Implementing the Nonlinear Oscillator Macromodel using Verilog-AMS Language

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Outline

● Introduction
● The nonlinear oscillator macromodel
● Implementation of the macromodel
● Simulation results
● Conclusions
Introduction

• Why we need oscillator macromodels?
  ▪ Oscillators are used widely – transmitters, microprocessors
  ▪ Simulations of oscillators are usually difficult and expensive
  ▪ Phase characteristics of oscillators under perturbations are of significant interests, but difficult to simulate using conventional methods

• Advantages of oscillator macromodels
  ▪ Fast without compromise of accuracy
  ▪ Plugged into simulators – SPICE
  ▪ Capture the phase characteristics under perturbations
Introduction (continued)

• Why we need nonlinear oscillator macromodels?
  ▪ Oscillator is inherently a nonlinear system
  ▪ Linear perturbation analysis doesn't apply to oscillators
  ▪ Linear models often fail to accurately predict phase deviations under perturbations

• Nonlinear oscillator macromodels
  ▪ Based on the oscillator phase noise analysis by Demir, Mehotra, and Roychowdhury
  ▪ Successfully capture nonlinear dynamics of oscillators – injection locking, cycle slipping, ...
Linear Perturbation Analysis

Unperturbed oscillator

\[ \dot{x} = f(x) \quad \rightarrow \quad x_s(t) \]

Perturbed oscillator

\[ \dot{x} = f(x) + b(t) \quad \rightarrow \quad x_p(t) = ? \]

Linear perturbation analysis

\[ \dot{x} = f(x) + b(t) \quad \rightarrow \quad x_s(t) + w(t) \]

If \( w(t) \) always small

\[ \dot{w}(t) \approx \frac{\partial f}{\partial x} w(t) + b(t) \]

\( w(t) \) can be made to grow UNBOUNDED despite \( b(t) \) remaining small

Nonlinear Perturbation Analysis

\[ \dot{x} - f(x) = b_1(t) + \tilde{b}(t) \]

neglect the amplitude perturbation in our discussions

\[ \dot{x} - f(x) = b_1(t) \]

\[ b_1(t) = v_1^T(t + \alpha(t)) b(t) u_1(t + \alpha(t)) \]

Perturbation Projection Vector (PPV)

\[ \dot{\alpha}(t) = v_1^T(t + \alpha(t)) b(t) \]

\[ \alpha(t) \rightarrow \text{Phase deviations} \]

Solution of perturbed oscillator

\[ x_p(t) = x_s(t + \alpha(t)) \]

Nonlinear Oscillator Macromodel

Nonlinear macromodel based on those equations
(X. Lai and J. Roychowdhury, ICCAD 2004):

\[ \dot{\alpha}(t) = v^T_1(t + \alpha(t))b(t) \]

\[ x_p(t) = x_s(t + \alpha(t)) \]

• Steps of building the macromodel:
  ▪ Simulate the full-sized unperturbed oscillator to get unperturbed solution and PPV
  ▪ Solve the nonlinear differential equation for \( \alpha(t) \)
  ▪ Get the perturbed solution

• Advantages of the macromodel
  ▪ Reduction of system dimension
  ▪ Speed-up of simulations
  ▪ Information of phase deviations
Implementing the macromodel using Verilog-AMS

Implement an oscillator under perturbation as a Verilog-AMS module

```verilog
module oscillator(in, out);
inout in, out;
electrical in, out, alpha;
......

\[ \dot{\alpha}(t) = v_1^T(t+\alpha(t))b(t) \]

\[ ddt(V(\alpha)) = PPV($abstime+V(\alpha))*V(in); \]

Time derivative operator in Verilog-AMS
Implementing the macromodel using Verilog-AMS (continued)

\[
\text{ddt}(V(\text{alpha})) = \text{PPV}($\text{abstime} + V(\text{alpha})) \times V(\text{in});
\]

periodic waveform, no analytical form

$table\_model$ is perfect for the job!

Usage:
- Store PPV waveform into a file, ppv.table
- $table\_model($abstime+V(alpha) \% period, "ppv.table", "L")
Implementing the macromodel using Verilog-AMS (continued)

Set up two branches:
branch (alpha) alpha1;
branch (alpha) alpha2;
...

perturbed_time = ($abstime + V(alpha)) % period;
ppv = $table_model(perturbed_time, "ppv.table", "L");

I(alpha1) <- -ppv * V(in);
I(alpha2) <- ddt(V(alpha))

\[ \dot{\alpha}(t) = v_1^T(t + \alpha(t)) b(t) \]

KCL at node alpha will force \( I(\alpha1) + I(\alpha2) = 0 \), so as $abstime proceeds, this nonlinear differential equation is solved at each time step.
Implementing the macromodel using Verilog-AMS (continued)

`include "discipline.h"
`include "constants.h"

// nonlinear macromodel implemented in Verilog-AMS
module oscillator(in, out);
// define nodes
inout in, out;
electrical in, out, alpha;

// define variables and parameter
real phase, pppv, period, omega, perturbed_time;

parameter real freq=1.0e9 from(0:inf);

// define branches
branch (alpha) alpha1;
branch (alpha) alpha2;

analog
begin
@(initial_step)
begin
// set up initial condition for eq(9)
V(alpha) <+ 0;
omega = 2.0*`M_PI*freq;
period = 1.0/freq;
end

// real perturbed time is given by
// $abstime + V(alpha)
// but our pppv table has only one period
// so take the modulus of period

perturbed_time = ($abstime+V(alpha)) % period;

// look up table to get pppv value
// $table_model(arg1, arg2, arg3)
// arg1: input (independent) variable
// arg2: name of the file storing the table
// arg3: interpolation method, L-linear

ppv = $table_model(perturbed_time,
"osc_ppv.table", "L");

// right hand side of eq(9)
// pppv: v1(t+alpha(t))
// V(in): b(t)
I(alpha1) <+ -ppv*V(in);

// left hand side of eq(9)
I(alpha2) <+ ddt(V(alpha));

// KCL at alpha forces
// I(alpha1) + I(alpha2) = 0
// so that eq(9) is solved at each time point

phase = V(alpha)*omega; // output only

// look up table to generate output
V(out) <+ $table_model(perturbed_time,
"osc_output.table", "L");
end
endmodule
Simulation Results

\[-C \frac{dv(t)}{dt} = \frac{v(t)}{R} + i(t) + f(v(t)) + b(t)\]
\[L \frac{di(t)}{dt} = v(t)\]

Oscillating freq: 1.0GHz, mag: 600mV

Simulate using Freescale's in-house circuit simulator, Mica, to get steady state solution and PPV waveform
Simulation Results (continued)

Macromodel (phase domain)

- $x_p(t) = x_s(t + \alpha(t))$

Full SPICE simulation (time domain)
Injection locking
(lines) macromodel (symbols) full SPICE simulation

Perturbation frequency: 1.02 GHz
Perturbation amplitude: 100 uA

Perturbation frequency: 0.98 GHz
Perturbation amplitude: 50 uA

See Lai and Roychowdhury, ICCAD 2004 for detailed discussions about injection locking
Simulation Results (continued)

Injection unlocking
(lines) macromodel (symbols) full SPICE simulation

Perturbation frequency: 1.1 GHz
Perturbation amplitude: 100uA

Perturbation frequency: 0.95 GHz
Perturbation amplitude: 50uA
Simulation Results (continued)

3 stage ring oscillator (used in Freescale products)

Apply a sinusoidal perturbation

Vdd

Control block

1.16 GHz

Nearly impossible to study the phase deviations using time domain methods (SOI floating body effect)

300 mosfets
2000 passive components

1.16 GHz
Simulation Results (continued)

qualitatively matches full SPICE simulation

SPICE simulation hasn't reached the real steady state yet!

System reduction: 1709 to 1
Speed-up: 969 sec to 9 sec

100X speed-up
Conclusions

- The nonlinear oscillator macromodel can be implemented in Verilog-AMS very compactly.
- The macromodel implemented in Verilog-AMS can be readily plugged into SPICE to perform simulations with other blocks.
- The macromodel is able to capture the nonlinear locking dynamics of oscillators.
- The macromodel can provide significant system reduction and speed up over full SPICE representation without loss of accuracy.