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OPERATIONAL AMPLIFIER MACROMODELS: A COMPARISON

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All major competitors in the operational amplifier markets are providing their customers Spice-based macromodels. These models give the designer a tool to do initial characterization and a limited amount of system troubleshooting. In the interest of faster simulation times and lower CPU memory requirements, macro topologies have been developed to simulate a majority of the op amp's performance characteristics. Several different approaches to creating macromodels have been used, each producing a macro with its own set of strengths and weaknesses. Circuit simulations have become increasingly important to the systems level designer. By using macros, the designer can quickly determine gross limitations of their design and correct potential problems in the circuit quickly at the computer terminal. Although it is not recommended that circuit simulation replace the bread board, many costly design problems can be quickly identified during the simulation cycle. By using a macromodel as a simulation tool, the designer may be able to shorten the design cycle of their circuit. This, of course, assumes that the model's level of accuracy is adequate for the design's constraints and trade offs. If the systems designer is aware of the capabilities and limitations of the macro that has been selected for the simulation phase, the entire design cycle can be significantly reduced. Many of the macro's limitations can also be overcome with easily implemented enhancements to the basic macromodel architecture, depending on the specific application requirements. A good selection of the correct model with appropriate enhancements enables the designer to use the op amp macromodel as an effective tool in system level circuit design.

Historically, circuit simulation tools, such as SPICE[1], were developed for the integrated circuit designer. SPICE uses detailed mathematical formulas, which emulate the behavior of actual devices. The IC designer uses simulation tools, such as SPICE, extensively during the circuit design cycle. The level of sophistication that the IC circuit designer requires is that every element is simulated as closely to actual performance as possible. As a consequence, the majority of elements in the simulated circuit are non-linear elements, such as bipolar transistors, field-effect transistors, etc. Because of the complex behavior of these non-linear elements in the Spice simulation environment, these elements require more simulation time and computer memory. With increased integrated circuit complexity, performance and size, simulation time and computer memory have become critical simulation constraints for the software and systems used by the IC designer.

This limitation has prevented the systems level designer from taking full advantage of the same simulation tools. As a result, macros have gained popularity as an alternative tool for circuit simulation at the systems level. Op amp macros are designed to model specific, predetermined amplifier characteristics. When Spice is used as the preferred software, the op amp macro is typically developed with one of two basic design approaches.

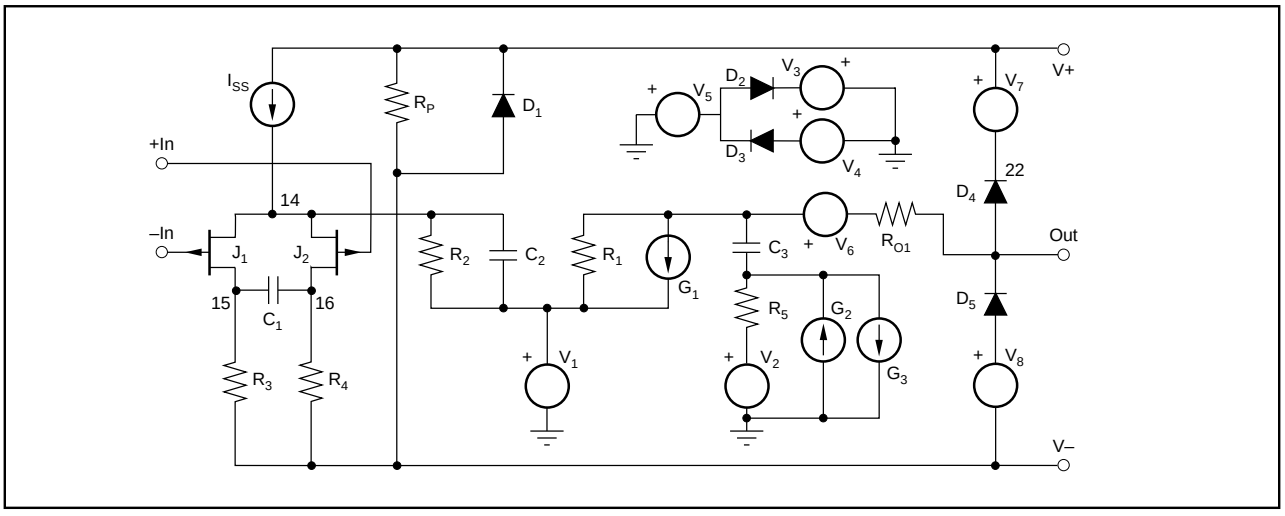

FIGURE 1. Boyle Macromodel Used to Simulate Operational Amplifiers.

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MACROMODEL DESIGN APPROACHES

The first basic macromodel design approach involves reducing the complexity of the circuit. For example, the input stage of an op amp can be reduced to a differential pair with a resistive load, biased with a current source. The actual op amp could have a cascoded differential input with active load and the current source biasing the input stage would be built using a transistor that would have the non-linearities associated with early voltage and collector resistance, etc. Throughout the macromodel circuit, transistors that are deemed non-critical are replaced with linear elements, such as current sources, resistors, etc. The reduction in complexity reduces the number of nodes in the circuit as well as the number of non-linear devices, both of which will reduce simulation time. To reduce simulation time even further, the transistors are as near to ideal as possible. This is done by reducing the number of transistor model parameters. The obvious benefit of this macromodel design approach is a reduction in simulation time; however, op amp performance is compromised to some extent. For example, the input stage of the model described does not model the common-mode input range of the amplifier properly.

A second method that is used in macromodelling is the build method. When this method is used, the designer of the macro characterizes the performance of the op amp and then builds the macro out of ideal linear elements, such as resistors, inductors, capacitors, dependent sources and independent sources. A good example of this topology would be the op amp hybrid pi-model where the input stage of the amplifier is a resistor. The voltage across that resistor is sensed by the gain stage, etc. The simulation time of this type of model is significantly faster than the first macromodel design method; however, the op amp performance is compromised to a great extent with this approach.

THE BOYLE OP AMP MACROMODEL

The Boyle Op Amp Macromodel[2] was designed using the simplification method to design the input stage and the build method for the remainder of the macro design. As shown in

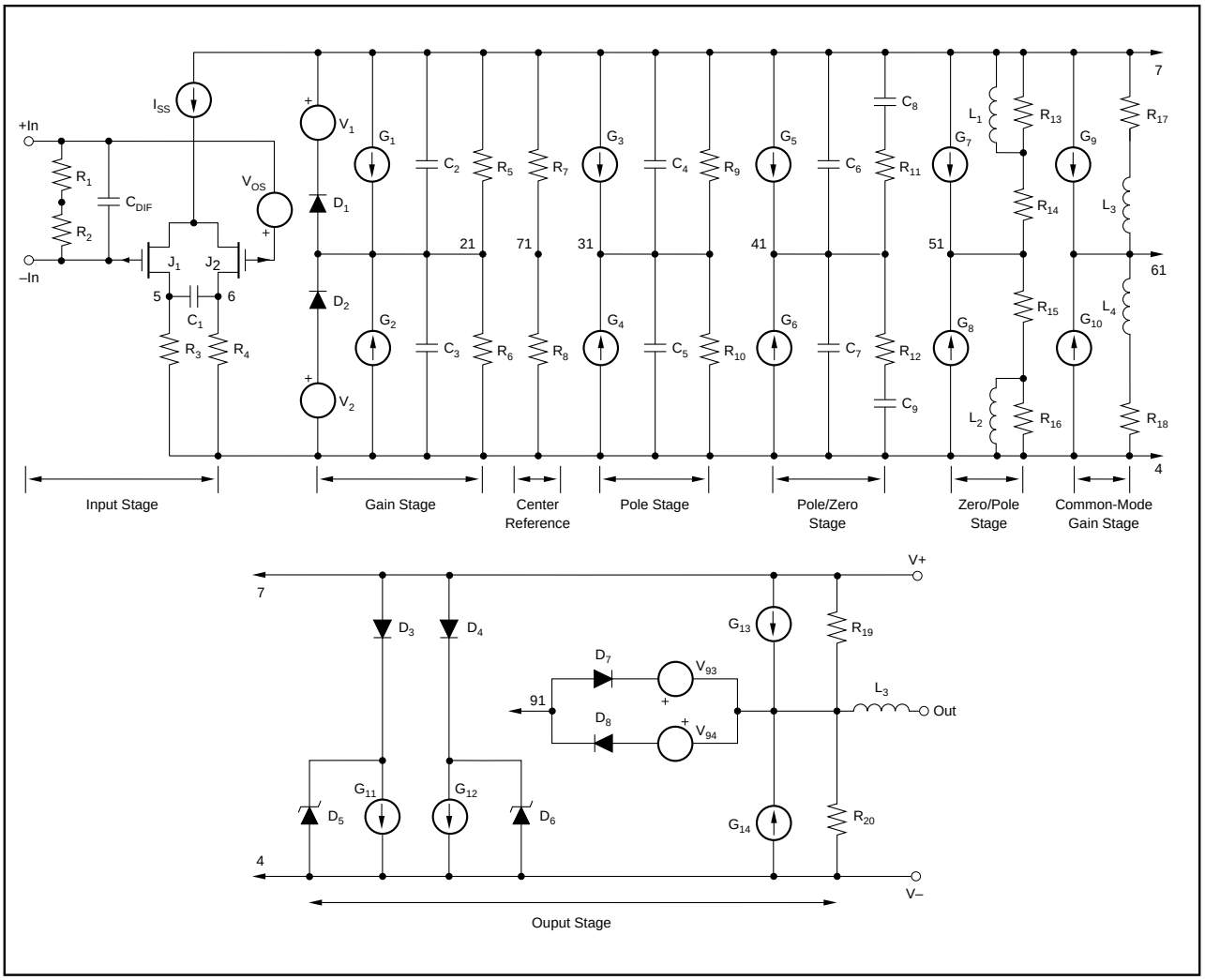

FIGURE 2. MPZ Op Amp Macromodel Blocks. Duplicate phase blocks are allowable in the macromodel design.

Figure 1, the only transistors in the Boyle model are used for the input differential pair of the op amp. All other elements are linear devices with the exception of a few diodes that are used as clamps. The ac parameters that this model topology simulates are slew rate, unity gain frequency, gain/phase for a one or two pole amplifier and a simplified ac output resistance. DC characteristics modelled are quiescent current, short circuit output current, output voltage swing maximums and minimums, input bias current, common-mode rejection ratio, and dc output resistance. The Boyle macromodel performance characteristics listed above suffice for many general applications. However, temperature performance, common-mode input range, offset voltage, offset current, input protection, power supply rejection, noise, THD, input impedance, good ac output resistance, and change in supply current versus supply voltage are a few of the more important parameters that are not modelled with the Boyle macro topology. Several op amp vendors have chosen to design their macros around the Boyle topology. Of the companies using the Boyle model that were researched, all added enhancements to the Boyle model to include a few more operational amplifier performance features.

THE MULTIPLE POLE/ZERO MACROMODEL

Another popular topology using both macromodelling methods is shown in Figure 2. The model shown in Figure 2 and the Boyle model (Figure 1) have identical input stages, but all of the remaining stages are different. This topology evolved from several sources[3,4] and is named after the midsection of the model, multiple pole/zero or MPZ. The midsection of this model can be expanded to include additional poles, pole-zero, or zero-pole stages. The MPZ macro has the same dc performance characteristics as the Boyle model as well as input offset bias current, input offset voltage and input differential impedance. The ac parameters that this model topology simulates are slew rate, unity gain frequency, gain/phase for a multiple pole/zero amplifier, CMRR versus frequency, and a simplified ac output resistance. In addition, the MPZ macro models change in quiescent current versus change in supply voltage, has no ground reference, and splits the output current between the supplies instead of sinking and sourcing from ground. A few of the MPZ limitations are a lack of temperature performance, poor modelling of common-mode input range, no input protection circuitry, no power supply rejection, no noise, no THD, and the ac output resistance is modelled with a one zero system.

THE BOYLE MACROMODEL VERSUS THE MPZ MACROMODEL

When comparing op amp macro performance, there are two simulation characteristics that are critical to the systems designer. The macro must model the electrical performance of the op amp in the designer's application of interest, and secondly, the macro must perform the simulation in a reasonable amount of time using a reasonable amount of computer memory.

When comparing the electrical performance of the Boyle model versus the MPZ model, the MPZ model provides several additional performance characteristics that the Boyle does not. For instance, the MPZ model models the same DC parameters that the Boyle model does and additionally input offset voltage and input offset bias current. The MPZ macro lacks a reference to ground which is sometimes convenient in level shift circuits where the Boyle model has several ground references in the circuit. Additionally, the MPZ macro draws output current from the supplies' nodes instead of the ground node. This is useful when power supply requirements are evaluated. The real power of the MPZ macro, however, is in the ac domain. If an op amp has more than two poles and/or additional pole/zero pairs in its transfer function, the Boyle model is unable to do an adequate job simulating the op amp.

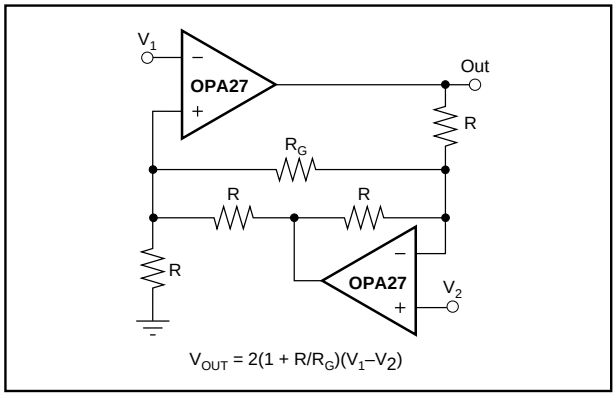

FIGURE 3. An Instrumentation Amplifier Using the Industry Standard OPA27.

To demonstrate this, the application in Figure 3 was chosen. A test to determine the ac accuracy of an op amp macromodel that is frequently recommended is to compare the simulated unity-gain transient response of the op amp to the actual performance of the device at the bench. Although this is a good place to start when performing the macromodel ac performance verification, most macros are optimized to have the correct gain/phase at the zero crossing of the transfer function (see Figures 4 and 5). When the application demands that the op amp macromodel performs with various configurations, the real power of the MPZ macromodel topology is easily demonstrated. The OPA27, a generic amplifier, is used to demonstrate. The simulated results of Figure 3 are shown in Figure 6. In Figure 6, the excessive phase of the two op amp instrumentation amplifier is modelled successfully by the MPZ macro (19.2% overshoot) and unsuccessfully by the Boyle model (9.3% overshoot). The scope photo in Figure 7 verifies the MPZ as being the more accurate macro for this application. On the other hand, the Boyle macro outperforms the MPZ macro in better simulation time and use of computer memory. When simulating one op amp, this is not a critical issue: however, in multiple amplifier applications the MPZ macro becomes CPU hungry. Assuming no convergence problems exist in the macros, the operating-point calculation is largely a function of

the number of circuit elements specified in the net list. With increased op amp complexity, the MPZ macro quickly begins to consume more simulation time. Similarly, the overhead run time of the ac analysis increases with each additional element. The transient analysis is much more difficult to quantify, because of numerous factors that come into play. The primary players are the number of transient iterations and the accuracy of the result needed for each calculation. In many instances, the MPZ macro will require that the programmer change the default values of the two variables in the .OPTIONS statement of Spice by increasing the number of iterations from 10 to 40 (ITL4) and changing the relative tol from 0.001 to 0.01 (RELTOL). If the designer can afford to sacrifice accurate ac performance from the macromodel, the Boyle model is the better choice.

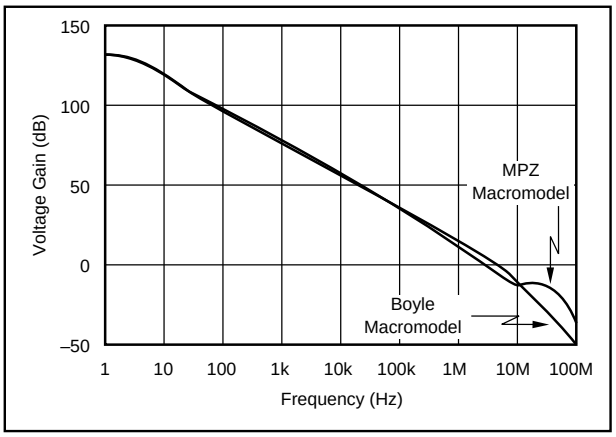

FIGURE 4. Spice Gain Plots of the OPA27 Boyle and MPZ Macromodels.

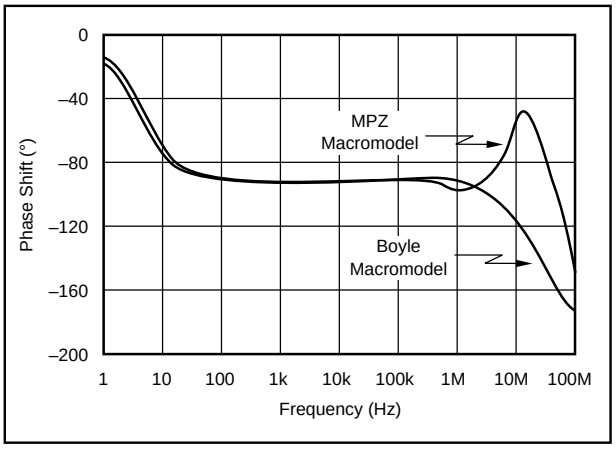

FIGURE 5. Spice Phase Plots of the OPA27 Boyle and MPZ Macromodels.

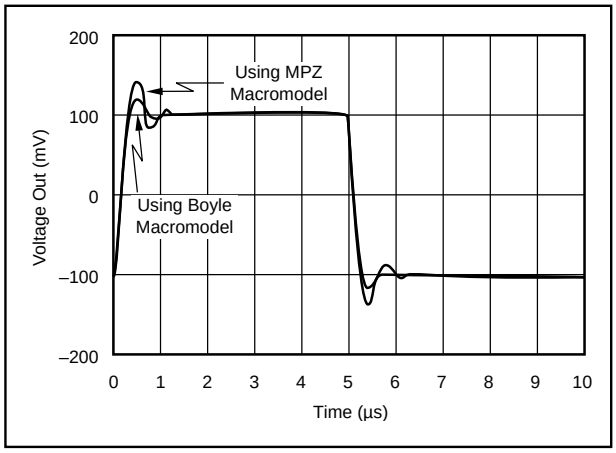

FIGURE 6. Spice Simulation of the Small Signal Transient Response of the Instrumentation Amplifier Shown in Figure 3.

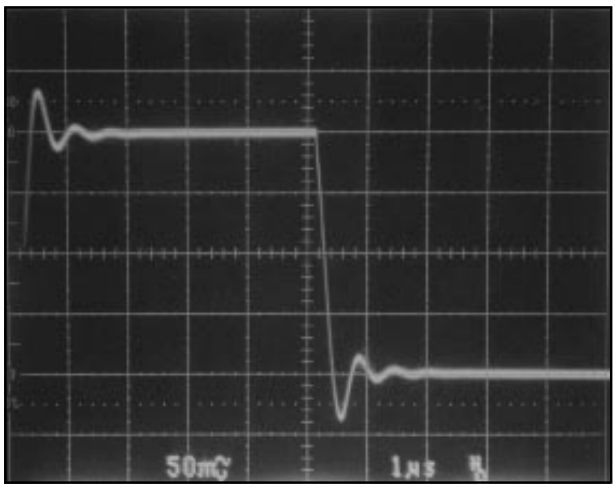

FIGURE 7. Scope Photo of the Small Signal Transient Response of the Instrumentation Amplifier Shown in Figure 3.

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