E8-262: Basics of Circuit Simulation/SPICE

Lecture: 4+5

Module 1: Electrical Challenges in High-Speed CPS

- Types of packages and PCBs
- Packaging Trends
- Review of Electromagnetic and Circuit basics
- Signal Integrity Introduction
- Power Integrity Introduction
- Electromagnetic Interference and Electromagnetic Compatibility Introduction
- Review of SPICE basics
- Lumped models, distributed RLGC, S/Y/Z parameters

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Topics: Modified Nodal Analysis

- Parser
- Linear Element: DC Operating Point Analysis
- Linear Element: Transient Analysis
- +Non-linear Element: DC Operating Point Analysis
- +Non-linear Element: Transient Analysis
- Electromagnetic Models in SPICE

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References

- L.O. Chua and P.M. Lin, Computer-Aided Analysis of Electronic Circuits: Algorithms and Computational Techniques, Prentice-Hall, 1975.
- J. Vlach and K. Singhal, Computer Methods for Circuit Circuit Analysis and Design, Van Nostrand Reinhold, New York
- William McCalla, Fundamentals of Computer-Aided Circuit Simulation, Kluwer Academic Publisher

History of SPICE:

http://www.omega-enterprises.net/The%20Origins%20of%20SPICE.html

- 1970: CANCER Project, R. Rohrer, L. Nagel and others – class project from Berkeley

Laurence W. Nagel and Ronald A. Rohrer, "Computer Analysis of Nonlinear Circuits, Excluding Radiation," *IEEE Journal of Solid State Circuits,* vol SC-6, pp. 166-192.

- 1972-To Date: SPICE "Simulation Program with Integrated Circuit Emphasis"
- HSPICE owned by Synopsys; PSPICE owned by Cadence;
- TISPICE (TI), Lynx (Intel), PowerSPICE (IBM), Titan (Infineon), Mica (Freescale) …

Parser

Sources:

- VName N+ N- V_value
- IName N+ N- I_value

DC Linear Elements:

- RName N+ N- R_value
- EName N+ N- NC+ NC- E_val (VCVS)
- FName N+ N- NC+ NC- F_val (CCCS)
- GName N+ N- NC+ NC- G_val (VCCS)
- HName N+ N- NC+ NC- H_val (CCVS)

Parser

Linear Elements in transient analysis:

- CName N+ N- C_value
- LName N+ N- L_value

Non-Linear Elements:

- Dname N+ N- Dmodelname
- Pname Nd Ng Ns Nb Pmodelname
- Nname Nd Ng Ns Nb Nmodelname

Example

```
* Test circuit o check the inverter performance

Vin 1 0 1
pm 2 1 3 0 pmos1
r1 2 0 5000
v1 3 0 2.5

.option post
.tran 0us 45ms 100us
.alter
Vin 1 0 sin (0 16.8 60 0ms 0 0)
*.dc VSource 1.88 1.89 0.01
.print v(0)
.print v(1)
.print v(2)
.print v(3)
.MODEL pmos1 cmosp ( W=10e-6 L=1e-6 )
.end
```


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Linear Elements:
DC operating point analysis

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Resistor Stamp

	N+	N-
N+	1/R	-1/R
N-	-1/R	1/R

Matrix

RHS

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Current Source Stamp

	N+	N-
N+		
N-		

Matrix

-Ik
+Ik

RHS

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Voltage Source Stamp

	N+	N-	i_k
N+			+1
N-			-1
i_k	+1	-1	

Matrix

V_k

RHS

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G Stamp (VCCS)

	N+	N-	Nc+	Nc-
N+			+G_k	-G_k
N-			-G_k	+G_k
Nc+				
Nc-				

Matrix

RHS

F Stamp (CCCS)

	N+	N-	Nc+	Nc-	i_J
N+					F_k
N-					-F_k
Nc+					1
Nc-					-1
i_J			1	-1	

Matrix

RHS

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E Stamp (VCVS)

	N+	N-	Nc+	Nc-	i_K
N+					1
N-					-1
Nc+					
Nc-					
i_K	1	-1	+E_k	-E_k	

Matrix

RHS

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H Stamp (CCVS)

	N+	N-	Nc+	Nc-	i_K	i_J
N+					1	
N-					-1	
Nc+						1
Nc-						-1
i_K	1	-1				-H_x
i_J			1	-1		

Matrix

RHS

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Matrix Solution

- Direct
  - Gaussian Elimination/ Sparse LU
  - Pkgs: Sparse1.3, SuperLU, Pardiso, MUMPS
- Iterative
  - Stationary Methods:
    - Gauss-Seidel
    - Gauss-Jacobi
    - Successive Over Relaxation (SOR)
  - Krylov subspace methods

LU Sparsity

Before LU

X	X	X	X	X
X	X			
X		X		
X			X	
X				X

After LU

X	X	X	X	X
X	X	X	X	X
X	X	X	X	X
X	X	X	X	X
X	X	X	X	X

X				X
	X			X
		X		X
			X	X
X	X	X	X	X

X				X
	X			X
		X		X
			X	X
X	X	X	X	X

Linear Elements: Transient Analysis

Transient Sources

- Pulse
- Exp
- Sin
- PWL

Integration Methods

- Forward Euler

$$\frac{y(t_n + h) - y(t_n)}{h} = y'(t_n)$$

- Backward Euler

$$\frac{y(t_n) - y(t_n - h)}{h} = y'(t_n)$$

- Trapezoidal

$$\frac{y(t_n + h) - y(t_n)}{h} = \frac{1}{2}\left[y'(t_n) + y'(t_{n-1})\right]$$

Other: Explicit and Implicit LMS

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Capacitor Stamp

Capacitor stamp

$$Q = CV$$

$$I = C\frac{dV}{dt}$$

$$= C\,\frac{V(t) - V(t-h)}{h}$$

$$= \frac{C}{h}V(t) - \frac{C}{h}V(t-h)$$

$$= \frac{C}{h}\left(V^{+} - V^{-}\right) - \frac{C}{h}\left[V^{+}(t-h) - V^{-}(t-h)\right]$$

Capacitor Stamp

	N+	N-
N+	C/h	-C/h
N-	-C/h	C/h

Matrix

C/h. v(t-h)
-C/h. v(t-h)

RHS

Capacitor Stamp (MNA)

	N+	N-	i_k
N+			+1
N-			-1
i_k	C/h	-C/h	-1

Matrix

C/h. v(t-h)

RHS

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Inductor Stamp

Inductor stamp

$$V = L \frac{di}{dt}$$

$$= L \frac{i(t) - i(t-h)}{h}$$

$$= \frac{L}{h} i(t) - \frac{L}{h} i(t-h)$$

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Inductor Stamp

Matrix

	N+	N-	i_k
N+			+1
N-			-1
i_k	+1	-1	-L/h

RHS

-L/h. i(t-h)

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Non-Linear Elements:

DC Operating Point
Transient Analysis

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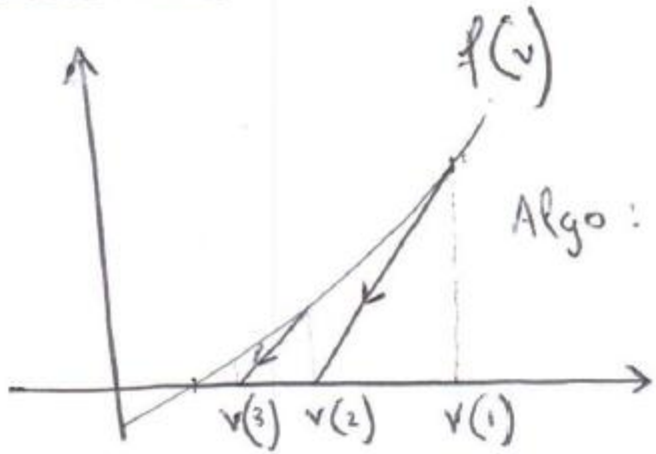
Newton-Raphson

Newton Raphson



$$f(v) = 0$$

Algo : $f(v(1)) + f'(v(1))\,(v(2) - v(1)) = 0$

NR : $v(2) = v(1) - \left[f'(v(1))\right]^{-1} f(v(1))$

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Diode Stamp

Diode NR using stamps

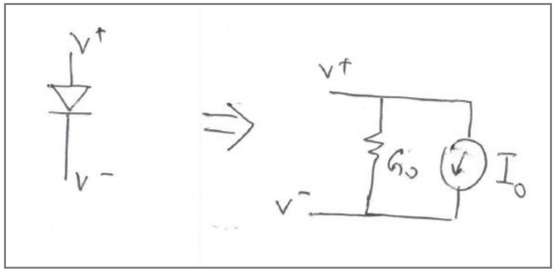
$$i_D \simeq i_D^{pre} + \left(\frac{\partial i_D}{\partial v_D}\right)^{pre} (v_D - v_D^{pre})$$

$$= \left(\frac{\partial i_D}{\partial v_D}\right)^{pre} v_D + i_D^{pre} - \left(\frac{\partial i_D}{\partial v_D}\right)^{pre} v_D^{pre}$$

$$= G_0 v_D + I_0$$

G_0 → conductance

I_0 → current source



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Diode Stamp

	N+	**N-**
N+	G_0	$-G_0$
N-	$-G_0$	G_0

Matrix

$-I_0$
I_0

RHS

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Diode Stamp

e.g.

(1)
$$I_D = I_S\left(e^{V/V_T} - 1\right)$$

$$\frac{\partial I_D}{\partial V} = \frac{I_S}{V_T} e^{V/V_T}$$

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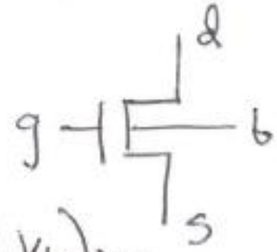
MOSFET Stamp

Level 1 Stamp for Mosfet.

$$I_{ds} = I_{ds}(V_{gs}, V_{ds})$$



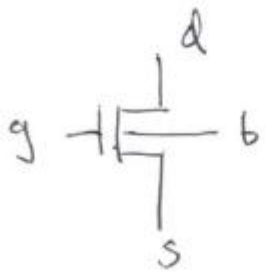
$$= \left(\frac{W}{L}\right) k' \left(V_{gs} - V_T - \frac{1}{2} V_{ds}\right) V_{ds}$$

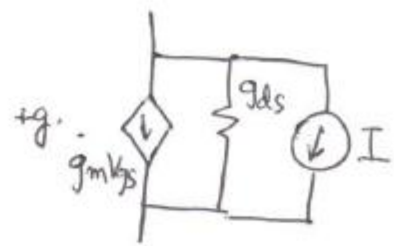
Assume $V_t \neq f(V_{bs})$ for simplicity.

$$\frac{\partial I_{DS}}{\partial V_{gs}} \equiv g_m = \frac{W}{L} k' V_{ds}$$

$$\frac{\partial I_{DS}}{\partial V_{ds}} \equiv g_{ds} = \frac{W}{L} k' (V_{gs} - V_T - V_{ds})$$

MOSFET Stamp





$$I_{DS} = I_{DS}^{pre} + \left(\frac{\partial I_{DS}}{\partial V_{DS}}\right)^{pre}\left(V_{DS} - V_{DS}^{pre}\right) + \left(\frac{\partial I_{DS}}{\partial V_{gs}}\right)^{pre}\left(V_{gs} - V_{gs}^{pre}\right)$$

$$\Rightarrow I_{DS} = g_{DS} V_{DS} + g_m V_{gs} + \left(I_{DS}^{pre} - g_m V_{gs}^{pre} - g_{ds} V_{ds}^{pre}\right)$$

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MOSFET Stamp

	Nd	Ns	Ng
Nd	gds	-gds-gm	gm
Ns	-gds	gds+gm	-gm
Ng			

Matrix

-I
+I

RHS

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Newton-Raphson Challenges

- Oscillatory functions
- Bad initial guess
- Derivative error
- Discontinuity

Electromagnetic Models in SPICE:
All Linear Models ☺
Heavily Coupled Models ☹

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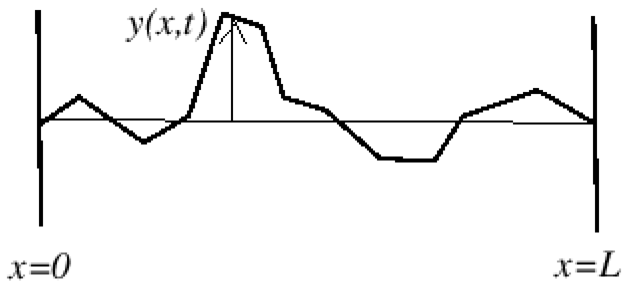
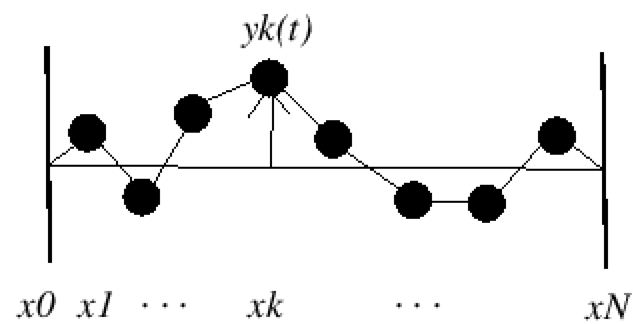
Lumped vs. Distributed

https://ccrma.stanford.edu/~jos/NumericalInt/Lumped_vs_Distributed_Systems.html

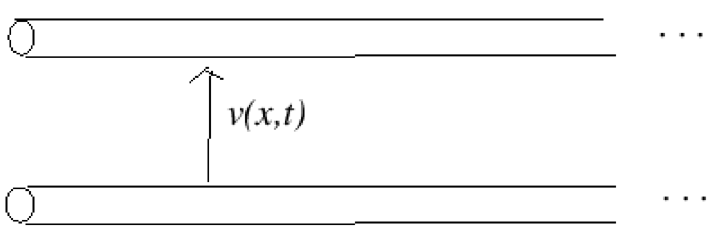
Distributed



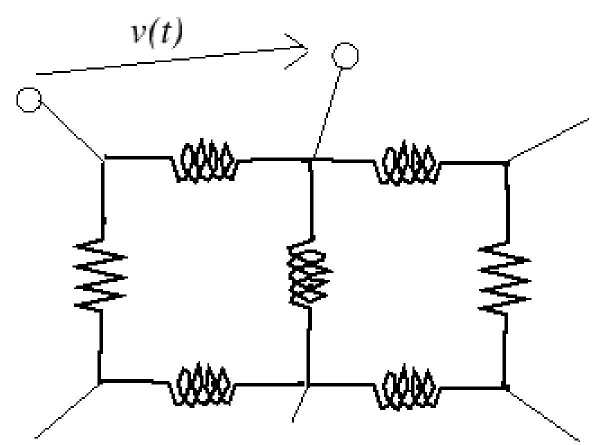
Lumped



Distributed



Lumped



RLGC Models: Lumped

- R, L, G, C (and coupling elements) extracted using quasi-static analysis

Accuracy?

1. Approximation of distributed effect by Lumped Elements:
Not Accurate

2. Distributed problem is solved in EM tool and the result expressed as Lumped elements:
Fairly Accurate
    - Quasi-static EM tool: Not accurate at high frequency
    - Full-wave EM tool: Sometimes not accurate in lumped element conversion using fitting

Transmission Line Models: Distributed

$$G(f) \cong G_o + \frac{f}{\sqrt{1 + (f/\ f_{gd})^2}} G_d$$

$$R(f) \cong R_o + \sqrt{f}(1 + j)R_s$$

$$G\omega = Go + \sum_k Gd_k \frac{j\omega}{j\omega + \omega_{pk}}$$

```
Wtest win 0 wout 0 N=1 RLGCMODEL=WE1 L=0.3
+ INCLUDEGDIMAG=yes
.MODEL WE1 W MODELTYPE=RLGC, N=1
+ Lo = 3.8e-07
+ Co = 1.3e-10
+ Ro = 2.74e+00
+ Go = 0.0
+ Rs = 1.1e-03
+ Gd = 0.07
+ wp= 0.07
```

HSPICE® Signal Integrity User Guide
A-2007.12

Accuracy?

1. 2D approximation: cross-section unchanged in length
2. TEM approximation in cross-section

S/Y/Z Models: Distributed

```
**S-parameter example
.OPTION post
.probe v(n2)
P1 n1 0 port=1 Zo=50 ac=1v PULSE 0v 5v 5n 0.5n 0.5n 25n
P2 n2 0 port=2 Zo=50
.ac lin 500 1Hz 30MegHz
.tran 0.1ns 10ns
* reference node is set
S1 n1 n2 0 mname=s_model
* S parameter
.model s_model S TSTONEFILE = ss_ts.s2p
Rt1 n2 0 50
.end
```

HSPICE® Signal Integrity User Guide
A-2007.12

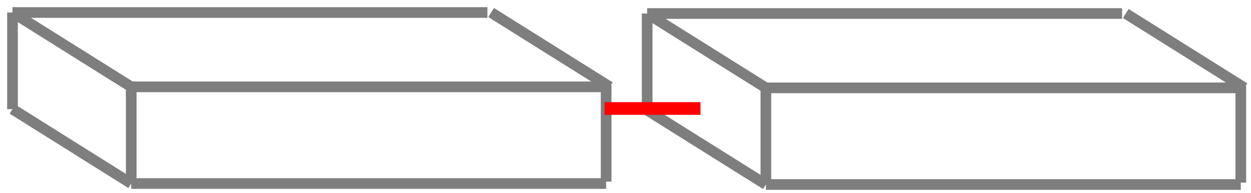
```
!
! touchstone file example
!
# Hz S MA R 50.0000
0.00000 0.637187 180.000 0.355136 0.00000
0.355136 0.00000 0.637187 180.000
......
! # HZ S DB R 50.0000
! 0.00000 -3.91466 180.000 -8.99211 0.00000
! -8.99211 0.00000 -3.91466 180.000
! ......
!
!# Hz S RI R 50.0000
! 0.00000 -0.637187 0.00000 0.355136 0.00000
! 0.355136 0.00000 -0.637187 0.00000
! ......
!
! 2-port noise parameter
! frequency[Hz] Nfmin[dB] GammaOpt(M) GammaOpt(P) RN/Zo
0.0000 0.29166 0.98916 180.00 0.11055E-03
0.52632E+08 6.2395 0.59071 -163.50 0.32868
0.10526E+09 7.7898 0.44537 175.26 0.56586
! ......
! end of file
```

Accuracy?

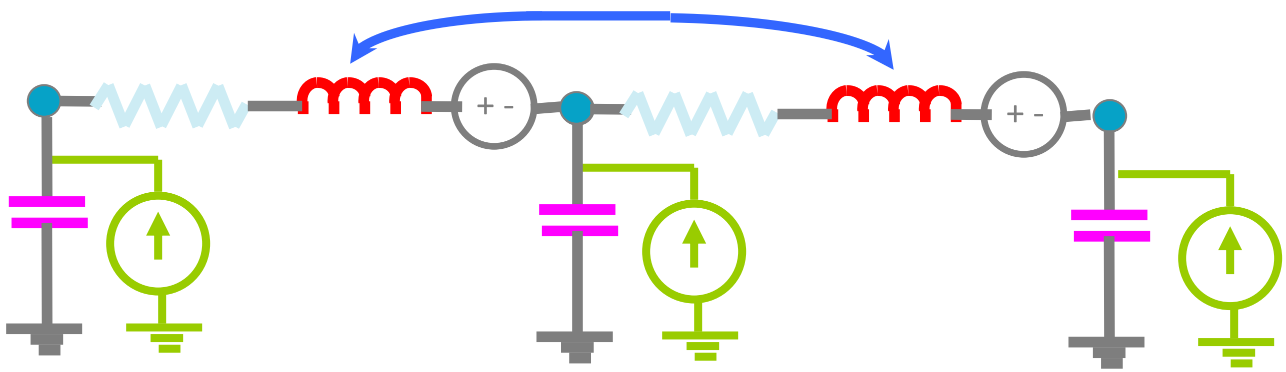
1. Accurate but time expensive both in extraction and simulation

PEEC: Lumped or Distributed?

Geometry



Conductor



Accuracy?

1. Accurate but time expensive
2. Conventional SPICE do not support delay elements

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