SPICE Macromodel Generation

Bob Ross, Teraspeed Labs, USA
bob@teraspeedlabs.com

European Virtual IBIS Summit
(with Virtual SPI2021)
May 12, 2021

Agenda

- Preliminary material
- Macromodel references
- Networks for poles and zeros (and their efficiencies)
- Operational amplifier open-loop response
- Operational amplifier macromodel example
- Conclusion

Teraspeed Labs

Automatic Implementation

- Starting point – Laplace transform extraction as ratio of polynomials is *s*
- Laplace transform formats or pole/zero formats not interchangeable between EDA tools
- Lowest common denominator – Berkeley SPICE RLC elements and controlled gain elements
- Implementation based on solving for poles and zeros and then cascading unit gain stages with efficient grouping.
- Automatic node numbering
- Stages referenced to one megohm (MΩ) resistor
- Teraspeed Labs

SPICE Macromodels

- G. Boyle, B. Cohn, D. Pederson, J. Solomon, "Macromodeling of Integrated Circuit Operational Amplifiers", IEEE Journal of Solid-State Circuits, Vol. SC-9, No. 6, Dec. 1974, Pp. 353-363
  - Dominant and second real pole
  - A commercial vendor macromodel adapted to illustrate a general behavioral macromodel generation strategy
  - Strategy can be applied to high-speed networks
- Cascaded SPICE elements are common practice from several vendors, but some macromodels use:
  - Real left-hand plane (LHP) poles and zeros
  - No right-hand plane (RHP) zeros
  - No complex poles or zeros
  - Extractions often based on frequency domain magnitude and phase measurements

Networks

- **Basic** Stages (simple poles and zeros or combinations)
- **Constructed** Stages (combining several basic networks for an overall set of poles and zeros
- **Utility** Networks for pole/zero cancelation
- **All-pass** Networks for cancellations
- Efficiencies relative to a single-pole stage (combined P+Z stages usually more efficient)
    - Parts per pole+zero relative to **3.0**
    - Nodes per pole+zero relative to **1.0**

Teraspeed Labs

Basic Stages

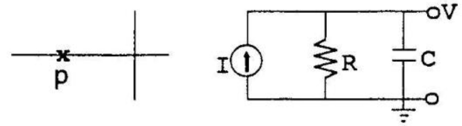
BASIC STAGES:

Real Zeros	Cmplx Conj Zeros	Real Poles	Cmplx Conj Poles	Poles+ Zeros	Stages	Parts	New Nodes	Parts Per P + Z	Nodes Per P + Z
1. **Real Pole**									
		X		1	1	3	1	**3**	**1**
2. **Real Pole, Real Zero** 2a. z < p		2b. z > p							
O		X		2	a, b: 1	4	2	**2**	**1**
3. **Complex-Conjugate Poles**									
			X X	2	1	4	2	**2**	**1**
4. **Complex-Conjugate Poles, Real Zero** 4a. $z < 2\sigma$		4b. $z > (\omega^2+\sigma^2) / 2\sigma$							
O			X X	3	a: 1 b: 1	5 5	2 3	**1.67** **1.67**	**0.67** **1**

Basic Stages

BASIC STAGES:

1. Real Pole

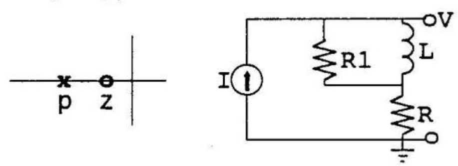


$$\frac{V}{I} = \frac{R}{(1 + s / p)}$$

$C = 1 / R p$

2. Real Pole, Real Zero

2a. $(z < p)$

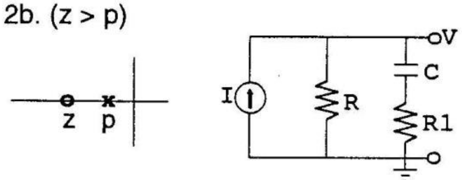


$$\frac{V}{I} = \frac{R(1 + s / z)}{(1 + s / p)}$$

$R1 = R / (p / z - 1)$

$L = R1 / p$

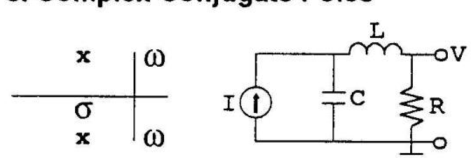
2b. $(z > p)$



$R1 = R / (z / p - 1)$

$C = 1 / R1\, z$

3. Complex-Conjugate Poles



$$\frac{V}{I} = \frac{R}{(1 + 2\sigma\, s / (\omega^2+\sigma^2) + s^2 / (\omega^2+\sigma^2))}$$

$L = R / 2\sigma$

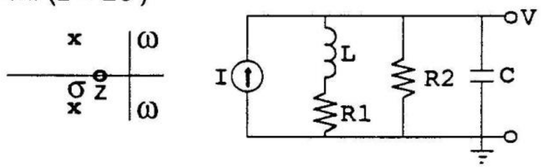
$C = 1 / L\, (\omega^2+\sigma^2)$

Basic Stages (Continued)

4. Complex-Conjugate Poles, Real Zero

$$\frac{V}{I} = \frac{R\,(1 + s / z)}{(1 + 2\sigma\, s / (\omega^2+\sigma^2) + s^2 / (\omega^2+\sigma^2))}$$

4a. $(z < 2\sigma)$



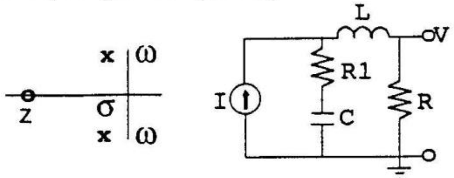
$C = z / R\,(\omega^2+\sigma^2)$

$R2 = 1 / C\,(2\sigma - z)$

$R1 = R\,R2 / (R2 - R)$

$L = R1 / z$

4b. $(z > (\omega^2+\sigma^2) / 2\sigma)$



$C = (2\sigma / (\omega^2+\sigma^2) - 1 / z) / R$

$R1 = 1 / C\,z$

$L = 1 / C\,(\omega^2+\sigma^2)$

Constructed Stages

CONSTRUCTED STAGES:

Real Zeros	Cmplx Conj Zeros	Real Poles	Cmplx Conj Poles	Poles+ Zeros	Stages	Parts	New Nodes	Parts Per P + Z	Nodes Per P + Z

4. **Complex-Conjugate Poles, Real Zero** (10 & 2)

4c. $(\omega^2+\sigma^2) / 2\sigma > z > 2\sigma$

O			X X	3	c: 2	8	4	**2.67**	**1.33**

5. **Complex-Conjugate Poles, Two Real Zeros** (11 & 2)

O O			X X	4	2 max: 3	9 13	5 7	**2.25** **3.25**	**1.25** **1.75**

6. **Complex-Conjugate Poles, Complex-Conjugate Zeros** (11, 12 & 2)

	O O		X X	4	3	14	7	**3.5**	**1.75**

7. **Two Real Poles, Complex-Conjugate Zeros** (12 & 2)

	O O	X X		4	2 max: 3	9 13	4 6	**2.25** **3.25**	**1** **1.5**

8. **Complex-Conjugate Poles, Real Pole, Complex-Conjugate Zeros** (12 & 4)

	O O	X	X X	5	min: 2 2 max: 4	10 10 17	5 6 8	**2** **2** **3.4**	**1** **1.2** **1.6**

9. **Complex-Conjugate Poles Real Pole, Complex-Conjugate Zeros, Real Zero** (11, 12 & 2)

O	O O	X	X X	6	3 max: 5	14 22	7 11	**2.33** **3.67**	**1.14** **1.83**

Utility Networks and Combinations for Construction

UTILITY NETWORKS AND COMBINATIONS FOR CONSTRUCTION:

Real Zeros	Cmplx Conj Zeros	Real Poles	Cmplx Conj Poles	Poles+ Zeros	Stages	Parts	New Nodes	Parts Per P + Z	Nodes Per P + Z

10. Complex-Conjugate Poles, Fixed Real Zero

O ^ fixed			X X	3	1	4	2	1.33	0.67

11. Complex-Conjugate Poles, Real Zero, Fixed Real Zero

11a. $z < 2\sigma$ 11b. $z > (\omega^2+\sigma^2) / 2\sigma$ 11c. $(\omega^2+\sigma^2) / 2\sigma > z > 2\sigma$ (by combination of 11a & 2)

O O ^or^ fix			X X	4	a: 1 b: 1 c: 2	5 5 9	3 3 5	1.25 1.25 2.25	0.75 0.75 1.25

12. Complex-Conjugate Zeros, Real Pole, Fixed Real Pole

12a. $p < 2\sigma$ 12b. $p > (\omega^2+\sigma^2) / 2\sigma$ 12c. $(\omega^2+\sigma^2) / 2\sigma > p > 2\sigma$ (by combination of 12a & 2)

	O O	X X ^or^ fix		4	a: 1 b: 1 c: 2	5 5 9	2 2 4	1.25 1.25 2.25	0.5 0.5 1

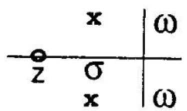
Teraspeed Labs

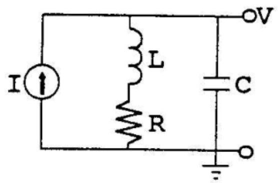
Utility Networks for Construction

UTILITY NETWORKS FOR CONSTRUCTION:

10. Complex-Conjugate Poles,
Fixed Real Zero

$$\frac{V}{I} = \frac{R\,(1 + s/z)}{\left(1 + 2\sigma\, s / (\omega^2+\sigma^2) + s^2 / (\omega^2+\sigma^2)\right)}$$





$L = R / 2\sigma$

$C = 1 / L\,(\omega^2+\sigma^2)$

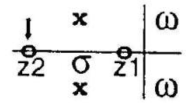
$z = 2\sigma$

Utility Networks (Continued)

11. Complex-Conjugate Poles, Real Zero, Fixed Real Zero

$$\frac{V}{I} = \frac{R\,(1 + s/z1)\,(1 + s/z2)}{(1 + 2\sigma s/(\omega^2+\sigma^2) + s^2/(\omega^2+\sigma^2))}$$

11a. $(z1 < 2\sigma)$

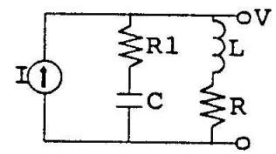


$L = R / z1$

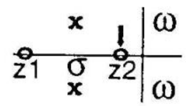
$C = 1 / L\,(\omega^2+\sigma^2)$

$R1 = R / (2\sigma / z1 - 1)$

$z2 = 1 / R1\,C$



11b. $(z1 > (\omega^2+\sigma^2) / 2\sigma)$



$C = (2\sigma / (\omega^2+\sigma^2) - 1 / z1) / R$

$R1 = 1 / C\,z1$

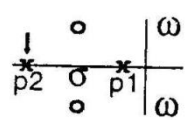
$L = 1 / C\,(\omega^2+\sigma^2)$

$z2 = R / L$

12. Complex-Conjugate Zeros, Real Pole

$$\frac{V}{I} = \frac{R\,(1 + 2\sigma s/(\omega^2+\sigma^2) + s^2/(\omega^2+\sigma^2))}{(1 + s/p1)\,(1 + s/p2)}$$

12a. $(p1 < 2\sigma)$

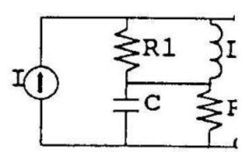


$C = 1 / R\,p1$

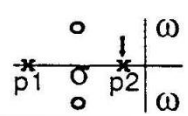
$L = 1 / C\,(\omega^2+\sigma^2)$

$R1 = R / (2\sigma / p1 - 1)$

$p2 = R1 / L$



12b. $(p1 > (\omega^2+\sigma^2) / 2\sigma)$



$C = 1 / L\,(\omega^2+\sigma^2)$

$L = R\,(2\sigma / (\omega^2+\sigma^2) - 1 / p1)$

$R1 = L / p1$

p2 = 1/RC

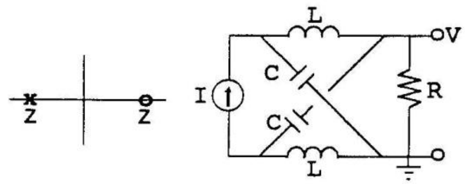
Teraspeed Labs

All-Pass Networks (Mirrored P/Z)

ALL-PASS NETWORKS FOR RIGHT-HAND PLANE ZEROS (WITH MIRRORED POLES):

13. RHP Real Zero, Fixed Real Pole

$$\frac{V}{I} = \frac{R\,(1 - s/z)}{(1 + s/z)}$$

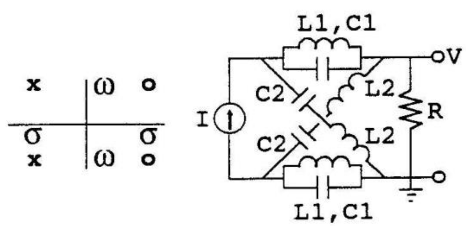


$L = R / z$

$C = 1 / R^2$

14. RHP Complex-Conjugate Zeros, Fixed Complex-Conjugate Poles

$$\frac{V}{I} = \frac{R\,(1 - 2\sigma\, s / (\omega^2+\sigma^2) + s^2 / (\omega^2+\sigma^2))}{(1 + 2\sigma\, s / (\omega^2+\sigma^2) + s^2 / (\omega^2+\sigma^2))}$$



$C1 = 1 / 2R\,\sigma$

$L1 = 1 / C1\,(\omega^2+\sigma^2)$

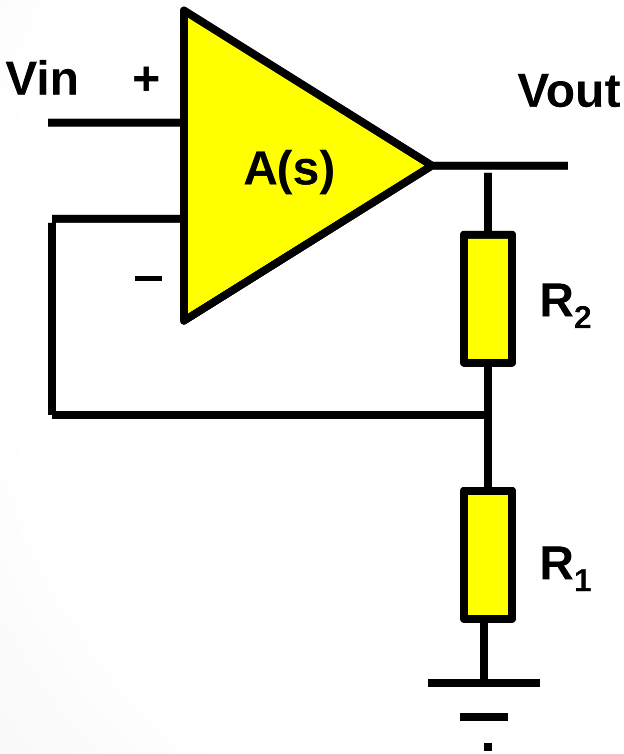
$L2 = R^2\,C1$

$C2 = 1 / L2\,(\omega^2+\sigma^2)$

ALL-PASS NETWORKS FOR RIGHT HAND PLANE ZEROS (WITH MIRRORED POLES):

Real Zeros	**Cmplx Conj Zeros**	**Real Poles**	**Cmplx Conj Poles**	Poles+ Zeros	Stages	Parts	New Nodes	**Parts Per P + Z**	**Nodes Per P + Z**
13. **RHP Real Zero, Fixed Real Pole**									
RHP **O**		**X** ^ fixed		2	1	6	3	**3**	**1.5**
14. **RHP Complex-Conjugate Zeros, Fixed Complex-Conjugate Poles**									
	RHP **O** RHP **O**		**X** fixed **X** fixed	4	1	10	5	**2.5**	**1.25**

Open Loop (OL) AC Model from Closed Loop (CL) Response



Extracted H(s) = Vout/Vin from time response = N(s)/D(s)

$G = (R_1 + R_2)/R_1$

$H(s) = A(s)/[1 + A(s)/G]$

$A(s) = H(s) + H(s)A(s)/G$

$A(s) = H(s)/[1 – H(s)/G]$

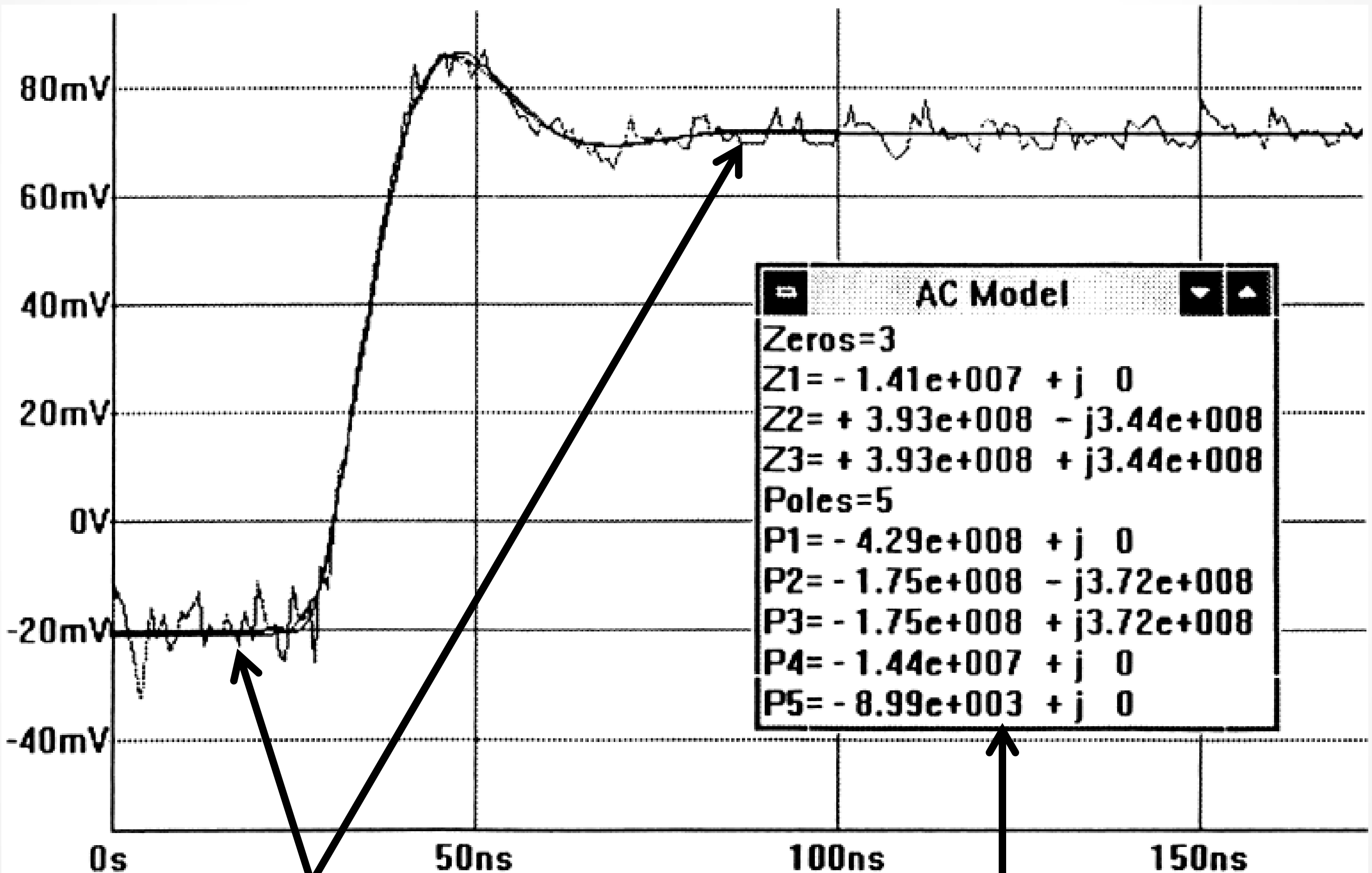
$A(s) = [N(s)/D(s)]/[1 – N(s)/GD(s)]$

$A(s) = N(s)/[D(s) – N(s)/G]$

Poles and zeros of A(s) produces OL AC Model

Teraspeed Labs

Operational Amplifier AC Model Example



Closed Loop Samples and Response

Open Loop Poles and Zeros

Generated SPICE Macromodel

AC Model

Zeros=3
Z1= - 1.41e+007 + j 0
Z2= + 3.93e+008 - j3.44e+008
Z3= + 3.93e+008 + j3.44e+008
Poles=5
P1= - 4.29e+008 + j 0
P2= - 1.75e+008 - j3.72e+008
P3= - 1.75e+008 + j3.72e+008
P4= - 1.44e+007 + j 0
P5= - 8.99e+003 + j 0

```
*
* SETUP PARAMETERS
*  NPN Bipolar Junction Transistor Input
*  Vcc = 15 V, Vee = -15 V
*  Input Stage Tail Current = 0.1 mA
*
* MEASURED (OR USER OVERRIDDEN) PARAMETERS
*
*  Srp = 135.3 V/us, Srn = 135.3 V/us
*  Avd = 94.211 dB at RL(Load) = 1e+009 kOhms
*  f(0dB) = 71.8 MHz, Phi(Phase Margin) = 222.2 deg
*
* ZEROS          Radians                         MHz
*  Real              Imaginary        Real              Imaginary
*  -1.41e+007        0                -2.24408          0
*  3.93e+008         -3.44e+008       62.5479           -54.7493
*  3.93e+008         3.44e+008        62.5479           54.7493
*
* POLES          Radians                         MHz
*  Real              Imaginary        Real              Imaginary
*  -8990             0                -0.0014308        0
*  -1.44e+007        0                -2.29183          0
*  -1.75e+008        -3.72e+008       -27.8521          -59.2056
*  -1.75e+008        3.72e+008        -27.8521          59.2056
*  -4.29e+008        0                -68.2775          0
*
*                 NON-INVERTING INPUT
*                 |  INVERTING INPUT
*                 |  |  POSITIVE POWER SUPPLY
*                 |  |  |  NEGATIVE POWER SUPPLY
*                 |  |  |  |  OUTPUT
*                 |  |  |  |  |
.SUBCKT OPamp     1  2 99 50 52
*
* INPUT STAGE (NO POLE)
*
R1    2    3    5e+011
R2    1    3    5e+011
R3    5    99   2930.88
R4    6    99   2930.88
I1    4    50   0.0001
IOS   1    2    1.095e-009
EOS   9    1    POLY(1)    59    49    -0.001136 1
Q1    5    2    7  QX
Q2    6    9    8  QX
R5    4    7    2421.07
R6    4    8    2421.07
*
EREF  98   0    49    0     1
*
```

Poles and zeros shown in radians and MHz in the macromodel

Terraspeed Labs

Low Frequency Pole

```
EREF   98    0    49    0    1
*
* SECOND STAGE POLE AT 1430.8 HZ
*
R21    100   98   1.50501e+008
C21    100   98   7.39098e-013
G21    100   98   6     5     0.000341195
V21    99    21   2.39393
V22    22    50   2.41393
D21    100   21   DX
D22    22    100  DX
*
* RHP COMPLEX ZEROS AT 62.5479 +/- j 54.7493 MHZ
* NEW LHP COMPLEX POLES AT 62.5479 +/- j 54.7493 MHZ
*
R101   105   98   1e+006
C101   101   98   1.27226e-015
C102   105   102  1.27226e-015
C103   105   103  2.88139e-015
C104   104   98   2.88139e-015
L101   101   98   0.00288139
L102   105   102  0.00288139
L103   101   103  0.00127226
L104   102   104  0.00127226
G101   102   101  49    100   1e-006
*
```

MHz	
Real	Imaginary
-2.24408	0
62.5479	-54.7493
62.5479	54.7493

MHz	
Real	Imaginary
-0.0014308	0
-2.29183	0
-27.8521	-59.2056
-27.8521	59.2056
-68.2775	0

```
*************** CONSTRUCTED STAGE ****************
*
* LHP REAL ZERO AT 2.24408 MHZ
* LHP COMPLEX ZEROS AT 62.5479 +/- j 54.7493 MHZ
* LHP REAL POLE AT 2.29183 MHZ
* LHP COMPLEX POLES AT 27.8521 +/- j 59.2056 MHZ
*
* LHP ZERO AT 2.24408 MHZ
* NEW LHP ZERO AT 80.0792 MHZ
* LHP COMPLEX POLES AT 27.8521 +/- j 59.2056 MHZ
*
R106   108   106   1e+006
R107   108   107   2.38227e+007
C106   107   98    8.34275e-017
L106   106   98    0.070922
G106   108   98    49    105   1e-006
*
* LHP COMPLEX ZEROS AT 62.5479 +/- j 54.7493 MHZ
* LHP POLE AT 2.29183 MHZ
* NEW LHP POLE AT 56.2663 MHZ
*
R109   110   109   1e+006
R110   109   98    18662.5
C109   110   109   6.94444e-014
L109   109   98    5.27888e-005
G109   110   98    49    108   1e-006
*
* LHP ZERO AT 56.2663 MHZ
* LHP POLE AT 80.0792 MHZ
*
R111   112   111   1e+006
R112   111   98    423218
L111   111   98    0.000841133
G111   112   98    49    110   1e-006
*
************ END OF CONSTRUCTED STAGE ************
```

Terasspeed Labs

5 Poles, 5 Zeros, 4 Cancelled P/Z

```
EREF  98   0    49   0    1
*
* SECOND STAGE POLE AT 1430.8 HZ
*
R21   100  98   1.50501e+008
C21   100  98   7.39098e-013
G21   100  98   6    5    0.000341195
V21   99   21   2.39393
V22   22   50   2.41393
D21   100  21   DX
D22   22   100  DX
*
* RHP COMPLEX ZEROS AT 62.5479 +/- j 54.7493 MHZ
* NEW LHP COMPLEX POLES AT 62.5479 +/- j 54.7493 MHZ
*
R101  105  98   1e+006
C101  101  98   1.27226e-015
C102  105  102  1.27226e-015
C103  105  103  2.88139e-015
C104  104  98   2.88139e-015
L101  101  98   0.00288139
L102  105  102  0.00288139
L103  101  103  0.00127226
L104  102  104  0.00127226
G101  102  101  49   100  1e-006
*
```

Cancellation

(9)

(14)

```
*************** CONSTRUCTED STAGE ****************
*
* LHP REAL ZERO AT 2.24408 MHZ
* LHP COMPLEX ZEROS AT 62.5479 +/- j 54.7493 MHZ
* LHP REAL POLE AT 2.29183 MHZ
* LHP COMPLEX POLES AT 27.8521 +/- j 59.2056 MHZ
*
* LHP ZERO AT 2.24408 MHZ
* NEW LHP ZERO AT 80.0792 MHZ
* LHP COMPLEX POLES AT 27.8521 +/- j 59.2056 MHZ
*
R106  108  106  1e+006
R107  108  107  2.38227e+007
C106  107  98   8.34275e-017
L106  106  98   0.070922
G106  108  98   49   105  1e-006
*
* LHP COMPLEX ZEROS AT 62.5479 +/- j 54.7493 MHZ
* LHP POLE AT 2.29183 MHZ
* NEW LHP POLE AT 56.2663 MHZ
*
R109  110  109  1e+006
R110  109  98   18662.5
C109  110  109  6.94444e-014
L109  109  98   5.27888e-005
G109  110  98   49   108  1e-006
*
* LHP ZERO AT 56.2663 MHZ
* LHP POLE AT 80.0792 MHZ
*
R111  112  111  1e+006
R112  111  98   423218
L111  111  98   0.000841133
G111  112  98   49   110  1e-006
*
************ END OF CONSTRUCTED STAGE ************
```

(11)

(12)

(2)

Cancellation

MHz

Real	Imaginary
-2.24408	0
62.5479	-54.7493
62.5479	54.7493

MHz

Real	Imaginary
-0.0014308	0
-2.29183	0
-27.8521	-59.2056
-27.8521	59.2056
-68.2775	0

Teraspeed Labs

Last Pole and Last Stages

```
                MHz
Real                Imaginary
-2.24408            0
62.5479             -54.7493
62.5479             54.7493

                MHz
Real                Imaginary
-0.0014308          0
-2.29183            0
-27.8521            -59.2056
-27.8521            59.2056
-68.2775            0
```

(1)

```
*
* LHP POLE AT 68.2775 MHZ
*
R113  113  98   1e+006
C113  113  98   2.331e-015
G113  113  98   49   112  1e-006
*
* COMMON MODE GAIN STAGE WITH ZERO AT 20 KHZ
*
R57   59   57   1e+006
C57   59   57   7.95775e-012
R58   59   98   1
E57   57   98   49   3    3.55745
*
```

```
* OUTPUT STAGE
*
R49   49   99   18005
R50   49   50   18005
ISY   99   50   0.0058135
R61   60   99   73.2
R62   60   50   73.2
L61   60   52   1e-012
G63   63   50   113  60   0.0136612
G64   64   50   60   113  0.0136612
G65   60   99   99   113  0.0136612
G66   50   60   113  50   0.0136612
V61   61   60   3.38846
V62   60   62   3.38846
D61   113  61   DX
D62   62   113  DX
D63   99   63   DX
D64   99   64   DX
D65   50   63   DY
D66   50   64   DY
*
* MODELS AND END
*
.MODEL QX NPN(IS=1e-015 BF=2076)
.MODEL DX D(IS=1e-015)
.MODEL DY D(IS=1e-015 BV=50)
.ENDS
```

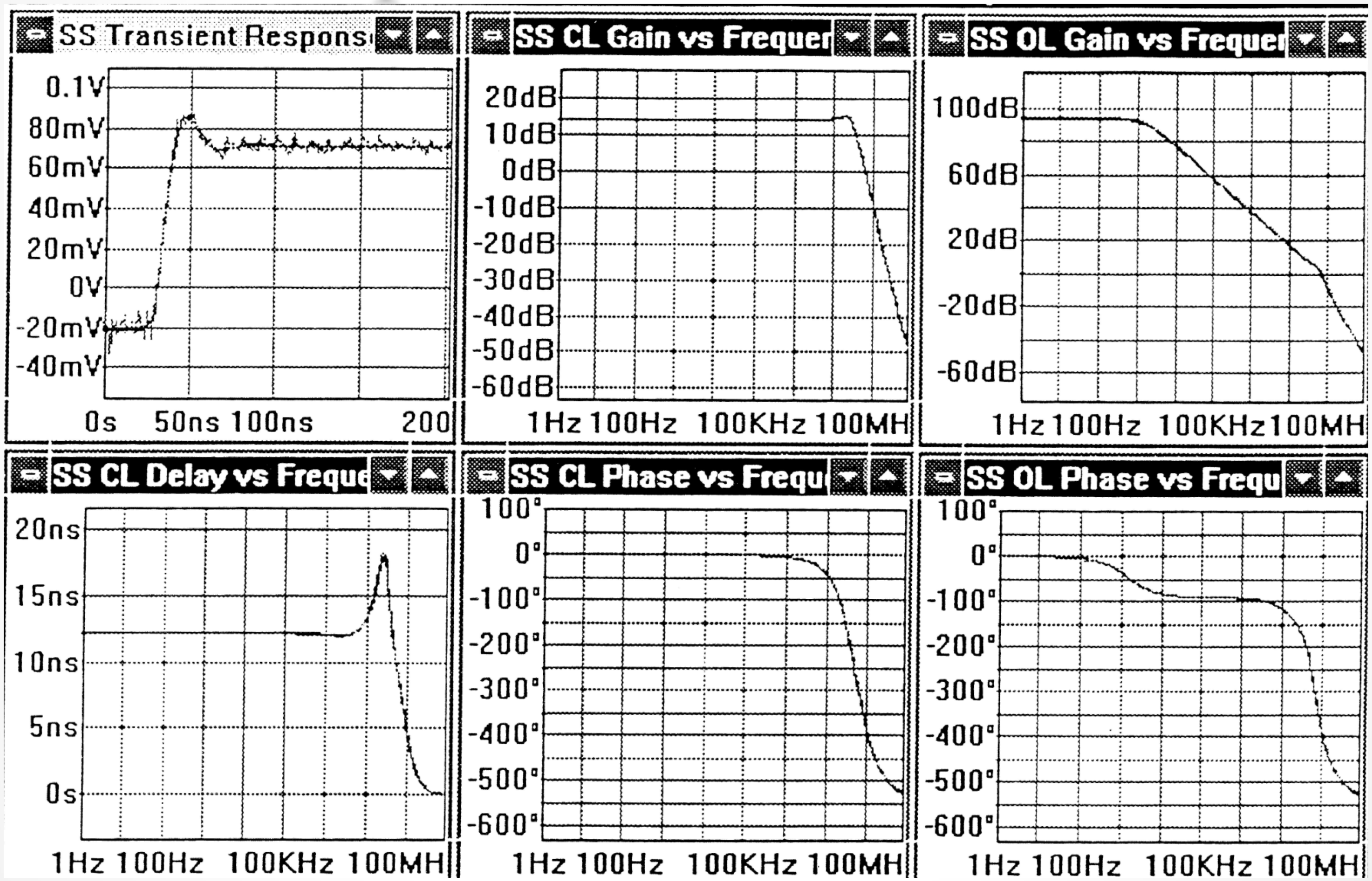
Teraspeed Labs

Build Strategy Demonstrated

- Sort (by magnitude) poles and zeros in four bins:
  - **Real poles** (lowest may be in early stage of operational amplifier)
  - **Complex-conjugate poles**
  - **Real zeros**
  - **Complex-conjugate zeros**
- Model complex-conjugate RHP zeros by all-pass networks 14 or 13 and then in priority order use 9, 8, 7, and 6
- Model real zeros in priority order 5, 4, and 2
- Model remaining poles by 3 and 1
- Apply pole/zero cancellation for any “new” or “fixed” poles or zeros

Teraspeed Labs

Frequency Plots from Laplace Transform



Teraspeed Labs

"SS" is small signal

Conclusion

- SPICE macromodel generation strategy shown using unity gain, cascaded RLC pole and zero stages
- Pole/zero cancellation is effective for adding RHP zeros
- Operational amplifier macromodel illustrates the process
- Process can be applied to any macromodel including those for high-speed applications

Teraspeed Labs