Large-Signal Frequency Domain Coupled Device and Circuit Simulation

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Outline

- Introduction
- Coupled device/circuit simulation
- Quasi-static, non-quasi-static, and modified Volterra series harmonic balance analyses
- Examples and performance comparison
- Conclusions

The Modeling Hierarchy

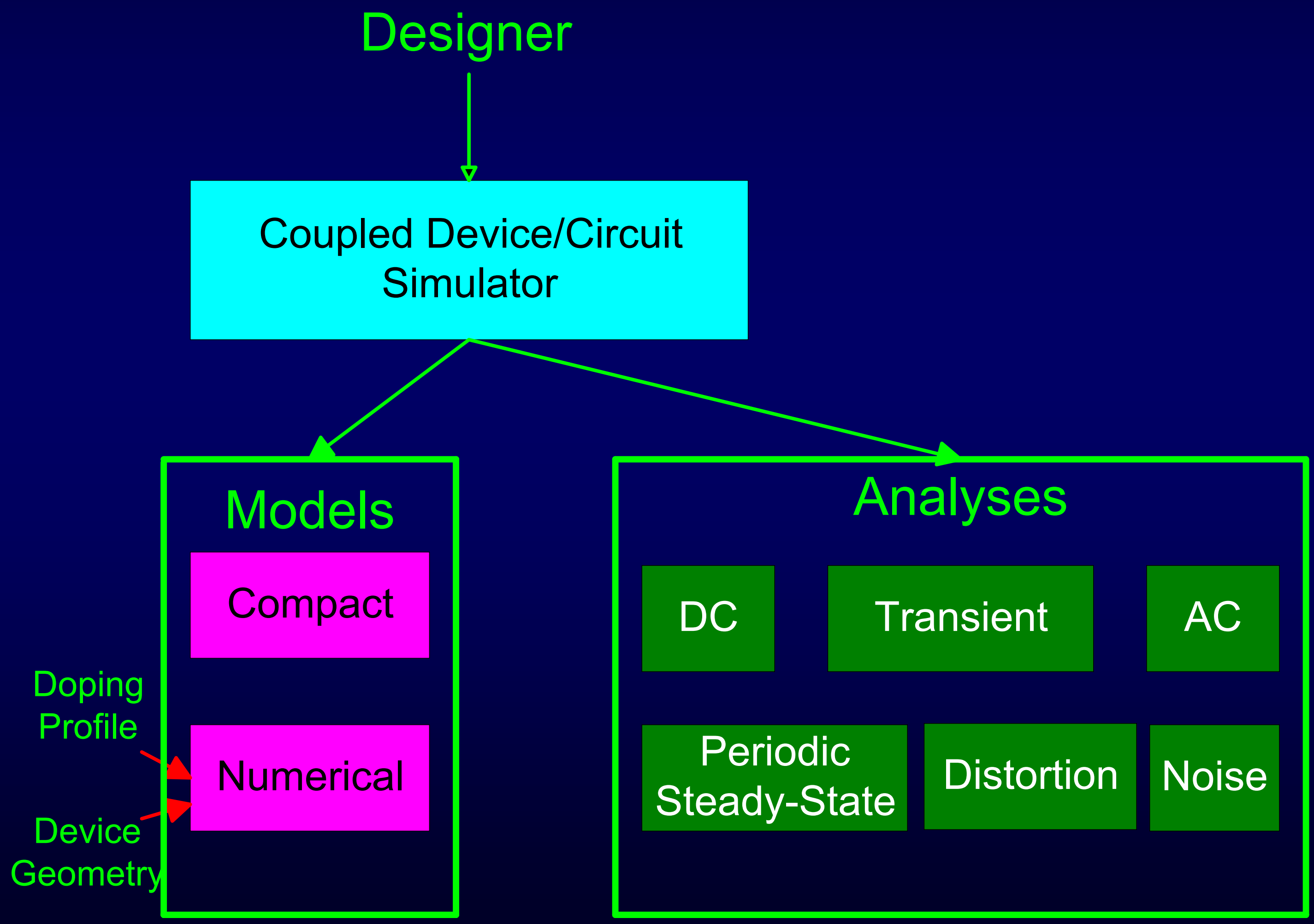
Speed ↔ Accuracy

High-level models	Lumped-element models	Compact models	Numerical models
VHDL-AMS	**RLC**	**BSIM3**	**PISCES**

Circuit/Device Simulation

- **Circuit simulation**
  - – Analytical (compact) models used: inaccurate under certain conditions
  - \+ Simulation of multiple devices in a circuit
- **Device simulation**
  - \+ Based on device physics: accurate
  - – Simulation of a single device, no circuit embedding
- **Coupled circuit/device simulation**
  - \+ Accurate
  - \+ Simulation of multiple devices

Coupled Device/Circuit Simulation



Numerical Model Equations

$$\nabla \cdot \varepsilon E = q(N_D - N_A + p - n)$$

$$\frac{1}{q} \nabla \cdot J_n = \frac{\partial n}{\partial t} - (G - R)$$

$$\frac{1}{q} \nabla \cdot J_p = -\frac{\partial p}{\partial t} + (G - R)$$

where

$$E = -\nabla \psi$$

$$J_n = -q\mu_n n \nabla \psi + qD_n \nabla n$$

$$J_p = -q\mu_p p \nabla \psi - qD_p \nabla p$$

Device terminal current and voltage

$$I_{device} = \int J_{n,p} \; at \; contact + \frac{d}{dt} \int \varepsilon E \; at \; contact$$

$$\psi \; at \; contact = f(V_{device})$$

Advantages

- **Simulate critical devices at the device level within a circuit**
  - Solve partial differential equations describing devices coupled to a circuit simulator
- **Predict performance of circuits in absence of compact models for devices**
- **Evaluate influence of process variations on circuit performance**

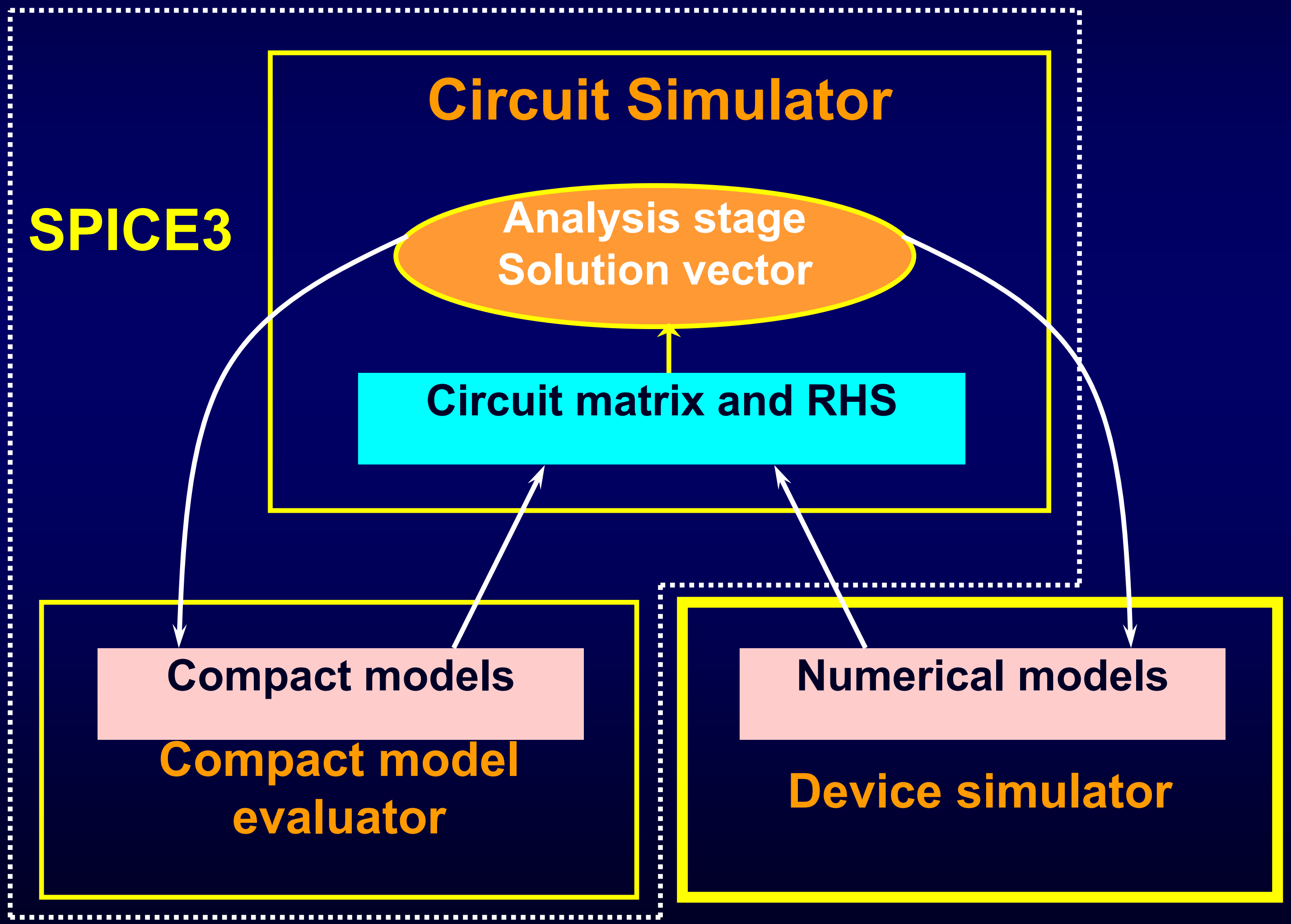
Application Examples

- Delay analysis of BiCMOS driver circuits
- Simulation of power devices
- Determination of switch-induced error in MOS switched-capacitor circuits
- Simulation of RF circuits
- Simulation of single-event-upset in SRAMs
- Validation of analytical models

Coupled Device and Circuit Simulator (CODECS)

- **Device-level simulator (PDE solver)**
  - Poisson’s and current-continuity equations
  - Accurate terminal conductances and capacitances provided to circuit-level simulator
- **Circuit-level simulator (SPICE3)**
  - Compact model evaluation
  - Simulation engine

Architecture of CODECS



RF Circuit Simulation

- **Accurate and efficient steady-state simulation of RF ICs required for**
  - Distortion, power, frequency, and noise
  - Gain and impedance characteristics
- **Simulation techniques**
  - Time-domain shooting method
  - Harmonic-balance method

RF Circuit Simulation Issues

- **Distributed effects in devices important for RF applications**
  - Use physical models in absence of accurate compact models
    - ⇨Coupled device and circuit simulation for RF circuits

Harmonic Balance Method

- Truncated Fourier series approximation of x(t)

$$x(t) \approx a_0 + \sum_{i=1}^{s} \left(a_i \cos(\omega_i t) + b_i \sin(\omega_i t)\right)$$

- For 2s+1 time samples $x_0 \ldots x_{2s}$

$$\mathbf{x} = \begin{bmatrix} x_0 \\ x_1 \\ \vdots \\ x_{2s} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & \cos(\omega_1 t_0) & \cdots & \sin(\omega_s t_0) \\ 1 & \cos(\omega_1 t_1) & \cdots & \sin(\omega_s t_1) \\ \vdots & \vdots & \ddots & \vdots \\ 1 & \cos(\omega_1 t_{2s}) & \cdots & \sin(\omega_s t_{2s}) \end{bmatrix}}_{\Gamma^{-1}} \underbrace{\begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ b_s \end{bmatrix}}_{X} = \Gamma^{-1} X$$

Harmonic Balance Method

- Circuit equations in time domain:

$$i(x(t)) + \frac{d}{dt} q(x(t)) + s(t) = 0$$

  - x(t) the vector of circuit waveforms
  - i is a vector of contributions from nonreactive elements
  - q is a vector of contributions from reactive elements
  - s stimulus vector

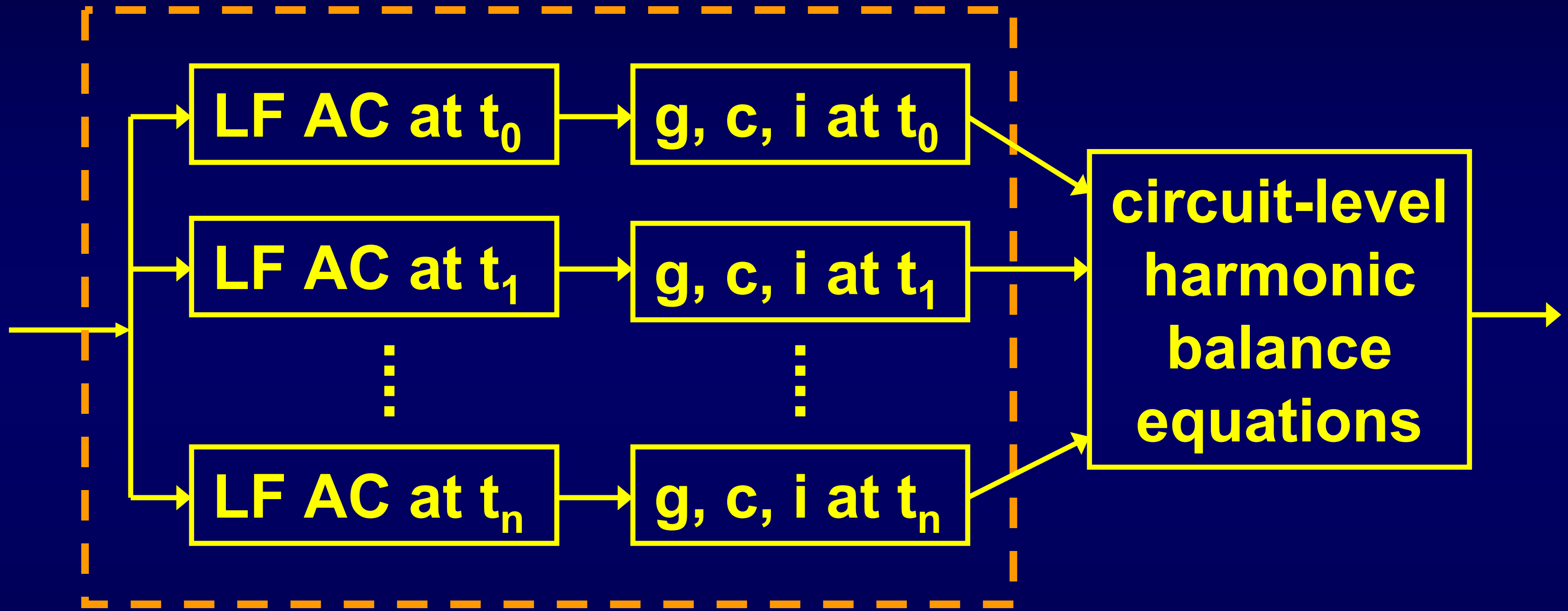
Harmonic Balance Method

- **Circuit equations in frequency domain:**

$$\Gamma i(\Gamma^{-1}X) + \Omega \Gamma q(\Gamma^{-1}X) + S = 0$$

  - X the Fourier coefficients of unknown waveforms
  - Γ and Γ^{-1} the discrete Fourier transform pair
  - i time-domain non-reactive elements
  - q time-domain reactive elements
  - S frequency-domain stimulus
  - Ω frequency-domain representation of time derivative

Quasi-Static Harmonic Balance



- **Harmonic balance at circuit level**
- **Quasi-static approach**
  - g and c based on static solutions of devices

Quasi-Static Harmonic Balance

- **Efficient**
  - Circuit waveforms as unknowns
  - Small harmonic balance matrix
  - No modification to device simulator
- **Accuracy problems**
  - When terminal voltages vary faster than device transit times
  - g and c are frequency dependent

$\Rightarrow$ **Non-quasi-static harmonic balance analysis**

Non-Quasi-Static (NQS) Harmonic Balance

- Solve the complete system of equations at both circuit and device levels

$$\begin{cases} f_d = d(w, v) + \dfrac{d}{dt}(a \cdot w) = 0 \\ f_c = \underbrace{I(w, v) + \dfrac{d}{dt} D(w, v)}_{i_d} + i(v) + \dfrac{d}{dt} q(v) + s = 0 \end{cases}$$

  - f_d and f_c device- and circuit-level equations
  - w and v device- and circuit-level unknowns
  - a is a constant $\in \{+1, -1, 0\}$
  - i_d currents from numerical devices
  - I and D conduction and displacement terms

NQS Harmonic Balance Equations

- Solve using Newton's method

$$\left(\begin{bmatrix} J_w & J_v \\ G^I_w & G^I_v + G \end{bmatrix} + T\begin{bmatrix} a & 0 \\ C^D_w & C^D_v + C \end{bmatrix}\right)\begin{bmatrix} \Delta w \\ \Delta v \end{bmatrix} = -\begin{bmatrix} f_d \\ f_c \end{bmatrix}$$

  - $T = \Gamma^{-1}\Omega\Gamma = \frac{d}{dt}$ in harmonic balance method
  - J_w, J_v, G^I_w, G^I_v, C^D_w, C^D_v, G, and C are corresponding derivatives to device- and circuit-level unknowns

NQS Harmonic Balance Solution

- Eliminate Δw

$$\Rightarrow \quad \Delta w = (J_w + Ta)^{-1}(-f_d - J_v \Delta v)$$

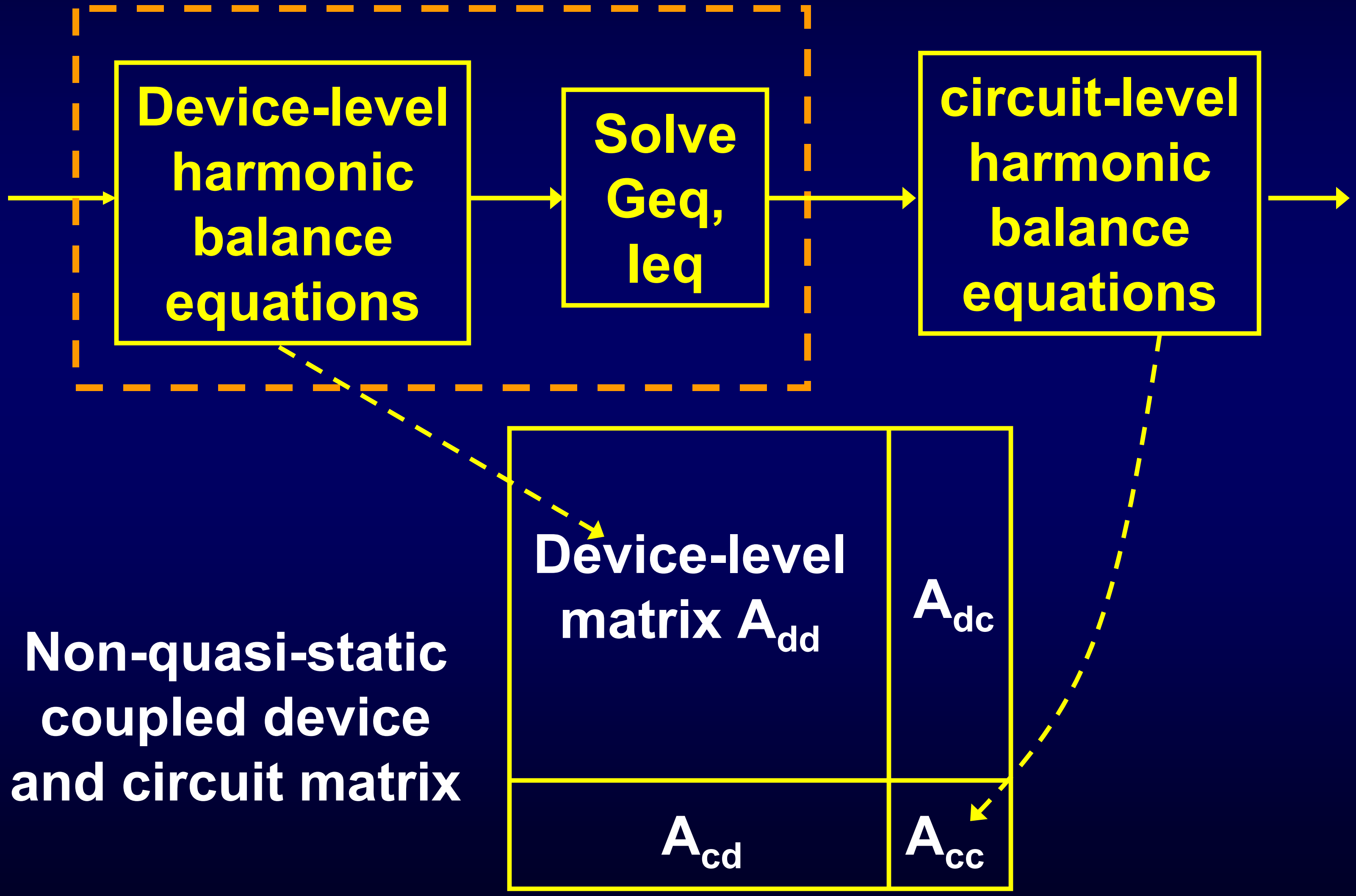
$$\left[G_{eq} + (G + TC)\right]\Delta v = -f_c - I_{eq}$$

where, $G_{eq} = (G_w^I + TC_w^D)(J_w + Ta)^{-1}(-J_v) + (G_v^I + TC_v^D)$

$$I_{eq} = (G_w^I + TC_w^D)(J_w + Ta)^{-1}(-f_d)$$

– G_{eq} and I_{eq} are the contribution of numerical device to the circuit-level equation

NQS Harmonic Balance Implementation



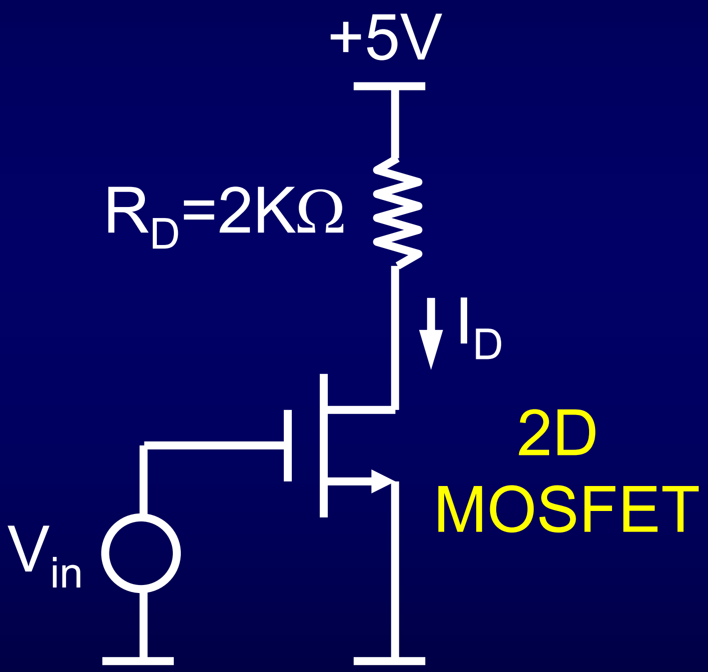
Non-quasi-static coupled device and circuit matrix

NQS Harmonic Balance Summary

- **Accurate for very high frequencies**
  - Harmonic balance at both device- and circuit- levels
  - Internal dynamics of devices taken into account
- **Expensive**
  - A large number of device-level unknowns
  - Large dense system matrix
  - Need extensive modifications to device simulator

Comparison of NQS and QS

- **Simple CS amplifier**

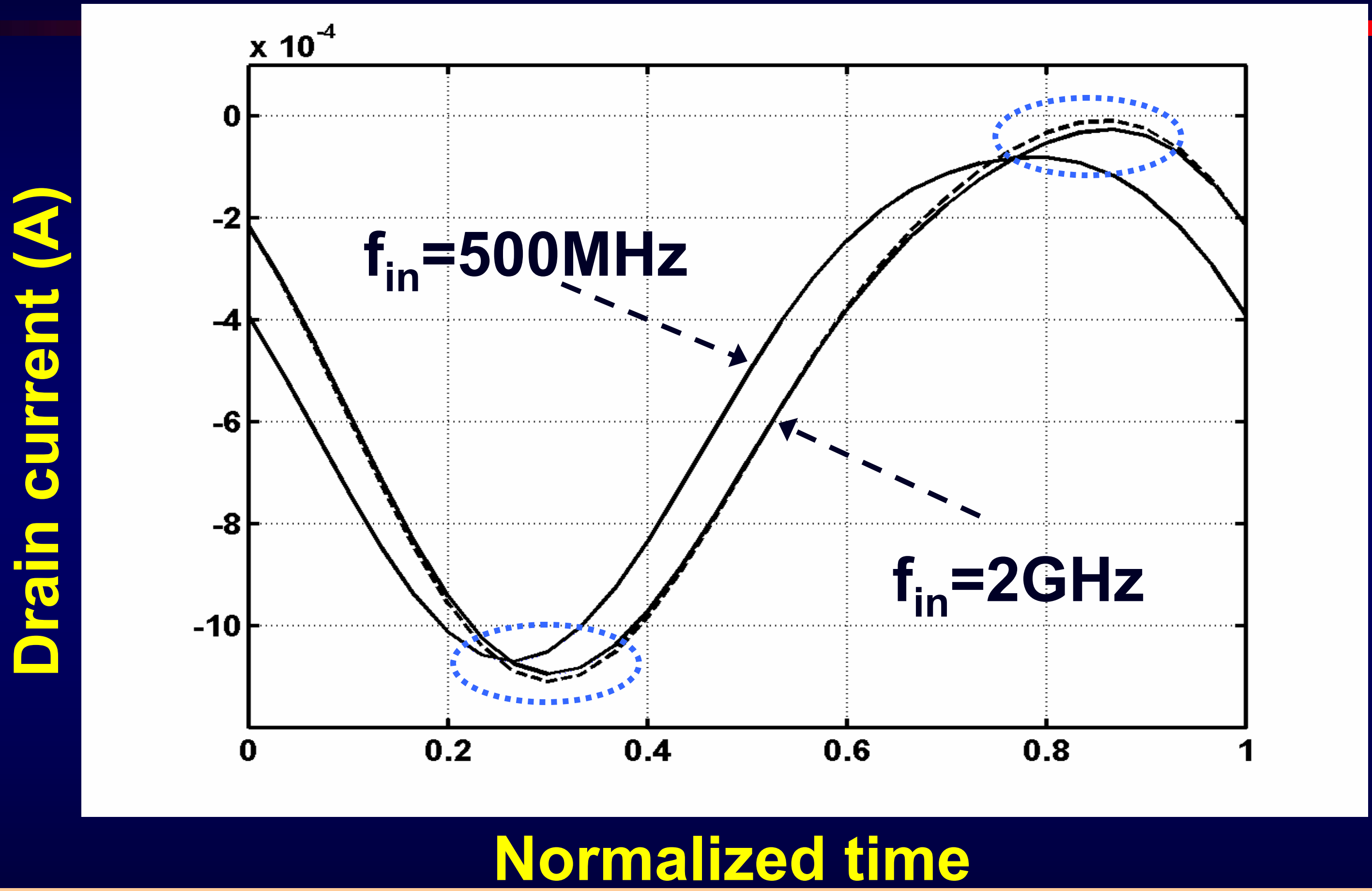


V_{in}=2+0.5sin(2π·f_{in}·t)

- f_{in}= 500MHz
  2GHz
  5GHz

- 2D MOSFET
  - Mesh points: 31x19=589
  - f_T=2GHz

Comparison of Accuracy (CS Amp)

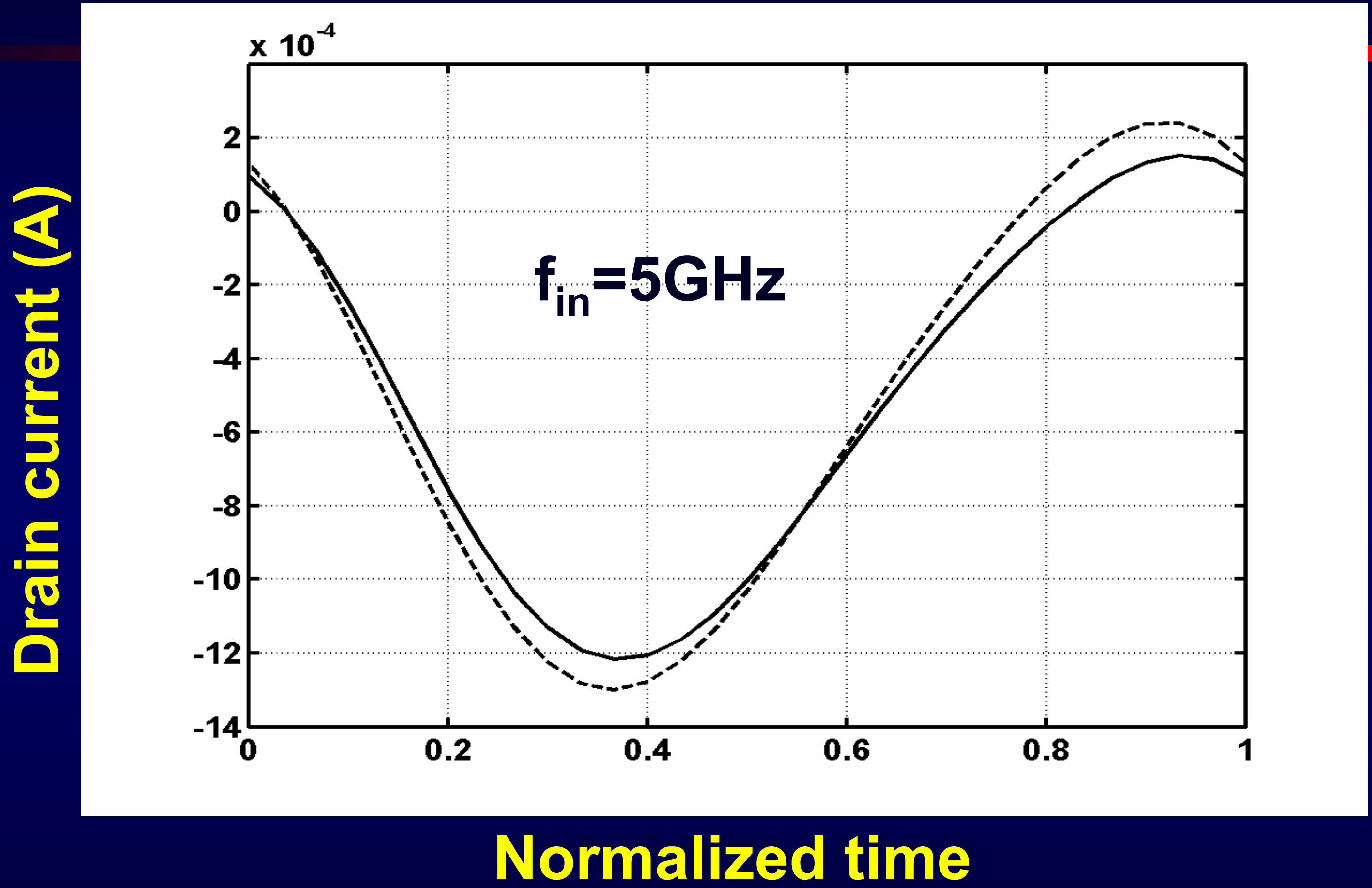


.... Transient

- - - Quasi-static harmonic balance (max error 3.8%)

—— Non-quasi-static harmonic balance

Comparison of Accuracy (CS Amp)



.... Transient

- - - Quasi-static harmonic balance (max error 16.8%)

—— Non-quasi-static harmonic balance

Comparison of Simulation Complexity (CS Amp)

	Quasi-static method	Non-quasi-static method	
No. freqs chosen	4	4	
Simulation time	14s	3840s	270x
Memory used	5.3M	103M	20x
No. eqns for HB at circuit level	28	28	
No. eqns for HB at device level	0	6447 (7x921)	
Largest matrix	921 x 921	6447 x 6447	

Comparison of Simulation Complexity (SCP)

	Quasi-static method	Non-quasi-static method
No. freqs chosen	4	4
Simulation time	22s	8640s
Memory used	6.9M	203M
No. eqns for HB at circuit level	56	56
No. eqns for HB at device level	0	12894 (7x2x921)
Largest matrix	921 x 921	6447 x 6447

390x

30x

Comparison of Sparse and UMFPACK

	Sparse	UMFPACK	
No. freqs chosen	4	4	
Simulation time	19650s	3471s	← 5.7x
Memory used	409M	165M	← 2.5x
No. eqns for HB at circuit level	63	63	
No. eqns for HB at device level	18858	18858	
Largest matrix	9429x9429	9429x9429	

Modified-Volterra-Series (MVS) Device Model

- First order modified Volterra series*
  - Terminal voltage

$$v(t) = \sum_{h=-H}^{h=+H} V_h e^{j2\pi f_h t}$$

  - Terminal current

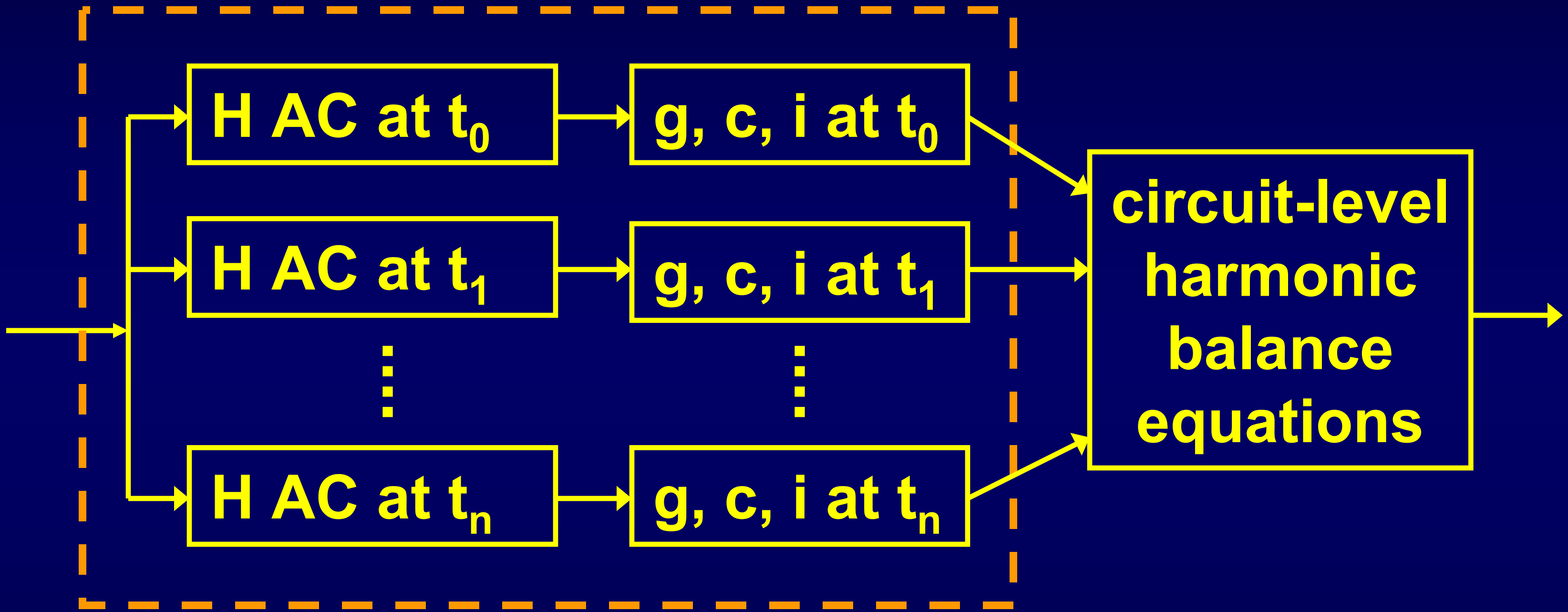
$$i_d = z_0(v) + \sum_{h=-H}^{h=+H} D\{v, f_h\} V_h e^{j2\pi f_h t}$$

Static current

$$Y(f_h, v) - Y(0, v)$$

* F. Filicori, G. Vannini. V. A. Monaco, July 1992.

MVS Harmonic Balance Implementation



- Harmonic balance at circuit level
- H AC analyses at H frequencies (longer time)
- i includes dynamic current

MVS Harmonic Balance Summary

- **Efficiency**
  - Circuit waveforms as unknowns
  - No modification to device simulator
  - Longer time for H AC analyses
- **Accuracy**
  - Frequency dependence of g and c
  - Small-signal internal dynamics
  - Improvement for high frequency and small amplitude signals

Differences Between Approaches

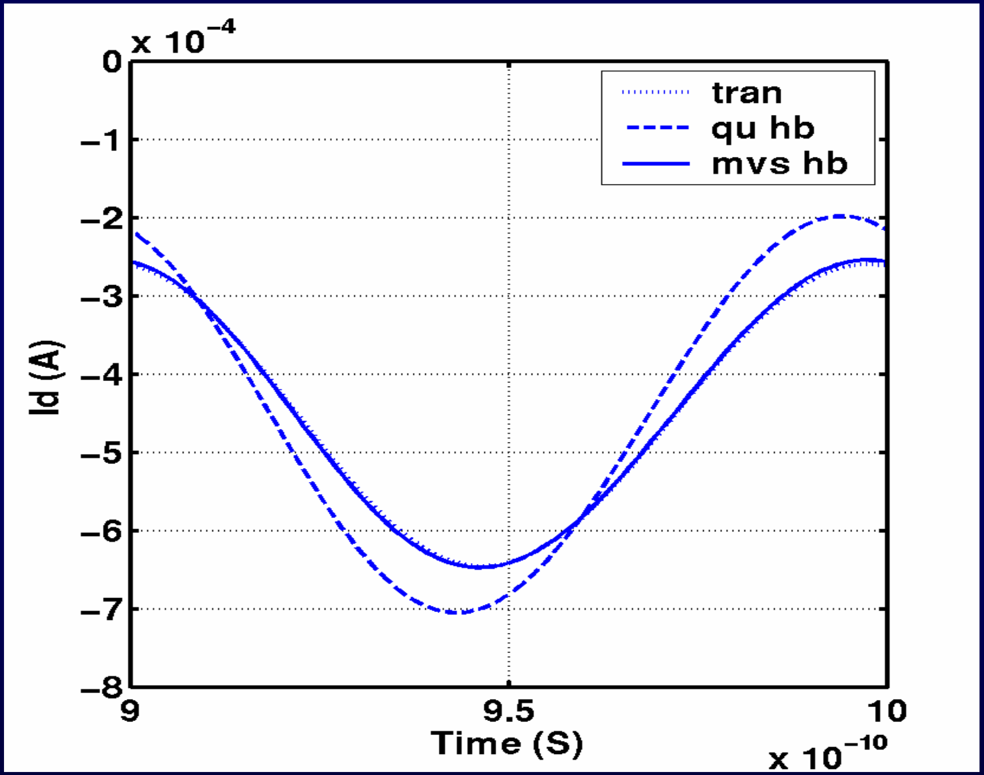
- **Handling of numerical device dynamics**

	Device terminal dynamics*	Large-signal internal dynamics	Small-signal internal dynamics
NQS	Yes	Yes	Yes
QS	Yes	No	No
MVS	Yes	No	Yes

* terminal dynamics $\frac{d}{dt}D(w, v)$

Accuracy Comparison of QS and MVS

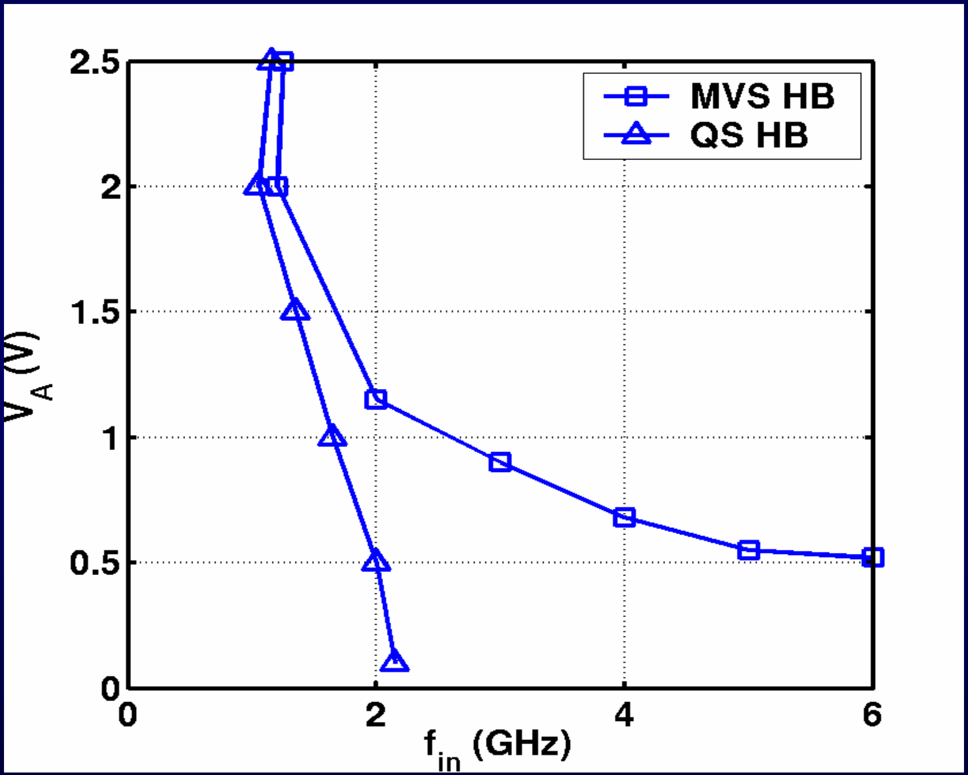
- **Simple CS amplifier** $V_{in}=2+0.1\sin(2\pi\cdot 10GHz\cdot t)$



- Accuracy improved with MVS HB
- Phase and magnitude errors from QS corrected

Constant Error (5%) Loci of QS and MVS

- $V_{in}=2+V_A \sin(2\pi \cdot f_{in} \cdot t)$

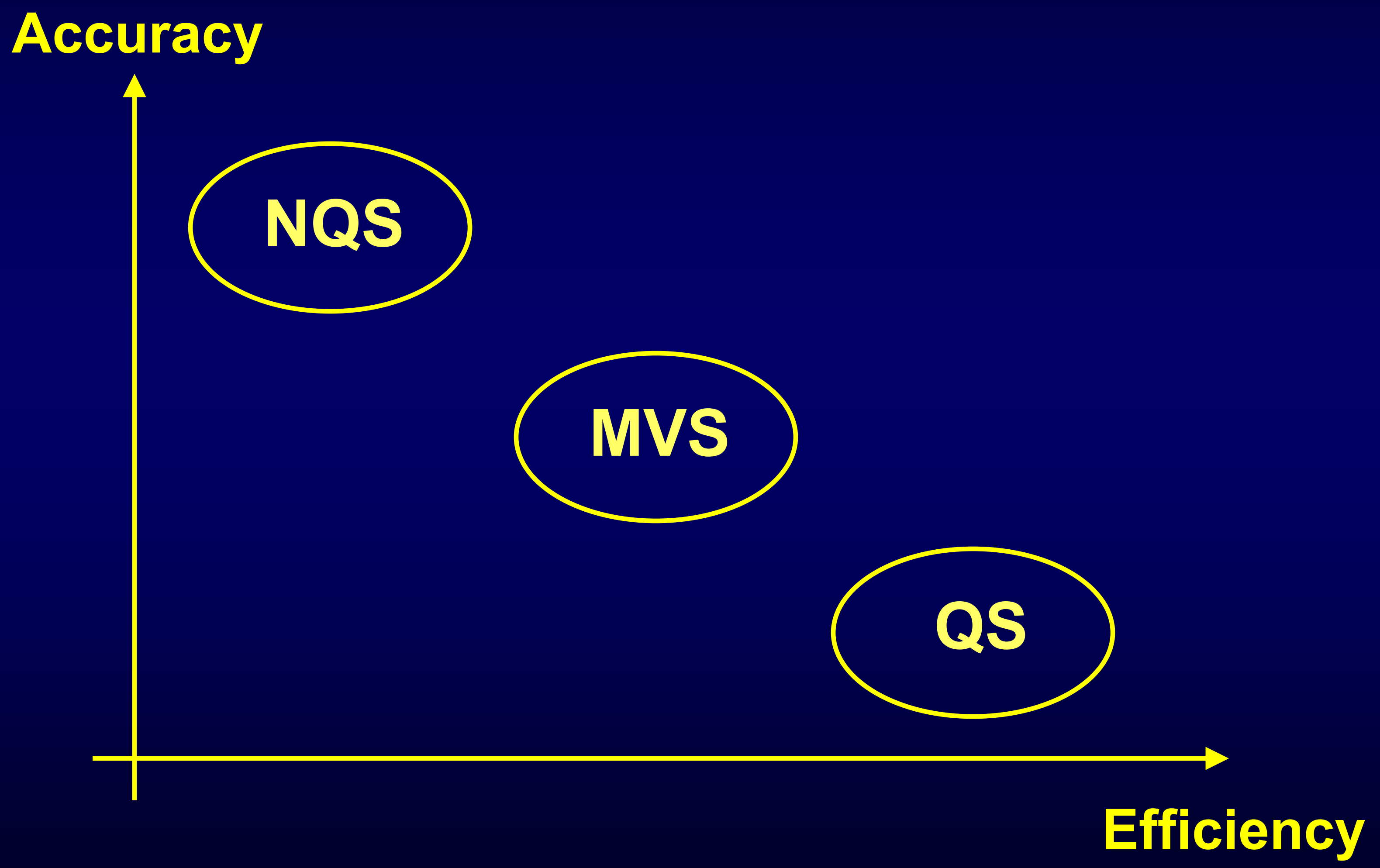


- Accuracy of MVS HB method depends on $V_A \cdot f_{in}$
- Accuracy of QS HB mainly depends on f_{in}

Summary of Harmonic Balance Implementation

	NQS method	MVS method	QS method
HB level	Circuit & device	Circuit	Circuit
Modifications to device simulator	Extensive	None	None
Memory used	Large	Small	Small
Simulation time	Slow	Fair	Fast
Accuracy	Excellent	Improved for small signals	Limited by f_T

Tradeoff Between Approaches



Conclusions

- Coupled circuit/device simulations for accurate simulation of circuits
- Provide a direct link between technology changes and circuit performance
- Frequency-domain harmonic balance method for RF applications
  - Three different implementation approaches
  - Tradeoff between accuracy and efficiency
- Need faster solution methods for PDEs

Backup

Static, Quasi-Static, and Non-Quasi-Static Models

- **Non-quasi-static (NQS) model:**

$$d(w,v)+\frac{d}{dt}(a\cdot w)=0 \qquad I_d = I_{cond}(w,v)+\frac{d}{dt}D_{displ}(w,v)$$

- **Quasi-static (QS) model:**

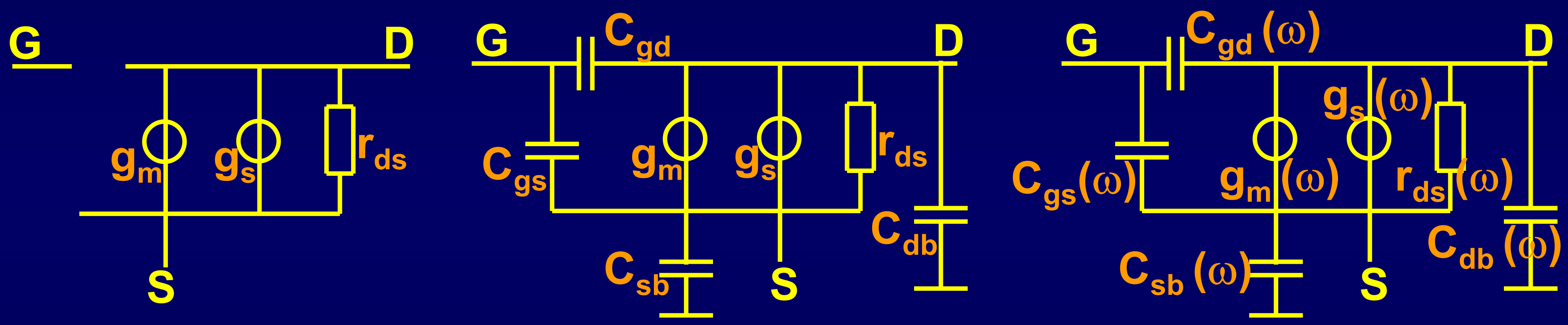
$$d(w,v)+\cancel{\frac{d}{dt}(a\cdot w)}=0 \qquad I_d = I_{cond}(w,v)+\frac{d}{dt}D_{displ}(w,v)$$

- **Static model:**

$$d(w,v)+\cancel{\frac{d}{dt}(a\cdot w)}=0 \qquad I_d = I_{cond}(w,v)+\cancel{\frac{d}{dt}D_{displ}}(w,v)$$

Static, QS, and NQS models (small signal)

- MOSFET small-signal model



Static model:	QS model:	NQS model:
C=0	$C(V_{bias})$	$C(V_{bias}, \omega)$
$G(V_{bias})$	$G(V_{bias})$	$G(V_{bias}, \omega)$