SPICE Op Amp Macromodels for Stability Analysis "Trust But Verify"

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Precision Linear Analog Applications

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Overview

There are only 2 things you need in an op amp macromodel to analyze stability problems:

Zo

(AC open loop output impedance)

Aol

(AC open loop gain)

Summary

1) Before any stability analysis is done check the SPICE op amp macromodel for proper Aol.

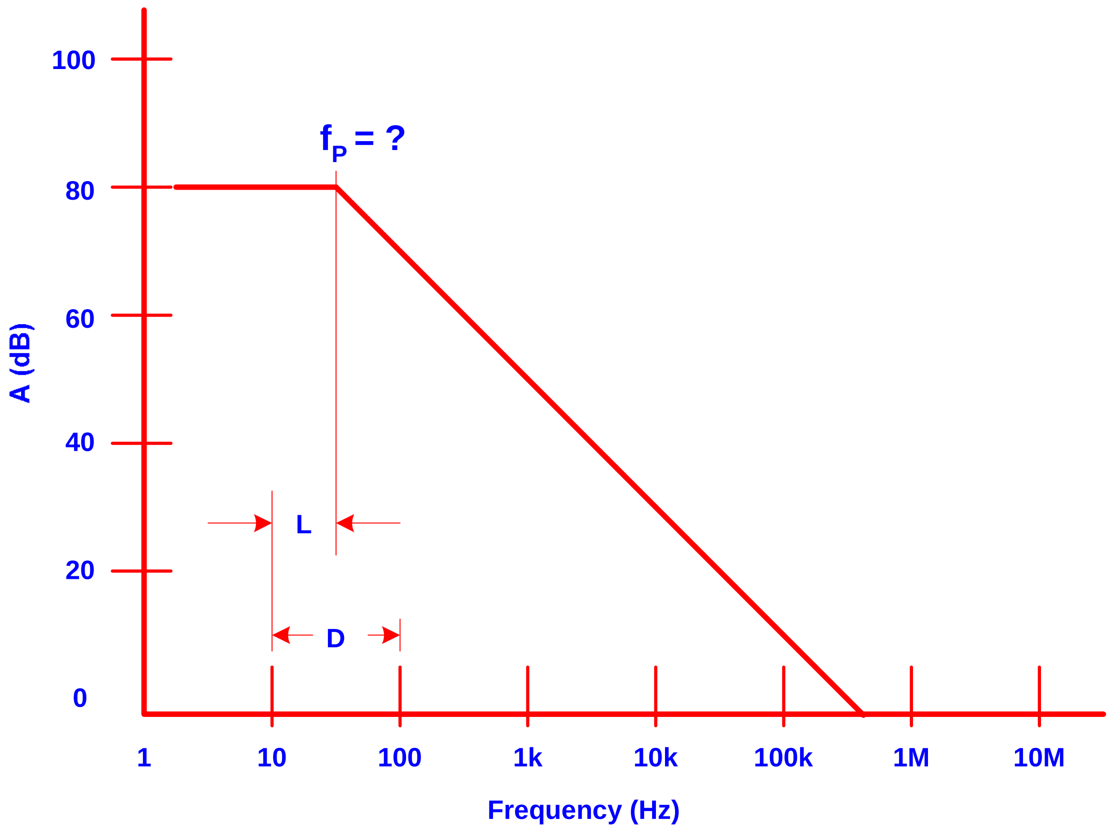
2) Before any stability analysis is done check the SPICE op amp macromodel for proper Zo (open loop output impedance).

2) Newer TI op amp datasheets give a Zo curve. Test in SPICE for Zo.

3) Older TI and competitor op amps usually have a Zout (closed loop output impedance curve). Test for Zout. If Zout is right Zo is right.

4) If op amp macromodel Zout or Zo does not match the datasheet build correct Aol and Zo from datasheet (use Aol and Zo or Zout curves. If Aol is correct you can just build an external Zo block

Log Scale Trick



Log Scale Trick (f_P = ?):

1) Given: L = 1cm; D = 2cm

2) $L/D = Log_{10}(f_P)$

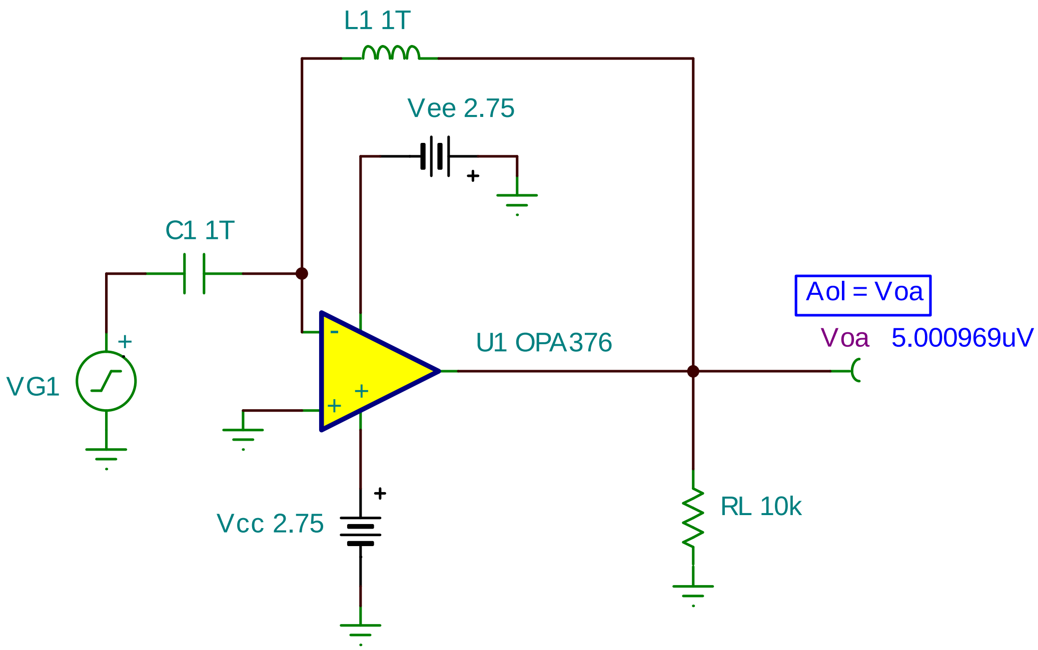
3) $f_P = Log_{10}^{-1}(L/D) = 10^{(L/D)}$
   $f_P = 10^{(L/D)} = 10^{(1cm/2cm)} = 3.16$

4) Adjust for the decade range working within –
   10Hz-100Hz decade **à**
   f_P = 31.6Hz

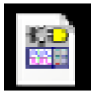
5) $L = Log_{10}(fp') \times D$
   $L = Log_{10}(3.16) \times 2cm = 1cm$
   where fp' = fp normalized to the 1-10 decade range –
   f_P = 31.6 **à** f_P' = 3.16

Analysis

Aol Test

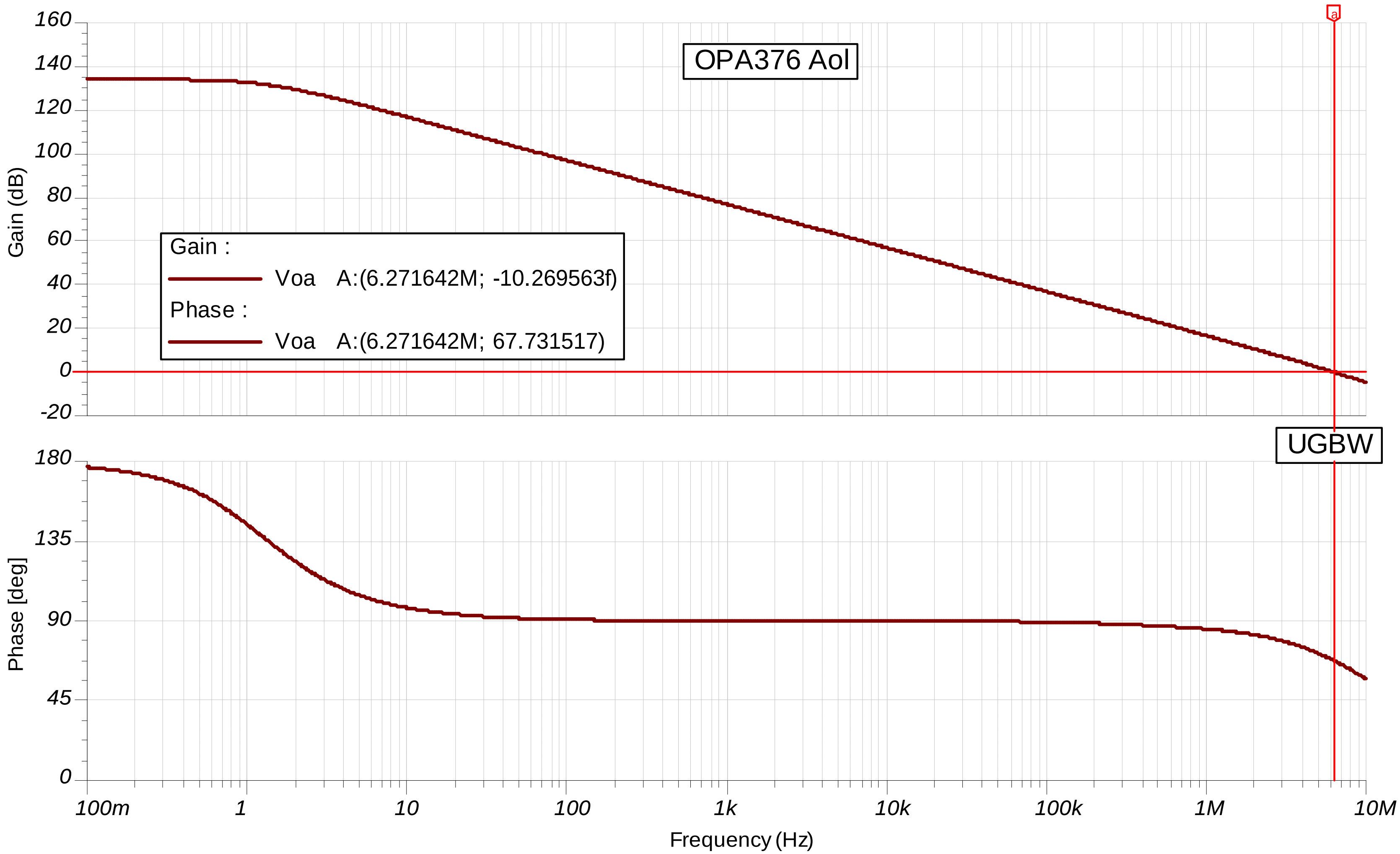


Note:
Check DC Operating Point first.
Op Amp must be in DC Linear region for AC Analysis to be valid.



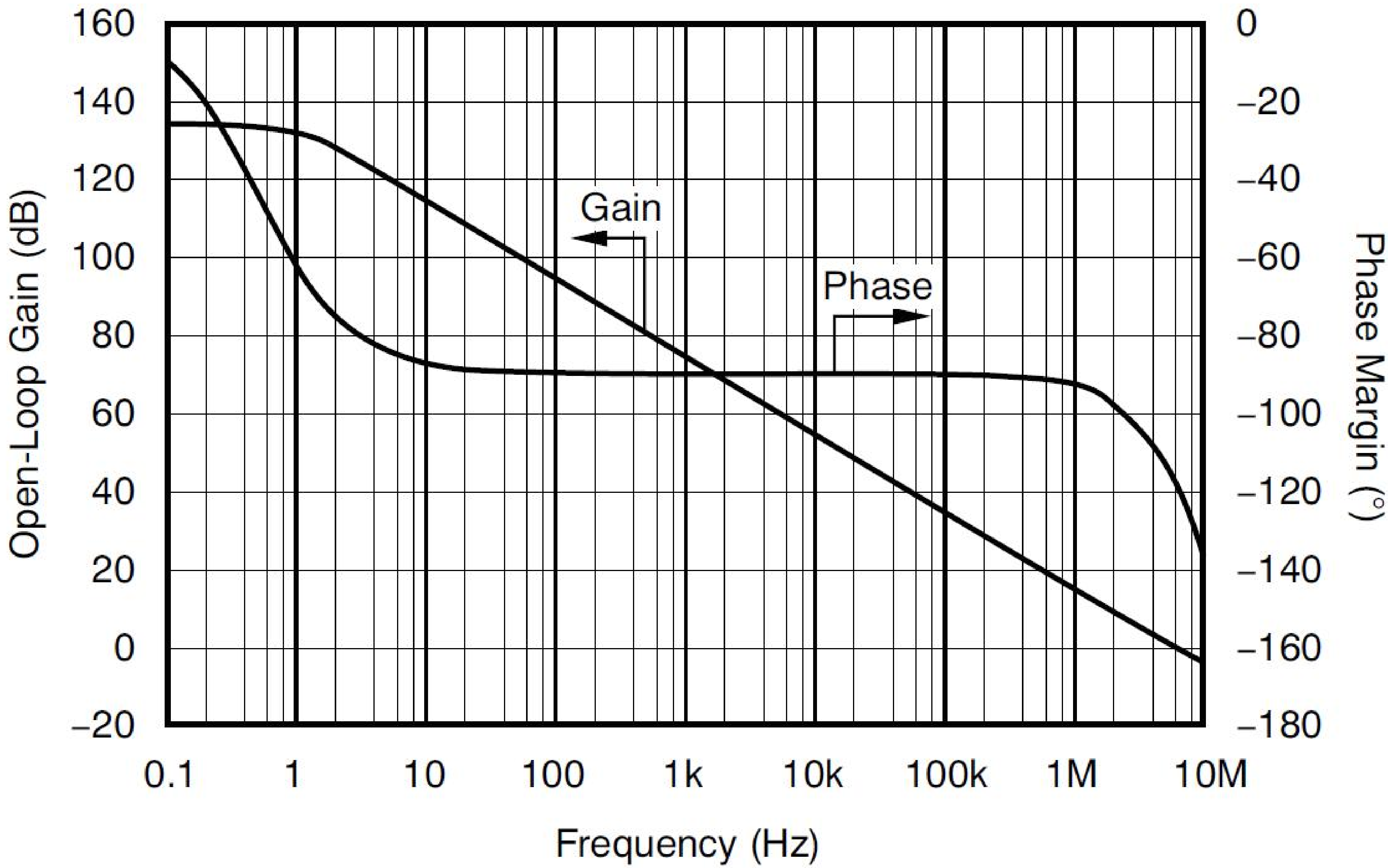
OPA376 Aol.TSC

Aol Test

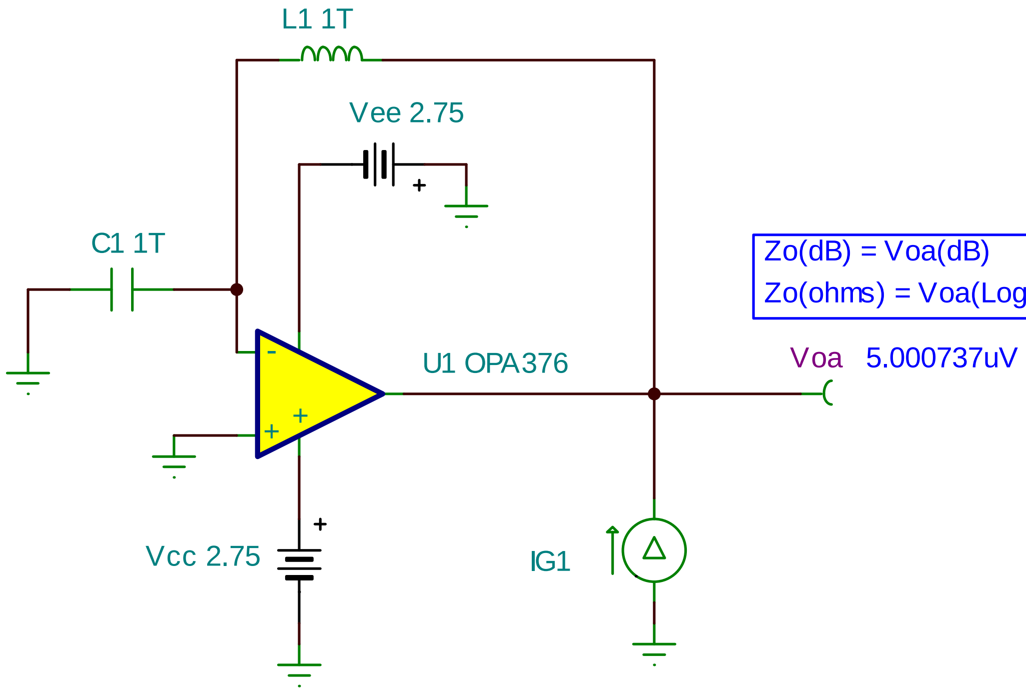


OPA376 Aol
Gain (dB)
160
140
120
100
80
60
40
20
0
-20
Gain :
Voa A:(6.271642M; -10.269563f)
Phase :
Voa A:(6.271642M; 67.731517)
UGBW
Phase [deg]
180
135
90
45
0
100m
1
10
100
1k
10k
100k
1M
10M
Frequency (Hz)
a

Aol Test


160
140
120
100
80
60
40
20
0
–20
0
–20
–40
–60
–80
–100
–120
–140
–160
–180
Gain
Phase
Open-Loop Gain (dB)
Phase Margin (°)
0.1
1
10
100
1k
10k
100k
1M
10M
Frequency (Hz)

Zo Test

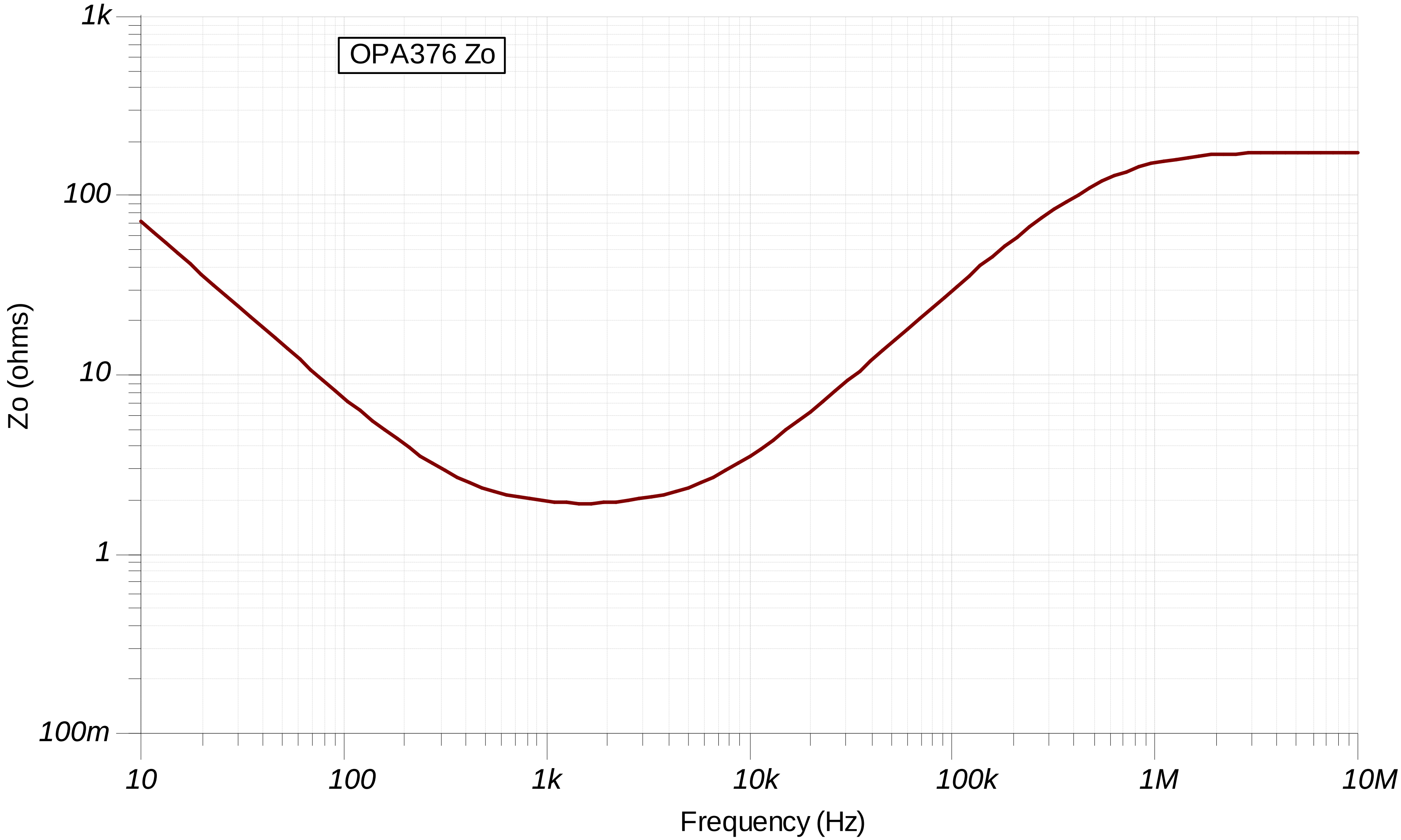


Zo(dB) = Voa(dB)
Zo(ohms) = Voa(Logartihmic)

Note:
Check DC Operating Point first.
Op Amp must be in DC Linear region for AC Analysis to be valid.

OPA376 Zo.TSC

Zo Test



OPA376 Zo
1k
100
10
1
100m
Zo (ohms)
10
100
1k
10k
100k
1M
10M
Frequency (Hz)

Zo Test

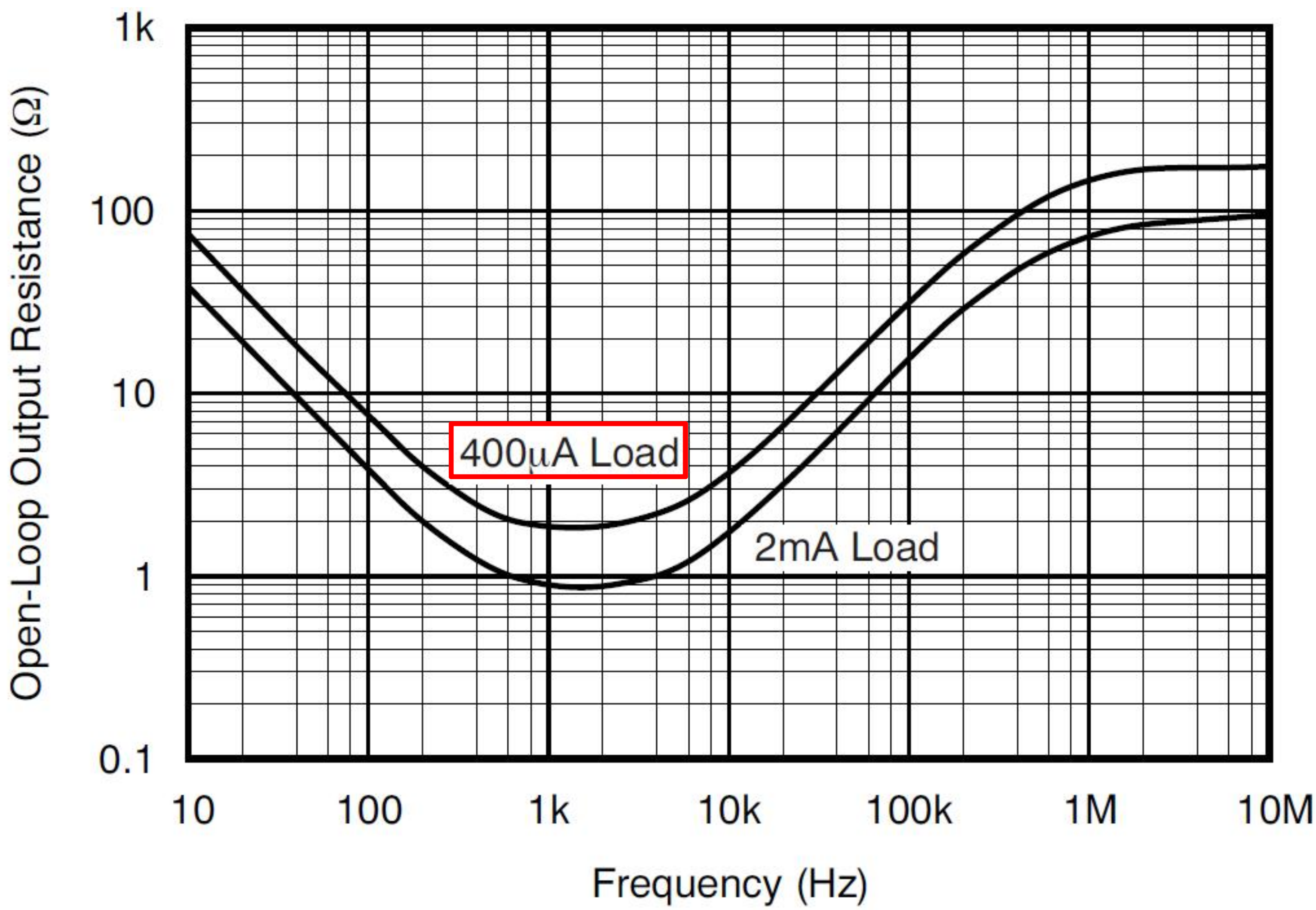
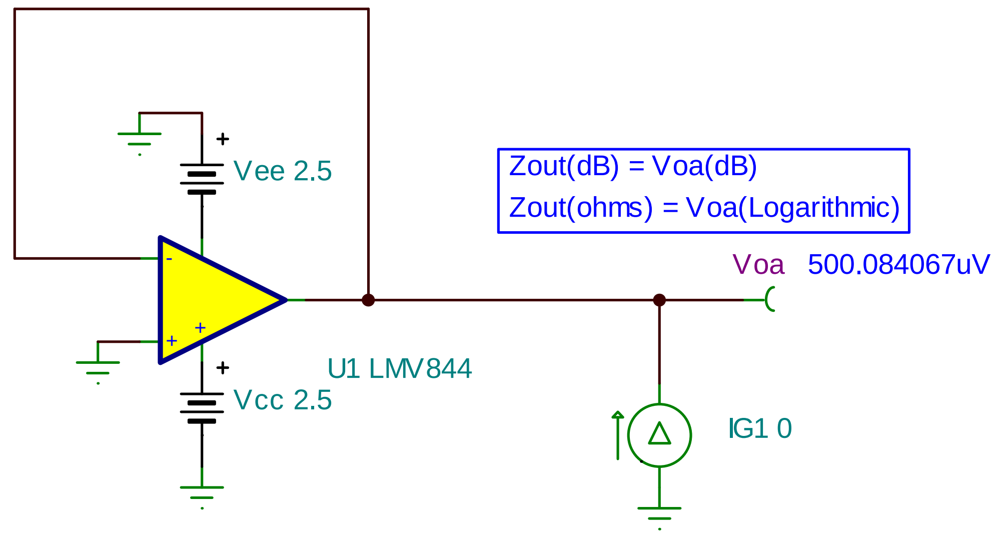


Figure 21. Open-Loop Output Resistance vs Frequency

Zout Test



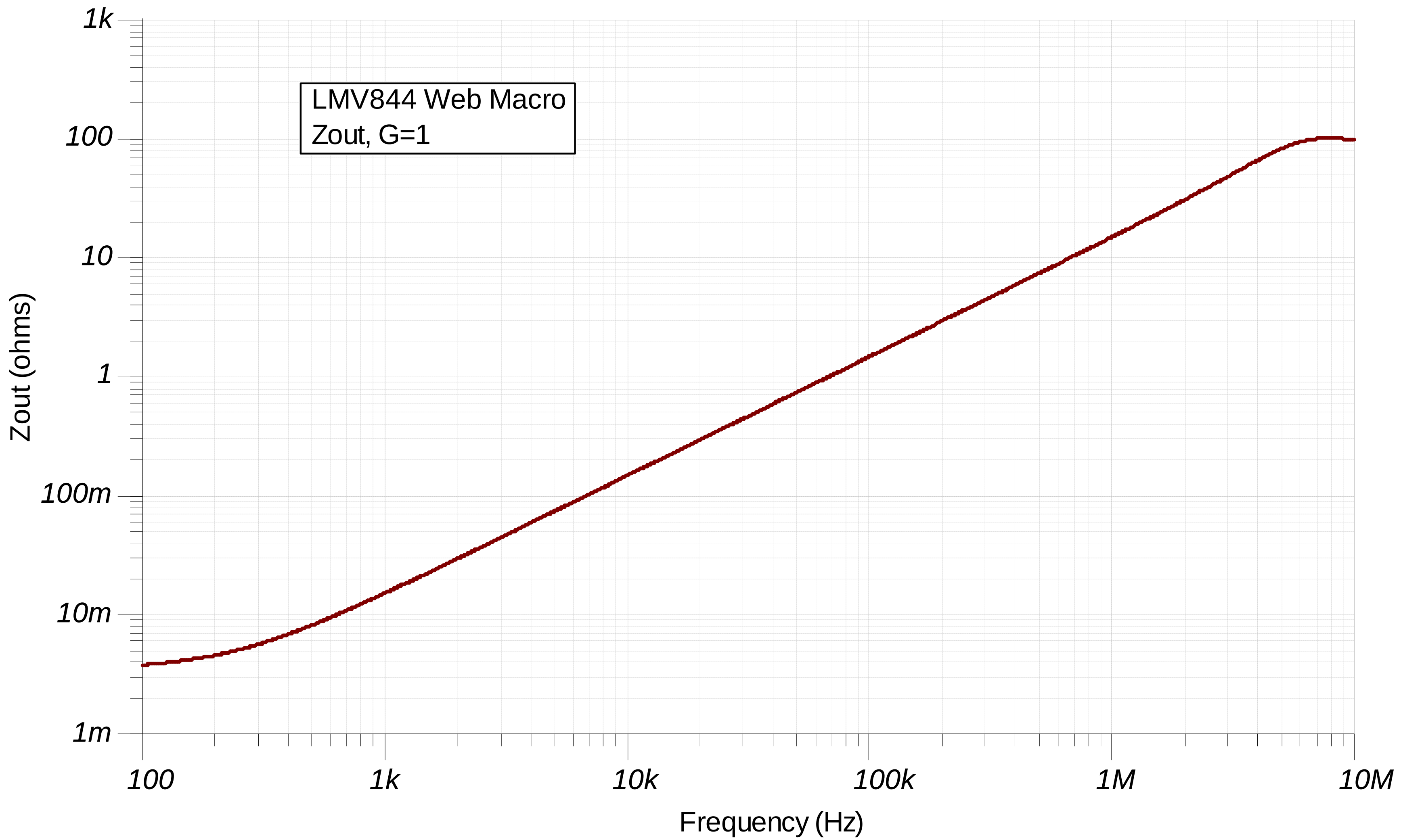
Zout(dB) = Voa(dB)
Zout(ohms) = Voa(Logarithmic)

Note:
Check DC Operating Point first.
Op Amp must be in DC Linear region for AC Analysis to be valid.

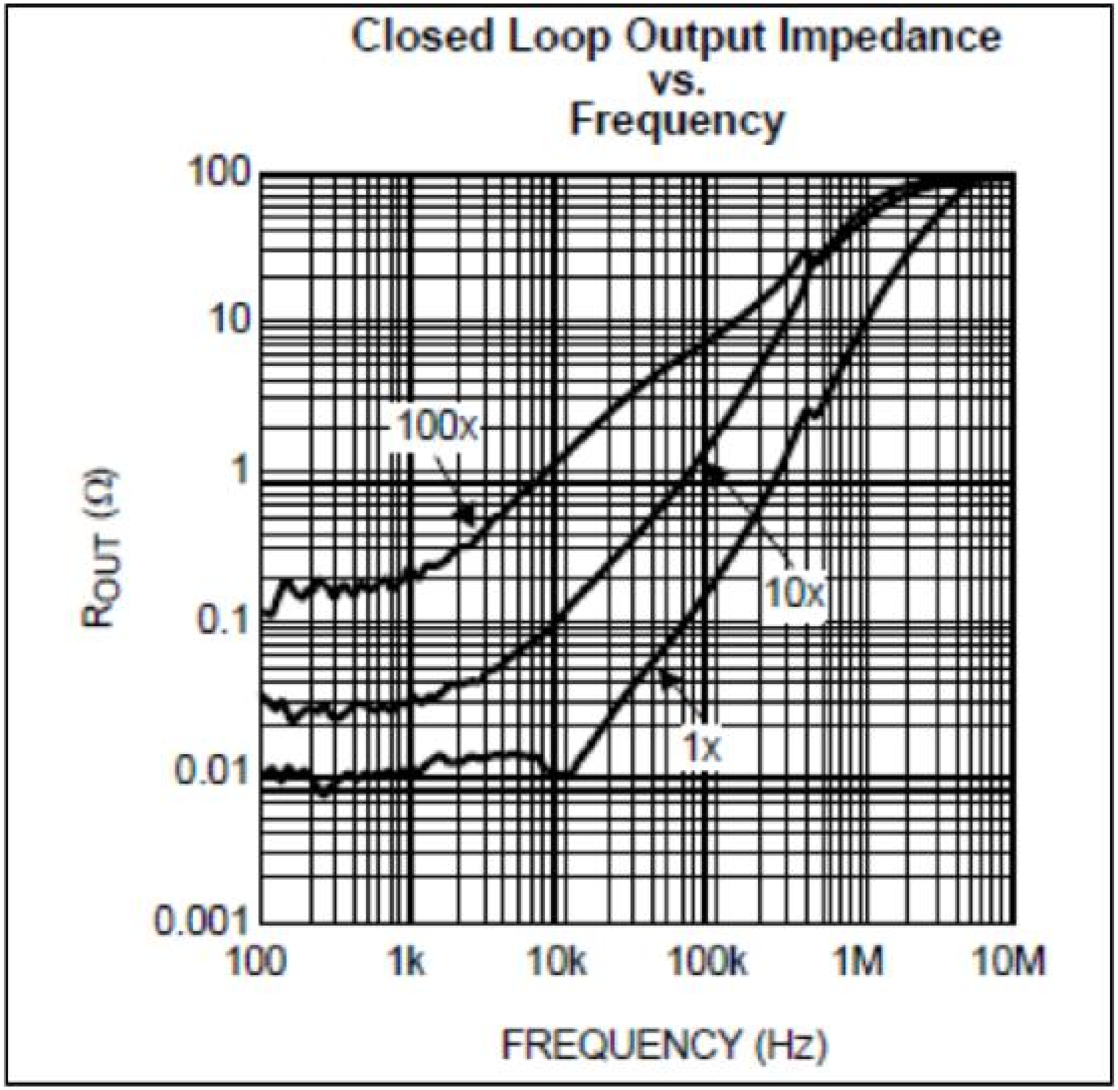
LMV844 Zout.TSC

Zout Test

Note Zout macromodel does NO MATCH datasheet - Contact Vendor to fix!!



Zout Test


Closed Loop Output Impedance
vs.
Frequency
100
10
1
0.1
0.01
0.001
100
1k
10k
100k
1M
10M
100x
10x
1x
ROUT (Ω)
FREQUENCY (Hz)

Op Amp Output Impedance

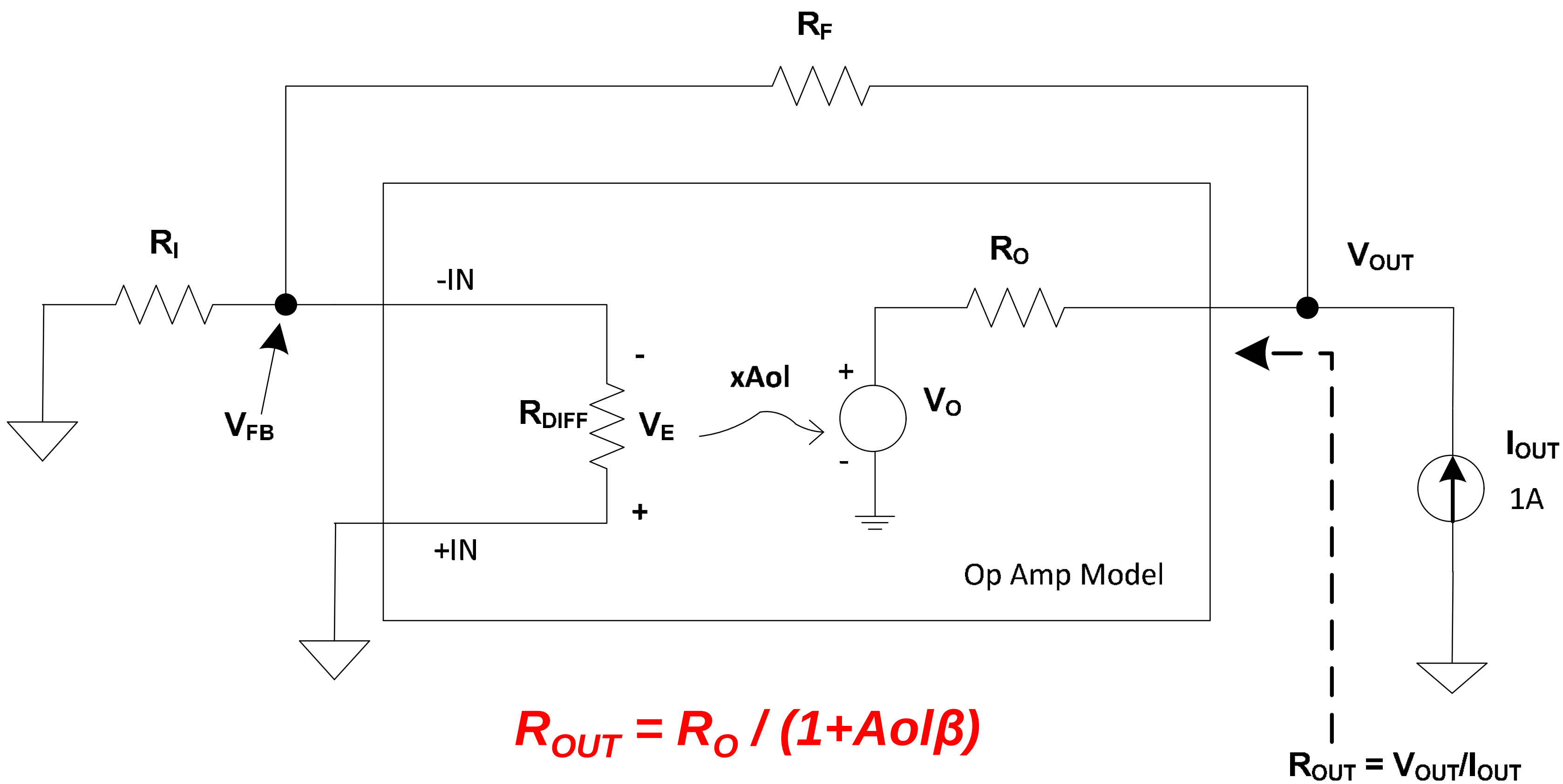
Open Loop (Z_O)
&
Closed Loop (Z_{OUT})

Op Amps and "Output Resistance"

Definition of Terms:

$\mathbf{R_O}$ = Op Amp ***Open Loop*** Output Resistance

$\mathbf{R_{OUT}}$ = Op Amp ***Closed Loop*** Output Resistance



$$R_{OUT} = R_O / (1 + Aol\beta)$$

From: Frederiksen, Thomas M. Intuitive Operational Amplifiers.
McGraw-Hill Book Company. New York. Revised Edition. 1988.

Derivation of R_{OUT} (Closed Loop Output Resistance)

1) $\beta = V_{FB} / V_{OUT} = [V_{OUT} (R_I / \{R_F + R_I\})]/V_{OUT} = R_I / (R_F + R_I)$

2) $R_{OUT} = V_{OUT} / I_{OUT}$

3) $V_O = -V_E \, Aol$

4) $V_E = V_{OUT} [R_I / (R_F + R_I)]$

5) $V_{OUT} = V_O + I_{OUT}R_O$

6) $V_{OUT} = -V_E Aol + I_{OUT}R_O$ *Substitute 3) into 5) for V_O*

7) $V_{OUT} = -V_{OUT} [R_I/(R_F + R_I)] \, Aol + I_{OUT}R_O$ *Substitute 4) into 6) for V_E*

8) $V_{OUT} + V_{OUT} [R_I/(R_F + R_I)] \, Aol = I_{OUT}R_O$ *Rearrange 7) to get V_{OUT} terms on left*

9) $V_{OUT} = I_{OUT}R_O / \{1+[R_I Aol/(R_F+R_I)]\}$ *Divide in 8) to get V_{OUT} on left*

10) $R_{OUT} = V_{OUT}/I_{OUT} =[I_{OUT}R_O / \{1+[R_I Aol / (R_F+R_I)]\}] / I_{OUT}$

Divide both sides of 9) by I_{OUT} to get R_{OUT} [from 2)] on left

11) $R_{OUT} = R_O / (1+Aol\beta)$ *Substitute 1) into 10)*

→ $R_{OUT} = R_O / (1+Aol\beta)$ ←

R_{OUT} vs R_O

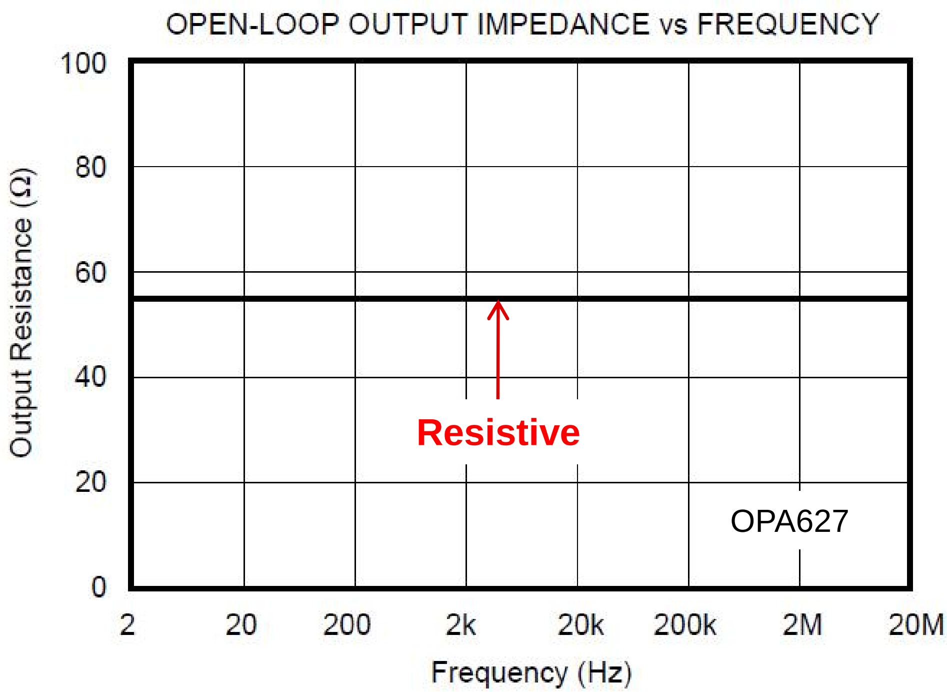
Ø R_O does *NOT* change when Closed Loop feedback is used

Ø R_{OUT} is the effect of R_O, Aol, and β controlling V_O

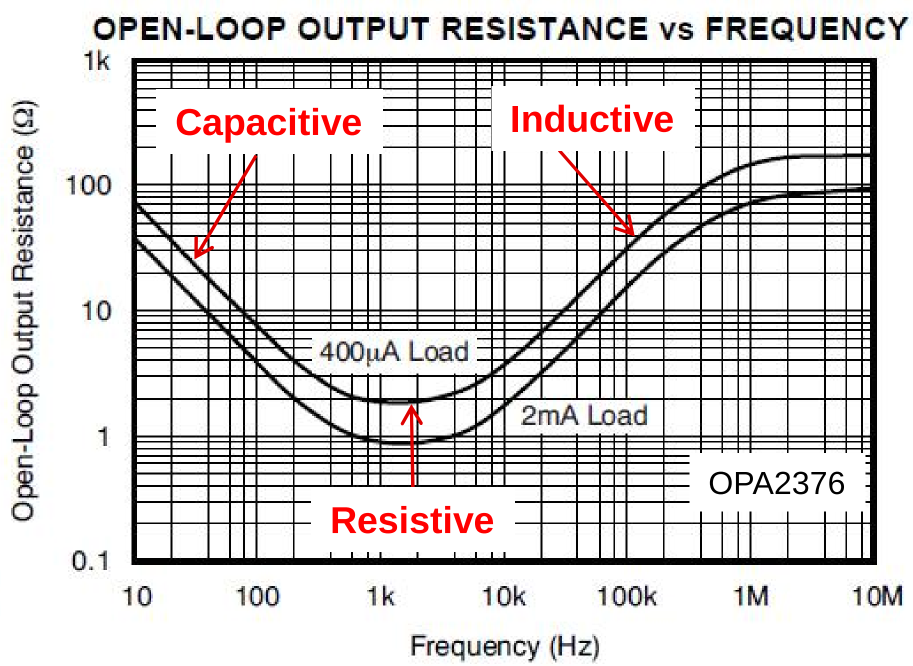
- ü Closed Loop feedback (β) forces V_O to increase or decrease as needed to accommodate V_O loading
- ü Closed Loop (β) increase or decrease in V_O appears at V_{OUT} as a reduction in R_O
- ü R_{OUT} increases as Loop Gain (Aolβ) decreases

When R_O is really Z_O!!

OPA627 has R_O

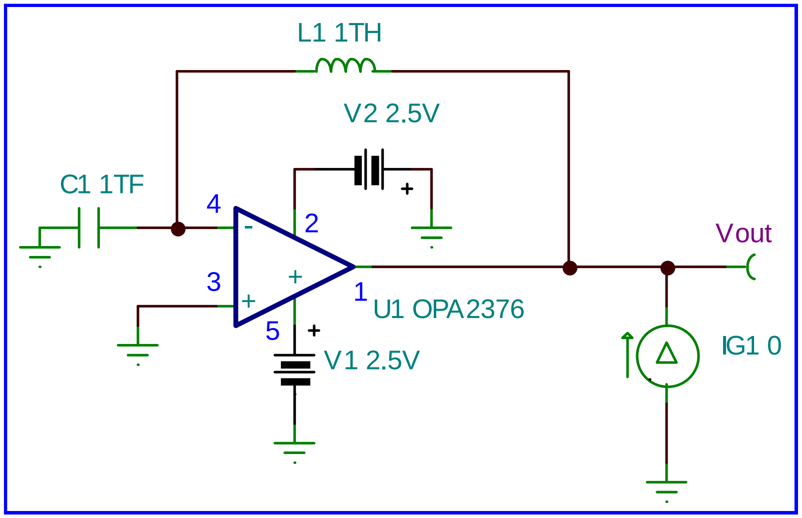


OPA2376 has Z_O

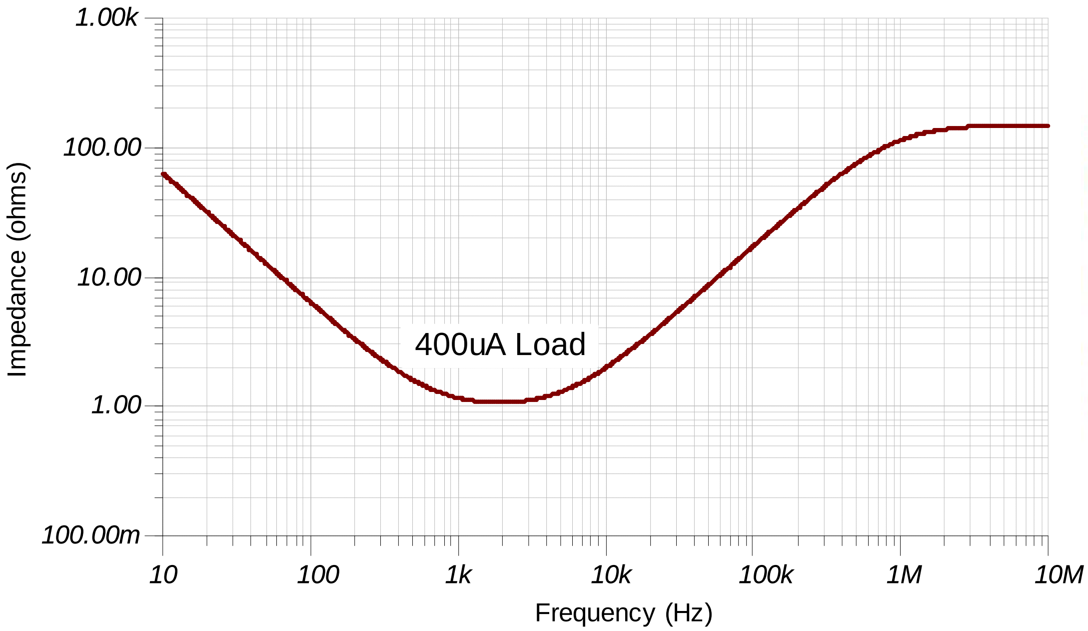


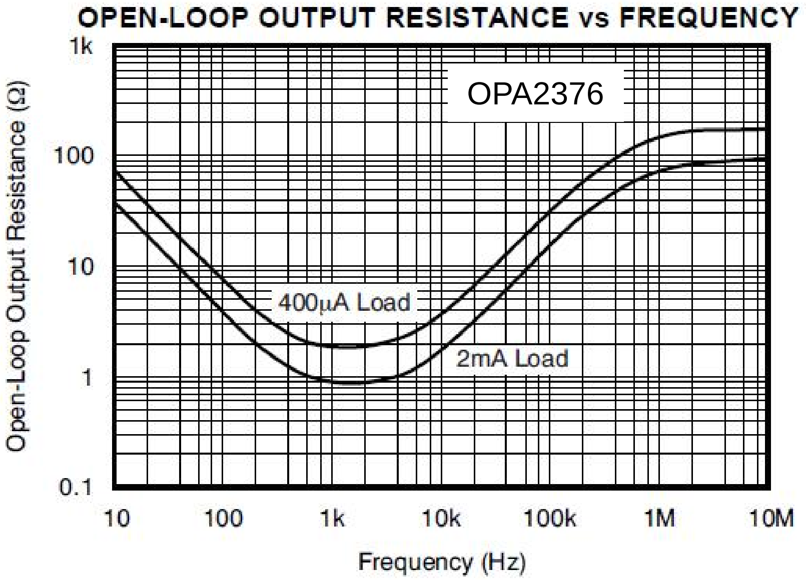
***Note:* Some op amps have Z_O characteristics other than pure resistance – consult data sheet / manufacturer**

With Complex Z_O, Accurate Models are Key!



SPICE Test of Op Amp Macro Zo :
Run SPICE AC Analysis
IG1is AC Current Generator
IG1DC Value = 0A for unloaded Zo
Zo = Vout
Convert Vout (dB) to Vout (Logarithmic)
Zout (ohms) = Vout (Logarithmic)





Texas Instruments

Some Data Sheets Specify Z_{OUT} *NOT* Z_O

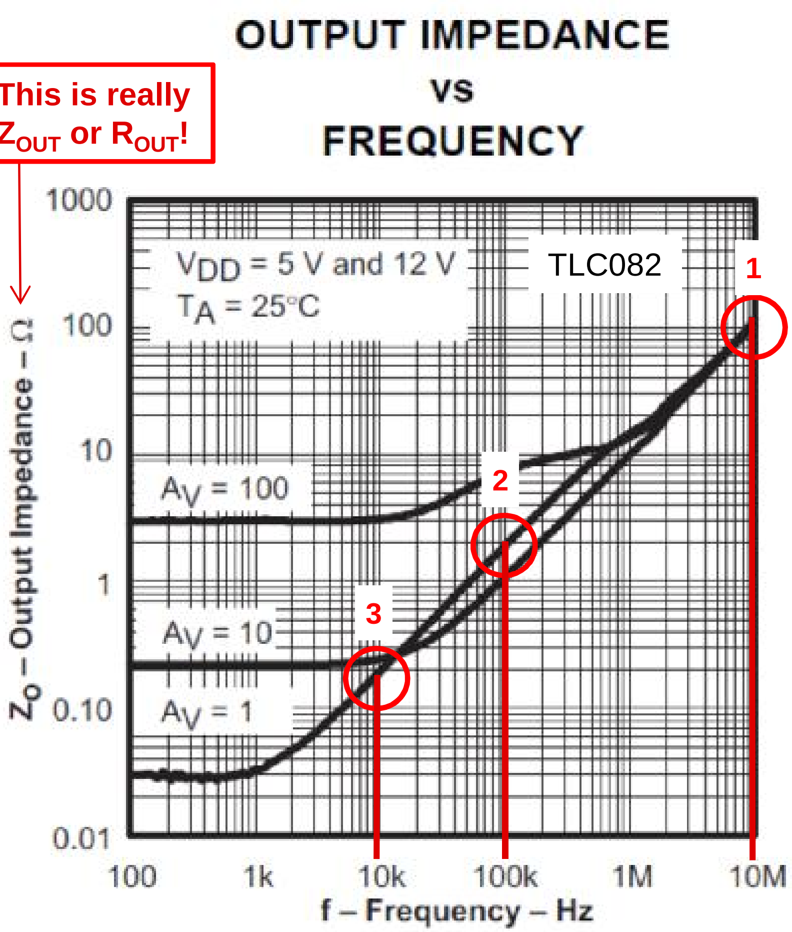
Recognize R_{OUT} instead of R_O:
R_{OUT} inversely proportional to Aol
R_{OUT} typically <100Ω at high frequency

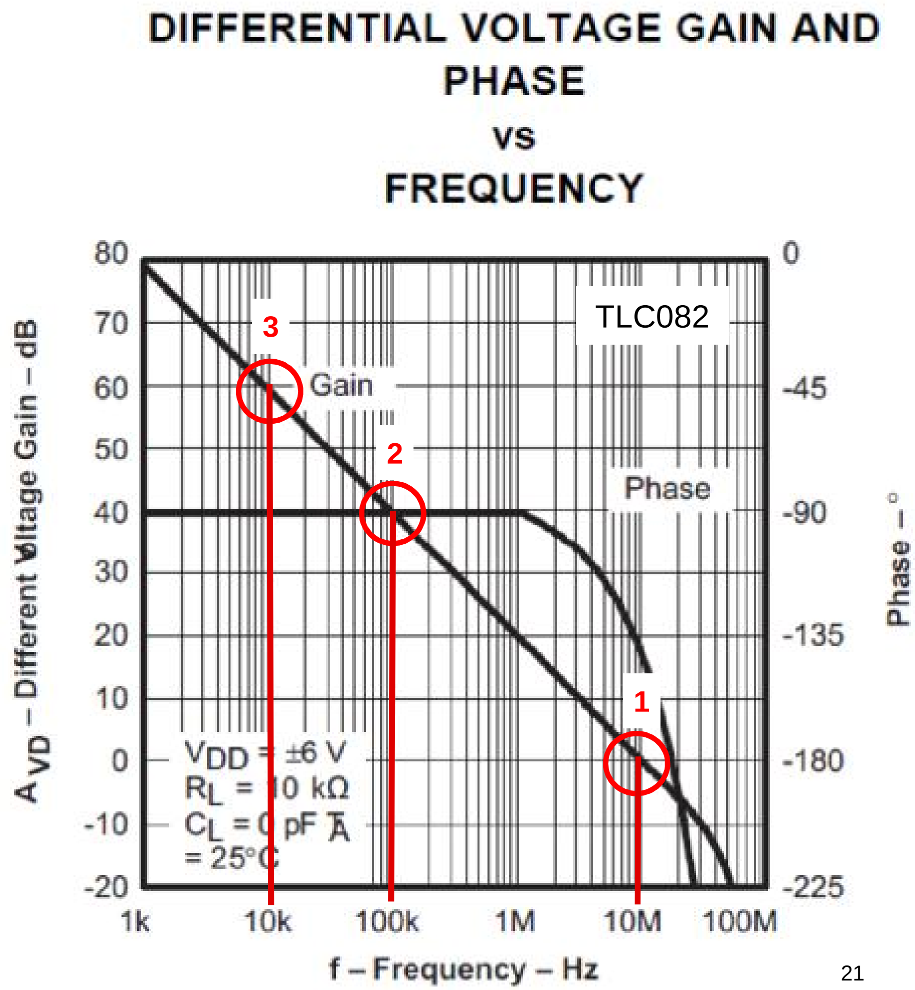
R_{OUT} is Inverse of Aol :

$$R_{OUT} = \frac{R_O}{1 + Aol\beta}$$

$$R_{OUT} \propto \frac{1}{Aol}$$

This is really Z_{OUT} or R_{OUT}!





Some Data Sheets Specify Z_{OUT} ***NOT*** Z_O

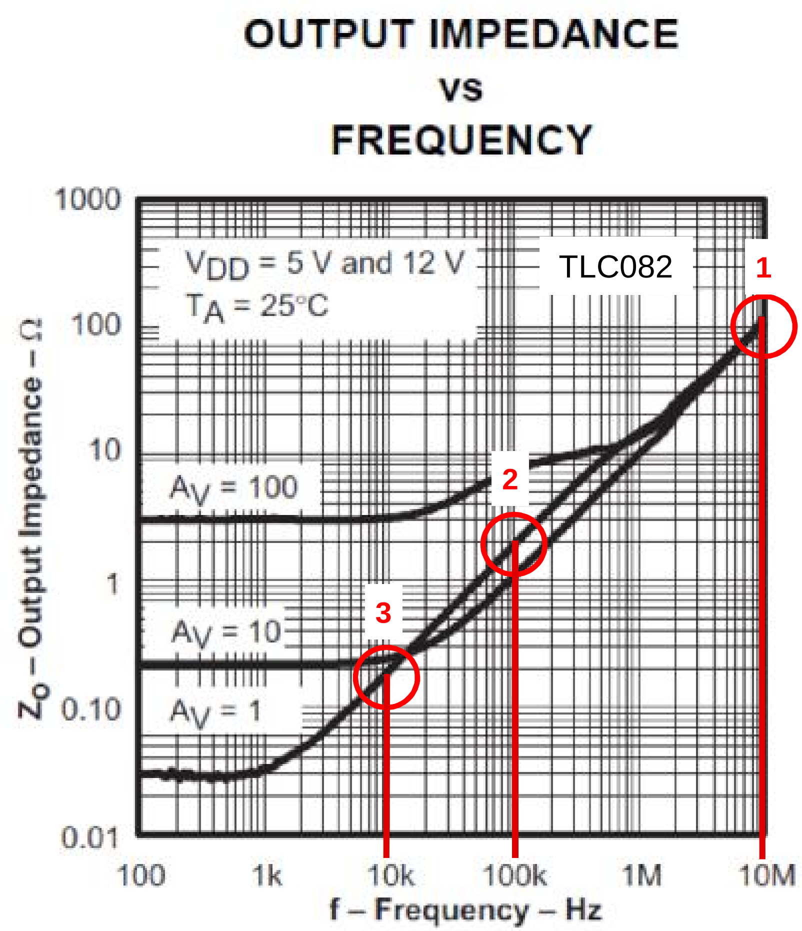
Point	frequency	Aol	R_{OUT} (A_V=1) Datasheet	R_{OUT} (A_V=1) Computed
----------	(Hz)	(dB)	(ohms)	(ohms)
1	10M	0	100	$R_O = 200$
2	100k	40	2	2
3	10k	60	0.2	0.2

Compute R_O from R_{OUT} where $Aol\beta = 1(0dB)$:

$R_{OUT} = 100\Omega$ for $A_V = 1$, $f = 10MHz$, $Aol\beta = 1(0dB)$

$$R_{OUT} = \frac{R_O}{1 + Aol\beta}$$

$$100\Omega = \frac{R_O}{1+1} \rightarrow R_O = 200\Omega$$



Appendix: Op Amp Stability Reference

For detailed, definition-by-example of 10 different ways to stabilize op amps driving capacitive loads, and additional technical information on solving op amp stability problems, visit the Texas Instruments E2E Forum at:

http://e2e.ti.com/support/amplifiers/precision_amplifiers/w/design_notes/2645.solving-op-amp-stability-issues.aspx

Download Part 1, Part 2, Part 3, and Part 4.

For more in-depth learning about op amps and op amp stability look at TI Precision Labs at:
www.ti.com/precisionlabs

Analog Engineer's Pocket Reference
A "must-have" for every Board/System Design Engineer
Download: http://www.ti.com/lsds/ti/amplifiers-linear/precision-amplifier-support-community.page#pocketref
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All Embedded Schematics in this presentation can be run in the Free TINA_TI SPICE simulator available at:

http://www.ti.com/tool/tina-ti