How to verify control loop design

Steve Sandler - October 30, 2013

Steve Sandler explains what every engineer should know about 'non-invasive' stability assessments.

The non-invasive stability assessment is a method that uses an output impedance measurement to accurately determine stability without access to the control loop. The non-invasive stability assessment, whether performed as a physical test or with a circuit simulation, is a fast, simple, and inexpensive means to verify or optimize any control loop design. This measurement is useful in almost all systems, though especially in high-speed, instrumentation, and RF systems. Improving stability reduces noise in a system, allowing better SNR, dynamic range, clock jitter and many other performance characteristics to be enhanced. Issues related to noise can be very difficult to trace and fix. Non-invasive testing is sometimes the only way to single out and eliminate potential stability problems.

As discussed in reference 1, the non-invasive stability assessment involves measuring the output impedance at the output of the regulator or switching converter. The phase margin is then determined mathematically from the characteristics of the output impedance. Following are four items you should know about the non-invasive phase margin measurement.

#1: Sometime Bode Plots Aren't a Choice
Many circuits do not have access to the loop which would allow a traditional stability assessment via a Bode plot. Some common examples where the control loop may not be accessible include voltage references, fixed voltage regulators and integrated audio amplifiers to name just a few. In other cases, you may have access to the feedback loop; however, components have to be lifted or traces cut. This is not usually acceptable in high reliability systems or in production hardware. In all of these cases, the non-invasive test provides a path for assessing the stability of the loop and optimizing the system performance. In addition, the non-invasive test is not limited by order of the system.

#2: The non-invasive stability test is an exact solution for second-order systems including the capacitor ESR.
The non-invasive stability assessment is not an approximation. The test results for a typical second-order system (which includes most linear regulators, voltage references, opamps and input filters) is an exact solution. Therefore, the non-invasive test can provide the exact Bode plot phase margin for all second-order systems, even without access to the control loop. The non-invasive method includes the impact of the output capacitor'(s) ESR, which is often the dominant parameter and is valid for phase margins up to approximately 70 degrees. In higher order systems, the non-invasive measurement is still a direct indication of stability, and perhaps a better indication than the Bode plot.

In order to check the accuracy of the test, the Agilent Advanced Design System (ADS simulator) was used to compare nine cases covering a wide range of phase margin and bandwidth solutions. The

simulation, which is equivalent to a bench test, provided both a traditional Bode plot and the non-invasive phase margin result for each case. An example of the Bode plot simulation and output impedance simulation is shown in Figure 1. The simulation results are taken from the closest, non-interpolated frequency, which does result in a very small error. An example of this small error is seen in the crossover frequency assessment, which indicates -0.007dB and not precisely zero. A comparison of the results for all nine cases is shown in Table 1.

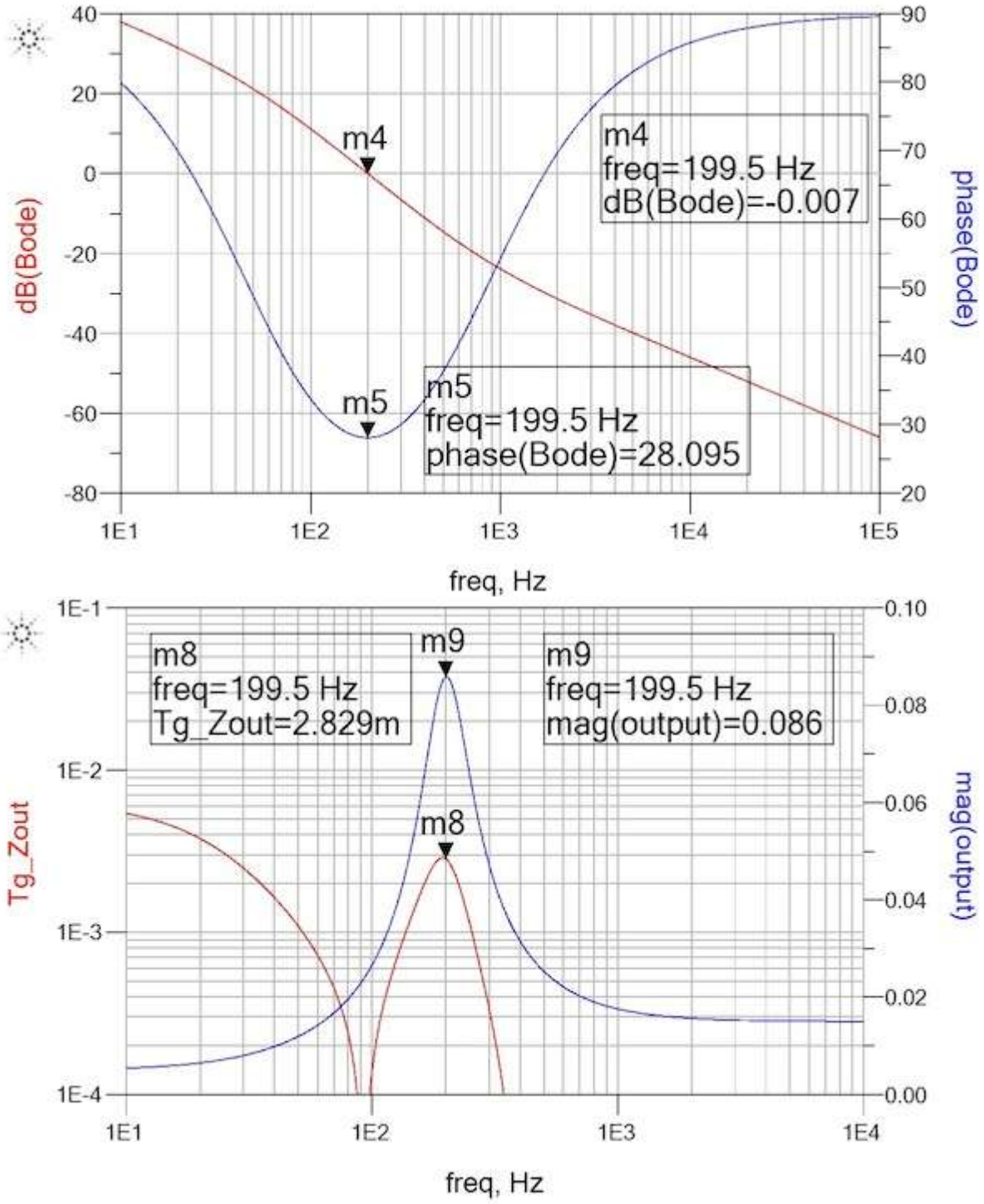

Figure 1 Simulated Bode plot and the output impedance curves. The output impedance is used to determine the phase margin.

Table 1: Comparison between simulated Bode plot and non-invasive results

Simulated Phase Margin Comparisons				
	Proposed	Bode	abs error	% error
Case 1	64.69	64.62	0.07	0.11%
Case 2	11.31	11.44	-0.13	1.14%
Case 3	51.83	51.82	0.01	0.01%
Case 4	51.87	51.85	0.02	0.04%
Case 5	53.20	53.13	0.07	0.14%
Case 6	28.11	28.04	0.07	0.25%
Case 7	52.20	52.81	-0.61	1.16%
Case 8	52.20	52.81	-0.61	1.16%
Case 9	4.79	4.80	-0.01	0.19%

Table 2: Comparison between experimental Bode plot and non-invasive results

Experimental Phase Margin Comparisons				
	Results		Errors	
Case	Math	Bode Measurement	abs error	% error
1	57.89	56.98	0.91	1.60%
2	58.02	59.85	-1.83	3.06%
3	39.78	38.63	1.15	2.98%
4	31.753	32.4	-0.65	2.00%
5	32.36	31.19	1.17	3.75%
6	15.14	15.2	-0.06	0.39%

Experimental results were also obtained for 6 cases, using the LM317 voltage regulator that allows both non-invasive and traditional Bode plot assessments. The phase margin comparison of the two methods, shown in Table 2 are all within 1.8 degrees of each other. These small differences reflect the small measurement errors associated with each measurement method. **#3: The Non-invasive Assessment Accurately Determines the Bandwidth of the Control Loop**

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A side benefit of the non-invasive assessment is that it also provides the exact control loop

bandwidth for second-order systems. The crossover frequency comparison between the simulated Bode plot and the non-invasive method are shown for all 9 cases in Table 3.

Table 3: Simulated crossover frequency comparisons

Simulated Crossover Frequency Comparisons				
	Proposed	Bode	abs error	% error
Case 1	130.40	130.70	-0.30	0.23%
Case 2	199.30	199.40	-0.10	0.05%
Case 3	253.50	253.56	-0.06	0.02%
Case 4	156.80	156.80	0.00	0.00%
Case 5	199.40	199.40	0.00	0.00%
Case 6	187.40	187.60	-0.20	0.11%
Case 7	224.20	225.60	-1.40	0.62%
Case 8	177.40	176.30	1.10	0.62%
Case 9	199.40	199.20	0.20	0.10%

The non-invasive method works equally well for input filter and switching converter assessments
The non-invasive measurement works equally well in the stability assessment of negative resistance switching converters and input filters. The traditional method of assessing input filter stability requires that the connection between the regulator and the filter be separated. The phase margin is then assessed using minor loop gain techniques. The non-invasive method does not require such separation and can directly provide the minor loop gain results either as a phase margin or as a loaded Q.

#4: The non-invasive method can measure high bandwidth loops without the interconnects a Bode plot requires

The non-invasive measurement is made using a VNA (or TDR/TDT equivalent). The use of a VNA allows measurements up to very high frequencies. This may not seem necessary in measuring power supplies. However, it is very useful for measuring high bandwidth loops, including video opamps and ADC buffer amplifiers, which can have very high bandwidths. The necessary interconnects would introduce significant measurement errors if such a loop was measured as a traditional Bode plot.

Reference

1. "New Technique for Non-Invasive Testing of Regulator Stability," Power Electronics, Steve Sandler, Sep. 1, 2011.