysis	
PSS Beat Frequency (Hz) 100M	
Sweeptype Sweep is Currently	Absolute
Frequency Sweep Range (Hz)	
Start-Stop = Start 100 Stop	50e6
Sweep Type Linear - Step Size Number of Steps	1000 <u>į</u>
Add Specific Points	
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Output Positive Output Node /SH_outš ◆ voltage Negative Output Node ▽sš	Select Select
Modulated Analysis	
Enabled	Options



- Simulation of noise in sampled circuits
- □ Example: Switch-C circuit
 - Here an NMOS switch with C=1pF, f_{clk}=10MHz
- Set up PSS analysis for the f_{clk}=10MHz clock

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□ Include sufficient number of *maxsideband* for accuracy



- □ Simulation shows 89µV of output RMS noise
 - Ideal $\sqrt{(kT/C)}$ value =64 μ V,
 - Simulation results close to the approximation of $\sqrt{(kT/C)}$



- Accuracy is tightened by using large number of *maxsideband* parameter
 - Determines how many sideband alias into the given band
 - Trades-off simulation time with accuracy
- □ For analytical details, refer to:

http://www.designers-guide.org/analysis/sc-filters.pdf

• A Sample and hold (S/H) is analyzed in the time domain as an ideal sampler in cascade with a zero-order hold (ZOH)



• The ideally sampled signal $v_{s}(t)$ is obtained by multiplying input with periodic pulse train



• The frequency spectrum of the impulse train is found from the fourier transform of the fourier series representation

$$v_D(t) = \sum_{k=-\infty}^{\infty} \delta(t - kT_s) = \sum_{n=-\infty}^{\infty} \frac{1}{T_s} e^{jn \cdot 2\pi f_s t} \Leftrightarrow V_D(f) = \sum_{n=-\infty}^{\infty} f_s \cdot \delta(f - nf_s)$$

• Multiplying with pulse train in time domain \rightarrow convolving with pulse train in frequency domain 1



• The S/H output is found by convolving $v_{s}(t)$ with the cascaded ZOH impulse response (a unit pulse, a fraction of the sampling period)



Convolving with ZOH in time domain → multiplying with sinc in frequency domain



• Result is the baseband filtered by the sinc main lobe, plus frequency periodic baseband replicas filtered by the sinc side lobes

$$V_{SH}(f) = mT_s \cdot \operatorname{sinc}_{\pi}\left(m\frac{f}{f_s}\right) \cdot \sum_{n=-\infty}^{\infty} f_s \cdot V_s(f - nf_s) = m\operatorname{sinc}_{\pi}\left(m\frac{f}{f_s}\right) \sum_{n=-\infty}^{\infty} V_s(f - nf_s)$$

- Shape of sinc function (and filtering of spectrum) depends on S/H duty cycle (m)
 - m<<1: sinc is wide but short, attenuation but little shaping of baseband or near images
 - m=1: sinc thin and tall, significant shaping of baseband and images, zeros at $f = nf_s$



- Sampling into the digital domain (A/D converter) acts as an ideally sampled system and replicates the spectrum at all clock harmonics
- Any spectrum energy outside of the Nyquist range gets folded/aliased into baseband
- SNR need be considered only within f=0→fs/2 because spectrum is symmetric about DC and repeats every fs (DTFT)

PXF/PAC Analyses for Basic Applications

- □ Ideal Sample and Hold (S/H)
- □ RC Band-limited S/H
- Switch Capacitor (SC) Buffer

Ideal Sample and Hold (S/H)



Expectation: Ideal S/H



- Assume a unity, nyquist band-limited input
- Like a input band limited AC analysis (like a PAC)



PAC: Ideal S/H

• Sweep from $0 \rightarrow f_s/2$: only looking at how input baseband modulates into other bands

• AC input is unity over all frequencies, therefore output is the sinc shaping of the modulated input baseband



PXF: Ideal S/H

• Sweep from $0 \rightarrow f_s/2$: only looking at how input frequencies modulate into the output baseband

 Resulting curves only show output baseband shaping (main lobe of sinc)





 F_{clk} =100 MHz

PSS beat freq=100M autocalculated maxacfreq=default

PXF output frequency range (100,50M) linear sweep, 1000 steps maxsideband=4

PAC: RC limited S/H



• Baseband input should modulate to output bands similarly to ideal case if RC constant designed correctly (PAC)

• S/H now has limiting bandwidth, so higher input frequencies will attenuate when modulating into output baseband (PXF)

• Set 1/RC = 2*pi*f_{clk}*7 => 700 MHz: C=1pF, R~230 ohms, W/L=9u/.18u

PXF: RC limited S/H



 Baseband input should modulate to output bands similarly to ideal case if RC constant designed correctly (PAC)



Periodic AC Response

F_{clk}=100 MHz

PSS beat freq=100M autocalculated maxacfreq=default

PAC input frequency range (100Hz ,50MHz), f_s/2 linear sweep, 1000 steps maxsideband=4

SC Buffer

- Ideal switches, no resistance
- Ideal OpAmp, no BW limit
- Sinc shaping slightly off due to reduction of duty cycle for non-overlapping phases

$$ZOH(f) = mT_s \cdot \operatorname{sinc}_{\pi}\left(m\frac{f}{f_s}\right)$$



Periodic AC Response







SC Buffer

- Ideal switches with resistance
- Ideal OpAmp, no BW limit



Adding the switch resistance of the SC Buffer: PAC

SC Buffer

- Ideal switches with resistance
- Ideal OpAmp with limited BW

Periodic AC Response



Periodic XF Response

Reducing the BW of the SC Buffer OpAmp: PAC (left) PXF (right)

- Ideal track and reset:
 - Analyzed as input multiplied by pulse train
 - Result is passband modulated by pulse train tones
 - No resistance yields no shaping in bands
 - Pulse train tones off due to non-overlapping clocks
 - PAC and PXF look identical



• Real track and reset:

Periodic AC Response

- Added switch resistances (R=1k, C=1p)
- Results in shaped, modulated passbands
- PAC: modulation from input passband into output sidebands
- PXF: modulation from input sidebands into output passband



Periodic XF Response



- Real track and reset:
 - Excessive resistance (R=10k, C=1p)



Periodic XF Response

Periodic AC Response

• Real track and reset:

Vo (harmonic=-4.00e+00)

Vo (harmonic=-2.00e+00)

100

200

freq (MHz)

300

400

175<u>-00 (harmonic=0.00e+00)</u>

150 -

125

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50.0

25.0

0

- Changing the resistance ratio scales the response
- DC and input clk harmonics modulating to output scaled by $2R_1R_2/(R_1+R_2)$ from ideal
- R₁=10k, R₂=1k, C=1p

Vo (harmonic=-3.00e+00)

Vo (harmonic=-1.00e+00)

Vo (harmonic=1.00e+00)

Periodic AC Response



Periodic XF Response

 $V_{in} - \Phi_1$



References

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