

A Tool and Methodology for AC-Stability Analysis of Continuous-Time Closed-Loop Systems

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Texas Instruments Inc.

**INTERNATIONAL CADENCE USER GROUP CONFERENCE
September 13-15, 2004
Santa Clara, CA**

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Abstract—Presented are a methodology and a DFII-based tool for AC-stability analysis of a wide variety of closed-loop continuous-time (operational amplifiers and other linear circuits). The methodology used allows for easy identification and diagnostics of ac-stability problems including not only main-loop effects but also local-instability loops in current mirrors, bias circuits and emitter or source followers without breaking the loop. The results of the analysis are easy to interpret. Estimated phase margin is readily available. Instability nodes and loops along with their respective oscillation frequencies are immediately identified and mapped to the existing circuit nodes thus offering significant advantages compared to traditional "black-box" methods of stability analysis (Transient Overshoot, Bode and Phase margin plots etc.). The tool for AC-Stability analysis is written in SKILL™ and is fully integrated in DFII™ environment. Its "push-button" graphical user interface (GUI) is easy to use and understand. The tool can be invoked directly from Composer™ schematic and does not require active Analog Artist™ session. The tool is not dependent on the use of a specific fabrication technology or Process Design Kit customization. It requires OCEAN™, Spectre™ and Waveform calculator capabilities to run.

Index Terms—AC stability, small-signal circuit stability, frequency instability, closed loop system stability.

I. INTRODUCTION

ALTHOUGH small-signal stability of analog and mixed-mode signal integrated circuits is a fairly old problem and has been studied in many ways both by circuit theory and in every-day practice, it is still a significant source of problems that may render a circuit non-operational under certain conditions. What is presented in this paper is a method[2] and a tool that allow small-signal circuit AC-stability to be evaluated for a continuous-time closed-loop systems without breaking the loop. This is especially useful where breaking the loop is very hard or impossible without affecting circuit's

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performance or biasing conditions. Moreover, the methodology employed by the tool can evaluate the stability not only of main-loop effects but also of local loops often present in current mirrors, bias circuits, emitter followers and other circuits that otherwise could go undetected and untested. The tool allows for automatic loop identification and full-circuit stability analysis, which gives better picture of the circuit's sensitive nodes/loops as opposed to black-box phase-margin AC-analysis. In this way, this method offers several advantages over the traditional methods of evaluating small-signal circuit stability as node pulsing during transient analysis and Bode/phase-margin-plots in AC-analysis.

A. Method principle

Besides the advantages already mentioned, although the method is similar to "node pulsing"(analysis of the circuit's transfer function response to a unit step-function)[1], it uses AC-analysis node excitation technique, which significantly speeds up the simulation and broadens the range of frequency coverage. The technique excites selected or all circuit nodes consecutively by applying an AC-current signal source to the tested node without changing the circuit under inspection at all. Then by analyzing the circuit's AC-response it evaluates each node's sensitivity/stability over a broad range of frequencies.

B. Assumptions and theory behind the problem

It is assumed that the system response can be adequately described by a second-order system transfer function[1] with both real and complex roots - that is a set of real or complex poles and zeros. The complex poles that can cause the system to oscillate are referred to as *dominant poles/roots*. They determine the circuit's *natural (oscillation) frequency*. In an unstable loop, inherent device noise or any signal at this frequency can start oscillations that lead to overall system instability. While in simulation such conditions are, generally, very difficult to simulate, an unstable system may begin to oscillate quite easily in the real-world. The *natural frequency*

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and *damping factor* of those oscillations are determined by the dominant root at this frequency, and thus not simply by the magnitude of the transfer function. That is why through means of AC-current excitation (at a node of the supposedly unstable loop) it is possible to determine the natural frequency and damping ratio by a simple measurement at any node (within the loop) without disrupting the normal circuit operation. This translates into a quantitative measurement of this loop's stability (*performance index*).

C. Method Limitations

Oscillations that are induced by large-signal effects (as signal delays due to transistor saturation, transient charge etc) will not be detected by this method. Therefore the method should be applied to continuous-time systems, or systems that at a given point in time could be viewed as continuous-time systems.

II. METHOD IMPLEMENTATION

As already mentioned in the introduction, to obtain a quantitative measure of each circuit node's *stability*, we carry out a number of simulations applying a broad-specter AC-current stimulus to every node of the circuit followed by a measurement of AC-circuit response at the same node. Since a *dominant root* at a normalized *natural frequency* ($\omega_n=1$) can be described by a second-order system transfer function:

$$T(s) = \frac{1}{s^2 + 2s\zeta + 1} \quad (1.1)$$

for the magnitude of the complex part we have ($s = i\omega$):

$$|T(\omega)| = \left| \frac{1}{-\omega^2 + 2(i\omega)\zeta + 1} \right| \quad (1.2)$$

To define the *stability plot* we first take the derivative of the magnitude of the system response with respect to frequency and normalize to both to frequency and magnitude. We further take one more time the derivative of the result with respect to frequency and normalize again with respect to frequency also:

$$P(\omega) = \left(\frac{d}{d\omega} \left(\frac{\frac{d}{d\omega} |T(\omega)|}{|T(\omega)|} \right) \cdot \omega \right) \cdot \omega \quad (1.3)$$

Through the second-order differentiation and normalization, this procedure filters out the effects of the real poles and zeros, while responding to the complex poles and zeros in the system. In this way, this function's plot will produce a negative peak at the *natural frequency* for every complex pole and a positive peak for every complex zero¹.

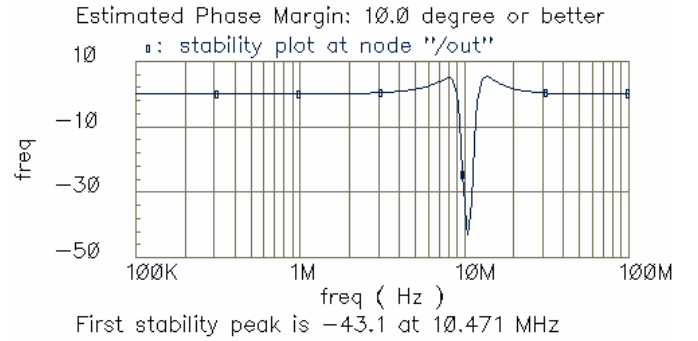


Figure 1 Example Stability Plot with a performance index of -43.1 magnitude at 10.471 MHz (natural frequency)

Furthermore, at the *natural frequency* $\omega = \omega_n = 1$ we have:

$$P(\omega_n) = -\frac{1}{\zeta^2} \quad (1.4)$$

By virtue of (1.4), having measured *stability plot* peak at the *natural frequency* i.e. loop's *performance index* $P(\omega_n)$, we determine loop's *damping ratio* ζ , and according to Table 1 – loop's corresponding phase margin [1].

Table 1 Key performance characteristics of a second order system or its dominant root.

Time domain		Frequency domain		Stability
ζ	Percent overshoot [%]	Phase margin [Deg]	Max magnitude	Performance index
1.0	0	-	-	-1.0
0.9	0	-	-	-1.2
0.8	2	-	-	-1.6
0.7	5	70	1.01	-2.0
0.6	10	60	1.04	-2.8
0.5	16	50	1.15	-4.0
0.4	25	40	1.4	-6.3
0.3	37	30	1.8	-11
0.2	53	20	2.6	-25
0.1	73	10	5.0	-100
0.0	100	0	∞	$-\infty$

III. THE STABILITY ANALYSIS TOOL

We have implemented a DFII based tool to carry out the task of running a number of circuit simulations determining each circuit node's *stability peak* value, more precisely – loop's *performance index* and *natural frequency* by the method described in sections I and II. The tool is integrated with Analog Artist™ simulation environment through OCEAN™'s application programming interface (API) functions. Although the tool presently supports only Spectre™ circuit simulator, tool's open and modular programming approach will easily allow for use of other circuit simulators (TIs Spice, cdsSpice™ etc.).

¹ Complex zeros (positive peaks in this plot) do not directly affect systems stability. In few cases though, it is important to consider the relative position

of a complex zero with respect to a close complex pole to determine the significance of the complex pole on the overall system stability.

A. Tool Features

At present, the following features are fully implemented:

- "Single Node" run mode - computes/simulates the stability peak and natural frequency of a single (selected on schematic) node (net). Generates stability peak plot and computes estimated phase margin
- "All Nodes" run mode - computes stability peaks and natural frequencies for all² nodes in the circuit/sub-circuit.
- Automatic & Manual Model Setup - auto-configures simulation device model files (if existing environment setup is present), or allows for manual setup/configuration.
- Design Variables Support - existing design variables are imported and configured through a GUI
- "All Nodes" run report - a sorted by each node's natural frequency text report is generated.
- Stability Peak's Special Cases Identification - the "All Nodes" report has been recently augmented with notices alerting the user of special cases: "end-of-range" and "min/max" peak types.
- Analog Artists' scale environment variable support.
- Annotation of Results on circuit schematic.
- Automatic Error and Diagnostic Reporting - auto-generated e-mails will be sent to help in error resolution and tool support.

B. Features in development

The following features are in various stages of implementation:

- Auto-zero all AC sources / stimuli in design prior to running the analysis
- Save and restore original Analog Artist result directory settings*
- Remote simulation/distributed/computer farm run capability
- In-tool corners setup
- In-tool sweeps (TEMP etc)

IV. TOOL'S ARCHITECTURE

The tool programming structure is benefiting from modularized code architecture and existing application programming interface (API) functions to interface with the CAD environment of Design Framework II (DFII). The latter approach allowed us to write code that is tool-independent as much as possible providing for future functionality expansion and support for different circuit simulators. The tool is programmed entirely in SKILLTM utilizing OCEANTM and Analog Artist's API calls to control DFII's Simulation EnvironmentTM (SE) and a target circuit simulator (SpectreTM). Although the tool uses resources generally

controlled through Analog Artist's interface, active Analog ArtistTM session is not required for the tool to run. The simulation environment setup, simulation job control and simulation results processing is done through OCEAN procedural calls. The simulation task itself is carried by a circuit simulator ("Spectre" in our case). Generalized tool architecture is shown on Figure 2.

V. PROGRAM FLOW CONTROL

Tool's procedural control starts with the user selecting either a single-node run mode or all-nodes run mode. In the case of a single-node analysis, an AC-current stimulus source is automatically attached to the net/node selected by the user on the schematic this and an AC-simulation is run across a broad frequency range. The small-signal amplitude of the response is obtained from the simulation results, and the stability plot function (1.3) is used to create the *stability plot* and to estimate the phase margin based on (1.4) and [1].

In both a single-node and all-nodes analysis runs it is challenging to obtain most of the simulation setup parameters (including design variables) automatically from a "current" Analog Artist session. Because there may be more than one active Analog Artist sessions, the auto-configuration of the simulation settings and options is not always trivial. At present current Analog Artist session is considered to be the session referred to by the session-ID returned from `asiGetCurrentSession()` call. In the future, it is planned to offer a user a way to browse and select from not only his currently active Analog Artist sessions, but also to be able to choose a previously saved Analog Artist's "state" and load most of the simulation setup from there. Due to inconveniences in obtaining the input argument (`sevSession-ID`) for most of the

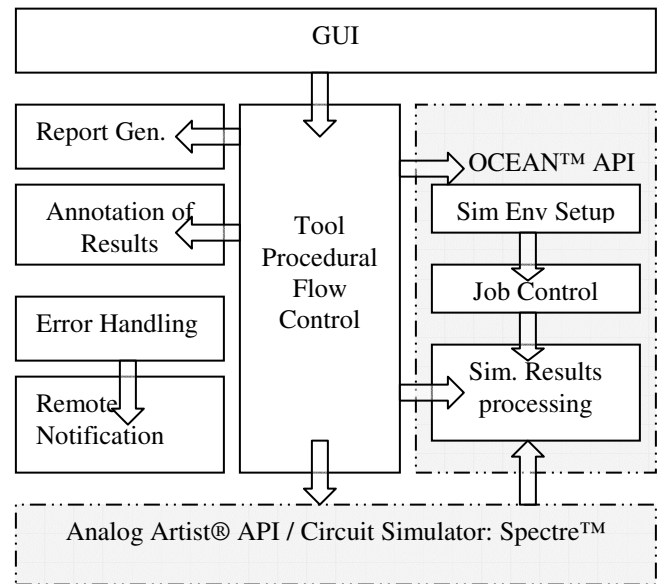


Figure 2 Stability Analysis Tool architecture

² Note: if the run is started while descended into a sub-circuit schematic, only the nodes of this sub-circuit will be analyzed

sev-prefixed procedural calls (sevSaveState(), sevLoadState() etc.) these functions prove not to be very useful. At future time, when the tool is to be integrated fully under Composer/Analog Artist's GUI these functions will be used and their usage will simplify many of the tasks that need more complex implementation at present.

VI. SUMMARY AND FUTURE DEVELOPMENT

As already mentioned a number of features are being added or pending implementation: remote server simulation and distributed computer farm run control, in-tool corner simulation, in-tool DC-sweep (TEMP, device parameters) simulation, importing configuration from Analog Artist's state files and others. Nevertheless, even with the functionality that is offered at present, the tool proved to be very useful in the troubleshooting and analysis of AC-stability problems in a wide variety of linear circuits. The advantages of the method described combined with the automation of the simulation tasks by the tool are easily evident and encourage further development of the functionality of this tool.

ACKNOWLEDGMENT

M. Milev thanks Rod Burt for the wonderful opportunity to develop the stability analysis tool based on [2], for his valuable suggestions on the tool usability and features, and for his help proofreading the initial draft of the paper.

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